PITTSBURGH CONFERENCE ON BL LAC OBJECTS

Edited by
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University of Pittsburgh
Department of Physics and Astronomy
1978

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PREFACE

Bl Lac objects are some of the most enigmatic objects in the Universe. While it is generally agreed that they are radio sources associated with star-like objects that emit strongly polarized and highly variable light, there is widespread disagreement over what other properties define the class. For example, is variability in radio flux or absence of emission lines a defining characteristic? They have attracted the attention of astronomers because of their clear relationship to QSOs on the one hand and galaxies on the other. Equally important they have called attention to a source of energy that is extremely compact and well ordered, even for a QSO-like object; one often encounters phrases such as "naked radio source" and "we are looking directly at the primary energy source" in the pages which follow. Thus BL Lac objects are distinct both in occupying an extreme location in the landscape depicting the QSO phenomenon, and exhibiting redshifts that in some cases satisfy everyone's (i.e., almost everyone's) criteria for being cosmological in origin.

Although they arrived on the scene just a few years after the discovery of QSOs, BL Lacs did not have the same impact on the astronomical community because of the sparse information retrievable from objects believed to emit only continuum radiation. All of this has recently been changed by (1) the discovery of stellar absorption lines and faint emission lines in BL Lac itself and in quite a few other BL Lacs; (2) the highly sensitive optical polarization surveys which have provided a crucial link between BL Lacs and the optically violent variable QSOs (OVVs); and (3) observations of radio polarization and variability which have indicated severe restrictions on physical models for compact radio sources. And these are just a sample of the exciting research activities underway. The result of these achievements was an evolution in our perception of BL Lac objects and a rapid growth in the number of conflicting observational results and theoretical ideas. It became evident that the time was ripe to hold a discussion meeting.

The idea of organizing a meeting on BL Lac objects arose in conversations between the Editor and friends in Pittsburgh. Further discussions among members of the organizing committee in Cambridge, England in the summer of 1977 resulted in the decision to hold the meeting in Pittsburgh during the spring of 1978. The purpose of the meeting was to sort out what was known, what was believed, what could be established, and what future observations and theoretical studies were indicated. As is customary for meetings of this type we planned to concentrate the scientific program around invited talks to be given by a small number of experts. This turned out to be impracticable due to the many new results that were coming forth in this fast changing field. The final program therefore contains papers of both types. They were distributed as follows: Discussion of the radio, optical and infra-red continua appeared on the first day of the meeting. UV and X-ray data, as well as optical and radio line data, were discussed on the second day. The third day began with a survey of theoretical models for compact radio sources, and ended with a panel discussion. The atmosphere at the meeting was one of excitement. Most of use felt that something new was being learned and that genuine progress was being made. It is hoped that the discussions following each paper and especially the panel discussion convey to the reader some idea of what was actually going on.

I wish to thank the following people: Mike Garfunkel, Chairman of the Department of Physics and Astronomy, for his encouragement at every stage of this venture; the NSF for making the necessary funds available; the other members of the organizing committee for expert advice that contributed to the success of the meeting; Karen Geisler, the conference secretary, for doing a difficult job so well; Virginia Rhodes for transcribing a difficult manuscript from tape; Ed Spiegel for giving a brilliant after-dinner speech; Ruth Garfunkel for organizing a wonderful cocktail party; and my wife Connie for arranging a magnificent banquet and contributing importantly to every aspect of the meeting. Finally, I want to thank the participants at the conference for making it what it was.

The Editor

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BL Lacertae Objects

A Survey and Review

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I. Introduction

Detailed reviews of the characteristics of those sources that are now referred to as BL Lac objects have been published (Kinman 1975, Stein, O'Dell and Strittmatter 1976) and it is not the purpose of this discussion to repeat the content of those summaries. Rather, it is the intent here to present some recent data and discuss the possible nature of these objects unencumbered by the censorship imposed by colleagues that insist that the truth of every statement be measured only by χ^2. In this spirit the probability that some of my interpretations are correct may be 75%, or 50%, or even only 10%. Nevertheless it is hoped that the ensuing discussion will stimulate future work so that our eventual degree of understanding will be substantially increased.

It was my assignment to "define BL Lac objects". Since this assignment was issued many one-sentence definitions have occurred to me, from those that are humorously ridiculous to those that at least attempt to be serious. For example, I might define BL Lac objects for the astronomical spectroscopist as totally uninteresting astronomical sources that are unworthy of investigation because they may exhibit neither emission nor absorption lines. To those who would disagree with this definition, or at least wonder why we are then having a meeting dedicated to discussing these objects, I would suggest that BL Lac objects are examples of our most direct observable link with the ultimate energy source of the quasi-stellar objects. To those who are still graduate students or postdoctoral research workers somewhat hesitant to incite possible antagonistic responses from more conservative senior colleagues, I would propose the "safe" definition that BL Lac objects are an extreme form of quasi-stellar objects with strong nonthermal continua extending from radio to optical frequencies. At least some of these objects exist as, or at, the nuclei of galaxies. As a purely formal matter, note that this definition requires following the lead of Burbidge and Burbidge (1967), who suggested broadening the original defining criteria for QSOs, "bearing in mind the discoveries made since these criteria were established" (p. 10 Burbidge and Burbidge 1967). Specifically it is proposed that the extended criterion, "Broad emission lines in the spectra, with absorption lines sometimes present" be further modified to include "or no observable lines at all."

Regarding the importance of the nonthermal continuum, I would like to hypothesize that if it is extrapolated to the ultraviolet it may be the prototype of the spectral-flux distribution required to photoionize the thermal gas of QSOs and thus be the origin of excitation of line spectra. If this is the case, the study of line spectra of QSOs may be telling us how the nonthermal spectral flux distribution extends to the ultraviolet. The study of the characteristics of this nonthermal source may be the means by which the origin of the enormous energy generated in the QSOs will be revealed.

II. Summary of Properties

The sources known as the BL Lac objects are generally characterized by being strongly variable at all wavelengths observed. Without any attempt to be comprehensive, strong optical variability has been noted from 0735 + 178 by Carswell et al. (1974), for example. Infrared variability has been observed for OJ 287 (Rieke 1972), 0235 + 164 (Rieke et al. 1976) and 0735 + 178 (O'Dell et al. 1978). It is generally the case, for those objects observed in the infrared part of the spectrum, that the optical and infrared flux changes are in phase, suggesting that the radiation in these wavelength bands arises in the same physical process. [By contrast, optical and infrared light changes of some novae are found to be quite out of phase indicating different origins of light in these bands. In this case it is thought that the observations can be explained by condensation of dust in the circumstellar region following the nova outburst (see eg. Ney and Hatfield 1978).]

The flux of radio frequency radiation has also been observed to vary rapidly with time during outbursts, as has been shown for objects such as OJ 287 (Kinman et al. 1974) and 0235 + 164 (Rieke et al. 1976). However, our understanding of the physical relationship between variability at radio wavelengths and that at optical and infrared wavelengths is quite incomplete. Pomphrey et al. (1976) examined data on several objects in a search for correlated optical and radio variability and found a statistically significant correlation only in the case of OJ 287 - a source that will be discussed further. It is also of interest that there was some indication of a radio flux increase after an optical-infrared outburst in this same object (Kinman et al. 1974). An examination of the data reveals that the relationship of the optical outburst to that at radio frequencies is not explainable on the basis of the expanding source model of nonthermal radio sources developed by Van der Laan (1966) and Pauliny-Toth and Kellerman (1966).

Other prominent characteristics of this class of objects are the relatively strong, featureless (frequently but not always) optical continuum and high degree of linear polarization. The lack of spectral lines may be explained in a variety of ways (Stein _et al_. 1976) but which of these is the correct explanation is yet to be determined for each source. Discrete spectral features at optical wavelengths (as in 0735 + 178, Carswell _et al_. 1974 and 0235 + 164, Burbidge _et al_. 1976, Rieke _et al_. 1976) and at radio wavelengths (as in the case of the 21 cm line in the spectrum of A0 0235 + 164 Roberts _et al_. 1976) when observed, have usually been seen in absorption. This indicates that thermal gas is present in some sources but that it is probably at relatively large distances from the source of nonthermal radiation. However, more recently, objects with strong nonthermal continua that do exhibit emission lines have been found, such as 1400 + 162 (Baldwin _et al_. 1977). The detection of lines is a problem that depends on contrast with the continuum and therefore on the strength of this variable component at any particular time. These objects represent examples of sources that are intermediate between objects that normally would be called QSOs and those with no lines.

The high degree of variable linear polarization observed (as in 0735 + 178 Carswell _et al_. 1974) indicates a nonthermal origin of the optical continuum and that this nonthermal radiation is not highly diluted by unpolarized sources of radiation such as that from stars or thermal gas. By contrast, objects containing much dust may exhibit some polarization by scattering processes (e.g. NGC 1068 Angel _et al_. 1976). Further, in the case of the highly polarized BL Lac objects the geometry of the source of the nonthermal continuum is relatively uniform - not randomly chaotic. If this were not the case the net polarization observed would be relatively small due to the cancellation of polarization from various regions within the source averaged over the beam diameter.

It has been shown that at least some of these BL Lac objects (which clearly have properties in common with at least some QSOs, as will be discussed later) are situated at, or may indeed be the nuclei of galaxies (Ulrich _et al_. 1975, Thuan _et al_. 1975, Miller, French and Hawley 1978). Since the Compton scattering dilemma first discussed by Hoyle, Burbidge and Sargent (1966), and in greater detail by Jones, O'Dell and Stein (1974a,b), clearly exists for BL Lac itself (adopting the now accepted redshift of z = 0.07) it is clear that this physical problem can no longer be used as a strong objection to the cosmological interpretation of redshifts of QSOs, _unless_ some galaxies in the universe do not conform to the _average_ redshift-distance relation of other galaxies (e.g. Tifft 1976). Although the association of some of these objects with galaxies may make some astronomers feel at ease with the universe, some astrophysicists working on the problem of the physical characteristics of energy generation in QSOs are still severely disturbed. For if objects such as BL Lac are at distances implied by the measured redshift and the Hubble relation, then the Compton scattering difficulty is not necessarily solved. Relativistic expansion of the source may be involved but further work is necessary to establish this since the observable nonthermal dynamic behavior of relativistically expanding sources has not been worked out in detail and compared with observations.

III. Recent Evidence on the Relationships Between Optical, Infrared and Radio Frequency Radiation

A. Continuity of Spectral-Flux Distribution

Since there is independent evidence at both radio and optical frequencies (through variability and polarization) of a nonthermal origin of radiation it is natural to explore the possibility that the spectrum of radiation extends smoothly through intermediate frequencies (as in the case of the synchrotron component of the Crab Nebula). Further, it is reasonable to hypothesize a common origin for radiation at all frequencies if continuity can be established. Unfortunately most of the sources are faint at the intermediate infrared and submillimeter wavelengths and the opacity of the terrestrial atmosphere obscures radiation over a wide spectral range. This makes it impossible to demonstrate continuity of the spectrum from radio to optical frequencies at the present time. Observations from space may eventually conclusively establish continuity.

Data at infrared wavelengths have been obtained on some sources. Such information on BL Lac was originally obtained by Oke et al. (1969). Strittmatter et al. (1972) observed the continuity of spectral-flux distribution from optical to infrared wavelengths of several sources and suggested that they were a class of QSOs. More recently data has been obtained on B2 1101 +38 and B2 1652 + 39 (Ulrich et al. 1975) showing similar properties of these BL Lac objects in galaxies. OJ 287 (Kinman et al. 1974, based on data of Rieke 1972) and A0 0235 + 164 (Rieke et al. 1976) have also been shown to exhibit continuity of nonthermal emission from optical to infrared wavelengths. O'Dell et al. (1977) showed that the spectral flux distribution of some objects of this type turn over steeply at visual wavelengths while others (e.g. 0735 + 178) are power law in character to the highest frequencies observed. However, there is considerable uncertainty involved in ascertaining the intrinsic shape of the spectral-flux distribution of some of these sources because of nonuniformity of interstellar reddening in our galaxy (see Heiles 1976 for a review of this problem).

The relationship of the optical-infrared spectral-flux distribution to that at radio frequencies has been investigated for only a few objects. The data of Kinman et al. (1974) on OJ 287 imply continuity to radio frequencies but this has not been conclusively demonstrated. An investigation of some of the brightest

3mm sources showed evidence for a relationship between non-thermal radiation at 3mm and that at infrared and optical wavelengths (O'Dell et al. 1978).

In summary, although radiation observed at radio, millimeter, infrared, and optical frequencies would appear to be related in at least some sources, lack of data over large ranges of the spectrum demonstrates the necessity of obtaining other evidence regarding the spectral continuity question.

B. Temporal Behavior of Spectral-Flux Distribution

The relationship between fluctuations of brightness at various wavelengths should contain information on physical conditions in the nonthermal source region of QSOs. Pomphrey et al. (1976) examined optical and radio flux variations statistically for a number of sources. Only for OJ 287 did it appear that there was any relationship. As discussed previously, this same source was studied in a coordinated effort at various wavelengths during a major outburst by Kinman et al. (1974). These observations indicate that an outburst at visual wavelengths was followed eventually by increasing flux at radio wavelengths. The development of the outburst as a function of time and frequency was clearly not in accord with theories of expanding nonthermal radio sources (van der Lann 1966, Pauliny-Toth and Kellerman 1966).

A significant change in the shape of the optical-infrared spectral-flux distribution of AO 0235 + 164 was observed approximately one year after a major outburst (O'Dell et al. 1977) although no change has been observed on time scales of months (Rieke et al. 1976).

Recent data obtained at the Mt. Lemmon Observing Facility of UM and UCSD on variable sources are summarized in Figures 1 through 4 (O'Dell et al. 1978). The most dramatic flux variations observed have occurred in the objects 0235 + 164, 0735 + 178, 0821 + 202 (OJ 287), 1308 + 326 and 1400 + 162. Pronounced changes in the shape of the visual-infrared spectral-flux distributions are observed to occur during transition phases of outbursts. The changes are most likely in the sense of becoming more curved downward toward higher frequencies during an increase in flux, straightening again toward a power law, and eventually becoming more downward curved again some time after maximum in the outburst. These changes in spectral-flux distribution during outbursts should be explainable in terms of high energy particle injection and energy loss processes. Compton scattering clearly must be an important process in these compact sources since the radiation energy density must be very large. The theoretical analysis of the characteristics of how such spectral-flux distributions develop in time and relate to radio outbursts have not yet been attempted. It is hoped that data such as that

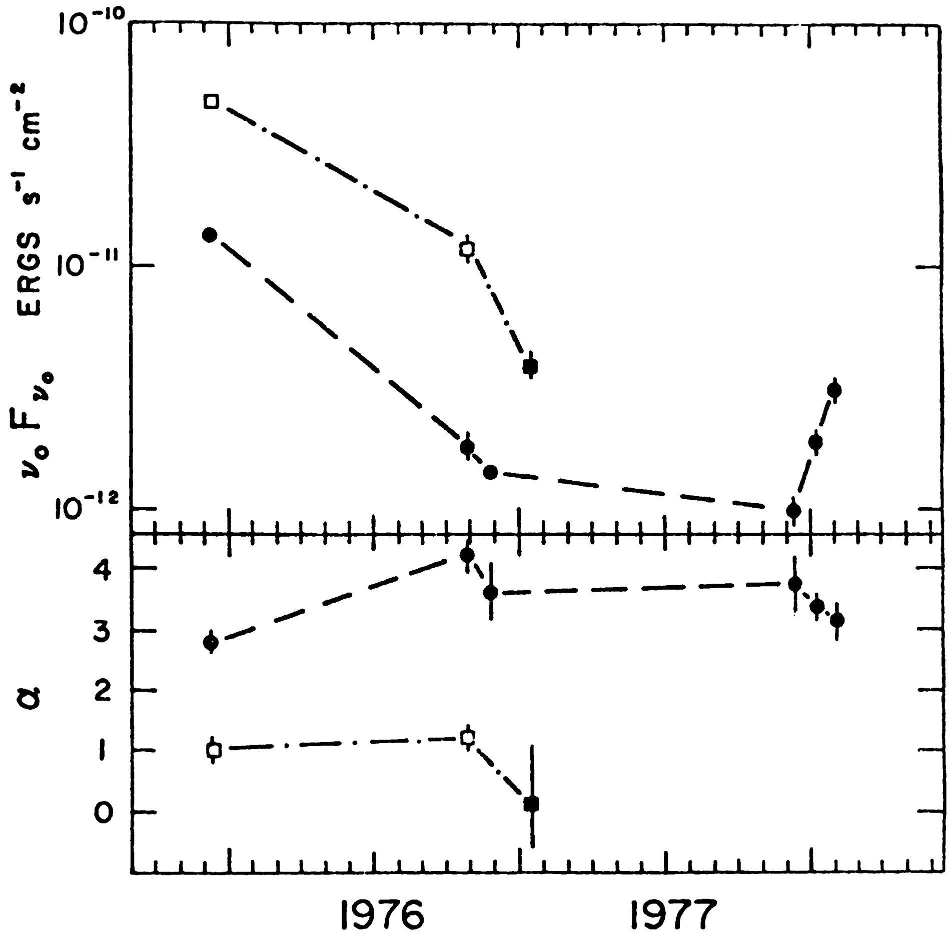

Figure 1

Monochromatic energy flux ($\nu_O F_{\nu_O}$) and spectral index (α) are plotted versus time (in months) for 0235 + 164. The square symbol refers to power law fits in the infrared (ν_O = 136 THz) while the circular symbol refers to fits at visual frequencies (ν_O = 540 THz). One sigma error bars are shown where appropriate. Filled symbols are used for measurements made with a 1mm (9arcsecond) aperture and open symbols are used for 2 and 3mm (13 and 27 arcsecond) aperture measurements.

[Data shown from "The Changes in Spectral-Flux Distribution During Variability of Extragalactic Nonthermal Sources 0.36μm - 3.5μm" by S.L. O'Dell, J.J. Puschell, W.A. Stein and J.W. Warner. Details of this work are published in The Astrophysical Journal-Supplement Series by University of Chicago Press. Application for permission to quote should be addressed to the Production Manager, The Astrophysical Journal, University of Chicago Press.]

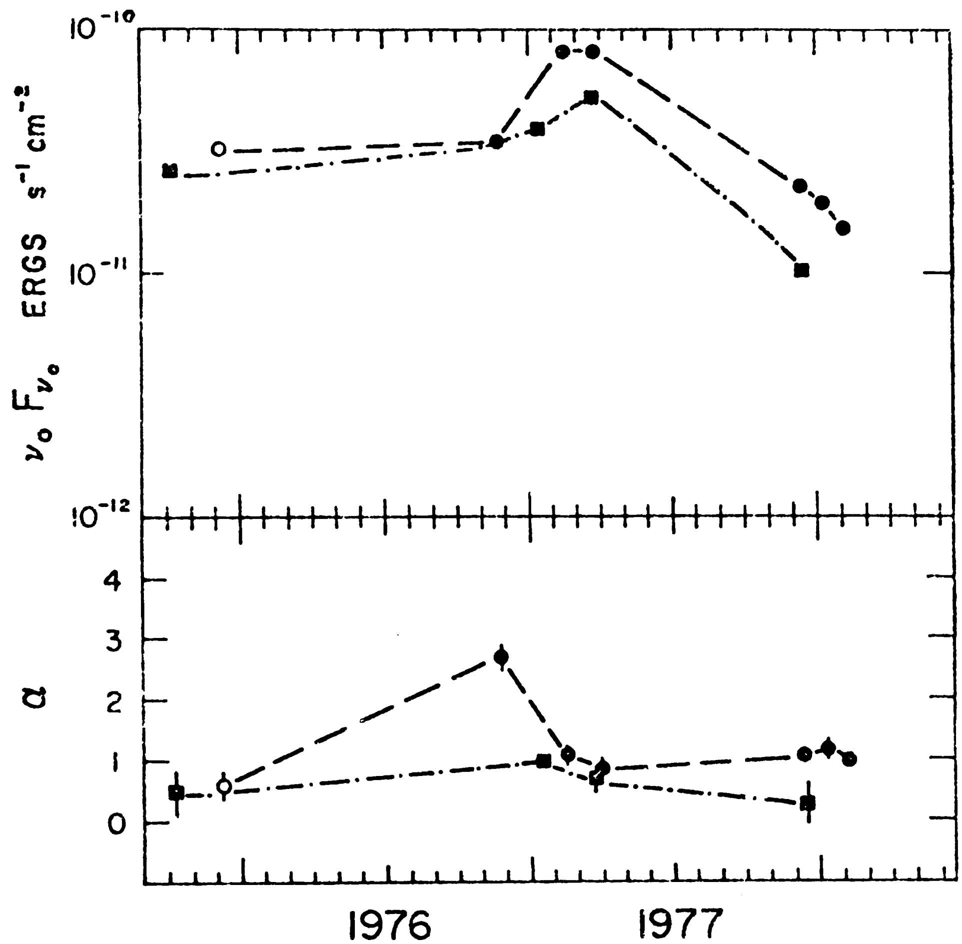

Figure 2

Monochromatic energy flux ($\nu_o F_{\nu_o}$) and spectral index (α) are plotted versus time (in months) for <u>0735 + 178</u>. The square symbol refers to power law fits in the infrared (ν_o = 136 THz) while the circular symbol refers to fits at visual frequencies (ν_o = 540 THz). One sigma error bars are shown where appropriate. Filled symbols are used for measurements made with a 1mm (9 arcsecond) aperture and open symbols are used for 2 and 3mm (18 and 27 arcsecond) aperture measurements.

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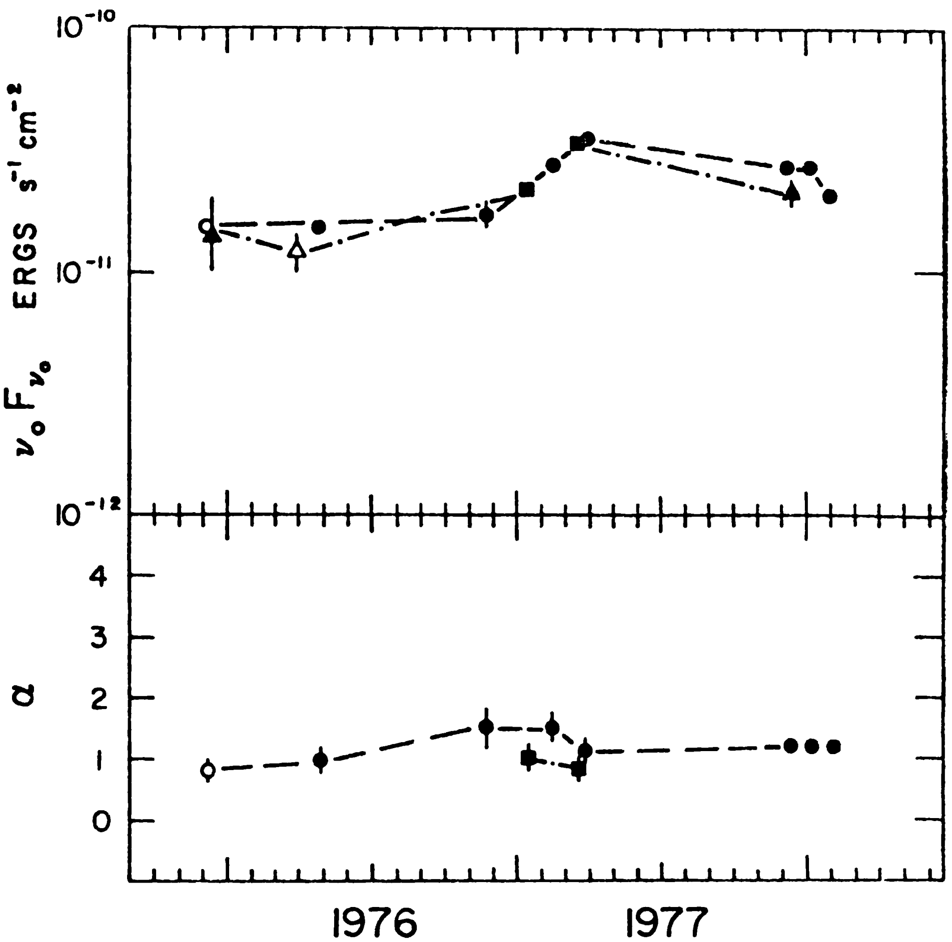

Figure 3

Monochromatic energy flux ($\nu_o F_{\nu_o}$) and spectral index (α) are plotted versus time (in months) for 0851 + 202. The triangular symbol refers to specific measurements of ν_o = 131 THz. One sigma error bars are shown where appropriate. Filled symbols are used for measurements made with a 1mm (9 arcsecond) aperture and open symbols are used for 2 and 3mm (18 and 27 arcsecond) aperture measurements.

[Data shown from "The Changes in Spectral-Flux Distribution During Variability of Extragalactic Nonthermal Sources 0.36μm - 3.5μm" by S.L. O'Dell, J.J. Puschell, W.A. Stein and J.W. Warner. Details of this work are published in The Astrophysical Journal-Supplement Series by University of Chicago Press. Application for permission to quote should be addressed to the Production Manager, The Astrophysical Journal, University of Chicago Press.]

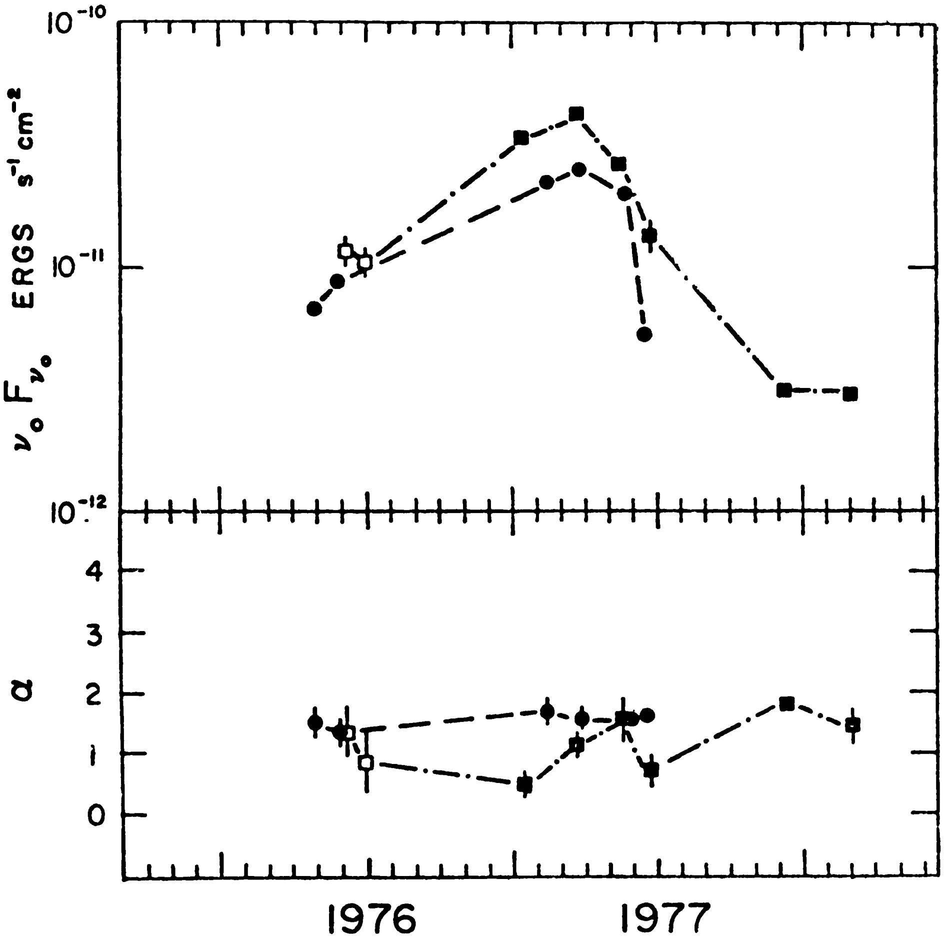

Figure 4

Monochromatic energy flux ($\nu_o F_{\nu_o}$) and spectral index (α) are plotted versus time (in months) for 1308 + 326. The square symbol refers to power law fits in the infrared (ν_o = 136 THz) while the circular symbol refers to fits at visual frequencies (ν_o = 540 THz). One sigma error bars are shown where appropriate. Filled symbols are used for measurements made with a 1mm (9 arcsecond) aperture and open symbols are used for 2 and 3mm (18 and 27 arcsecond) aperture measurements.

[Data shown from "The Changes in Spectral-Flux Distribution During Variability of Extragalactic Nonthermal Sources 0.36μm - 3.5μm" by S.L. O'Dell, J.J. Puschell, W.A. Stein and J.W. Warner. Details of this work are published in The Astrophysical Journal-Supplement Series by University of Chicago Press. Application for permission to quote should be addressed to the Production Manager, The Astrophysical Journal, University of Chicago Press.]

presented here will help motivate further studies of this type in which various models for particle injection, energy loss, geometry, etc. may be examined.

C. Polarization

Supporting evidence in favor of the common origin of at least the variable optical and infrared radiation from BL Lac was provided through measurements of polarization. The linear polarization of the optical and infrared radiation from this object was found to be the same both in degree and position angle to within the accuracy of the measurements (Knacke et al. 1976). Subsequent measurements of 0735 + 178 and B2 1101 + 38 (Rieke et al. 1977) seem to indicate a common origin of infrared and optical polarization in these sources as well. There is an indication of a small change of position angle from optical to infrared wavelengths in data on 0735 + 178. A large difference in position angle between optical and infrared was observed in the same work for OI 090.4. It is not certain how to interpret such a rotation and it is important to find if other sources exhibit such a characteristic. The most obvious implication is that nonthermal radiation at various frequencies arises in spatially separate regions.

The above evidence has little bearing on the question of the relationship between optical-infrared emission and that at radio frequencies. Recent data (Table 1) indicate that at least some objects exhibit strong linear polarization at millimeter wavelengths (Rudnick et al. 1978). The degree of linear polarization was high and the position angle measured for OJ 287 was shown to be the same from optical to radio frequencies. The degree of polarization slowly decreased with frequency over this broad span of the spectrum. BL Lac exhibited the same degree and position at optical, infrared and 3mm wavelengths within errors. These data constitute strong evidence for a common origin of radiation over this broad span of frequencies from these sources. However, in some objects, complications may arise at longer radio wavelengths due to possible multiple components, optical depth effects, Faraday rotation, etc. The high degree of polarization observed implies a rather uniform geometry for the region in which the radiation originates. Further data relating polarization at various wavelengths is anticipated in a series of coordinated radio, millimeter, infrared and optical observations. These data show that nonthermal emission at optical and infrared wavelengths is most strongly related to that at millimeter wavelengths rather than that at longer radio wavelengths.

D. X-rays

Most BL Lac objects that have been examined for X-ray emission have not been detected (Margon et al. 1976, Ulmer et al. 1976). At least one object, B2 1101 + 38 (Mk 421),

Source	Date	Wavelength Band	$I^{(mJy)}$	$Q^{(mJy)}$	$U^{(mJy)}$	$m^{(\%)}$	$n^{(°)}$
OJ 287	22-3 Nov, '77	3.7 cm	3500 ± 125	-254 ± 11	74 ± 5	7.6 ± 0.3	82 ± 3
	2-5 Dec, '77	9 cm	5150 ± 260	-430 ± 77	-45 ± 54	8.2 ± 1.5	93 ± 6
	5-7 Dec, '77	3 mm	4850 ± 240	-605 ± 77	-31 ± 77	12.4 ± 1.5	92 ± 6
	7 Dec, '77	2.28μm	20.8 ± 0.9	-2.9 ± 1.1	2.1 ± 1.4	17 ± 5	72 ± 10
	11 Dec, '77	0.44μm	2.9 ± 0.2	$-.63 \pm .06$	$.37 \pm .02$	25 ± 1	75 ± 1
	6-7 Jan, '78	0.44μm	3.1 ± 0.1	$-.87 \pm .04$	$.17 \pm .02$	28.4 ± 0.8	84.4 ± 1
	3-4 Feb, '78	0.44μm	2.4 ± 0.1	$-.33 \pm .04$	$.24 \pm .01$	17 ± 1	72 ± 2
BL Lac	22-3 Nov, '77	3.7 cm	3190 ± 160	-121 ± 5	154 ± 14	6.2 ± 0.4	64 ± 4
	2-5 Dec, '77	9 cm	2610 ± 130	-120 ± 57	82 ± 70	~5	~75
	5-7 Dec, '77	3 mm	2160 ± 110	128 ± 69	-15 ± 70	~5	~0
	7 Dec, '77	2.28μm	59.4 ± 6.1	3.0 ± 0.7	-2.9 ± 0.7	7 ± 1.7	158 ± 8
	11 Dec, '77	0.44μm	2.5 ± 0.1	0.19 ± 0.02	0 ± 0.02	7.6 ± 0.8	0 ± 3

Table 1 - Polarization as a function of wavelength for BL Lac and OJ 287

has been detected (Ricketts et al. 1976, Margon et al. 1978). Since compact sources of a high luminosity of synchrotron radiation should be ideal candidates for sources of synchrotron-self-Compton x-ray emission, it is somewhat of a mystery as to why many more have not been detected. A detailed examination of this question has not been published although the quoted upper limits have been used as input to the derivation of physical parameters in the synchrotron-self-Compton theory of Jones et al. (1974a,b).

IV. Continuity of Properties of BL Lac Objects and Emission Line QSOs

A discussion of the properties of BL Lac objects as QSOs should contain reference to examples of "normal" QSOs (those by which identification is based on relatively large emission line redshifts) that have properties in common with the BL Lac objects. The apparent gap between many of the observed characteristics of BL Lac objects and what might be termed "average properties" of QSOs is bridged by the violently variable QSOs. Examples of this class of QSOs are 3C 279, 3C 345, 3C 454.3 and 3C 446 (refer to the recent compilation of QSO data by Burbidge et al. 1977 for detailed references). These objects are observed to have emission line redshifts of 0.538, 0.595, 0.859, 1.404 respectively.

The early history of QSO research in general, including reference to many properties of the strongly variable sources, is summarized in the book of Burbidge and Burbidge (1967). Other reviews of the subject are those of Burbidge (1967), Schmidt (1969) and more recently Strittmatter and Williams (1976).

The properties that this class of QSOs has in common with the BL Lac objects are strong variability and highly variable polarization at both optical wavelengths (e.g. Visvanathan 1973, Stockman and Angel 1978) and radio wavelengths (e.g. Kellerman and Pauliny-Toth 1968). They are all relatively strong radio sources with spectra that exhibit the existence of a high frequency component characteristically demonstrated by F_ν increasing with increasing frequency in a manner similar to many BL Lac sources (Kellerman and Pauliny-Toth 1971, O'Dell et al. 1978). Such spectral behavior at high radio frequencies usually indicates the presence of a compact core source (Kellerman 1974).

There is some evidence that the optical continuum of QSOs of this class is steeper than other QSOs and more like that of at least some other BL Lac objects such as BL Lac itself (Strittmatter and Williams 1976). However note that many BL Lac objects have quite hard continua (e.g. $F(\nu) \propto \nu^{-1}$). In many cases it is very difficult to derive the intrinsic shape of the spectral flux distribution of extragalactic objects because of the uncertainties involved in correcting for interstellar extinction in our own galaxy (e.g. Heiles 1976).

An unbiased statistical analysis of the relative shapes of the continuum of emission line QSOs and BL Lac objects would be in order. However, it may be difficult to arrive at any definitive conclusions because of the uncertainties involved.

The matter of the continuity of objects with and without spectral lines is beginning to be resolved. At first it appeared that BL Lac objects were totally distinct from QSOs in exhibiting no spectral lines. Then objects with strong nonthermal continuum emission were found that contained only absorption lines in their spectra. The object 1400 + 162 was then discovered and it *exhibits a strong* nonthermal continuum *as well as a weak emission line. Another* subsequent example (3C 371) of an object with apparent *composite nature (galaxy,* emission lines, strong continuum) has been found by Miller (1975). Thus, as high quality spectral information is obtained on more sources it appears that the detection of lines is, at least to some extent, a problem of contrast with the strength of the continuum. A continuity of all properties with the "classical QSOs" appears to be emerging.

A further interesting question involves the relation between emission line QSOs that are radio sources, emission line QSOs that are not radio sources and the BL Lac objects which are generally only weak radio sources at centimeter and longer radio wavelengths. Recall that the radio spectra of the BL Lac objects frequently peak at millimeter (or perhaps submillimeter) wavelengths (e.g. O'Dell et al. 1978) and that the optical brightness of these objects seems to be more directly related to the millimeter wave flux than to that at longer wavelengths (see also Owen and Mufson 1977). Further, only a small fraction of QSOs identified in optical emission line searches appear to be radio sources (Sramek and Weedman 1978).

V. BL Lac Object Phenomena as the Most Direct Observable Link with the Energy Source of the QSOs

It seems widely accepted, if not proven for every object, that the source of emission lines of QSOs is photoionization of gas by a nonthermal spectrum extending into the ultraviolet (see summary discussions of Strittmatter and Williams 1976, Weedman 1977, Osterbrock 1978). These emission lines when observed redshifted, constitute one of the original defining characteristics of a quasi-stellar object *(Burbidge and Burbidge 1967).* It has been proposed (Stein, O'Dell and Strittmatter 1976) that BL Lac objects are an extreme form of the QSO phenomenon with unusually strong continuum, however, emission lines are absent (for a variety of possible reasons not to be reexamined here). Thus, it is proposed that the definition of a QSO should be extended to include sources that exhibit the nonthermal properties reviewed here.

What are the characteristics and origin of the nonthermal photoionizing spectrum hypothesized to explain the observed emission lines from "classical QSOs"? Unfortunately not much is known at present about the nonthermal continuum of QSOs with emission lines. The statements made generally describe such a continuum that is typically $F(\nu) \propto \nu^{-1}$ extending to ultraviolet wavelengths (see Strittmatter and Williams 1976 for a review of this aspect). A proper deduction of the shape of the nonthermal component requires subtraction of radiation from thermal gas components and reddening within our galaxy and also perhaps within the object. Note that a spectral flux distribution of $F(\nu) \propto \nu^{-1}$ is typical also of many BL Lac objects (O'Dell et al. 1977, although recall earlier comments about the uncertainty of correcting for interstellar reddening in our galaxy). As a working hypothesis it would seem reasonable to consider typical nonthermal BL Lac characteristics as being the prototype of the required nonthermal continuum of QSOs in general, with the strength of the nonthermal component being the variable parameter.

Models of quasi-stellar objects will generally have the following characteristics in common: (a) compact nonthermal photoionizing source of size less than 10^{17}cm (perhaps much smaller) surrounded by gas which is the source of emission lines and including some gas in the line of sight as the source of the absorption lines. The details of the physical origin of the nonthermal continuum from this core source are uncertain but it is probably explainable in terms of synchrotron radiation of high energy electrons producing radiation extending from radio to optical and ultraviolet wavelengths (Jones, O'Dell and Stein 1974a,b). The energy source may be a massive compact object (e.g. Lynden-Bell 1969, Pringle et al. 1973), massive rotating object (Morrison 1969), or some other entity not yet proposed. It would seem, however, that the characteristics and origin of the nonthermal continuum are our most direct observable link with the energy generator. The characteristics of the emission lines, absorption lines etc. raise interesting questions about radiation-gas coupling and lead to information about chemical abundances in QSOs (see Strittmatter and Williams 1976), but the lines are a secondary consequence resulting from a relationship similar to that of a galactic H II region to the photoionizing stars or the excitation of the filaments in the Crab Nebula to the pulsar generating the energy. Thus understanding the physical origin of the nonthermal spectral flux distribution of QSOs (at all frequencies) may be the only means by which we are eventually able to understand the source of energy of these objects.

Perhaps further speculation is premature. However, it is natural to attempt to understand the relationship of BL Lac objects, radio quiet QSOs, "normal" emission line QSOs originally identified as radio sources, radio galaxies, Seyfert galaxies etc. Are these various types of objects related in the sense of some variation of physical parameters, or are they related in some evolutionary sense? Answering this question is obviously one of the goals of research in this area. However, one scenario of the evolution of the continuum source might involve the generation of a nonthermal spectrum peaking originally at submillimeter or infrared wavelengths with little evidence of an optical or radio source; evolution into a BL Lac object with radio and optical emission - however with an inverted self absorbed radio spectrum; eventual evolution into a normal core - halo radio source such as that of the first QSOs discovered at radio frequencies.

VI. Problems

There are a number of questions that have arisen about the BL Lac objects for which there are still no satisfactory and conclusive answers. It is worthwhile outlining some of them so that no one is misled into believing that all the problems are solved. Some of the puzzles that remain are as follows:

(1) What is the relationship of these objects with active nuclei of galaxies such as Seyfert galaxies? Is there an evolutionary sequence, or do the various observable characteristics indicate different physical environments?

(2) How does a nonthermal spectral flux distribution extending from radio to optical frequencies naturally arise in these objects? It is popular to discuss compact massive objects as the energy source. If so, how are high energy particles accelerated and what spectrum is radiated?

(3) How is the importance of Compton scattering apparently minimized in these objects. A large number of high energy electrons in a high synchrotron radiation photon density would imply large fluxes of Compton scattered x-rays, yet there has been only one published detection up to this time at these photon energies (B2 1101 + 38 Margon *et al*. 1978). It is possible that relativistic expansion may be an important aspect of the problem (e.g. Rees 1967, Jones, O'Dell and Stein 1974a,b). Particle beaming may be another interesting possibility (Woltjer 1966).

(4) What is the physical process by which x-rays are generated in those BL Lac objects detected at these photon energies such as B2 1101 + 38 (Margon *et al*. 1978)? Compton scattering as discussed in item (3) (above) is the likely source but the details of this matter should be explored further. Is the origin of x-rays in these objects at all related to the origin of x-rays in Seyfert galaxies (e.g. Baity *et al*. 1975)?

(5) If the origin of emission lines in QSOs and active nuclei of galaxies is attributable to photoionization by a nonthermal source and if this nonthermal source is related to the BL Lac phenomenon, then what is the physical mechanism coupling the nonthermal source to the lines? Although astronomers have been working on interpretation of emission line spectra of QSOs for many years the details of interaction between the source of energy and the emission line region seem unknown (see review of Strittmatter and Williams 1976).

(6) If BL Lac objects are extreme examples of QSOs, some of which have been observed at, or as, the nuclei of galaxies, then other emission line QSOs should be imbedded in a galaxy of stars. This has not generally been demonstrated for "classical" QSOs. It has been shown that 3C 48 (Wampler et al. 1975) and 4C 37.43 (Stockton 1976) are apparently imbedded in rather extensive H II regions. On the other hand, if QSOs are not associated with galaxies of stars, then what is the origin of the heavy elements observed spectroscopically in emission and absorption?

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"The time has come for astronomy to take its place as a major branch of physics." (Fred Hoyle in Preface to Astronomy and Cosmology - A Modern Course, W.H.Freeman, San Francisco, 1975)

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DISCUSSION

F. PACINI:

(a) Could you compare the time scales involved in the variability at radio and optical wavelengths?

(b) Quote a rough figure for the shortest time scales over which the intensity varies by a factor of order 2 or so.

W. STEIN:

(a) There is some evidence of shorter time scales at optical wavelengths.

(b) At optical wavelengths significant changes have been observed on a time scale of $\sim$1 day.

M. BURBIDGE:

You spoke about steep spectra being perhaps produced by dust. What about the possibility of seeing the 2200 Å feature (dust-produced) in e.g. AO 0235+164, assuming $Z \geq 0.85$?

W. STEIN:

A search for such a feature would be an excellent idea. However it is a matter of signal-to-noise in scanner data. I'm not directly familiar with what might be realistic in this regard.

H. STOCKMAN:

Regarding the suggestion that dust absorption may cause the extreme steepness of the optical spectrum ($\alpha > 1$), how can a BL Lac have enough dust to dramatically change the color of the intrinsic continuum ($\tau_{scattering} >> 1$) without simultaneously destroying the high polarization seen in the optical ($P \gtrsim 10\%$)?

W. STEIN:

Dust extinction may redden the spectral-flux distribution either by (a) grains in our galaxy or (b) those in the region around the source. Your point is well taken but I do not think anyone has worked out a detailed model. The results would depend on the geometry chosen.

A. PACHOLCZYK:

What is the lowest radio frequency at which the BL Lac objects are observed to be definitely variable?

F. OWEN:

230 MHz.

COMMENT BY P. VERON:

The fastest variability we have observed officially (in the B band) in BL Lac objects was a change of one magnitude in 26 hours in BL Lac itself.

A SURVEY OF RADIO PROPERTIES OF BL Lac OBJECTS

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and

Department of Physics,
Virginia Polytechnic Institute and
State University

The radio properties of BL Lac objects affect the ways by which BL Lac objects are discovered. They play an important role in determining the relation between BL Lac objects, (emission line) QSOs, and galaxies. Certain radio observations of BL Lac objects yield constraints on, or estimates of, their distances. Finally, the rapid radio variability in both total intensity and polarization which is characteristic of BL Lac objects can be used to decide between possible emission mechanisms and sources of energy involved in the BL Lac phenomenon.

Nearly all known BL Lac objects have been discovered because they are radio sources. Since BL Lac objects are easily confused with galactic stars, high-redshift QSOs, N-galaxies, and even planetary nebulae, the sample available for study and comparison with other classes of object is inhomogeneous. The methods by which BL Lac objects are "identified" and recognized influence the characteristics of this sample. BL Lac itself was identified on the basis of approximate radio-optical position coincidence supported by optical color and morphology (slightly elliptical blue nucleus, red hazy envelope) with VRO 42.22.01, a radio source <u>noticed</u> because of its centimeter-excess spectrum (MacLeod and Andrew 1968). The next BL Lac objects to be identified, OJ 287 and Pks 0735+17, were also selected on the basis of unusual radio spectra (Blake 1970). The identifications themselves depended only on accurate position coincidence: 3 arcsec rms combined radio-optical position errors are small enough that reliable identifications can be made with any objects visible on the National Geographic-Palomar Observatory Sky Survey (PSS) prints, regardless of color or morphology. The neutral "stellar object" Pks 0735+17 would probably have been dismissed as a galactic star if a less accurate radio position had been available, and

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* Alfred P. Sloan Foundation Fellow.
+ Operated by Associated Universities, Inc., under contract with the National Science Foundation.

many later BL Lac identifications have resulted from improved position measurements of previously known radio sources. When the first complete sample of BL Lac objects identified with radio sources found in a high-frequency survey becomes available, it will probably contain a much higher fraction of NSOs than the currently known sample of BL Lac objects.

Several other distinguishing characteristics of BL Lac objects - high optical brightness, strong optical polarization, intense millimeter-wavelength emission - have been exploited to uncover new BL Lac objects. After Schmitt (1968) recognized that the optical object associated with VRO 42.22.01 is the variable star BL Lac, Biraud (1971) compared lists of radio sources and variable stars and made the matches Pks 1514-24 = AP Lib and ON 231 = W Com. The peculiar-spectrum radio sources OI 090.4 and OJ-131 were identified as BL Lac objects on the basis of optical polarimetry of fields centered on relatively inaccurate radio positions (Tapia et al. 1977). The recognition that GC 0109+22 and GC 1308+32 are BL Lac objects occurred because both sources are exceptionally strong at 90 GHz (Owen and Mufson 1977).

A number of BL Lac objects were found by serendipity during searches for high-redshift QSOs and for radio galaxies. Both BL Lac objects and high-redshift ($z \gtrsim 3$) QSOs can appear red or neutral on the PSS, and both may have no UV excess. So far, most high-redshift QSO candidates have proved to be lineless-spectrum objects (Strittmatter et al. 1974). The low success rate of this type of QSO search is partly due to the tendency to observe the optically brightest candidates first, a procedure which is biased in favor of the relatively bright BL Lac objects. The NSO Pks 0528-250 was one such QSO candidate which has no strong emission lines; but its absorption redshift is $z = 2.812$, making it something of a high redshift BL Lac Object (Jauncey et al. 1978) (Fig. 1).

The story of how Pks 0528-250 was recognized illustrates just how chancy the discovery of "peculiar" objects can be. The radio source was first found in the Ohio survey (OG-247) and was incorrectly identified with a 16 mag BSO 3 arcmin to the south. It later appeared in the Parkes 2700 MHz survey and was tentatively associated with a faint "star" near the pencil-beam radio position (Bolton, Shimmins, and Wall 1975). Because the source has a flat radio spectrum, its position was remeasured with the N.R.A.O. interferometer, and the star identification was confirmed (Condon, Hicks, and Jauncey 1977). The identification was considered to be a good high-redshift QSO candidate on the basis of its color, and its optical spectrum was obtained with a photon-counting scanner on the 3.8 m Anglo-Australian Telescope. As the absorption spectrum began to build up, the experienced optical observers present thought they were just seeing a galactic star and wanted to go on to the next object. Fortunately, a radio astronomer (D. L. Jauncey), less familiar with stellar spectra and confident that the identification was correct, asked that the observation be continued until a good spectrum was obtained.

A 408 MHz radio survey of optically selected bright galaxies (Colla et al. 1975) led to the identification of two of them (the Markarian galaxies Mrk 421 and Mrk 501) as BL Lac objects. An independent 5 GHz survey of Markarian galaxies (Sramek and Tovmassian 1975)

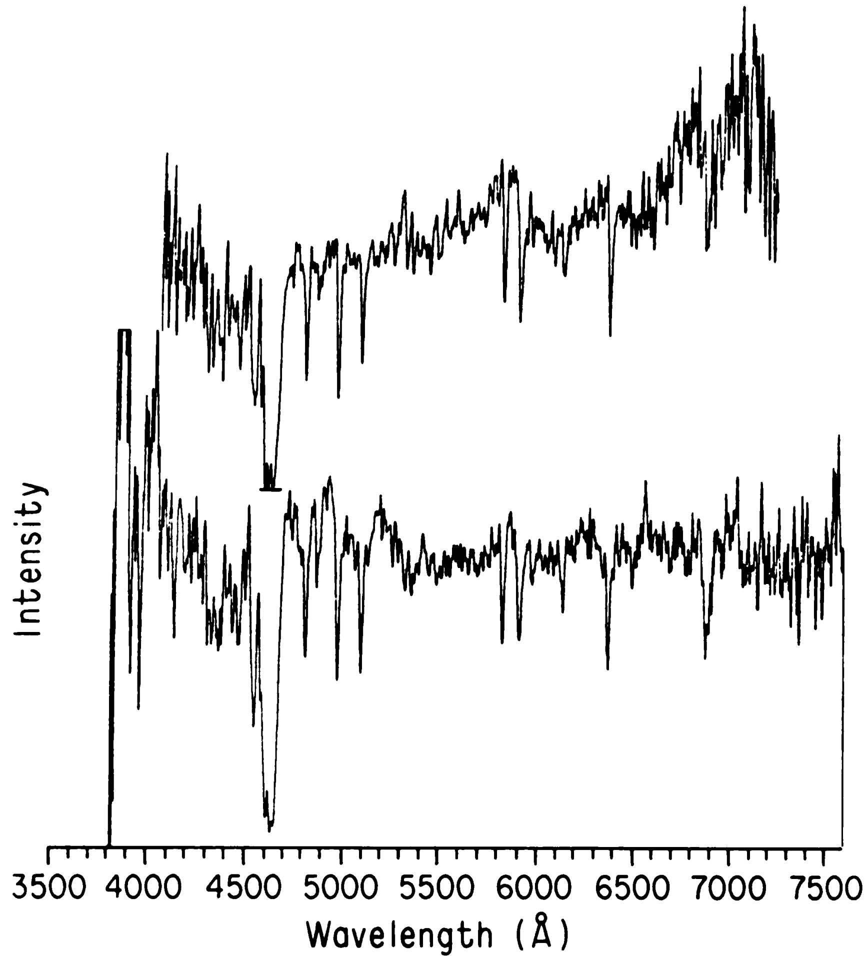


Fig. 1 IDS scans of Pks 0528-250 taken in January and February 1976. The January scan (lower) was taken with 10Å resolution; the February scan (upper) with 5Å resolution.

detected these two plus two new BL Lac objects, Mrk 11 and Mrk 180. The Markarian BL Lac objects are distinct in having flat spectra; nearly all the remaining radio Markarians, even the Seyferts, have steep radio spectra (Kojoian et al. 1976).

If the known BL Lac objects are to be compared with radio QSOs and galaxies, the reference sample should be one found at short (centimeter) wavelengths. About 75% of all QSOs found at 6 cm. have "flat" spectra [$\alpha < +0.5$, where $\alpha \equiv -d\,(\mathrm{Ln}\ S)/d(\mathrm{Ln}\ \nu)$] below 5 GHz, while not more than 29% of the galaxies do (Pauliny-Toth 1977). Indeed, the presence of a compact flat-spectrum radio nucleus usually entails optical nuclear emission as well. The average optical nuclear brightness associated with a compact radio source can be estimated by extending the radio spectrum to optical frequencies with a spectral index $\alpha = +0.7$, starting at the frequency at which the source becomes optically thin

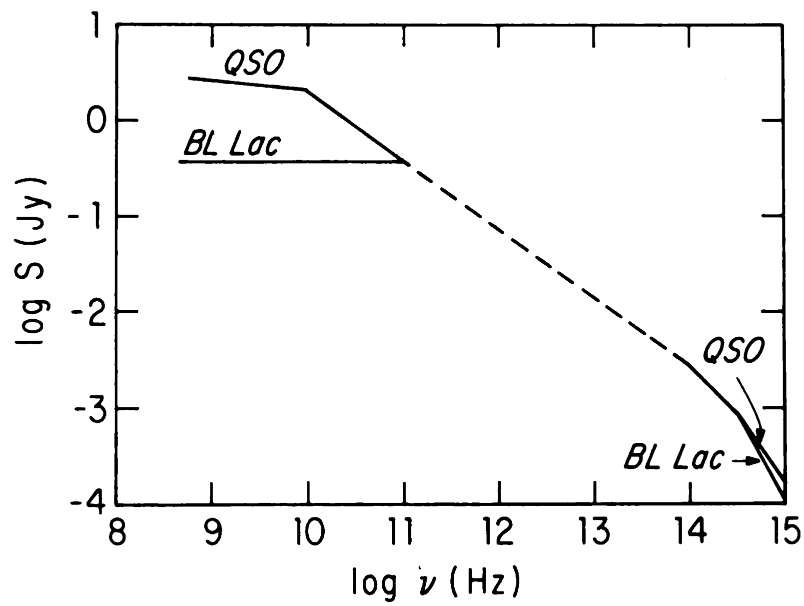
(Condon, Jauncey, and Wright 1978). A 1 Jy source turning over at $\lambda=6$ cm. corresponds to an $m_p=+18$ optical nucleus. BL Lac objects as well as radio QSOs obey this rule. The relatively high average optical brightness of BL Lac objects is a result of their often being synchrotron self-absorbed up to millimeter wavelengths.

When BL Lac objects and QSOs are identified with radio sources in homogeneous samples, the BL Lac objects are found to be 1 or 2 magnitudes brighter than the QSOs on the average (Fanti et al. 1975; Usher 1975). Thus it is said by radio astronomers that BL Lac objects have exceptionally strong optical (and millimeter wavelength) emission. But for the way in which the identifications are made, it would be just as natural to say that the difference between BL Lac and QSO spectra is that BL Lac objects are deficient in centimeter and longer wavelength radio emission. The latter view accords better with several other observations which have led to BL Lac objects being characterized as "naked" radio sources (Altschuler and Wardle 1975).

The continuum spectra of "typical" QSOs and BL Lac objects found in a centimeter-wavelength radio survey might be constructed as follows. The median optical spectral index of a BL Lac object is $\alpha = +1.8$ (Stein, O'Dell, and Strittmatter 1976), only a little steeper than that of flat (radio) spectrum QSOs (Oke, Neugebauer, and Becklin 1970). The spectral index drops to $\alpha \lesssim +1$ in the near infrared, $10^{14} \lesssim \nu \lesssim 3\cdot10^{14}$ Hz. For QSOs the median radio spectral index is $\alpha = +0.2$ below 5 GHz (Pauliny-Toth and Kellermann 1972). The typical QSO is optically thin above 10 GHz (Altschuler and Wardle 1975). BL Lac objects differ in having slightly flatter radio spectra, $\alpha \simeq 0$, and in remaining optically thick up to perhaps 90 GHz (O'Dell et al. 1978). From the turnover frequency up to 10^{14} Hz, both QSOs and BL Lac objects have spectral indices $\alpha = +0.7$ (Condon, Jauncey, and Wright 1978). When the infrared fluxes of BL Lac objects and QSOs are matched, the spectrum in Fig. 2 results.

This model spectrum is not universal. The best counterexample is the BL Lac object 1400+162 which has an extended, steep spectrum radio source (Baldwin et al. 1977). It is worth noting that, while flat- or inverted-spectrum galaxies are rarely found in radio surveys, optically selected elliptical galaxies frequently contain weak nuclear radio components that are self-absorbed even at millimeter wavelengths (Heeschen and Conklin 1975). Apparently the starlight from these nearby galaxies is bright enough to swamp any possible nuclear light.

One consequence of the spectra shown in Fig. 2 is that BL Lac objects are under-represented relative to QSOs when both are found in radio surveys. About 1 BL Lac object is found per 10-20 QSOs in a 5 GHz survey of sources stronger than 0.6 Jy (Shaffer 1978). BL Lac objects might be the most common type of radio source in a millimeter-wavelength survey (Owen and Mufson 1977). It is interesting to speculate that they will also be relatively numerous in future 5 GHz surveys of faint ($S < 0.1$ Jy) radio sources. Flat-spectrum QSOs seem to be so intrinsically luminous that few faint ones should be seen (Fanaroff and Longair 1973), yet many faint flat-spectrum sources are observed (Davis 1977). The number counts of faint sources at 5 GHz also indicate a pronounced contribution from a new population of flat- or inverted-spectrum objects (Wall 1978). From admittedly meager redshift data it appears that many BL Lac objects are nearer ($z \lesssim 0.1$) and hence 10 to 100 times



less luminous than radio QSOs; they may well comprise the "new population". Although most studies of BL Lac objects have been directed toward understanding them as individual sources, the possibility that BL Lac objects will become important in observational cosmology should not be ignored.

Some estimates of, and limits to, the distances of BL Lac objects have been determined by radio astronomical means. The rotation measure of BL Lac was noted as being "consistent with" an extragalactic distance for BL Lac (MacLeod and Andrew 1968). Comparison of 21 cm emission and absorption profiles in the direction of BL Lac shows that it is at least 200 pc away and is probably extragalactic (Pigg and Cohen 1971). The galactic latitude distribution of BL Lac objects and the similarity of their radio sources to QSO radio sources favor an extragalactic origin. Only in the case of the source CL4 is there evidence that a BL Lac object is inside our galaxy. An upper limit to its parallax sets a lower limit of 80 pc to its distance, and the lack of 21 cm absorption appears to indicate that CL4 is not extragalactic (Webster and Ryle 1976). Probably the greatest uncertainty in this surprising result is caused by the coarse velocity resolution (13.2 km s^{-1}) of the absorption data. For example, the distance of Cyg X-3 estimated from a hydrogen absorption spectrum with 1.69 km s^{-1} resolution (Chu and Bieging 1973) is significantly larger than a previous estimate based on a profile with 12.7 km s^{-1} resolution.

The fraction of radio-selected BL Lac object identifications which are in or near (within 30 arcsec of) galaxy-like nebulosities is considerably greater than the fraction of radio QSOs associated with nebulosities. This suggests that many BL Lac objects are inside galaxies or groups of galaxies not more distant than $z \approx 0.3$, the maximum redshift at which most galaxies are easily visible on the PSS prints. The significance of these associations should be investigated by optical observers. The combination of rapid radio variability and lack of inverse-Compton X-ray emission from BL Lac objects (Margon et al. 1976) also favors the view that most BL Lac objects are not so distant as the redshift distances of QSOs.

Radio and optical observations of the $z = 0.524$ redshift system associated with the BL Lac object AO 0235+164 have led to the conclusion that this redshift is cosmological (Wolfe et al. 1978). If this conclusion is correct, the exceptionally violent variability of AO 0235+164 (Ledden, Aller, and Dent 1976) implies either relativistic expansion or some emission mechanism capable of producing brightness temperatures approaching 10^{15} K.

The radio property of BL Lac objects which has attracted the most attention is rapid and strong variability of both total intensity and polarization. The centimeter-wavelength variability time scale is often as short as a few weeks, while most QSOs vary only over months or years (Andrew et al. 1969; Altschuler and Wardle 1975, 1977). In November 1975 the 2.8 cm flux density of AO 0235+164 exceeded 10 times its lowest level (MacLeod, Andrew, and Harvey 1976). If the redshift of AO 0235+164 is cosmological, then its light-travel radius indicates a peak brightness temperature $T \approx 10^{15}$ K (Ledden, Aller, and Dent 1976). Reconciling such high brightness temperatures with the $T \approx 10^{12}$ K upper limit for the proper brightness temperature of an incoherent electron-synchrotron source cooled by inverse Compton scattering is a difficult astrophysical problem (Burbidge, Jones, and O'Dell 1974). However, the low-frequency variability observed in the QSOs CTA 102 and 3C 454.3 (Hunstead 1972) is no less difficult to understand; and it is likely that the same explanation will suffice for both BL Lac objects and QSOs.

Linear polarization variability data are best displayed on a polar diagram in which the distance of a point from the origin is proportional to the degree of linear polarization, and the angular coordinate of the point is twice the polarization position angle. With this representation, there is a fairly clearcut distinction between BL Lac objects and QSOs. Most QSOs have a constant component of linear polarization which is larger than the variable component, so that all of the points representing time variations over several years lie within one quadrant of the polar diagram. Most of the polarized flux of a BL Lac object is variable, and the points are scattered all about the origin (Altschuler and Wardle 1975) (Fig. 3).

In the case of BL Lac itself, the polarization position angle changes were the same at 20, 11, and 3.8 cm. during the period 1971-1973. This is evidence that the polarization position angle depends primarily on the magnetic field direction rather than on Faraday rotation or optical depth effects. VLB measurements made during the same period show that the major axis of the nuclear radio source maintained a constant position angle, so the magnetic field direction seems to be independent of source orientation (Kellermann et al. 1977). During the large outburst of AO 0235+164 in 1975, the linear polarization position angle rotated through a very large angle. This rotation is remarkably similar to the rotation seen in pulsars and will be described in detail by J. Ledden later in the conference.

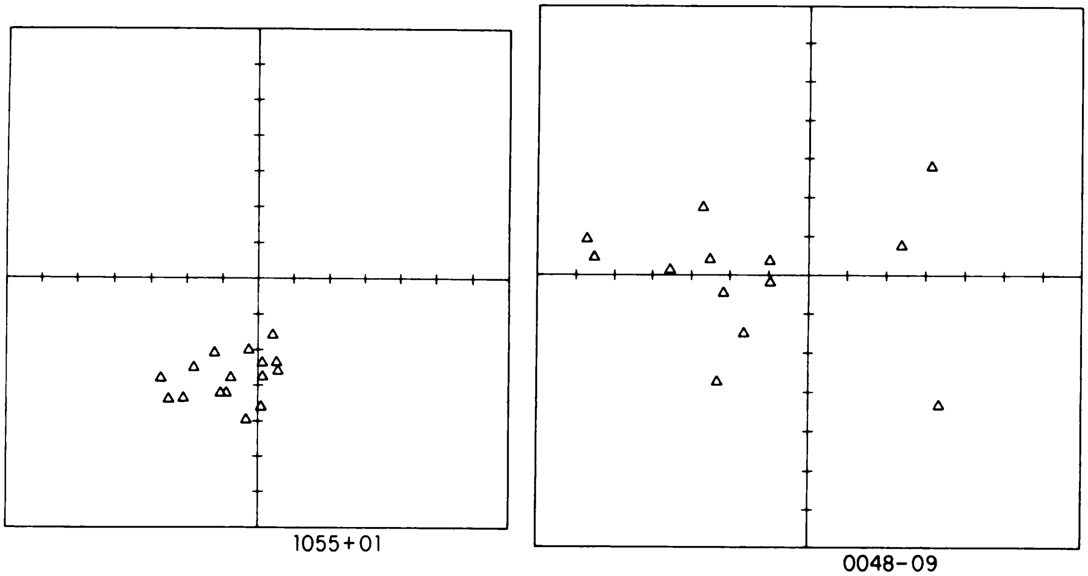


Fig. 3 Polarization variability at λ = 3.7 cm of a QSO (1055+01) and a BL Lac object (0048-09). From Altschuler and Wardle (1975).

Another difference between BL Lac object and QSO variability is that there have been correlated long-term radio and optical outbursts in the BL Lac objects AO 0235+164 (Ledden, Aller, and Dent 1976) and OJ 287 (Pomphrey et al. 1976), while radio and optical outbursts in QSOs seem to be uncorrelated. Recently it was found that the linear polarization position angle of OJ 287 is the same from optical through millimeter to 3.8 cm wavelengths (Rudnick 1978), indicating that both the radio and optical emission arises in a single region with a well-ordered magnetic field. It may be that many QSOs and BL Lac objects contain such central regions, but additional compact radio components overpower them or cover them up. OJ 287 is an exceptionally "naked" source, and it provides the strongest case for a common radio and optical emission mechanism.

The differences between the radio sources in BL Lac objects and flat-spectrum QSOs have been emphasized in the preceding discussion. They are not so great, however, that any given radio source could be reliably classified as being associated with a BL Lac object or QSO on the basis of radio data alone. It is only "on the average" that distinctions between the radio sources in QSOs and BL Lac objects can be made. In fact, it is easier to distinguish QSOs and BL Lac objects from galaxies found in high-frequency radio surveys. Just as the radio properties of QSOs and galaxies are not used as defining characteristics of these classes of objects, so it may not be appropriate to use rapid radio variability and strong radio polarization as defining characteristics of BL Lac objects.

The rapid variability of both BL Lac objects and QSOs is most difficult to explain when it occurs at long ($\lambda \gtrsim$ 1 m) wavelengths, since the brightness temperatures obtained from light-travel-time arguments are greatest at low frequencies (Jones and Burbidge 1973). Two recent observations of low-frequency variables are relevant to the radio emission mechanisms of BL Lac objects and QSOs. First, no extragalactic sources have been observed to scintillate in the interstellar medium at 408 MHz (Armstrong, Spangler, and Hardee 1977) or at 430 MHz (Condon and Dennison 1978). Some of the upper limits to the 430 MHz scintillation indices are sufficiently strong that they require the radio sources in the variables CTA 102, 3C 454.3, and possibly AO 0235+164 to be larger than the variability time scale multiplied by the speed of light. [Unfortunately it is not possible to use interstellar scintillations to prove that AO 0235+164 is "exceeding the speed limit" (Scheuer 1976) because the source may be broadened by scattering in the z = 0.524 intervening object.] This indicates relativistic expansion, regardless of the emission mechanism, if the sources are at their redshift distances; and it implies brightness temperatures less than about 10^{14} K in any case.

318 MHz flux-density measurements of complete samples of radio sources stronger than 3 Jy at 1400 MHz or 1 Jy at 5000 MHz show that at least 1/3 of all flat-spectrum ($\alpha < +0.5$) sources vary on time scales of several years or less, while steep-spectrum sources do not (Condon et al. 1978) (Fig. 4). Most of these low-frequency variables are QSOs,

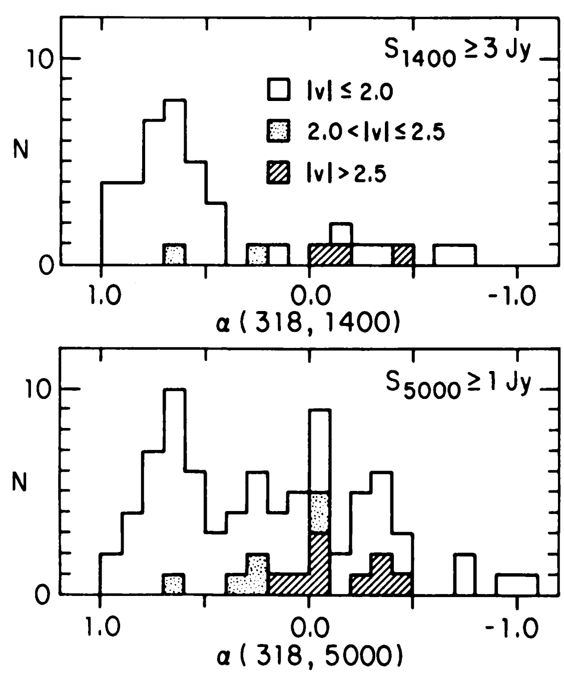


Fig. 4 Spectral index distributions of variable and non-variable sources in samples complete at 1400 MHz and 5000 MHz. Sources with variability index "V" between 2.0 and 2.5 are possibly variable, and $|V| > 2.5$ sources are probably variable.

but two (AO 0235+164 and 0256+07 = OD 094.7) are BL Lac objects. Low-frequency variability is a common phenomenon (thus excluding models with special geometries) occurring in the same types of sources that are high-frequency variables, and steep-spectrum coherent emission mechanisms are not operating. Rather, it seems that relativistically expanding incoherent electron-synchrotron radio components will suffice to explain the rapid variability of both BL Lac objects and QSOs.

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DISCUSSION

A. PACHOLCZYK:
I want to know if there is any observation of an extragalactic radio source that shows positive evidence of interstellar scintillation.

J. CONDON:
There is no detection of interstellar scintillation in an extragalactic source at any frequency.

A. PACHOLCZYK:
Isn't that a little strange? Wouldn't the explanation of this be that the calibration of scintillation observations is done with pulsars and maybe a particular pulsar is influencing the calibration?

J. CONDON:
The most important scintillation parameter deduced from pulsar observations is the angular size ψ of the phase fluctuation pattern on the scintillating screen, since the scintillation index of a source much bigger than ψ is directly proportional to ψ. This angle is not easily influenced by scattering in the immediate vicinity of the pulsar, so the largest uncertainties in ψ are probably due to inhomogeneities in the general interstellar medium. The value of ψ is known to within a factor of two, I believe.

A. PACHOLCZYK:
Wouldn't you expect some distant QSO to be small enough to scintillate?

J. CONDON:
Yes, if its brightness temperature exceeds about 10^{14}K, either because it is highly relativistic or because some special high-brightness emission mechanism is operating, it could be small enough to scintillate.

A. PACHOLCZYK:
So I would like to see such an observation to really convince myself about the reality of this effect.

J. CONDON:
Unfortunately, there may not be any QSOs that are actually that small.

B. DENNISON:

There probably aren't any that are small enough no matter how far away they are. The angular size is independent of distance once you get to a redshift of about one anyway. No QSO would approach being small enough to show this effect.

D. SHAFFER:

From redshifts of 0.5 on up the angular size for a given linear size is the same due to cosmology so they don't get smaller as they go further away. If the brightness temperature limit is 10^{12}K, they will always be bigger than about 0.5 milliarc sec. You have to get down to about 10^{-6} arc sec. to see interstellar scintillation.

J. CONDON:

The Arecibo 430 MHz observations are sensitive enough to detect interstellar scintillations of sources at least as large as $2 \cdot 10^{-4}$ arc sec. Lack of scintillations sets a lower limit to the source angular size which we compare with the light-travel time sizes of variable sources. We calculated these light-travel time angular sizes for two cosmologies which span the range of likely models:

(a) $q_o = 0$ and $H_o = 50$ kms^{-1} Mpc^{-1}, which gives you the smallest angular size, and

(b) $q_o = 1$ and $H_o = 100$ kms^{-1} Mpc^{-1} for the largest angular size.

For the variable sources CTA 102 and 3C 454.3, the scintillation lower limits are about 4 times the light-travel size.

A. PACHOLCZYK:

But the problem here is only a factor of 4. The ratio of the light-travel time size differs by a factor of 4 from the scintillation size. Could that factor of 4 be eliminated by changing for example the parameters of interstellar scintillation?

J. CONDON:

Yes, if we pushed all the parameters in the right direction, it could be changed. This limit however is a fairly conservative limit. In addition to the factor of 4, the scintillation size lower limits are the 99.8% confidence limits. I would be surprised if that actually changed very much.

J. FELTEN:

With respect to your explanation of Scheuer's observations (Scheuer, P.A.G. 1976, MNRAS, **177**, 1P) of AO 0235+164, do the time variations you discuss pertain solely to the radio or do they include optical observations also? My question is would it be possible for an intervening galaxy to wipe out the scintillations without wiping out the time variations?

J. CONDON:

Yes, that was my point. Scheuer's conclusion was that because AO 0235+164 did not scintillate as a radio source, it had a large angular size. But it is also a rapidly varying radio source. The broadening due to an intervening galaxy will, to first order, not smear out the time variations, but will destroy the scintillations in an interstellar medium similar to our own. So the lack of interstellar scintillations in the case of AO 0235+164 does not imply that the radio source "exceeds the speed limit". This point is discussed by Armstrong et al. (1977, A.J., 82, 785).

M. REES:

If the intergalactic medium was very clumpy and contained a lot of clouds at $T = 10^4$K, similar to that which people invoke to explain QSO absorption lines, is it possible that every line of sight could give you enough small angle scattering to broaden angular sizes to $\geq$0.1 milliarc sec? If this were so, the observations of interstellar scintillations in general would be as inconclusive as this test plainly is for AO 0235+164.

J. CONDON:

We have calculated that. The angular size that would scintillate at the sensitivity level of the Arecibo observation is a few times 10^{-4} arc sec. If the intergalactic medium has the same clumping factor as the Kolmogorov power law spectrum in the density fluctuations, then the density of the intergalactic medium has to be 2-10 times the closure density to suppress scintillations for a source at z = 1 or 2. However, lower total densities could do the job if the electron density fluctuations are increased accordingly. To avoid intergalactic broadening, one could observe nearby sources like BL Lac and observe them at high frequencies.

M. REES:

Does it really have sort of two phase structure? Did you take that into account in your calculation? In other words, so that you have dense clouds at $T = 10^4$K embedded in a much more diffuse medium.

J. CONDON:

All we dealt with was a normalized electron density fluctuation spectrum that is the same as in our Galaxy.

W. DENT:

I don't think it's fair to conclude that the radio variability characteristics of BL Lac objects differs from that of QSOs. For example, 0735+178 has a time scale on the order of a couple of years, characteristic of most QSOs. BL Lac on the other hand did have the fastest time scale as you can see on the graph [*Ed.: See p. 66*]. Back in the early '70s it was a very rapid variable but its time scale has changed so that now instead of 0.1 years, the time scale is about 1 year. Our unpublished observations of the BL Lac 1215+130 (AP Lib) show it not to vary at 7.9 and 15.5 GHz from 1971, when we begin observing it, to now.

J. CONDON:

I would agree with that. I hope that I didn't leave the impression that all BL Lac objects vary faster than the QSOs. That isn't the case. The variability time scales of BL Lac objects and QSOs overlap sufficiently that no clearcut distinction between them can be made. But the median variability time scales of large groups of BL Lac objects and QSOs can be compared; and it appears that BL Lac objects on the average vary somewhat more rapidly (e.g., Altschuler, D.R., and Wardle, J.F.C. 1975, Nature, 255, 306).

S. COLGATE:

If you take the ubiquitousness of the absorption lines in QSOs as a measure of the clumping rather than a Kolmogorov spectrum, does this allow you to avoid the strictness of the argument about the confrontation of a factor of 4 in the scintillation argument?

J. CONDON:

I don't know. We did the simplest empirical thing which was to use the fluctuation spectrum of our Galaxy.

S. COLGATE:

To me the frequency of the absorption lines is a critical measure of what fluctuation density you should take.

J. CONDON:

That might be the case. Although most of these low frequency variables are not at such high redshifts as where the absorption lines become ubiquitous.

S. COLGATE:

So what you really have to look for is a correlation between no absorption lines in a highly variable BL Lac and the lack of interstellar scintillation. Has that been done?

J. CONDON:

In the case of BL Lacs, AO 0235+164 is out the window. In the case of QSOs I would say that QSOs with redshifts of about 1 like 3C 454.3 do fall into that category. There are some lower redshift low frequency variables that are ripe for this sort of test. At $z = 0.2$ you might expect very few absorption redshifts.

F. OWEN:

I want to extend the similarity between QSOs and BL Lac objects in the millimeter region. We (Owen, F.N., and Mufson, S.L. 1977, A.J., **82**, 776) have done surveys of sources that have been discovered at 6 cm. and that have flat spectra, independent of the optical property, and when you select the ones that are still strong at 3 millimeters you find that the percentage of BL Lac objects has increased. But still at least half of the sources could be called QSOs. From the radio properties alone I do not think you could distinguish the QSOs from the BL Lac objects. The only real difference is that the QSOs appear to be somewhat fainter optically so that the drop between the radio and optical is a larger factor with the QSOs. If you just examine the BL Lac objects you tend to find a lot of sources that are partially resolved by the interferometer. But you also find this with QSOs if you select them in the same way. So I think you can make the general statement that based on present evidence there is no distinguishing radio characteristics between QSOs and BL Lac objects. There is no evidence that the BL Lac phenomenon is different from the QSO phenomenon.

D. WILLS:

I think that the evidence for CL4 being a BL Lac object in our Galaxy is not very strong. There are some recent optical measurements by Argue (Argue, A.N., Clements, E.D., Harvey, G.M., and Elsmore, B. 1978, Observatory, to be published) and some measurements that we did on the sky survey prints which show that there is something like a 2 arc sec. difference between the radio and optical positions. Both positions are very accurate. Baldwin's spectrum was not published because it is noisy - the object is faint. It is an interesting radio source but it may in fact have nothing to do with the optical object.

G. BURBIDGE:

Do you think it is a misidentification?

D. WILLS:

Yes.

H. SMITH:

If you compare the morphological similarities between the radio properties of QSOs and spiral galaxies on the one hand, and BL Lac objects and ellipticals on the other, isn't it really true that there are no spiral galaxies that are truly powerful radio sources. By and large there is not a continuity in radio properties from spiral galaxies to QSOs. If you want to look at galactic type radio sources for QSOs you need elliptical galaxies. Isn't that right?

J. CONDON:

That is correct. Not only do spiral galaxies fail to produce classical double radio sources, but the luminosities of spiral radio sources are much less than the strongest radio sources in QSOs, BL Lac objects, and elliptical galaxies. For this reason, many radio astronomers associate both BL Lac objects and radio QSOs with elliptical galaxies rather than spirals.

G. SETTI (COMMENT):

With regard to the time variability of extragalactic sources at low radio frequencies, I wish to report on some results which have been obtained at Bologna at 408 MHz (Fanti et al., in preparation). A sample of $\sim$50 radio sources has been monitored for $\sim$3 years with an average time interval between observations of 1 month. About 20 sources are very well known variables at high frequencies. Of these, 50% show, including 3C 454.3, variability at 408 MHz. For the other 50% no statement can be made as yet. It may very well turn out that most, if not all, radio variables at high frequencies are also variable at low frequencies. The time scales involved are typically of a few months, which lead to brightness temperatures very much in excess of 10^{12}K.

One object, 1524-13, which is wildly variable at 408 MHz, does not appear to be variable at high frequencies.

J. PERRY:

If there aren't always distinguishing radio characteristics between QSOs and BL Lac objects, but the QSOs appear optically fainter, shouldn't you be finding faint BL Lac objects which are "high redshift" objects? If they are in nuclei of galaxies and if there are galaxies that are far away and if the only difference is the absence or presence of gas around them, shouldn't high redshift BL Lac objects be showing up?

J. CONDON:

They should, but I think only in very sensitive radio surveys. Radio surveys have never been done at frequencies higher than 5000 MHz; and to go back to a typical spectrum for a BL Lac object, it turns out that between a wavelength of 3 mm. where Owen had been observing, and optical wavelengths, the spectral index of flat-spectrum radio sources is always about 0.7 with a scatter of about 0.09. So the real difference lies about here at 6 cm. (see fig. 2) where the surveys are done. I would say that in a strong-source 6 cm. survey you only find bright BL Lac objects and that in a faint source 6 cm. survey there should be a lot of faint high-redshift BL Lac objects.

M. DAVIS:

Do you see any more differences between the one third of the flat-spectrum sources that you found to be variable and the two-thirds that you did not?

J. CONDON:

Some of the ones that were variable are the most active variables at high frequencies, but other than that there is no obvious difference between the two types. I would guess that if this sort of observation were continued, nearly all the flat spectrum sources would turn out to be low frequency variables.

G. BURBIDGE:

How many BL Lac objects are you talking about in all of these comparisons? The only list I know about is the one in Annual Reviews (Stein, W.A., O'Dell, S.L., and Strittmatter, P.A. 1976, Ann. Rev. Astr. Ap., **14**, 173).

J. CONDON:

The Annual Review list contains about 30 or 40 BL Lac objects. I was concentrating on them in the comparisons. Almost everybody that's doing optical identifications has a half a dozen candidates in his pocket, but so little is known about them that I would hesitate to lump them into a useable sample yet.

G. BURBIDGE:

But when you make these comparisons, how good are your samples in terms of the correctness of your conclusions. [laughter.]

J. CONDON:

Given that there are only 30 to 40 useable BL Lac objects right now, only those characteristics which are strikingly different show up, like variations on the time scale of a week or really significant turnovers in the low frequency radio spectrum. Those are the characteristics that I would believe in: also the strong polarization.

D. SHAFFER:
The same sources that are in that list show up in all these radio sources.

G. BURBIDGE:
There aren't a large number of new ones cropping up?

D. SHAFFER:
I don't think so. If you identified the 6 cm. surveys, you find the objects appearing in the Annual Review list.

J. CONDON:
I would say that the BL Lac objects that we know now and the characteristics that we are quoting are "fair" characteristics, but the possibility that there are BL Lac objects of a "different nature" that are also common cannot be excluded. For example, 1400+162 has much different radio properties than all the rest.

H. SMITH:
I would like to comment on this briefly. In the Molonglo survey, which is a low frequency survey, there are a lot of objects classified as continuum spectrum objects in the original optical work, and were called BL Lac objects. When better optical observations came along they were found to be stars that did not have particularly strong lines. The number of BL Lac objects began to drop. So optical astronomers are well advised to be careful about classifying objects as BL Lac objects until they are really sure that a particular object has a continuous spectrum as well as some of the other characteristics.

G. BURBIDGE (To H. Smith):
You don't think this cautionary tale about Dave Jauncey has any meaning?

A. WOLFE: (to J. Condon)
You discussed 0528-250 as a BL Lac object. On the basis of its radio properties, is it a highly variable object?

J. CONDON:
Yes, it is a very compact radio source. It has a low-frequency turnover at about 3 GHz, and it is also a strong optical variable, so it has a lot of the earmarks of a BL Lac object, but it may not be one.

A. WOLFE:
Is its optical spectrum like that of AO 0235+164? The reason I am asking that is because the very strong Lyman alpha line indicates that it contains a lot of hydrogen and perhaps a lot of dust. So I am wondering whether 0528-250 has a steep spectrum like that of 0235+164 which also has a lot of hydrogen and perhaps dust, in which case the steep spectrum in both objects could be due to reddening by dust.

J. CONDON:

No, the optical spectrum of 0528-250 is not that steep. The main reason that it is neutral in color is because the Lyman alpha line is completely black.

J. WARDLE:

Has anybody found or looked for what you might call a radio-quiet BL Lac object? I was wondering if anything had turned up in your surveys.

J. CONDON:

There are no known "radio-quiet" BL Lac objects, although IZw 186 is an "optically-selected" BL Lac object (see Stein, W.A., O'Dell, S.L., and Strittmatter, P.A. 1976, Ann. Rev. Astr. and Ap., **14**, 173). I don't know of any current optical searches for BL Lac objects, but some have been proposed and may start soon. One could look for faint variable stars at high galactic latitudes or for stars with continuous power-law spectra. The polarimetry technique used to identify OI 0904 and OJ 131 (Tapia, S., Craine, E.R., Gearhart, M.R., Pacht, E., and Kraus, J. 1977, Ap.J. (Letters), **215**, L71) might also be used to find radio-quiet BL Lac objects.

It is not obvious that truly radio-quiet BL Lac objects exist at all. They might be expected by analogy with the radio-quiet QSOs, but the analogy has a serious flaw. By definition BL Lac objects are optically variable and polarized, so their optical emission is likely to be synchrotron radiation. The only QSOs which are strongly variable and polarized contain nuclear radio sources; radio-quiet QSOs seem to be unpolarized and not violently variable optically. If the optical continuum of radio-quiet QSOs is not synchrotron radiation, then there can be no analogous radio-quiet BL Lac objects.

E. CRAINE:

I wonder if you could comment on the reliability of the radio spectral indices in view of the fact that BL Lac objects tend to be radio variables?

J. CONDON:

Obviously the radio spectral indices are a little messy, but I think that they are not so messy as to destroy the statement about QSOs having stronger low-frequency components than BL Lac objects, because the BL Lac objects are distinctly naked radio sources regardless of their violence and variability.

F. OWEN:

We have just completed an 11 frequency project from 318 MHz to 9 GHz, looking at a lot of these sources. The conclusions are based on observations that are all done at the same time. So the influence of variability of spectral indices is not a serious thing.

A SURVEY OF RADIO POLARIZATION AND VARIABILITY IN BL LACERTAE OBJECTS

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1. INTRODUCTION

Since 1971, the NRAO* three element interferometer has been used to monitor the flux density and linear polarization at $\lambda\lambda$ 11.1 and 3.7 cms of over one hundred compact extragalactic radio sources. From the beginning, several BL Lac Objects were included in the program, and many others have been added since then. At the present time we have amassed between twenty and forty five observations on each of twenty seven BL Lac Objects. The data through June 1975 for twelve of these are presented in (1), and discussions of this earlier data are given in (2) and (3).

The purpose of this paper is to provide an overview of the radio properties of BL Lac Objects as a class, rather than to discuss the detailed behavior of individual sources. In particular we shall draw attention to both similarities and differences between the radio properties of BL Lac Objects and those of quasars.

2. THE OBSERVATIONS

Table I summarizes the observational data on twenty seven BL Lac Objects. Column 1 lists the sources in the usual r.a./dec notation, and column 2 gives other common names. A "V" in the third column denotes that we have found the flux density to vary at one or more wavelengths with a confidence level of $\geq$ 99%. Column 4 gives the mean spectral index between λ 3.7 cms and λ 11.1 cms (with $S \propto \nu^{\alpha}$). Column 5 gives a measure of the degree of variability at λ 3.7 cms, calculated as the r.m.s. scatter in flux density divided by the mean flux density. Column 6 compares the amplitudes of the variations at the two wavelengths: R = r.m.s. scatter in flux density at λ 3.7 cms divided by the r.m.s. scatter in flux density at λ 11.1 cms. Column 7 indicates that extended structure has been observed surrounding the compact source at radio (R) or optical (O) wavelengths. Column 8 gives the highest degree of linear polarization observed to date at λ 3.7 cms, and column 9 lists the corresponding quantity at optical wavelengths, taken from (4).

3. THE FLUX DENSITY VARIATIONS

3.1 The Incidence of Variability

While the majority of the radio sources identified with BL Lac Objects are clearly variable, not all of them are. Those that are variable have flat or centimeter excess spectra in the usual way (5), and their distribution of spectral indices is indistinguishable from that of the variable quasars. Two sources in Table I have flat spectra and have not yet shown significant variations. But these are both faint sources and our observations of them are not yet extensive. However, the remaining five non-variable sources have steep optically thin spectra, and it is likely that these will not exhibit variability even with continued monitoring. Thus a centimeter excess spectrum and radio variability, although common, are <u>not</u> necessary properties of the radio sources identified with BL Lac Objects.

*The National Radio Astronomy Observatory is operated by Associated Universities Inc., under contract with the National Science Foundation.

TABLE I. Summary of the Observations

(1) r.a./dec.	(2) Name	(3) Vari- ability	(4) α	(5) σ/<s> (%)	(6) R	(7) Extended Structure	(8) m_{max}(%) Radio	(9) Optical
0048-09	OB-081	V	.4	25	2.5	R	9.3	14
0133+47	DA55	V	.3	20	1.2		3.6	
0219+42	3C66A		-.3	<7		R	4.5	14
0235+16	AO	V	.3	51	1.6	O	3.8	25
0256+07		V	.0	16	4.0	R	3.7	
0300+47	4C47.08	V	.3	15	1.4		11.5	
0735+17	OI 158	V	.1	22	2.4		4.7	31
0814+42	OJ 425	V	-.0	17	1.3		9.8	
0329+04	OJ 049	V	.1	16	1.2	R	4.8	
0851+20	OJ 287	V	.3	41	2.4	O	16.6	29
0912+29	OK 222	V	-.2	13	1.0	R	14.7	13
1020-10			-.5	<3			9.2	
1057+10			-.7	<9			22.1	10
1101+38	Mk 421	V	.1	6	>1.5	R,O	3.7	6
1147+24	OM 280		.1	<5		R	2.5	13
1205-00		V	.2	21	>5.0	R	7.5	
1215+30	ON 325	V	.1	8	>2.4	R	6.3	14
1219+28	W Com	V	.0	19	.9	O	5.8	10
1514-24	AP Lib	V	.1	17	1.1	R,O	4.4	6
1538+14	4C14.60	V	.1	6	.8		9.3	22
1727+50	I Zw 186		.0	<3		O	11.3	6
1749+09	OT 081	V	.5	35	3.2		7.2	9
2155-15	OX 192	V	.0	9	.8	R	8.5	
2200+42	BL Lac	V	.3	32	1.4	O	6.4	19
2207+02			-1.0	<6		R	14.0	
2254+07	OY 091	V	.3	30	2.5	R,O	8.1	21
2335+03	4C03.59		-.8	<3		R,O	6.1	

The incidence of radio variability among BL Lac Objects (20/27) does appear to be significantly higher than that among quasars (14/38 for the quasars in (1)). However, this may be misleading. Many BL Lac Objects have been discovered by their centimeter excess spectra, while the selection criteria for the quasars in (1) were not well defined, so it is probable that steep spectrum non-variable BL Lac Objects are under represented in Table I. If we consider only those sources with centimeter excess spectra, then the difference in the incidence of variability between the two groups becomes less marked (18/20 for the BL Lac Objects, and 10/17 for the quasars). At least part of the residual difference between the two groups can be attributed to the higher degree of variability (see section 3.2) and shorter time scales (2) commonly found among BL Lac Objects. Thus it appears that the incidence of variability is determined more by the shape of the radio spectrum at short wavelengths than by the nature of the optical identification.

3.2 The Degree of Variability

In order to define a more homogeneous sample for comparison purposes, from now on we shall restrict the discussion to those BL Lac Objects in Table I and those quasars in (1) that do exhibit variability in flux density. If this is done, there is a significant difference between the two groups in their degree variability (see column 5, Table I). This is defined simply as the r.m.s. scatter in flux density divided by the mean flux density. For the BL Lac Objects this ratio has a median value of 18%, and five sources have values ≥ 30%. For the quasars, the median is 12%, and none have values over 30%. These results are shown in Figure 1. They loosely mirror what is observed at optical wavelengths, where it is found that most BL Lac Objects fall into the category "optically violent variable" (OVV), whereas only about 13% of quasars are in this category (4), (6).

3.3 The Spectrum of the Outbursts

In general the amplitudes of the outbursts at λ 11.1 cms are only slightly smaller than at λ 3.7 cms (column 6, Table I). The ratio of the amplitudes can be estimated statistically as R = r.m.s. scatter in flux density at λ 3.7 cms ÷ r.m.s. scatter in flux density at λ 11.1 cms. Figure 2 shows a histogram of R (corrected for noise) for the twenty variable BL Lac Objects in Table I. The median value of R is only 1.5. This is consistent with the behavior noted by Andrew et al (9) for a much larger sample of variable sources, who found that in general the amplitude of the outbursts could be described by $S_{max} \propto \lambda^{-0.4 \pm .15}$. This is quite different from the predictions of the "standard" expanding source model (7), where the expected value of R is 3.0 if the power law index of the relativistic electron energy spectrum is 1.0, and is larger for larger values of the index. This suggests either that there is continuous injection of relativistic electrons during most of the outbursts (e.g. (8)), or else that the opacity at λ 11.1 cms is never very high. This effect is common to nearly all variable radio sources (3,9), and is an important point of departure from the simpler theoretical models.

4. EXTENDED RADIO STRUCTURE

A new result is that half of the sources in Table I have extended radio structures that are resolved by the three element interferometer. These structures are usually rather faint, having steep spectra, and angular sizes in the range 10 to 200 arcsecs.

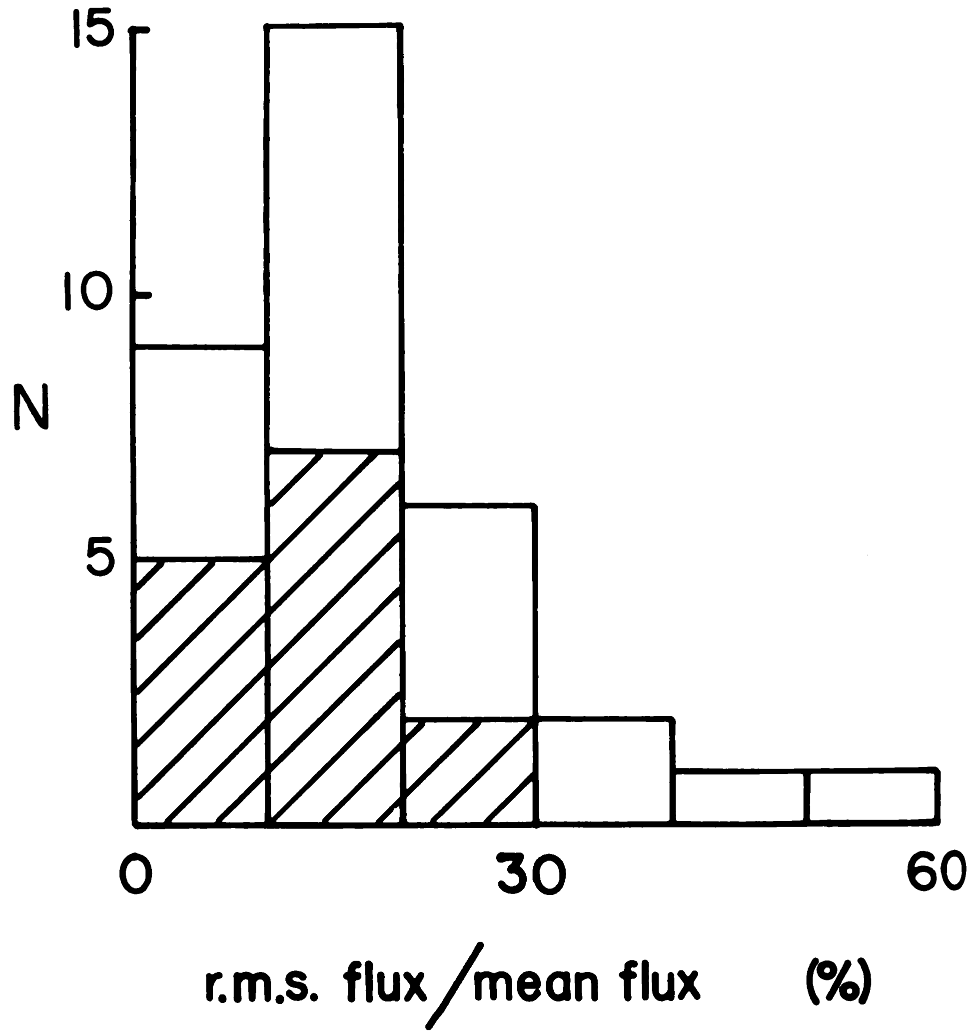

Figure 1. Histogram of the degree of variability at λ 3.7 cms of BL Lac Objects (unshaded) and quasars (shaded)

The structures have been determined only in one position angle (∿70°) during the course of the monitoring program, using the interferometer in a variety of configurations. The visibility functions of two resolved sources are shown in Figure 3a, together with the visibility function of an unresolved source (OJ287), for comparison.

As might be expected, the presence of extended structure correlates with a steepening of the radio spectrum at long wavelengths, which also indicates the presence of an optically thin component (see Figure 3b). Sources such as BL Lac and OJ287 have spectra that decrease monotonically down to at least 100 MHz, and show no sign, at centimeter wavelengths, of structure larger than a few arcseconds down to a level of 2% of the total flux.

At present there is little information available on the morphology of these extended structures. Three obvious possibilities are 1) simple halos built up by repeated outbursts from the active nucleus, 2) the fading remnants of a previous phase in the evolution of BL Lac Objects, or 3) a jet-like structure similar to that found in the quasar

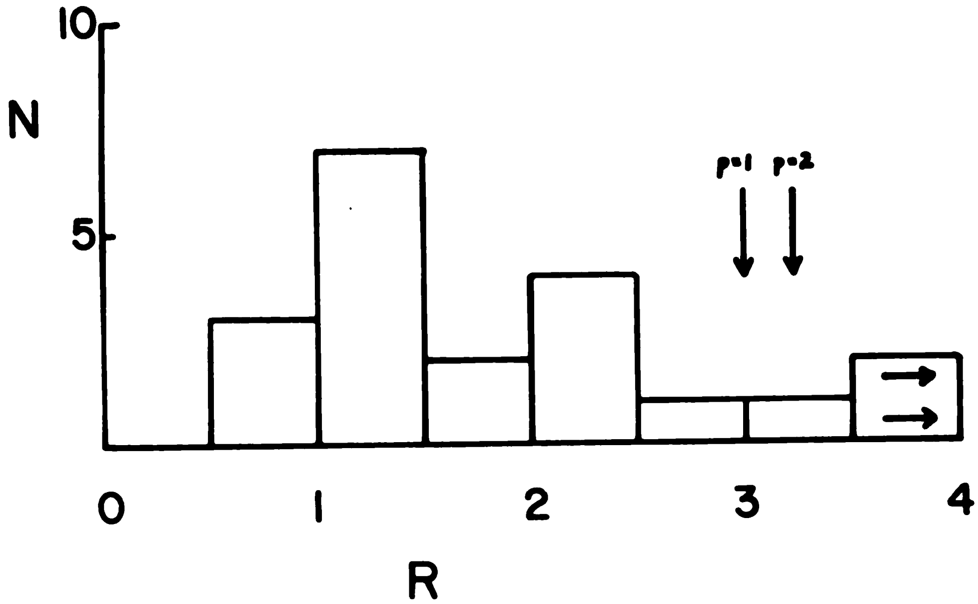

Figure 2. Histogram of R for twenty variable BL Lac Objects. R is a measure of the amplitude of the variations at λ 3.7 cms compared to the amplitude at λ 11.1 cms. The arrows mark the expected values of R according to the "standard" expanding source model, for two values of the slope of the electron energy spectrum (where $N(E) \propto E^{-P}$).

3C273. Conway and Stannard (10) have found such a structure in 1514-24 (AP Lib), where at 408 MHz the source is an asymmetric double with a separation of 7 arcsecs. We also note that to date there has been no case of a "classical double" structure found among BL Lac Objects.

The extended radio structure does not correlate with the presence of optical nebulosity. This is not surprising since the optical nebulosities exhibit spectra and colors characteristic of galaxies (11), and presumably have little to do with non-thermal processes.

5. LINEAR POLARIZATION

5.1 The Degree of Polarization

One of the most distinctive properties of BL Lac Objects is the behavior of the linear polarization. At optical wavelengths (12,13,14), the degree of polarization is very high (up to 31%) and rapidly variable (on a time scale of days or less). In these respects, BL Lac Objects are similar to the "Optically Violently Variable" quasars, but quite different from the vast majority of quasars, whose degree of polarization is never more than 2%.

At radio wavelengths we find rather similar behavior. The degree of polarization does not usually reach such high values as at optical wavelengths (see Table I), and the fluctuations are less rapid (∿ weeks rather than days), but the comparison with the variable quasars still shows clear differences. This is shown in Figure 4, where the largest degree of polarization, m_{max}, observed at λ 3.7 cms in the course of our monitoring program is plotted as a histogram. The median values of m_{max} are 3.9% for the quasars and 6.4% for the BL Lac Objects. More striking is the fact that the largest degree of polarization found to date in a

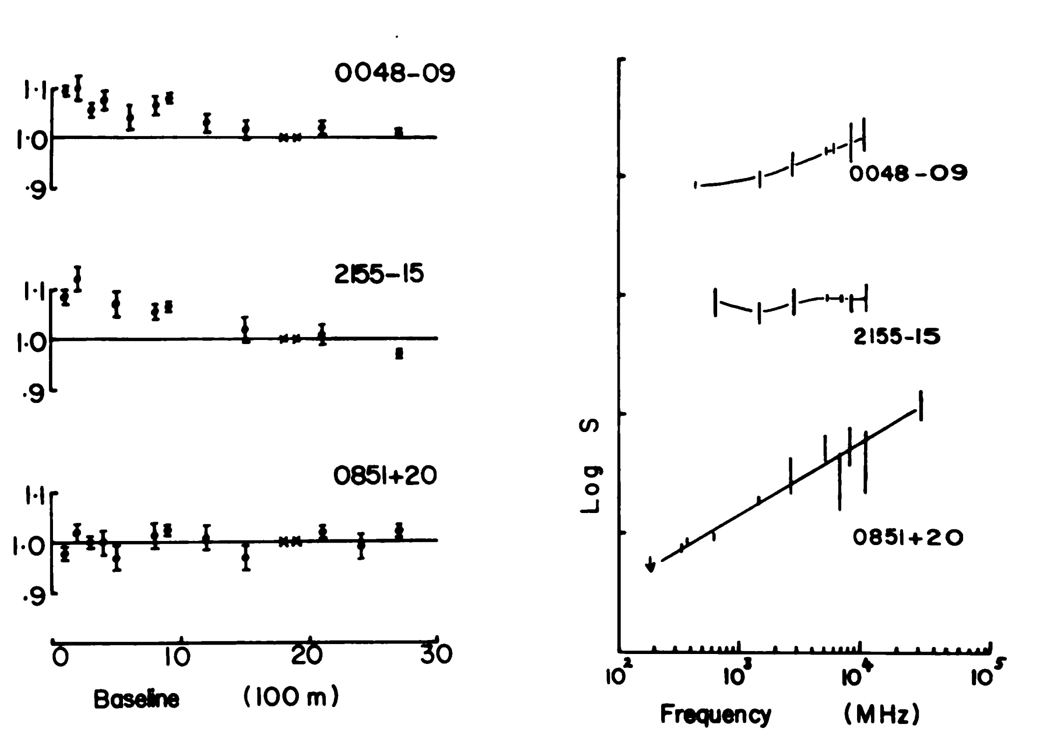

Figure 3. Visibility functions at λ 11.1 cms for three BL Lac Objects. All three sources are variable, so the visibilities are normalized to unity at 1800 m and 1900 m, since these spacings occur in most of the configurations used. Also shown are spectra for these sources. The zeros of the flux density scale are displaced, and the error bars represent the range of values found in the literature.

variable quasar is 6.5% for 0736+01, while nearly half of the BL Lac Objects (9/20) have values of $m_{max} \geq 10\%$. It appears that a large and variable degree of linear polarization at centimeter wavelengths may be a sufficient (but not necessary, c.f. optical wavelengths) condition for identifying a compact extragalactic radio source as a BL Lac Object

Various interpretations of this result are possible (see also (14)), but a high degree of linear polarization certainly implies a well ordered magnetic field in the radio emitting region, if the radiation is synchrotron radiation. This might suggest that the energy density in the magnetic field is at least comparable to the energy density of the relativistic particles, at times. The majority of compact radio sources, by contrast, appear to be particle dominated (15). (It should be noted, however, that this ratio of energy densities is very difficult to determine accurately, being very sensitive to relativistic motions and varying as the seventeenth power of the observed angular size.)

5.2 The Correlation between the Radio and Optical Polarization

The exact relationship between the polarization seen at radio wavelengths and that at optical wavelengths is unclear at present. This is partly because these sources are so rapidly variable, and partly because there has been little systematic monitoring at optical wavelengths.

In the previous section we drew attention to the fact that as a class BL Lac Objects tend to be more strongly polarized than quasars, at both radio and optical wavelengths. However, comparing columns 8 and 9 of Table I shows no obvious correlation between m_{max}(radio) and m_{max}(optical) for individual sources. In particular, very high degree of polarization have been observed in 0235+16 and 0735+17 at optical wavelengths, but the degree of polarization at radio wavelengths has always been rather modest.

In the case of OJ287 there is evidence of similar <u>long term</u> trends in the polarization at optical and radio wavelengths. Figure 5 shows yearly means of the radio and optical Stoke's parameters Q/I and U/I, for 1971 through 1976, plotted against each other. The radio data are at λ 3.7 cms, and the optical data are from T. Kinman (personal communication).

On a time scale of a year or more the correlation is quite good; at radio wavelengths the degree of polarization is about half that found at optical wavelengths, and the position angles are similar.

The lower degree of polarization of the radio radiation is certainly not due to Faraday depolarization (see next section). Presumably the radio radiation comes from a region where the magnetic field is slightly less ordered but has a similar orientation and undergoes similar changes to the field in the optically emitting region. OJ287 is the only source for which there are sufficient optical data to make this comparison. We do not know if similar long term trends are to be found in other BL Lac Objects.

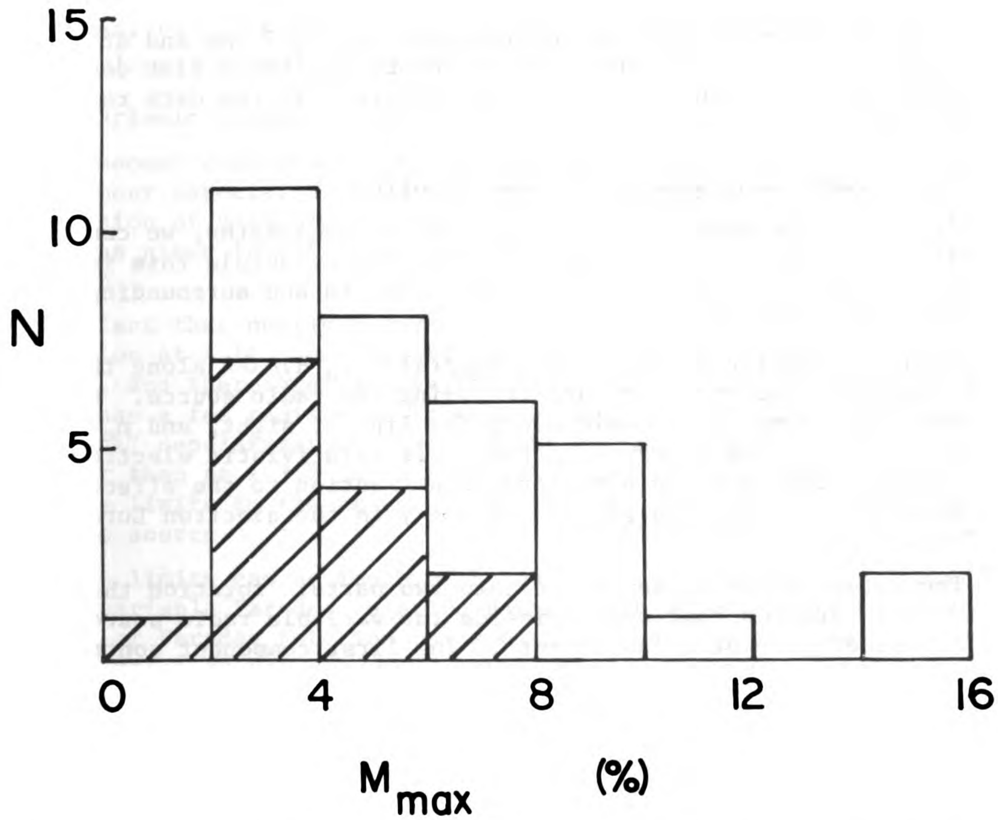

Figure 4. Histogram of m_{max}, the largest degree of linear polarization observed at λ 3.7 cms for the variable BL Lac Objects (unshaded) and quasars (shaded).

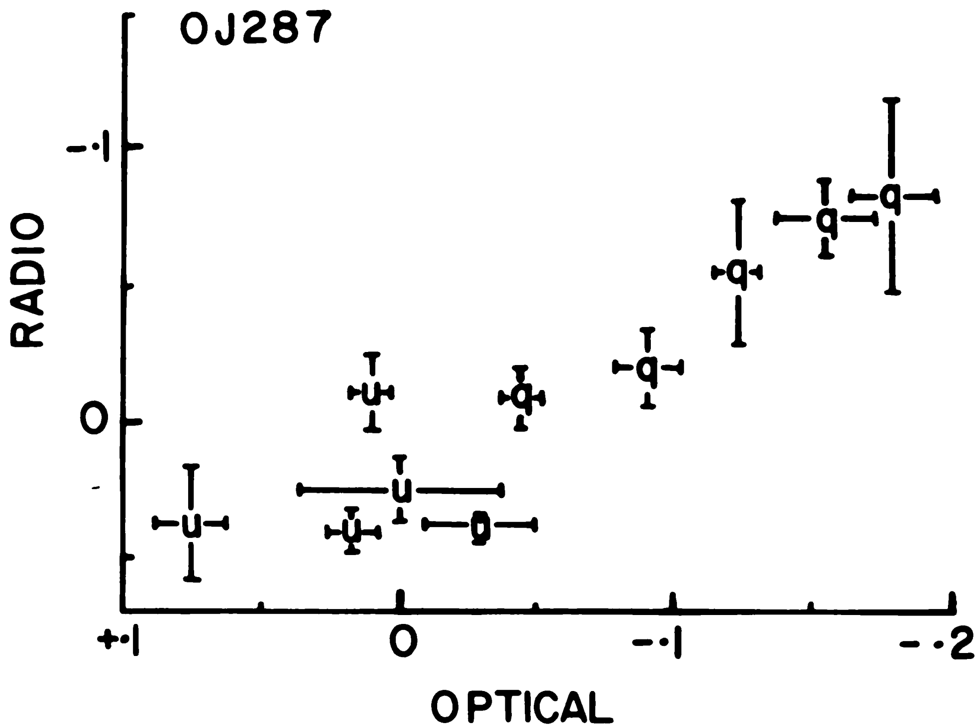

Figure 5. Yearly means of the polarization at λ 3.7 cms and at optical wavelengths. Q and U have been normalized by the total flux densities. The error bars represent the r.m.s. fluctuations in the data rather than measurement errors.

5.3 The Constant Component of Faraday Rotation

Since we have measurements at two radio wavelengths, we can search the data for evidence of Faraday rotation. In principle this is a very sensitive probe for low energy electrons both in and surrounding the variable radio source.

Faraday rotation measures the integral $\int n_e H_{//} \, d\ell$ along the line of sight from the observer up to and including the radio source. $H_{//}$ is the component of the magnetic field along the line of sight, and n_e is the number density of low energy electrons. If relativistic electrons are also present, they make an additional contribution to the effective electron density of $\sim n_{relativistic}/\gamma^2$, where γ is the electron Lorentz factor (16).

The integral can be separated into two parts: rotation that occurs outside and rotation that occurs inside the variable radio source. We shall consider each of these in turn. The first component contributes a constant rotation in position angle, $\Delta\chi$, between λ 3.7 cms and λ 11.1 cms. The rotation may occur in our own Galaxy, in the intergalactic medium, or in the galaxy surrounding the BL Lac Object itself. At high Galactic lattitude, the contribution from our own Galaxy is small, and there is little evidence of Faraday rotation in the intergalactic medium (17). Thus the constant component of Faraday rotation for high lattitude sources can be attributed mainly to thermal plasma surrounding the active nucleus, and in principal may give a clue as to whether the very weak emission lines observed in BL Lac Objects are due to a lack of gas or because of some other reason.

In order to compare BL Lac Objects to quasars in this respect, we restrict ourselves to sources with $|b^{II}|>25°$, but include the nonvariable sources, since we are basically interested in the difference between sources with strong and weak emission lines without regard to nuclear activity. We also restrict ourselves to observations where the degree of polarization is greater than 2.5% at both wavelengths, so that the position angle measurements are sufficiently accurate. We then compute the average $\langle\Delta\chi\rangle$ for all the observations of each source that meet these criteria.

We find a small but significant difference between BL Lac Objects and quasars, in that BL Lac Objects tend to have a smaller value of $\langle\Delta\chi\rangle$ than quasars, which may indicate the presence of less thermal plasma surrounding the nucleus. The largest value of $\langle\Delta\chi\rangle$ for the BL Lac Objects is 41°, while seven out of seventeen quasars have values of $\langle\Delta\chi\rangle$ in excess of this. Similarly, five of the twelve BL Lac Objects have $\langle\Delta\chi\rangle$ less than 5°, while only one quasar is in this category. A value of $\langle\Delta\chi\rangle \lesssim 5°$ corresponds to $\int n\, H_{//}\, d\ell \leq 9\times10^{-6}$ cm^{-3} G pc.

This result is suggestive, but should not be taken too seriously, since (1) the statistics are less than overwhelming, (2) the magnetic field strength outside the nucleus is unknown and (3) the differences in $\langle\Delta\chi\rangle$ are not nearly large enough, by themselves, to account for the difference in emission line intensities between quasars and BL Lac Objects. The approach does, however, offer a potentially useful way of probing the environment of a variable radio source. In principle it can be sensitive to very low electron densities, since the rotation measure is directly proportional to the electron density rather than to its square (c.f. bremsstrahlung, optical line emission).

5.4 The Variable Component of Faraday Rotation

The second contribution to the observed Faraday rotation is a varying component associated with the variable radio source itself. A detailed discussion of variable Faraday rotation in both BL Lac Objects and quasars was given in (18), but the results are so striking that they bear repetition.

The fact that nearly all variable radio sources exhibit variable polarization at λ 11.1 cms, implies that the variable source itself is polarized, and therefore Faraday rotation inside the variable component is less than a few radians at this wavelength. Otherwise we would see "front-back" depolarization (19) and the degree of polarization would be much lower than at λ 3.7 cms. This simple observation was used in (3) to set severe limits to the amount of thermal plasma mixed in with the variable radio source.

These limits can be improved by an order of magnitude by looking for signs of variable Faraday <u>rotation</u> rather than <u>depolarization</u>. A variable component of Faraday rotation has a distinctive observational signature: we would expect to see changes in the position angle of polarization at λ 3.7 cms that are echoed at λ 11.1 cms with an amplitude nine times larger. Inspection of all the polarization data in (1) reveals no obvious cases of such behavior, and in several cases the position angle changes are well correlated between the two wavelengths, with the <u>same amplitude</u>. (The BL Lac Objects 0735+17 and OJ287 are excellent examples.) For these sources we can place upper limits of a few tenths of a radian on any variable component of Faraday rotation at λ 11.1 cms.

By making use of the observed brightness temperature of the source, (either measured using VLBI, or inferred from the time variations), we can derive results that do not depend directly on the magnetic field strength. In particular, the ratio of relativistic to non-relativistic electron densities can be written as $n_{relativistic}/n_e \gtrsim 5\times10^{-10}\ T_b/\chi$, where T_b is the brightness temperature of the radio source (in K) and χ is limit on the Faraday rotation (in radians), both measured at the same wavelength. (See (18) for the derivation of this result.) In the best cases we find $\chi<1/10$ radian, and in nearly all cases $\chi<1/2$ radian. T_b is typically $\sim10^{12}$K from VLBI measurements and in certain sources (eg. 0235+16) may be as high as 10^{15}K, inferred from the time scale of variability. Thus we derive a strong upper limit on the density of thermal electrons mixed in with the variable radio source, of $n_e<10^{-3}\ n_{relativistic}$. In several cases the limit is certainly an order of magnitude lower.

This limit applied to both variable quasars and BL Lac Objects and sets some drastic constraints on the physical processes giving rise to the variable radio source. For comparison, n_e is some ten orders of magnitude less than the electron densities inferred from the quasar emission line regions (20)! Certainly, the acceleration mechanism for the relativistic electrons appears to be amazingly efficient.

The limit is so strong that we would also expect to see Faraday rotation by low energy relativistic electrons, even though this is reduced by the square of the electron Lorentz factor. In fact it can be shown that the low energy end of the relativistic electron energy spectrum must fall off sharply below a Lorentz factor of fifty or so.

One way of satisfying the twin requirements of (1) virtually no thermal plasma; and (2) a low energy cut off in the electron energy spectrum could be by means of a relativistic blast wave (18)(21)(22)(23), leading to a Maxwellian electron energy spectrum at a temperature equal to the brightness temperature of the radio source. Certainly, the lack of observed Faraday rotation is a fundamental constraint that must be satisfied by any theoretical model for the variable radio sources in quasars and BL Lac Objects.

6. SUMMARY AND CONCLUSIONS

In this review we have concentrated on the radio properties of BL Lac Objects as a class, rather than discuss individual sources in detail. In particular we have drawn attention to both the similarities and differences between the radio properties of BL Lac Objects and quasars. Also we have restricted the discussion to the observational data, and have made few attempts at theoretical interpretations. Our intention is to give an impression of what BL Lac Objects look like at radio wavelengths, rather than to build models.

The main conclusions can be summarized as follows. (1) While the majority of BL Lac Objects found so far have centimeter excess spectra and exhibit radio variability, some do not. Five sources in Table I have steep, optically thin spectra, and have shown no sign of variability. (2) BL Lac Objects tend to exhibit larger relative changes in flux density than quasars. (3) As in most variable radio sources, the amplitude of the outbursts at longer wavelengths are larger than predicted by the standard expanding source model. (4) Many BL Lac Objects also contain low brightness steep spectrum radio components, with sizes in the range 10-200 arcsecs. (5) The maximum degree of linear polarization observed in BL Lac Objects is significantly greater than for quasars. (6) There is little correlation between the radio and optical polarization on short time scales. However, OJ287 shows long term trends that are similar at the two wavelengths. (7) As in quasars, there is no sign of Faraday rotation associated with the variable source. This allows stringent upper limits to be set on the ratio of non-relativistic to relativistic electrons inside the variable radio source.

ACKNOWLEDGEMENTS

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DISCUSSION

H. MILLER:
Going back to that polarization data you presented for OJ 287, it looked as though the total flux did not change at all during the time which the polarization increased by about 12%. It looks as though something that was depolarizing the radiation before, suddenly ceased to depolarize it. In other words it converted unpolarized radiation back to polarized radiation. Is that a reasonable explanation of what's going on?

J. WARDLE:
Are you saying that you suddenly take away a depolarizing screen?

H. MILLER:
Yes.

J. WARDLE:
I think in that case you should see enormous changes in polarization position angle, in the same way as when you introduce such a screen.

H. MILLER:
Then it looks as though the unpolarized flux would then have to drop to exactly cancel out the increase in polarized flux. Maybe that happened.

J. WARDLE:
I am pretty sure that didn't happen, but let's argue that out later in detail.

W. DENT:
Is there a difference in the spectral index between the core components of the BL Lac objects and the weak extended ($\sim$10 arcsec) component which you see with the interferometer?

J. WARDLE:
The extended structure appears to have a steep spectrum. Measurements taken at both wavelengths indicate a normal spectrum for a structure of this size.

S. COLGATE:
What limits does the Faraday rotation place on the ratio of the densities of non-relativistic to relativistic electrons?

J. WARDLE:

I find that n(non-relativistic)/n(relativistic) $\lesssim 10^{-4}$ for electrons inside the radio source.

M. REES:

There is another way to interpret the lack of internal Faraday depolarization. It could of course be explained on the hypothesis that the compact components consist of an electron-positron plasma.

M. DAVIS:

Can the degree of variability of BL Lac objects have been artificially increased relative to the QSOs by the inclusion of steep spectrum quasars in your sample?

J. WARDLE:

No, the steep spectrum quasars and BL Lac objects are effectively excluded by limiting the sample to only those sources which do exhibit variability.

P. USHER:

Would you expect to see much change in the total flux when there is only a 8% change in polarization?

J. WARDLE:

Yes, the accuracy of the total flux measurements is 3-4%.

W. DENT:

At mm. wavelengths the fractional variability of all sources is greater than at cm. wavelengths. This is true for quasars as well as BL Lac objects. The existence of a constant cm. component in QSS (radio QSOs) but not in BL Lac objects would explain the apparent higher degree of variability in BL Lac objects.

J. WARDLE:

At cm. wavelengths, there is not enough flux in the extended structures to account for the difference in degree of variability.

G. SHIELDS:

In the dramatic case where the polarization dropped from 15% to a much smaller value as the flux increased only slightly, the drop in polarization cannot be dilution by a weak new component. Could this result from injecting into the existing source, a fresh supply of particles whose low energy tail produced Faraday depolarization?

J. WARDLE:

I tried to say this before. Any change in Faraday optical depth will manifest itself by large changes in polarization position angle. We do not see this!

M. REES:

You show tentative evidence that there was less Faraday rotation due to an external medium in the BL Lac objects than in the quasars and you said that this may be due to different types of galaxies. It could also be an orientation effect in the same type of galaxy. If BL Lac objects are objects in which we are looking along a beam direction which is the rotation axis then again one would expect a systematically lower amount of Faraday rotation in the BL Lac objects than in the quasars.

J. WARDLE:
That is a very interesting point.

A. SMITH (To J. Wardle):
You showed a convincing correlation between the radio and optical polarizations of OJ 287. Before drawing general conclusions from this, it is well to note that of 22 sources investigated in detail by Pomphrey <u>et al</u>. (1976, <u>A.J.</u>, <u>81</u>, 489), OJ 287 was the only one to show significant long-term correlation of radio and optical total fluxes. So OJ 287 may be atypical.

J. WARDLE:
I think that may very well be true. All the data we have found for other BL Lac objects don't show even the remotest relationship between optical and radio polarization and OJ 287 may be a simpler object or kinder to us.

Polarization and Flux Density Variations in BL Lac and OJ 287 at Centimeter Wavelengths

by

Hugh D. Aller and John E. Ledden

The bulk of the observational data presented here was obtained in the course of the variability monitoring program at the University of Michigan at frequencies of 8.0 and 14.5 GHz, but in some cases our data will be combined with results from other observatories. BL Lac and OJ 287 are the best studied BL Lac objects, and from studying them the general characteristics of the variability are becoming apparent. In this presentation we would like to focus on three important characteristics determined from the variability in these objects: A. particle injection or acceleration occurs either continuously or discretely at many closely spaced epochs; B. the source(s) of energetic particles are contained in a volume which is small compared to the size of the emitting region producing the centimeter-wavelength radiation; and C. the magnetic field structure in the emitting region maintains the same dominant orientation over several "outbursts."

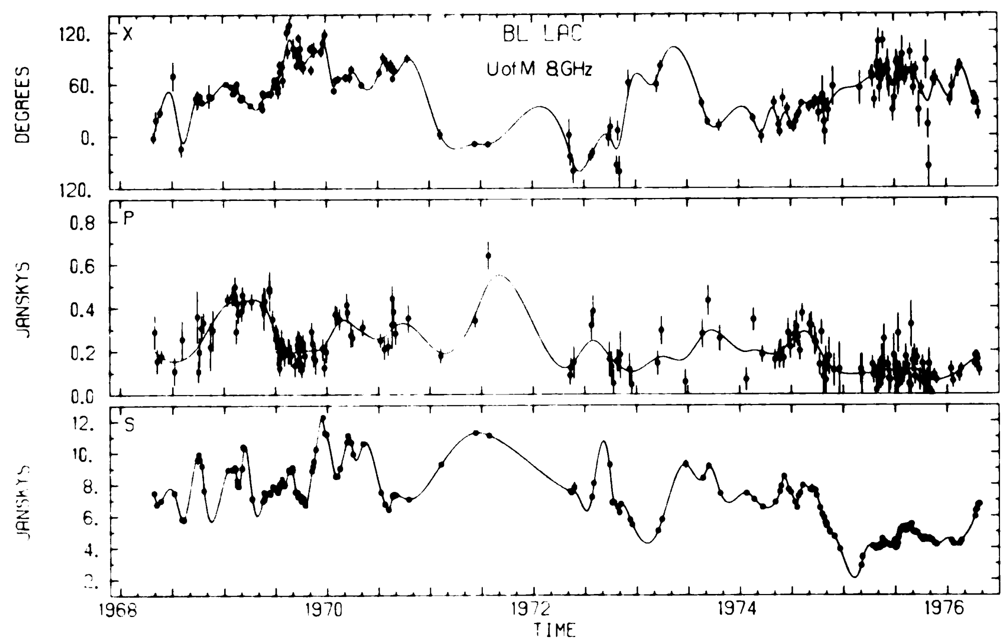

FIGURE 1

The gross nature of the variability in these objects is well illustrated in Figure 1 which shows the University of Michigan data at 8.0 GHz for BL Lac during the period January 1968 through April 1976. The bottom panel displays the total flux density, the middle panel shows the polarized flux density (the degree of linear polarization multiplied by the total flux density) and the top panel presents the position angle of the electric vector versus time. Smoothing cubic splines (Reinsch 1967) have been passed through the data. Many successive "outbursts" are evident, and in many cases the outbursts clearly overlap in time.

Observations by Dent and Kapitzky (1976) show that the activity in this source continued during the gap in our data in 1971 and 1972. The general impression is that one is viewing an intrinsically stochastic process of particle injection or acceleration over a prolonged period of time (Andrew, Harvey and MacLeod 1975). Based upon the rapid changes that we have observed in the flux density of this source during several isolated periods of intensive monitoring, it is evident that most variations have not been resolved in time. Note the deep minimum in the flux density of BL Lac in early 1975. This is the deepest known minimum in this source and was observed over the frequency range of .25 to 300 GHz (Erickson and Fisher 1975, Elias et al. 1978).

The linear polarization of this source has varied rapidly and erratically with the observed degree of polarization occasionally exceeding 10 percent. The polarization variability clearly does not follow the flux density variations, and the state of polarization is in fact often the same over several outbursts in the total flux density. The polarization position angle has varied over a wide range (note that the scale presented extends beyond 180 degrees), but there are long periods when the position angle in this source remains near the same value. Kinman (private communication) has also noted this behavior in radio data at other frequencies. The source of the stability or memory of the magnetic field is not known.

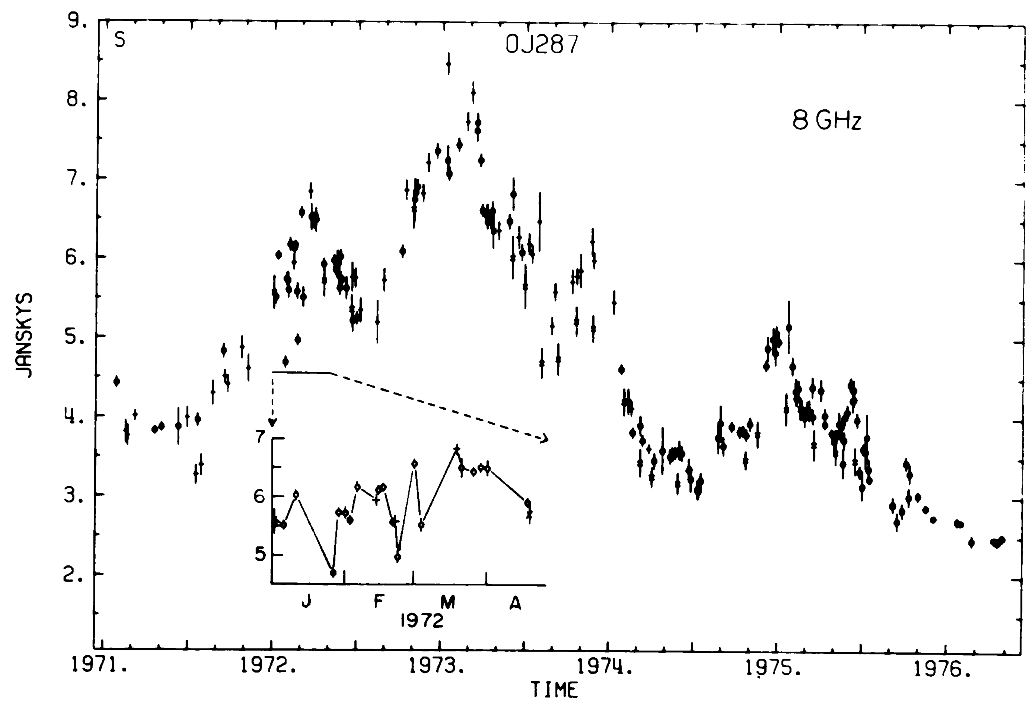

FIGURE 2

We would now like to discuss the time-dependence of the particle injection or acceleration in these sources and the (observationally) related question of the opacity due to (presumably) synchrotron self-absorption. Figure 2 shows the observed flux density of OJ 287 at 8 GHz versus time. This plot includes observations by Dent and Kapitzky (1976), Altschuler and Wardle (1976) and Aller, Ledden and Aller (1978) designated by +, X and O respectively. At first glance there appear to be two large outbursts in 1972 and 1973 followed by a general decline in 1973-1974 and a smaller outburst which peaked in early 1975. The insert in the figure presents the data in early 1972 on an expanded time scale and shows that the "outburst" in 1972 is in fact a summation of many rapid outbursts. We interpret each of these rapid bursts as being the result of a separate particle injection or acceleration event. The intensive, multifrequency study of OJ 287 during January 1972 by Kinman et al.(1974) and the long-term monitoring program of Medd et al. (1972) both found changes in flux density of comparable rapidity as those shown here. The rapid decay of these sub-outbursts indicates that the radiating particles leave the emitting region or dissipate their energy within a matter of days. Thus particle injection or acceleration must be occurring over most of the time period of the outbursts in order to keep the flux density at a high level.

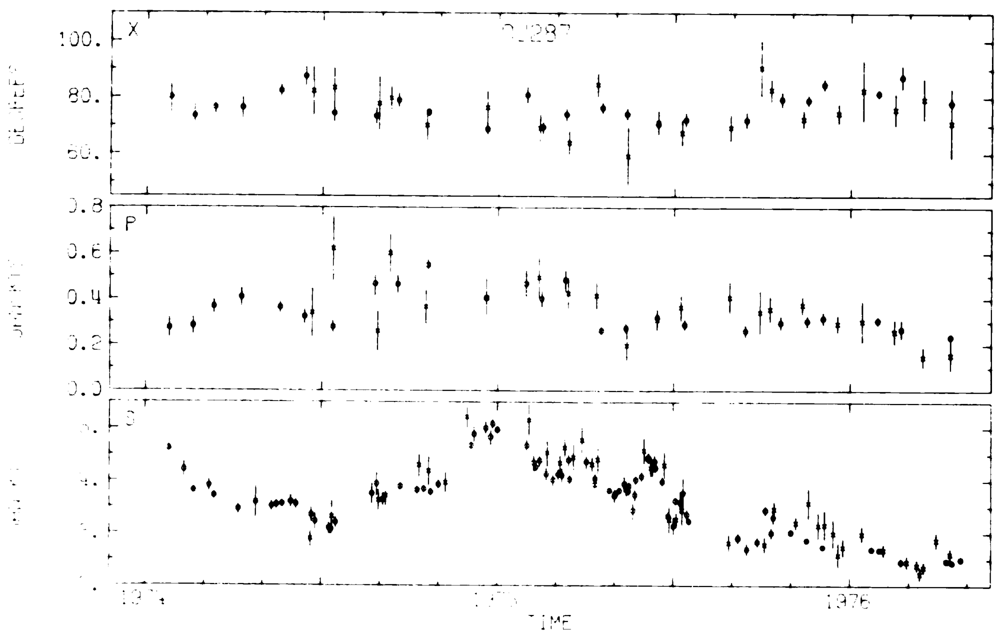

FIGURE 3

The "flickering" of the source is also very evident during the activity which peaked in 1975. Figure 3 displays daily averages of the total flux density and monthly averages of the polarized flux density and polarization position angle data obtained at the U. of Michigan between January 1974 and April 1976. The crosses are data at 14.5 GHz and the open circles are data at 8.0 GHz. It is apparent that a succession of rapid bursts occurred during this period (peaking in the maximum near 1975.0). There is a high degree of correlation between the total flux densities at the two frequencies: the amplitudes of the variations are comparable and there is little or no time delay between the variations at the two frequencies. This behavior is consistent with the hypothesis that the emitting region was predominantly transparent during the time period and that we are seeing the results of a fluctuating rate of particle injection or acceleration. The linear polarizations at the two frequencies were essentially the same during the time period so that there is no evidence that frequency-dependent effects were present in the emitting region. There was no significant Faraday rotation in the source and the opacity must have been low during this time period. Incidently, the degree of polarization attained by this source (at least 15 percent at 8 GHz) is the highest that we have observed in the integrated radio radiation of a variable extragalactic object.

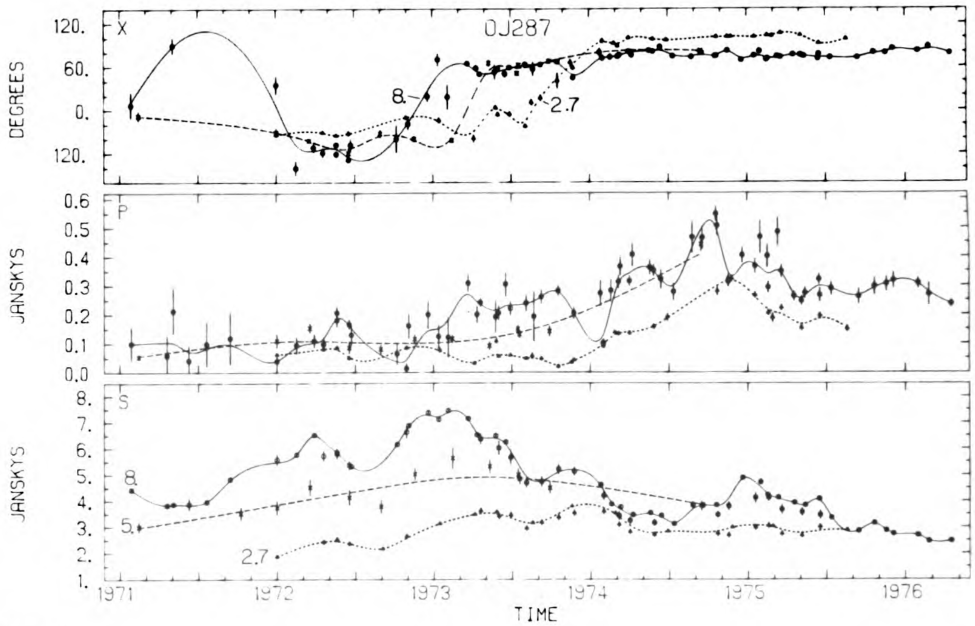

FIGURE 4

The nature of OJ 287 changed between 1973 and 1974. Prior to 1973 there was no obvious direct correlation between observed variations at optical and at radio wavelengths (Kinman et al.1974), but after 1973 there was a high degree of apparent correlation between the variations observed in the two wavelength regions (Pomphrey et al.1976). We believe that this change in behavior was the result of the emitting region becoming predominantly transparent at centimeter wavelengths as the overall rate of particle injection or acceleration in the source decreased. Evidence for the decreased opacity of the radio emitting region is presented in Figure 4. This figure shows the total flux density and polarization position angle at three frequencies: 2.7 GHz (Altschuler and Wardle 1976, Kapitzky 1976), 5 GHz (Gardner et al. 1975, Ryle et al. 1975, and Seielstad and Berge 1975) and 8 GHz (Altschuler and Wardle 1976 plus monthly averages of the U. of Michigan data). Relatively stiff smoothing cubic splines are drawn through the data to help separate the different frequencies. The decrease in the overall opacity in the emitting region can be inferred from the flattening of the spectrum of the total flux density (i.e., the ratio of the 8 GHz to 2.7 GHz flux densities approaches unity in 1975) and especially from the behavior of the linear polarization. Between 1972 and 1974 the polarization position angle at all three frequencies rotated by approximately 100 degrees. As suggested by Seielstad and Berge (1975), this behavior is very similar to the jump of 90 degrees which Dent (private communication 1968, cf. Aller 1970) first pointed out is expected when a synchrotron source evolves from being opaque to transparent. We believe that this must be the correct interpretation because the jump first appeared at the highest frequency (8 GHz) and then propagated to the lower frequencies which would have become transparent at successively later times. Following the shifts in the polarization position angles, the degree of polarization increased to a high value at all three frequencies. This type of behavior is also expected as an opaque source becomes transparent. The variations in the polarized emission from the source can not be uniquely associated with individual "outbursts", but the polarization evolved in a manner which is consistent with the observed overall variation in total flux density. This source also shows a remarkable stability of the polarization position angle and polarized flux density over a long period of time. Measurements at the U. of Michigan indicate that in the frequency range of 4.8 GHz through 14.5 GHz the polarization position angle was still in the range of 75 to 80 degrees and the polarized flux density was still approximately 0.2 Jy during March 1978.

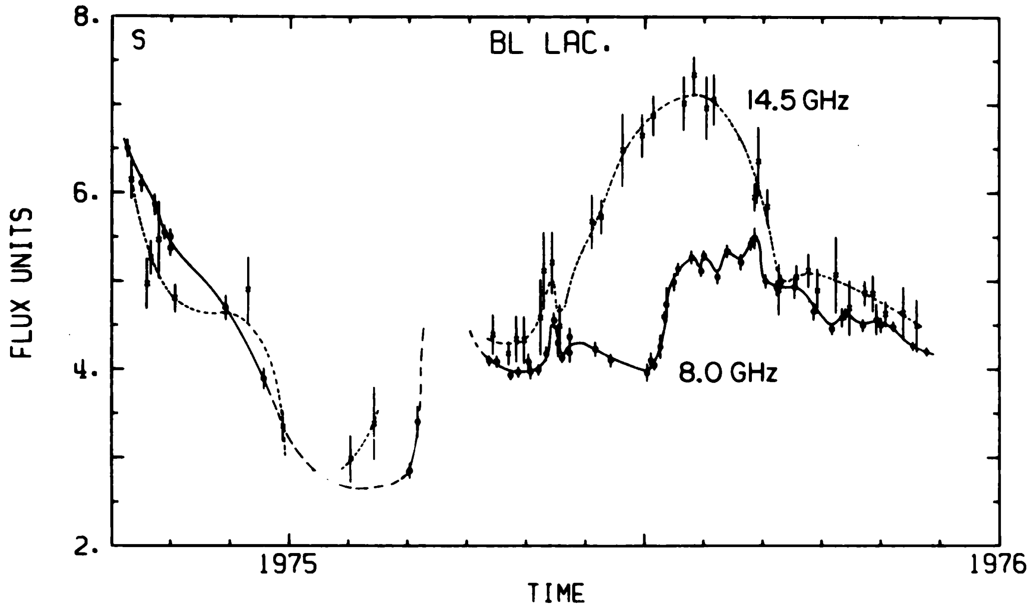

FIGURE 5

Finally we wish to discuss the flux density variations in BL Lac at 8.0 and 14.5 GHz which occurred during 1975 and which are shown in Figure 5. The unusual feature of the data is the very different behavior of the observed flux densities at 8.0 and 14.5 GHz during May through August 1975. The rapid rise in the 8.0 GHz flux within a two week period in July was not accompanied by any comparable increase at 14.5 GHz; and the rate of rise at 8 GHz during this short period was significantly greater than the maximum rate observed at any time during the outburst at 14.5 GHz. The absence of a corresponding jump at the higher frequency rules out the possibility that the 8.0 GHz event was produced by the sudden injection or acceleration of additional particles in July. We believe that the sudden increase is due to the effects of self-absorption by previously accelerated particles in the outer parts of the emitting region (between us and the site of newly injected or accelerated particles). If the particles injected prior to May 1975 provided significant opacity at 8.0 GHz, we would not see the radiation of recently-injected or accelerated particles until they reached the virtual surface where the absorption depth in the line of sight is approximately unity at 8.0 GHz. Although these fresh particles would not become visible until a later time at 8.0 GHz, they would be evident at the higher frequency (where opacity is lower) at an earlier epoch in the form of a new outburst at the higher frequency.

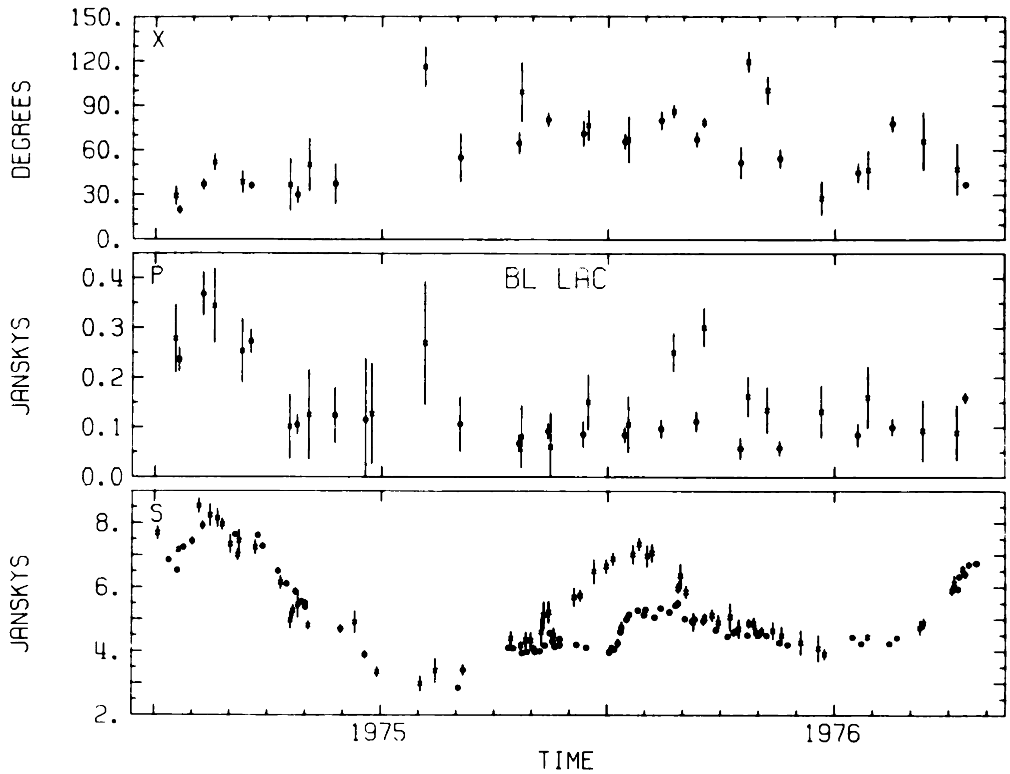

FIGURE 6

The linear polarization data for BL Lac shown in Figure 6 provides independent evidence that at least a portion of the emitting region was opaque during this time period. The X's represent the 14.5 GHz data and the 8.0 GHz data are shown as open circles. Daily total flux densities and monthly averages of the polarization data are plotted. Note the generally close agreement in the polarization position angles and polarized flux densities except during the period after the maximum in the 1975 outburst. There was apparently a polarized "outburst" which was observed only at 14.5 GHz, and we interpret the absence of a comparable variation in polarization at 8.0 GHz as being the result of higher opacity at the lower frequency. The emitting region never became sufficiently transparent during the outburst for the region producing the polarized radiation at 14.5 GHz to be observable at 8.0 GHz.

The significance of this type of burst (BL Lac exhibited similar behavior during 1969) is that it provides evidence that newly accelerated or injected particles originate in a region where the absorption depth along the line of sight is high. The characteristics of the observed flux density variations in these sources are consistent with the hypotheses: A. that a major source of opacity is synchrotron self-absorption due to the radiating particles themselves and B. that the particles are constantly being generated (rather than being produced in isolated bursts) in a region which is small compared to the dimensions of the entire radiating volume. According to this picture, an "outburst" is the result of an increase in the particle generation rate, and we believe that the outburst in BL Lac during 1975 is an example of a case where the remnants of one "outburst" have partially absorbed the emission from a following event of enhanced particle generation.

In conclusion, the variability data in both total flux density and linear polarization favor source models which provide a continuous supply of radiating particles from a relatively small region of the object. The long-term stability (over at least several outbursts) of the magnetic field orientation in the emitting regions appears to place restrictions on the disruptive effects that the source of particles (and the radiating particles themselves) have on the emitting region.

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[Ed.: *Discussion of this paper is included in discussion following paper by Ledden and Aller on p. 64*].

Rotation in the Radio-Emitting
Region of AO 0235+164

John E. Ledden and Hugh D. Aller

The object AO 0235+164 underwent a large outburst at optical, infrared, and radio frequencies during the second half of 1975 (Ledden, Aller and Dent 1976; MacLeod, Andrew and Harvey 1976; Rieke et al. 1976). During the outburst, we monitored the linear polarization and total flux density at 8.0 and 14.5 GHz with the 26-meter telescope at the University of Michigan Radio Astronomy Observatory. The total flux density observations from September 1975 to April 1976 are shown in Figure 1 where O's represent measurements at 8.0 GHz and X's at 14.5 GHz.

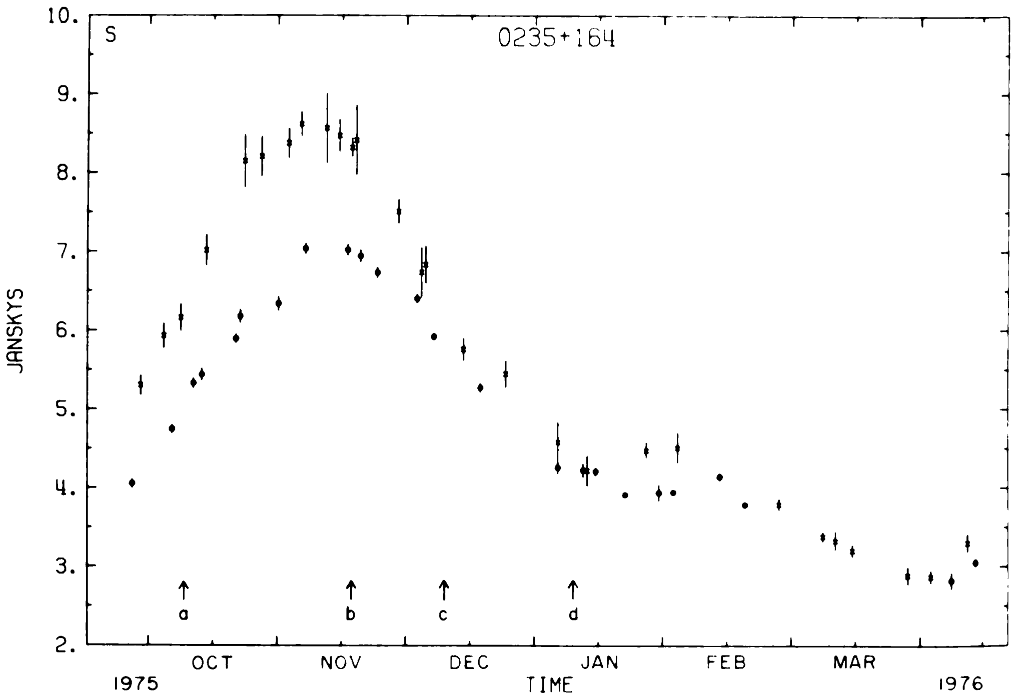

FIGURE 1

Our observations began after the outburst was already in progress. Observations at 10.6 GHz made at Algonquin Observatory indicate that the outburst began around July 1975 at a level below 1.5 Jy (MacLeod et al. 1976). The total flux density rose rapidly to maxima at both frequencies during November. Note that the amplitude of the outburst was greater and the time of maximum was earlier at the higher frequency. The same behavior is observed for many outbursts from variable extragalactic radio sources and it can be produced by opacity within the source. After the maxima, the flux density decreased almost as rapidly as it had increased. In late December the decay abruptly ceased. During January the flux density was nearly constant and may have even increased slightly. In February it again began to decrease but at a much slower rate than previously. The decline continued until early April when another outburst began.

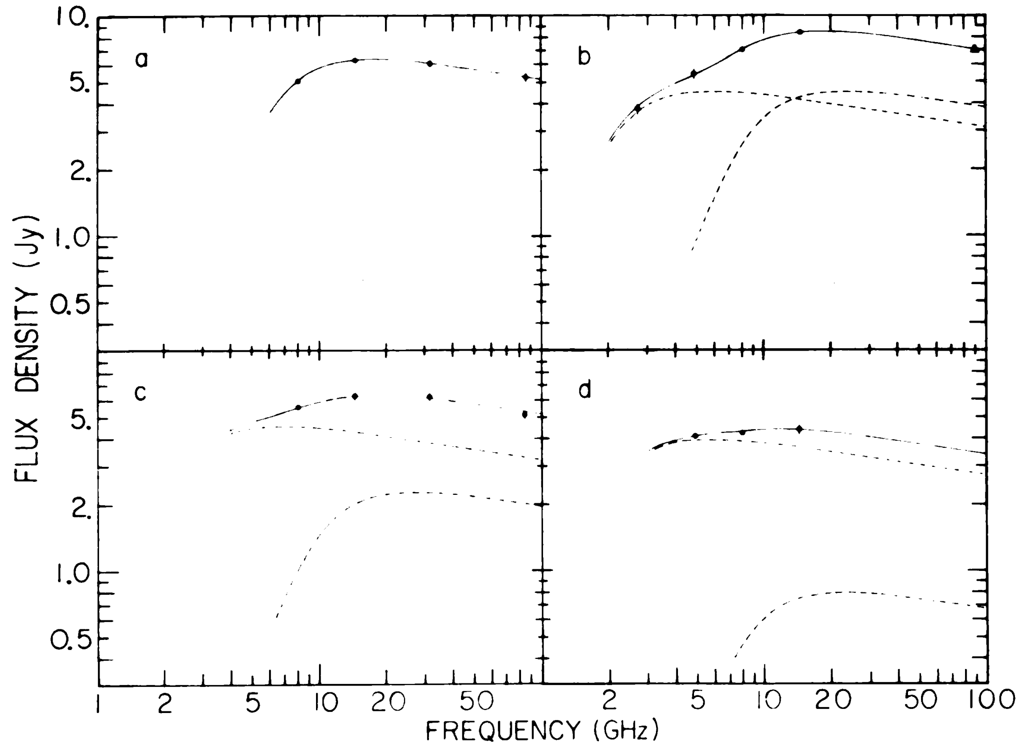

FIGURE 2 From Ledden et al. 1976

The arrows at the bottom of Figure 1 indicate four epochs for which radio spectra were constructed. Those spectra are shown in Figure 2. The features which we would like to point out here are the low-frequency turnover in the spectra and the linear shape of the spectra at high frequencies. As the outburst progressed, the turnover moved to lower frequencies. The turnover indicates the existence of significant opacity within the source at the lower frequencies but it was always transparent at the high frequencies. The total flux density variations and the spectra have been discussed in detail elsewhere (Ledden et al. 1976) and will not be considered further here.

Let us now turn our attention to the linear polarization observations which are shown in Figure 3. The total flux density measurements are shown in the bottom panel for reference. The polarized flux density measurements are displayed in the middle panel and the position angle is shown in the top panel. As in figure 1, the symbols O and X indicate measurements at 8.0 and 14.5 GHz respectively. Throughout the time period shown here, the polarized flux density was generally low and difficult to detect. For instance, no significant polarized flux density could be detected at 8.0 GHz during most of October 1975. The polarized flux density increased during November and remained at a detectable level through January 1976. Thereafter it decreased and was only marginally detectable for the remainder of the period.

The most interesting variations took place in the position angle. Before the end of October, the data are consistent with the hypothesis

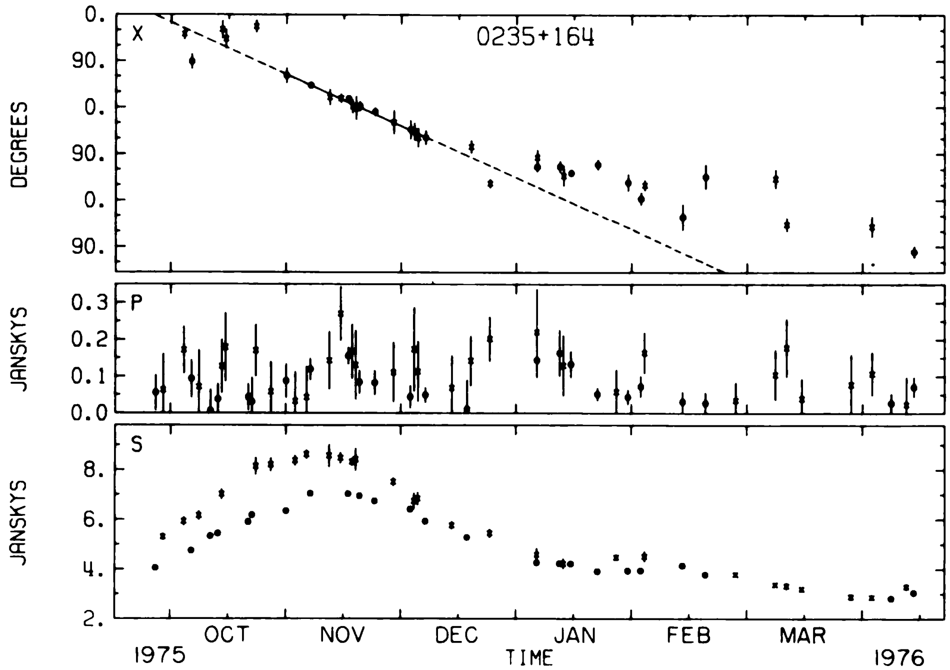

FIGURE 3

that the position angle at 14.5 GHz was constant. At the end of October, the position angle began to rotate systematically at both frequencies. Within the accuracy of the measurements, the rotation was linear at the rate of -3.3±0.1 degrees per day which corresponds to a period of 54 days for a rotation of 180 degrees. The linear rotation lasted for at least 40 days during which the position angle changed by 130 degrees. That period is indicated by the solid portion of the line in Figure 3. There was no significant difference between the position angles at the two frequencies during the linear rotation.

The linear rotation apparently ceased sometime during the second half of December. That is indicated by the deviation of the January measurements from the dashed extrapolation of the linear rotation. During January the position angle was constant within the accuracy of the measurements. The total change in the position angle from October 1975 to January 1976 was 260 degrees. After January the position angle was difficult to determine for both frequencies because of the low polarized flux density and the observed values of the position angle scatter widely.

The lack of any significant difference in the position angles at the two frequencies during the linear rotation places severe constraints on possible models. It rules out Faraday rotation as a possible cause. Any position angle shift caused by Faraday rotation should be 3.3 times as large at 8.0 GHz as at 14.5 GHz, and this was clearly not observed. Similarly, opacity effects are not likely to have been responsible for the linear rotation. If the opacity due to synchrotron self-absorption changes from optically thick to thin or vice versa, a 90 degree change in position angle would be expected to occur for a uniformly oriented magnetic field (Aller 1970). That is insufficient to explain the much larger changes which were observed. Several transitions of the optical depth between opaque and transparent would be required to explain the amplitude of the observed variations. If there were an inhomogeneous magnetic field, then decreasing opacity could reveal regions of the magnetic field with different orientation, thereby causing the position angle to change. Some combination of those two possibilities is also conceivable. In any case the frequency-dependence of opacity due to synchrotron self-absorption (or thermal absorption) would be expected to produce time differences between the changes observed at different frequencies. Such an effect has been observed for OJ 287 as described in the previous paper (Aller and Ledden 1978), but no similar effect is visible in the data for AO 0235+164. Any model which could produce the observed variations in position angle through opacity effects would have to be carefully contrived to produce the linear rotation and to avoid any significant differences between the two frequencies.

The most straightforward and natural mechanism for producing the linear rotation of the position angle is rotation of the magnetic field within the emitting region. The behavior of the position angle observed for AO 0235+164 is strikingly similar to that seen in the integrated pulse profiles of some pulsars (Lyne, Smith, and Graham 1971, Manchester 1971). It is commonly accepted that rotation is the primary factor affecting the observed behavior of pulsars; and in fact, the position angle changes are considered good evidence in favor of that interpretation. Linear rotation of the position angle is readily produced by models of a rotating magnetic field (Radhakrishnan and Cooke 1969; Ferguson 1976). The similarity of the behavior seen in AO 0235+164 to that observed for some pulsars suggests that the same basic mechanism may be involved. Despite the similarity in the linear polarization behavior, however, an outburst in the total flux density of AO 0235+164 is probably not the same phenomenon as a pulse from a pulsar. At present there is no sign of any periodicity in the radio outbursts which have been observed from AO 0235+164.

It is important to determine how often the linear rotation of the position angle occurs and what factors affect its visibility. The differences between the observed position angles and the extrapolation of the linear rotation indicated by the dashed portions of the lines in Figure 3 show that the linear rotation was not visible during October 1975 and January 1976. In fact, as mentioned previously, the position angle was apparently constant during those months. We have searched for evidence of the linear rotation from February to April 1976 by checking consecutive observations. The same check was made for the 8.085 GHz data for AO 0235+164 presented by Altschuler and Wardle (1976). In both cases the results were negative.

One factor affecting the visibility of a linear rotation in the polarization position angle may be opacity due to synchrotron self-absorption. At the beginning of the paper, we pointed out indications of significant opacity within the source. The opacity might obscure the emitting region which is responsible for the rotation in position angle. The evidence for significant opacity is strongest for October 1975 and January 1976, the time periods immediately before and after the interval during which the linear rotation was observed.

It is interesting to compare the radio observations with the optical observations of the linear polarization. Unfortunately only two optical measurements are available for comparison (Rieke _et al_. 1976). The first was made on October 4, 1975. The degree of linear polarization was 25 percent, much larger than the 1.6 percent observed at 14.5 GHz. The position angle was 154 degrees, which as pointed out by Ledden et al. (1976), agrees within the error with the value of 149±8 degrees for the average at 14.5 GHz during early October. An extrapolation of the linear rotation backward in time yields even better agreement with a value of 155±8 degrees. It is not clear to us which is the physically significant agreement. The existence of some agreement might be expected in view of the simultaneous radio and optical outbursts. The second optical measurement made on January 4, 1976 gave a degree of linear polarization of 6 percent at a position angle of 126 degrees. That position angle is different from both the observed radio position angle of 65±9 degrees and the extrapolation of the linear rotation to 30±8 degrees. The large decrease in the degree of optical linear polarization suggests a gross change in the optical emission region which might be related to the lack of agreement between the optical and radio measurements in January. The possibility of a relationship between the radio and optical linear polarization merits further investigation.

In summary we have observed an unusual linear rotation of the polarization position angle over at least 130 degrees during the large radio outburst from AO 0235+164. There was no significant difference between the position angle change at the two observing frequencies which rules out Faraday rotation and places severe restrictions on potential models. The most plausible explanation is a rotation of the magnetic field within the emitting region. Further radio and optical monitoring of the linear polarization and total flux density of AO 0235+164 should certainly be undertaken. This work was supported in part by the National Science Foundation under Grants: Ast 76-24638 and GP-42194.

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DISCUSSION

D. ALTSCHULER (to Aller):

You gave evidence that at some time OJ 287 was transparent because the flux variations at different frequencies were not time delayed. Later you said that the outbursts are opaque at the beginning. I want to know if it is your interpretation that this is the evidence for particle injection which you suggest occurs at the initial time of the "event".

H. ALLER:

The fact that the flux density rises and decays rapidly and simultaneously at two frequencies indicates that the source is predominently transparent. Our interpretation is that particle injection must have occured at many epochs in order to maintain the flux density at the high level during the outburst. In the case of OJ 287 during 1972 and 1973, the particle injection rate was sufficiently high that the source contained an opaque core. In the case of the later 1975 event, the overall particle injection rate was significantly lower and the opaque core (if present) represented only a small part of the emitting region.

J. MacLEOD (to Ledden):
Perhaps the reason that you see some order in the position angle of that source (AO 0235+164) is because that is one of the few cases that you have a relatively isolated outburst. It's not contaminated by the previous outbursts because they're very small. It may be that you are actually centering on one outburst. If that's the case it would be interesting to look at IIIZw2 which is undergoing a similar outburst at the moment because you may get some ordered movement in the position angle.

G. BURBIDGE (to Ledden):
What is the rotation period, about 100 days?

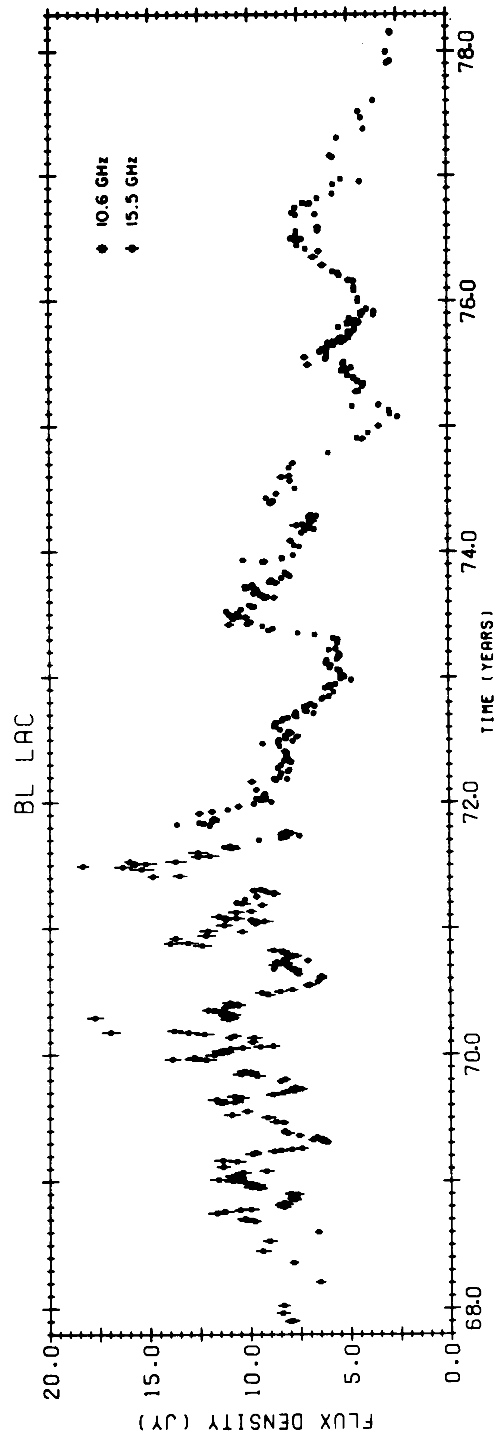
J. LEDDEN (to G. Burbidge):
For a rotation of 360° the period would be 108 days.

J. CONDON (to Ledden):
Are there any total-intensity VLB maps showing major-axis position angle rotation during the time of the polarization rotation?

J. LEDDEN:
As far as I know there were no VLB observations carried out on AO 0235+164 at that time. (D. Shaffer later confirmed this.) The source was not well known at that time.

W. DENT (a comment):
If I may draw your attention to the data posted on the wall over there [*Ed.: See figure on following page.*] This shows the same behavior for BL Lac that H. Aller described for OJ 287. If you superpose those two curves for BL Lac one on top of the other, you can see the two different frequencies simultaneously. You see that the upper curve which is 2 cm. and the lower curve which is 4 cm. will track almost precisely except in those instances where there is a very large outburst. In the first one-third of the data you see some very large outbursts at 2 cm. that don't rise nearly as high at 4 cm. This is a clear indication that the outbursts themselves are opaque but that the slowly varying base-level component is always transparent. So there must be at least a couple of components there and the outbursts have at certain times a sufficient number of particles to render them opaque.

H. ALLER:
Yes, I agree that when there is a large particle injection event (resulting in a high flux at high frequencies) the sources become opaque at the lower frequencies.



[Ed.: *This figure shows the 10.6 and 15.5 GHz light curves of BL Lac presented by W. Dent.*]

F. OWEN (to Ledden):

Could the sources be only partially transparent, for example with a radially decreasing density distribution.

J. LEDDEN:

Yes, certainly. In general they appear to be partially opaque.

A. PACHOLCZYK (to audience):

Could circular polarization provide a clue as to whether we have a relativistic plasma with non-relativistic ions, or a plasma of relativistic electrons and positrons in BL Lac objects? If there are practically no thermal electrons, as polarization observations indicate (see talk by Wardle), and if the lower energy cut-off in the distribution of relativistic electrons corresponds to a critical frequency close to the observed frequencies, there should be circular polarization due to propagation effects (Faraday pulsations) in the first case. Would there be circular polarization in the second case (electron-positron plasma)?

G. BURBIDGE:

Dr. O'Dell?

S. O'DELL:

Zero circular polarization would result.

A. PACHOLCZYK:

Are you sure? Do you think it's zero because one vector rotates in the opposite direction to the other and the effect simply cancels out, or is your answer based on a deeper reasoning?

S. O'DELL:

I did not compute it.

A. PACHOLCZYK:

It would be a simple calculation at high frequencies, but not at low frequencies. I think this problem is too complex to rely on intuition. Does anyone know about any work done on this problem? Is any circular polarization observed in BL Lac objects?

P. HODGE:

The average circular polarization of OJ 287 since 1977, August is less than the standard deviation of 0.17%.

J. LEDDEN:

On the basis of measurements made at Westerbork, significant detections of circular polarization at wavelengths of 21 and 49 cm. have been reported for BL Lac (e.g. Weiler, K.W. and Raimond, E. 1976, _Astr. and Ap._, _52_, 397; Weiler, K.W. and Wilson, A.S. 1977, _Astr. and Ap._ _58_, 17). Variability of the circular polarization at 21 cm. has also been claimed (Ekers, R.D., Weiler, K.W., and van der Hulst, J.M. 1975, _Astr. and Ap._ _38_, 67).

T. JONES:

It's also true that the effect on circular polarization depends on the particle energy distribution. If you cut off this distribution very close to the frequency at which you are observing, you don't get much circular polarization.

VLBI OBSERVATIONS OF BL LACERTAE OBJECTS

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Very long baseline interferometry (VLBI) radio observations allow one to observe the structure of a radio source with resolutions on the order of some milliarcseconds. A VLBI system consists of several antennas with independent local oscillators. Signals received at the antennas are tape recorded and later correlated in special purpose processors. Typically, the interferometer visibility phase is lacking for VLBI data, and interpretation of the results depends on model fitting to the visibility amplitudes. See Cohen (1973) and Cohen et al. (1975) for discussions about observing, calibrating, and model fitting and its pitfalls.

An angular size of $0\overset{''}{.}001$ ($\sim 5 \times 10^{-9}$ radians) corresponds to physical sizes of 1, 10, and $\sim$ 30 ℓ.y. for z = 0.01, 0.1, and $0.5 \lesssim z \lesssim 3$ respectively ($H = 50$, $q_o \sim 0.05$). Thus, sources whose flux densities vary on short time scales (weeks to years) are candidates for VLBI observations. Radio sources with centimeter excess spectra are also expected on theoretical grounds to have very compact structure. [Centimeter excess (CE) is defined here as $\alpha \gtrsim -0.4$, where $S \propto \nu^{\alpha}$ (beware of definitions of α with the opposite sign!)]. Such sources presumably contain synchrotron self-absorbed components. Typically, such components have a radio spectrum similar to that shown in figure 1. The

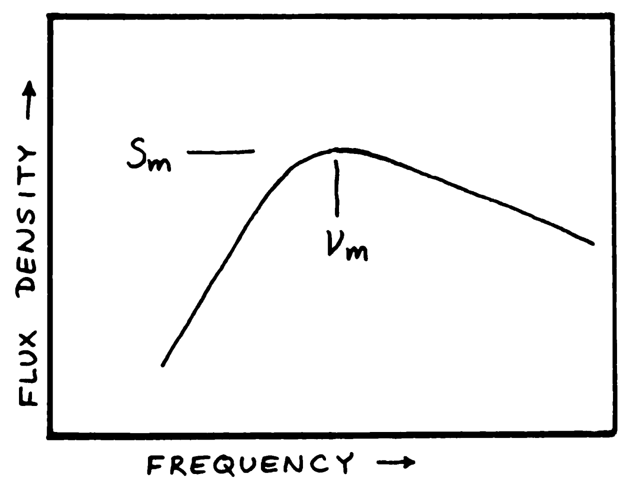

Fig. 1. Radio spectrum of typical isolated self-absorbed synchrotron source. Both axes are logarithmic.

relationship between component size (θ in arcsec), magnetic field (B in Gauss), peak flux density (S_m in flux units. 1 flux unit (f.u.) = 10^{-26} W m^{-2} Hz^{-1}), and peak frequency (ν_m in MHz) is

* Operated by Associated Universities, Inc. under contract with the National Science Foundation.

$$B \approx 2.5 \times 10^{-8} \frac{\nu_m^{\,5}\,\theta^4}{S_m^{\,2}(1+z)} \quad \text{(Terrell 1966).} \qquad (1)$$

Radio sources with spectra more complex than represented in figure 1 usually consist of multiple components with different peak fluxes and frequencies. A few sources seem to have an "onion skin" appearance and get more compact at higher frequencies. These sources probably have a radial gradient of particle energy, particle density, and/or magnetic field (Condon and Dressel 1973, de Bruyn 1976, Marscher 1977).

BL Lac objects (BLO's), many of which have rapid flux density variations and many of which have CE spectra, are prime candidates for VLBI observations. Table 1 is a listing of some BL Lac and related objects. Most of them are from the listings of Kinman (1976) and Stein et al. (1976). The table gives the IAU designation of the object, another name by which it is perhaps better known, a designation of the type of radio spectrum: N for normal ($\alpha \lesssim -0.5$) and CE for centimeter excess, and whether or not it has been detected in a VLBI experiment. Y and N stand for yes and no on detections, a blank means the object has not been observed. [Most published observations can be found in Kellermann et al. 1970, 1971; Cohen et al. 1971; and Gubbay et al. 1977; and references therein. Preston et al. (1975) list all sources detected by VLBI at that date. Private communications from R. Preston and J. Ledden have also been used to compile the Table. Specific references for individual sources will be given in the discussions below.] An asterisk in the VLBI Detection column denotes a source which is discussed specifically later in this paper. Some of the spectrum determinations are questionable because so little data exist; and a few of the sources, such as 0521-365, have a spectral index on the borderline between normal and CE spectra.

Table 1 is certainly a heterogeneous collections of sources, but two features appear to be very common for BL Lac objects: most have CE spectra and most are detectable in VLBI observations. These facts are related, as noted earlier. It is likely that compact components could be detected in nearly all the CE sources which have not been observed with VLBI.

Let us briefly compare high resolution structure observations with other characteristics of BLO's. One of the outstanding features of BLO's is rapid time variability of radio and optical luminosity. Time scales can be shorter than a week, indicating sizes $\lesssim 0.02$ ℓ.y. Such sizes are smaller than observed directly. For BL Lac there is definite structure on the 0".001 scale, or several light years at $z = 0.07$. Thus only localized regions of the source take part in the rapid variations, at least for BL Lac. The brightness temperatures inferred for the variable region are very high. In BL Lac, an object whose size is ~ 1 light month has a brightness temperature $\gtrsim 10^{14}$ °K if it is radiating more than a flux unit. Such temperatures should cause rapid inverse Compton scattering "cooling" of the radiating particles (Kellermann and Pauliny-Toth 1969). The radio variations do show a tendency for a very sudden outburst to be followed by a not-quite-as fast decay. This may be a manifestation of inverse Compton effects. A search for the scattered photons, at optical and X-ray wavelengths, might be fruitful at such times (July 1971 and July 1973, for instance. See Figure 2a.).

TABLE 1

VLBI Observations of BL Lac Objects

Source		Radio Spectrum	VLBI Detection	Source		Radio Spectrum	VLBI Detection
0048-097		CE	Y	1215+303	ON 325	CE	Y
0219+428	3C 66A	CE	Y	1219+285	W Com	CE	Y
0235+164		CE	Y*	1225+206		N	
0300+47		CE	Y	1307+121		CE	
0422+005		CE	Y	1308+326		CE	Y
0521-365		N	Y	1400+162		N	
0537-441		CE	Y	1514+197		CE	Y
0548-322		?		1514-241	AP Lib	CE	Y
0735+178		CE	Y*	1538+149		CE	Y
0754+100	OI 090.4	CE	Y	1652+398	Mk 501	CE	Y
0808+019		CE	Y	1656+053		CE	Y
0814+425	OJ 425	CE	Y	1727+502	1Zw 186	CE	Y
0818-128	OJ -131	CE	Y	1749+096	OT 081	CE	Y
0829+046		CE	Y	1807+698	3C 371	CE	Y*
0851+202	OJ 287	CE	Y*	2117+025	OX 029	CE?	
0906+430	3C 216	CE	Y	2131-021		CE	Y
0912+297		N?	Y	2200+420	BL Lac	CE	Y*
0957+226		N		2201+044		CE	Y
1057+100		?		2223-052	3C 446	CE	Y
1101+384	Mk 421	CE	Y	2254+074	OY 091	CE	Y
1147+245		CE	Y	2335+031		CE	

At least for OJ 287 and BL Lac, there is radio structure over a range of size scales. At 18 cm, OJ 287 was definitely resolved with $\theta_{Gaussian} \gtrsim 0''.0022$ in 1974.4 (Shaffer and Schilizzi 1975) whereas the source was $\lesssim 0''.0005$ at 2.8 cm at about the same epoch (Kellermann et al. 1977). This source may be of the "onion skin" type. BL Lac is smaller at 2.8 and 3.8 cm than at 13 and 18 cm (unpublished data).

There is little, if any, relationship between radio polarization data and radio structure at wavelengths of a few centimeters. The polarization varies rapidly both in percentage and position angle (Altschuler and Wardle 1976), and almost certainly is dominated by activity in individual components rather than over-all structure. In this respect, the BL Lac objects are similar to compact quasar sources.

It is not clear if the infrared and optical continuum spectra are an extension of the radio spectra or not. A spectral index of ~ -1 from 10^{11} to 10^{13} Hz would suffice to connect the radio and optical spectra in figure 1 of Strittmatter et al. (1972). If the same ensemble of electrons is radiating at radio and optical wavelengths, there is a lifetime problem for the optically-radiating electrons. Equation 1 predicts magnetic fields on the order of a milligauss for components with sizes $\sim 0''.001$ and spectral peaks near 10 GHz. The lifetimes of electrons radiating at optical wavelengths in such a field are well under a year. Observations of optical polarization and its variability probably do require a non-thermal radiation mechanism that is variable on very short time scales.

Let us now look in more detail at several of the BL Lac objects.

BL Lac. (z = 0.0695: Miller et al. 1978. $0''.001 \approx 7$ ℓ.y.) The spectrum (Strittmatter et al. 1972) is clearly centimeter excess. This source has been observed at many frequencies in many VLBI experiments. However, there has been little detailed work on the structure and the structure is so variable that it is difficult to relate observations at different epochs.

The source has been best studied at high frequencies: 3.8, 2.8, and 2.0 cm. Figure 2a shows the flux density history of BL Lac from 1969 through 1977, at 3.8 cm. The data in the figure are from Dent and Kojoian (1972), Dent and Kapitzky (1976), Altschuler and Wardle (1976), and the NRAO interferometer calibration data (Williams, private communication). VLBI experiments have been indicated by arrows in figure 2a. The letter C stands for Clark et al. (1973), W for Wittels et al. (1975), and K for Kellermann et al. (1977).

The observations of Clark et al., which started in February 1971, showed that the source maintained a preferential position angle of about 0 degrees, and that it had a tendency to appear smaller when stronger. The same position angle persists through the observations of Wittels et al. (1975), and at least until 1974.5 (Kellermann et al. 1977). (I think there are some calibration errors in some of the Wittels et al. data which cause them to call the source more complex than it really is.) Our unpublished 18 cm data from the end of 1975 also show the same position angle. Since the polarization position angle is variable, it seems that polarization has little relationship to the overall structure (or vice-versa). In most compact radio

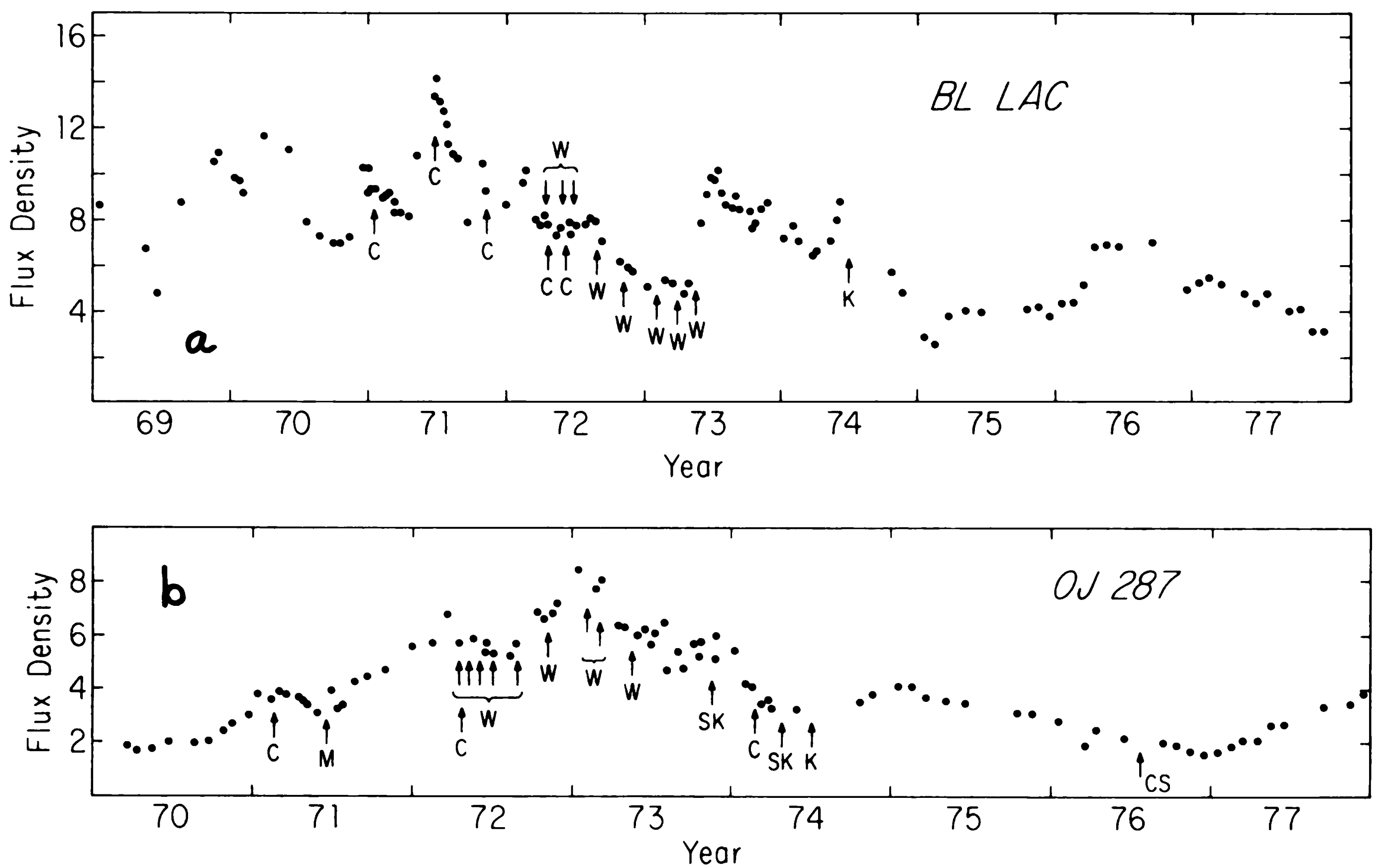

Fig. 2. Flux density histories at 3.8 cm for a) BL Lac and b) OJ 287. Dates of VLBI observations are indicated by lettered arrows. Refer to text for explanation of letters.

sources, the energy in particles apparently exceeds the total magnetic energy, so the field probably has little influence on the particles. The two quasi-stable polarization states at 3.8 cm in Altschuler and Wardle's data (1971 through 1972, and mid '73 through '74) are not too far from alignment with the structure.

The best over-all model for the structure seems to consist of a very small component, responsible for the flux-density variations, separated by 1 to 1.5 milliarcsec from a somewhat larger and weaker but constant component. Only in the 2 cm data of Kellermann et al. (1977) is there fairly good evidence that the components are really spatially separated. All the other 3.8 and 2.8 cm data could be fitted with core-halo models with a small, variable core and a long (if $\sim 0\overset{''}{.}0015$ is considered long!), very skinny (axial ratio $\lesssim 0.4$) halo. A variable component as part of a double or as a core will produce the effect noted by Clark et al. (1973) that the source looks smallest when it is strongest (provided the variable component is only slightly resolved). I do not know of any VLBI in early 1975 when the source was at its weakest. That probably would have been a good time to determine the size of the extended component. The flux level at that time ($\sim$ 2.5 f.u.) is comparable to the strength of the extended components in the models of Kellermann et al. (1977).

The data at 13 and 18 cm are sparser (Kellermann et al. 1970, 1971; Broderick et al. 1972; Gubbay et al. 1977; and our unpublished results), but definitely show the source to be more extended than at 3.8 or 2.8 cm. The position angle of the source structure is also near zero degrees at lower frequencies. We have not been able to discern more than one component at these frequencies, but that may be due to insufficient angular resolution. (The earth isn't big enough!)

Perhaps the biggest unsettled question about the BL Lac structure variations is whether or not the components move. The maximum correlated flux density follows the total flux density quite well. (Especially if a $\sim$ 20% increase is applied to the Wittels et al. (1975) data. Their entire scaling seems low to me.) With limited (u,v)-plane coverage, changes in flux density are likely to be interpreted as changes in size if no visibility minima are observed, as has usually been the case for BL Lac. However, the observations are also consistent with no changes in size of the source. There does seem to be a different position angle at various times, however, for the structure. Some of this variation may be a resolution effect. The model and (u,v) tracks in Kellermann et al. (1977), shown here in figure 3, illustrate this effect. The position angle of the compact component is noticeably different from the position angle of separation of the two components. On shorter baselines, the double PA is the dominant factor, whereas on the longer baselines the larger component is resolved out and all the action comes from just the small component with its different position angle. It is tempting to speculate that different outbursts occur within a region rather than at just one location, but existing data cannot settle the question. Very accurate position measurements would be useful, but it seems likely that extensive VLBI observations, at the highest possible resolution, will be required to determine the nature of the radio emission from BL Lac.

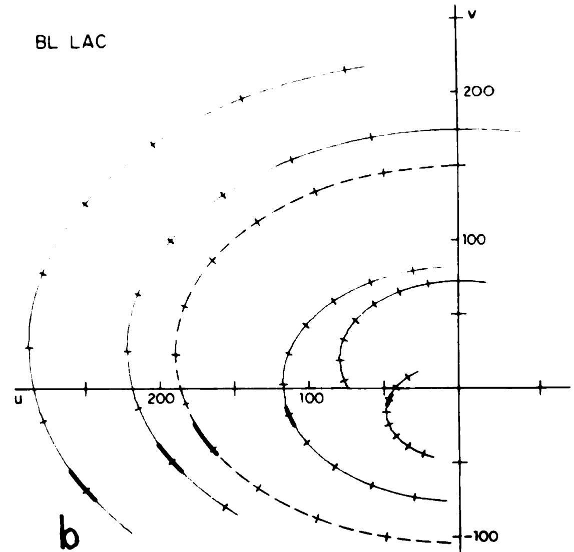

Fig. 3b. Tracks in the (*u*, *v*)-plane for BL Lac. *Solid lines*, 2.8 cm; *dashed line*, 2 cm. Heavy line indicates the location of the visibility maxima on each track. Ticks are spaced 1 hour apart.

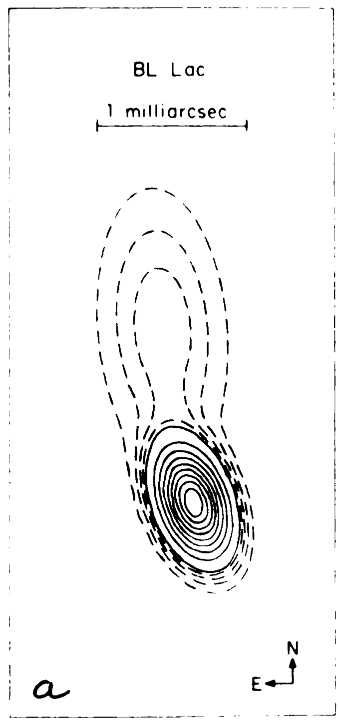

Fig. 3a. Structure of BL Lac at 2.8 cm based on fringe amplitude data taken at 2.8 and 2 cm wavelength. Solid contours are 10% of peak surface brightness; dashed contours are 8, 6, 4, and 2%.

OJ 287. [No redshift. One emission line (Miller, this conference)]. This source also has an inverted spectrum (Strittmatter et al. 1972). Its total flux varies rather rapidly, but not quite so spectacularly as BL Lac. Figure 2b shows the 3.8 cm "light" curve, from the same references as for BL Lac except that the earliest data (1970-71.5) are at 4.5 cm from Medd et al. (1972). Also indicated in the figure are the dates of various high frequency VLBI experiments. The identifiers are C - Cohen et al. 1971, 1975; M - Matveyenko et al. 1974; W - Wittels et al. 1975; SK - Shaffer and Kellermann unpublished 2 cm results; K - Kellermann et al. 1977; and CS - Cohen and Shaffer unpublished 2.8 cm results.

OJ 287 underwent a long outburst from 1970 to the end of 1976, with various short-term fluctuations superimposed. The apparent size of the source increased during this interval. The component separation as a function of time for an assumed double source is shown in figure 4. (Gaussian sizes in the literature, from the references for figure 2b, have been converted to the equivalent double separation.) The source was unresolved until early 1974, although it may have had a weak halo (Kellermann et al. 1977). By the middle of 1976, the source was highly resolved at 2.8 cm on a transcontinental baseline. Because it was so resolved, we have little data with which to model the source, but it seems to be best represented by a double with component separation greater than 0″.001 in PA ∿ 30° (Cohen, private communication). Since the start of a new outburst in 1977, the source has been unresolved, and the correlated flux density has been following the increase in total flux density (Fort et al. private communication).

I interpret the 1970-1976 outburst as having two stages. Initially, the source was unresolved, generally increasing in strength,

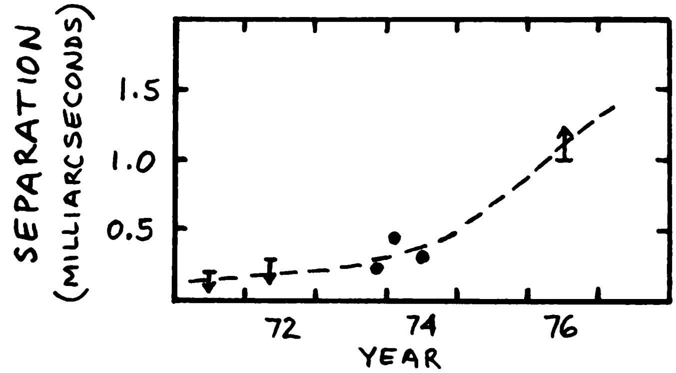

Fig. 4. Separation as a function of time for proposed double source in OJ 287.

and optically thick, at least at 11 cm. The source was being "pumped up" with high energy electrons, which were confined to a region < 0".0003 across until about mid-1973. The peak brightness temperature was about 2 x 10^{12} °K at 3.8 cm in January 1973. Subsequently, the source began to expand. The rapid changes in percentage polarization, and positional angle of polarization at 11 cm, at this time (Altschuler and Wardle 1976) probably occurred as the source became optically thin. The total flux density decreased, probably because of adiabatic losses by the electrons. Once the expansion began, it was fairly rapid. The angular size went from ∿ 0".0003 in 1973 to ∿ 0".001 in mid-1976, or ∿ 0".0003 yr^{-1}. This is the expansion rate of the double. We cannot tell what happened to the sizes of the individual components.

At lower frequencies, OJ 287 appears to have a larger size. We may be observing different components, or we may just be seeing the effect of a non-uniform source. At 13 cm, Gubbay et al. (1977) and Preston (private communication) find a size of about 0".001 for 1972-1975, although the source could be somewhat smaller if some ($\lesssim$ 30%) of the flux density came from a more extended halo. At 18 cm, Shaffer and Schilizzi (1975) found the source to have a gaussian size of 0".0022 in 1974.4. My unpublished 18 cm data at the end of 1975 show an essentially unresolved ($\lesssim$ 0".001) source. Apparently there are fairly rapid structure changes even at this rather long wavelength.

0235+164. (z_{abs} = 0.524 and 0.852: Burbidge et al. 1976; Rieke et al. 1976). This CE object had a spectacular outburst at radio, infrared, and optical wavelengths in November 1975 (Rieke et al. 1976; Ledden et al. 1976).

The only pre-outburst VLBI observation was at 430 MHz in 1970 which showed the source to be unresolved at a size limit of ∿ 0".02 (Galt et al. 1977). The source has been observed several times since the outburst and has been essentially unresolved at 932 MHz (θ < 0".006; Wolfe et al. 1978), 13 cm and 3.6 cm ($\theta \lesssim$ 0".002 and $\theta \lesssim$ 0".0006 respectively; Cotton et al. private communication) and 2.8 cm. Our unpublished data at 2.8 cm for February 1977 give a hint of some structure in the source, oriented roughly East/West. All these later observations took place from one to one and a half years after the outburst. There does not appear to have been any very rapid expansion of the source. Continued monitoring is desirable.

0735+178. (z_{abs} = 0.424: Carswell et al. 1974). There is not much information on the structure of this source, but since its redshift is known, it is a reasonable candidate for further study. Unlike 0235+164, it has been partially resolved in most observations to date.

The source was unresolved, at fairly low resolution, at 49 cm in 1967: $\theta < 0''.015$ (Jauncey et al. 1970). At 18 cm in early 1978, the size was $\sim 0''.0036$ (Shaffer and Marscher, unpublished). At 13 cm, the size appeared to be $\sim 0''.0014$ in 1969 (Kellermann et al. 1970), but was larger ($\sim 0''.0028$) in mid-1977 (Cotton et al., private communication). These two observations indicate that either the source has expanded greatly in 8 years ($v/c \sim 4$) or the structure is more complicated than the simple gaussians used to derive the apparent sizes. At 3.6 cm in mid-1977, Cotton et al. (private communication) find part of the source to be in a very small core ($\theta \lesssim 0''.0002$). Our 2.8 cm measurements of early 1978 (Shaffer and Marscher, unpublished) show the source to be definitely resolved and having multi-component structure on a $\sim 0''.0005$ scale.

3C 371. (z_{em} = 0.0506: Miller 1975). This object, although definitely a galaxy showing both emission and stellar absorption lines, has been related to BL Lac objects because of its optical variability and polarization.

We have undertaken a program to monitor structure changes in this source. The first observations, from early 1977, show that most of the flux density at 2.8 cm comes from a compact component that is unresolved ($\lesssim 0''.0004$) in PA $\sim$ 140°-150° and extended ($\sim 0''.0008$ gaussian or possibly a double with separation $\sim 0''.0005$) in PA $\sim$ 30°-40°. This orientation is consistent with the low visibility measured by Cohen et al. (1971) at 3.8 cm in PA = 53°. The optical polarization position angle is variable and probably is not related to the structure. At 13 cm, 3C 371 is appreciably resolved and much bigger than at the shorter wavelengths (Broderick et al. 1972; Preston, private communication).

Summary

Most objects categorized so far as BL Lac objects have centimeter excess radio spectra, indicating compact radio structure. VLBI observations confirm compact structure in all BLO's searched to date.

BL Lac itself which is probably the most variable radio source known (in terms of the average value of dS/dt) shows variable structure as well, but the experimental coverage has not been good enough to determine the true nature of the structural variations. OJ 287 underwent a long outburst from '70 to '76. The later, declining stage of the outburst coincided with an expanding source. Again, the data are rather sparse, and many details of the expansion are lacking. The expansion is roughly consistent with injection models, although the injections must have been prolonged. The source was optically thin during at least the second half of the outburst.

At the shortest wavelengths where VLBI experiments are routinely performed (2, 2.8, 3.8 cm), the BLO's are quite small, with individual components typically smaller than 0".001. Such sizes are quite usual for quasar and radio galaxy CE sources as well. At 13 cm wavelength, the BLO radio sources tend to be somewhat more compact than QSO sources (Preston, private communication). There is perhaps a tendency for multiple components to be less common in the BLO's. Most other sources studied at short wavelengths have two or more discrete components.

The BLO's share with other CE sources the almost universal rule that sources look bigger at longer wavelengths. I think that, in most cases, different components are being observed at the lower frequencies. However, detailed observations at several frequencies are required to determine if there really are several components of different sizes or if non-uniform components are being observed.

BLO's are not unique in showing structure variations. See the review by Cohen et al. (1977). BL Lac itself varies more rapidly than most sources, but 3C 120 shows comparably fast visibility changes. BL Lac is somewhat unusual in that its variations can be modeled by changes in strength of a relatively stationary component. Most structure variations of other sources involve definite component motions, a feature probably common to OJ 287.

I would like to thank my many colleagues for data in advance of publication, especially Bob Preston of JPL, Bill Cotton of MIT, Jack Ledden of VPISU, and Dave Fort of NRC, Canada. Claude Williams of NRAO provided flux density values for BL Lac and OJ 287 from 1975 to date. I thank Ken Kellermann for comments on this paper and many useful discussions.

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DISCUSSION

H. ALLER:

What is the lead time needed for notification in order that a source be included in a VLBI experiment at the present time?

D. SHAFFER:

The experiments are specifically scheduled 3 to 4 months ahead of time. With the VLB network there is basically an observing session scheduled every 2 months, usually involving at least Haystack, NRAO, and Owens Valley. With a 2-month delay, you could probably get an individual object looked at.

K. JOHNSTON:

I would like to make a comment on that. I received a call from Art Wolfe last December (1977) after he found out from J. Miller that 3C 446 was undergoing an outburst. [*Ed.: See talk by J. Miller on 3C 446.*] We did make VLB observations on that object in January and March, 1978, so the lead time in this particular case was only 1 month.

D. SHAFFER:

On a high priority basis you cannot expect to start detailed monitoring and get it every 2 months for the next year unless you have a really important object. 3C 446 was an unusual case and therefore was scheduled immediately.

ANONYMOUS:

Was OJ 287 expanding with superluminal velocities?

D. SHAFFER:

You tell me the redshift and I'll tell you whether or not it was.

J. KROLIK:

How much of a technical job is it to do VLB observations at higher frequencies on BL Lac objects?

D. SHAFFER:

The highest frequency at which we have performed successful VLB experiments is 22 GHz (1.3 cm.). There was an unsuccessful attempt at 8 mm. There are no good receivers at wavelengths below 1.3 cm. We are limited by the bandwidth that we can record, so you cannot buy back sensitivity with a broad bandwidth as you can with a continuum single-dish observation.

K. JOHNSTON:

Could you say something about what the limiting flux level a source must be for you to get VLB information?

D. SHAFFER:

At 1.3 cm. I think we can get reasonable structure information on a source that is a couple of Jy in strength. At 2.8 cm. or 3.8 cm., if Goldstone is included, we can work well below 1 Jy.

F. PACINI:

How much of the radio emission comes from a region surrounding the ultracompact components?

D. SHAFFER:

Wardle finds that ∿10% of the total emission comes from a ∿10 arc sec. halo, at least for some sources.

K. JOHNSTON:

How do the correlated and total flux densities compare for BL Lac?

D. SHAFFER:

To within our calibration accuracy of about 10%, which assumes that at least one of the sources we observed was unresolved at some part of its (u,v) track, the peak correlated flux density equals the total flux density for BL Lac. Such behavior is different from sources like 3C 120 or 3C 273 where the fringe visibilities involve more like 30-40% of the total flux.

G. BURBIDGE:

Is there some place where all of this is also published?

D. SHAFFER:

The discussion will appear in the paper that I have written. Most of the information on the slide has been published but not in a single publication. We have not done detailed observations of these things because we felt that our time would be better invested in some other sources that would perhaps be simpler; that we could understand. We haven't followed BL Lac, for instance, with the same attention that we have followed 3C 345. There are very few objects for which we have detailed information.

THE OPTICAL CONTINUA OF BL LAC OBJECTS

by

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The rapidity and nature of the optical variations in BL Lac are discussed. The evidence for long term trends in the polarization of OJ 287 and its implications are noted. Observational techniques are described for separating the compact central non-thermal source from the nebulous component. Provisional results for four BL Lac objects give spectral indices for the non-thermal components and support the idea that the nebulous components are elliptical galaxies.

INTRODUCTION

BL Lac objects are like quasars except that their optical spectra are continuous or only contain quite weak features. They are also distinguished by showing rapid variations not only in their optical flux but in their linear polarization. Their energy distribution can be found from simple broad band photometric measurements (e.g. UBV) because they have no strong spectral features. It is found that these objects have roughly power law spectra $F(\nu) \propto \nu^{-\alpha}$, where the spectral index α lies in the range $0.7 < \alpha < \sim 2$; this is consistent with the optical emission being synchrotron radiation. In the case of OJ 287, a good correlation has been observed between long term flux changes in the visible and at 10 μ (Rieke and Kinman 1974) which suggests that, over this waveband, the radiation is emitted by the same mechanism. On the other hand it has been noted that changes in the spectrum of this waveband of 0235 + 164 did occur during rapid flux changes (Rieke et al. 1976) and that differences in the position angle of the linear polarization between the visible and infrared have been observed in 0735 + 178 and OI 090.4 (Rieke et al. 1977): the interpretation of these effects is still uncertain.

Although a considerable literature exists which describes the optical monitoring of BL Lac objects (and quasars in general), many interesting questions concerning the flux variations remain unanswered. We do not know for certain whether or not periodic effects are present. The reality of some of the most rapid changes that have been reported is open to question and it is unclear whether the rates of increase and decline of brightness are equally rapid or not. It is known that rapid variations in the linear polarization occur and that the polarization can exceed 30% on occasion but there has been little analysis of these results nor have they been used to place constrictions on possible models. These problems are touched upon in the first half of this paper. A very interesting complication to the photometry of BL Lac objects arises because some of these objects are embedded in a nebulosity. It is possible and indeed likely that all BL Lac objects

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

are associated with nebulosity (as was originally postulated by Sandage for quasars) and that we only see the nebulosity in the case of those that are nearby and where the non-thermal compact source is not very much brighter than the galaxy. In several instances (Mark 421, AP Lib, Mark 501, Zw 1727+50 and BL Lac) a spectrum has been obtained of the nebulosity which shows red-shifted stellar absorption features: this suggests very strongly that the nebulosity is a galaxy in which the non-thermal source is embedded. These BL Lac objects are of particular interest since the red shifts can be used to establish distances. Suitable photometry is therefore needed which can separate the radiation of the non-thermal source from that of the galaxy so that we can not only study the energy distribution of both sources but also study the distribution of light in the galaxy. Since the distances are known these are the only cases where the absolute brightness of both the non-thermal source and the galaxy can be reliably estimated for the BL Lac objects. The seond half of the paper is taken up with this problem. A review and summary of photometric information about BL Lac objects may be found in Kinman (1975) and Kinman (1976).

OPTICAL FLUX VARIATIONS

There is no definite evidence for periodic variations in the flux of BL Lac objects. In the case of OJ 287, a period of 39^m has been found by Visvanathan and Elliot (1973) and also by Frohlich, Goldsmith and Weistrop (1974) but was not confirmed by Kiplinger (1974). Weak evidence for an 8 day period in this object was found by Kinman et al. (1974); an 8-day variation in the polarization observed by Shakhovskoy and Efimov (1977) is interesting but could well be fortuitous agreement. A small amplitude "flicker" on a time scale of a few minutes observed in BL Lac by Racine (1970) was not confirmed by Veron and Veron (1976).

Attempts to find periods greater than $\sim$ 10 days require very long stretches of data and as Deeming (1975) has shown from an analysis of Kinman's observations of 3C 345, the effects of impressed periodicities such as the year and the lunar and calendar months are quite marked. An apparently simpler problem would be to find the form of the power spectrum--for example we might wonder whether it corresponds to 1/f noise (c.f. Press, 1978)--but even this requires better data than is currently available. One problem is that the usual assumption that we are dealing with a stationary process is probably wrong. Thus between 1968 June and 1970 September, the night to night rms variation of BL Lac was ± 0.298 mag while between 1970 October and 1972 December, this parameter was ± 0.165 mag.

Any analysis of optical monitoring results requires an accurate assessment of the observational errors and this is not always easy to do. One factor (which is sometimes overlooked) is that if a nebulosity is present (as in the case of BL Lac), the magnitude will be a function of aperture size if the observations are photoelectric and will be a function of many factors such as the focal ratio, the emulsion and the exposure time if the observations are iris measurements of photographic images. Figure 1 shows a comparison of photographic observations of BL Lac made with small telescopes: the Meudon and O.H.P. Schmidt telescopes (Bertaud et al. 1973), the Herstmonceux 26-inch F/10 refractor (Tritton and Brett, 1970) and the author's observations with the Lick 20-inch F/7 astrograph. The much smaller scatter between the

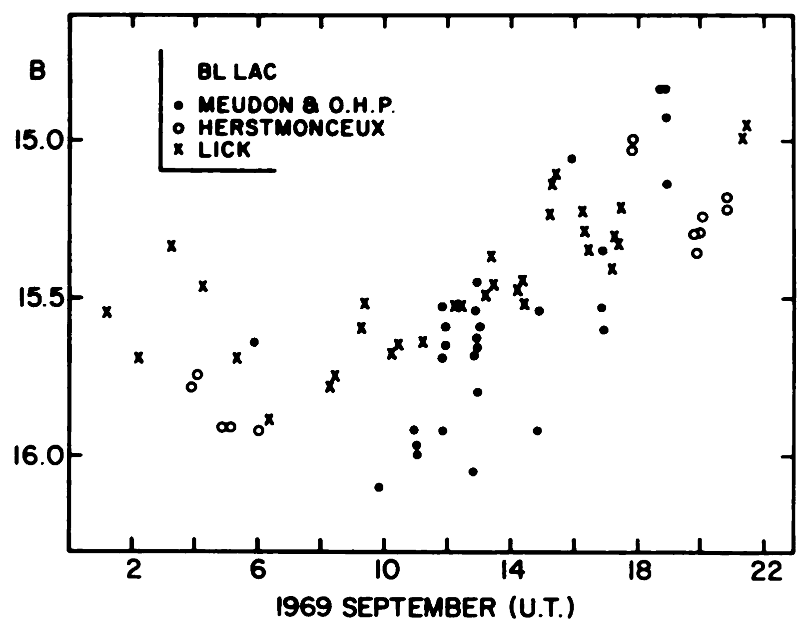

Fig. 1 The photographic monitoring of BL Lac: a comparison of the results from three sources

observations on a given night at Lick and Herstmonceux suggests that a considerable amount of the scatter in the Meudon and O.H.P. observations on a given night must be spurious. It also seems likely that there are systematic differences (which could be magnitude dependent) between the three sets of observations and it is not easy to combine them all satisfactorily into a single light curve.

The literature contains several examples of claims for very rapid changes of brightness in BL Lac objects: for a bibliography see Elliot and Shapiro (1974). Weistrop (1973) for instance made photoelectric observations which showed a change $\sim$ 1.5 mag in the order of an hour in December 1972. Veron (1975) has compared these observations with photographic observations made on the same night and concluded that Weistrop's observations should be discarded. Evseev et al. (1974) also have published observations which disagree with Weistrop's result. It is usually quite difficult however to decide whether the unsupported claims of any single observer should be accepted. One might guess that the best chance of finding real effects would be in relatively long runs of fairly homogeneous data. Veron (1975) has concluded that the maximum rate of change in her data is 2.1 magnitudes per day for BL Lac. An example of a very sudden change of brightness of this object is shown in Fig. 2. In this case we have B magnitudes from the Meudon and O.H.P. Schmidt telescopes and the Lick Astrograph. Visual plates taken with the Lick 12-inch refractor were also available and these were converted to B magnitudes by assuming a B-V of 1.0. Despite the scatter, it seems reasonable to suppose that an increase in brightness of $\sim$ 0.6 magnitudes or more took place between July 10.05 and 10.35 UT

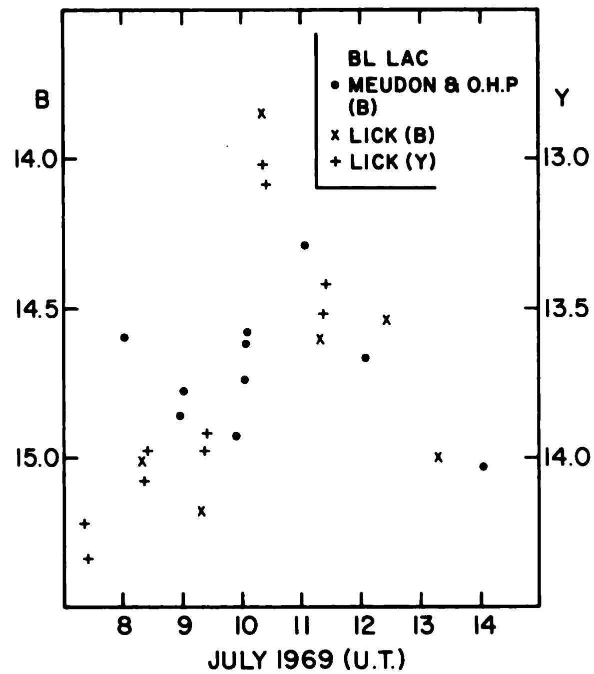

Fig. 2 An example of a rapid change in the optical continuum flux of BL Lac

and this would indicate a maximum rate of change of brightness similar to that suggested by Veron. Miller (1977) has suggested that if the maximum rate of change of a Type II supernova ($\sim$ 0.25 mag day^{-1}) is exceeded by that of a QSO then supernovae are unlikely to be the source of the QSO energy. It may also be noted that a supernova near maximum light shows little or no linear polarization.

If we consider that the fluctuations in the brightnesses of BL Lac objects are caused by a series of events, it is of interest to know whether the rate of rise and rate of decline in brightness are equal since this will help define the nature of the event. In Table 1 we have analysed 100 night-to-night variations of BL Lac. We may expect that variations of 0.1 mag or less are strongly influenced by observational error and hence they will contain little information about the real changes. For changes of larger amplitude there seems little evidence for an asymmetry but it must be remembered that this simple analysis only refers to a single time interval--one day. The interesting analysis of Fahlman and Ulrych (1975) showed that asymmetrical pulses were compatible with the 100-day time-averaged light curve of 3C 273 but the amplitude of the fluctuations (in magnitudes) were considerably smaller than in our examples of BL Lac.

TABLE 1

ANALYSIS OF 100 NIGHT-TO-NIGHT CHANGES IN THE B MAGNITUDE OF BL LAC DURING THE YEARS 1968-1971

It Got Brighter	47 Times	: Average Change 0.20 ± 0.03 Mag
It Got Fainter	50 Times	: Average Change 0.20 ± 0.02 Mag
	No Change 3 Times	
	If the Change Exceeded 0.10 Mag :	
It Got Brighter	25 Times	: Average Change 0.32 ± 0.05 Mag
It Got Fainter	36 Times	: Average Change 0.26 ± 0.03 Mag
	If the Change Exceeded 0.25 Mag :	
It Got Brighter	13 Times	: Average Change 0.45 ± 0.09 Mag
It Got Fainter	9 Times	: Average Change 0.52 ± 0.52 Mag

OPTICAL POLARIZATION

Linear polarizations of more than 30% have been observed in BL Lac objects and as in the case of the flux, the variations can be quite rapid. Unfortunately the amount of data which is currently available is still rather small and often, in the case of any one object, rather heterogeneous in origin. It has been pointed out for the quasar 3C 345 (Kinman 1977) that if annual means of the normalized Stokes parameters are taken, a slowly changing systematic component is found which may be related to other properties of the object. In Fig. 3 we show a similar analysis for the BL Lac object OJ 287 in which the annual means of the normalized Stokes parameters have been plotted. The data were taken from Kinman *et al*. (1974), Kikuchi *et al*. (1976), Shakhovskoy and Efimov (1977) and unpublished observations by the author. The first point to notice is that the annual means are not usually zero and the second is that they follow a systematic trend increasing in amplitude at a nearly constant position angle ($\sim 90°$) and then decreasing again. The first year (1971) coincided with the time when the object was brightest ($V \sim 12.5$) but the annual mean polarization was at its smallest. The largest annual mean polarization was reached in 1974 when the object was at about its faintest in recent years ($V \sim 15.0$). Kikuchi *et al*. (1976) have suggested that this behaviour is consistent with a basic polarized component being present which becomes more prominent as the object gets fainter. The radio polarization observations of OJ 287 by Altschuler and Wardle (1976) show a rather stable position angle during 1974 and 1975 of $99° \pm 1\overset{\circ}{.}6$ and $76° \pm 1\overset{\circ}{.}2$ from 11 pairs of observations at 11.1 cm and 3.7 cm respectively. The intrinsic position angle (after correction for Faraday rotation) is thus 73° (close to the optical value) and it is interesting that the percentage polarization at these wavelengths also seems to have gone through a maximum at this time.

The "Christmas-Tree" quasar model which interprets the flux as being made up from a series of outbursts from unconnected sources also predicts that the polarization should increase as the brightness decreases. In this case when the brightness is high, there are more contributing sources and one would expect their net polarization would therefore be smaller. It is difficult to understand however (if the

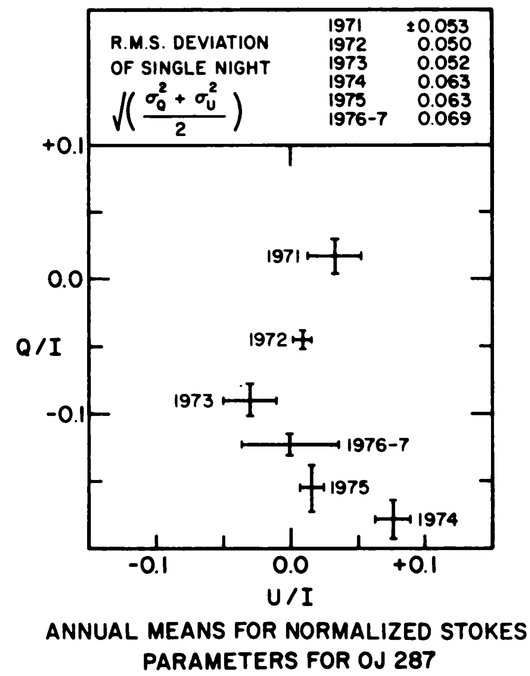

Fig. 3 Long term variations in the optical polarization of OJ 287

sources are unrelated) why the position angle has remained so constant. In fact the short term variations which are represented in Fig. 3 by the differences σ_Q, σ_U of the nightly normalized Stokes parameters Q, U from their annual mean value, show little change from year to year even though the total flux has varied by a factor of ten. This would certainly not be expected if the flux changes simply represented an increase or decrease in the frequency of similar events. The ordered behaviour of the polarization is much more what would be expected from a single source.

We note that if BL Lac objects are all galaxies which contain strong sources of non-thermal radiation, then the polarization will tend to become smaller when the unpolarized galaxy light becomes comparable in size with that of the non-thermal source. In this case the polarization will become a function of aperture size as is shown in the next section.

BL LAC OBJECTS WITH EXTENDED IMAGES

(a) Methods

We noted in the introduction that the BL Lac objects which are associated with nebulosity are particularly important since in several cases it has been possible to determine the red shift of the nebulosity and so find the distance of the object. We need to make photometric observations of these nebulous BL Lac objects which will allow us to separate the light of the non-thermal polarized source from that of the nebulosity. Also, we need to know about the distribution of light in the nebulosity if we are to identify it with a given kind of galaxy.

There are several possible ways of separating the non-thermal and thermal radiation and we will make some comments on their various advantages and disadvantages here. One possibility is to use quite small apertures to achieve high spatial resolution; this is a necessity with spectrographs when the spectral resolution depends on the aperture size. Figure 4 shows how the light loss varies with aperture size (for B and V wavebands) under conditions of apparently tolerantly good seeing (1".0-1".5): the light loss was assumed to be negligible for a 30" diameter aperture. It is seen that the light loss generally will be very serious with apertures as small as 4" diameter although clearly the size of the error is seeing dependent. Spatial resolution with small apertures can therefore only produce acceptable results if some method of compensating for this effect is found. In addition the errors due to atmospheric dispersion must be minimized. Another way to isolate the non-thermal component is to observe it at an infrared wavelength such as 10 μ. Thermal radiation will be negligible at this wavelength compared with a power law non-thermal radiation which increases rapidly in the infrared if its spectral index ~ -1. Unfortunately this only tells us about one wavelength of the non-thermal source and nothing about the nebulosity. Visvanathan and Oke (1968) attempted to separate non-thermal from thermal radiation in NGC 1068 by observing the wavelength dependence of the polarization. They assumed that a non-thermal component itself would have no wavelength dependence and that the observed change was due to a variable dilution of non-thermal radiation with unpolarized galaxy light as a function of wavelength. The amplitude of the effect increases with decreasing aperture size (Fig. 1 in Visvanathan and Oke (1968)) and undoubtedly a combined photometric flux and polarization measurement as a function of both wavelength and aperture size would provide an ideal set of data. Apart from the variation of position angle with wavelength found by Rieke et al. (1977 (see Introduction)), the present observational evidence suggests that the polarization of the non-thermal component is independent of wavelength. This would not be expected if, for instance, the source became optically thick at longer wavelengths. Nordsieck (1976) has suggested models which predict a dependence of polarization on spectral index, so a variation might be expected in cases such as 0735 + 178 where the spectrum is curved: only a rotation has been formed however. Recently Maza, Martin and Angel (1978) have determined the spectral indices of the non-thermal sources in two BL Lac objects from the variation of the polarization with wavelength and the assumption that the nebulosity had the colors of a suitably redshifted elliptical galaxy.

Clearly there is a great advantage in using small apertures (as in all photometry) if only a way can be found to minimize the seeing-dependent errors from light loss. Probably the best solution will involve the use of a high-resolution two-dimensional array of solid state detectors which will cover enough field so that the effects of seeing can be determined from the profiles of nearby field stars. Until such devices are available we must make the best of simpler methods.

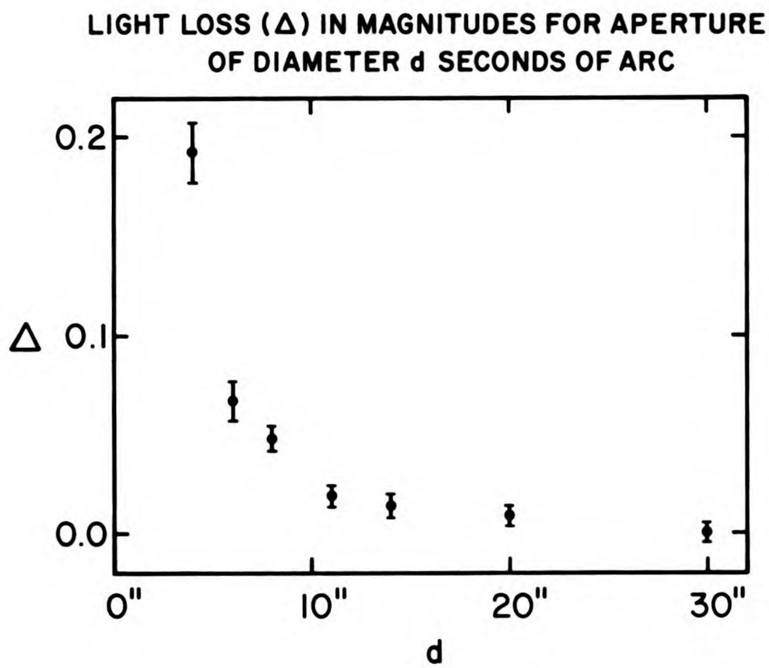

Fig. 4 The light loss in the B and V wavebands at a photometric aperture

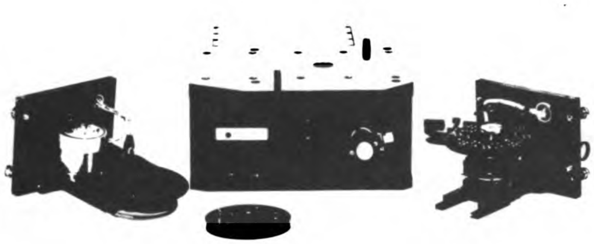

Fig. 5 The Kitt Peak Mk II computer-controlled photometer. The filter assembly is to the left and the aperture wheel assembly is to the right.

Figure 5 shows a simple computer-controlled photometer in which both filters (on the left) and apertures (on the right) can be rapidly changed by stepper motors which are under computer control. The telescope is also under computer-control so that photometric measurements can be made automatically in a sequence: object, comparison star, sky, object, comparison star, ... Tests on a pair of nearby bright stars show that with this technique systematic and random errors from scintillation light-loss can be reduced to about $\pm$ 0.01 mag for a 6".0 aperture and less for larger apertures. The systematic errors due to atmospheric dispersion can be greatly reduced by using a computer program to make small pointing corrections to the telescope as a function of the waveband: alternatively a Risley prism may be used. It may be noted that atmospheric dispersion can also affect measurements of the wavelength dependence of polarization if it causes spurious changes in the ratio of the light of the polarized point source to that of the unpolarized extended source.

Some nearby BL Lac objects have particular problems which require special observing techniques. Thus Markarian 421 (B2 1101 + 38) is close to two very bright stars so that there is a strong gradient of scattered light from these stars across the nebulosity. Therefore the outer parts of the nebulosity were observed using the chopping-secondary of the KPNO 1.3 meter reflector which allows a scan to be made at any position angle at a set of equidistant points as described by Strom, Strom, Jensen, Moller, Thompson and Thuan (1977). The scattered light was determined on the same night from scans which were similarly positioned relative to the first-magnitude star β Gem which (in the V band) is 86 and 366 times brighter than the stars near Markarian 421. An accurate correction for the scattered light was obtained this way.

Another interesting object (PKS 0548-322) which poses special problems is shown in Figure 8. A normal photographic enlargement of a IIIaJ plate taken at the CTIO 4-Meter prime focus is shown below and shows the BL Lac object (in the center) surrounded by about a dozen somewhat fainter compact galaxies in the 5' x 5' field. This area was scanned on the PDS microdensitometer and the frequency histogram of the densities was examined. This enabled a density range to be determined which was just greater than that of the sky background. The upper picture in Figure 8 is a playback on the PDS microphotometer in which the lower and upper extremes of this density range have been made to correspond to white and black respectively. In this way the faint nebulosity surrounding 0548-322 has been brought out with high contrast and this BL Lac object is seen to be much larger than the other galaxies in its vicinity. In this case, aperture photometry can only be used for a radial distance up to about 10" from the nucleus because of crowding by other stars and galaxies in the field, although the nebulosity extends well beyond this. The photographic densities were therefore converted to relative intensities (using the normal photographic techniques) and those pixels in the neighborhood of the confusing stars and galaxies were rejected. The mean values of the intensities of the remaining pixels (in other words, a surface brightness) were then computed as a function of radial distance from the center of PKS 0548-322. Finally the photoelectric aperture photometry within 10" of the nucleus was used to calibrate the photographic photometry and so obtain the radial light distribution of the nebulosity. It should be noted that this technique uses only the PDS microphotometer and the normal batch processing capabilities of the

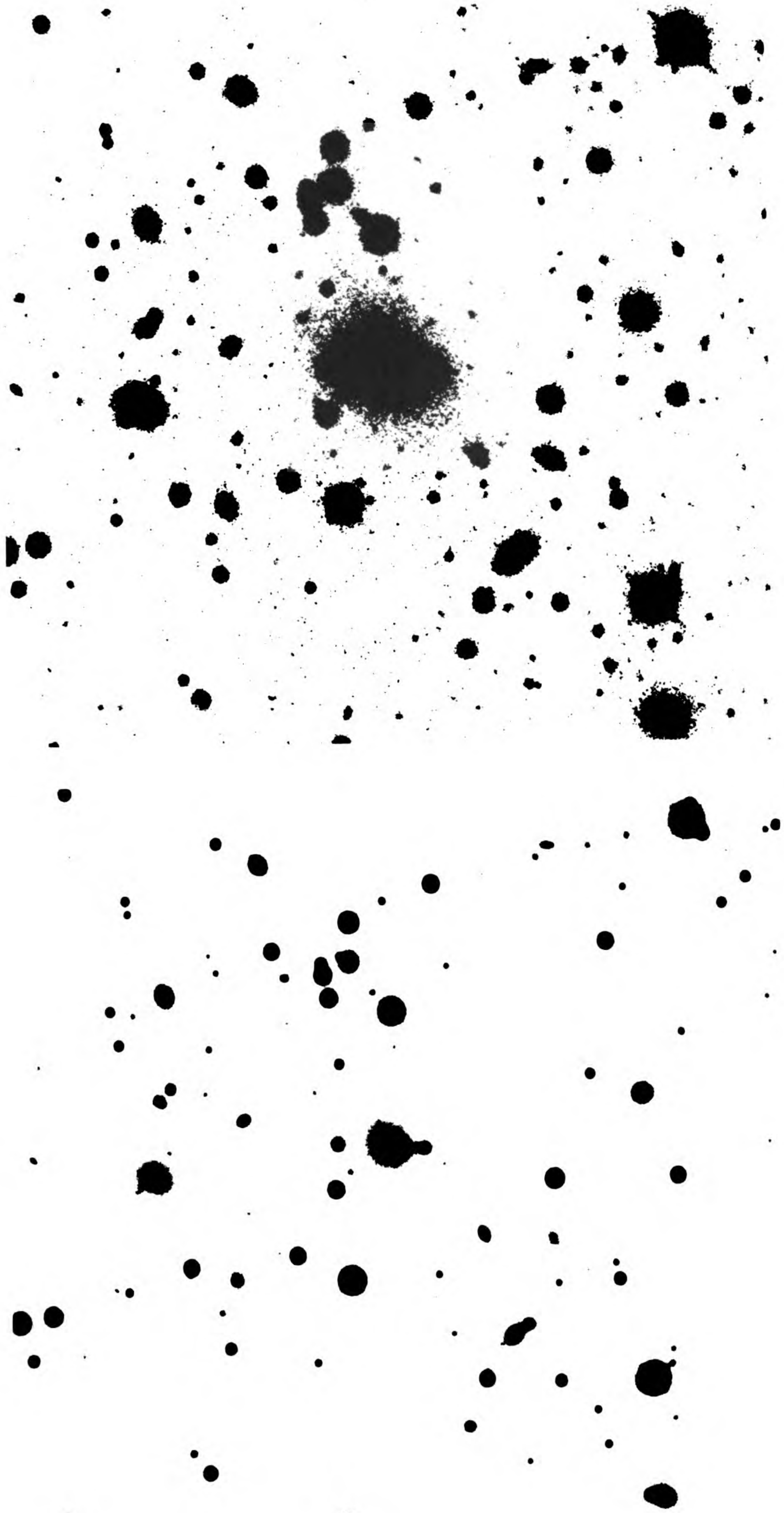

Fig. 8 The BL Lac object 0548-322 (for details see text).

Kitt Peak CDC 6400: it uses no special equipment and is therefore of general application. If only the flux at different wavelengths as a function of aperture size is available, then a separation of the non-thermal from the nebulous component can only be made if we assume that the non-thermal component is essentially a point source at the center of the object; an error will be made if in fact this non-thermal radiation is significantly extended. If the data is plotted as a function of flux (S) versus aperture radius (r), the problem becomes one of extrapolating the relation between (S) and (r) to $r = 0$ in order to obtain an estimate of the brightness of the central point source. An advantage of this method is that the S(r) determined on one night when the compact non-thermal source has one brightness will only differ by a constant value from the S(r) determined on another night when the non-thermal source has another brightness. It is therefore possible to fit together the results of several nights in order to determine the S(r) relation as well as possible.

Having found the S(r) curve, the run of surface brightness with r can be examined to see if it is a better fit to the exponential disk distribution $I \sim I_o e^{-\beta r}$ commonly found in spiral galaxies or the $r^{1/4}$ distribution found in spheroidal systems. In the systems discussed here, the law for spheroidal systems gave a better fit and this was also in agreement with the colors found for the nebulosity. In order to extrapolate the S(r) curve to $r = 0$, it was found convenient to use the Hubble relationship $I = I_o/(a + r)^2$ for the surface brightness distribution, so that the flux within a radius r is given by

$$S(r) = 2\pi I_o [\ell n(\frac{a+r}{a}) - \frac{r}{a+r}] +$$

the contribution of the central non-thermal component.

It is felt that the weakest part of this analysis lies in the assumption that this type of extrapolation is permissible. It is possible that a good fit might be obtained to the form of a normal galaxy in the outer parts of the nebulosity, but the brightness distribution might be quite unlike that of a normal galaxy close to the very bright non-thermal nucleus. If in fact an error is being made by this assumption, then we may expect to obtain a different value for the properties of the non-thermal source than that found, say, from the polarization analysis.

Clearly, at present, no method is free from uncertainties and the use of a variety of approaches is essential if a proper understanding of these objects is to be obtained.

(b) Results

The aperture-photometry techniques discussed in the previous section have been applied to four BL Lac objects: 0548-322, Markarian 421, Markarian 501 and I Zw 1727+50. In all of these cases a redshift has been determined for the nebulosity which shows that the nebulosity is some kind of galaxy. Provisional results and comments are published here. As noted above, even though these objects are variables, it is possible to combine observations at different epochs in order to improve the determination of the light distribution in the nebulosity. It is therefore hoped that future additional observations will produce more accurate photometric distributions of the nebulosity.

These can then be used to re-interpret older observations so that our knowledge of the properties of the non-thermal component should also improve with time.

0548-322 was originally discussed as a BL Lac object by Disney (1974) but he was unable to decompose it satisfactorily into an elliptical galaxy and a credible non-thermal source. Later Fosbury and Disney (1976) obtained a redshift of 0.069 from absorption lines in the nebulosity using an image-dissector scanner and deduced a spectral index of 2 $\pm$ 0.5 for the non-thermal source. The radial distribution of the surface brightness of 0548-322 in B_3 magnitudes* per square second of arc is shown in Figure 6. An exponential light distribution should produce a linear relation of surface brightness B_3 against r while the spheroidal distribution should have B_3 linear against $r^{1/4}$. The photographic observations alone (filled circles) scarcely allow a distinction, but taken with the single photoelectric observation of Fosbury and Disney, the agreement with the spheroidal

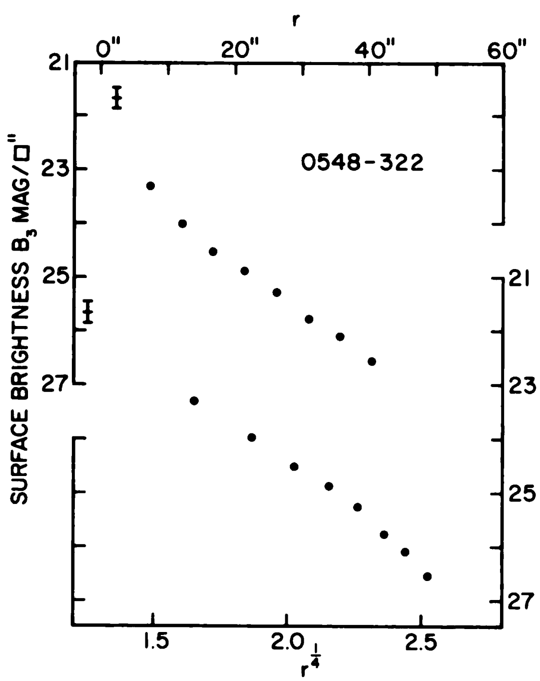

Fig. 6 The radial distribution of the B_3 surface brightness of the nebulosity in 0548-322 as a function of r (above) and $r^{1/4}$ (below). The filled circles are the author's observations and the cross is the scanner observation of Fosbury and Disney.

* The B_3 magnitude = B - 0.3 (B-V) corresponds to the response of the IIIa-J emulsion with a GG 385 filter [Schweizer, 1976].

distribution is better. The photoelectric observations were made with the CTIO 1.5 m reflector (1977 Nov. 11 and 12 UT), the KPNO 1.3 m reflector (1977 Dec. 7 and 8 UT) and the KPNO 2.1 m reflector (1978 March 4) using the star 54" North of 0548-322 as a comparison star with V = 13.298, B-V = 0.754. No significant changes due to a variation in the non-thermal component were found.

The photoelectric observations were fitted to a Hubble type law with a = 4".7 and this gave a central point source with V = 16.35 and B-V = 0.62 or (corrected for extinction at latitude 26°) V = 16.23, B-V = 0.57. This color corresponds to a spectral index α of 1.95 which is in good agreement with the value of 2 $\pm$ 0.5 found by Fosbury and Disney.

The nebulosity has V_{26} = 14.73 and B-V = 1.17 and after correction for both K-term and galactic extinction this gives V_{26} = 14.48, B-V = 0.92. Since the redshift is 0.069, the absolute magnitude M_V will be -23.60 for H_0 = 50 kms^{-1} Mpc^{-1} and -22.7 for H_0 = 75 kms^{-1} Mpc^{-1} showing that the nebulosity is very probably a giant elliptical galaxy. We note that in this case the non-thermal component is less than one quarter as bright in the V waveband as the galaxy as given by V_{26}. The object is recognized as a BL Lac object because it is relatively close and the central point source has a much higher surface brightness than the part of the galaxy surrounding it.

Disney's single photoelectric observation (March, 1974) agrees well with ours in B but not his V which seems $\sim$ 0.4 mag too faint. The evidence to date suggests that this object is currently not variable and further observations would be desirable to check this. This BL Lac object is surrounded by many compact galaxies which could well be part of a cluster to which it belongs. The galaxy 97" E and 18" S of the BL Lac object has V = 16.24, B-V = 1.11 $\pm$ .02, through a 21" aperture--roughly as bright as the non-thermal component of the BL Lac object. It will be interesting to obtain redshifts of these objects to see if they have the same redshift as the BL Lac object. If this is indeed a small cluster, then the galaxies are so close to the BL Lac object ($\sim$ 100 kpc) that tidal interaction may well have occurred.

Results for the other three BL Lac objects will only be summarized here and published in detail elsewhere:

Markarian 421 (B2 1101+38) was found to have nebulosity with a redshift of 0.0308 by Ulrich *et al*. (1975). Ulrich (1978) has now confirmed this and shown that Markarian 421 is a member of a small cluster of galaxies. As remarked above, the photometry of its nebulosity presented particular difficulty because it is so close to two bright stars. The central component was found to vary over the range 13.59 < V < 13.91 and the spectral indices were in the range 0.72 to 0.85 which is in good agreement with the value 0.8 found by Ulrich *et al*. (1975) and 0.92 found by Maza, Martin and Angel (1978).

The galaxy component has a light distribution which is good match to the elliptical galaxy M87. Since the object is relatively nearby (185 Mpc if H_0 = 50 kms^{-1} Mpc^{-1}), it is relatively extensive and the V = 26.0 isophote has a radius of 63". The observed brightness and colors are V_{26} = 13.25; B-V = 0.96; U-B = 0.37, which after correction for the K-term (after Pence, 1975) gives V_{26} = 13.19; B-V = 0.96; U-B = +0.37 which is a satisfactory fit to an elliptical galaxy.

Polarimetric observations of Markarian 421 were also made with an unfiltered S11 photocathode and HNP'B polaroid. The photometric properties of this combination are known approximately from observations of stars of known colors and non-thermal sources of known spectral index so that it was possible to predict from the galaxy model how the polarization should change with aperture. The predicted and observed change with aperture agree quite well and this, together with the agreement with results found by different methods for the spectral index, gives us considerable confidence in this particular result.

I Zw 1727+5015 has recently been observed spectroscopically by Oke (1978) who found a redshift of 0.0554 for the nebulosity and deduced a power law spectrum for the non-thermal source with spectral index 1.6.

The object is somewhat variable and after correction for extinction the central component was found to have $16.90 < V < 16.95$ and a spectral index in the range 0.93 to 0.80 (June to October, 1977) which is significantly different from the value given by Oke. The galaxy, after correction for extinction, has V_{26} = 16.03, B-V = 1.02 and U-B = 0.42. This, after correction for the K-term and assuming that H_0 = 50 kms^{-1} Mpc^{-1} gives M_V = - 21.7 compared with $M_V = -21.9 \pm 0.3$ given by Oke.

Clearly further observations of this object are needed to resolve the discrepancy over the spectral index.

Markarian 501 was shown to have a redshift of 0.0337 by Ulrich et al. (1975). The object appears as an elliptical galaxy with a stellar-appearing nucleus which has a continuous spectrum. The ellipticity of the galaxy is quite pronounced having (a-b)/a = 0.25 where the axes a = 37" and b = 28". Only rather limited photometry is available and these give (after correction for extinction) V $\sim$ 14.4 for the central component and a spectral index $\sim$ 1.9 which is very different from the value ($\sim$ 0.8) found earlier by Ulrich et al. (1975) and more recently by Maza et al. (1978). The galaxy (after correction for extinction) has V_{26} = 13.25, B-V = 0.97, U-B = 0.53. Further observations are definitely needed to resolve these discrepancies. Figure 7 shows the provisional colors of the nebulosities as a function of redshift. It is seen that they are very similar to those of the first-ranked elliptical galaxies observed by Sandage (1973), although they are systematically slightly bluer. It is not known whether this systematic color difference is an artifact of the measuring technique or whether it represents a real difference between these objects and Sandage's sample.

At present only limited conclusions can be drawn from this data but some points can be made:

(1) The absolute magnitudes of the galaxies cover a range of nearly two magnitudes. If H_0 = 50 kms^{-1} Mpc^{-1}, the brightest is 0548–322 with M_V = - 23.6 and the faintest is I Zw 1727+5015 with M_V = - 21.7. This is about twice the brightness range in Oke's sample.

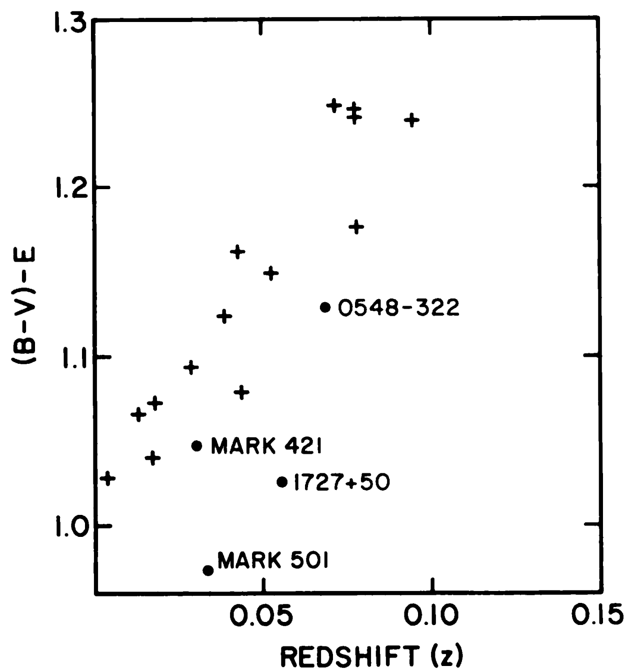

Fig. 7 Provisional B-V colors for the nebulosities of four BL Lac objects as a function of redshift (z). The crosses are Sandage's measurements for giant elliptical galaxies. The interstellar extinction correction (E) was derived according to Sandage (1973).

(2) The spectral indices of the power laws of the non-thermal component also seem to cover a range from 0.7 to perhaps 2.0. They are not all characterized by a power-law spectrum with $\alpha \sim 1.6$ as in Oke's sample.

(3) There is some indication that the objects with an intrinsically brighter non-thermal component are more variable, but this will require more data for confirmation.

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DISCUSSION

H. MILLER:
We have observed B2 1101+138 (Mk 421) and B2 1652+39 (Mk 501) and have found the multi-aperture photometry consistent with the underlying galaxy component being a giant elliptical galaxy.

T. KINMAN:
In my analysis I have tried to make as few assumptions as possible about the nature of the object: there are quite enough assumptions that have to be made anyway. The effect of a strong non-thermal source on the center of a galaxy is unknown and I am somewhat worried that the inner parts could be different from a normal elliptical galaxy even if the outer parts are unchanged.

A. WOLFE:
Are these objects you just discussed violent optical or radio variables? In other words if you assign a cosmological redshift to these objects and work out an angular size by dividing the light-travel distance by the cosmological distance do you run into severe brightness temperature problems as with BL Lac?

T. KINMAN:
Probably only B2 1101+38 (Markarian 421) would be put in the class of OVV variables because Miller has shown that in the past it has been much more active and bright than it is now (H.R. Miller 1975, Ap.J., 201, L109.

A SEARCH FOR HIGHLY POLARIZED BL LACERTAE OBJECTS

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Steward Observatory

and

S. Tapia
Lunar and Planetary Laboratory

Introduction

Historically, the BL Lacertae objects have been an interesting by-product of spectroscopic surveys for quasistellar sources. Discoveries of the majority of these objects occurred when suspected optical counterparts of previously unidentified radio sources were found to exhibit featureless spectra as opposed to the hoped for high redshift emission line spectra. The consequence has been that the discovery of new BL Lacertae objects has generally been a result of accident rather than carefully planned searches for such objects.

With the increased interest in BL Lacertae objects it has become apparent that there is some merit in searching specifically for these objects. The first approach that comes to mind is to continue spectroscopy of suspected optical counterparts of compact radio sources, however practice quickly demonstrates several shortcomings to this technique. Spectroscopy of such objects is very time consuming, often requiring large aperture telescopes. In many cases optical identification of good candidates is hampered by poor radio positions and furthermore, there is reason to believe that a rather small percentage of such candidates may in fact be BL Lacertae objects.

Although improved radio positions are becoming available for increasing numbers of radio sources, it is unrealistic to anticipate radio interferometry for all good candidates in the near future. Deep transmission grating spectroscopy for a search of emission line QSO's may be used effectively in the absence of high accuracy radio positions, but this approach is not applicable to continuous or absorption line spectrum objects and hence is of little value in the discovery of BL Lacertae objects.

We wish to demonstrate that it is possible to take advantage of the characteristically high linear polarization of the BL Lacertae objects to conduct a search for such highly polarized objects without the requirement of accurate radio positions. Further, we assert that this type of search is more time efficient than other techniques employed in the past.

We have taken a dual approach to the problem of conducting a polarization search for new BL Lacertae objects. Working with a sample of radio sources with moderately accurate radio positions, we have obtained simultaneous photographic polarimetry of all objects near each candidate radio position by use of a double calcite plate placed in front of an image tube camera and we have also observed individual objects by use of a photoelectric polarimeter in order to detect objects not measurable on the plates or in some cases to provide more quantitative polarimetric data.

This survey has yielded positive results in that we have succeeded in identifying four new BL Lacertae objects, as well as several new candidates, with a minimum of effort and feel that this system is suitable for use with telescopes of only moderate aperture. In the remainder of this paper we describe our technique, summarize our results and make some suggestions for future application of this type of survey.

Technique

We have obtained photographs in polarized light with the combination of a double calcite plate (Serkowski 1960) and a multialkalai extended red image tube camera at the Cassegrain focus of the Steward Observatory 2.29m reflector. The two calcite plates were oriented at nearly 90° with respect to each other to produce images of the same shape but of opposite polarization. Use of the double calcite plate produces two pairs of opposed images, one pair fainter than the other. Figure 1 is representative of our photographs, in this case the field of the source OQ 530 in which we have identified a highly polarized BL Lacertae object.

All of the exposures were unfiltered with an exposure time of two minutes on IIaD plates. Two exposures were made of each field, the calcite plate unit being rotated through 45° between exposures. The image tube camera was used to reduce exposure time. The 40mm image tube photocathode was completely covered by our calcite plate; at the scale of the 2.29m telescope (10"/mm) we obtained useful data for a field 6.5 arc min in diameter.

We have supplemented our photographic material with observations using the Minipol photopolarimeter (Frecker and Serkowski 1976) coupled to the 1.5m reflectors of the University of Arizona Catalina Station and the Mt. Lemmon Observatory. All objects in some of our fields were examined only with the photopolarimeter, in most cases however the photopolarimeter was used in conjunction with the photographic material.

We note that the photographic material was not used in order to obtain quantitative measures of the degree of linear polarization or position angle, but rather as a method of extracting highly polarized objects from a field of unidentified objects.

The Survey Sample

Although it is conceivable that there may exist a class of radio quiet BL Lacertae objects, we have constrained our search to those objects which exhibit radio emission from a compact or point source. We have selected a list of such sources from the Special Source List (SSL) of the Ohio State University Radio Observatory. Although we continue to examine a number of radio source fields, we report here our results for a sample of 60 fields. The sources we have selected

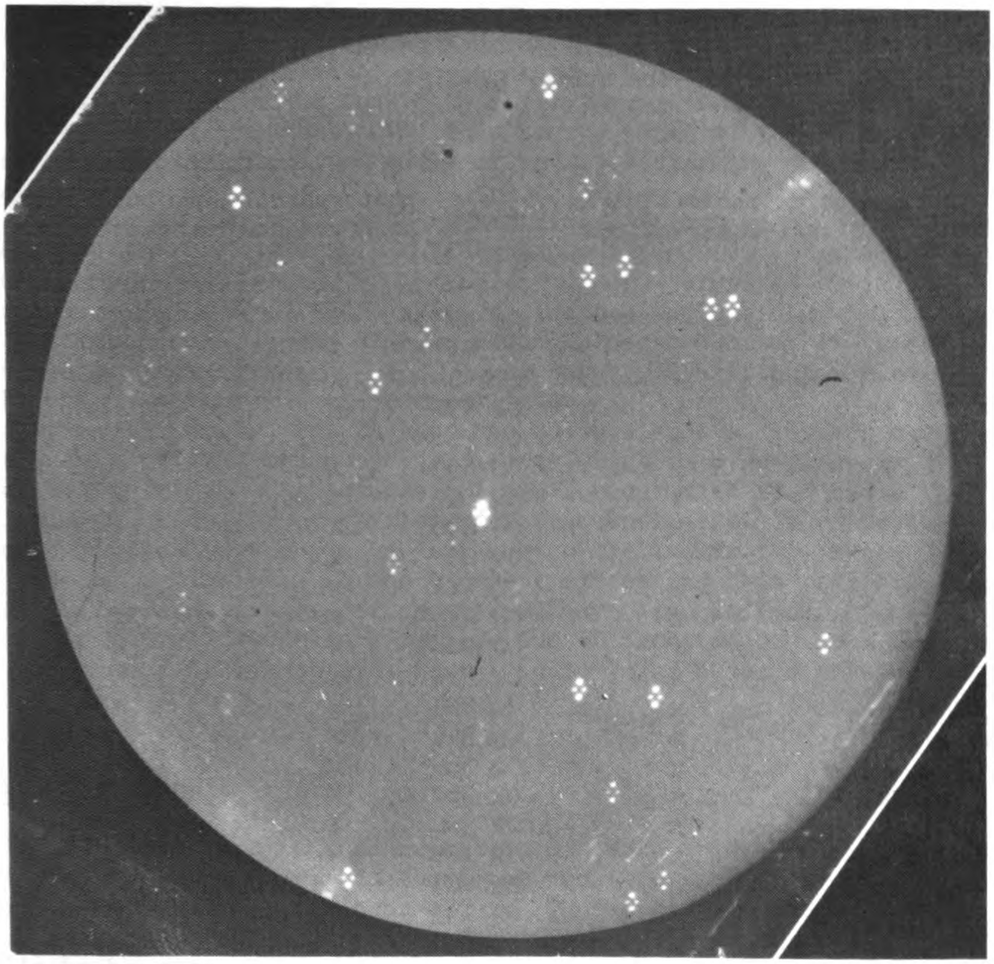

Figure 1. Reproduction of the field of OQ 530 as photographed with the double calcite plate. The four images produced with this analyzer are clearly visible for the brighter objects in the field.

Table 1

The Survey Sample

field	photographic observations	photoelectric observations	field	photographic observations	photoelectric observations
OF 042	x		ON 197	x	x
OF 176	x		OP 217	x	
OG 316		x	OP 254	x	
OG 147		x	OP 471	x	
OG 185		x	OP-086	x	
OH 128		x	OP 094	x	x
OH 335		x	OQ 004	x	x
OI 130		x	OQ 206	x	
OI 478		x	OQ 217	x	x
OI 090.4		x	OQ 122	x	x
OJ 320	x	x	OQ 123	x	x
OJ-131		x	OQ 028	x	x
OJ 448	x	x	OQ 530	x	x
OJ 063	x	x	OQ 244	x	x
OJ 164	x	x	OQ 346	x	x
OK 403	x	x	OQ 366	x	
OK 240	x	x	OQ 367	x	x
OL 343	x	x	OR 306	x	x
OM 613	x	x	OR 109	x	x
OM 214	x	x	OR 407	x	x
OM 452.5	x	x	OS 135		x
OM 455	x	x	OS 440		x
OM 163.5	x	x	OS 053		x
OM-170	x		OS 459		x
OM-072		x	OS 063		x
OM 488		x	OS 364.6		x
ON 001.4	x	x	OS 188		x
ON 503	x	x	OS 595		x
ON 254	x	x	OT 316		x
ON 189	x	x	OT 129		x

have radio errors on the order of 30 arc seconds although there is a large range of errors represented. All of these sources have been the subject of radio observations at several frequencies since their original detection and thus have fairly complete spectra in the range of about 400 to 5000MHz. The Ohio source names of the objects examined for this paper and the modes of their observation are listed in Table 1.

There is an additional, rather crude, selection effect which has been applied to our sample which must be discussed. Figure 2 is a reproduction of a radio "color-color" diagram prepared by Pacht (1976) in which are plotted radio spectral indices α_1 and α_2 for 412 extragalactic objects. This diagram is of interest here as it illustrates the general distribution of QSO's of known redshift and the BL Lacertae objects as a function of spectral index.

Significantly, the BL Lacertae objects show a distinct clustering in an elliptical region of the diagram which is predominately characterized by flat radio spectra. Since sources with flat radio spectra display BL Lacertae properties more frequently than other sources, we have selected a number of objects which lie inside this region of the color-color diagram. In the interest of testing this relation further and to serve as a sort of control, we have also included in our sample fifteen sources which fall outside the BL Lacertae region. The positions of our program fields in the radio color-color diagram appear in Figure 3.

The Photographic Program

The photographic data reduction was done by measuring pairs of images of all stars within about one arc minute of the radio position with a Cuffey iris astrophotometer. In addition to measuring the most likely candidates (i.e. those nearest the radio position) it was desirable to have measures of a number of field stars to improve differentiation of the more highly polarized objects in the field. Astrophotometer readings were converted to B magnitudes by use of calibration photographs of photometric sequences around M3 (Sandage 1970), PKS 0735+17 (Veron and Veron 1975) and 3C66A (Craine et al. 1975). In general our astrophotometer measurements had accuracies of $\pm$ 0.1 mag.

In an ideal case the two opposing images of each star on a plate should be of equal brightness if the object is unpolarized, and the deviation from equality of brightness of the images is a measure of the degree of linear polarization. In practice the image size measurements are affected by the brightness of the star as well as the optical properties of the system (mainly the calcite plate). For fainter objects the images fall off the linear portion of the HD curve of our plates and the errors of measurement become too large at or below 19mag. For bright stars the images grow to the point of contaminating the pair. This contamination occurs for stars brighter than about 13 mag on our plates.

Figure 4 is a plot of the magnitude of the image on the plate*

* Note that there are four images of each object on the plate, one bright pair and one faint pair. In some instances the measurements for the faint pair are plotted in addition to or instead of the bright pair and these magnitudes refer only to the brightness of an image on the plate and not the apparent magnitude of the object represented.

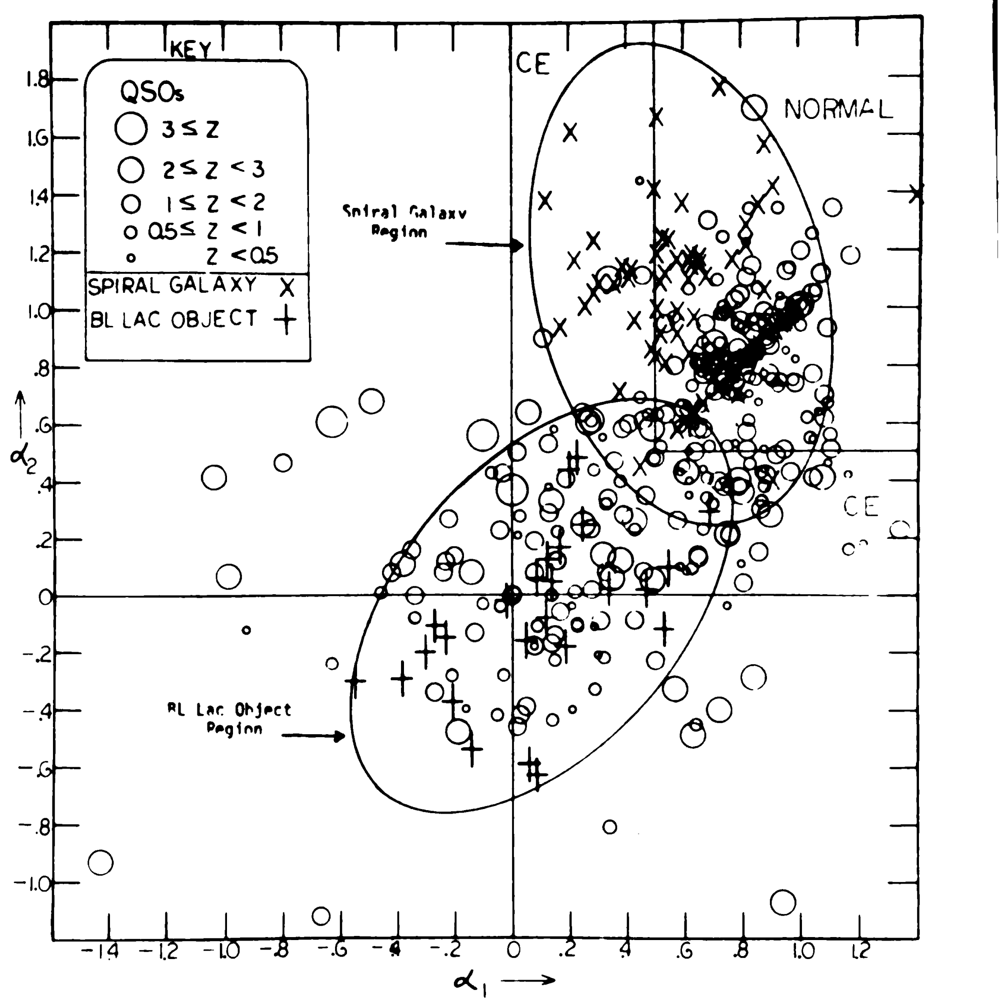

Figure 2. The radio "color-color" diagram for QSO's, spiral galaxies and BL Lacertae objects reproduced from the work of Pacht (1976). The spectral index α_2 (1415-5000MHz) is plotted vs. the spectral index α_1 (408-1415MHz). The partial separation between spiral galaxies and BL Lacertae objects is indicated.

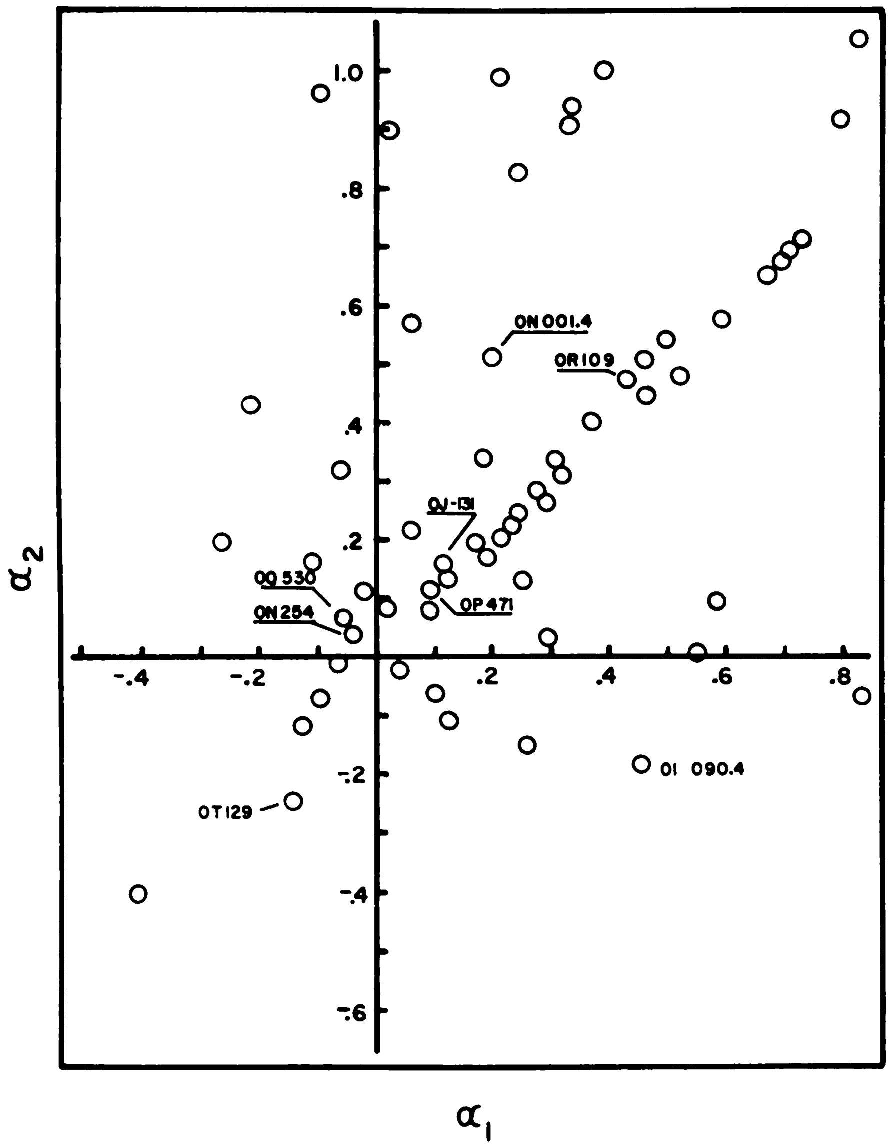

Figure 3. The radio "color-color" diagram for the sources included in our search program. Abscissa and ordinate as in Figure 2. Labels have been added for the confirmed BL Lacertae objects and four candidates.

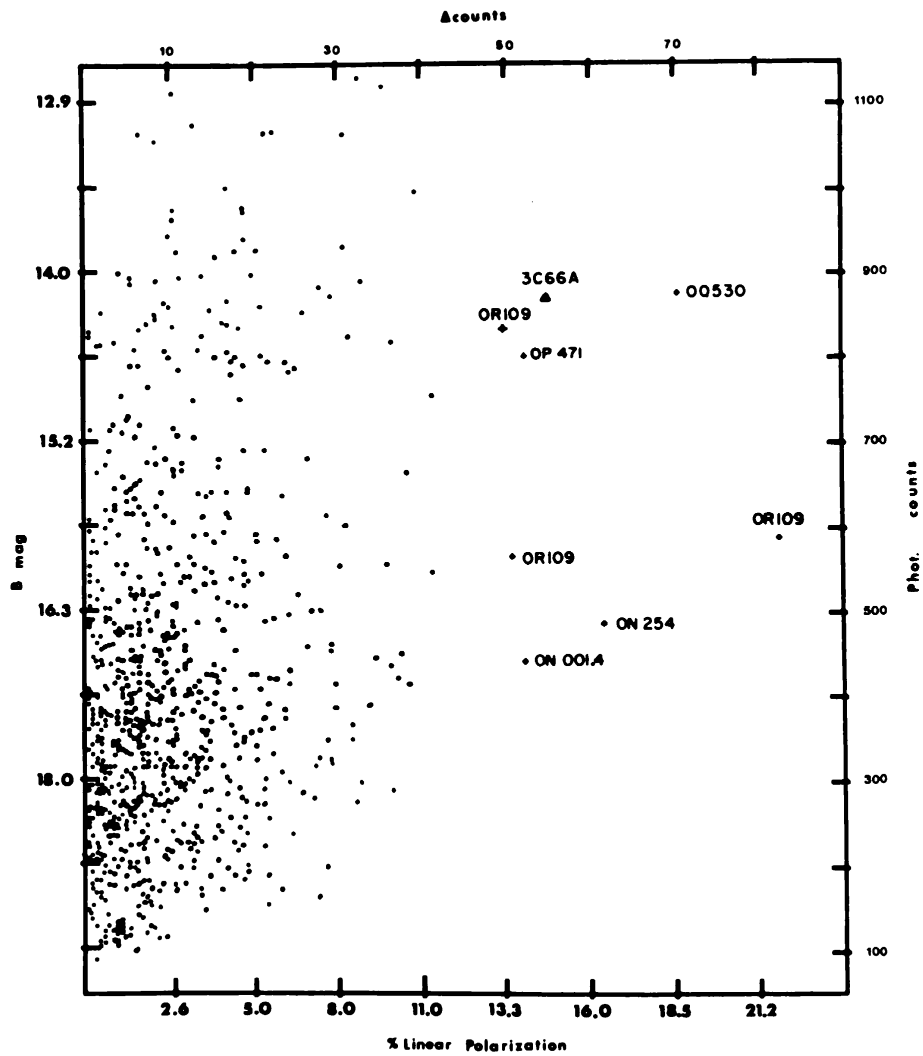

Figure 4. The percentage of linear polarization versus the B magnitude for the optical objects surrounding the radio sources included in our search program. For 13 < B mag < 19 the detection threshold of linear polarization appears to be 12%.

vs. degree of polarization for our program objects. Since each field is photographed at least twice to allow for the 45° rotation of the calcite plate, there are at least two points plotted for each object. The scatter in this diagram is largely a reflection of the aforementioned errors inherent in the magnitude measurements but it seems apparent that objects which appear at about the 12% or greater polarization level can be detected by this technique. In general those objects which fall in this region of the diagram were considered to be excellent BL Lacertae candidates and were subsequently observed photoelectrically, or in some cases spectroscopically. A discussion of individual objects in the diagram appears later in this paper.

The Photopolarimeter Program

Photopolarimeter observations were made of objects in several program fields as indicated in Table 1. In some cases only a few objects in each field were observed, generally those which were too bright for proper measurement on the photographic plates or in some cases fainter objects which were suspected candidates from the photographic data. When a field was observed only with the photopolarimeter, all objects visible in the field were measured. Since the photopolarization system is much more quantitative and useful to much lower levels of polarization it was felt that supplementing the photographic program in this manner would lead to discovery of some BL Lacertae candidates which fell below our photographic polarization detection limits. It should be noted that several program fields were examined with the photopolarimeter alone. Significantly, although a greater number of subsequently confirmed BL Lacertae objects was identified with the photopolarimeter than in the photographic program, all of those objects were highly polarized at the time of discovery and would no doubt have been detected by photographic observations.

Polarized Objects

Of those objects in our survey which are most highly polarized, we discuss below those which have been confirmed as BL Lacertae objects and those which appear to be good, though unconfirmed, candidates.

OI 090.4

OI 090.4 was originally discovered to be a BL Lacertae object through this program by means of the photopolarimeter observations; our results have been detailed by Tapia *et al.* (1977). Observations were first made in February 1976 and have continued since. The optical object is stellar in appearance and shows considerable small amplitude optical variation over a range of 14.2 to 15.2 mag. Linear polarization is high and quite variable, ranging from 4.5% to 26%. Further observations of OI 090.4 (Rieke et al. 1977) indicate rapid variability of infrared and visible polarization and further that the polarization is independent of wavelength between the visible and 2.2μ region. The position angle of linear polarization rotates through the visible and infrared. Examination of plate archives yields a light curve for OI 090.4 dating from 1892; the object shows considerable variability over a range of about 2 mag with an average of about 16.3 mag (Baumert and Craine 1978). The spectrum of OI 090.4 is featureless; a finding chart is given by Tapia et al. (1977).

OJ-131

OJ-131 was discovered in the same fashion as OI 090.4 (Tapia et al. 1977), Polarization observations were first made in March 1976 and have continued since. The object seems stellar in appearance with perhaps a suggestion of structure on the Palomar plates. OJ-131 shows a range of optical variation from 14.6 to 17.5 mag. Linear polarization is quite high and variable, ranging from 8.6% to 35.6%. Historical light curve data are sparse (Baumert and Craine 1978) but suggest variation in the range 16.5 to 17.5 mag. The recent data of Tapia et al. (1977) shows substantially greater variation. The spectrum of OJ-131 is continuous; a finding chart is given by Tapia et al. (1977).

This object provides a particularly compelling example of the value of this type of survey: Adam (1978) reports that the optical counterpart of OJ-131 is a "non-quasar" (implying that it is a star), however the identification of the candidate object observed by Adam, made by Radivich and Kraus (1971), is incorrect. It is likely that in the absence of accurate radio positions and as a consequence of the resulting incorrect optical identifications, spectroscopic surveys are failing to find many of the interesting optical counterparts to compact radio sources. Since our program allows economical polarization observations of all optical objects in the radio field we succeeded in identifying one of the most highly polarized BL Lacertae objects known, an object previously overlooked because of the identification problem.

OQ 530

The object OQ 530 was first detected in our photographic data (see Figure 1) as a very good candidate for a BL Lacertae object with a linear polarization of nearly 19% in April 1976. Next to OR 109 (see below) it appeared to be the best candidate in the photographic data. The object was independently discovered in 1977 and confirmed as a BL Lacertae object which exhibits a very active optical light curve, generally in the range of 12 to 15 mag (Miller 1978). We have obtained photoelectric observations of the linear polarization in the range 5% to 15%. The spectrum of OQ 530 is featureless; a finding chart is given in Figure 5.

OT 129

The field of OT 129 was observed with the photopolarimeter and found to contain an object with a linear polarization of 27%. Though this object was in our original program list, we have since noted that spectroscopic observations were made (Wills and Wills 1976) which were classified as inconclusive but with the suggestion that the object might be a BL Lacertae object (the spectrum is more red than that of a QSO and appears featureless). In view of the high linear polarization of this object we now confirm it as a BL Lacertae object. A finding chart is given in Figure 5.

BL Lacertae Candidates

The diagram of Figure 4 should be used as a guide for selecting candidates which appear to be highly polarized. Selection of such objects remains somewhat subjective in the sense that there is no clearly defined line between polarized and unpolarized objects and hence some ambiguity remains for all but the most extreme cases. We indicate below those objects which we feel should be examined further for BL Lacertae properties.

OR 109

The field of OR 109 contains a double object which appears highly polarized on our plates (~22%). This is probably a spurious result as the spectrum of the brighter object is that of a star, however it is interesting to note that the fainter object, only one or two seconds away from the brighter, is distinctly nebulous but rather compact. We have been unable to obtain good quality spectra of this object; it may be continuous. The high degree of polarization is almost certainly a result of contamination by the proximity of the images. Interestingly, the pair of images for the fainter object are distinctly different in brightness and this object should be observed further.

ON 254

The next best candidate in the photographic data (after OQ 530, see above) is ON 254. This object is bright (about 13 mag) and appears to be polarized at about 16% - 17%. This object falls immediately next to OQ 530 in the radio color-color diagram of Figure 3, almost at the origin of the diagram and hence has an extremely flat radio spectrum.

OP 471

Our candidate for OP 471 is polarized at about 14% - 15% and has a very flat radio spectrum (Figure 3). We have no further observations of this object at present.

ON 001.4

Our candidate for ON 001.4 is polarized at about 14% - 15%. This object does not have a very flat radio spectrum (see Figure 3) but nonetheless lies well within the BL Lacertae region of the radio color-color diagram. We have no further observations of this object at present.

Summary

It is apparent that polarization observations provide an efficient technique for identifying new BL Lacertae objects. In the case of highly polarized objects ($\geq$ 12-15%) the photographic technique described above is quite valuable. Although the precision of this approach is not high, it has the tremendous advantage of great speed, particularly in the case that radio positions of the survey sample are of low accuracy. In one night, with the 40mm image tube camera at the 2.29m telescope, we succeeded in obtaining 82 photographs of 41 fields on which all objects within a 6 arc min diameter area around the radio position could be measured to a limit of about 19 mag. In order to more quantitatively examine candidate objects, or to search for less highly polarized objects, we found photopolarimetry to be very useful. It has

Table 2

Summary of Polarized Survey Objects

Ohio name	position	B mag	% linear polarization	Ohio Survey installment
OI 090.4	0754+10	14.2-15.2	4 - 26	VI
OJ-131	0818-12	14.6-17.5	8 - 36	IV
OQ 530	1418+54	12 - 15	5 - 19	V
OT 129	1717+17	17.5	27	III
OR 109	1505+10	14.5:	22?	III
ON 254	1232+29	16:	16 - 17?	I
OP 471	1343+45	14.5:	14 - 15?	V
ON 001.4	1200+04	14.5:	14 - 15?	VI

I Scheer, D.J. and Kraus, J.D. A.J. 72, 536 (1967).
III Fitch, L.T., Dixon, R.S. and Kraus, J.D. A.J. 74, 612 (1969).
IV Ehman, J.R., Dixon, R.S. and Kraus, J.D. A.J. 75, 351 (1970).
V Brundage, R.K., Dixon, R.S., Ehman, J.R. and Kraus, J.D. A.J. 76, 777 (1971).
VI Ehman, J.R., Dixon, R.S., Ramakrishna, C.M. and Kraus, J.D. A.J. 79, 144 (1974).

become apparent that highly polarized BL Lacertae objects tend also to have substantial variability in their degree of linear polarization and for this reason there is some advantage to observing candidate fields in several epochs with the photographic technique.

Of the 60 radio fields we examined in this report we have identified four new BL Lacertae objects which are highly polarized and suggested four candidate objects which must be observed further. It seems reasonable to believe that at least two of the candidates will prove to be identified as BL Lacertae objects, in which case our detection rate is about 10% for our total survey sample. It is interesting to note that of the first 20 fields we studied, two contained highly polarized BL Lacertae objects (OI 090.4 and OJ-131), again a detection rate of 10%.

Figure 3 indicates the positions of our program objects in the radio color-color diagram; all four of our confirmed BL Lacertae objects fall well within the BL Lacertae region. Of the candidate objects two, ON 254 and OP 471, fall nearly at the origin of the diagram and two, OR 109 and ON 001.4, fall near the upper limits of the region. Of the objects which fell outside this region, none had any detectible polarization. Had the original sample been rigorously limited to objects within this region (i.e. very flat radio spectra) the detection rate would have been raised to about 18%.

There is one object in our sample which falls outside the BL Lacertae region of the radio diagram: OM 163.5. This object was observed by Baldwin et al. (1973) to have a continuous spectrum and a brightness of about 18 mag. The object is invisible on our plates and must have been fainter than 20 mag at the time of our observation.

We would like to encourage other observers to pursue the search for new BL Lacertae objects by use of the photographic polarimetry technique which offers a very fast, simple to implement method suitable for use with telescopes of moderate aperture. Some limitations of the technique must be recognized however. In our program we also detected the objects OM 280 and 3C66A (Craine 1977) which were observed for control purposes, however the object PKS 0735+17 (Craine 1977) was not sufficiently polarized during the epoch of our plates to be clearly detected. Likewise, the object OQ 530, which is dramatically evident in our photographic data could have been missed by this technique had it been observed at a later date when it was polarized only 5%. In a search for highly polarized BL Lacertae objects conducted by photographic means alone it is highly desirable to obtain several pairs of plates at different epochs in order to enhance the probability of a detection.

In selecting a sample for this type of survey it is a clear advantage to examine sources which exhibit flat radio spectra, however some caution must be used. It is unusual to find a set of radio sources with fairly completely observed radio spectra in which all observations at different frequencies date from the same epoch. Often the radio spectrum is represented by observations made at widely varying epochs using different telescopes at different frequencies. In the case of the BL Lacertae objects, which are notoriously variable, this can result in a false representation of the shape of the radio spectrum. Subsequent placement of the candidate source in a radio diagram of the type presented here can be subject to substantial, usually undetermined, error. Potential users of this technique should thus be aware that selection of the radio sample should be made very carefully and should perhaps extend somewhat beyond the BL Lacertae region identified above in the case of uncertain or poorly determined radio spectra.

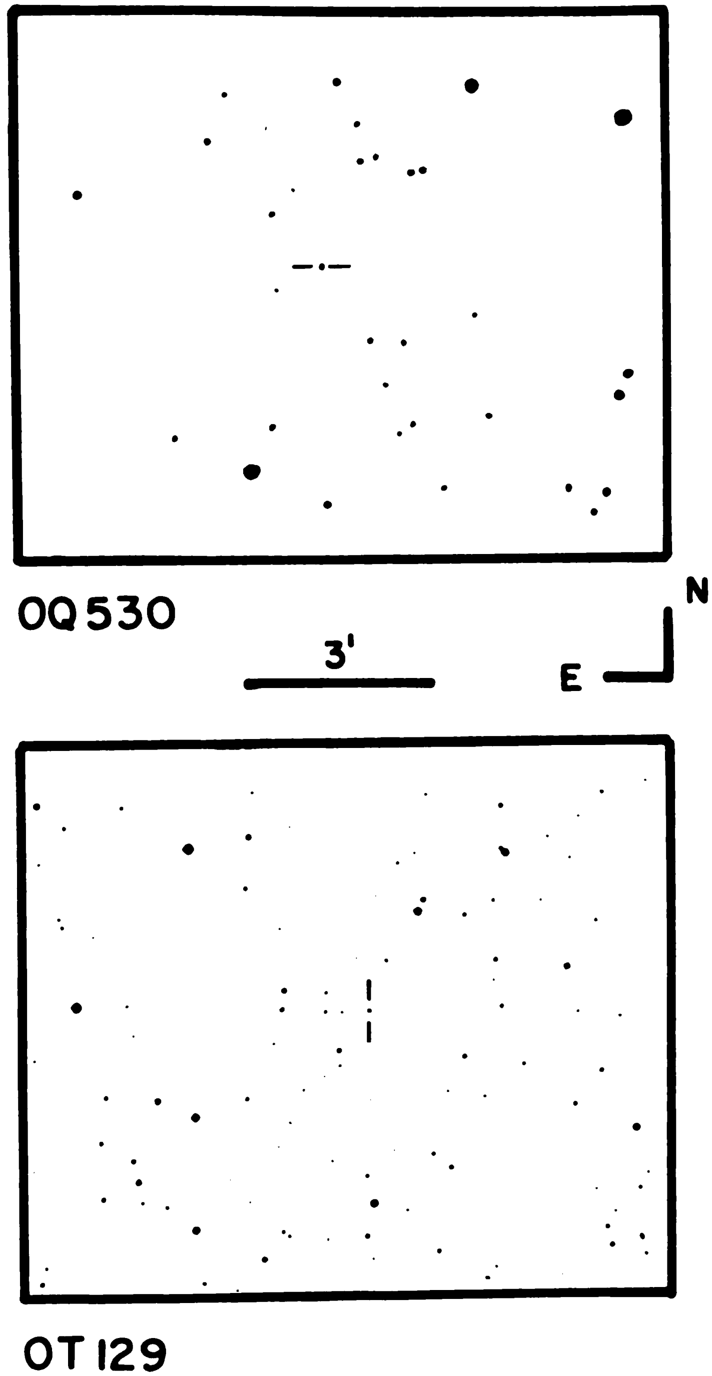

Figure 5. Finding charts for OQ 530 and OT 129.

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DISCUSSION

H. MILLER:
We have found that OQ 530 (1418+54) has a range of $\Delta B \geq 4.8$ mag. However it has been relatively inactive in recent years.

E. CRAINE:
It's been very stable in terms of optical brightness but the polarization has varied substantially over a fairly short period of time. Although it tends to hang down at 5% it has been as high as 20%.

H. ALLER:
Have you considered using this technique to search "blank fields" for radio-quiet BL Lac objects?

E. CRAINE:

No, I think the returns from this type of search would be very low.

H. ALLER:

I would like to comment that it would be most interesting to apply this technique to randomly selected star fields in order to discover a sample of optically selected BL Lac type objects which are not subject to various biases. These biases are introduced by only observing fields of radio sources with pre-selected characteristics.

E. CRAINE:

In principle this idea is attractive but in practice I don't think very reasonable due to several difficulties. Our field size is rather small and is best suited for searching a limited field which may contain a suspected candidate. If one extrapolates the expected number of such objects in a very simple minded way (i.e. from the space density of QSOs) it is apparent that in order to achieve significant statistics rather large fields must be sampled. With our equipment that means obtaining a great number of photographs. The alternative is to utilize a Schmidt type system to look at a large number of sources simultaneously. This is not practical with the calcite plate because of the scale problem (i.e. by producing four images of each object we would be superposing images of adjacent objects.) Use of a polaroid, even with a large rotating prism, produces a very high detection threshold ($p \sim 15\%$). We might expect to do better by introducing a different set of biases, perhaps based on the optical spectral index.

M. BURBIDGE:

Was your observational limit 18-19 mag? I note that all your new objects are considerably brighter than this - do you think this is a real absence of faint BL Lac objects?

E. CRAINE:

Our observational limit was about 18-19 mag. There are two things that came out of this program that were very interesting. This program is not complete by any means but one thing is that we did not find any faint BL Lac objects. The second thing is that although the majority of the objects that we detected were discovered with the photopolarimeter as opposed to photographic techniques, those were all cases where photographic observations had not been made. In fact every single object that was detected with the photopolarimeter, with which we should have been able to see objects down to 1% polarization, was so highly polarized that it would certainly have been detected by the photographic technique. I'm not sure exactly what that's telling us except that these things tend to be highly polarized. Another way to say this - perhaps more likely than an absence of faint BL Lac objects, we are seeing a deficiency of highly polarized faint BL Lac objects.

J. PERRY:

Comment: If Condon's point this morning about BL Lac objects being fainter at 6 cm. than QSOs is correct, then one wouldn't expect optically faint (high redshift) BL Lac's to show up in this study.

Is a spectrum available on the faintest object in your sample? If so, is there any evidence of absorption, since if its absolute magnitude is similar to the bright BL Lac objects at $z \sim 0.6$, its redshift should be >1, and would be expected to probably show absorption if the QSO absorption is due to intervening galaxies.

E. CRAINE:

There is a rather low quality spectrum which appears featureless. We don't have sufficient spectroscopy at present to make any conclusive comments with regard to the presence of absorption lines in OT 129.

D. SHAFFER:

I think you're being a little harsh on radio source identifiers. You can in fact, go out and measure the positions of 100 sources in one day to an accuracy of 1 arc sec., especially for these flat spectrum sources. The other recent identifications done with interferometer positions are almost 100% reliable.

E. CRAINE:

I realize that radio positions of high accuracy are now obtained routinely. My comments are based on unpleasant experiences with many of the "optical identifications" already in the literature which have been based on subjective criteria as well as (then) inaccurate radio positions. A huge number of these objects have been observed to be stars and although the situation has improved dramatically, I think all optical observers must be aware that the published literature still contains very incorrect identifications. In retrospect, identifications made in the first half of the decade should have indicated only radio error boxes rather than specific objects within these boxes which may have met some criterion (red? blue? etc.) which was in fashion at the moment.

K. JOHNSTON:

I'd like to address that question. I think that radio positions today can be measured as accurately as 0.01 arc sec. I think that radio astronomers would like to get a hold of your list because BL Lac objects make excellent calibrators, for instance, for the VLA. Right now this is a subject close to my heart because that is what I am doing, calibrating the VLA. These sources have very little structure out to baselines as large as 36 Km. and we can measure very accurate positions.

E. CRAINE:

Let me make one comment. I am not trying to deliberately anti-gonize radio astronomers. I've done some of that work myself. The point I want to make is that the radio surveys are very good and I think that there are some tremendously good candidates in there. I think some of them are being missed because people involved in optical spectroscopy programs get very frustrated when they start turning up stars off these identifications. Spectroscopy is a time consuming business and if you burn up one night doing just one of these fields to get a list of stars, you have a problem. I think it would be better to indicate in these identifications that this is an error box rather than the object itself.

M. DAVIS:

We have discussed the question where you have done a survey of some hundred regions that were based on radio positions. It would be very interesting to get accurate radio positions now and see if any of your BL Lac objects do not correspond to the radio source. That gives an upper limit on the number of radio-quiet BL Lac objects.

E. CRAINE:

I agree with that and that is something we want to do.

D. WILLS:

How long does it take to measure all the objects on one of these plates? Do you hold out any hope of getting any positional accuracy?

E. CRAINE:

It took us a long time because we were involved in other projects. You can measure it in ten minutes or less.

B. WILLS:

Why did you say that it wasn't worthwhile to look at pieces of sky without radio sources? There are perhaps 10-100 times more radio-quiet QSOs than radio QSOs, so an unbiased search may yield a worthwhile number of radio-quiet BL Lac type objects. (A reason could be correlation of radio emission strength with optical polarization.)

E. CRAINE:

I don't like pointing the telescope at a random area of the sky and taking a picture through the calcite plate and looking to see whether a polarized object comes up. I would rather be a little bit more careful in my selection of the fields I observe. I think it will work for getting BL Lac objects. I want to try doing it. Also are you convinced that there are 100-100 times more radio-quiet BL Lacs than radio BL Lacs? I haven't seen one yet.

ON THE POLARIZATION AND MASS OF BL LAC OBJECTS

by

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ABSTRACT

Optical polarization measurements have been obtained for 12 BL Lac objects, including many repeated observations during a night. It is found that the shortest time scale for substantial changes in polarization is ~ 10 hours. Fluctuations with a 1 day characteristic time are common. We identify this time with the dynamical time scale of the most luminous material close to a black hole, at radius $r \sim 10\ GM_H/c^2$. It follows that the typical mass is $\sim 2 \times 10^9\ M_\odot$. Observations over several years show 5 out of 12 objects have a preferred orientation of position angle, perhaps defined by the angular momentum vector of accreted material.

I. INTRODUCTION

The optical polarization of BL Lac objects is an important clue to the nature of their power production. Radiation in the optical and infrared accounts for most of the total energy output of both these objects and QSOs, but the rapid variability characteristic of BL Lac objects indicates an extremely compact source. It seems probable that the primary emission of radiation is in the form of polarized light. Very few infrared polarization measurements have been obtained, but those at 2.2μ by Knacke et al. (1976) and Rieke et al. (1977) generally show the infrared and visible polarizations being equal when measured at the same time. The 2.2μ emission thus shares the same fluctuations as the visible. If indeed the visible and infrared radiation from BL Lac objects is coming directly from matter accreting onto a massive black hole, then the minimum time scale of fluctuations indicates the size of the emission region, and hence the mass of the black hole. In this paper we report a study of polarization where the main purpose has been to determine what are the most rapid variations.

In practice it is easiest to explore the time scale of variability of BL Lac's through measurements of their visible polarization. They have the property that the linear polarization Stokes parameters often vary as much as or even more than the total intensity (Visvanathan 1974). In this situation polarization changes are easier to detect than intensity changes, because the measurement is internal and does not rely on measurements of standards. Previous studies of polarization (see Craine, 1977, for details of individual objects), have established that the polarization can change substantially from night to night, but very little work has been done to search for more rapid fluctuations.

If accreted material forms a disc, then one might expect the orientation of the angular momentum vector to define a preferred direction in the position angle of polarization. We report here observations obtained for some objects over several years which show the polarization angle, though variable, is confined to a limited range of directions.

II. OBSERVATIONS AND NOTES ON INDIVIDUAL OBJECTS

The monitoring for short term variability of this project required the dedicated use of a telescope for several months. The 36" telescope of Steward Observatory was available, though the existing foci (Newtonian and coudé) were not suitable for polarimetry because of oblique reflections. We rebuilt the top of the telescope as follows: a pierced 10" flat at the top of the tube reflects the f/5 beam from the primary down to a convex tertiary mirror. This brings the light to an f/9 quasi-prime focus, where the polarimeter is mounted. A motor driven pierced flat reflects the star field to an ISIT television acquisition camera, so the telescope can be operated remotely. The polarimeter makes use of a Pockels cell to modulate polarization at ~ 100 Hz, and light is detected by two gallium arsenide photomultipliers, RCA type 31034A. The data from pulse counting circuits are accumulated and recorded by a Nova 800 computer located with the television monitor in a control room below the observing floor.

The observing sequence was to integrate for seven minutes first with the object in the aperture (10 arc seconds diameter), then with the sky alone. Periodically a nicol prism was inserted in the light path, to determine instrument efficiency. All data have been corrected for night sky emission and instrument efficiency. No attempt was made to obtain accurate photometry during the survey, because of the small aperture chosen to reduce sky background, and because we did not wish to spend time observing standards. Approximate magnitudes from the count rate are given below. Data were obtained over the period November 1977-May 1978 on most clear dark nights when the polarimeter was not required on the larger telescopes. Unfortunately the winter weather was extremely poor, and very few observations were obtained in January, February and March.

Twelve program objects were selected on the basis of their brightness and all the results, some 3-400 measurements, are listed in Table 1, and plotted in Figures 1-14. The tabulated errors are computed from the number of detected photoelectrons, assuming that photoelectron statistics in the star and sky measurements are the only source of error. In fact

TABLE 1 - POLARIZATION MEASUREMENTS OBTAINED WITH THE STEWARD 36" TELESCOPE IN A BAND 3200 - 8600 Å, WITH A 10 ARC SECOND APERTURE. JD IS GIVEN - 244,3400.

0219+42 = 3C66A

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
49.8031	12.25	1.12	28.1	2.6
49.8184	12.56	.96	19.1	2.2
49.8351	12.25	.81	21.9	1.9
49.8691	10.30	.87	25.2	2.4
49.8864	10.50	.82	25.3	2.3
49.9017	11.28	.92	29.8	2.3
50.8420	14.10	.72	26.8	1.5
50.8628	10.96	.76	25.0	2.0
50.8795	12.35	.71	30.1	1.6
52.8434	12.02	.82	23.2	2.0
52.8621	11.59	.82	21.5	2.0
55.7844	13.28	.65	22.8	1.4
55.7983	11.96	.75	23.7	1.8
56.6746	12.21	.93	24.5	2.2
56.6871	10.53	.72	23.4	2.0
58.6885	11.68	1.46	16.6	3.6
59.7948	15.99	1.94	19.5	3.5
60.6524	13.37	.83	18.6	1.8
60.6678	12.78	1.00	20.6	2.2
61.7503	13.52	1.39	15.0	3.0
61.7698	13.83	1.04	16.5	2.4
62.6684	15.52	.72	17.6	1.3
62.6892	12.24	.66	20.5	1.5
63.8260	11.35	.78	17.0	2.0
63.8469	12.09	.50	16.9	1.2
64.6927	12.41	.70	16.8	1.6
64.7066	11.48	.62	15.4	1.6
65.8406	11.19	.93	15.3	2.4
65.8476	10.84	.82	16.3	2.2
91.7115	10.60	.52	10.9	1.4
92.7705	11.20	.71	12.7	1.8
92.8122	9.77	.90	9.3	2.7
93.6046	9.42	.98	14.2	3.0
93.6351	9.82	1.13	9.7	3.3

AO 0235+16*

93.9375	16.64	.76	67.7	1.3
93.9479	18.06	.94	68.6	1.5
94.9250	18.72	.54	68.9	.8
95.9167	22.72	.66	66.3	.8

0318+41 = NGC 1275

52.8920	1.64	.23	159.8	4.0
52.9031	1.33	.23	153.1	4.9
55.9010	1.96	.23	169.3	3.4
56.7010	1.86	.21	169.0	3.2
56.7114	1.42	.20	169.0	4.0
56.7219	2.31	.20	166.1	2.4
56.7358	1.84	.20	167.4	3.1
56.7246	2.04	.26	154.0	3.6
58.7427	1.66	.29	150.4	5.0
58.7559	1.61	.25	149.4	4.4
59.7364	2.17	.47	156.6	6.2
59.7538	1.44	.22	150.7	4.2
59.7733	1.73	.41	143.3	6.7
60.7045	1.81	.20	161.2	3.3
60.7198	1.91	.20	164.6	3.0
60.8524	1.71	.15	158.9	2.5
61.6948	2.39	.39	150.7	4.6
61.7052	3.10	.28	141.2	2.5
61.7184	2.73	.22	147.1	2.3
61.7330	2.71	.24	151.6	2.5
61.8052	2.51	.25	146.3	2.9
61.8385	3.03	.25	150.5	2.4

*Data from the 90" telescope. JD is given -2443300.

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
62.6989	2.98	.20	157.2	1.9
62.7198	2.52	.26	152.2	3.0
62.7871	2.82	.19	158.0	2.0
63.8538	2.87	.15	150.3	1.5
64.7233	2.72	.16	161.8	1.7
64.8052	2.42	.15	156.1	1.8
64.8614	2.92	.15	152.8	1.5
64.8726	2.81	.14	153.7	1.5
65.6781	3.39	.25	149.3	2.1
65.6878	2.60	.23	150.2	2.5
65.7010	3.01	.23	146.9	2.2
65.7351	3.01	.23	151.3	2.2
65.7767	2.76	.17	150.9	1.8
		PKS 0422+00		
49.9573	15.91	1.52	142.9	2.7
49.9726	12.01	1.86	142.1	4.4
56.8045	17.94	1.16	161.8	1.9
56.8177	16.54	.94	162.0	1.6
56.8281	17.85	.93	160.5	1.5
56.8483	18.14	1.02	161.2	1.6
57.9135	20.64	1.63	152.9	2.3
57.9316	22.24	1.43	153.6	1.8
58.7774	15.24	1.20	163.5	2.3
58.7878	16.88	1.24	166.7	2.1
60.8052	14.13	1.03	165.6	2.1
60.8156	13.49	.89	166.1	1.9
62.7545	9.86	1.12	163.3	3.3
62.7684	11.02	.96	167.5	2.5
63.8816	13.21	.88	165.7	1.9
63.8969	13.21	.79	165.7	1.7
64.8267	11.90	.98	164.6	2.4
64.8392	10.89	1.00	167.4	2.6
64.8483	14.39	.80	166.1	1.6
64.8864	11.74	.89	165.0	2.2
64.8969	11.12	.98	163.8	2.5
65.8698	17.26	1.14	157.4	1.9
65.8823	14.01	1.37	155.0	2.8
90.8052	6.05	1.01	10.3	4.7
90.8177	7.69	1.64	9.1	6.1
91.7566	10.66	.60	6.1	1.6
91.7809	10.23	.59	8.3	1.6
91.7948	12.22	.61	3.4	1.4
93.6872	11.25	1.86	168.5	4.7
93.7358	11.43	1.12	165.1	2.8
94.7421	12.08	.67	159.0	1.6
94.7636	14.31	.66	165.7	1.3
94.7830	11.34	.66	164.7	1.7
94.7969	11.98	.64	164.4	1.5
112.6768	8.96	.62	5.2	2.0
112.6907	9.08	.61	8.2	1.9
		PKS 0735+18		
51.8649	20.40	.90	159.6	1.1
51.8823	19.90	.90	162.9	1.2
52.9489	19.30	1.40	164.6	2.0
55.9358	23.66	.60	160.5	.7
55.9489	24.24	.56	161.8	.7
56.8899	20.20	.69	157.5	1.0
56.9017	22.51	.53	158.8	.7
56.9156	21.98	.49	158.2	.6
56.9274	22.57	.48	158.2	.6
56.9351	23.56	.49	158.2	.6
57.9510	21.98	.58	156.2	.8
58.8483	20.02	.57	153.8	.8
58.8712	21.63	.62	154.1	.8
59.9094	22.15	1.54	150.7	2.0

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
59.9239	24.27	1.20	154.5	1.4
60.8670	22.08	.44	154.3	.6
60.8774	21.50	.39	154.4	.6
61.8774	18.40	3.00	154.8	4.8
61.9330	23.03	1.60	157.7	2.0
61.9628	22.38	1.12	157.4	1.4
63.9163	20.83	.40	152.2	.6
63.9302	20.71	.38	152.2	.5
64.9184	20.88	.41	152.7	.6
64.9274	21.37	.44	151.9	.6
65.8073	20.87	.59	154.8	.8
65.8170	23.04	.58	151.0	.7

0754+10 = OI 090.4

51.9142	5.34	.83	10.4	4.5
51.9302	3.06	.81	5.3	7.6
55.9670	8.73	.71	.6	2.3
55.9809	9.54	.62	1.9	1.9
56.9489	13.87	.63	.6	1.3
56.9608	13.72	.58	1.6	1.2
56.9719	13.57	.59	1.7	1.3
57.9698	9.82	.59	3.2	1.7
58.8920	10.22	1.36	5.8	3.8
58.9059	8.74	.58	1.8	1.9
58.9163	9.06	.50	176.4	1.6
60.8913	18.49	.47	10.1	.7
60.8976	17.26	.42	9.0	.7
60.9146	17.77	.42	8.6	.7
63.9469	11.44	.42	6.4	1.1
63.9601	11.48	.39	6.0	1.0
64.9420	9.18	.45	5.8	1.4
64.9531	7.81	.40	4.6	1.5
64.9705	8.37	.39	6.3	1.3
65.9038	11.33	.72	1.7	1.8
65.9191	10.19	.45	5.0	1.3
90.8712	10.82	.36	12.0	.9
90.8844	10.72	.41	13.5	1.1
90.9205	11.25	.40	11.9	1.0
90.9337	11.03	.40	12.6	1.0
90.9927	11.06	.45	13.6	1.2
91.0240	12.39	.61	10.7	1.4
91.0414	10.84	.45	11.4	1.2
91.8677	5.55	.40	2.9	2.0
91.8886	6.70	.40	10.3	1.7
91.8990	6.73	.41	10.3	1.7
91.9365	7.70	.37	10.7	1.4
91.9789	8.35	.40	12.5	1.4
92.0191	9.40	.42	11.4	1.3
92.0393	10.43	.41	12.7	1.1
92.9379	9.75	.43	14.8	1.3
92.9615	10.37	.43	16.7	1.2
93.7622	9.25	.63	17.0	2.0
93.7914	9.18	.75	18.2	2.3
93.8122	7.89	.90	19.7	3.3
93.8261	8.25	.86	20.2	3.0
94.8226	11.06	.45	20.2	1.2
94.8462	10.75	.41	18.9	1.1
94.8608	11.11	.40	20.0	1.0
112.7115	10.50	.47	1.3	1.3
112.7393	10.20	.46	178.8	1.3
112.8421	10.58	.52	1.1	1.4

0818-12 = OJ-131

50.9753	14.07	.66	73.7	1.3
51.9795	18.56	.70	77.2	1.1
51.9927	12.83	.72	82.0	1.6
55.9962	17.20	.78	80.7	1.3

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
56.0101	19.75	.71	81.7	1.0
57.0045	18.17	.73	84.8	1.2
57.0184	19.88	.87	89.0	1.2
57.9927	13.99	1.03	86.7	2.1
58.9823	14.25	1.83	88.5	3.7
60.9608	18.02	.67	81.6	1.1
60.9712	17.73	.58	81.0	.9
63.9934	10.51	.60	95.4	1.6
64.0066	10.49	.56	94.6	1.5
65.0114	12.02	.62	91.0	1.5
65.0198	12.56	1.20	93.7	2.7
91.9198	25.72	.47	68.8	.5
91.9615	25.27	.47	69.1	.5
92.0032	24.39	.45	68.4	.5
92.9823	17.70	.63	67.7	1.0
93.8400	15.64	1.27	62.4	2.3
93.8608	19.08	1.35	66.7	2.0
93.8955	20.46	.81	67.8	1.1
93.9302	15.36	.78	68.7	1.5
93.9518	16.37	.87	66.8	1.5
93.9671	16.92	.87	70.1	1.5
94.8712	17.83	.41	71.1	.6
94.8851	18.92	.58	70.5	.9
94.9004	17.95	.45	70.2	.7
94.9143	19.28	.40	69.9	.6
94.9302	18.19	.39	69.5	.6
94.9441	18.92	.40	69.7	.6
94.9580	18.67	.37	70.0	.6
112.7879	11.52	.57	68.9	1.4
112.8025	12.65	.56	67.0	1.3
112.8573	12.07	.56	67.2	1.3

0851+20 = OJ 287

58.9545	21.52	.76	84.8	1.0
58.9649	22.89	.70	85.3	.9
60.9344	22.29	.54	85.8	.7
60.9462	22.18	.47	86.0	.6
61.9892	21.56	.93	79.7	1.2
62.0101	22.47	.65	79.6	.8
63.9760	19.78	.50	79.6	.7
64.9830	19.41	.44	82.7	.7
64.9962	19.44	.42	83.4	.6
65.9371	17.64	.79	81.9	1.3
65.9489	18.40	.47	82.5	.7
65.9635	18.28	.52	82.8	.8
144.7497	11.95	.42	74.1	1.0
144.7649	12.80	.39	73.8	.9
144.7948	12.78	.36	76.3	.8
144.8184	13.32	.41	75.3	.9
144.8393	12.55	.37	77.2	.9
144.8629	13.02	.42	76.4	.9
145.7587	12.41	.42	78.5	1.0
145.7774	13.41	.46	79.1	1.0
145.7983	11.57	.45	78.2	1.1
146.6594	15.03	.75	74.8	1.4
146.7705	16.65	1.24	75.0	2.2
173.6913	18.66	.46	72.4	.7
174.6865	17.86	.48	71.7	.8
174.7004	17.60	.48	73.2	.8
174.7191	16.20	.49	72.6	.9
174.7337	17.24	.52	72.2	.9
178.6455	14.84	.60	62.8	1.2
178.6663	12.83	.47	64.0	1.1
178.6976	13.50	.48	65.3	1.0
178.7115	13.91	.47	66.5	1.0
178.7601	14.01	.57	64.2	1.2
178.7719	13.59	.56	65.2	1.2
178.7865	13.07	.58	64.8	1.3

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
178.7969	13.64	.63	64.6	1.3
178.8073	14.20	.67	64.7	1.3
179.7851	14.19	.86	65.1	1.7
179.7983	14.07	.87	62.9	1.7
		1147+24 = OM 280		
112.8955	10.72	.98	149.8	2.6
117.8400	10.06	.99	146.0	2.9
117.8990	7.71	.88	154.1	3.3
117.9129	7.13	.87	152.1	3.5
144.8906	8.96	1.05	139.5	3.4
145.8434	9.49	2.39	134.1	5.4
145.8698	7.35	1.33	137.3	5.2
147.9295	5.60	1.10	138.9	5.6
147.9434	7.60	1.09	141.1	4.1
173.7386	3.86	.84	155.0	6.4
174.7643	7.06	.98	148.9	4.0
		1215+30 = ON 325		
144.9288	14.70	.92	174.4	1.8
144.9531	17.48	.76	169.6	1.2
144.9962	16.73	.63	172.3	1.1
145.0087	14.80	.84	168.1	1.6
173.7788	7.71	.72	178.5	2.7
173.8031	7.57	.64	171.5	2.4
173.8170	8.16	.67	172.6	2.4
173.8316	8.01	.69	171.0	2.4
173.8483	7.41	.61	175.2	2.4
174.7920	7.05	.67	176.2	2.7
174.8087	8.71	.65	177.7	2.1
174.8254	7.94	.64	176.0	2.3
174.8413	8.20	.59	173.2	2.1
178.8240	11.09	.55	173.7	1.4
178.8420	11.23	.58	174.8	1.5
178.8601	11.44	.60	172.5	1.5
178.8733	11.09	.60	173.0	1.5
179.8149	9.37	.76	175.2	2.3
179.8330	9.30	.73	175.6	2.2
180.7337	13.49	1.74	1.0	3.7
180.7712	15.90	2.36	174.5	4.4
		1514-24 = AP LIB		
173.8719	5.34	.61	3.7	3.3
173.9087	2.77	.60	6.3	6.5
174.8656	3.72	.80	6.9	6.1
178.8906	4.30	.53	22.8	3.6
178.9045	5.13	.57	18.6	3.2
178.9191	4.46	.58	15.3	3.8
179.8899	3.32	1.49	13.7	12.9
179.9038	4.70	1.11	14.4	6.8
181.8698	3.66	.96	22.4	7.6
181.8955	3.20	1.48	23.6	13.2
		1652+39 = MK 501		
173.9344	3.35	.24	134.8	2.1
173.9601	2.93	.23	134.3	2.2
173.9698	2.95	.24	138.9	2.3
173.9802	3.18	.23	130.8	2.1
174.9108	2.16	.30	133.3	4.0
174.9483	2.92	.25	135.8	3.6
174.9629	3.25	.25	138.7	2.2
174.9844	3.05	.25	131.5	2.3
178.9441	2.41	.21	143.1	2.5
178.9691	2.46	.21	144.7	2.4
178.9858	2.25	.21	138.1	2.7

JULIAN DATE	POLARIZATION (PER CENT)	SIGMA	POSITION ANGLE	SIGMA
179.9406	1.99	.30	137.2	4.3
179.9566	2.31	.35	141.9	4.3
180.9080	2.86	.50	130.5	4.9
180.9441	2.24	.60	141.6	7.6
181.8365	1.20	.43	133.5	10.2
181.8441	1.66	.40	123.6	6.9
181.9163	2.34	.36	140.6	4.5
181.9351	2.51	.35	135.5	3.9
181.9497	2.27	.34	144.0	4.3

2200+42 = BL LAC

31.6732	10.12	.34	158.4	.9
31.6906	10.34	.34	158.5	.9
31.7267	10.27	.31	159.9	.9
31.7628	10.86	.34	161.6	.9
31.7989	10.66	.34	162.7	.9
31.8364	9.30	.34	164.3	1.0
49.6628	9.71	.36	166.5	1.1
49.7274	7.89	.48	162.9	1.8
49.7455	7.65	.62	163.8	2.3
50.7920	8.81	.40	152.5	1.3
50.8059	8.16	.41	150.5	1.4
50.8219	7.73	.42	148.2	1.6
51.6267	1.55	.41	174.4	7.6
51.6573	2.47	.34	169.3	3.9
51.6726	2.10	.34	157.1	4.6
51.6913	1.46	.32	159.5	6.4
51.7073	2.17	.35	151.6	4.5
51.7267	2.40	.35	157.8	4.1
51.7413	2.24	.35	151.1	4.3
56.6302	5.93	.44	163.5	2.1
56.6406	5.96	.40	162.0	1.9
56.6524	5.90	.40	161.6	1.9
58.6114	6.79	.39	145.0	1.6
58.6295	7.03	.41	145.1	1.7
58.6455	6.28	.43	141.6	2.0
59.6781	4.94	.34	131.9	2.0
59.7184	3.04	1.22	130.8	11.5
60.6024	3.50	.27	163.4	2.2
60.6191	3.58	.27	163.9	2.1
60.6351	3.75	.27	166.5	2.0
60.7489	2.88	.53	156.3	5.3
60.7608	2.69	.43	157.6	4.6
61.6191	3.05	.56	169.4	5.2
61.6420	1.74	.36	163.5	6.0
61.6545	3.53	.36	157.9	2.9
62.5962	4.56	.29	144.0	1.8
62.6080	4.04	.27	145.8	1.9
62.6212	3.65	.29	144.5	2.2
62.6330	3.34	.28	144.9	2.4
62.6448	3.58	.27	141.5	2.1
63.6809	4.28	.55	121.9	3.7
63.6948	4.28	.62	124.8	4.2
64.6177	5.54	.33	134.6	1.7
64.6378	5.86	.33	136.5	1.6
64.6538	6.81	.33	138.2	1.4
64.6705	6.63	.30	137.9	1.3
64.7406	7.39	.40	139.9	1.5
64.7573	7.61	.36	142.9	1.3
64.7705	7.61	.36	146.6	1.3
65.6038	9.32	.52	146.8	1.6
65.6156	8.32	.54	145.5	1.9
65.6344	8.80	.64	146.6	2.1
65.6448	8.71	.85	140.7	2.8
65.6566	7.67	1.18	147.0	4.4
91.6129	10.71	.39	5.3	1.0
92.6407	5.18	.36	20.3	2.0
92.6525	4.64	.31	22.3	2.0
92.6643	4.55	.33	20.5	2.1
94.6254	5.11	.43	154.8	2.5

there are other sources of error, and these must be borne in mind in deciding if apparent changes in polarization are real. Because the star and sky measurements are not simultaneous, changes in the sky contribution, particularly if it is strongly polarized by moonlight, can give errors in our data. Even the dark sky through a 10 second aperture gives a count rate equal to a star of magnitude about V ~ 16, so the sky is nearly always a significant contribution, even when the moon is down. Changes in transparency and cirrus can change the sky background, and hence the deduced polarization. Care was taken to eliminate this, but a few data points may be significantly in error from this source. In many other types of observations one can reject data on grounds of inconsistency, knowing that the properties must be constant. However, for the BL Lac objects we cannot, and have not, rejected any data point on the ground that it looks bad, because it could represent real changes on a time scale of a few minutes.

Observations over a number of years of some of the program objects have been made (by TDK) with the Kitt Peak 2.1 and 4.0 meter telescopes using an HNP'B Polaroid analyser and an unfiltered S11 photocathode. Before May 1973, observations were made with H. M. Dyck's polarimeter; after that either the Mk I or Mk II computer-photometer was used in the polarimetric mode. Normally 10" or 12" diameter apertures were used. In the case of AP Librae a 10".2 diameter aperture was used for all observations except that of 1976 May 5 when a 11".0 diameter aperture was used. The results of these observations are listed in Table 2.

A discussion of the observations of each object and other polarimetry, when available, is given for individual objects. Comparison of data in different optical bands is legitimate, since BL Lac objects generally show polarization whose strength and position angle is wavelength independent over the optical spectrum.

3C 66A = 0219+42

The polarization of this source was rather steady over the 40 day observation period with V ~ 15.5, shown in Fig. 1. The position angle rotated monotonically from ~30° to 15° and the polarization was ~12%. For the initial 16 days of data 29 measurements yield $\bar{P}$ = 12.29, σ = 1.37%. The standard deviation is somewhat larger than expected from counting statistics. The data in Table 2 show that both the position angle and polarization strength of 3C 66A close to the same value in four measurements over the years 1974-1976. For all observations the angle varies at most ±16° from a mean of 31°, while the strength is nearly always in the range 12 ± 2%. 3C 66A is the most stable in polarization of all our sample.

AO 0235+164

While not part of the main program of observations, we have included data obtained with large telescopes in Tables 1 and 2. The recent observations in Table 1, obtained when the source was faint (V ~ 18) shows it to be strongly polarized and steady over three nights. During outburst (Table 2) it was strongly variable on a time scale of months. More data are needed to determine the faint phase morphology.

NGC 1275

The data over a two week period of continuous monitoring (Fig. 2) show the polarization generally increasing from 1.5 to 3%, while the

TABLE 2 - POLARIZATION MEASUREMENTS OBTAINED AT KITT PEAK NATIONAL OBSERVATORY IN A BAND 3200-6000Å

OBJECT	DATE	(UT)	p(%)	dp(%)	θ	dθ
3C 66A	1974	Oct 14	13.8	± 0.4	18°	± 0°8
	1974	Oct 15	13.4	0.4	24°	0.8
	1975	Feb 10	10.9	0.3	26°	0.8
	1976	Feb 23	8.9	0.4	47°	1.2
AO 0235+164	1975	Oct 4	24.6	± 0.4	154°	± 0°5
	1976	Jan 4	6.1	6.1	126°	5.5
	1976	Feb 23	10.0	1.5	81°	4.2
0422+004	1975	Oct 4	16.9	± 0.7	6°	± 1°2
	1976	Jan 4	10.7	0.4	152°	1.0
	1976	Feb 23	3.6	0.4	169°	3.1
	1977	Jan 24	8.7	0.8	20°	2.6
	1977	Jan 25	9.7	0.7	32°	2.0
1127+24.5	1974	Feb 16	1.6	± 0.8	103°	±13°6
	1974	Feb 22	3.2	0.4	6°	3.7
	1974	Mar 26	2.7	0.4	136°	4.1
	1974	May 17	6.1	0.4	132°	1.8
	1974	Jun 18	13.2	0.7	151°	1.5
	1975	Feb 11	6.2	0.6	73°	2.7
B1215+30	1971	Dec 10	7.3	± 0.2	150°	± 0°8
	1972	Jan 15	5.4	0.2	135°	1.0
	1972	Feb 13	5.8	0.2	166°	1.1
	1972	Feb 14	5.2	0.2	145°	0.9
	1972	Feb 20	7.7	0.1	139°	0.5
	1972	Feb 21	8.2	0.2	140°	0.8
	1972	Mar 8	6.9	0.1	153°	0.6
	1972	Mar 10	6.3	0.2	143°	0.7
	1972	Apr 20	5.5	0.2	141°	1.2
	1972	Jun 11	12.6	0.4	162°	1.0
	1973	Jan 8	11.2	0.3	152°	0.7
	1973	Apr 26	13.5	0.2	156°	0.4
	1974	Feb 22	6.2	0.4	150°	1.6
	1974	Mar 24	8.6	0.3	156°	0.9
	1974	Jun 18	4.7	0.6	176°	3.8
	1975	Feb 11	8.7	0.6	162°	2.0
	1976	May 6	8.2	1.2	152°	3.9
	1977	Jan 25	6.6	0.9	151°	4.0
AP Librae	1973	Apr 27	1.9	± 0.2	168°	± 3°5
	1973	May 30	4.2	0.3	165°	2.1
	1974	Jun 18	5.7	0.5	17°	2.4
	1974	Jun 21	5.1	0.5	11°	2.9
	1976	May 5	6.8	0.9	172°	3.6

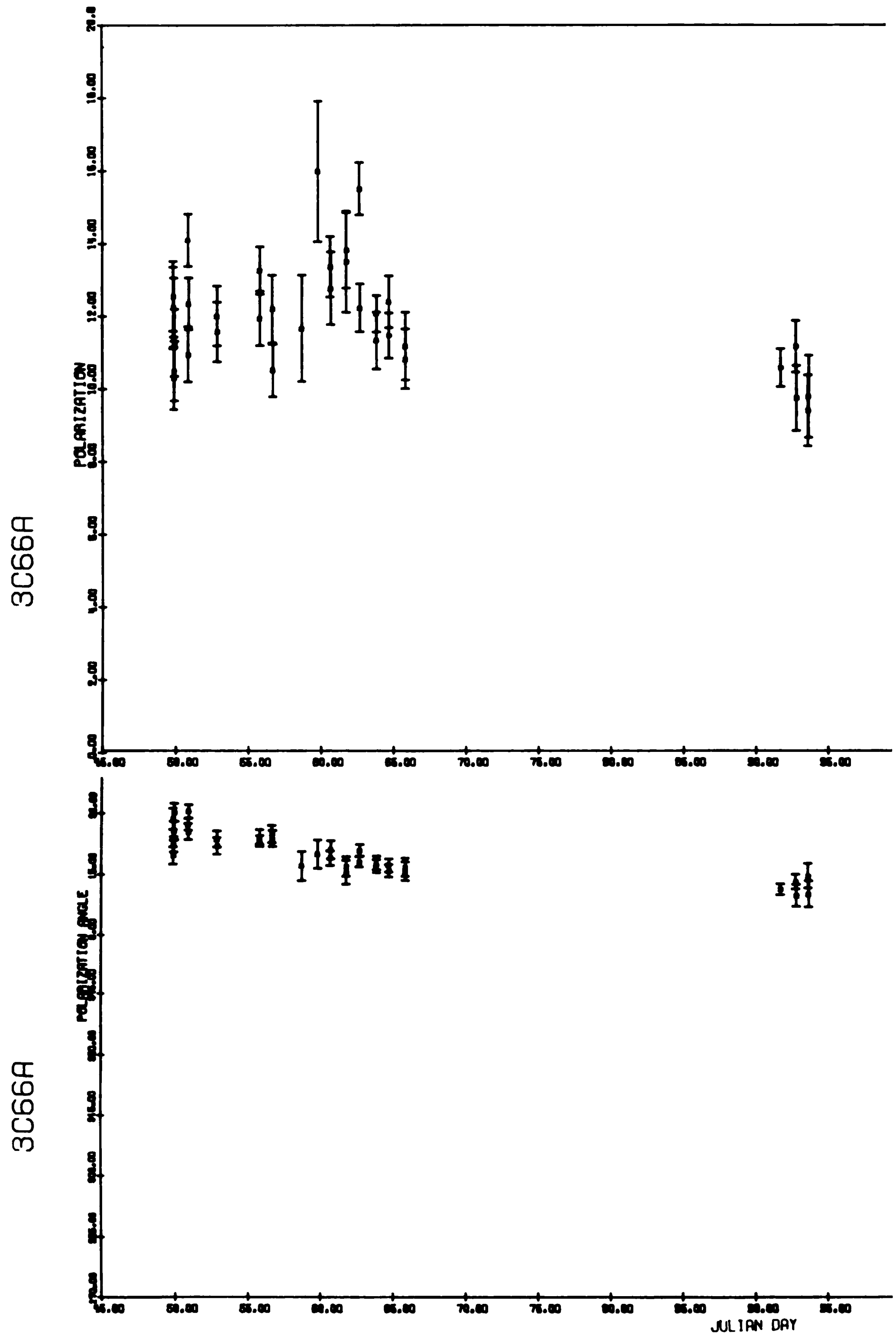

Figure 1

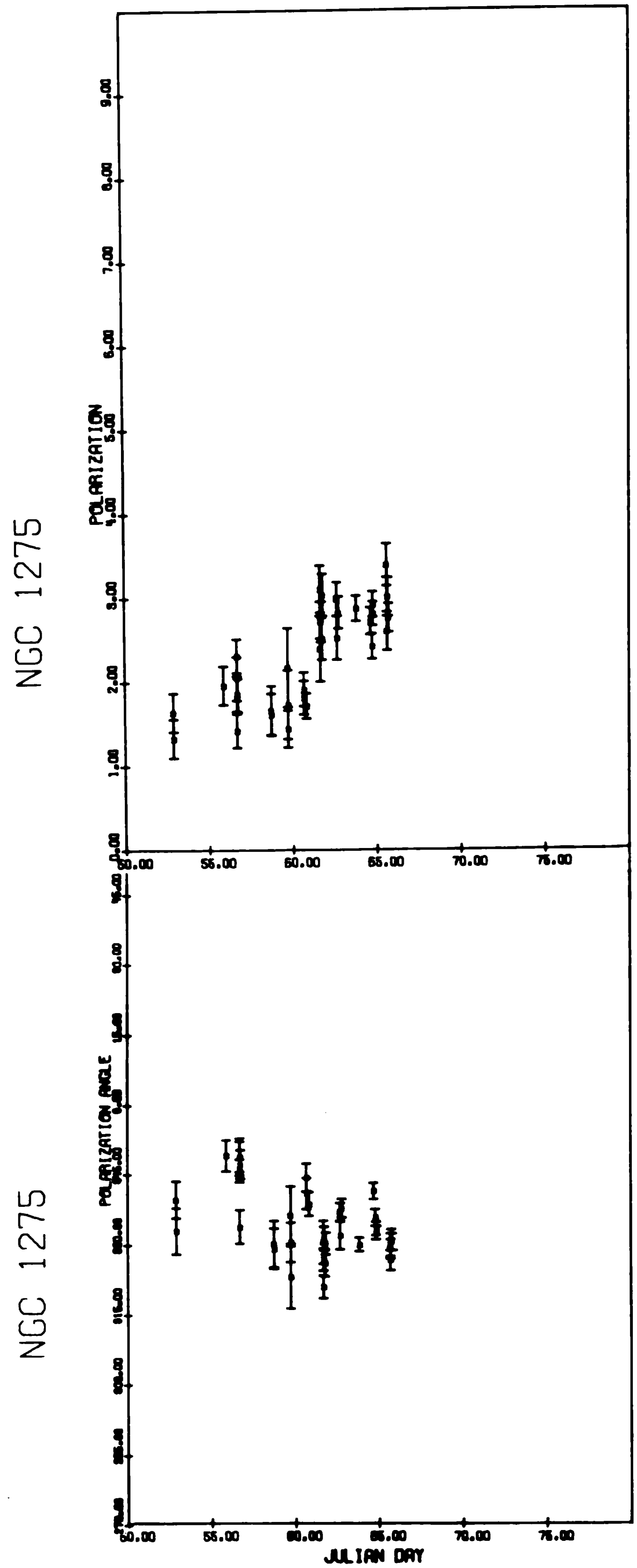
NGC 1275
POLARIZATION
NGC 1275
POLARIZATION ANGLE
JULIAN DAY
50.00
55.00
60.00
65.00
70.00
75.00

Figure 2

position angle varies significantly and erratically from night to night, over a total range of 20°. On a time scale of hours there does appear to be a significant steady change of position angle of 8° over a 3 1/2 hour period on day 64. (Note that the observed polarization of the source is modified by interstellar polarization by our own galaxy, estimated by Martin, Angel and Maza (1977) to be 1.6% at 133°.) Our new observations show that the night-to-night variations of position angle of up to 20° reported by Martin et al. are typical of this source, and confirm that the nuclear source of continuous emission has the polarimetric properties of a BL Lac object. Further evidence in favor of its being considered a BL Lac object is given by Veron (1978).

PKS 0422+004

Our data over a two month baseline are shown in Fig. 3. The strength of polarization is highly variable from 6.5% to 21%. Large changes of up to 10% take place in a few days, and there are occasional abrupt changes of 5% from night-to-night. The position angle was typically ~ 165°, with maximum excursions of ± 20° from this value. There are occasional abrupt changes of angle of 10° from night-to-night. No runs in a night longer than ~ 1 hour were obtained, and there is no significant variability on this short a time scale.

The observations over the period 1975-1977 in Table 2 also show large changes in amplitude from 3.6-17%, and position angle from 152° to 32°. Again there is an abrupt change of 12° in position angle on two successive nights (January 1977). The total range of position angle is 77° for all observations over 2 1/2 years, suggesting there may be a long term stability about an average of ~ 0°.

0422+004 was in a mild outburst during these observations. Kinman (1976) reported the magnitude was up from 16-17 to V = 14.96 in January 1976. The magnitude was 15-16 during the 1978 run of observations. In January 1977, Owen et al. (1978) found it to be a strong source (1.7 Jy) at 90 GHz.

PKS 0735+178

Our observations over a 14 day run shown in Figure 4a show strong polarization of average 21.8%, with position angle varying fairly smoothly over the range 151°-162°. The standard deviation of the observed polarization magnitudes is 1.37%, compared with a typical standard deviation of 0.6% computed from photoelectron statistics. We believe the variations may be significant and represent real day-to-day fractional changes of ± 0.06. Previous polarimetry of 0735+178 by Carswell et al. (1974) when the magnitude was ~ 16 showed much more activity, with large changes of both magnitude and direction on a time scale of 10 days. The source was around 15th magnitude during our observations.

OI 090.4 = 0754+10

Our data extending over 56 days when the magnitude was 14.5-15, have large variations of strength of polarization, from 3% to 18.5% (Fig. 5). The time scale of these changes is less than one day. From night-to-night the polarization strength varies almost randomly. Observations were made over a 4 hour observing period on two successive nights (90 and 91) (Fig. 6). On the first night the polarization measurements over four hours were rather steady with a mean of 11.2% and standard deviation of 0.57%, little more than that expected from counting statistics. On the next night though, the polarization was found to

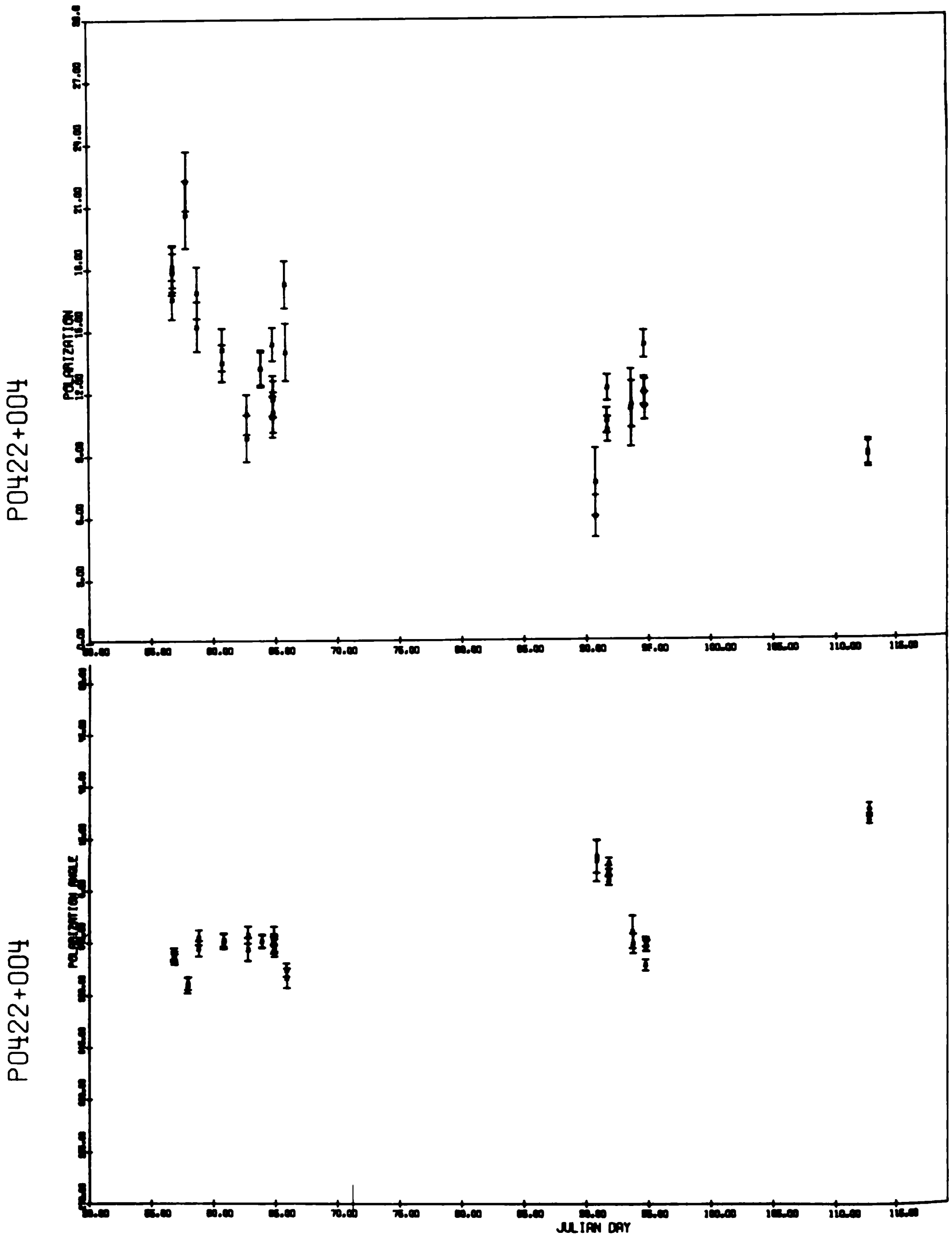
P0422+004
POLARIZATION
P0422+004
POLARIZATION ANGLE
JULIAN DAY

Figure 3

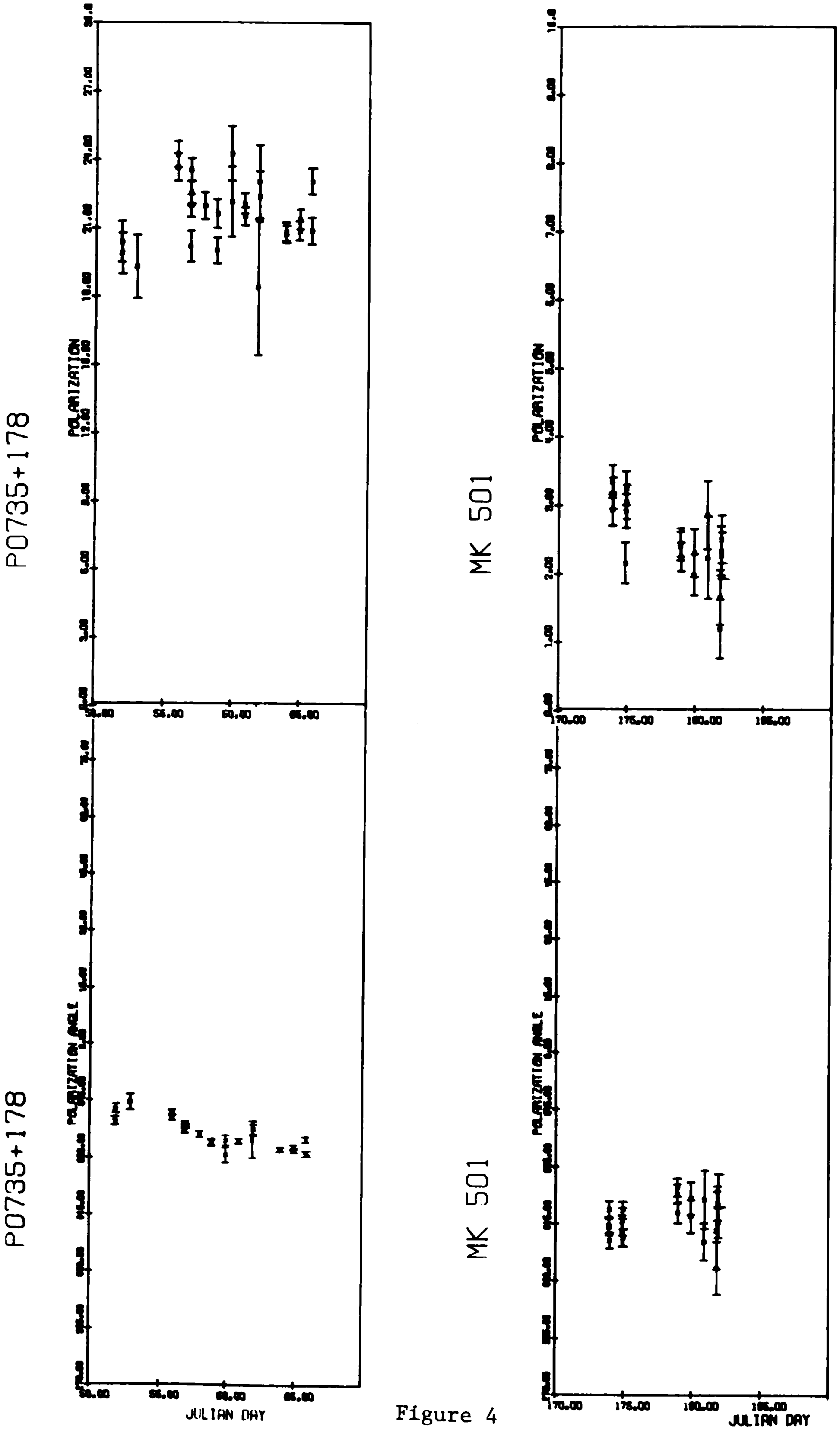
P0735+178
POLARIZATION
MK 501
POLARIZATION
P0735+178
POLARIZATION ANGLE
JULIAN DAY
MK 501
POLARIZATION ANGLE
JULIAN DAY

Figure 4

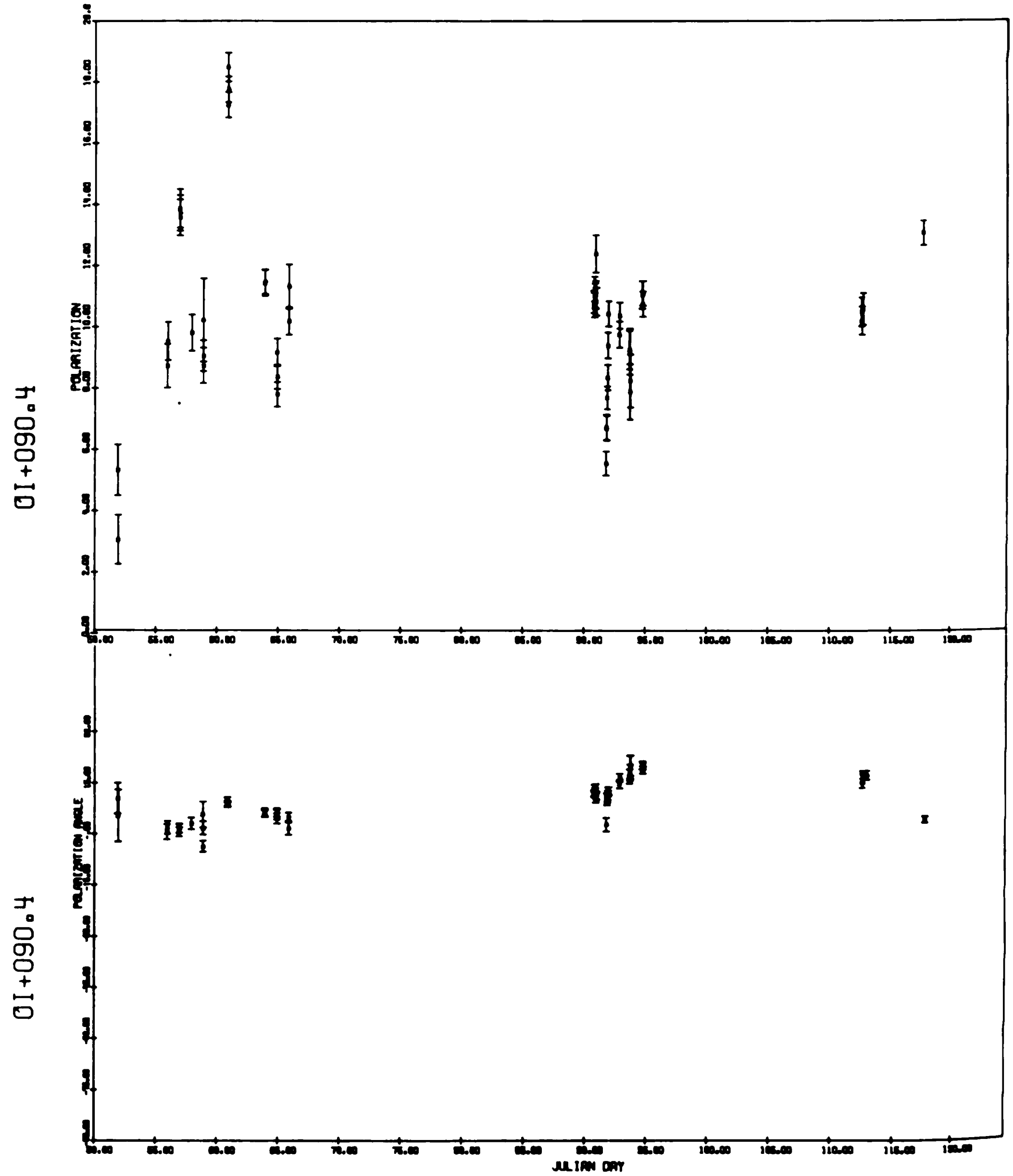
OI+090.4
POLARIZATION
OI+090.4
POLARIZATION ANGLE
JULIAN DAY

Figure 5

0I+090.4

0I+090.4

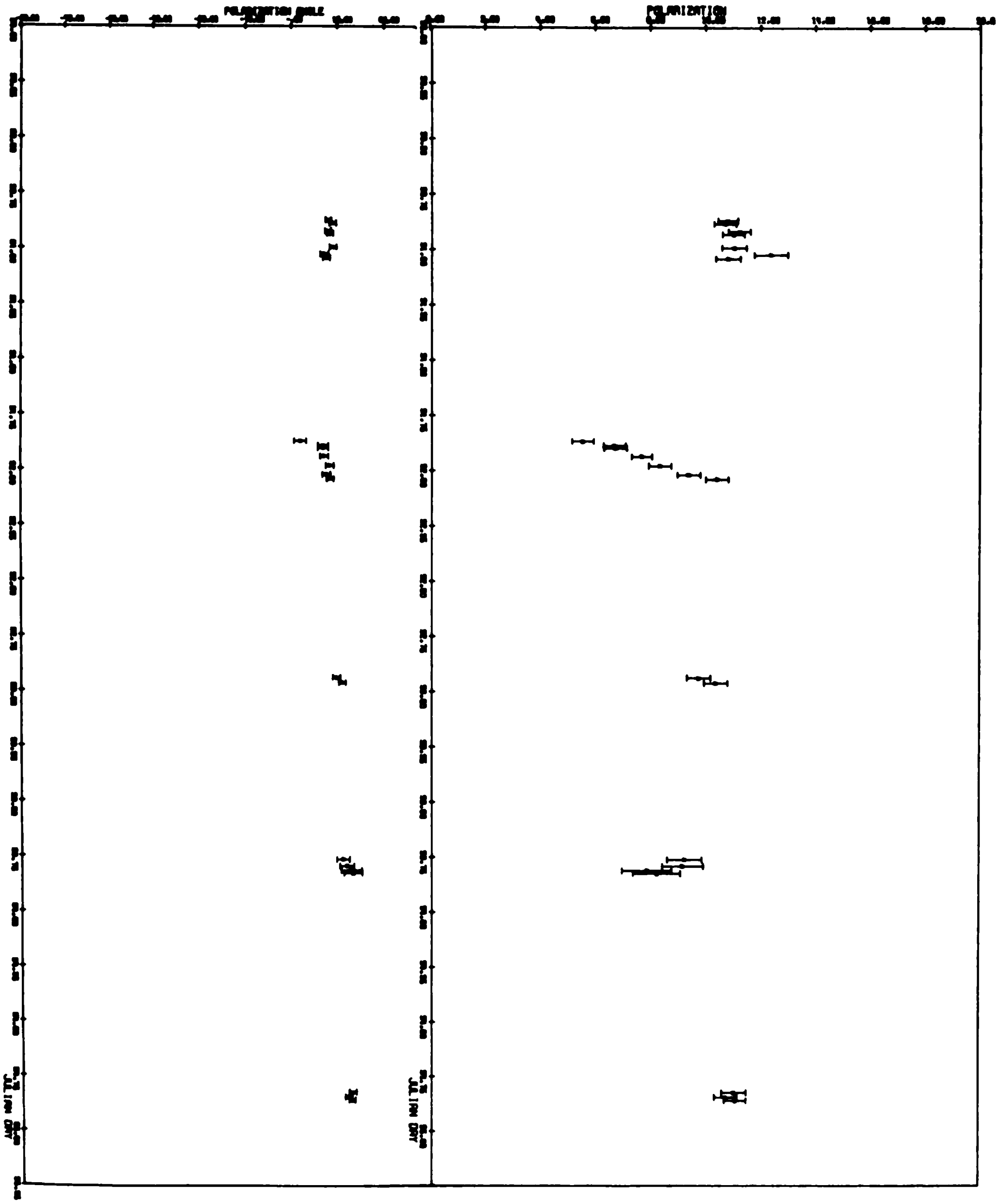

Figure 6

be rising steadily, from 5.5 ± .4%, the first data point, to 10.4 ± .4%, the last. The characteristic time scale for variation in this object is thus around 10 hours. It is remarkable that on both nights the position angle remained very steady at ~12° ± 2° (except for one data point at 3° ± 2°, a probable glitch). Over the entire observing period the position angle was remarkably constant, considering the large amplitude of variability. The extreme range was only 21°, from 179° (day 58) to 20° (day 94).

Rapid and large variability of OI 090.4 is also found in the optical polarization measurements previously reported by Tapia et al. (1977). All of their data points are separated by several days or more, except for two showing the polarization dropping from 25% to 12% on successive nights. Observations in the visible and infrared over six successive nights are reported by Rieke et al. (1977). The polarization is variable from night-to-night, and in fact this is the first object where rapid variability of the infrared polarization has been observed directly. OI 090.4 also has the distinction of showing a large (30°) difference in position angle between optical and infrared polarization measured simultaneously.

OJ-131 = 0818-12

Our data, shown in Fig. 7, extend over 62 days, during which the polarization strength varied between 10 and 25%, and the magnitude was ~15. As in OI 090.4 there is little correlation in the night-to-night measurements, indicating a time scale of less than one day. The position angle varied between extreme values of 68° and 95°. It did not vary strongly over a few days. The data for the first 15 days show a smooth increase in position angle of 1.2°/day, with only one data point out of 15 more then 3° from this fit. Three and two hour runs on days 93 and 94, respectively, do not show convincing evidence for variability on this short a time scale (Fig. 8). One point out of six on day 93 falls significantly (4σ) from the mean value, but there is no clear trend and one point could be in error. The rather small changes in position angle in our data are in contrast to the large variations in both position angle and strength of polarization over three successive nights reported by Tapia et al. (1977).

OJ 287 = 0851+20

The magnitude of polarization varied between 13 and 22% over the 4 months of observation (Fig. 9). Variations from night-to-night are barely discernible. A rather smooth change of 4% in polarization over a week is seen at the beginning of the data, and again at the end. The position angle measurements lie between 63 and 86°. Again the variations from night-to-night are not large, but the data do seem to show small abrupt changes which are significant, for instance the position angle rotates from 86° to 80° between the second and third days of observation. The error of the mean for each night is less than 1°. While more data are needed to be certain, it does appear that small scale fluctuations on a day time scale are superposed on somewhat larger changes over weeks and months.

As has been noted by several authors (e.g., Rudnick et al. 1978 and references there), the position angle of polarization of OJ 287 has remained fairly constant at 80° for several years, over wavelengths from 5 cm to 0.5μ. We note though that during the outburst in 1971-72 the optical position angle varied widely with no preferred direction (Visvanathan 1974).

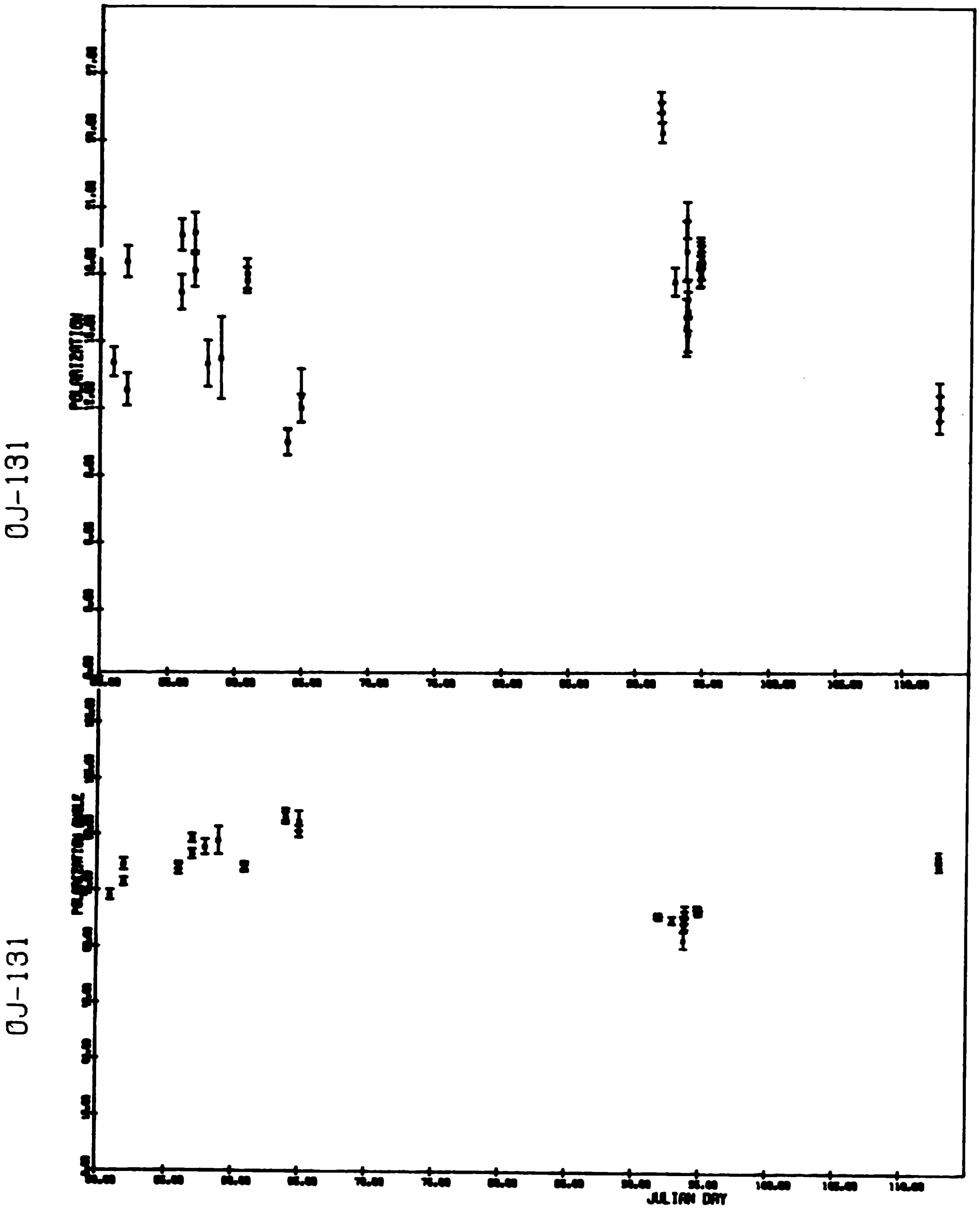

Figure 7

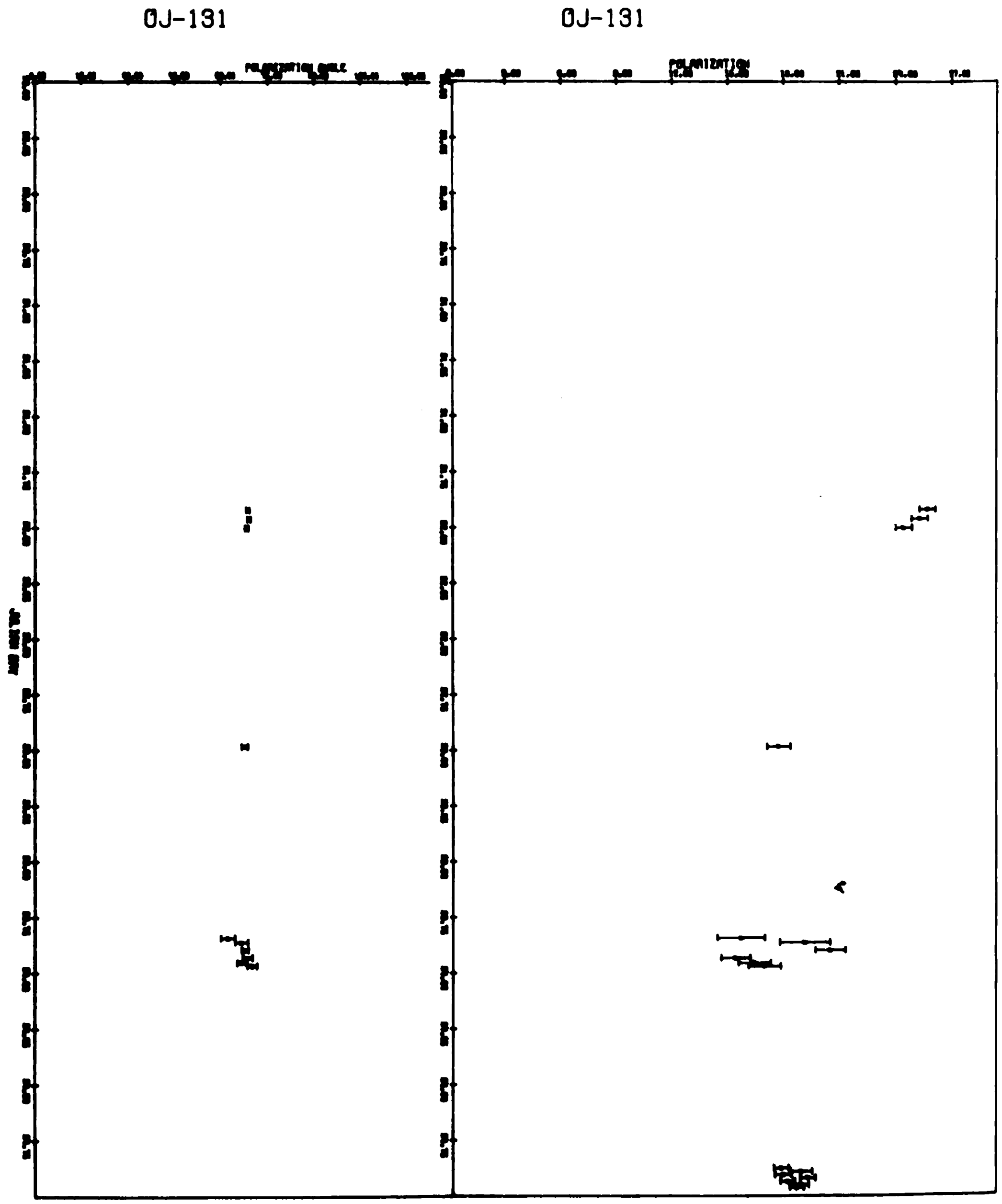

Figure 8

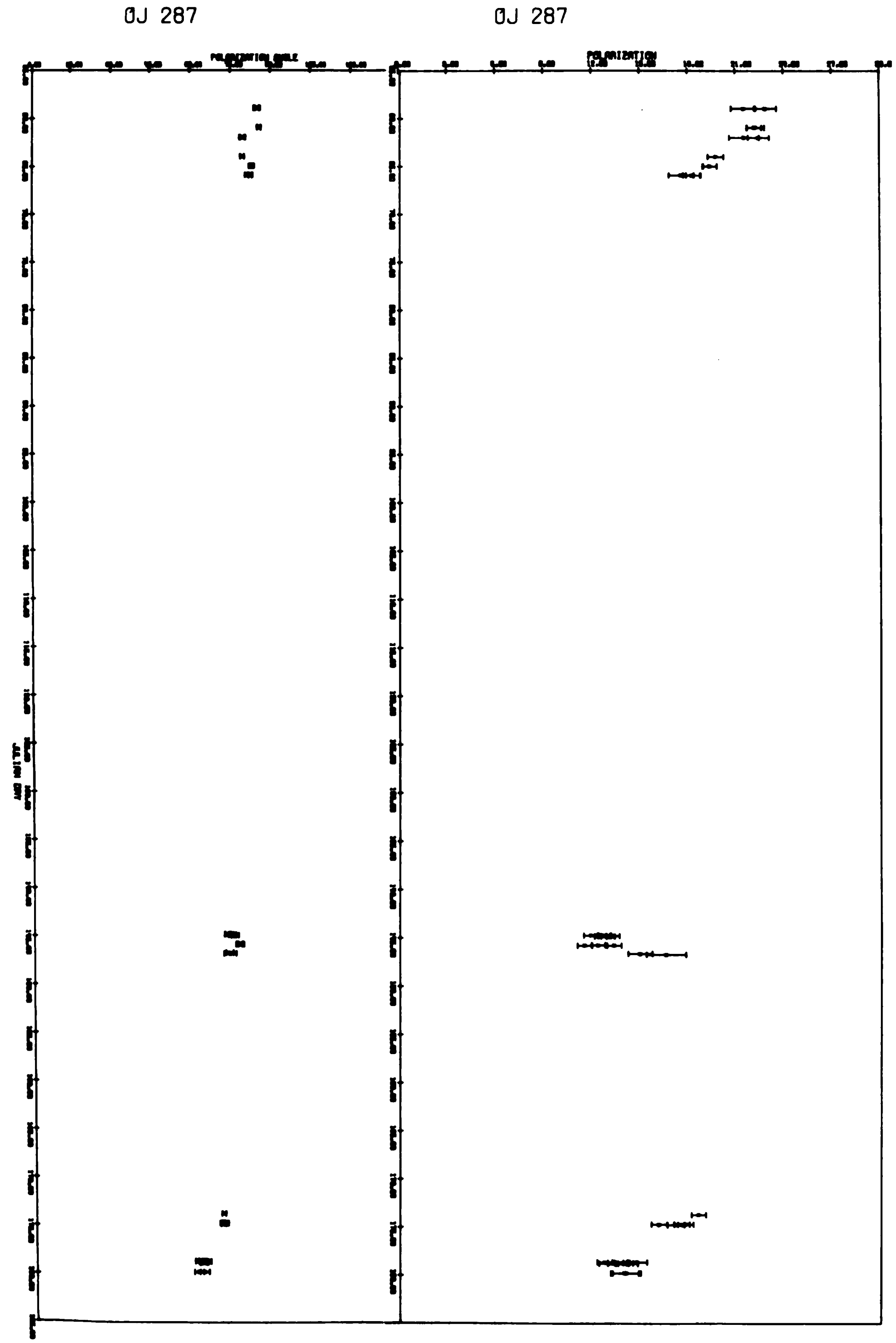

Figure 9

OM 280 = 1147+24

Only a few sparse measurements were obtained at the 36" telescope, showing polarization between extremes 4% and 10% over a two month period (Fig. 10). Most measurements are fairly close to 8% polarization, but on one night, 173, a single measurement gave 4%, a deviation of more than 3σ from this. The position angle does appear to vary significantly from month-to-month, by a total of 15°. There is no significant evidence for hour-to-hour variability. The source was rather faint during these observations, with V ~ 16.

In Table 3 are listed observations over a one year period 1974-75. The polarization ranges from 1.6-13%, and position angles are in apparently random directions.

ON+325 = B2 1215+30

The strength of polarization varied between 8% and 16% over the 36 day baseline shown in Fig. 11. While there are not many data points, there do appear to be significant changes of a few percent from night-to-night, certainly over a few nights. The position angle by contrast was remarkably stable, with a mean of 173° and possible deviations of no more than ± 5°. The magnitude was ~ 15.3.

Extensive observations since 1971 are given in Table 1. These show polarization in the range 5-13%, and the position angle always in the range 135-176°. Strittmatter et al. (1972) observed ON 325 over two months in 1972, and found polarization varying between 4.5 and 7.3% from one month to the next. Most position angle measurements were at ~ 143° with the exception of one point at 120°. The mean and standard deviation of all observations to date is 161° ± 15°.

AP Lib = 1514-24

This was the least well observed object for short term variability with only 10 data points in all, over 8 day period (Fig. 12). The mean polarization in this period was ~ 3.8%. Individual points range from 2.3 to 5.3%, suggestive of real fluctuations, though no point is more than 3σ from the mean. Variable dilution by the surrounding galaxy caused by guiding errors may be responsible for lower values of polarization. The position angle did vary significantly from ~ 5° at the beginning of the run to 19° on day 178.

The observations since 1973 in Table 3 show polarization in the range 2-7%, and position angles within the restricted range 165°-17°. AP Lib is thus another BL Lac object in which there is long term memory of position angle. For all the observations above and by Strittmatter et al. (1972) we find $\theta = 6 \pm 16°$ (standard deviation).

Mk 501 = B2 1652+39

Data at the 36" telescope were obtained only over an 8 day period. The polarization (which is significantly diluted by unpolarized light from the surrounding galaxy) did weaken more or less steadily from a mean of 3.1 ± .12 on the first night to 2.0 ± .2 on the last (Fig. 4b). The position angle measurements scatter by a few degrees about the mean of 138°, but the accuracy is poor because the polarization is low, and there are no certain trends from night-to-night or hour-to-hour.

Observations reported by Ulrich et al. (1975) show very similar polarization. Over two months in 1973 the position angle was rather steady at 143 ± 3°, while the strength of polarization varied between 1.8% and 3.0%. These data were obtained mostly with a 10 arc second

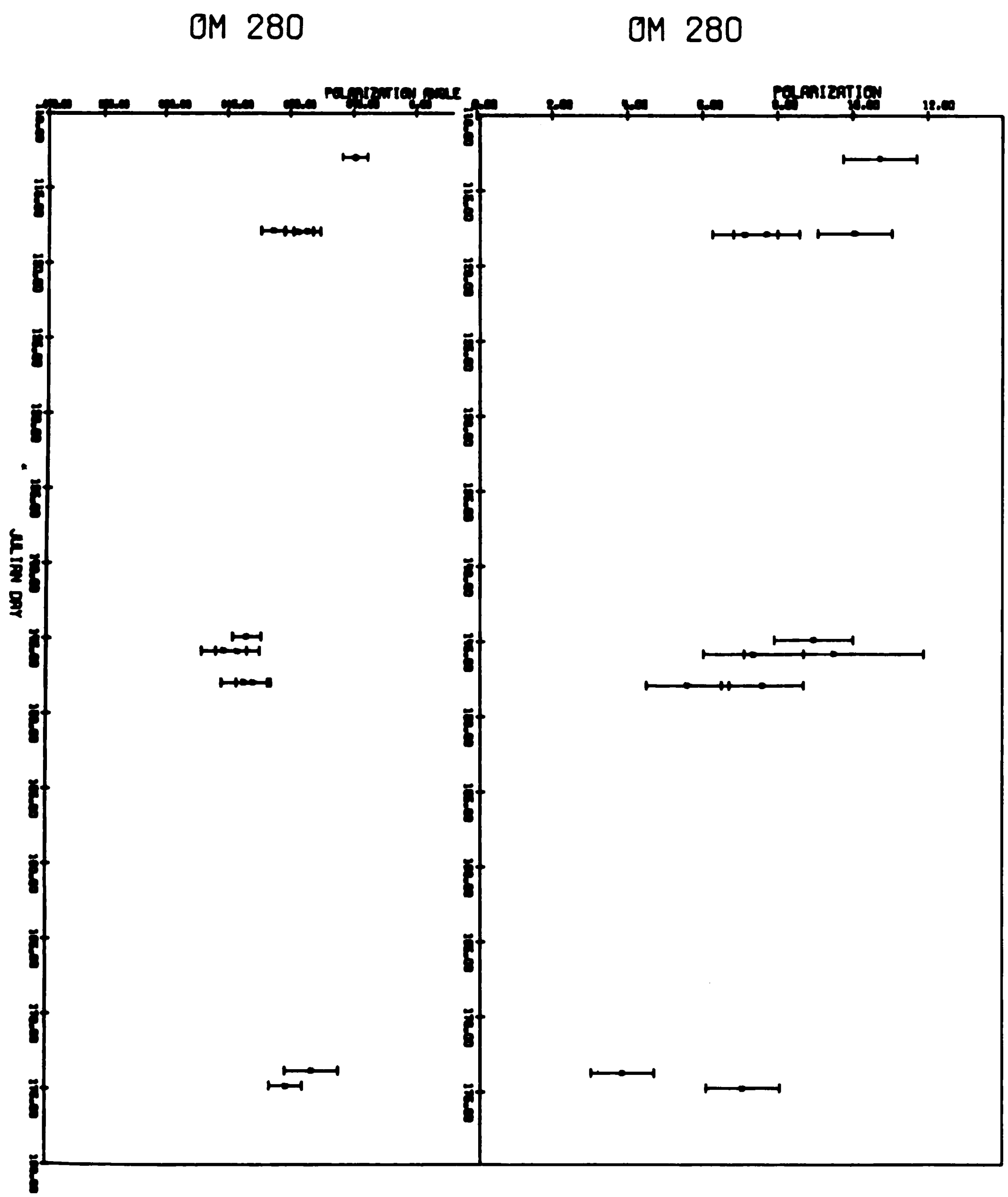

Figure 10

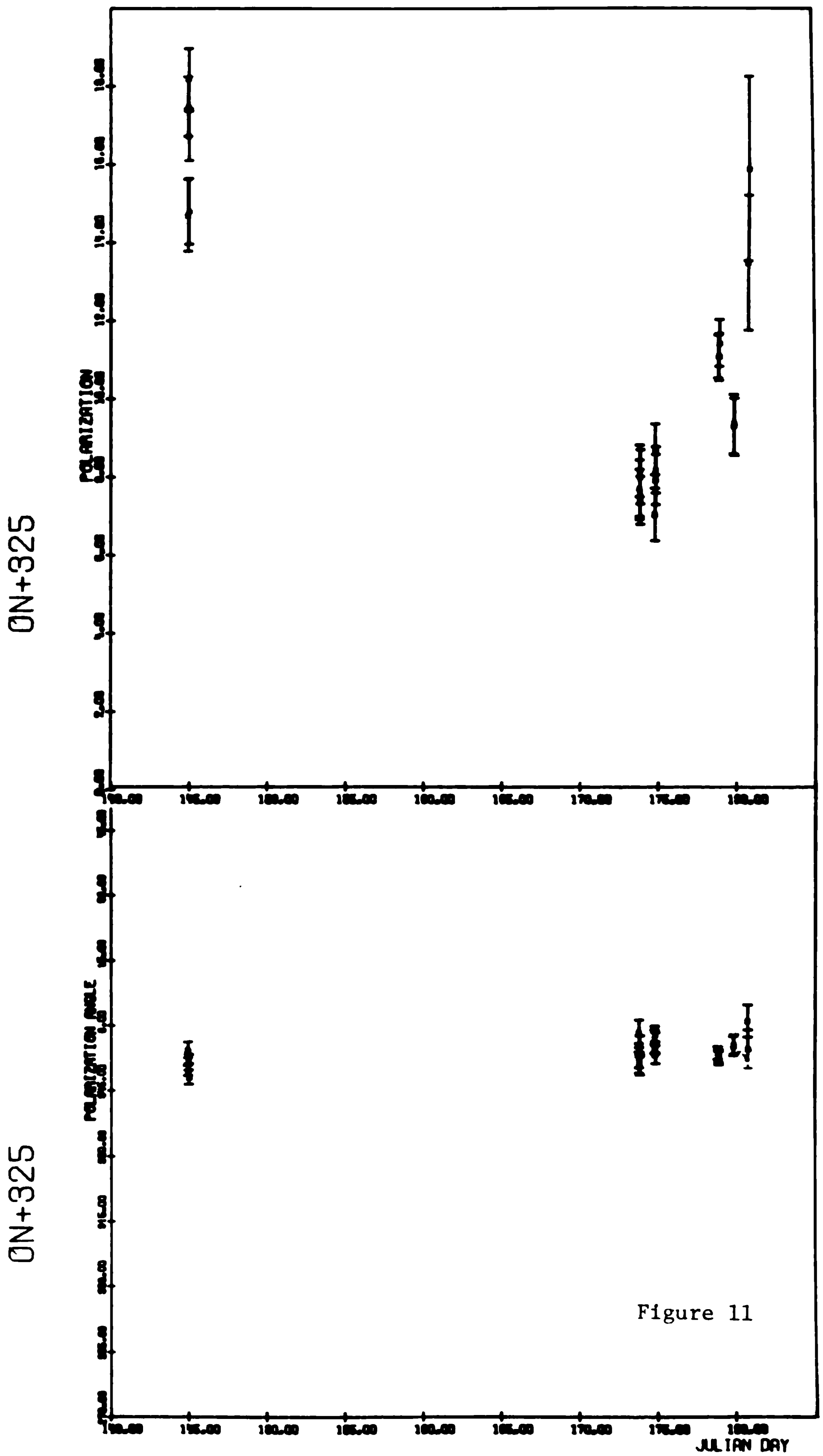

Figure 11

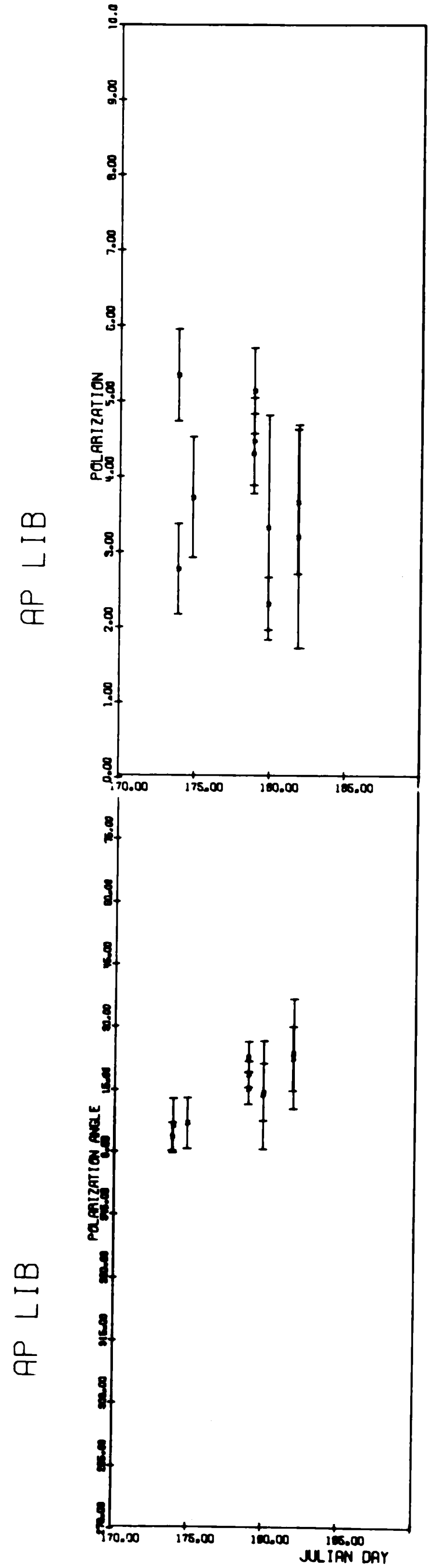

Figure 12

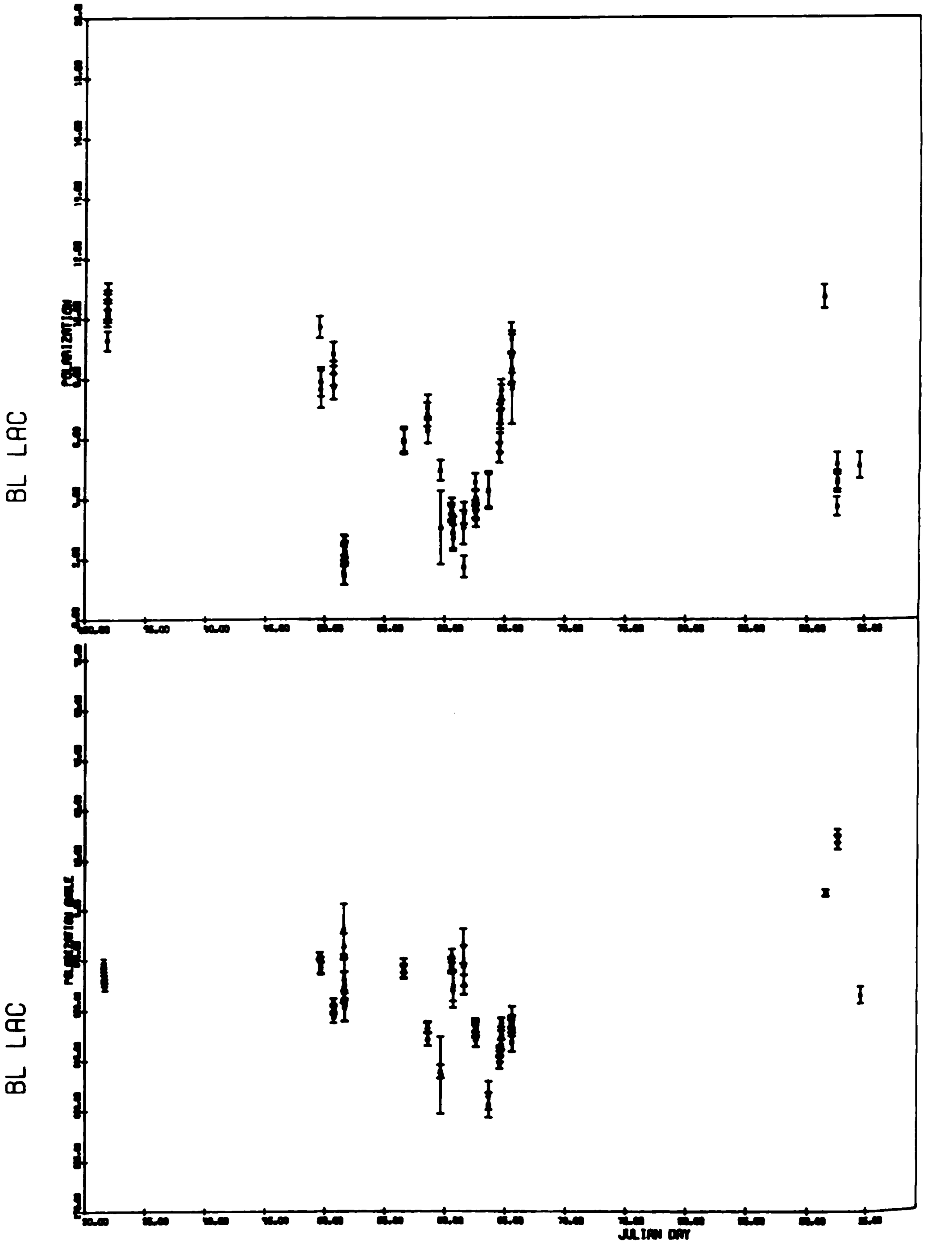

Figure 13

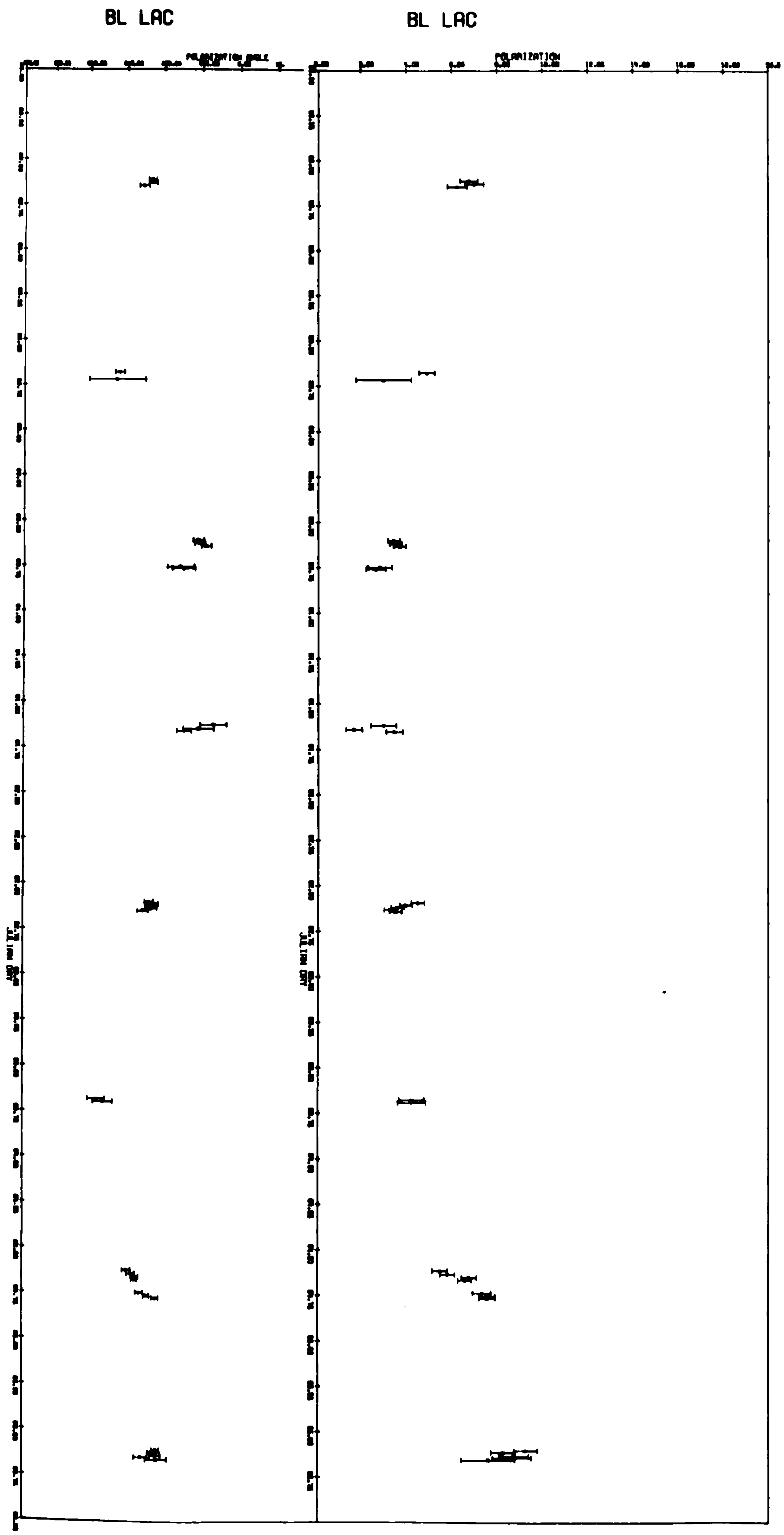
BL LAC
BL LAC
POLARIZATION ANGLE
POLARIZATION
JULIAN DAY
JULIAN DAY

Figure 14

aperture, and so these strengths can be compared directly with ours. Unless the agreement in position angle over a 5 year period is fortuitous, it would seem the position angle is nearly constant on this time scale.

BL Lac = 2200+42

The polarization was never found very strong (10%) during our observing period of 45 days, but was extremely variable, sometimes changing more than 5% from night-to-night (Fig. 13). The position angle changes were the largest of any source observed, ranging over 90° from 123° (day 63) to 20° (day 92), with changes up to 30° from night-to-night. Four runs of a few hours were obtained to study variability on an hour-to-hour time scale. On day 31 the angle rotated steadily through 6° during a four hour run, while the polarization was steady at 10%. On day 51 over 2.7 hours the position angle θ rotated ~ 15°, while the polarization P remained low and fairly constant at ~ 2%. On day 60 over 3.8 hours θ rotated ~ 6° while P dropped ~ 0.9%. On day 64 θ rotated 12° in 3.7 hours, while P rose from 5.5 to 7.6%. Data from days 58-66 are plotted on an expanded scale in Fig. 14.

III. DISCUSSION

It is clear that there is a rich variety of polarization properties within our sample of 12 objects, and no one set of characteristics can be regarded as typical. This diversity is one of the important results of the survey. Variability can range from at one extreme, that of BL Lac itself which shows, apparently all the time, large erratic changes in polarization and angle from night-to-night. At the other extreme is 3C 66A, which over several years shows only small variations about a mean polarization of ~ 12% at ~ 20°. Some objects show large changes in amplitude of polarization while position angle remains fairly steady (OI 090.4, OJ-131). In other objects (NGC 1275), rapid fluctuations are more obvious in position angle than in magnitude.

The most significant result is that we have put a lower limit on the time scale of variability seen in any object. We find that large amplitude changes of polarization, of both magnitude and position angle, can take place in ~ 10 hours, but not much less than this. All the individual data points are plotted in the figures, not nightly averages. In nearly every case the points either group around a mean with deviations consistent with photoelectron statistics, or show a smooth trend over several hours. Only one or two of all data points are seriously inconsistent with adjacent points, and we believe these are probably due to other sources of error, as discussed in Section II. The most outstanding example of rapid variability is in OI 090.4 on day 91, when the polarization increased steadily from 5 to 10% in 4 hours. Large amplitude variability with 1 day time scales is found in BL Lac, OJ-131, and 0422+00. Some objects, such as NGC 1275 and probably OJ 287 also show variability on a time scale of one day, in the sense that polarization changes, though not very large, do not show a smooth trend over several days, but jump erratically from night-to-night.

The simplest interpretation of the variability time scale, τ, of BL Lac objects is that it gives the maximum size of the source of emission, $c\tau$. For those variable on a 1 day time scale, this size is 2.6×10^{15} cm. (This is not a strict upper limit since we could imagine that it is only a small highly polarized portion of the total emission that is varying. Even in an extreme variable, like OI 090.4, a variable pure polarized component need be only 10% of the total flux.)

If we imagine that observed light is directly from matter accreting onto a black hole, then it is reasonable to suppose that the most rapid variations give the characteristic dynamical time of bright material closest to the black hole. Following Shields (1977) we take the appropriate radius to be ~ 10 GM_H/c^2. Setting this equal to 1 light day yields a mass of 2 x 10^9 $M_\odot$ for the black hole. (For one millisecond variations in a black hole X-ray binary the same relation gives a mass of 20 $M_\odot$.)

A mass of 2 x 10^9 $M_\odot$ for a BL Lac black hole is not out of line with that expected from other considerations. Making the same argument as Burbidge and Hoyle (1968) we find the black hole would have to be of about this mass if the luminosity were maintained at 10^{45} ergs/sec for a Hubble time, with an energy yield of 0.2 of the accreted mass. Of course, we do not know how long these objects last, but the accretion rates required (0.1 $M_\odot$/year) could be maintained indefinitely at the center of a large elliptical galaxy. Another argument suggesting large mass is that from the Eddington limit. When in an outburst, the BL Lac object can reach luminosities of 10^{48} ergs/sec (Rieke *et al*. 1976). If this were radiation at the Eddington limit, the central mass would be ~ 7 x 10^9 $M_\odot$. From the observational side, there is now evidence on dynamical and photometric grounds that the giant elliptical radio galaxy M87 contains a central mass of 5 x 10^9 $M_\odot$ (Sargent *et al*. 1978, Young et al. 1978). As Kinman and Miller have shown at this conference, BL Lac objects also appear to reside in giant elliptical galaxies. The two types of object may thus be rather similar in structure, though we note that the central stellar core in M87 does not show the polarization properties of a BL Lac object (Schmidt, Peterson and Beaver 1978).

Turning from the short term to the long term polarimetric behavior of BL Lac objects, the results presented here show that 5 out of 12 program objects show long term stability of position angle over several years. These are 3C 66A, OJ 287, ON 325, AP Lib and Mk 501. As mentioned in Section II, this property had already been pointed out for OJ 287. The discovery of stability in nearly half our sample now shows this to be a common feature of BL Lac objects. Perhaps with more extensive observations even those with wide ranging angles would show a significant non zero mean Stokes vector. The polarization direction may be defined in some way by the rotation axis of the accreted material. For AP Lib and Mk 501 the host elliptical galaxy is resolved on direct photographs, and one can check if the galaxy and polarization orientations are correlated. Unfortunately, AP Lib appears as E0 in the published plate by Disney, Peterson, and Rogers (1974). Mk 501 does show an elliptical image in the Palomar Sky Survey with the major axis at ~ 165°. This is not very well aligned with our polarization mean (6° $\pm$ 15°), but perhaps a long term polarization average, with the irregular variations better suppressed, would be in better agreement.

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DISCUSSION

J. MILLER:
With regard to the optically violent variable QSOs, were they undergoing an outburst at the time you were measuring the polarization or not?

R. ANGEL:
I think they were not active at the time we measured the polarization.

J. MILLER:
Was 3C 446 undergoing an outburst?

R. ANGEL:
The V magnitude was about 16.7 when we saw the rapid variability. [*Ed.: Normally it is 18.4*].

M. BURBIDGE:
Are the very strong emission lines in NGC 1275 polarized?

R. ANGEL:
I think they are not. We have some data tucked away and preliminary reduction shows the lines to be unpolarized.

M. BURBIDGE:

That's important, it would be interesting to compare them with the emission lines in NGC 4151.*

R. ANGEL:

Yes, I'll bet dollars to doughnuts that they're (the lines in NGC 1275) not polarized.

ANONYMOUS:

Do you have spectral polarimetry data for PHL 5200?

R. ANGEL:

No, but we hope to get it very soon.

E. CRAINE:

Roger, one thing that we are worried about concerning the BL Lacs is whether at certain times they dip down in polarization below our level of detectability. Can you estimate the percentage of time that these BL Lacs remain highly polarized?

R. ANGEL:

About 1/3 of our sample of BL Lac objects are never strongly polarized (NGC 1275, Mk 501, Ap Lib, and Mk 421 are good examples). The remaining BL Lacs generally show strong polarization, but dip down below 5% polarization a small fraction of the time.

F. PACINI:

You use the argument of the Eddington limit of 10^{47} ergs/sec. I think that this number is very model-dependent. Once you put in rotation you generate a whole new class of models where the energy is extracted from the central body and it is carried out by large scale e.m. fields. In this case the Eddington limit does not apply.

R. ANGEL:

Yes, the Eddington limit arguments are suggestive but not conclusive.

J. MILLER:

Since you didn't mention it, I'd like to bring it up. At optical wavelengths as at radio wavelengths the polarization changes substantially without any detectable light variation. I don't understand this. I tried to imagine how you could build such a device in the laboratory that would provide strong variations in the percentage polarization without varying the position angle and the total light. In QSOs you have a lot more parameters to fool around with but I still think that this is a fundamental,

*[Ed.: *In his talk Dr. Angel compared the polarization properties of Seyfert nuclei to those of BL Lac objects and QSOs. He emphasized that the similar polarization of the permitted emission-lines and continuum of most Seyferts indicates polarization by dust. Possible exceptions to this are the Seyfert I galaxies NGC 4151 and Mk 486, which have unpolarized lines and polarized continua.*]

extremely important problem. Have you been able to simultaneously follow the photometry as well as the polarization?

R. ANGEL:
Unfortunately our setup is not devised to do photometry, but I think that now that we understand the morphology of polarimetry we are in a position to go in and take some typical things and do just that.

B. BURKE (to J. Miller):
You said this morning that this same sort of thing happened at radio frequencies.

J. MILLER:
At radio frequencies it is easier to devise schemes that will rotate the position angle of polarization. But we saw that those don't seem to work in the radio either.

C. HAZARD:
I just wanted to clarify whether the radio QSOs that are weakly polarized at the 1% level are any different from the radio-quiet QSOs that are unpolarized. I don't suppose you found any difference.

R. ANGEL:
At the time we looked at the distribution of polarizations in 40 QSOs it appeared that the radio-loud QSOs were more polarized (1978, Ap.J. Lett., **220**, L67). With a larger sample now, this effect is not significant (see talk by Stockman this volume).

J. WARDLE:
I want to make two points. One is that if NGC 1275 is a BL Lac object, it has radio properties which to the radio astronomer make it look quite different from BL Lac objects.

R. ANGEL:
Well it has a lot of material in front of it.

J. WARDLE:
The other thing is that I have looked 2 or 3 times for day-to-day variations in the polarized flux of BL Lac, OJ 287 and they are sort of there, but they are not large fluctuations.

R. ANGEL:
Well we'd be in terrible trouble if there were because we know the size of the emitting region, and it's very much bigger than a light day.

K. KELLERMANN:
No, you don't know that.

R. ANGEL:
Don't you know it from VLB maps of BL Lac?

K. KELLERMANN:
You don't know whether or not a significant fraction of the radio component is in a tiny light-day core.

A REPORT ON THE LINEAR POLARIZATION SURVEY OF BRIGHT QSOs

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Abstract

Since December 1977, we have observed 58 more QSOs for linear polarization as a continuation of the survey of bright QSOs reported by Stockman and Angel (1978). Three QSOs, 0752+258, 1150+497, and 1156+295, show polarizations $\gtrsim 4\%$, with the latter two showing evidence of extreme photometric or polarimetric variability. The remainder of the sample had rather low polarizations, $\lesssim 1\%$. When the 58 are added to the sample of 44 previously reported, the distribution of polarization for all QSOs is similar to that obtained with the first sample. In particular, the general distribution is well confined below $P \lesssim 2\%$ with an average polarization (rms) of 0.6%. While the first sample showed a tendency for radio quiet QSOs to have less polarization than typical radio QSOs, this does not now appear significant in the larger sample. Thus the BL Lacertae-like high polarizations shown by the violent variable QSOs seem to characterize a separate class of QSOs, qualitatively different from most. If the strong polarizations seen in BL Lacertae objects and the OVVs are intrinsic to the central source of radiation in all active galactic nuclei, then a depolarizing mechanism such as Faraday rotation or scattering must be present in most QSOs and Seyfert galaxies. A depolarization model which utilizes a surrounding cloud thick to electron scattering predicts a steepening in the X-ray spectrum for photon energies $\gtrsim$ 50 keV. This can be tested with X-ray satellite observations.

I. Introduction

The BL Lacertae objects (BLLs) resemble one subclass of QSOs, the optically-violent variables (OVVs), in every respect save the strong emission lines which characterize QSOs in general (Stein, O'Dell, and Strittmatter 1976). In particular, OVVs and BLLs show strong optical linear polarization ($P \gtrsim 5\%$), variability in their optical flux and polarization over a time scale of days, strong flat spectrum radio emission, and a steep, optical spectral index. In turn, the OVVs resemble other QSOs in their emission-line spectra and high luminosity.

Two characteristics which neither BLLs or OVVs share with the general class of QSOs is their small time scales of optical variability and their strong optical polarization. While it was soon realized by the early workers that most QSOs lack the 5-15% polarizations seen in the extreme OVVs: 3C 446, 3C 345, 3C454.3, and 3C 279, these studies were either too limited or too insensitive to explore the actual distribution of polarization in QSOs as a whole. Thus the general impression was formed that the OVV phenomena was simply an extreme example of general QSO characteristics. Preliminary results of a more sensitive polarization survey of bright QSOs begun last fall indicates this initial impression was incorrect (Stockman and Angel 1978, hereafter SA). While most QSOs do show a measurable linear polarization in the optical ($\overline{P}$ ~ 0.6%), the distribution of polarization falls to zero by P ~ 2% and thus does not appear to extend smoothly to the OVVs. Put differently, if the distribution of polarization were approximately gaussian about P ~ 0.5%, the number of QSOs with P ~ 5% would be vanishingly small.

Since the fundamental polarimetric differences between OVVs and most QSOs may shed some light on the BLL and OVV phenomena and provide some clues about the central energy source within all these objects, we are presenting at this conference the latest results of the bright QSO polarization survey. In addition to finding four additional highly polarized QSOs, we have been able to better define the distribution of polarization for QSOs as a class. The distribution is similar to that obtained from the preliminary survey and is presented in §II along with comments concerning the four highly polarized QSOs. In §III, we discuss the implications of the survey results for theories which presume a common central energy source for QSOs, OVVs, and BLLs.

II. The Polarization Data

In September 1977. we observed 44 bright QSOs ($m_V \lesssim 17$) from the Burbidge, Crown and Smith (1977) catalog. The polarimetric data for these 44 and a description of the observational technique have been reported in SA. Beginning in December 1977 and following through to March 1978, we have observed 58 additional QSOs in a continuation of that survey. The observational technique was identical to that reported by SA. The sky-subtracted efficiency corrected data for the 58 recently observed QSOs are shown in Table 1. As in SA, we emphasize that only polarizations such that P ≳ 3σ should be regarded as detections. In the remainder of this section, we discuss several of the highly polarized QSOs, the distribution of polarization for QSOs as a whole, and additional results from an extension of the survey started by Richard Moore.

a) Highly Polarized QSOs

0752+258 (OI 287)

This highly polarized QSO (P ~ 8.0% and θ ~ 141°) was observed on 7 December 1977, 13 January 1978 and 10 February 1978. The polarization was essentially identical on all three occasions. Two-color polarimetry (λλ3200-5600 and λλ6000-8600) obtained on 13 January with Moore was consistent with the amplitude and position angle of polarization being identical in the two bands to 0.7% and 3° respectively. The redshift of OI 287 has been determined by Wills and Wills (1976) to be 0.446 with sharp [OII] and [OIII] emission (λλ3727, 4959, 5007) observed as well as MgII (2798). Since no other work has been done on this object and specifically no evidence of variability has been cited, we can only suggest that 0752+258 is an OVV candidate, although the stability of polarization is not typical and may indicate a different phenomena.

1150+497 (LB 2136, 4C 49.22)

This object was observed on 4 April 1978 when its estimated magnitude was m_V ~ 17.7. On two other occasions (February and March) the object had been at least 0.5 magnitudes fainter despite a published magnitude of m_P = 16.1 (Lynds and Wills 1968). The redshift of 0.334 was reported by Lynds and Wills (1968) and confirmed by Burbidge (1968). Strong MgII and HI as well as [OIII] and [NeV] are seen in emission. Although the polarization measured is just 5σ and continued study of the object is desirable, we do not hesitate in classifying 1150+497 as an OVV due to its strong variability.

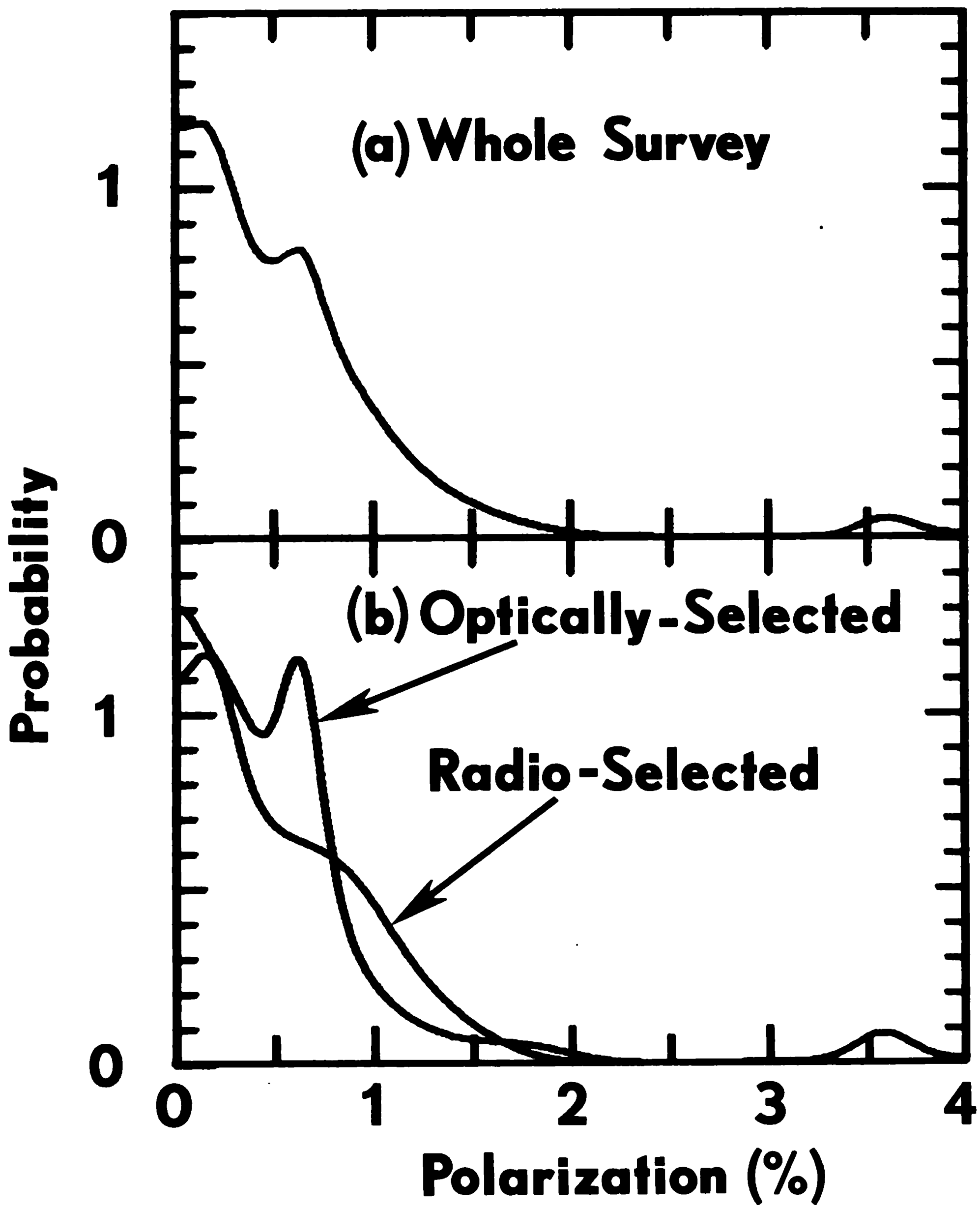

Figure 1. Frequency distribution of polarization for 102 QSOs (58 in Table 1 and 44 reported in SA). The top panel (a) shows the distribution for all 102. In the lower panel (b), the separate distributions for optically-selected and radio-selected QSOs are shown. The highly polarized QSOs, 3C 446, OI 287, and 4C 29.45 lie off the graph.

1156+295 (4C 29.45, Ton 599)

This object was observed on 10 February 1978 yielding the polarization shown in Table 1 and also on 14 March when the polarization was quite different ($P = 4.78 \pm 0.25$, $\theta = 119 \pm 2°$). Thus the object can be defined as an OVV on these measurements alone. The redshift of 0.728 was suggested by Burbidge (1968) on the basis of one emission line identified as MgII. Schmidt (1974) confirmed the redshift by also observing [CIII] (λ1909) emission. Recently Richstone and Schmidt (1978) have obtained a spectral index of $\alpha = 0.93$ ($F_\nu \propto \nu^{-\alpha}$).

1246-057

This object has the highest polarization (P = 1.9%) of the 36 optically-selected QSOs in the sample, and is mostly responsible for bringing the optically-selected QSO distribution of polarization into rough agreement with the radio-selected QSOs (minus the OVVs) distribution. Osmer and Smith (1977) have obtained SIT vidicon spectra of the object and find strong PHL 5200-like absorption troughs at a $\Delta V \sim 15{,}000$ km s^{-1} and with a width of ~ 5000 km s^{-1}. Since PHL 5200 also shows high polarization (P ~ 4%) which presumably stems from the expanding scattering envelope (SA), the polarization in 1246-057 may be caused by the same agent. Naturally both objects are good candidates for moderate resolution spectropolarimetry.

b) OVV Survey

As an extension to the bright QSO survey, Richard Moore at Steward has begun a survey of reported variable QSOs which otherwise would not have been observed (either too faint or too far south). Of 14 QSOs observed so far, he has found two to be highly polarized. One, 3C 279, is a known OVV and was found to have $P = 4.0\% \pm 0.7\%$, $\theta = 66° \pm 5°$ (14 March 1978). The other, 0403-133, which does show strong photometric variability, showed $P = 3.9\% \pm 0.6$, $\theta = 3° \pm 4°$ (13 January 1978). The remaining 12 objects had lower polarizations with a distribution consistent with the larger survey's.

c) The Distribution of Polarization

We have added the data from Table 1 (58 QSOs) to that reported in SA (44 QSOs) and have obtained the distribution of polarization for the 102 QSOs observed to date. The distribution, which is shown in Figure 1, is found by an iterative deconvolution method suggested by Lucy (1974) and discussed in SA. In Figure 1, the top panel shows the distribution of polarization for all 102 QSOs (3C 446, OI 287, 4C 29.45 lie off the graph). The distribution is similar to that obtained for the preliminary sample of 44 QSOs and shown in SA. Aside from the few OVVs and PHL 5200 clustered at P ~ 3.5 - 4%, the distribution shows the great majority of QSOs to have P < 1% with almost <u>none</u> above 2%. The corrected rms polarization for QSOs with P < 3%, is $\overline{P} \sim 0.6\%$. As in SA, we have further divided the sample into radio-selected (66) and optically selected (36) QSOs. The distributions for each subset are shown in the lower panel of Figure 1. Except for the highly polarized QSOs, which are all radio-selected, and the small bumps and valleys, which are not significant, the two distributions are similar. Both have corrected rms polarizations of $\overline{P} \sim 0.6\%$. In SA, with only 13 optically-selected QSOs observed, the two distributions were thought to differ at the ~ 3σ level. The difference between the conclusion reached in SA and that in the present work can be ascribed to a better statistical sample in the present work (almost triple the number of optically-selected QSOs) and to the influence of 1246-057, an unusual optically-selected QSO (see §IIa). In summary, the results of the distribution analysis with 102 QSOs observed are: i) excepting two unusual classes of QSOs with high polarizations - the OVVs and probably PHL 5200-type QSOs - most QSOs have low

TABLE I

Object	Survey	Polarization(%)	Angle(deg.)
0044+030	PKS	0.27±0.21	179 ± 22
0348+061	NAB	1.39±0.51	158 ± 10
0414-060	PKS	0.78±0.22	146 ± 8
0454+039	PKS	0.32±0.28	147 ± 25
0642+449	OH 471	1.67±0.88	2 ± 15
0710+118	3C 175	0.10±0.27	48 ± 73
0736+017	PKS	0.46±0.27	178 ± 16
0738+313	OI 363	0.19±0.23	32 ± 34
0742+318	4C 31.30	0.58±0.18	5 ± 9
0752+258	OI 287	7.98±0.44	141 ± 2
0839+616	4C 61.19	0.52±0.64	54 ± 35
0847+191	LB 8741	0.61±0.40	119 ± 19
0848+164	LB 8775	1.37±0.54	27 ± 11
0906+484	PG	1.08±0.30	148 ± 8
0955+326	TON 469*	0.18±0.24	102 ± 37
0958+550	MKN 132	0.23±0.25	46 ± 32
1001+054	PG	0.77±0.22	74 ± 8
1004+130	PKS	0.94±0.19	87 ± 6
1011+250	TON 490	0.37±0.28	88 ± 22
1019+309	OL 333	0.27±0.46	76 ± 49
1028+313	B2	0.25±0.23	166 ± 25
1038+064	4C 06.41	0.62±0.24	149 ± 11
1048-090	PKS	0.85±0.30	96 ± 10
1049+616	4C 61.20	0.83±0.34	176 ± 12
1055-045	OS	0.84±0.54	155 ± 18
1100+772	3C 249.1	0.71±0.22	76 ± 8
1103-006	PKS	0.37±0.26	138 ± 20
1104+167	4C 16.30	0.56±0.21	160 ± 11
1128+315	B2	0.95±0.33	172 ± 10
1137+660	3C 263	0.35±0.20	97 ± 16
1146-037	PKS	0.40±0.27	42 ± 20
1150+497	LB 2136*	3.98±0.78	142 ± 6
1156+295	4C 29.45	9.24±1.19	24 ± 4
1157+014	PKS	0.91±0.61	30 ± 19
1202+281	GQ COMAE	0.34±0.15	162 ± 13
1208+322	B2	1.03±0.24	26 ± 7
1211+334	ON 319	0.91±0.49	143 ± 16
1214-064	OS	1.11±0.64	19 ± 17
1217+023	PKS	0.18±0.28	151 ± 45
1219+775	MKN 205	0.35±0.16	119 ± 13
1225+310	B2	0.16±0.24	150 ± 46
1226+023	3C 273	0.21±0.04	52 ± 6
1229-021	PKS	0.10±0.53	168 ± 90
1229+204	TON 1542	0.61±0.12	118 ± 6
1246+377	BSO 1	1.71±0.58	152 ± 10
1246-057	OS	1.87±0.31	139 ± 5
1257+346	B 201	0.65±0.39	46 ± 17
1304+346	B 340	0.65±0.37	13 ± 16
1317+277	TON 153	0.15±0.20	94 ± 38
1318+291	TON 155	0.51±0.39	17 ± 22
1318+291	TON 156	0.61±0.28	51 ± 13
1321+294	TON 157	1.20±0.27	111 ± 6

1340+289	B2	0.81±0.35	45 ± 12
1351+640	PG	0.66±0.10	11 ± 4
1356+581	4C 58.29	0.40±0.29	116 ± 20
1421+330	MKN 679	0.32±0.32	80 ± 29
1510-089	PKS	1.90±0.40	79 ± 6
1612+262	TON 256	0.07±0.13	152 ± 52

NOTES: OS indicates Osmer and Smith (1977). Radio-selected QSOs with optical identification names are indicated by an asterisk.

intrinsic polarization $\overline{P} \sim 0.5 - 0.6\%$; ii) the distribution of polarization for these QSOs ($P \leq 2\%$) is too sharply defined to appear connected to the highly polarized QSOs; iii) radio-selected and optically selected QSOs (minus the OVVs) have essentially the same distribution.

III. Depolarization Models

The strong linear polarization in the radio and optical flux from BLLs is so universal and so distinctive that it is almost certainly an intrinsic characteristic of their underlying radiation source. The similar polarization and variability seen in the OVVs and in NGC 1275 suggests that BLLs, QSOs and Seyfert galaxies may all share the same fundamental source of energy. If this is the case, we must then explain the lack of polarization in most QSOs and Seyferts as the result of depolarization rather than a difference in the basic powerhouse. This picture is made more attractive by the fact that at least one OVV, 3C 454.3 has been observed to show very low polarizations (<1%) following a prolonged period of very high polarization and variability (SA and J. Miller 1978 private communication). In the rest of this section we will discuss briefly two mechanisms for depolarization, Faraday rotation and scattering.

a) Faraday Rotation

Light traversing a medium with an embedded magnetic field will have its position angle of linear polarization rotate by an amount ϕ given by

$$\phi = 2.4 \times 10^4 \nu^{-2} n_e H \cos\theta \text{ radians/cm}$$

where ν is the frequency of the light ($\nu \gg \nu_{cyclotron}$), n_e is the thermal electron number density (cm^{-3}), H is the magnetic field in gauss and θ is the opening angle between the field and the direction of propagation. For optical light ($\nu \sim 6 \times 10^{14}$) and $\theta \sim 30°$, the total rotation can be expressed as

$$\phi\ell = 0.05\ \tau_e H$$

where τ_e is the Compton optical depth (H is presumed constant over the pathlength ℓ). Since the flux we observe has a finite bandwidth and has components which have traveled through various pathlengths to escape the medium and thus have varying degrees of rotation, Faraday rotation can significantly reduce any intrinsic polarization if $\phi\ell \gg 1$ radian. If Compton scattering is to be unimportant as a depolarizing agent ($\tau_e < 1$), we require a field $H \gg 20$ gauss. Fields the order of 100-1000 gauss are not impossible and are often invoked in synchrotron models for the radio and optical emission in QSOs. If Faraday rotation is the dominant depolarizer, we would expect any residual polarization to show a rapid variation of position angle with wavelength. This has not been observed in several observations of low-polarized (~1%) QSOs in two-colors, PHL 658 and 3C 48, where the position angle is roughly constant in the two bands. However these studies are incomplete and more observations are necessary.

b) Scattering

The polarization of a scattered photon generally depends as much on the angle of scattering as on the incident polarization. Thus if a QSO's central source of optical radiation is embedded in a cloud which is optically thick to scattering but not absorption, the radiation which escapes after suffering several scatterings will have forgotten its original polarization but may not have its spectrum changed appreciably. If we assume that a single scattering will randomize a photon's polarization and wish to involve such a scattering cloud to reduce the ~10% polarizations found in BLLs and OVVs to the 0.6% polarizations seen in QSOs, the clouds must have an optical depth $\tau \gtrsim 3$. Furthermore, if the cloud is asymmetric, the optical depth must be considerably greater in order that the asymmetry of escape not induce polarizations of several percent (Angel 1969). We also note that, since photons diffuse out of the thick cloud with a time scale of $\ell\tau/c$, variations in the input luminosity on smaller time scales will not appear in the emergent flux.

Two possible scatters in QSOs are dust and free electrons (bound-bound scattering as in PHL 5200 will not be considered). Dust clouds which are optically thick to scattering are almost certainly present in most Seyfert galaxies. Evidence for dust comes from the large infrared excesses observed (Rieke 1978) and from the cases where the observed polarization is due to scattering (NGC 1068, Mk 231, IC 4329A, and Mk 376, see Angel et al. 1976, Stockman et al. 1976). In QSOs, however, the evidence for dust is not as strong. None of the survey QSOs exhibit the strong, wavelength dependent polarizations typical of dust scattering. Nor is the dust feature at 2200Å seen in many high redshift QSOs. Furthermore, the infrared fluxes, when available in low redshift QSOs, are usually consistent with an extrapolation of the optical flux. It appears that within the neighborhood of the QSO's central source, dust has either not been allowed to form or has been swept out by a high radiation pressure.

We now consider the case for electron scattering in QSOs. Since the Compton cross section is independent of wavelength ($h\nu \ll mc^2$), any residual polarization either by shine-through or by an asymmetric scattering cloud will be wavelength independent. This is consistent with our preliminary two-color observations of weakly polarized QSOs. As mentioned previously, the scattering cloud will tend to smooth out temporal variations in the luminosity. We can thus set an upper limit to the size of the scattering cloud by the observed 1 month - 1 year variations seen in many QSOs, most of which were presumably unpolarized:

$$R < \frac{\Delta t c}{\tau} \sim 3 \times 10^{17} \; (\Delta t \text{ years } 3/\tau) \text{ cm.}$$

This upper limit places the electron cloud toward the inside of the emission-line region. For $R \sim 10^{17}$ ($n_e \sim 5 \times 10^7$ for $\tau = 3$) and low electron temperatures ($kT \ll 1$ keV), the cloud will emit radiation in the optical ($L \sim 10^{43}$ ergs sec^{-1} for $kT \sim 1$ eV) or in the hard UV ($L \sim 10^{45}$ ergs sec^{-1} for $kT \sim 100$ eV) which may contribute to the broad emission lines observed. For $kT \gtrsim 1$ keV, the cloud would have an X-ray luminosity,

$$L_x \sim 10^{44} \; (\tau/3)^2 \; (kT/10 \text{ keV})^{1/2} \; (R/10^{17}) \text{ ergs sec}^{-1}$$

This X-ray luminosity is somewhat smaller than what is observed in the three QSOs so far detected in X-rays ($L_x \sim 2\text{-}100 \times 10^{44}$ ergs sec^{-1} 2-10 keV, Margon 1978). Some of the observed luminosity may be intrinsic to the central source, however, since BLLs show a very hard X-ray spectrum with $L_x \sim 3 \times 10^{44}$ ergs sec^{-1} (Mushotzky, see the Tuesday morning session).

In addition to providing a moderate optical/X-ray luminosity, the scattering cloud can alter the spectral distribution of the light which passes through it. If the cloud is infalling or outflowing, the diffusing radiation will be significantly heated or cooled if the diffusion velocity (c/τ) is less than the flow velocity (or $|\dot{M}| \gtrsim 100\ (R/10^{16})\ M_\odot$ $year^{-1}$). Also, if the electron temperature is sufficiently high, $kT_c \gtrsim mc^2/\tau^2$, the optical and X-ray luminosity ($h\nu \lesssim kT$) will be significantly increased by Compton scattering (Katz 1976). Since temperatures much above T_c will create a flat emergent optical spectrum, which is not typical of QSOs, we can set an upper limit to the temperature of $kT \lesssim mc^2/\tau^2 \sim 50$ keV. Conversely, high energy X-rays ($mc^2 > h\nu > kT$) emitted by the central source will be significantly cooled by Compton scattering if $h\nu \gtrsim mc^2/\tau^2$ (Illarionov and Sunyaev 1972). Thus for both cases the electron scattering cloud model predicts a steepening in the X-ray spectrum above $h\nu_{max} \sim mc^2/\tau^2_{min} \sim 50$ keV. Higher optical depths will result in a lower energy cutoff.

The electron scattering cloud model for depolarization appears to be consistent with the present optical and X-ray data. Since the model predicts a break in the observed X-ray spectrum near 50 keV for QSOs with low polarizations, X-ray satellite observations of 3C 273 and other bright, unpolarized QSOs would be of great interest.

Acknowledgements

The polarization observations reported in §II were part of a continuing polarization survey of bright QSOs undertaken by the author and J.R.P. Angel. The author is pleased to thank Richard Moore for assistance during the observations and for sharing the preliminary results of his variable QSO survey and two-color polarization survey prior to publication. The author also acknowledges the interest and advice given by P. A. Strittmatter. Polarization studies at Steward Observatory are supported by NSF grant AST 75-17845.

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DISCUSSION

A. WOLFE (To H. Stockman):
What do you think of the idea of classifying NGC 1275 as a nearby optically violent variable? [*Ed.: The question of the appropriate classification of NGC 1275 arose in Dr. Angel's talk.*]

H. STOCKMAN:
I don't think it's as luminous as some of the OVV's.

A. WOLFE:
I accept that the total luminosity is less than some of the more luminous OVV's, but from its polarization properties, you are saying that it is not much different from the OVV's.

R. ANGEL:
Yes, it looks like a BL Lac object.

A. WOLFE:
Except for the presence of the emission lines.

P. VERON:
The main difference between the BL Lac objects and the Seyfert I galaxies is that while both of them have a variable star-like nucleus, Seyfert I galaxies have broad emission lines and the BL Lac objects have narrow emission lines similar to those found in Seyfert II galaxies. In NGC 1275 there is no broad component similar to the one you find in Seyfert I galaxies. That is why I call NGC 1275 a BL Lac object rather than a Seyfert galaxy.

M. BURBIDGE:
The emission lines in NGC 1275 are much stronger than what you see in BL Lac objects. They are also broader. Therefore I would catagorize NGC 1275 as a Seyfert galaxy.

P. VERON:
I would not say that the lines are stronger, but that the non-thermal continuum in NGC 1275 is weaker.

J. MILLER:

Do you have spectrophotometry at the same time that you have polarimetry? In other words did you take spectra at the same time that you measured high polarization? In the case of 3C 446, the lines just about vanished during the period from 1977, August to December because the continuum was so strong. I think this brings up the point that P. Veron was mentioning; that is, that the continuum completely swamps the lines. When this happened in 3C 446 the polarization increased to 15%. I am curious as to whether this is a universal property of violently variable objects when they show strong polarization, or whether or not the outburst in 3C 446 was just a chance case.

H. STOCKMAN:

No, we do not have spectrophotometry or even photometry. [*Ed.: See Miller's talk on 3C 446.*]

T. KINMAN:

I want to comment on some of the selection effects that are operating in your results. The OVV objects with strong polarization come from the 3C catalog. I find it hard to believe that this is a general property of objects in the 3C catalog. Can you estimate the fraction of QSS which are OVV objects?

H. STOCKMAN:

Our sample of QSOs comes from the Burbidge, Crowne, and Smith catalog (1977, Ap.J. Supp., 33, 113) and is based on optical luminosity ($m_V \leq 17$). It includes sources from the 3C, 4C, PKS, and Ohio surveys. Out of 66 radio-selected QSOs (QSSs) we see 5-6 strongly polarized objects (depending whether PHL 5200 is indeed a radio source). Thus about 8-10% of QSS's appear strongly polarized and thus qualify for our definition of OVVs. Richard Moore at Steward is presently investigating in more detail the correlation of rapid variability and high polarization.

H. MILLER:

Most of the OVVs that I have been observing are from the PKS catalog and not from the 3C catalog.

ON THE COMPOSITE NATURE OF THE BL LACERTAE OBJECTS MARKARIAN 421 AND 501

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AND

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ABSTRACT: New polarization data for Markarian 421 and 501, in several spectral bands from 0.36μ to 0.84μ, are presented. Wavelength dependence of the linear polarization is found for both objects. A model consisting of a mini-BL Lacertae object embedded in the nucleus of an elliptical galaxy is developed. The spectral index of the power-law energy distribution of the mini-BL Lac, and the relative contribution to the total flux in the B band are found to be 0.92 and 88% for Markarian 421, and 0.83 and 68% for Markarian 501. Potential application of the technique to other BL Lacertae objects is discussed.

A full account of this work will be published in The Astrophysical Journal, September 1, 1978.

OBSERVATION OF A BL LAC OBJECT WITH THE IUE SATELLITE

by the IUE Science Commissioning Team (read by M.V. Penston - Astronomy Division, ESTEC, Villafranca Satellite Tracking Station, European Agency).

1. THE IUE SATELLITE

The International Ultraviolet Explorer (IUE) was launched on January 26th into a geosynchronous orbit from Cape Cañaveral as a joint project of NASA, the European Space Agency and the British Science Research Council. The satellite contains a 45 cm (18 in) telescope which feeds two spectrographs - one covering the short wavelength region, 1150-2000 Å, the other the long wavelengths, 1800-3000 Å. The spectrograph designs feature collimators, echelle gratings and spherical cross disperser gratings which give resolutions of 0.1 to 0.2 Å. The echelle gratings can be covered by plane mirrors giving low dispersion formats with resolutions of 6 Å. It is the low dispersion which is used for the observations described here. The images are recorded on an SEC television camera which is coupled to an ultraviolet converter. The spectral image is telemetered to either Goddard Space Flight Center or the European Space Agency's Villafranca Satellite Tracking Station (VILSPA).

At VILSPA, in the Guadarrama Valley 30 km west of Madrid, Spain, we operate IUE for 8 hours per day, via a Xerox Sigma 9 control computer. We uplink to the satellite by VHF and receive downlink telemetry on S-band. As well as having the function of a normal ground station, we are a true observatory to which visiting observers come to take part in the observing shifts. This is possible because of the continuous contact with the satellite provided by the geosynchronous orbit. Thus the visitor can identify his target star and make real-time decisions about the future of the observing programme based on his data as it comes in. In addition we have an on-site staff of seven astronomers at VILSPA who will assist visitors and occasionally make their own observations with IUE. For a fuller description of IUE and VILSPA see, for example, Macchetto (1976).

2. EXTRAGALACTIC OBSERVATIONS

Soon after launch the IUE Science Commissioning Team made so-called "high-priority" observations to guard against any premature failure. Objects observed in the extragalactic segment of this programme include one elliptical galaxy, M 87, one spiral galaxy, M 81, one Seyfert class one, NGC 4151, one Seyfert class two, NGC 1068, one quasar, 3C 273, and one BL Lac object, B2 1101+38 = Mk 421. All were observed at low dispersion.

Of the four "active" objects, three, 3C 273, NGC 4151 and NGC 1068 show emission lines in the ultraviolet as they do in the optical. The other, the BL Lac object, shows no emission lines but the form of the continuum spectrum is not notably different from that of the others and in particular the flux is seen to extend to 1150 Å, i.e. to the short-wavelength limit of IUE. The table below shows the equivalent widths of Lyman α and Balmer β together with the spectral index α, ($f_\nu \propto \nu^\alpha$), of the continuum radiation between 1150 and 5000 Å using IUE data and near-simultaneous OBV photometry kindly provided by

Alex Smith (private communication).

TABLE: Equivalent widths and spectral indices

OBJECT	$\omega_{L\alpha}$ (Å)	$\omega_{H\beta}$ (Å)	α
NGC 1068	>500	25	-1.98
NGC 4151	∿120	45	-1.74
B2 1101+38	<12		-1.51
3C 273	71	67	-0.99

A simple theory can be used to relate the equivalent width of recombination lines like Hβ and Lα to the spectral index if it is assumed that the spectrum extends with the same slope shortward of 912 Å and is completely absorbed in the HI bound-free continuum. For Hβ this relationship is given in a recent paper by Fosbury and Penston (1978) and it is not difficult to construct a similar theory if the recombination ratio of Lα to Hβ intensity is known.

It seems clear that the BL Lac object is weak in recombination lines compared to the other active objects, which in turn generally fit the simple theory above. The simple minded conclusion seems to be that in at least one BL Lac object the absence of lines is caused by an absence of gas rather than any shortage of ultraviolet photons. However more complex models are surely possible awaiting only the ingenuity of theoreticians. For example, any gas that is present might not be on line of sight to the ultraviolet source, the non-thermal spectrum might through a conspiracy of nature be cut off just shortward of 1150 Å or alternatively the gas might be too hot to emit lines in the spectral regions observed to date.

This brief note covers only a few points from the initial extra-galactic observations of IUE which will be discussed in detail in a forthcoming paper in Nature. (Boksenberg *et al*. 1978).

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DISCUSSION

M. BURBIDGE:
What absorption lines did you see in NGC 4151 and 3C 273?

M. PENSTON:

I won't say anything now about the absorption lines in 3C 273 because it is a result of doubtful certainty. In NGC 4151 we see absorption at CIII λ1176, NV (which is 3,500 kms^{-1} broad), SiII, CII, SiIV, CIV, AlIII, possible FeII and MgII in addition to optical absorption at Hβ and HeI λ3889.

G. BURBIDGE:

Are there any emission lines present in NGC 4151?

M. PENSTON:

Yes, all the emission lines that one expects to see are present. We see Lα, OI, OIV/SiIV, NIV], CIV, HeII, OIII], NIII], CIII], CII], NeIV, MgII and the OIII Bowen lines, but no NV.

P. STRITTMATTER:

Can you resolve the SiII absorption lines into the ground state and fine structure levels and if so, is there absorption from the fine structure level?

M. PENSTON:

SiII absorption is weak but looks fairly broad so that this may be happening. The same is true for the CII fine structure line.

P. STRITTMATTER:

Yes, but those lines are separated only by about 1Å whereas the SiII lines are separated by 7 or 8Å.

A. WOLFE:

The 2800Å feature in the BL Lac object looks like MgII in emission. How broad is it?

M. PENSTON:

It's extremely broad. I don't think we should take that seriously yet since the certainty of the reality of this feature is questionable.

A. WOLFE:

Does it have very low signal-to-noise?

M. PENSTON:

Yes, it is of somewhat low signal-to-noise and in addition the calibration is uncertain.

J. KROLIK:

Did you measure the CIII] 1909 line in 3C 273?

M. PENSTON:

Yes, the equivalent width is 13Å.

X-RAY OBSERVATIONS OF Mk 501 AND I Zw 1727+50

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ABSTRACT

X-ray signals from Mk 501 and I ZW 1727+50 have been observed by the A-1 instrument on HEAO A. Fluxes are 5.6×10^{-6} and 1.3×10^{-6} Jy, correspond to source luminosities of 3.0×10^{44} and 2.0×10^{44} erg s^{-1}.

INTRODUCTION:

This paper concerns observations made on Mk 501 and I Zw 1727+50 carried out during the first 30 days of HEAO-1. The A-1 experiment on HEAO-1 was designed to provide mapping of the full X-ray sky, mainly in the 0.8-15 keV spectral band at 1° x 4° FWHM angular resolution and with an effective area of 0.66 m^2. Full sensitivity is achieved by adding together observations made on successive rolls of the spacecraft. Plots of this summed data show recognizable responses from sources with intensity as low as 0.2 UFU (UHURU Flux Units). At high galactic latitudes these sources contain mainly a mix of two source types: galaxy clusters and active galaxies, including BL Lac objects.

This paper describes the instrumentation providing the data base, and shows emission vs. view angle from summed data scans for the sky region containing Mk 501 and for the sky region containing IZw 1727+50. Evidence for Mk 501 variability is discussed and a probable first observation of BL Lac 1727+50 is reported.

Instrument

The HEAO-1 X-Ray Observatory carries four X-ray astronomy instruments covering the spectral energy range from about 100 eV to 10 MeV. Among these is the A-1 experiment, which is a collection of seven large area plastic window proportional counters sensitive in the band 0.5 keV to 25 keV. Four of the counters in this array are used as a single sensor of effective area 0.66 m^2. These four counters are mechanically collimated to provide a 1° x 4° FWHM field-of-view. It is this group of counters which is used to map the X-ray sky. As the HEAO spacecraft slowly rolls about a vector pointing at the sun, the counters look out at the sky in a direction perpendicular to the spacecraft rotation vector. Thus they scan the sky along lines of fixed ecliptic longitude, observing a 4° wide band of sky during each roll (35 minutes). Each day the ecliptic longitude band being mapped shifts by 1° due to the yearly motion of the earth about the sun so that a full mapping of the sky is achieved each six months. Sources of 1 or 2 UFU intensity are visible on individual scans, but it is necessary to add data from successive rolls to achieve sufficient time on source to carry out source mapping below the ~1 UFU level.

Sky Mapping in the Mk 501 Region

Figure 1 shows 1-day data sums for scans crossing the sky region near Mk 501. The bottom trace was obtained mostly on Day 231, 1977; successively higher scans cover Days 232 to 243. Only data for which radiation belt particle interference was relatively low were included in making the data sums. The data plots are in the form of counts $cm^{-2}s^{-1}$ vs. roll angle, where roll angle is an angle measure closely approximating ecliptic latitude. Maximum signal is expected from Mk 501 on Day 237 at a roll angle of 61.6°. On most days Mk 501 is seen without interference by other strong sources. However, on Days 231 and 232 the galaxy cluster A 2199 is observed at a Roll Angle 60.1°. On these days Mk 501 was near the edge of the field of view and was seen only as a shoulder on the A 2199 response peak.

If Mk 501 were a steady X-ray source, the response signal for the source should grow monotonically, directly in proportional to the collimator response, from zero on Day 229 to a maximum on Day 237, and should decay similarly from Day 237 to zero on Day 245 due to collimator vignetting. Figure 2 shows the observed intensity vs. time corrected for this collimator response. The error limits shown are double the formal 1-σ errors provided by a source fitting program which provides a least square fit to the collimator function, outputting intensity and source position and errors for both of these. The conservative approach of doubling of the error limit is based on a judgment as to the accuracy within which the fitting program determines the background count rate on which the source signal is superposed. The fitting program determines off-source background fluxes by subtracting other fitted sources from the observed count rates prior to a fitting Mk 501. In some cases source confusion in the immediate vicinity of MKN 501 caused the background fit to fail to match the background as judged by eye. In these cases hand fitting was used to obtain the plotted intensity value. The intensity data for Days 230, 231, and 232 are compromised by the nearby signal from A 2199, and are indicated by open circles in Fig. 2. The data are suggestive of a fairly steady flux with a 2-σ increase occuring on Day 235.

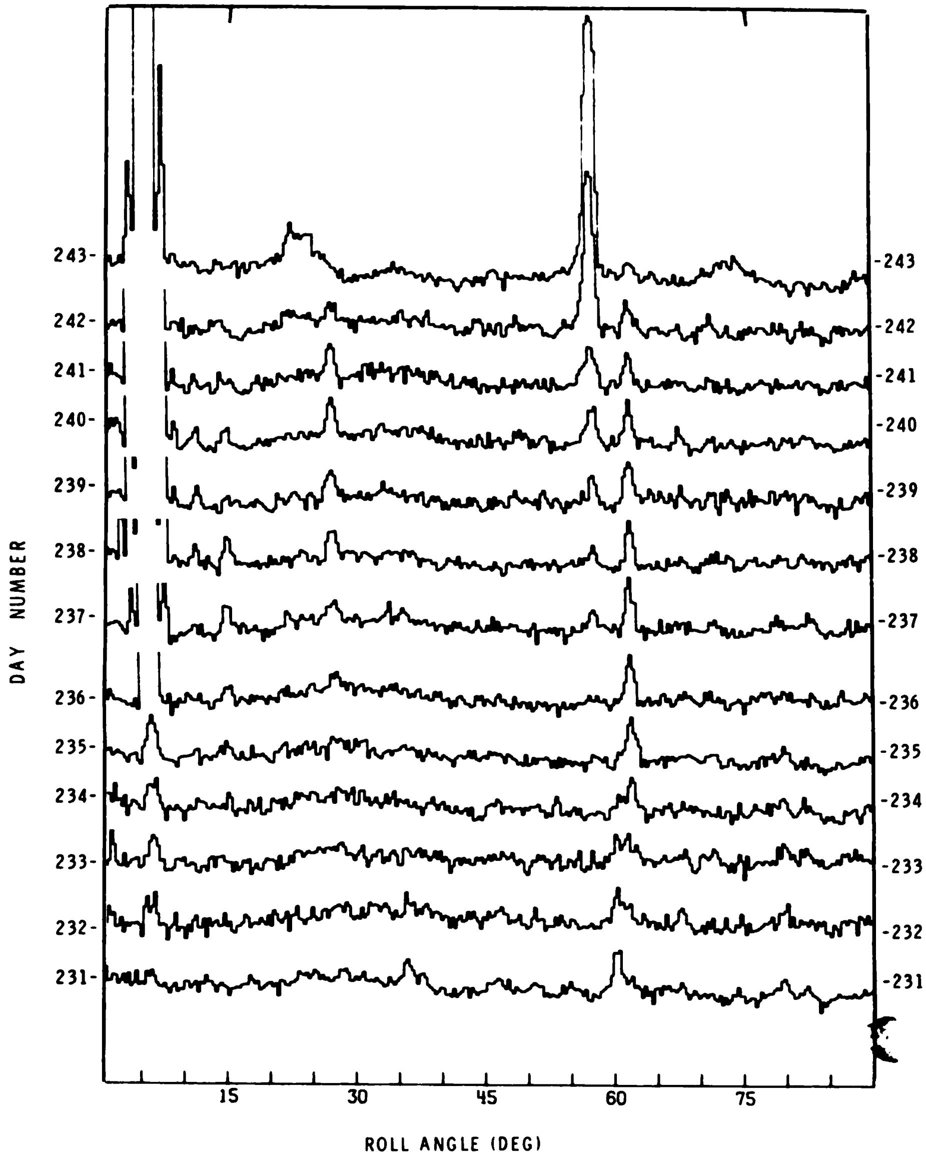

Fig.1. One-day data sums covering portions of the view scan crossing Mk 501. Each day the view scan is offset one degree towards increased ecliptic longitude. The roll angle closely approximates ecliptic latitude. The signal from Mk 501 is seen at 61.6°. The intensity scale is linear up to about 2 x the peak intensity of Mk 501, above which logarithmic compression is imposed.

The mean X-ray intensity of Mk 501 based on Figure 2 corresponds to a 2 keV flux of $5.6 \pm 0.4 \times 10^{-6}$ Jy. The 1-10 keV flux assuming a Mk 501 spectrum $N(E) \alpha E^{-2}$ is 1.3×10^{-11} erg $cm^{-2}s^{-1}$. Using the red-shift value Z = .034 for the source, the corresponding 1-10 keV source strength, calculated as per Oke (1978), is 3.0×10^{44} erg s^{-1}. If the X-ray intensity at 2 keV is compared with a V band intensity of .0126 Jy as measured by Tapia et al. (1976) one calculates a visible-X-ray spectral index of 1.14.

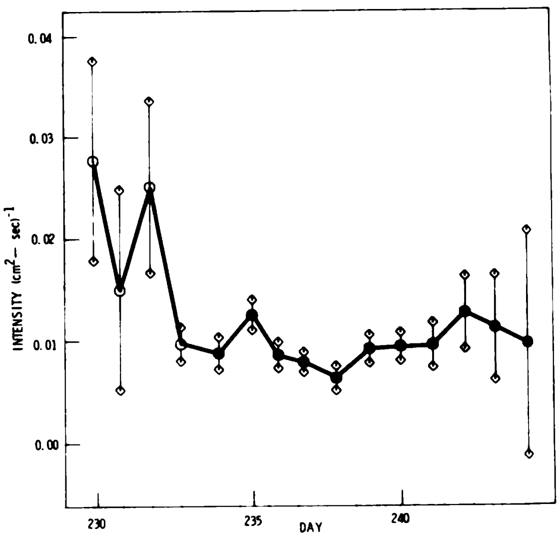

Fig.2. Intensity of Mk 501

Figure 3 shows the 1-σ error box for Mk 501. Ecliptic latitude was determined by fitting the collimator response function to the response of the 1° x 4° scanning modules. Responses of a single 1° x 1/2° FWHM collimated counter was used to determine ecliptic longitude. The small dark bar marks the location of the optical/radio source.

Several unrelated but interesting features are worth noting on the scans shown on Figure 1. The weak source seen on Day 237 at scan angle 57.5° is due to HZ Her in its off condition. The star was directly viewed by the detector on Day 241. The enormous intensification that begins on Day 242 is due to source turn-on. The source observed peaking on Day 240 at Roll Angle 27.2° is galaxy cluster A 2204. The shorter interval during which the source is observable is due to its lower ecliptic latitude. The generally elevated background level seen between Roll Angle 15° and 40°, e.g., on Day 235, is due to diffuse X-ray emission from the N Polar Spur.

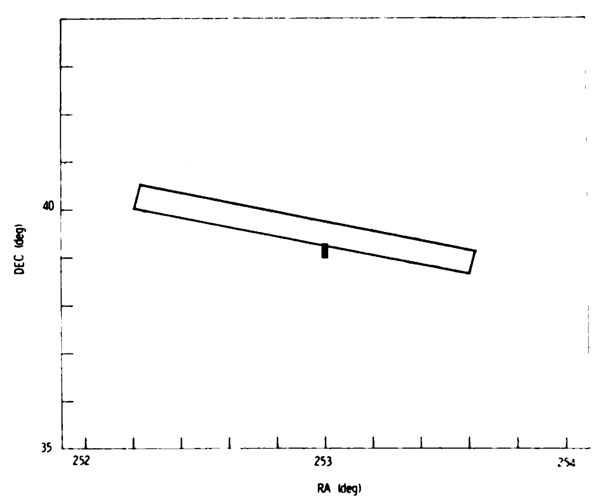

Fig.3. 1-σ error box for Mk 501

Sky Mapping in the I Zw 1727+50 Region

Figure 4 shows summed data for the region of the sky containing I ZW 1727+50, a BL Lac object which has not been previously observed in X-rays. The bottom two traces are each sums of four consecutive and independent days of data, with the lowest trace covering Day 243 to Day 246 and the other covering Day 247 to Day 251. The top trace is an eight-day sum comprising the two 4-day sums. The signal at the position I ZW 1727+50 is seen at Roll Angle 73.1° The signal from this source was detected on sums of single days of data for eight consecutive days due to the high ecliptic latitude of the source. No interesting objects except I ZW 1727+50 were within the error box obtained for this source (Fig. 5). For that reason we assume that the emission is from the BL Lac object. The 2 keV intensity deduced for the source is $1.4 \pm 0.2 \times 10^{-6}$ JY. The corresponding 1-10 keV source flux, assuming a E^{-2} photon spectrum, is 1.5×10^{-11} erg $cm^{-2}s^{-1}$. Assuming Z=0.0544, this corresponds to a 1-10 keV source luminosity of 2.0×10^{44} erg s^{-1}. Combining the X-ray intensity with Tapia's V band intensity (Tapia et al. 1976), one obtains a visible X-ray spectral index of 1.1.

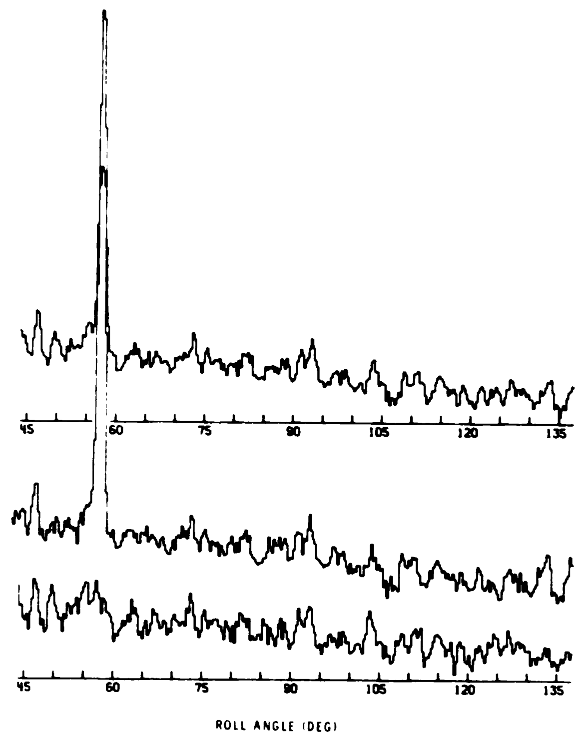

Fig.4. The bottom two curves are independent 4-day data sums of scans crossing I ZW 1727+50. The top curve is an 8-day sum combining the two data sets.

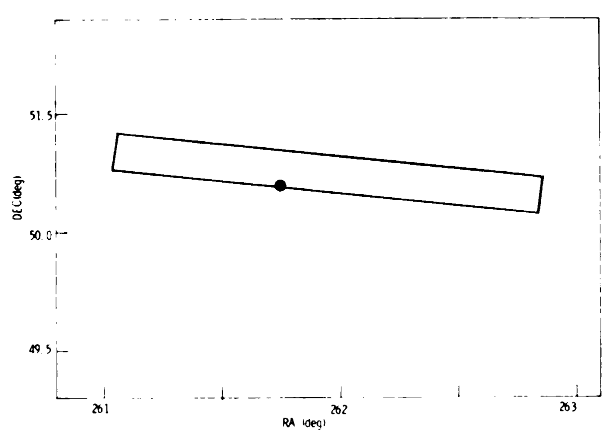

Fig.5. 1-σ error box for I ZW 1727+50.

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ACKNOWLEDGMENTS

The instruments providing data for this paper were built and operated under the direction of E. T. Byram and D. D. Brousseau. Data processing is a team effort under direction of K. S. Wood with key contributions from W. D. Evans, W. N. Johnson, R. L. Kinzer, D. P. McNutt, J. F. Meekins, J. Samimi, G. H. Share, S. D. Shulman, H. W. Smathers, W. Snyder, and D. J. Yentis. R. L. Kinzer provided the figures on which the paper is based. The overall study is directed by H. Friedman.

DISCUSSION

S. COLGATE:
What was the statistical noise in the X-ray raw data?

T. CHUBB:
The 1-σ error for Mk 501 on Day 237 is 7%. The error is half due to count statistics and half due to difficulties in estimating the background on which the signal is superposed. For I Zw 1727+50, assuming that the source is constant over Days 243 through 251, the 1-σ error is 17%, again based on doubling the fitting errors to take into account uncertainties in the X-ray background.

H. MILLER:
What were the dates of the observations of Mk 501 which exhibited possible X-ray variability?

T. CHUBB:
A 2-σ increase may have occurred on Day 235.

X-RAY OBSERVATIONS OF BL LAC OBJECTS

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The BL Lac objects MK501 and MK421 have been observed by the HEAO-1 experiment A-2 in the 2-60 keV band. Their spectra are similar with best fitting power laws having energy index $-.2 < \alpha < .2$. There was no detectable X-ray absorption with implied column densities $N_H < 1.5 \times 10^{22}$ at/cm^2. MK421 was a factor 6 weaker in November 1977 then in May 1977. A new identification of PKS0548-322 with a source near 4U0543-31 is suggested.

I. INTRODUCTION

The recent 40" error box for MK501 (Schwartz et al. 1978) and the small .04 sq. deg. error box for MK421 (Cooke et al. 1978) confirms the existence of X-ray emitting BL Lac objects. Both of these objects were identified as BL Lac objects in the core of giant elliptical galaxies by Ulrich et al. (1975) and are the closest of the BL Lac objects with known redshifts (Stein, O'Dell and Strittmatter 1976).

II. OBSERVATION

MK421 was observed by the GSFC experiment on OSO-8 from days 138 to 140 1977. The GSFC experiment on HEAO-1 observed MK421 on days 324-331 of 1977, MK501 on days 231.5-241.5 and PKS0548-322 on days 256-265 of 1977. Both the HEAO and OSO-8 detectors are low background proportional counters sensitive over the range 2-60 keV. The OSO-8 data were taken in a pointed observation while the HEAO data were obtained during the all sky scan.

III. SPECTRA AND TIME VARIABILITY

The BL Lac X-ray spectra are remarkable for their hardness and lack of low energy absorption (Figures 1 and 2). The best fit to the MK421 data for a power law has a photon index $\alpha = .91$ (+.45, -.50), (90% confidence errors) and a column density $N_H < 8 \times 10^{21}$ at/cm^2. We note that the spectrum has a soft X-ray excess for E < 3.2 keV,

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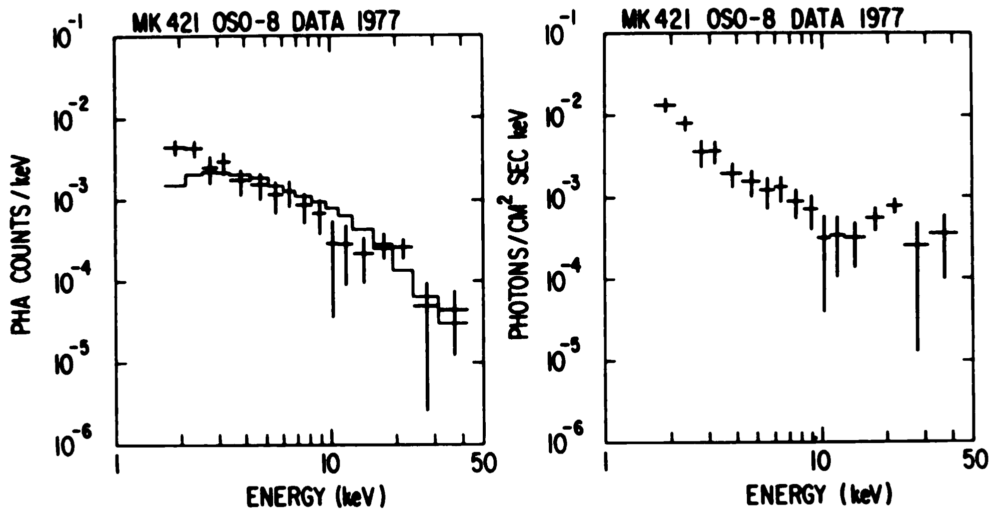

Figure 1a - Pulse height spectrum for Mk 421 with a power law fit of photon index α∿1.0 indicated.
1b - The energy spectrum of Mk 421.

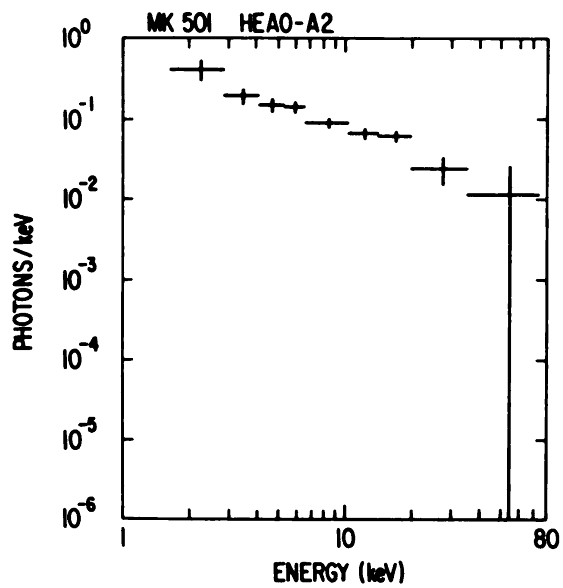

Figure 2 - The energy spectrum of Mk 501

relative to the best fit. A thermal model is not well determined and kT > 30 keV is required. For MK501 the best fit has $\alpha = 1.2$ (+.2,-.2) and $N_H \leq 1.8 \times 10^{22}$ at/cm^2; a thermal fit requires kT > 50 keV and is a poorer fit. We also see a soft X-ray excess in this spectrum. The spectral index for both of these sources is identical, within errors, to the high frequency radio spectral index. MK421 has a 2-10 keV luminosity on days 138-140 of $\sim 5.3 \times 10^{-11}$ ergs/cm^2 sec while MK501 had a 2-15 keV luminosity of 8.9×10^{-11} ergs/cm^2 sec.

There is only slight evidence in our data for day to day variability in these sources (Figures 3 and 4).

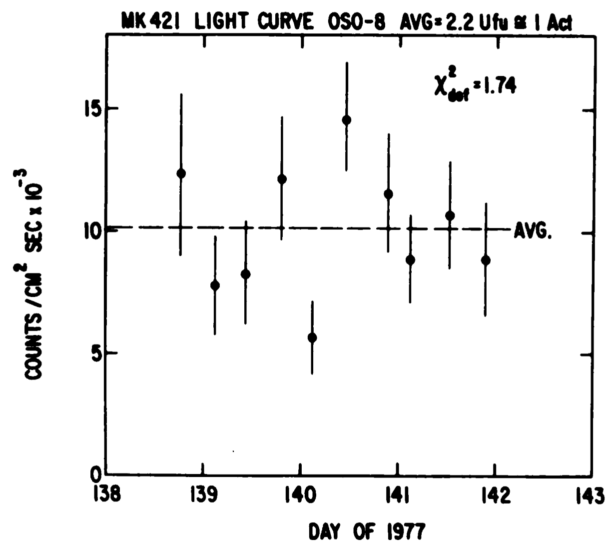

Figure 3 - Light curve for Mk 421

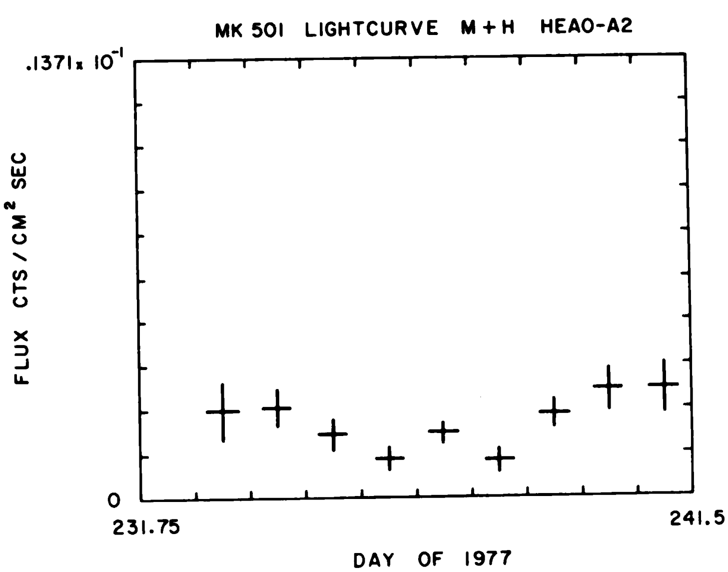

Figure 4 - Light curve for Mk 501

Comparison of the HEAO-1 and OSO-8 fluxes for MK421 show a factor 6 decrease from May till Nov. 1977. Our HEAO detection in Nov. 1977 is 7.9×10^{-12} ergs/cm^2 sec in the 2-10 keV band. This confirms the strong variability of this source in the X-ray band.

IV. OTHER BL LAC OBJECTS

For the 16 BL Lac objects in the list of Stein et al. in our data base we can set a 2-10 keV upper limit of 2.5×10^{-11} ergs/cm sec with the exception of PKS0548-322 which is detected at this level (Figure 5). This source is near 4U0531-31. For some of these objects there is a hint of X-ray emission at a level 2-3 times below the upper limit quoted but our experiment suffers from source confusion at this level.

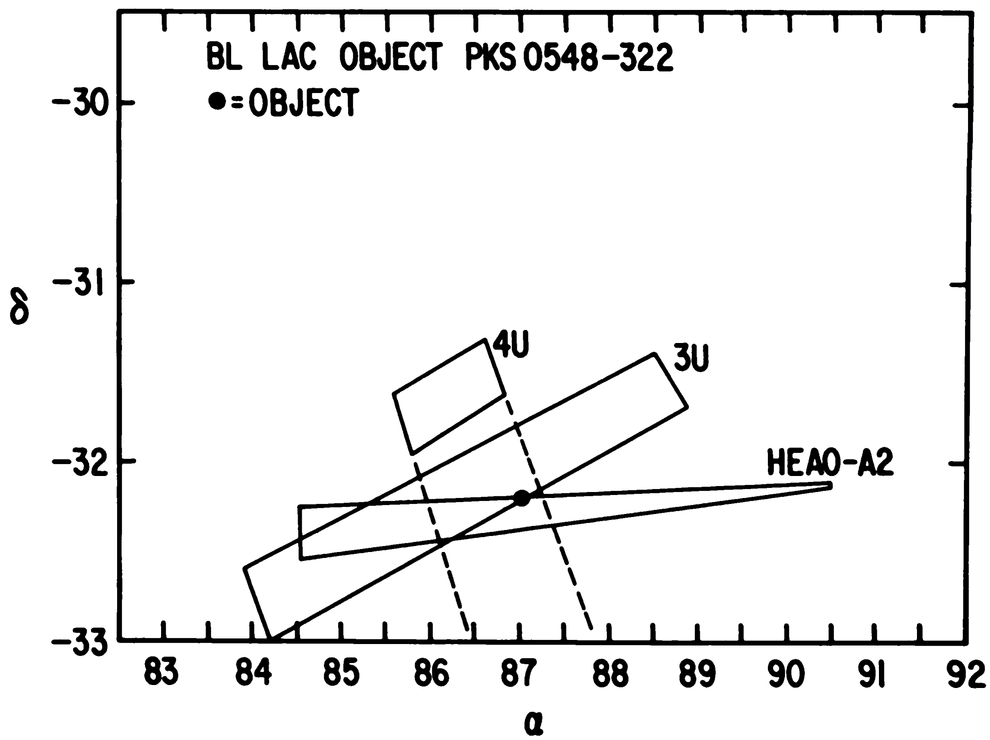

Figure 5 - X-ray position for PKS 0548-322

V. DISCUSSION

PKS0548-322 is relatively close by with a z $\approx$ .069 (Fosbury and Disney 1976). The 2-10 X-ray luminosity, $L_x \approx 4 \times 10^{44}$ ergs/sec, is similar to the optical luminosity of 3×10^{44} ergs/sec. For MK501 the X-ray and optical luminosity are 2.4×10^{44} and 3×10^{44} ergs/sec respectively. MK421 has an enormously variable X-ray luminosity ranging from 3×10^{43} to 3.2×10^{45} ergs/sec (Cooke et al. 1978) and an optical luminosity $\sim 6 \times 10^{44}$ ergs/sec. Thus for all 3 X-ray BL Lac objects the X-ray emission is of the same order or greater than the optical luminosity. This is similar to the situation in X-ray emitting Seyfert galaxies. If the X-ray spectrum continues with the same slope out to 100 keV the energy budget of these objects is dominated by the X-ray emission.

The lack of a low energy X-ray turnover is consistent with a picture in which the nuclei of these objects are deficient in gas. Most type 1 Seyferts show X-ray column densities of $N_H \gtrsim 5 \times 10^{22}$ at/cm^2. However the recently discovered class of X-ray emitting emission line galaxies have lower column densities with $N_H \gtrsim 2 \times 10^{22}$ at/cm^2. Thus qualitatively speaking MK501 and MK421 have considerably less gas then type I Seyfert nuclei which may explain the lack of strong emission lines.

The synchrotron self-Compton mechanism (Jones, O'Dell and Stein 1974) is suggested as a source of the X-ray emission by the presence of a flat high frequency radio component and the similar slope of the X-ray and radio emission. Such analyses have been performed for MK421 by Margon, Jones and Wardle (1978) and for MK501 by Schwartz et al.(1978). Such models require simultaneous radio and X-ray observations for confirmation.

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DISCUSSION

R. BLANDFORD:
When you were looking for variability in these sources, were there simultaneous radio observations?

R. MUSHOTZKY:
We don't know of any simultaneous radio observations of these sources. We would greatly appreciate any information about such observations. I sent out a broadcast letter in 1977, August and I received no positive replies. For future reference I wish to point out that HEAO-1 will look at a source when it is 90° from the sun. Thus all sources overhead at twilight will be monitored.

F. PACINI:

In those cases in which you have not detected X-rays, is your limit still compatible with an X-ray luminosity comparable to the optical luminosity?

R. MUSHOTZKY:

The problem as pointed out by Dr. Chubb is that we are confusion limited and we are limited to perhaps one count per box that you see. We find positive emission from many positions that are coincident with BL Lac objects. Marginally, our X-ray upper limits are $\sim 2 \times 10^{-11}$ ergs/cm^2 sec in the 2-10 KeV band. If the optical luminosities are 13.5-15.5 mag., the X-ray luminosities could be comparable.

B. BURKE:

You say that you are a factor of 2 flux above the confusion limit, whatever that means. To clarify this could you answer the following questions?

1) What is your confusion criterion?
2) Under your assumptions, what is the probability that you have a chance coincidence?

R. MUSHOTZKY:

1) 10 beam widths per source! We have 10,000 beam widths on sky, with a logN-logS curve normalized to Ariel-V we expect $\sim$300 sources at 1 Ufu* over the whole sky and $\sim$1000 sources at 1/2 Ufu. Thus we are confused at $\sim$1/2 Ufu.

2) An object at $\sim$1 Ufu would have $\sim$3% probability of chance.

S. COLGATE:

You interpreted the $\alpha = 0.91$ spectrum for Mk 421 as being non-thermal on the basis of some prejudice that 50 keV is too high of a temperature. If the temperature were 200 keV, would it fit alright?

R. MUSHOTZKY:

No thermal models can be flatter than 1.3 power law slope because the quantum mechanical Gaunt factor is steeper than that. A slope of 0.9 would rule out any thermal model. At the 9% confidence level thermal models of extremely high temperature are acceptable. For Mk 501 no such model is acceptable.

S. COLGATE:

Does that exclude self-Comptonized models?

R. MUSHOTZKY:

Those can never be ruled out without simultaneous radio, optical and X-ray measurements. In that regard I'd like to ask you (K. Johnston) a question. Can you tell me whether the radio flux

*Ed.: 1 Ufu corresponds to 1 count/sec detected by the UHURU satellite; 1 Ufu = 2×10^{-11} ergs cm^{-2} s^{-1} between 2 and 10 keV.

of Mk 421 was dramatically different in 1977, November than it was in the Spring of 1977? The X-ray flux decreased during this period.

K. JOHNSTON:
We only started looking at it in November, 1977. Simultaneous radio and X-ray measurements were made of Mk 421 in 1977, November and of Mk 501 in 1978, February using HEAO-1 for the X-ray measurements and the VLA for the radio measurements. We are at present reducing the data at NRL.

OPTICAL SPECTRA OF BL LACERTAE OBJECTS

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I. INTRODUCTION

This paper presents a discussion of the spectroscopic properties of a sample of BL Lacertae objects. It is well known that the spectral features of objects in this class are weak when they can be detected at all, and therefore considerable care in the treatment of and familiarity with the observational data is required in order to discuss this topic meaningfully. In this spirit, this review is not intended in any way to be a survey of the literature, but rather a summary of our work at Lick Observatory on a group of objects which is reasonably representative of the properties of the class in general, at least insofar as we know the properties.

Optical spectrophotometry can provide various kinds of information about BL Lac objects. If no spectral features can be identified, then of course a redshift cannot be determined reliably. In this case, we are restricted to data on the spectral energy distribution, polarization and light variations, the subjects of other papers at this meeting. However, a redshift determination provides, in the conventional interpretation, a measure of the distance and allows interpretations of observational phenomena in a more fundamental sense. Also, the optical spectrum can contain information other than that required for a redshift determination, because the spectral features themselves can offer physical insights considerably beyond those provided by purely continuum or broad-band measurements. For these reasons we have felt the fairly lengthy observing times required for these difficult objects were justified.

The observations discussed in this paper were all made with the Lick Observatory 3 m Shane reflector using the Cassegrain image-tube scanner; the instrument and its use have been described elsewhere (Miller, Robinson, and Wampler 1976). Normally two entrance apertures are used, one measuring sky and the other sky plus object, and the object is switched between the two apertures often, typically every 8 minutes. At the conclusion of the observations of an object, equal times will have been spent with the object in each aperture, and the data are reduced to keep the data from the two aperatures separate. The result is two sky-subtracted spectra formed by different light paths through the instrument, so that a comparison of the two will facilitate

TABLE 1

REDSHIFT SUMMARY

Object	Z	Z from
3C 66A	(0.444?)*	Mg II em. at 4044 Å?
PKS 0735+17	$\gtrsim$ 0.424	Mg II abs.
OJ 287	0.306:	[O III] λ5007 at 6538 Å.†
MRK 421	0.030	galaxy component
MRK 180	0.044	galaxy component
B2 1308+326	0.996 0.879	Mg II em, [Ne V] Mg II abs.
1400+162	0.245	[O III], [O II], Hβ em.
AP Lib	0.049	[O III], galaxy component
MRK 501	0.034	galaxy component
I Zw 1727+50	0.055	galaxy component
3C 371	0.050	[O III], [O II], [N II], galaxy component
BL Lac	0.0695	[O III], [N II], Hα em. galaxy component

*Highly uncertain

†Tentative - see text for discussion.

the separation of real features from noise features. In addition, observations of the same object from different nights are examined independently as well as in sum to further substantiate the reality of observed features, though in some cases spectral features can only be seen in the low noise, summed spectra. An illustration of the procedure is given in a paper of ours on BL Lac (Miller and Hawley 1977; hereafter Paper I).

II. REDSHIFTS

In the course of this investigation three different types of spectra have been encountered: (1) spectral features of the stars of an associated galaxy, (2) weak emission lines characteristic of a low density gas, and (3) absorption lines characteristic of a low density gas in front of the continuum source. While the first two types permit a direct determination of the redshift, the third kind of spectrum yields a lower limit to the redshift of the BL Lac object itself in the most straightforward interpretation of the observations. Many BL Lac objects we observed show absorption features produced by the interstellar medium of our galaxy, but this aspect will not be discussed here. Table 1 is a list of all of the BL Lac objects we have observed sufficiently to derive good spectrophotometric data. The first column gives a commonly used designation for the object, and the third column lists the spectral features which led to the value of z given in the second column. Comments on the various objects are as follows:

3C 66 A. This object is one of two in our study for which we feel we still have not measured a definitive redshift in spite of having very good data. There appears to be a broad emission feature centered at 4044 Å. There is a fair amount of noise in our data for the blue and violet spectral regions, so we are not certain of the reality of the feature. If it is real, the most likely identification would be with Mg II λ2800 at a redshift of 0.444. This redshift would place [O III] λ5007 in a spectral region highly confused by H_2O absorption in the earth's atmosphere, so its lack of detection would be understandable. Clearly the redshift 0.444 cannot be considered reliable, and the object deserved more attention.

PKS 0735+17. The only spectral feature definitely visible in our data is strong absorption ($W_\lambda \simeq 4.6$ Å) at ~3986 Å. This line has been the subject of several previous studies (see, for example, Carswell et al. 1974) and its identification with Mg II gives rise to the z listed, which is presumably less than or equal to z for the object.

OJ 287. Our spectra of this well-studied object show only one definite, sharp emission feature at 6538 Å with an observed flux of 1.6×10^{-15} erg s^{-1} cm^{-2}. The most likely identification of this feature is with [O III] λ5007 at z = 0.306. Using this value for z, we also see a weak emission feature at the appropriate wavelength for [O III] λ4959 in our two independent spectra, but we would not have noticed this without having made the λ5007 identification. The lack of detection of any other features in our data is consistent with what we know about the emission spectra of other BL Lac objects. It is also consistent with the lack of any nebulosity associated with OJ 287 even if it is located in a luminous galaxy. Other possible identifications for the λ6538 feature are with [O I] λ6300 or blue-shifted Hα, both of which we consider highly unlikely. Mg II λ2800 at 3656 Å and Hα at 8570 Å should be looked for to confirm our tentative redshift.

Markarian 421. This object has been studied in several earlier investigations by others (see, for example, Ulrich et al. 1975), and our redshift agrees with earlier determinations. It is based on the absorption features of the associated galaxy which we detected both strongly diluted in the nuclear region and clearly in the outer region using an annular aperture.

Markarian 180. The redshift comes from the diluted features of the associated galaxy observed in the nuclear region and agrees well with the value presented by Ulrich elsewhere in this volume.

BL 1308+326. The redshift of this object comes from the identification of a fairly strong, broad emission feature at 5586 Å as Mg II λ2800. The flux in the line is 3.8 x 10^{-15}erg s^{-1} cm^{-2}. This identification is consistent with the broad profile of the line and the expected lack of other easily detectable features at this redshift given our wavelength coverage (3800 to 8000 Å) and what we know about typical emission-line spectra of QSQs. There is possibly an additional sharp emission feature at ~6831 Å which can be identified with [Ne V] λ3425 at the same redshift. We also detect a weak doublet in absorption at 5252.4 Å (W_λ = 0.41 Å) and 5264.4 Å (W_λ = 0.39 Å) which we identify with Mg II λλ2796, 2803 at z = 0.879. We note that, at its observed highest brightness (Liller 1976) B2 1308+326 was among the most optically luminous objects known in the universe.

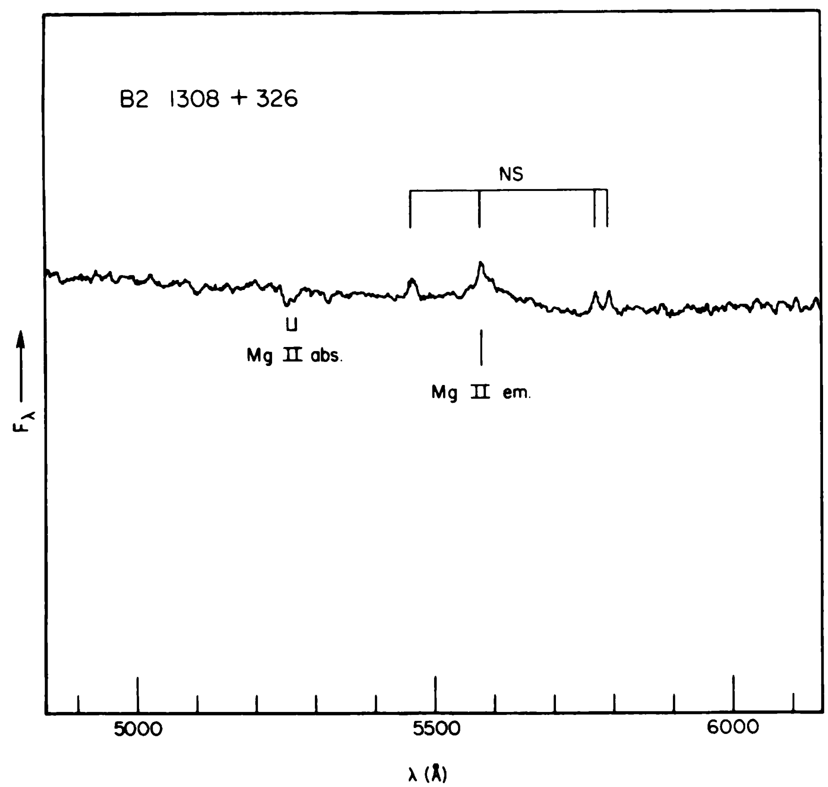

Fig. 1 - A portion of the spectrum of B2 1308+326. NS marks the positions of partially uncancelled night-sky lines. The lower boarder represents the zero flux level.

1400+162. A paper on this object, which is apparently located in a cluster of galaxies, has been published by Baldwin et al. (1977). We identify the following emission lines:

λ_{obs}	I.D.	z	Flux erg s^{-1} cm^{-2}
4639	[O II] 3727	0.245	4.8×10^{-16}
6051	Hβ	0.245	2.3×10^{-16}
6170	[O III] λ4959	0.244	2.1×10^{-16}
6236	[O III] λ5007	0.245	4.9×10^{-16}

We also note that Hβ appears to have a broad profile, though we would need better data to be more certain and quantitative about this.

AP Librae. We were only able to obtain a limited amount of observing time on this object, and because of its southerly declination, the spectrophotometric data is of lower quality than usual. The redshift agrees with earlier determinations (see, for example, Disney et al. 1974). We derive fluxes for [O III] λ5007 of 5.6×10^{-15} erg s^{-1} cm^{-2}. The uncertainty is about a factor of two.

Markarian 501. We observed this very briefly (16^m), but the galaxy component shows at good contrast. The redshift comes from Mg Ib of the galaxy. No emission lines were detected in the nucleus. The redshift is in good agreement with that published by Ulrich et al. (1976).

I Zw 1727+50. The galaxy features show at good contrast, and the measured redshift agrees fairly well with one published recently by Oke (1978). No emission lines were detected in the nucleus.

3C 371. A detailed discussion of this object was published earlier by one of us (Miller 1975).

We present here a list of measured line fluxes, probably accurate to 50% or so.

λ_{obs} Å	I.D.	z	F_{obs} 10^{-15} erg s^{-1} cm^{-2}
3914	[O II] λ3727	0.0501	7.6
5104	Hβ	0.0499	1.6
5208	[O III] λ4959	0.0501	5.4
5256	[O III] λ5007	0.0498	12.5
6621	[O I] λ6300	0.0509	4.7
6915	Hα *	(0.0537)*	> 10.
7061	[S II] λ6717	0.0513	2.3
7074	[S II] λ6731	0.0510	2.3

*May contain [N II] λ6584; partly absorbed by atmospheric B band. The measured redshifts for the various lines do not differ significantly.

BL Lac. This object was the subject of two of our papers (Paper I and Miller, French, and Hawley 1978, hereafter Paper II), which give details on the spectrum. Below is a list of measured line fluxes, probably accurate to a factor of two or so.

λ_{obs}	I.D.	z	F_{obs} 10^{-16} erg s^{-1} cm^{-2}
5292	[O III] λ4959	0.0671	7.0
5350	[O III] λ5007	0.0686	9.1
7007	Hα	0.0677	6.2
7034	[N II] λ6584	0.0684	6.2

III. NUCLEAR COMPONENT

We now turn our attention to the properties of the nuclear, nonstellar components of the BL Lac objects we have observed. Table 2 summarizes the information we have been able to extract from our data. The second column gives the average V magnitude for the data on each object. We determined the spectral index α, defined by $F_\nu \propto \nu^\alpha$; best describing each of the continua by converting the data to log F_ν versus log ν. A straight line was fitted to the entire observed continuum, typically extending from 4000 to 8000 Å, after regions contaminated by features were excluded. The errors in the values are probably less than ±0.1. In addition, the best parabola was fitted to the continuum

TABLE 2

NONTHERMAL COMPONENT

Object	V	α	M_V	$L_\nu(3000\ \AA)$ erg $sec^{-1}Hz^{-1}$	$L(\lambda_1 \rightarrow \lambda_2)_0$ erg sec^{-1}
3C 66A	15.3	-1.38			
PKS 0735+17	15.8	...	$\lesssim$-25.7	$\gtrsim 2.2 \times 10^{30}$	$\gtrsim 2.4 \times 10^{45}$(2800-5600)
OJ 287	15.7	-1.37	-24.8	1.6×10^{30}	1.3×10^{45}(3065-6125)
MRK 421	13.2	-1.08	-22.1	1.7×10^{29}	1.2×10^{44}(3900-7800)
MRK 180	15.9	...	-19.7	...	...
B2 1308+326	16.2	-1.62	-27.2	1.3×10^{31}	8.6×10^{45}(2000-4000)
1400+162	17.7	-1.59	-22.4	1.5×10^{29}	1.3×10^{44}(3200-6400)
AP Lib	15.2	...	-20.0	...	...
MRK 501	17.2	...	-20.1	...	...
I Zw 1727+50	16.6	...	$\gtrsim$-19.9	...	...
3C 371	15.4	-1.35	-20.7	3.9×10^{28}	3.3×10^{43}(3800-7600)
BL Lac	15.0	(-1.55)*	-23		

*From Thuan et al. (1975).

to investigate curvature of the spectrum. Only one object, PKS 0735+17, showed significant amounts of curvature, and the parabolic fit was a good one; the spectral index varied from $\alpha \approx -3$ at $\lambda \sim 4000$ Å to $\alpha \approx -1$ at ~ 8000 Å. None of the values for α were corrected for reddening except that listed for BL Lac, which was taken from the paper of Thuan et al. (1975). Objects for which no spectral index is given are those with such a strong galaxy component that it wasn't possible to derive a reliable value from our data. We derived the other parameters by adopting $H_o = 75$ km s^{-1} Mpc^{-1} and $q_o = 1.0$. For the objects in which a galaxy was not seen, or seen only weakly, the absolute visual magnitude, M_V, was computed from the flux at 5480 Å (rest) as determined from the best fit discussed above the monochromatic luminosity at 3000 Å, L_ν (3000 Å), was computed similarly. In some cases these calculations required extrapolating the curve beyond the region observed. For the objects in which a galaxy was strongly visible, M_V was computed from the observed flux at 5480 Å (rest) after the galaxy contribution was subtracted (see below); no attempt was made to compute L_ν (3000 Å) for these objects, as this wavelength always fell outside the range observed and no nonthermal continuum fit was available for extrapolation. Finally, we also list the luminosities derived by integrating the best fit continuum energy distribution over the approximate observed range, from 4000 to 8000 Å. We list the wavelength range in the rest frame of the object corresponding to this observed range.

It should be recalled that since all of these objects are highly variable, the values for the absolute magnitudes and luminosities given in the table represent averages over our observations. Nevertheless, we feel the results show clearly that there is a rather large range of luminosities for the nucleus of BL Lac objects. Objects such as Mrk 180, AP Lib, and 3C 371 have such relatively weak central objects that the galaxy component is obvious in good quality spectrographic data. For luminous objects such as B2 1308+326 and PKS 0735+17, even a very luminous galaxy would be very difficult to detect given the brightness of the central object. All of the lower luminosity objects also have the lowest redshifts, but the selection effects that are likely to be responsible for this are obvious. The high luminosity objects tend to have higher redshifts, which would suggest that they are less common than the lower luminosity ones. The total range of luminosities in the table is over a factor of 300. B2 1308+326 has a visual luminosity more than 100 times that of a first-ranked giant elliptical. It is interesting to note that some BL Lac objects such as AO 0235+164 and B2 1308+326 have been observed to vary themselves by more than a factor of 100. The overall conclusion to be drawn from these data is that BL Lac objects produce energies over a very large range.

IV. GALAXY COMPONENTS AND EMISSION LINES

For all objects with $z < 0.07$ we detect the spectral features of stars of an associated galaxy. We do not detect galaxian features in any objects with greater redshifts. However, given the luminosities of the nuclear components of these objects, we would not have expected to detect the features of even a very luminous galaxy at the measured redshifts with our data. We can summarize this by stating that presently available data are consistent with all BL Lac objects being located in galaxies, the detectability of which is dependent on the

TABLE 3

GALAXY COMPONENT, [O III] EMISSION

Object	Z	$M_V^{\dagger}$ (size) (kpc)	L [O III] erg sec^{-1}
MRK 421	0.030	-20.2 (1.3 x 2.2) -19.2 (2.3 - 4.6)*	
MRK 180	0.044	-19.3 (1.9 x 3.1)	
AP Lib	0.049	-20.6 (2.1 x 3.5)	2.6×10^{40}
MRK 501	0.034	-19.3 (1.5 x 2.5)	
I Zw 1727+50	0.055	-19: (2.3 x 3.8)	
3C 371	0.050	-20.0 (2.1 x 3.5)	6.1×10^{40}
BL Lac	0.0695	-19.8 (3.8 x 4.6) -19.0 (3.5 - 5.8)* -21.1 (total)	1.9×10^{40}
1400+162	0.245	....	5.6×10^{40}
OJ 287	0.306:	....	2.8×10^{41}
NGC 1052	0.005		3.2×10^{39}

*Annulus data.

†First-ranked giant E $M_V = -22.4$ (Sandage 1972). All data for $H_o = 75$, $q_o = 1$.

respective luminosities of the central object and galaxy, the redshift, and the signal-to-noise ratio of the data.

In all cases where a galaxy is detected, it appears to be an elliptical. Numerous studies with direct photography, electronography, and multi-aperture photometry of the extended light around several of the low redshift BL Lac objects have shown that this light is very smoothly distributed in a manner similar to that observed in ellipticals. In addition, all spectroscopic data support the conclusion that the detected associated galaxies are ellipticals. For example, our data (Paper II) for the galaxy associated with BL Lac indicate that its spectrum is entirely normal for a giant elliptical.

As we pointed out in Paper II, finding an exact spectroscopic match for two elliptical galaxies is complicated by the fact that line strengths in E galaxies are dependent on both the absolute magnitudes and the radial distances from the center of the galaxies. Nevertheless the equivalent widths of strong features such as Mg Ib, H and K of Ca II, and the G band do not vary by large amounts ($\lesssim$ 20%) over the brightest 2 or 3 magnitudes of giant E galaxies. Table 3 lists absolute magnitudes of the galaxy components we have detected. These were derived from the equivalent widths of the Mg Ib feature only, as this is by far the best measured feature in our spectra. By comparing the equivalent widths to the average of those measured by us for the same feature in the luminous giant ellipticals NGC 1052 and NGC 4472, we estimated the relative contributions of the galaxy and nonstellar components. From the redshifts and the observed continuum fluxes in this wavelength region, we then derived values for the absolute magnitudes of the galaxy component. Since the wavelength of Mg Ib is close to the effective wavelength of the V filter, this magnitude provides a reasonable estimate for M_V. Because the Mg Ib feature was measureable only to moderate accuracy with our data and results depend on only one feature, we estimate the magnitudes given in Table 3 could be in error by as much as 0.7 mag. The exceptions to this are 3C 371 and BL Lac where the magnitudes come from earlier, more accurate studies (Miller 1975; Paper II) and have errors less than 0.1 mag. Except for BL Lac, the magnitudes given are uncorrected for aperture and redshift so that they refer to variously sized regions of the galaxies; the galactic dimensions corresponding to the apertures used are also listed. For BL Lac we also list a total magnitude based on an extrapolation to Sandage's metric diameter using his curve-of-growth; BL Lac is also the only object for which we corrected for galactic reddening (see Paper II for details).

In spite of the uncertainties in the magnitudes given in Table 3, we feel the evidence is good that there exists some range in the absolute magnitudes of the galaxies associated with BL Lac objects. Though all of these are luminous galaxies, it appears that Mrk 421 and AP Lib have more luminous galaxies than those associated with Mrk 180 and BL Lac. More accurate data, especially measurements covering a more homogeneous set of galactic dimensions, are needed to make this statement very quantitative. However, it is interesting to note that the magnitude we derived for the galaxy associated with BL Lac is about 1.3 mag. fainter than that derived by Sandage (1972) for a first-ranked cluster elliptical, -22.4. The data in Table 3 tends to confirm the relatively lower luminosity of the BL Lac galaxy and suggest that Mrk 421 is about one magnitude brighter and hence is close in brightness to a first-ranked elliptical. While all of the detected galaxies are of high luminosity, this of course does not rule out the possibility that BL Lac objects could exist in lower luminosity galaxies.

We also list in Table 3 the luminosity derived from the [O III] $\lambda 5007$ emission line detected in 6 BL Lac objects; the measuring errors are about a factor of two. The surprising thing is the small range of luminosities. For comparison we also give the [O III] luminosity for the giant E galaxy NGC 1052, one of the strongest-lined such galaxies, and note it is down by a factor of 10 compared to these BL Lac objects. [O III] lines of this luminosity would probably escape detection in typical BL Lac objects. On the other hand, [O III] line emission from normal QSOs is typically 100 times or more that found for the BL Lac objects. Beyond noting that $H\beta$ in 1400+162 appears to be broad and Mg II $\lambda 2800$ in B2 1308+326 is a relatively broad feature (full width at half maximum ~ 50 Å), we can't comment on the width of the permitted lines because of their weakness; at our resolution (~ 10 Å), the forbidden lines are all unresolved.

V. CONCLUDING REMARKS

We can make the following summary remarks about the results presented in this paper.

1. The BL Lac phenomenon covers a wide range of luminosities. Our data indicate that the nuclear object can have optical luminosities ranging from less than that of a luminous giant elliptical galaxy to over 100 times the luminosity of such a galaxy.

2. In all cases where a galaxy is detected, the evidence from spectroscopy and direct photography is that it is an elliptical galaxy. No evidence has been found for a spiral galaxy associated with a BL Lac object. Though all galaxies detected are very luminous, there is evidence that there is a small range of luminosities for the galaxies amounting to possibly one magnitude or more.

3. Nearly three-fourths of the objects we studied showed emission lines. Typically the lines are much weaker than those observed in QSOs, but stronger than the ones seen in some giant E galaxies. The fact that all detected galaxies are ellipticals supports the idea that the weakness of emission features in BL Lac objects results from there being only small amounts of gas in the systems.

4. The data are consistent with the statement that all BL Lac objects are located in giant elliptical galaxies, but this cannot be proved at present.

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DISCUSSION

H. SMITH:
You say that in all cases that when you detect a galaxy it is an elliptical galaxy. Aren't you really saying you detect a late type stellar population? Could you really discriminate against a galaxy like M31 for example?

J. MILLER:
That's right. You could arrange it to be an Sa type galaxy; that is, a very large dominant central bulge in a spiral galaxy would produce a spectrum similar to an elliptical galaxy. But careful studies by direct photography, multi-aperture photometry, and electronography indicate that the extended light distributions are very smooth and fit that expected for a giant E galaxy very well [*Ed.: See talk by Kinman*].

I should also mention that when I detect emission lines in several of these objects, they occur in the nucleus. When I look through an annulus I don't see emission lines so the emission lines are confined to the nucleus rather than to some outer spiral arm as perhaps they should be in a spiral galaxy.

G. BURBIDGE:

I want to ask you about that. You do see emission lines even though they may be weak. At the same time you said and other people have been arguing that there is no gas in BL Lac objects, but there is gas presumably. Could you say something about how much gas is present?

J. MILLER:

You have to know something about the temperature and the density to do that. By analogy suppose the elliptical is like NGC 1052. The mass of the gas in NGC 1052 is somewhere between 10^3 and 10^6 solar masses. It's a low density, low temperature HII region. If the density goes up the mass of course decreases.

G. BURBIDGE:

But many people think that NGC 1052 is an anomolous elliptical galaxy. It is one of the rare ones with emission lines. Whatever is happening in the central region presumably has done something and there probably is gas floating around that originated from that event.

J. MILLER:

E galaxies that show emission lines in their nuclei are in the minority, but not at all rare. It is the case that the emission lines seen in some of the BL Lac objects are about 10 times more luminous than the strongest observed in E galaxies. Clearly the E galaxies with BL Lac objects in them are highly "non-typical" by virtue of the nuclear object, and the existence of emission from the nucleus could be related to that object or something might have happened in the galaxy that triggered the release of gas. The galaxy around BL Lac is not a young galaxy. It is not a recently formed galaxy. It's what I would call a mature galaxy. Perhaps something has happened in the galaxy evolution which has created a central object and deposited gas around it. The point I made was that the stellar content (luminosity, evolutionary state) was entirely normal for a giant E galaxy at the observed redshift.

M. ULRICH:

Jack Baldwin found a correlation between the equivalent widths and the absolute intensity of the continuum of quasars (1977, Ap.J., **214**, 678). If the redshift of 1308+326, z = 1.0, is correct where does this object fall in the correlation found by J. Baldwin.

J. MILLER:

The correlation was reported for CIV and, to some extent, Lα emission. I only observed MgII emission, so I can't really comment except to point out that highly variable objects with constant line fluxes can only fit the Baldwin relation exactly at one brightness.

J. KROLIK:

Just how much flux is there in these emission lines, in particular, in the MgII permitted lines?

J. MILLER:

We derived about 7×10^{42} erg/sec. for the luminosity of MgII in 1308+326.

J. KROLIK:

I have a second question. When you see one line and when another is questionable then how unique is your redshift?

J. MILLER:

It isn't. You have to fold in some other things, for example, whether or not you expect those two lines to be the most easily detected. In all cases except OJ 287 and 3C 66A, the redshifts are highly likely to be correct. In each case they are based on more than one line. The only one that differs from these is 1308+326 and that's based on a certain emission feature, a probable emission feature, and one absorption line at lower z.

G. BURBIDGE:

But that's a QSO.

J. MILLER:

No, I think that 1308+326 is very similar to 3C 446.

G. BURBIDGE:

Yes, that's why it's a QSO.

D. RICHSTONE:

Is the statement emphasized by J. Gunn last summer - that if you can spectrally resolve the nebulosity around a BL Lac object or a QSO, it will show a stellar contribution only if it is a BL Lac object - still true?

J. MILLER:

I haven't checked everything, but so far as I know that is still the case. Remember that we are talking about a limited number ($\sim$3) of QSOs. The fuzz around 3C 48 and 3C 249.1 contain emission lines, not stars. But it is still an open question about what produces the optical radiation in the jet near 3C 273; published observations indicate that it is not similar to the gas near 3C 48. In the case of BL Lac objects, I don't know of any case where the fuzz has been looked at and you see emission lines.

G. BURBIDGE:

AO 0235+164!

J. MILLER:

That's not what I would call a symmetrical fuzz around a star-like object.

G. BURBIDGE:

It's still fuzz.

D. RICHSTONE:

On the photograph I saw it wasn't even clear that it was fuzz.

J. MILLER:

It's nearby fuzz and it was only marginally resolved. Just to complete this discussion I've done the same type of study on QSOs which are two magnitudes above the Hubble line for first ranked giant elliptical galaxies asking the following question: Do they also have giant ellipticals in them? In virtually no case did they contain one. At a signal-to-noise ratio that would put these BL Lac spectra to shame - I'm almost embarrassed for the amount of observing time I put into this project - I did not see MgIb absorption features at a level you would expect to if there was a luminous giant elliptical associated with the QSOs. So they are different. I think that's an important result.

D. RICHSTONE:

Could we briefly come back to 1308+326? What is its redshift?

J. MILLER:

Z = 0.997.

D. RICHSTONE:

So CIV λ1549 is not accessible which is the real Baldwin criterion for the Hubble relation.

M. PENSTON:

Since the matter has been alluded to, I should say that the IUE data shows that 3C 273 lies close to Baldwin's relationship between the CIV equivalent width and the luminosity. The Seyfert galaxies however violate this relationship with the luminosities being much lower while the CIV equivalent width lies in the same range. I haven't checked what upper limit we have for CIV in the case of BL Lac objects.

J. MILLER:

The other problem is that these BL Lac objects are so highly variable that the equivalent width is a function of when you observe them. It's not quite clear to me how you tie them into the Baldwin calibration because the equivalent width is not linearly related to the luminosity. If the luminosity goes up and down it produces a proportional change in equivalent width. As a result it can't possibly always obey the Baldwin relation even if it obeys it one time.

G. SETTI:

Did you try to observe galaxies in a cluster in the direction of 3C 66A?

J. MILLER:

I never had the right combination of ingredients going into a night. I have seen them on the TV screen and they are very tempting.

G. SETTI:

Your answer suggests that 3C 66A is in a cluster.

J. MILLER:

It should be done, but it requires about 3 or 4 hours of observing time which is 5% of this entire program. I just haven't had the time.

H. ARP:

I published a redshift for 3C 371 obtained with the old image tube spectrograph (1970, Ap.Lett., 5, 75). I observed [OII]. Is that the same redshift as yours?

J. MILLER:

Yes, you also measured neighboring galaxies because it's in a small cluster. 3C 371 is extended, it connects with two neighboring galaxies. It's rather strange.

DISCOVERY OF A NEW BL LAC OBJECT IN AN ELLIPTICAL GALAXY

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The BL Lac objects which are surrounded by a nebulosity are particularly interesting for the three following reasons:

1 - Spectrographic observations of the nebulosity itself have, in several cases, revealed the presence of absorption lines of stellar origin which, at once, establishes that the nebulosity is a galaxy and gives its redshift.

2 - The study of the luminosity distribution of the nebulosity allows one to determine the morphological type and the absolute luminosity of the galaxies in which a BL Lac nucleus is present. (see the article by T. D. Kinman in this volume).

3 - When a large enough number of galaxies with BL Lac nuclei are known it will be possible to select a representative sample of them from which the space density and luminosity function can be determined and then compared to that of other types of galaxies with active nuclei such as Seyfert galaxies or galaxies with compact nuclear radio sources.

At the present time, less than half a dozen of galaxies with BL Lac nuclei are known. We present here the results of recent spectrographic observations of a new one: Markarian 180. We also give some results on Markarian 11 which does not seem to be related to BL Lac objects but which, like Markarian 180, has a nearly flat radio spectrum at high radio frequencies. The radio spectra of Markarian 11 and Markarian 180 were measured at 7 frequencies between 2.7 and 15.5 GHz by Kojoian et al. (1976). We have not been able to find the radio positions of Markarian 11 and Markarian 180, however they must be quite precise since both galaxies were observed at 2.7 and 8.1 GHz with the NRAO three-element interferometer.

Markarian 180 was included in our observing program because it looked potentially interesting for three reasons:

(i) it is a Markarian galaxy and therefore has an UV excess.
(ii) its image on the Sky Survey is spheroidal much like the image of a distant elliptical.
(iii) it has a flat radio spectrum (Kojoian et al. 1976). Our spectrographic observations of Markarian 180 are described

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in detail in Ulrich (1978) but it is worth summarizing them here: Trailed spectra of the nucleus taken in 1976 showed no emission nor absorption lines, and showed an intense UV continuum qualitatively similar to that emitted by a typical BL Lac object like OJ 287. Spectral scans of the nebulosity itself taken with the IDS scanner at Kitt Peak National Observatory show the K and H lines, the G band, and the line FeI λ4384. These lines are usually found in the spectra of elliptical galaxies and establish that the nebulosity around Markarian 180 is a galaxy and give its redshift, z = 0.0458.

Figure la shows an image-tube photograph of Markarian 180 taken by H. C. Arp at the prime focus of the 200-inch telescope at Hale Observatories. The smooth distribution of light around the nucleus and the absorption lines present in the spectrum of the nebulosity are all consistent with the nebulosity being an elliptical galaxy. Note that in all cases of BL Lac objects surrounded by a nebulosity and where the nebulosity has been well studied spectrographically and photometrically, the nebulosity appears to be an elliptical galaxy. This is in contrast with Seyfert-type nuclei which are found mostly in spiral galaxies (and also in a small fraction of radio galaxies which have an intense central radio source). Figure lb is a reproduction of a 4m prime-focus photograph taken by C. R. Lynds at Kitt Peak National Observatory of B2 1652+39 ≡ Markarian 501. This object is one of the first ones for which it was unambiguously established that the nebulosity is a galaxy (Ulrich et al. 1976).

We observed Markarkian 11 spectrographically because, like Markarian 180, it has a nearly flat spectrum between 2.7 and 15.5 GHz. Markarian 11 differs from Markarian 180 in that its image on the Palomar Sky Survey is elongated like that of a fairly distant spiral or SO galaxy. The spectral scans of the central region obtained at Kitt Peak National Observatory show several absorption lines including prominent Balmer lines. Moreover, viewed through the telescope the object does not appear to have a stellar-like nucleus. It seems, therefore, that, at the present time, the optical properties of Markarian 11 are different from that of a BL Lac object. However, this object is interesting in that it has 2 properties which usually do not appear simultaneously in a galaxy: its radio spectrum is fairly flat at high radio frequencies and its optical spectrum shows strong Balmer lines indicating that a part of the stellar population is fairly young. It would be of interest to map the radio emission in Markarian 11 to distinguish between a point source and an extended emission region; in the latter case the high frequency radio spectrum could be of thermal origin. Clearly this object deserves further study.

It is a pleasure to thank Drs. T. D. Kinman and C. R. Lynds for interesting discussions. I am also grateful to Dr. H. Arp for taking a large scale photograph and to Dr. F. N. Owen for measuring the 90 GHz flux density of Markarian 180. The support of the National Science Foundation through grant AST 73-0531 is gratefully acknowledged.

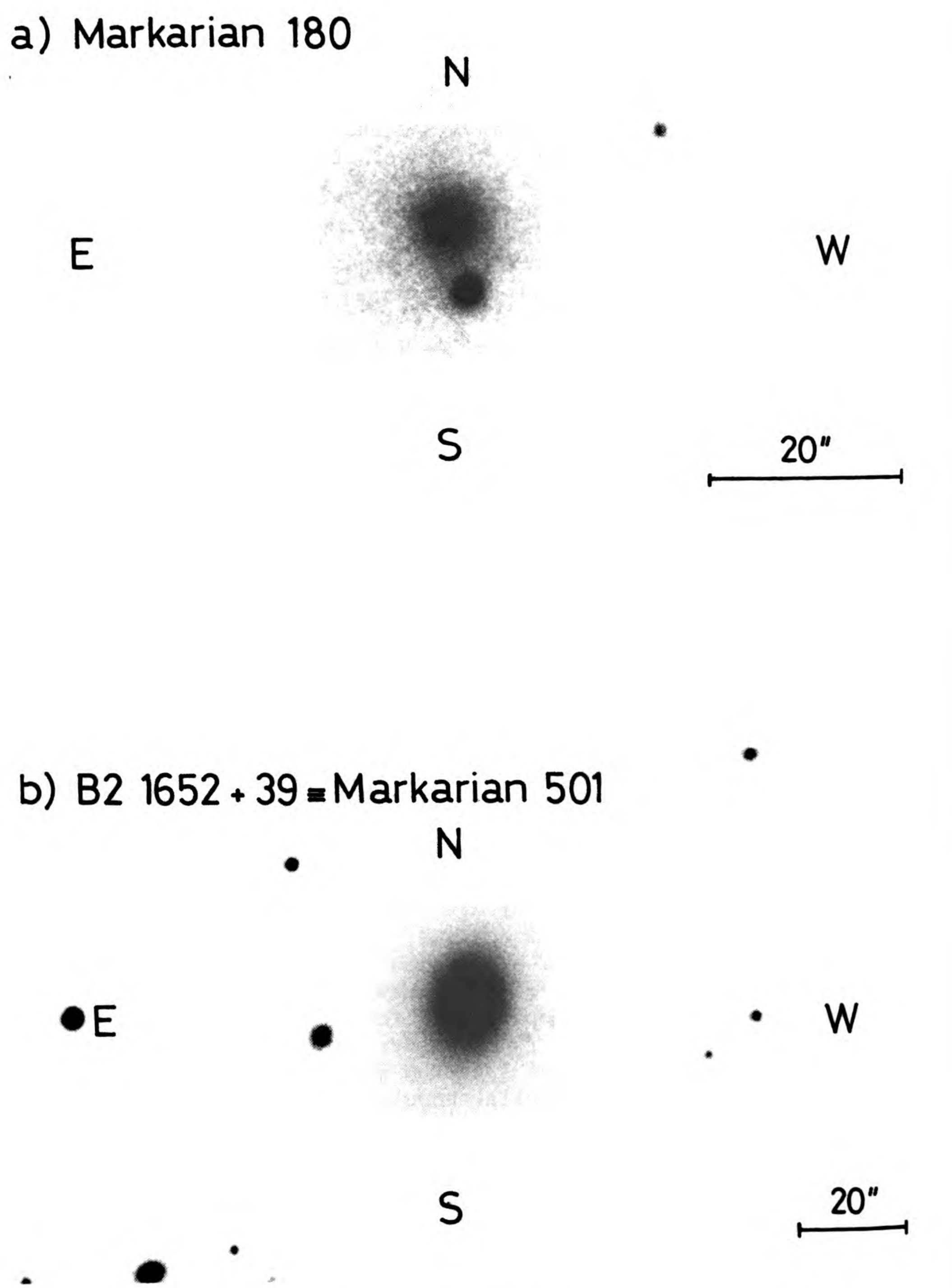

Fig.1.- Two examples of BL Lac Objects surrounded by a nebulosity. In both cases, the distribution of light around the nucleus, the appearance on direct plates and the spectral lines present in the spectrum of the nebulosity, are all consistent with the nebulosity being an elliptical galaxy. (Information on the photographs is given in the text).

Appendix:

Table 1

Markarian galaxies which have a BL Lac type nucleus

B2 1101+38 ≡	Markarian 421	z = 0.03
B2 1652+39 ≡	Markarian 501	z = 0.03
	Markarian 180	z = 0.046

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DISCUSSION

G. BURBIDGE:
How accurately is the radio position of Mk 11 located with respect to the nucleus of the galaxy?

M. ULRICH:
A radio astronomer can best answer this question at this time.

G. BURBIDGE:
It could be something like 3C 455, for example, where the radio identification turned out not to be on the galaxy at all (Arp, H.C. et al. 1972, Ap.J. Lett., 171, L41). Because this is such a rare occurrence for that type of galaxy, the radio source could turn out to be a QSO. It may be 20 arc sec. away.

K. KELLERMANN:
The positional identification from interferometer measurements is probably better than 1 arc sec.

G. BURBIDGE:
So the radio source would be at least on the face of the galaxy.

K. JOHNSTON:

That's not clear because we don't know what source it is.

K. KELLERMANN:

No, Sramek (Sramek, R.A., and Tovmassian, H. 1975, Ap.J., **196**, 339; Kojoian, G. *et al*. 1976, Ap.J., **203**, 323) did it in his radio survey of Markarian galaxies.

G. BURBIDGE:

It would be interesting to check that because of the rarity of this type of galaxy being associated with this type of radio source.

K. KELLERMANN:

It's hard to believe that Sramek misidentified it.

D. WILLS:

Who obtained the earlier spectrogram of Mkn 11, and when? Secondly, what is the evidence that Mkn 180 is a BL Lac object?

M. ULRICH:

The earlier spectrogram of Mkn 11 was taken by Weedman and Khachikian circa 1968 (1968, Astrophysics, **4**, 243). The evidence that Mkn 180 is a BL Lac object comes from:

(i) flat radio spectrum; in particular Frazer Owen measured its flux density at 90 GHz; in March 1976 it was 170 m Jy (private communication).

(ii) Stellar-like nucleus; very blue.

(iii) Trailed image tube spectra taken in March 1976 show no lines in emission or absorption; the energy distribution from these spectra qualitatively resembles that of OJ 287 which we observed with the same spectrograph.

A. SMITH:

Mkn 11 appeared highly resolved in the photo that was shown. Does it have a distinctly stellar nucleus?

M. ULRICH:

The nucleus viewed through the 2.1 m telescope at KPNO does not look stellar. No large scale direct photograph of this galaxy has yet been taken.

PHOTOMETRIC DISTANCE ESTIMATES OF BL LACERTAE OBJECTS AND THE RADIO COLOR-MAGNITUDE DIAGRAM

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Since BL Lacertae objects have generally unknown redshifts, it is worthwhile to obtain as much information as possible on their distances. The possibility exists that the photometric variability statistic B(max), along with the two component model for radio and N-galaxies (Sandage 1973) can be used to set lower limits to redshifts of these sources. The R(max) versus α (5 GHz) correlation (Usher 1975) may then imply the existence of a BL Lacertae sequence in a pseudo radio "color"-magnitude diagram. This in turn prompts inquiry into the relationship of BL Lacertae sources to quasars and other sources in a bona fide radio color-magnitude diagram of the sort first proposed by Heeschen (1960).

B(max) is the numerically largest (i.e. the faintest) magnitude recorded for a source, and can be corrected amongst other things for galactic extinction A_B. The index

$$R^5_B\,(\max) = B(\max) - A_B + 2.5 \log F(\max; 5) \qquad (1)$$

is proportional to the logarithm of the maximum ratio of radio flux density at 5 GHz to optical flux density; α is used in the sense $\nu dF/Fd\nu$; for variable sources, α is our best estimate of the slope of the upper envelope $F(\max, \nu)$. The bibliography contains all references to data used in this paper, except that B(max) for PKS0048-097 (Usher et al 1974) has been found to be 17.5.

From the Hubble diagram constructed by Sandage (1972), it is evident that no quasar or quasi-stellar galaxy lies appreciably to the faint side of the radio and N-galaxy line; and when B(max) statistics are compiled for quasars in the 8^h and 15^h Sandage-Luyten survey fields (Sandage and Luyten 1969), and for sources with photometric histories compiled from archival records (e.g. Angione and Smith 1970; Shen and Usher 1970; Eachus and Liller 1975; Liller and Liller 1975; Miller 1977; Pica 1977; Pollock 1975; Usher 1975) still all lie within or above the radio-galaxy distribution (Usher 1978). This is consistent with the existence of a fundamental lower limit in luminosity set by underlying E or N systems.

Ten years ago, in the short paper which first drew attention to the unusual properties of the variable radio star BL Lac, Schmitt (1968) noted marginal evidence for nebulosity around the source. Since then many BL Lacertae-type objects have been found with fuzzy extensions, and are now known or thought to be associated with galaxies (e.g. Oke and Gunn 1974; Wlerick et al 1974; Craine et al 1975; Kinman 1975; Ulrich 1978). Thus it is likely that their optically faintest magnitudes B(max) are at least as bright as those of radio-galaxies at the same redshift in the Hubble diagram. The statistical likelihood of this being true can be gauged from Figure 1, which shows the small number of BL Lacertae objects having both good photometric histories and reasonably certain redshifts (0235 + 164; 0430 + 05; 0521-36; 0735 + 178; 1101 + 38; 1514-24; 1727 + 50; 1807 + 69; 2200 + 42). When B(max) - A_B for these BL Lacertae objects (filled circles) are compared with

N and radio galaxies (Sandage 1972, 1973; Spinrad et al 1975, 1977) as in the inset to Figure 1, the two distributions match quite well. The single exception so far is PKS0735 + 178. (The Seyfert galaxy 3C120 is included in this sample because its high frequency radio properties are indistinguishable from those of the more active BL Lacertae sources; the weak line N galaxy 3C371 is also included because of its similarities to BL Lacertae objects; e.g. Oke 1978; Miller 1975; Usher 1975).

Thus, mindful of the caveats expressed by Kinman (1978) it follows that B(max) statistics can generally supply approximate lower limits to redshifts; the probability that the limit is close to the actual redshift is presently estimated to be about 80%, with a standard deviation in log Z of about 0.1. For example, for sources 0048-097, 0109 + 22, 0829 + 04, ON231 and OY 091 we estimate Z ≈ 0.1 (or greater) while for ON325, Z ≈ 0.07 (or greater).

If the above arguments are generally true for the whole BL Lacertae population, then the R(max) - α correlation for these sources may have a simple explanation (at least to a first approximation). Inasmuch as underlying galaxies would then furnish standard candles by which to estimate redshifts, B(max) - A_B would equal 5 log Z to within an additive constant, with a sigma of about 0.4 magnitudes. (Cosmological effects are assumed negligible). Then from equation (1), R_B^5(max) would be proportional to 2.5 log[F(max;5) Z^2]

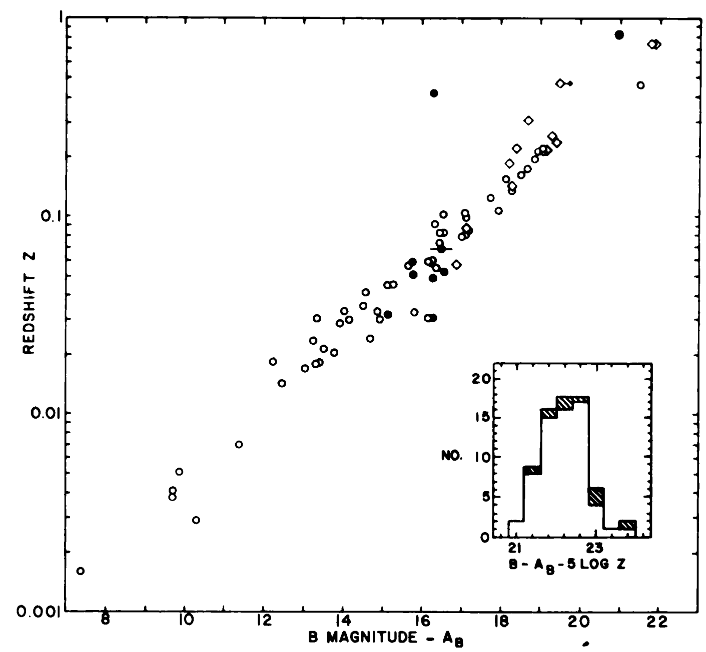

Figure 1 -- Hubble diagram for N galaxies (diamonds; faintest B magnitudes at largest diaphragm apertures), and E galaxies (open circles; B_{26} magnitudes), corrected for extinction A_B, from the work of Sandage (1972, 1973) and Spinrad et al (1975-1977). Filled circles show BL Lacertae objects with known redshifts and good photometric histories; they are compared with N and radio galaxies in the inset, except that PKS 0735 + 178, which lies above the galaxy line, is omitted.

and would then in effect become an absolute monochromatic radio magnitude at maximum flux density F. The existence of a sequence of BL Lacertae objects in the R(max)-α diagram would then imply that this is a sequence in a pseudo-radio-color-magnitude diagram. A recent version of such a R(max) - α diagram for BL Lacertae objects (filled circles) is shown in Figure 2. The open circles represent "normal" quasi-stellar sources, and are added simply for comparison purposes, i.e. the above arguments do not necessarily pertain to them. Newly added BL Lacertae objects are 0235 + 164, 0109 + 22, 0048-097, OE110 and 1308 + 326.

From Figure 2 it appears that the BL Lacertae sequence sets the limit for normal quasars, but the question arises as to where such a sequence might be located in a real radio color-magnitude diagram.

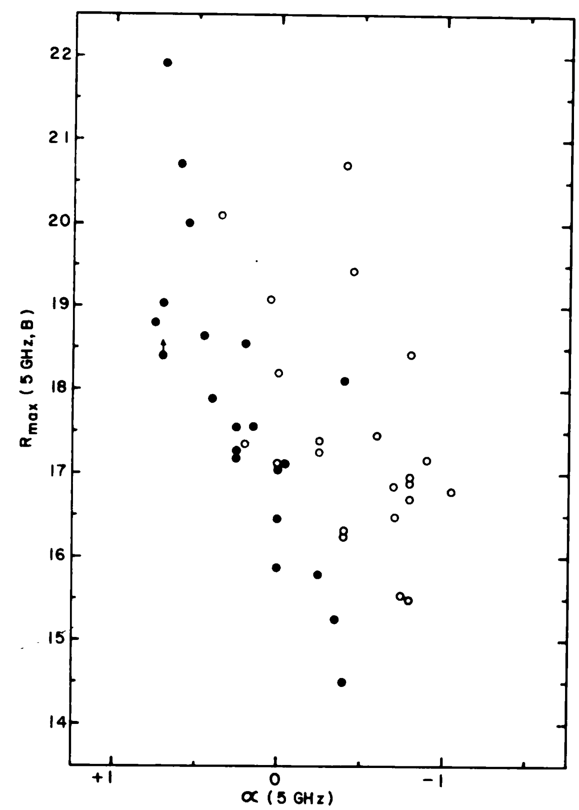

Figure 2 -- $R_{max}(5, B)$ is proportional to the logarithm of the ratio of maximum flux density at 5 GHz to optical flux density at 0.44 μm; α is the spectral slope d log F/d log ν at 5 GHz, or the slope of the upper envelope for variable sources. Filled circles denote BL Lacertae objects, open circles other quasars.

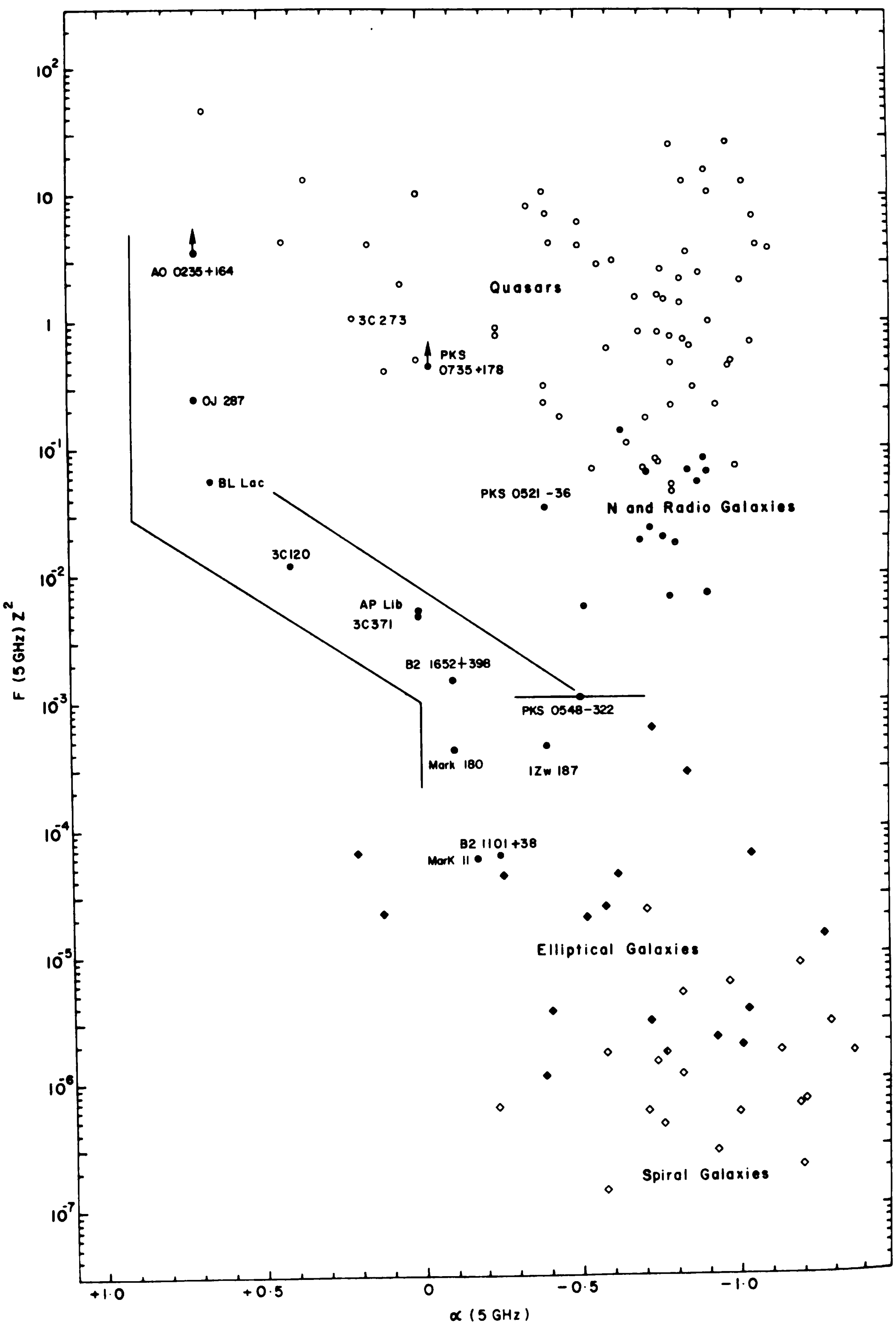

Figure 3 - - Radio Color-Magnitude diagram at 5 GHz

Such a diagram is shown in Figure 3. Only BL Lacertae sources with known redshifts can be plotted, but the position of OJ 287 is shown based on the redshift estimate Z ~ 0.2 of Kinman (1975). Lower limits to F Z^2 are due to absorption line spectra and the assumption of Doppler redshifts. The zig-zagged line is our estimate of the limit to the BL Lacertae sequence, while the sloping lines have the same slope as the middle portion of the BL Lacertae sequence in Figure 2. Figure 2 and the arguments leading up to it suggest that most or all BL Lacertae sources are located near or within the lines. The BL Lacertae sequence appears to lead off from the elliptical galaxy distribution of Sramek (1975) and, progressing via such objects as Markarian 180, AP Lib, and the eponymous BL Lac, the sequence seems to terminate near the edge of the normal quasar distribution with such violent variables as OJ 287 and AO 0235 + 164.

It has been suggested that BL Lacertae objects are young quasars (Usher 1975). If so, extended components might dominate the radio emission as time progresses, and the sources would evolve to the right in Figure 3. Such a scheme might explain the locations of PKS 0735 + 178 and the weak line N galaxy PKS 0521-36 in the diagram. The vertical coordinate of the distribution is probably a function of the rate of energy generation, as well as time.

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[Ed.: *Discussion of this paper follows paper by Danziger et al., p. 209*].

THE NATURE OF PKS 0521-36*

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SUMMARY

The radio source PKS 0521-36 has weak optical emission and absorption features, but otherwise has the characteristics of a BL Lac object. We show that the emission spectrum is of low ionization and resembles that of the collisionally ionized gas in NGC 1052. The absorption features are attributable to an underlying population of late-type stars with the same redshift as the ionized gas. The optical spectral index is about -1, but this may steepen before the Lyman continuum. From the nature of the emission spectrum it is probable that PKS 0521-36 contains at least 10^5 $M_\odot$ of ionized gas.

1. INTRODUCTION

The steep-spectrum radio source PKS 0521-36 was identified with an N galaxy by Bolton, Clarke and Ekers (1965). From very weak features in the blue part of the spectrum, Westerlund and Stokes (1966) deduced an emission line redshift of Z = 0.061. However, Searle and Bolton (1968) revised this to Z = 0.055 when they obtained a red spectrum which showed [OIII] λλ4959, 5007 and Hα with [NII] λ6584.

The optical flux is variable on a time scale as short as a few months with a total amplitude of about one magnitude in V (Eggen, 1970; Shen, Usher and Barrett, 1972). The infrared and optical colours are consistent with the object being a normal galaxy with $V \sim 15^m$ together with a non-thermal nuclear source which has been as bright as $V = 14^m$ (Eggen, 1970; Westerlund and Wall, 1969; Andrews, Glass and Hawarden, 1974). With $H_o = 50$ (km/sec)/Mpc, the radio source has a monochromatic luminosity at 1410 MHz of 2×10^{25} W/Hz/sr and the underlying galaxy an absolute magnitude $M_V \sim -22.6$.

In this paper we present new observations of the optical spectrum of PKS 0521-36 and discuss its relationship to the active elliptical galaxies and the BL Lac objects.

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*Read by Dr. P. Veron.

2. OBSERVATIONS

During the period January-December 1976, three observations of PKS 0521-36 were made with the image-dissector-scanner and one with the image-photon counting system on the Anglo-Australian Telescope. These have been calibrated and combined to yield the composite scan shown in Fig. 1. The input apertures were 2 x 4 and 1 x 4 arcsec for the IDS and IPCS scans, respectively, and the resulting spectral resolutions 10 and 4 Å (FWHM). The relative flux scale as a function of wavelength is determined to about ±15% over the observed range; however, we do not place enough reliance on the absolute spectrophotometry to say whether the nucleus varied significantly during the period of observations. The justification for combining the four scans is the apparent constancy of the [OIII] emission line equivalent widths.

3. RESULTS AND DISCUSSION

Figure 1 shows the object to have weak emission lines on a continuum which is not perfectly smooth. The structure in the continuum we interpret as a contribution from a late-type stellar absorption spectrum superposed on a blue power-law continuum from the nucleus. The emission and absorption line redshifts of $Z_{em} = 0.0554 \pm 0.0001$ and $Z_{abs} = 0.0552 \pm 0.0003$ are indistinguishable. The relative emission-line intensities have been measured and appear in Table 1 on a scale such that $I(H\alpha) = 286$. The observed continuum is fitted by a power law ($f_\nu \propto \nu^{+\alpha}$) with an index $\alpha = -1.4$. From the equivalent width of the NaI D-line compared to the value measured in normal elliptical galaxies, we estimate that the contamination by starlight is about 20% at that wavelength. We have therefore subtracted this proportion of an elliptical galaxy spectrum from the composite scan to estimate that the pure power-law index is close to $\alpha = -1$.

The low ionization emission lines are strong, and the spectrum shows a close resemblance to that of the active elliptical galaxy NGC 1052 (Fosbury et al., 1978; Koski and Osterbrock, 1976) which is thought to have a collisionally ionized spectrum. No reddening correction has been made for either of the objects in Table 1.

The weighted mean of the three IDS scans yields AB(5500) = 14.6, which is consistent with the range in V magnitude discussed by Eggen (1970). The Hα luminosity, corrected to the rest frame of the galaxy, is then $L(H\alpha) = 2.6 \times 10^{41}$ erg per sec. The relative strength of [OII] λ3727 suggests that there is little collisional de-excitation, and we therefore assume that $N_e \lesssim 10^4/\text{cm}^3$. If $T_e \simeq 10^4$ K, the mass of ionized gas must therefore be greater than $10^5\ M_\odot$.

4. CONCLUSIONS

If the nucleus of PKS 0521-36 were surrounded by gas optically thick to the Lyman continuum, and the power-law spectrum extended from the optical to the ultraviolet with $\alpha \simeq -1$, then the equivalent width of H_β would be ∿100 Å, which is much greater than observed. Although the weakness of the observed Balmer lines could be explained if the gas only covered a small fraction of the sky seen by the continuum source, the presence of collisional ionization argues in favour of a lack of

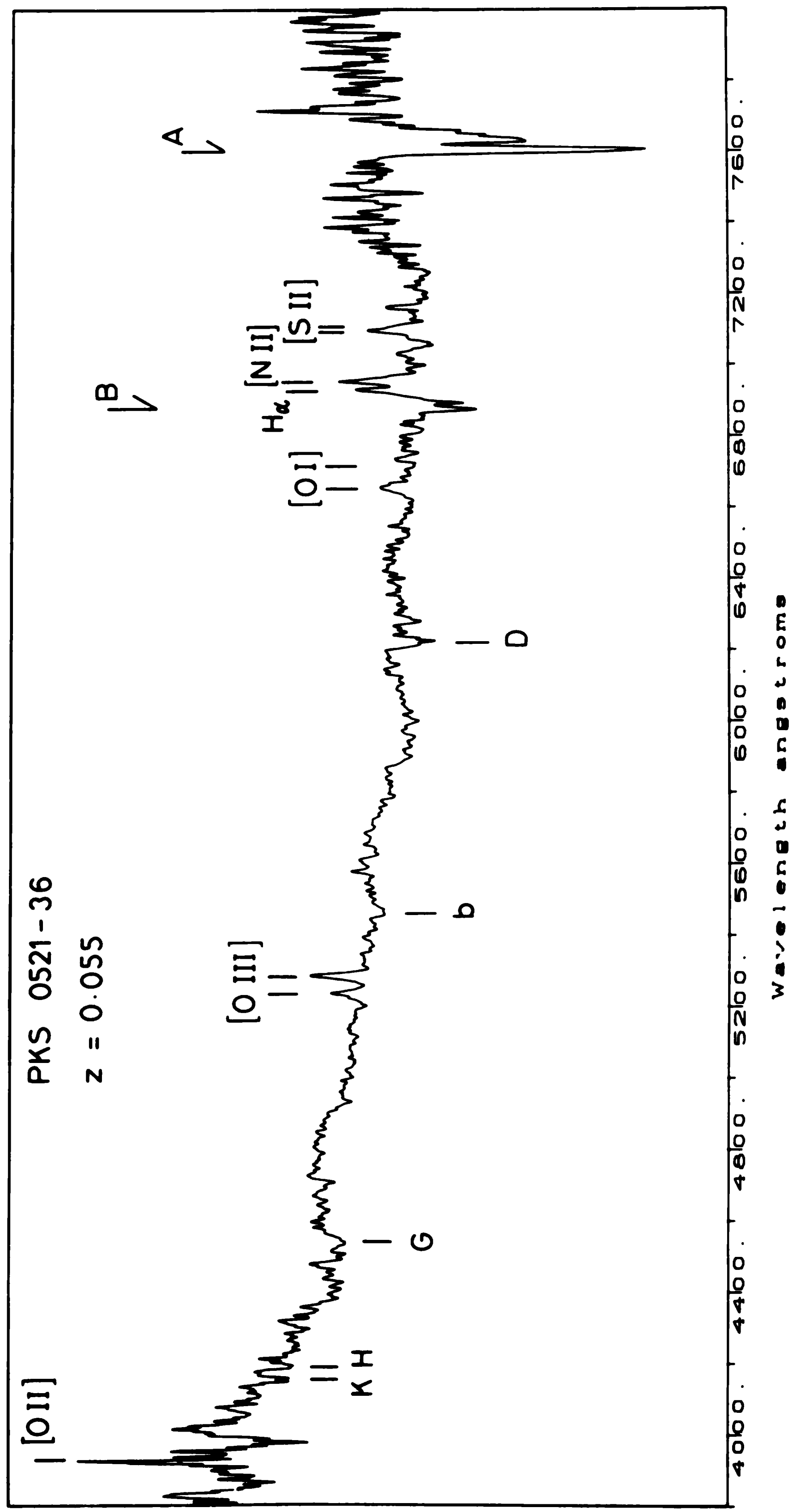
PKS 0521-36
z = 0.055
[O II]
K H
G
[O III]
b
D
[O I]
Hα
[N II]
[S II]
B
A
4000.
4400.
4800.
5200.
5600.
6000.
6400.
6800.
7200.
7600.
Wavelength angstroms

Table 1

Relative emission line intensities in PKS 0521-36 compared to NGC 1052 [scaled to $I(H\alpha) = 286$]

Line	Relative intensity	
	PKS 0521-36	NGC 1052
3727 [OII]	840	800
4959 [OIII]	117	76
5007 [OIII]	272	223
6300 [OI]	152[a)]	147
6563 $H\alpha$	286	286
6584 [NII]	423	300
6725 [SII]	268	301

a) There may be a significant contribution to the strength of this line by [SIII]λ6312, since it appears to be broader than the other lines and has a wavelength greater than that expected from the redshifted [OI]λ6300 line. This has been previously noted in PKS 1718-649 by Fosbury et al. (1977).

ionizing radiation.

PKS 0521-36 shows the characteristics of a BL Lac object except that weak spectral features can be seen. If the optical non-thermal continuum were weaker, it would resemble the active elliptical galaxies; if it were stronger, the classification would be as a normal BL Lac object.

Note added subsequent to the conference. Recent optical photography reveals a jet emerging from the nuclear region of PKS 0521-36. This and recent high resolution radio observations will be discussed in a forthcoming paper.

Acknowledgements

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DISCUSSION (papers by Usher and Danziger et al.)

B. WILLS (To Veron):
I want to ask Dr. Veron about Dr. Danziger's observations. Do you know what aperture was used, and where on the galaxy it was? Was the aperture located on the nucleus?

P. VERON:
It was on the nucleus and the aperture was 2 x 4 arc sec^2.

B. WILLS:
I want to comment further about the BL Lac nature of PKS 0521-36. In regard to its radio variability, it doesn't vary very much at all. I have observed it over a period of about 3 years at a number of frequencies, 6 cm. being the highest frequency, and I don't find it to vary very much at all.

K. KELLERMANN:
Only a small fraction of the total flux is in that compact component. It still may vary by quite a bit, but the relative variation may be washed out by the strong constant component.

B. WILLS:
Yes, it has a very steep spectrum.

K. KELLERMANN:
There are VLB observations which indicate the presence of a compact component.

J. MILLER:
I would like to comment on something that Dr. Veron said. He based a series of progressive steps starting with the position of NGC 1052 assuming that the gas is collisionally ionized. I think that with the BL Lac objects the emission lines could arise in a collisionally ionized gas, but the first step of that argument is very uncertain because it requires the establishment of the OIII temperature in NGC 1052 and that depends on a measurement of [OIII] λ4363 which sits right next to the very strong FeI absorption feature. Unless you remove the galaxy contribution very precisely, you will make a gross error in temperature. I tried to do it carefully for the past 3 years and I am still unhappy with the results: I get a temperature on the order of 10,000 to 15,000K with the conventional interpretation of photoionization rather than collisional ionization. It's a very difficult measurement to make and one reason I haven't published it is because Don Osterbrock was the first to measure it (Koski and Osterbrock 1976, Ap.J. Lett., 203, L49) and I hesitate to rush into print and contradict him until I am absolutely certain [*laughter*]. All I am saying is that your result should be treated with considerable caution.

E. CRAINE (To Usher):
Joe Miller has just summarized redshift data for BL Lacertae objects which are more recent than your original sample. Can you make a comparison between your predicted redshifts and those measured by Miller?

P. USHER:

The redshift estimate for OJ 287 would be at least 0.1 based on a Palomar 48 inch Schmidt plate by Luyten of the 8^h Sandage-Luyten survey field in 1966. If I recall, J. Miller found a single line at λ6538, so one would look for its identification shortward of about λ5950 in that case.

The redshift of 1308+326 would be about 0.3 or more based on Liller and Gottlieb's magnitude from the blue Palomar Sky Survey (IAU Circ 2939, 1976). This is quite a bit less than J. Miller's redshifts, but is consistent with them.

These are the only two I could comment on.

H. MILLER:

How do Seyfert galaxies fit into the progression from elliptical galaxies to BL Lac objects in your diagram?

P. USHER:

I haven't examined Seyferts other than 3C 120 in any detail, but certainly that's the next thing to do.

OPTICAL SPECTROSCOPY OF BL LACERTAE OBJECTS AND THEIR RELATIVES

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I. ABSORPTION LINE SYSTEMS IN BL LACERTAE OBJECTS

I shall restrict this discussion to absorption lines from gas intervening along the line of sight to BL Lac objects rather than absorption lines due to a stellar component associated with the BL Lac object as described in Joe Miller's previous paper. The BL Lacertae objects for which such absorption line systems have been reported are listed in Table 1. Summarizing the meager information available, the absorption line systems all have redshifts $z < 1$, showing the Mg II resonance doublet $\lambda\lambda 2796.3, 2803.6$. In some cases other features are seen: Mg I $\lambda 2852.1$, Fe II $\lambda\lambda 2344.2$, 2374.5, 2382.8, 2586.7, 2600.2, and in one case Mn II $\lambda\lambda 2576.9$, 2594.6, 2606.5. All of these features are zero-volt transitions; absorption from excited fine structure levels, although searched for, has not been detected. Qualitatively the absorption line spectra of BL Lac objects resemble the interstellar absorption line spectrum of a galactic star (e.g. ζ Oph, Morton 1975) with larger line equivalent widths. On the other hand detection of absorption lines in BL Lac objects is historically different from the case of quasi-stellar objects, while the high redshift ($z \gtrsim 2$) QSOs typically show multiple absorption redshift systems, also at high redshift. As we will discuss later, it is likely that this is a selection effect.

TABLE 1

Absorption Line Systems in BL Lac Objects

Object	V	z_a	References
AO 0235+164	19.5-14.5	0.524 0.821	Burbidge *et al.* (1976) Rieke *et al.* (1976) Roberts *et al.* (1976)
PKS 0735+178	15-16	0.424	Carswell *et al.* (1974) Peterson *et al.* (1976)
B2 1308+326	14.5-16.5	0.87	Miller (1978)

Two objects have been studied in some detail, PKS 0735+178 and AO 0235+164:

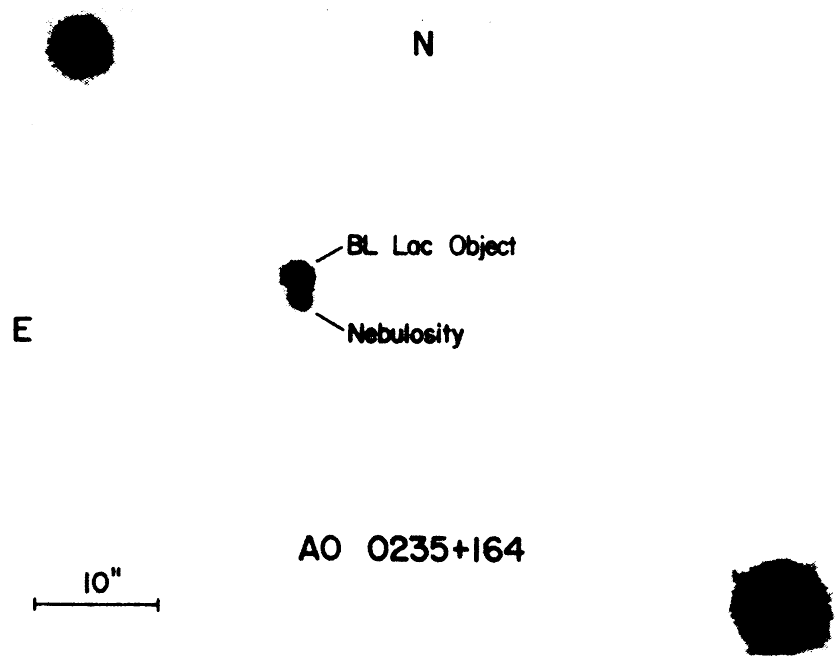
a) PKS 0735+178

The BL Lacertae object PKS 0735+178 is the first in which absorption features were reported. Carswell et al. (1974) reported a pair of absorption lines which they interpreted as the Mg II doublet at a redshift z = 0.424. A more detailed study by Peterson et al. (1977) also finds Fe II $\lambda2599$. Based on their equivalent widths and the lack of detectable 21 cm absorption they suggest that in the absorbing cloud $N_H \sim 4 \times 10^{18}$ with normal magnesium abundances. Sargent and Boksenberg (private communication) have observed the Mg II doublet in 0735+178 at high resolution, finding that each line is composed of multiple components each a few km s^{-1} wide.

b) AO 0235+164

The Arecibo Occultation radio source AO 0235+164, identified as a BL Lacertae object by Spinrad and Smith (1975), experienced a radio-optical outburst in 1975 (Rieke et al. 1976; Ledden et al. 1976; MacLeod et al. 1976) reaching a maximum optical brightness over 5 magnitudes brighter than minimum. High resolution spectra obtained near maximum showed absorption features in two redshift systems z = 0.524, 0.851 (Burbidge et al. 1976; Rieke et al. 1976). Both systems show the Mg II resonance doublet and lines from the 2300 and 2600 Å Fe II resonance multiplets. The stronger z = 0.524 system, reproduced in Figure 1, also shows features due to Mn II and Mg I $\lambda2852$. Additional weak features appear to be present which cannot be explained as features in either of the two well established redshift systems. Subsequent radio observations (Roberts et al. 1976) have detected 21 cm neutral hydrogen absorption in the z = 0.524 system. These results will be discussed in detail by Art Wolfe later in this conference. A detailed curve of growth analysis of the absorption line spectrum of AO 0235+164 has been performed by Wolfe and Wills (1977) who find the Mg:Mn:Fe abundances to be roughly solar. There is a problem in interpreting the metal/H ratios from the optical/21 cm data due to the multiple cloud structure of the absorbing material evident from the higher velocity resolution radio observations (Wolfe et al. 1978).

AO 0235+164 is unique among QSOs and BL Lacertae objects, not only because it exhibits two well established redshift systems with z < 1, but also because the absorbing material in one redshift system has been optically identified. A faint nebulosity extends 2-3" south of the BL Lac object (Spinrad and Smith 1975) which has been studied optically by Smith et al. (1977). Figure 1 shows this nebulosity to be compact, almost stellar in appearance. Spectrophotometric observations of the nebulosity show emission lines of [O II], Hβ, and



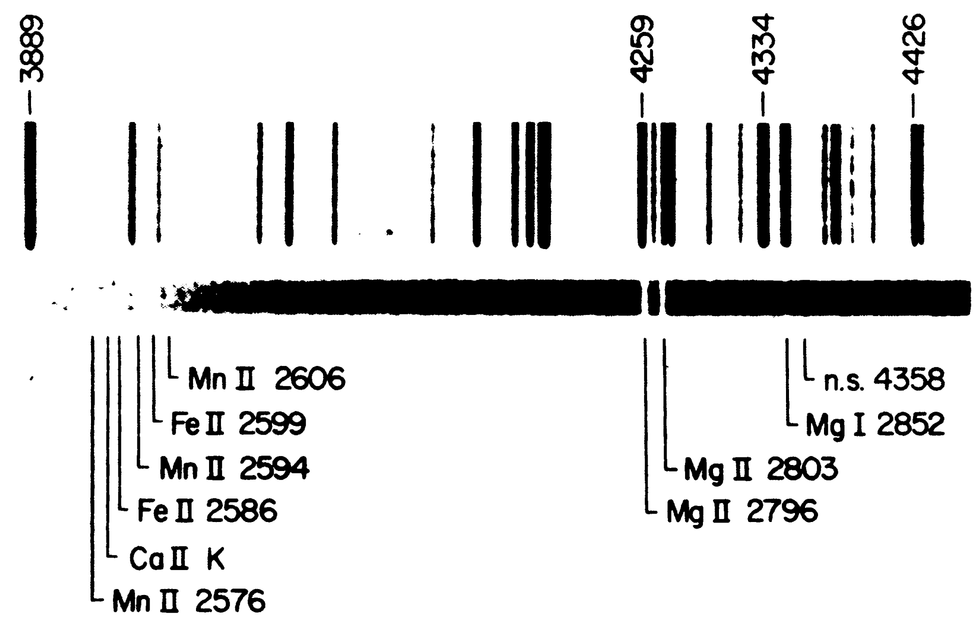


Fig. 1a. The field of AO 0235+164 showing the BL Lacertae object and the adjacent nebulosity.

Fig. 1b. Spectrogram showing the z = 0.524 absorption line spectrum of AO 0235+164 which is produced by material associated with the "nebulosity."

[O III] at the lower, $z = 0.524$, redshift. Thus material producing the absorption appears to be associated with this "nebulosity." Understanding the nature of this material would therefore seem to be important to understanding the nature of the absorption-line redshift systems seen in QSOs and BL Lac objects. While the presence of two $z < 1$ systems was at one time suggested to distinguish AO 0235+164 from absorption line QSOs, a number of QSOs have recently been seen to show absorption at relatively low redshift. The case of PKS 0454+039 with $z_a = 0.859, 1.154$ (Burbidge et al. 1977) is quite similar, for example.

The principal question is, of course, is this "nebulosity" material which is associated with the BL Lacertae object and thus presumably ejected from AO 0235+164 at relativistic velocity or is it material (presumably in a galaxy) at a cosmological distance corresponding to $z = 0.524$ which is merely intervening along our line of sight to AO 0235+164. The existence of the $z = 0.851$ system suggests that $z_{AO} > 0.85$; thus for ejection models $v_{rel} \gtrsim 0.2c$. The arguments may be summarized as follows. The central condensation and dimensions of the nebulosity are consistent with the presence of an intervening spiral or irregular galaxy. Also the optical absorption line spectrum is similar to that expected from the interstellar medium in a late type galaxy (e.g. ζ Oph, Morton 1975), and the 21 cm absorption line structure is similar to 21 cm absorption profiles of sources seen through our own Galaxy (Hughes, Thompson, and Colvin 1971). The continuum from the nebulosity is quite red suggesting that the galaxy must be highly inclined to the line of sight in order to produce substantial reddening in the galactic disk. The column density of material and 21 cm absorption structure would also suggest that $i \lesssim 10°$.

On the other hand, the probability for two galaxies (presuming that the $z = 0.851$ is produced in the same manner) along the line of sight to an object with $z \sim 1$ is quite low, $P \sim 5 \times 10^{-4}$. Considering that such absorption may not be particularly uncommon (Williams and Weymann 1978), this number is uncomfortably small. The probability was calculated using a galaxy cross section currently thought to be reasonable for a late type galaxy like M101 ($M_B = -21$, $R \sim 20$ kpc). If one ascribes the majority of absorption systems in QSOs to intervening galaxies, one may turn the question around and ask what galaxy cross section would be required. This would require column densities $N_H \sim 10^{18}$ with normal heavy element abundances at diameters as great as 0.5 Mpc (Roberts et al. 1978).

A second difficulty with the intervening galaxy hypothesis is the luminosity in the emission lines. Assuming a normal Balmer decrement, we have for the nebulosity

$$L(H\alpha) \gtrsim 1 \times 10^{42} \text{ erg s}^{-1} \quad ,$$

whereas the maximum Hα luminosity for nearby spirals is

$$L_{ScI}(H\alpha) \approx 1 \times 10^{41} \text{ erg s}^{-1} \quad .$$

The Hα luminosity of the nebulosity is at least an order of magnitude greater than even the most luminous nearby spirals. Thus any galaxy would necessarily be an active (but narrow lined) galaxy. The line luminosities and ratios are similar, however, to the emission lines seen in the nebulosity surrounding the QSOs 3C 48 (Wampler et al. 1975), 4C 37.43 (Stockton 1976), and 3C 249.1 (Richstone and Oke 1977).

Peterson et al. (1977) have reported a possible variation in the equivalent width of the Mg I absorption line in the sense that the line appears stronger on spectrograms obtained later in its outburst, after those of Burbidge et al. (1976) and Rieke et al. (1976). This might suggest that the ionization of the absorbing material had decreased, from which one would infer that the absorbing cloud must be close to the BL Lac object. Unfortunately, since its outburst, AO 0235+164 has been too faint for high dispersion spectroscopy to confirm this result.

Sanitt (1977) has proposed a gravitational lens model for AO 0235+164 which proposes to explain the brightness of the BL Lac object by gravitational focusing due to a massive galaxy at z = 0.524. However, the lack of a secondary image at either optical or radio wavelengths probably rules out any significant effect. Another, admittedly speculative suggestion has been made by Wolfe et al. (1978) that possibly the BL Lac object was ejected away from us with $v \sim 0.2c$ by the active galaxy at z = 0.524.

No completely satisfactory explanation exists. The preferred suggestion depends on one's belief that we understand something about the characteristics and space density of galaxies compared to the difficult physical problems posed by the energetics of ejecting large amounts of material at relativistic velocity and the very large ratios of ejection velocity/velocity dispersion for these absorbing clouds.

II. RANDOM OBSERVATIONS RELEVANT TO THE NATURE OF BL LACERTAE OBJECTS

a) Steep Spectrum 3C QSOs

It has been suggested that a steep optical continuum is related to the other properties of BL Lacertae objects and optically violently variable QSOs (c.f. Stein, O'Dell, and Strittmatter 1976). While the mean spectral index for BL Lac objects does appear to be steeper than the mean for QSOs, as discussed by Stein (1978) a steep optical

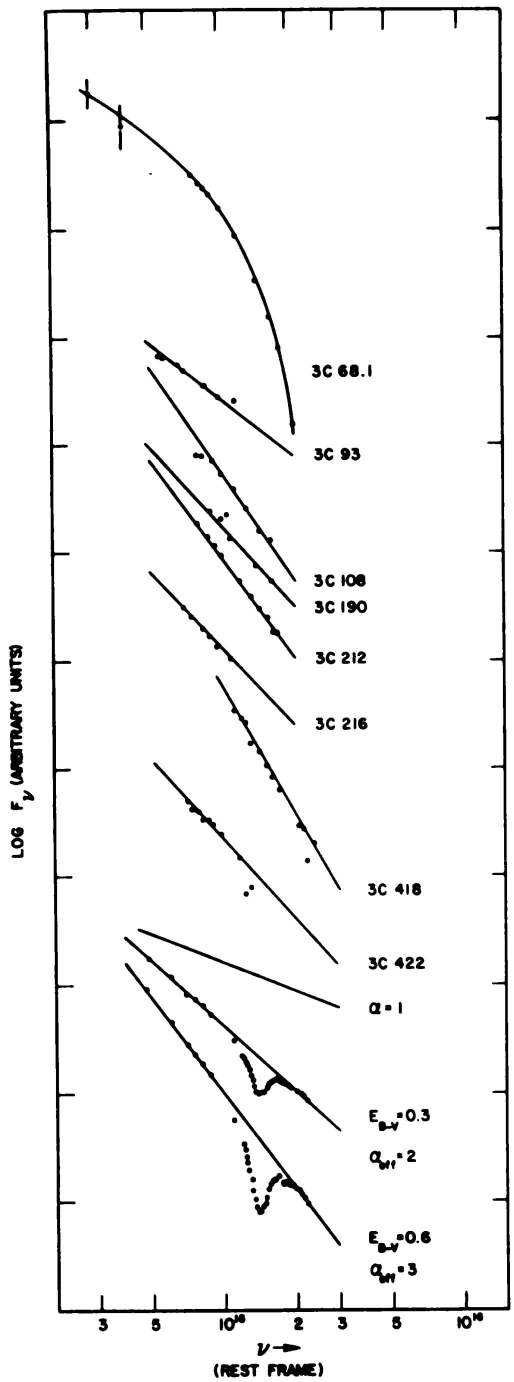


Fig. 2. The rest frame continuum energy distributions of a sample of faint red 3C QSOs. A power law continuum with $\alpha = 1$, reddened by the Galactic extinction curve with $E_{B-V} = 0.3$ and $E_{B-V} = 0.6$ is shown for comparison. None of the objects shows a significant "2200 Å feature" in absorption.

spectrum is certainly not a necessary condition. In addition, a red optical continuum does not necessarily signal a BL Lac object or OVV QSO. Figure 2 shows the optical continuum spectra of eight 3C QSOs studied by Smith and Spinrad (1979). The optical spectral indices of this sample range from 1.5 to steeper than 4 and the majority are steeper than any of the BL Lacertae objects listed in the review of Stein, O'Dell, and Strittmatter (except AO 0235+164, $\alpha \approx 4$). The redshifts of these QSOs range from 0.4-1.7, typical of 3C objects, and their magnitudes range from 18-21. These objects are thus relatively low luminosity QSOs. It would be tempting to appeal to reddening by dust in a galactic disk surrounding the QSO to explain the red colors and low luminosities. While dust is very effective at steepening the continuum of an object (see Figure 2), the lack of "2200 Å" absorption rules out dust like that in our Galaxy. These QSOs would appear to be intrinsically faint steep spectrum objects. None of these QSOs appears to be highly variable. The presence of emission lines with normal equivalent widths (particularly C IV λ1549) suggests that photoionization by the nonthermal source is not the excitation mechanism in at least these QSOs.

An interesting sidelight of this investigation is the discovery that 3C 93 and 3C 216, previously classified as BL Lac objects, are in fact relatively strong lined QSOs. The spectrum of 3C 93 is shown in Figure 3. While possible variability of the lines cannot be ruled out, it is more likely that these two objects were misclassified

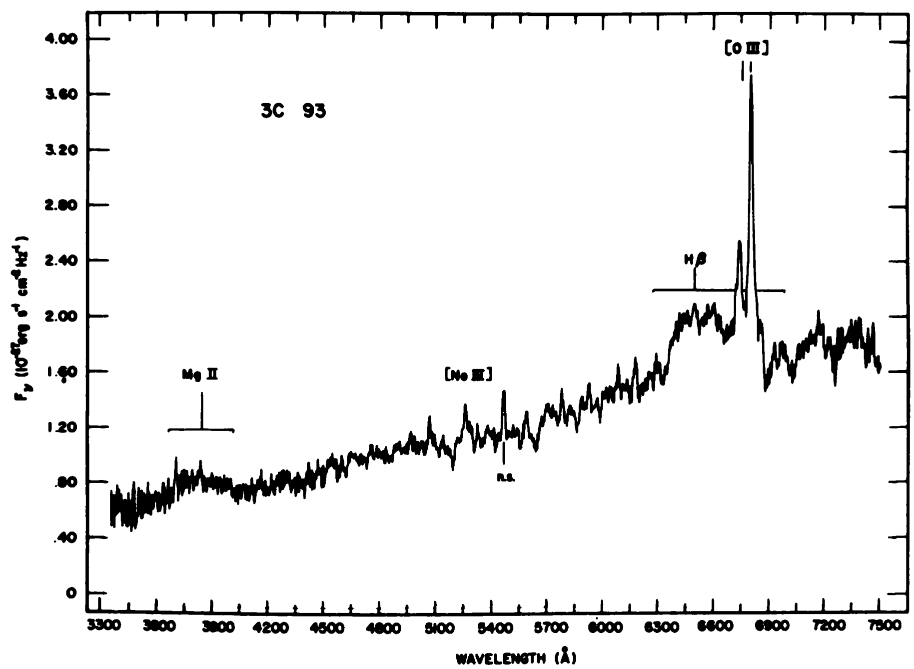


Fig. 3. Lick Observatory scan of the QSO 3C 93 previously believed to be a BL Lacertae object.

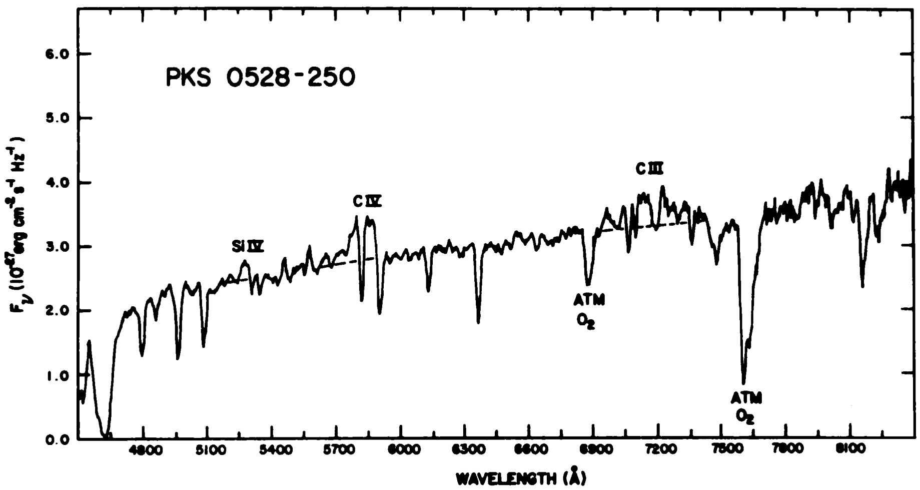
because the strong emission features fall beyond the red sensitivity cutoff of the photographic plates used before electronic detectors were available. 3C 66A is the only remaining BL Lac object in the Revised 3C Catalog. The absence of BL Lac objects from this low frequency survey underscores the importance of the compact source to the BL Lac phenomenon.

b) PKS 0528-250

The object associated with the Parkes radio source PKS 0528-250 has been suggested to be a "high redshift BL Lacertae object" by Jauncey et al. (1978) based on a strong absorption line system at $z = 2.81$, an apparent lack of emission features, and optical variability. The presence of such a high redshift object would be somewhat surprising considering that those BL Lacertae objects for which redshifts have been measured have relatively low redshifts, $z < 1$ (Miller 1978). Recent data obtained at Lick Observatory (Smith, Jura, and Margon 1978) show that PKS 0528-250 does in fact have emission lines of C IV, C III] and Si IV at a redshift $z = 2.765$; Lα is presumably masked by the strong damped Lα absorption and the very large number of absorption features short of the Lα absorption trough. Detection of the other lines is difficult because they are badly chopped up by the strong absorption line spectrum and they are at a redshift which is unexpectedly 3500 km s^{-1} lower than the absorption line redshift. While the emission line redshift is not very well determined, Figure 4 shows clearly that the C IV and Si IV absorption line doublets at $z = 2.81$ fall on the red wing of the emission profile.

While PKS 0528-250 does not appear to be a BL Lac object, it is a particularly interesting object in its own right, because it exhibits one of the largest $z_{abs} > z_{em}$ differences and also because a curve of growth analysis appears possible for the $z = 2.81$ absorption line system. The $\lambda\lambda$1855, 1863 Al III lines appear to be on the linear part of the curve of growth; thus the classical doublet ratio method may be used to perform an abundance analysis. Smith, Jura, and Margon (1978) find the Doppler parameter $b \sim 75$ km s^{-1} and suggest that the abundances of silicon, sulfur and perhaps aluminum are about a factor of ten lower than solar. The "2200 Å" dust feature is not present at $z = 2.81$ so depletion onto grains does not appear to be plausible. This abundance analysis must be considered somewhat tentative since, if the absorption lines are in fact composed of several components each with very small velocity dispersions, as in PKS 0735+178 and AO 0235+164, then significant amounts of these elements could be "hidden" in a single very optically thick cloud, while the bulk of the absorption would come from optically thin regions.

The nature of this absorbing material is also uncertain. The velocity difference $\Delta v \sim 3500$ km s^{-1} is very large for the random motion of a galaxy in a cluster containing the QSO, yet the lack of Si II fine structure absorption implies a very large distance of the absorbing cloud from the QSO hence very large QSO mass for infall.



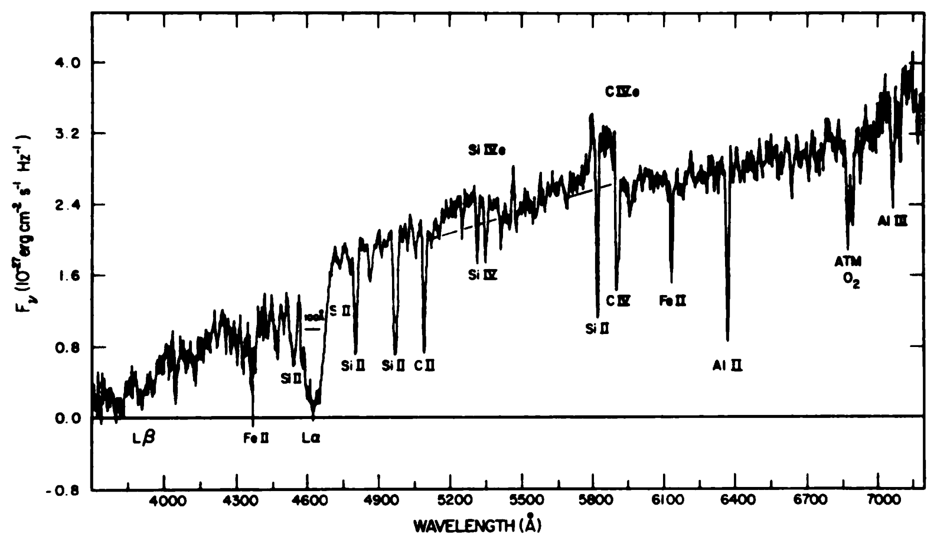


Fig. 4. **Intermediate dispersion scans of PKS 0528-250. Emission features of C IV, C III], and Si IV are clearly present. Note that the C IV and Si IV absorption features fall on the red wing of the respective emission lines.**

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DISCUSSION

H. ARP:

In that last object, 0528-250, do you have any suggestions why that CIII] is so broad?

H. SMITH:

No. I worried about it a little bit. It's different from other QSOs but the absorption lines are tearing up the continuum very badly, so that it's difficult to tell exactly what the line profiles are.

H. ARP:

But it is very broad.

H. SMITH:

Yes it is very broad. If our interpretation is correct, it's quite different from other higher redshift QSOs where CIII] has the same width as Lα and CIV and SiIV. The lack of a clear CIII] was one of the things that led the PKS group (Jauncey *et al*. 1978, Ap.J. Lett., 221, 109) to say that 0528-250 did not have an emission line redshift. They saw the same bump that we interpret as CIV but didn't see CIII] and said "well we would expect to see it".

P. STRITTMATTER:

Although I agree with you that most QSOs have narrow CIII]λ1909, less than that seen in 0528-250, similar wide features are observed in PHL 957 (Coleman et al. 1976, Ap.J. 207,1) and B2 1225+31 (Wilkerson et al. 1978, Ap.J., 223, 364) two of the brightest QSOs. My question is how bright is 0528-250?

H. SMITH:

It's variable between about 17.5 and 19.5. It was about 18 when we observed it.

J. PERRY:

First, as regards AO 0235+164. One of the consistency tests you can make of the location of the nebulosity is the luminosity of the central object. I have checked it out using the luminosity of the Hβ line which leads to a visual luminosity. At 20 kpc. the ionization-level of the gas that you observe in absorption is consistent with photoionization by the central source at the same redshift; it's not too bright. That is an important constraint.

What is your opinion of Wolfe's suggestion (Wolfe et al. 1978, Ap.J. 222, 752) that AO 0235+164 is ejected backwards from the "galaxy".

A. WOLFE:

I'll talk about that later.

H. SMITH:

I don't think it's any worse than any of the other interpretations.

A. WOLFE:

I want to ask you about the luminosity of the Hα line in the nebulosity? Huchra (1977, Ap.J. Suppl, 35, 171) wrote a paper about emission lines in Markarian galaxies. I noticed that some of the brighter Mkn galaxies had Hα luminosities similar to what you observed and they weren't that few in number.

H. SMITH:

One could put an active galaxy in front of AO 0235+164

A. WOLFE:

I want to point out that I'm not talking about Seyfert type Markarian galaxies which are very rare.

H. SMITH:

I dislike that coincidence but once in history of the Universe you can do it. Secondly, the [OIII] lines and probably Hβ are unresolved at our dispersion whereas active galaxies tend to have broader lines.

A. WOLFE:

I meant the narrow-lined Markarian galaxies. In terms of total luminosity they appear very similar to your nebulosity.

AN ERUPTIVE BL LAC OBJECT WITH A HIGH REDSHIFT, 0846+51W1

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and

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ABSTRACT

An optically identified radio source was observed to brighten from $\underline{V} \sim 19.5$ mag to $\underline{V} = 15.7$ mag in less than one month (Arp, Willis, and de Ruiter, 1975). Additional optical and radio observations are now reported. They show: (1) At maximum light outburst the continuum is featureless and the object has all the radio and optical characteristics of a BL Lac object (excepting polarization, which is unknown). (2) The normal light level is between $\underline{V} = 19$ and 21 mag. (3) Throughout its phases the optical $\underline{B}$-$\underline{V}$ and $\underline{U}$-$\underline{B}$ colors are appreciably redder than any quasar. (4) The spectrum at minimum light has emission lines that yield a redshift of $\underline{z} = 1.860$. (5) The BL Lac object lies only 12" south of the southern member of a pair of interacting spirals. (6) One possible emission line is not identified in the $\underline{z} = 1.86$ redshift system. This could be part of a second emission-line redshift system. The latter would require confirmation by additional observation.

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DISCUSSION

P. VERON:

Did you suggest that the small redshift* comes from the small thing? [*Ed.: The "thing" referred to can be seen in the accompanying photograph as the faint nebulosity located S.E. of 0846+51W1.*]

H. ARP:

No, I specifically checked the small nebulosity off to the side to see that I wasn't getting any light from that. We can clearly rule that out. If there are two emission line redshifts in that object, they are both coming from that 1 arc sec. seemingly stellar image.

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*[*Ed.: In his talk Dr. Arp mentioned that an emission line observed at 4891A could not be identified with any known transition at z=1.86. He suggested that this might be MgII λλ2800 emission from a second redshift system with z=0.747. As supporting evidence he stated that the unusually broad CIII] λ1909 line at z=1.86 might actually be a blend of this line with OIII λ3133 emitted at z=0.747. Also a weak feature observed at 6510Å could be [OII] λ3727 emitted at z=0.747.*]

Fig. 1. 0846+51W1 and the Surrounding Field

M. BURBIDGE:

What was the angular separation of the fainter nebulosity just south of 0846+51?

H. ARP:

The small nebulosity is 2" southeast of the 0846+51W1. Arp measured it to be at V = 22, B = 22.8 mag. It does not have obvious emission lines so that it could not have contaminated the observations of 0846+51W1. Aside from its closeness there seems to be no indication that it is associated with 0846+51W1 as the nebulosity near AO 0235+164 is suspected to be.

J. MILLER:

What was the size of the slit?

H. ARP:

0.9 arc sec.

J. PERRY:

What was the apparent magnitude at maximum?

H. ARP:

15.7! At $z_{em} = 1.87$ this object is among the intrinsically brightest of the QSOs assuming $z_{em} = z_{cosmological}$.

J. PERRY:

What is the redshift of the galaxies?

H. ARP:

The two interacting galaxies are z = .070 and the third one up in the chain is at z = .050. There are some others in the chain for which I have not obtained any redshifts.

J. PERRY:

And there's no indication of absorption?

H. ARP:

You saw the spectrum. I wish we could see absorption, but I think it's just a matter of going to higher dispersion.

J. PERRY:

Practically every QSO with a redshift close to 1.8 has a 100% probability of showing absorption. The absorption should be most visible when the object is bright if it is due to intervening objects.

H. ARP:

I think it's an ideal candidate for showing absorption except that it is a little faint.

M. ROBERTS:

This peculiar object (0846+51W1) is rather close to two of the galaxies on your slide. Are there any morphological peculiarities exhibited by the galaxies?

H. ARP:

Now that you ask, I must admit that there is a short jet-like feature coming out of the nucleus of the nearest spiral and pointing in the general direction of 0846+51W1. I want to point out that there is some precedent for this so I won't be accused of invoking a posteriori statistics. The first is a QSO observed by Bolton and Peterson (Bolton, J. and Peterson, B. 1974, "Formation and Dynamics of Galaxies", I.A.U. Symposium No. 38. ed. J.R. Shakeshaft (Dordrecht: D. Reidel), p. 222) which was discussed in the Australian meeting in which there is a QSO that falls right in a line of galaxies: the QSO falls right by the arm of the galaxy. The second is one that Stocke published recently (Stocke, J. and Arp, H. 1978, Ap.J., 219, 367) in which two QSOs line up along the line joining a pair of interacting galaxies. The probability for the interacting pair occurring by chance this close to 0846+51W1 is 6×10^{-4}.

D. WILLS:

The λ3133 line [*Ed.: See footnote to question by P. Veron.*] is usually not a very strong line and only rarely seen. Do you think it really helps the interpretation of the second emission redshift?

H. ARP:

Yes, I think so because as you can see there is even an indication of a little doubling at that wavelength and it is just about the right separation from the CIII] λ1909 line at $z = 1.86$.

D. WILLS:

But isn't its strength unusual?

H. ARP:

I realize that the λ3133 line is usually not a very strong line but combined with the $z = 1.86$ CIII] line that is already there I think the identification is pretty good. I would also like to point out that there is a difficulty with the night sky subtraction in that the λ5460 line comes in so it really needs higher dispersion. It really needs a good job of sky subtraction before it can be confirmed.

D. RICHSTONE:

I wanted to echo Peter Strittmatter's point about the breadth of CIII] lines in QSOs. I've recently done a survey of about 40 high-z QSOs and I don't think that it is at all uncommon for the CIII] λ1909 line to be broader than the CIV 1550 line in velocity. He (Strittmatter) mentioned the two famous cases, but I think there are many more.

H. ARP:

I was interested in earlier statements about this. In 0846+51W1 the supposed CIII] line is both broader and stronger, or almost as strong as CIV. It looks wrong, too strong in integrated strength. Moreover, the best addition of spectral data looks to me as if there is a weaker line coming in at about 5473Å on the red side of the λ5460 line attributed to CIII] in the z = 1.860 system. It seems quite possible to me that if a small OIII λ3133 line were subtracted, the CIII] line might look much more normal.

H. MILLER:

I have two questions about the radio variability that you reported. The first is what was the time scale involved and secondly is it correlated in any way with an increase or decrease in the optical variability?

H. ARP:

At 1415 MHz the flux decreased from 400 mJy in 1970 to 190 mJy in 1975. This is really all the time data we have on the radio behavior. Willis and Oosterbaan have made recent observations at Westerbork, but they have not been reduced yet.

J. PERRY:

I would like to go back to the question of absorption. When the object is at its brightest is when you should see absorption by intervening objects. That's in fact what happened in the case of AO 0235+164, the absorption came up when the object got brighter.

H. ARP:

Just a point of explanation. When this erupted in 1975 we were doing mostly multi-channel scans at the 200" which of course have quite low resolution for seeing absorption lines. About half-way through, the SIT spectrograph came on line and those later observations were at a much higher resolution but 0846+51W1 was much fainter by then.

3C 446 AS A BL LAC OBJECT

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I. INTRODUCTION

Since it is now well established that some BL Lac objects have redshifts that indicate their luminosities are comparable to those of typical luminous quasistellar objects, it is reasonable to ask if any QSOs have properties that would put them in the BL Lac class. To answer this question requires a definition of what are the crucial phenomena which an object must exhibit to be considered a BL Lac object. We feel the following three aspects of the various optical phenomena are essential:

1. The object is starlike, possibly surrounded by nebulosity. When a redshift is available, the object is of high luminosity.

2. Large light variations occur ($\Delta m > 1.5$ mag), sometimes very rapidly (time scales of days to weeks).

3. The optical light can be highly polarized (up to 35%), and the polarization varies rapidly (time scales of days) in both amount and angle.

The above are characteristics of a very compact object and suggest that, when we observe BL Lac objects, we are observing directly the central energy source. Weakness of spectral features is also considered to be a characteristic of BL Lac objects, but we feel that this is a secondary property, not a defining one. It is the direct view of the central object, as indicated by the above three primary characteristics that makes BL Lac objects of great importance, not that their emission lines are weak or absent, though this aspect certainly raises important questions.

Given the above characteristics, the subset of QSOs known as the optically violently variables (OVVs) would appear to be directly related to the BL Lac class; they are known to exhibit large light variations and some have been observed to be strongly polarized. We are currently engaged in a study of OVV QSOs to investigate carefully the properties of these objects and their possible relationship to the BL Lac class. As QSOs, they do have prominent emission lines, and thus we have the opportunity to derive important information in addition to that contained in the continuum data.

Our program includes a sample of approximately 20 objects ascribed to the OVV class. There is no question that this sample is not a uniform collection of objects, since there are no generally agreed set of defining characteristics for the OVVs and our collection was selected from several sources. Probably the only one thing they all definitely have in common is that they have varied by over a half magnitude sometime during this century. A few, such as 3C 279, 3C 345, 3C 446, and 3C 454.3 have been observed to vary quite a bit more than this and are considered prototypes for the class. We were fortunate to catch 3C 446 while it was undergoing an outburst during the second half of 1977, and this paper presents our observations and conclusions about this object. We also present some observations of PKS 0420-01 which suggest that it is also related to the BL Lac class. The equipment and reduction procedures used are the same as for the study of BL Lac objects we present elsewhere in this volume.

II. SPECTROPHOTOMETRY

We derived continuum magnitudes at 4200 Å, given in parentheses, on the following 5 nights in 1977: August 20 (17.8), October 8 (17.1), November 16 and 17 (17.0), and December 8 (17.2). All of these measurements indicate that 3C 446 was going through an outburst, since at minimum it is about 5-10 times fainter. Also, it is not clear that the peak had been reached in December when 3C 446 became too close to the sun to be observed further. We note that two emission lines normally readily detectable, C III] λ1909 and Mg II λ2800, appeared at low contrast against the strong continuum and might not have been detectable at all on lower quality data.

We find that, for the entire observing period, the continuum between 4000 Å and 8000 Å can be fitted very well with a power law ($F_\nu \propto \nu^\alpha$) with spectral index $\alpha = -2.04 \pm 0.1$. There is marginal evidence that the continuum may get a bit flatter ($\Delta\alpha \sim 0.1$ to 0.2) in the red, but better data than ours would be required for a reliable, quantitative statement to be made. This is a bit redder than any of the BL Lac objects we studied. E. J. Wampler has provided us with unpublished data he obtained on the spectral energy distribution of 3C 446 during the period 1966-1969. Over that time the mean m(4200) was roughly 18.5, about a factor of 4 times fainter than when we observed it. From his data, we derive $\alpha = -2.01 \pm 0.1$, over the range 4000 Å to 8200 Å, with no significant evidence for curvature. Thus the spectral index is seen to be constant over a substantial change in energy output.

We are also able to compare emission-line fluxes observed in 1977 with those obtained by Wampler ten years earlier. We have been able to reliably measure C III] λ1909 only, for which we derive $1.4 \pm 0.4 \times 10^{-14}$ erg cm^{-2} s^{-1}, by averaging over five nights' data. Wampler's data yield 1.3×10^{-14} erg cm^{-2} s^{-1}, with about a 25% error, so the evidence is good that the flux in this line has not varied significantly in a ten-year period, in spite of substantial continuum flux variations.

III. ABSORPTION LINES

We were surprised to discover the presence of a relatively sharp doublet in absorption in our data, since 3C 446 has been studied extensively in the past, and no report of such features exists in the literature. The pair are at 5163.8 Å and 5177.5 Å; the obvious identification based on the spacing and analogy to other objects is with the Mg II λ2800 doublet. This identification yields a redshift $z = 0.8472$, substantially smaller than $z_{em} = 1.404$. We also definitely detect Fe II λ2586 and λ2599 at this redshift, but the data are too noisy to the blue of these features to permit a reliable detection of other expected Fe II lines. We measure $W_\lambda(\lambda 2795.5) = 0.99$ Å and $W_\lambda(\lambda 2802.7) = 0.80$ Å in the observed frame with an absolute error of about 25%; there is no question that the k component is stronger than h, though the doublet appears to be moderately saturated. Figure 1 shows the average of all our data in the blue spectral region.

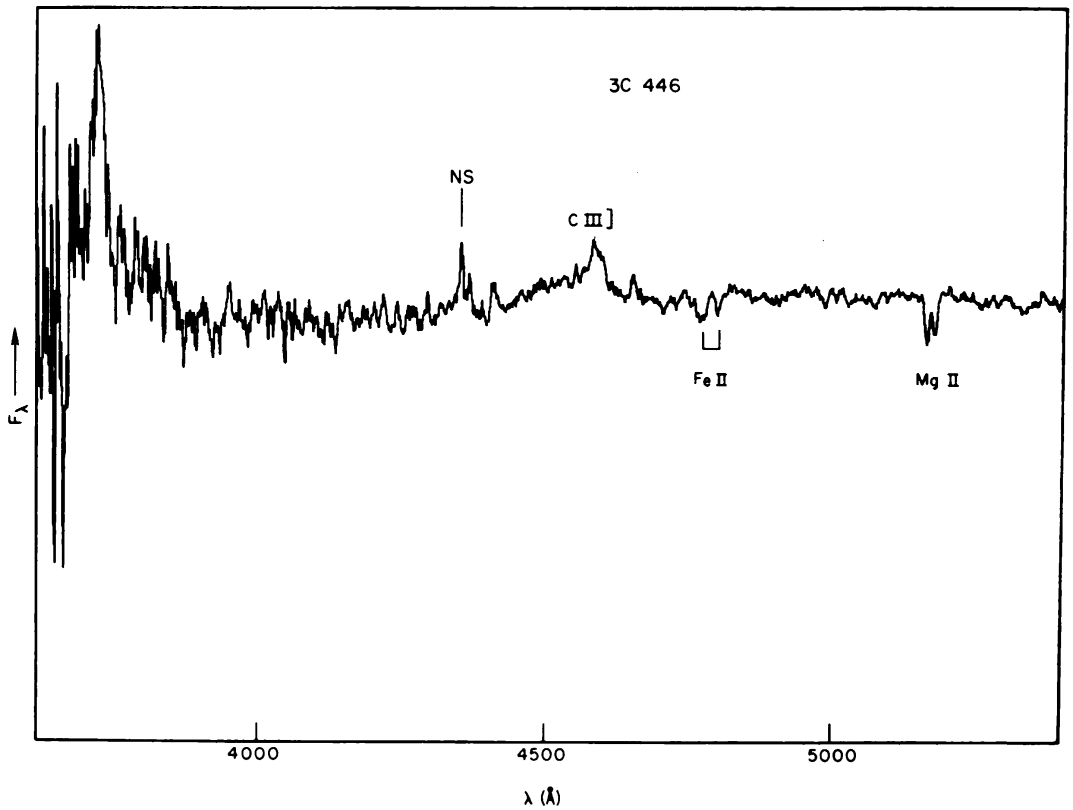

Fig. 1 - A portion of the spectrum of 3C 446. C IV in emission can be seen at the left where the tube response is declining rapidly toward the blue. NS marks the position of the residual of a night-sky Hg line. The lower boarder marks the position of zero flux.

IV. POLARIZATION MEASUREMENTS

We measured the linear polarization of 3C 446 on 4 nights in 1977 using the polarimeter devised by Nordsieck (1974; see also Miller 1975). The results are given in Table 1 and represent the average values over the interval 3800 Å to 5800 Å.

TABLE 1

POLARIZATION OF 3C 446

1977	%	
Oct. 8	16.4 ± 3.9	100.0 ± 3°.0
Nov. 16	16.8 ± 4.2	161.3 ± 4°.2
Dec. 8	10.0 ± 0.5	142.6 ± 4°.7
Dec. 9	13.2 ± 1.6	137.3 ± 6°.1

It is clear from the table that the polarization was very high and variable. In particular, the difference between the percentage polarizations on the two consecutive nights in December is significant, and the time interval between the measurements corresponds to only about 10 hours in the rest frame of the object. It should also be mentioned that Stockman and Angel (1978) also observed 3C 446 during this outburst and noted a significant rotation of the position angle of polarization in a few hours.

V. DISCUSSION

In terms of the discussion given in §I, 3C 446 could be called a BL Lac object, since it exhibits the primary characteristics -- high light variability and high and rapidly variable polarization -- of the class. Also, it is a compact radio source as are the BL Lac objects. As we did for the BL Lac objects (Miller, French, and Hawley; this volume), we can compute various measures of the average continuum luminosity during our observing period (adopting $H_o = 75$, $q_o = 1$): $M_V \simeq -27.7$, L (3000 $Å_{(rest)}$) = 2.1×10^{31} erg s^{-1} Hz^{-1}, and L = 1.1×10^{46} erg s^{-1}, integrating the continuum from 1664 Å to 3228 Å in the rest frame. These luminosities are within a factor of 2 of those derived for B2 1308+326, the most luminous BL Lac object we observed, showing that this characteristic of 3C 446 does not separate it from the BL Lac class. It is interesting to note that B2 1308+326 also shows Mg II λ2800 at a lower redshift. Preliminary results from a search by A. Wolfe (private communication) for 21-cm absorption in 3C 466 at the redshift of the Mg II absorption have been negative, so in this sense 3C 446 differs from the BL Lac object AO 0235+164.

The principal difference between 3C 446 and members of the BL Lac class is the existence of prominent emission lines in its spectrum, at least when it is faint. In spite of the high degree of variability of 3C 446, our data indicate that C III] λ1909 has not changed its luminosity from that observed ten years ago. It is important to examine other emission lines for constancy as well, but we have not been able to do this with data available to us at present.

It is an open question how typical 3C 446 is of the OVV QSOs. We have preliminary results on another OVV, PKS 0420-01, observed in December under relatively poor conditions. It appeared to be undergoing an outburst, it had high polarization ($\sim$8%), and the polarization varied significantly in a 24-hour period. In addition, the spectral features appeared at low contrast. Also extremely interesting is the detection of Mg λ2800 in absorption at $z = 0.633$ ($z_{em} = 0.914$). So the similarity in all aspects to 3C 446 is obvious. It remains for the future to investigate how many other OVV QSOs have close similarities to BL Lac objects, but available information suggests that the two discussed in this paper definitely do. These OVV QSOs furnish us with the possibility of examining the BL Lac phenomena in objects with prominent emission lines, and it is hoped that future studies of them may lead to greater understanding of both QSOs and BL Lac objects.

We wish to thank E. J. Wampler for furnishing us his unpublished data. This research was supported in part by NSF Grant AST 76-20843.

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DISCUSSION

F. OWEN:
During the past two years we have noticed that 0420-01 is one of the sources undergoing an outburst at millimeter wavelengths. We originally called this object a QSO, but one by one we see the sources which are strong at millimeter wavelengths turning out to have BL Lac characteristics. I wonder if we were to look closely at all strong millimeter sources, if we will find a homogeneous sub-class of objects.

J. MILLER:
Is 0420-21 rather compact?

F. OWEN:
Yes it is and it is one of the strongest millimeter sources in the sky right now.

J. CONDON:
It is also variable at 318 MHz.

A. WOLFE:

I just want to point out one difference between 3C 446 and AO 0235+164. Brian Andrew and K. Johnston measured a radio flux for this object during the optical outburst and unlike AO 0235+164 it did not vary simultaneously.

J. MILLER:

Miley observed 3C 446 with the VLA at the time of the optical outburst. He finds an optically thick component in the radio spectrum at very high frequencies and suspects that this is the place to look for variations. This is in addition to a lower frequency component which does not vary.

M. ULRICH:

I would like to make a comment on another object which is intermediate between BL Lac objects and normal quasars. The object 0827+24 has a very flat radio spectrum, it is $\sim$1 Jy at 90 GHz, and in that respect is related to BL Lac objects. However in addition to an absorption line redshift at $z = 0.525$, the optical spectrum shows several strong emission lines.

D. SHAFFER:

Bob Brown has observed 3C 446 with the interferometer at Green Bank at 8 GHz. He finds that it has not undergone a radio outburst. It is also being monitored with a VLB interferometer.

A. SMITH:

In connection with the remarks made about the millimeter outburst in 0420-01; we have observed a major optical outburst of about 2 magnitudes, which peaked at the beginning of 1975. This is an interesting and isolated event which should be followed up. It would seem to present an unusually good opportunity for further radio/optical correlations, in this case with a possible time delay of 2 to 3 years.

K. KELLERMANN:

As I recall there was an optical outburst in 3C 446 about 10 years ago of about 3 magnitudes (Burbidge, G.R., and Burbidge, M. 1967, "Quasi-Stellar Objects" [San Francisco: Freeman], p. 77). The radio outburst was delayed about 1 year.

J. MILLER:

That's one of the reasons I suggest that it is important to get a good time baseline prior to the next outburst.

W. DENT:

I want to ask you about when the optical outburst in 0420-01 began because that is extremely important to correlate with the radio outburst.

J. MILLER:

When we first looked at it it was already underway. If anybody is monitoring this object optically and sees anything happen, please let me know.

W. DENT:

And I might add that 3C 446 is not increasing at millimeter wavelengths either. This is important because one would expect an outburst at these wavelengths to occur before any centimeter outburst.

J. COCKE:

Is there any particular cosmological model that you refer to for the higher redshift objects when you calculate the absolute magnitude in rest frame of the source?

J. MILLER:

Yes, I assume $H_0 = 75 \text{ kms}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 1$.

J. COCKE:

What happens to the luminosity when you vary H_0 and q_0 within observed limits?

J. MILLER:

The luminosities change by at most about a factor of 2.

NEW OBSERVATIONS OF PKS 0735+17 AND AO 0827+24

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PKS 0735+17

This object shows all the characteristics of a BL Lac type object at both optical and radio wavelengths. In addition it has a pair of absorption lines which Carswell et al. (1974) identified with MgII$\lambda\lambda$2796, 2803 at a redshift of $z_a = 0.424$. On the basis of these observations, Wolfe and Burbidge (1975) applied the doublet-ratio method to determine physical conditions in the absorbing gas, suggesting that if a search for 21-cm absorption is unsuccessful, an intervening galaxy is unlikely to be the cause of the optical absorption. Low upper limits have now been placed on the optical depth of 21 cm absorption (Roberts 1976), so in order to study constraints on the absorbing region the observations presented here were undertaken to improve the accuracy of the MgII doublet ratio and to search for and measure equivalent widths for MgI, FeII, MnII and CaII lines since these may be able to support or exclude the possibility of the absorbing material's being within a "normal" intervening galaxy. Recently Peterson et al. (1977) observed a value of 1.14 for the doublet ratio and also detected the FeIIλ2599 line (see Table 1). Very high resolution observations by Boksenberg et al. (1976) have revealed velocity structure in the MgII lines.

The present work is based on carefully calibrated photographic spectrograms obtained in February 1977 using the McDonald Observatory ultraviolet image tube spectrograph ("UVITS") on the 2.1 meter Struve reflector. A 2-stage Carnegie image tube was used with nitrogen-baked IIIaJ plates (resolution 6 Å (FWHM)). Nine blue-ultraviolet and three red exposures were obtained, with exposures and focus optimized for different wavelength ranges. The plates were scanned with the Skylab PDS microdensitometer at the University of Texas' Department of Astronomy. Fig. 1 shows a region of the spectrum optimized for the FeIIλ2600 lines. (This gives poor signal-to-noise in the region of the MgII λ2798 lines since two plates exposed well at 3700 Å were overexposed at 4000 Å.) The equivalent widths resulting from all data obtained for this object are summarized in Table 1. Note that calibration uncertainties are not included in the errors. These are expected to be 5 - 10%. Note that the contribution of calibration uncertainties to the uncertainty in the doublet ratio is negligible, since the ratio is quite close to 1. At the end of the table upper limits to observed equivalent widths are given for any lines that may exist in the observed wavelength ranges indicated.

The present preliminary curve-of-growth analysis of the results assumes a single absorbing cloud having a Maxwellian distribution of velocities. Although the results of Boksenberg et al. (1976) show each MgII line to be split into four different components separated by 50 - 70 km s^{-1}, each having $\sigma_{Doppler}$ ~5 km s^{-1}, the overall conclusions arrived at here should be correct, although not the details. I also assume that the cloud covers the continuum source, an assumption justified partly by the observed small source size and rapid variability.

Fig. 2 shows two possible solutions for the velocity dispersion (σ) and the column density (N) of the Mg^+ atoms. The MgII lines are shown as points (the error bars are impossible to show on this scale). The vertical bars show the most likely range of the FeII lines, and the upper limit nearby is that for FeIIλ2373. The high column density solution is not as good a fit as the low column density one, but neither can be ruled out by these data (see Discussion). The high column density solution would require $\frac{X(Fe)}{X(Mg)} \sim 0.003$ and $\frac{X(Mn)}{X(Mg)} < 0.0001$ compared with 0.8 and 0.0066 "solar" values. Also to obtain τ (21-cm) < 0.02 would require a spin temperature, T_S, >8000° K. The low column density solution requires $\frac{X(Fe)}{X(Mg)} \sim 0.5$ and $\frac{X(Mn)}{X(Mg)} <$ 0.065, both consistent with solar values. In this case T_S > 5° K, consistent with the ~100°K determined for clouds in our own galaxy. The present results do not rule out the intervening galaxy hypothesis.

Note the strength of the interstellar CaII lines; PKS 0735+17 is at low galactic latitude (18°) but in the direction of the anticenter (l = 201°). Their equivalent widths may be compared with the 2σ upper limits (<0.21 Å) given for these lines in the z = 0.424 system, which suggests that the high-redshift absorbing material may not be similar to the Galactic interstellar medium.

AO 0827+24

Strictly, this object should not be mentioned at this conference. It has been included in some lists of BL Lac objects presumably because of its large amplitude optical variability, radio variability, flat radio spectrum, and perhaps also because its optical spectrum shows absorption lines, characteristic of neutral gas, seen in two other BL Lac type objects, PKS 0735+17 and AO 0235+16 (Ulrich and Owen 1977, Wills and Wills 1976). However it has (not particularly weak) emission lines, one, previously reported (Strittmatter et al. 1974, Ulrich and Owen 1977, Wills and Wills 1976), at λ = 3701 Å and another, found on scans with the new McDonald Observatory Cassegrain Digicon Spectrograph, and an IDS detector on the old "UVITS", at λ = 5424 Å. These lines may be identified with CIII]λ1909 and MgIIλ2798, giving an emission line redshift z_e = 0.939.

This object was observed in order to determine equivalent widths for the MgII and FeII absorption lines and to search for red-shifted CaII interstellar lines. Table 2 gives preliminary values for the equvalent widths. They are comparable with other neutral-hydrogen absorption line

TABLE 1

Equivalent Widths - 0735+17 $z = 0.4243$

	λ_o	f	$W_{\lambda obsd}$ †	$W_{\lambda rest}$ (Å)
Fe II	2343.5	1.08_{-1}	0.94±0.15	0.66±0.11
Fe II	2366.9	2.38_{-3}	<0.28	<0.20
Fe II	2373.7	3.95_{-2}	<0.32	<0.22
Fe II	2382.0	3.28_{-1}	0.70±0.13	0.49±0.09
Fe II**	2395.6	2.76_{-1}	<0.32	<0.22
Mn II	2576.1	2.88_{-1}	<0.27	<0.19
Fe II	2585.9	5.73_{-2}	0.06±0.11	0.42±0.08
Mn II	2593.7	2.23_{-1}	<0.30	<0.21
Fe II#	2599.4	2.03_{-1}	1.03±0.10	0.72±0.07
Mn II	2605.7	1.58_{-1}	<0.26	<0.18
Fe II**	2628.3	1.62_{-1}	<0.26	<0.18
Mg II*	2795.5	5.92_{-1}	2.43±0.09	1.71±0.06
Mg II*	2802.7	2.95_{-1}	1.98±0.09	1.39±0.06
Mg I	2852.1	1.90_{0}	0.25±0.07	0.18±0.05
Ca II	3933.7	6.88_{-1}	<0.30	<0.21
Ca II	3968.5	3.41_{-1}	<0.30	<0.21
Ca II - K	3933.7	6.88_{-1}	0.52±0.08	
Ca II - H	3968.5	3.41_{-1}	0.49±0.08	

Observed Upper Limits (see also above) - 2.5σ	
4300-4600	0.28Å
4600-4900	0.25Å
4900-5400	0.36Å
5400-6400	0.33Å

†Upper limits are approx. 2.5σ. Only (rms) noise errors are given. This may be compared with the Peterson et al. value, $\frac{2.14}{1.88} = 1.14 \pm 0.09$.

*Doublet ratio = 1.23±0.07 (noise error only).

**Lines arising from excited fine-structure levels.

#Peterson et al. find $W_{obs} \sim 1.2$Å, but are uncertain of its detection.

systems (see, for example, Fig. 2 of Burbidge *et al.* (1977)), perhaps more saturated. The upper *limit* to the CaII lines is not yet as useful as that for PKS 0735+17.

Acknowledgements: I thank D. Wills and A. Uomoto for observing help, and O. Strohacker for help with PDS scanning. I am especially grateful to P. M. Rybski, and R. G. Tull and S. Vogt, for development of the IDS and Digicon detector-spectrograph combinations, and to P. Kelton and T. Montemayor who wrote the control programs for the spectrographs. The observations were made at the McDonald Observatory of the University of Texas with the help of NSF grant no. AST76-81338.

Table 2: Preliminary Equivalent Widths for AO 0827+24, z_a = 0.424 System

	λ_o (Å)	$W_{\lambda rest}$ (Å)
Fe II	2382.0	1.9
Fe II	2585.9	1.4
Fe II	2599.4	1.9
Mg II	2795.5	2.9
Mg II	2802.7	2.2

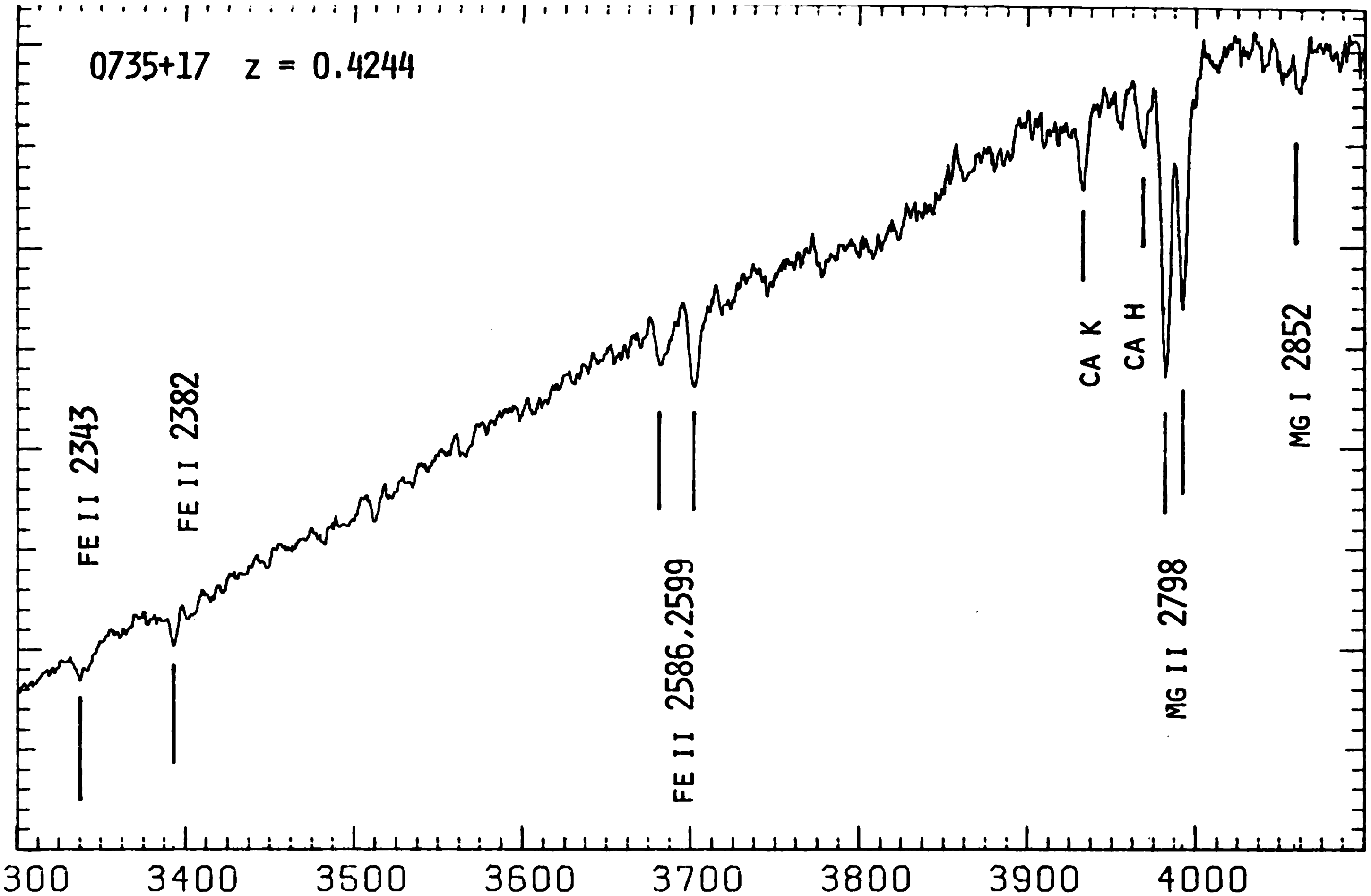

Fig. 1 The weighted sum of several intensity scans of spectrograms of the BL Lac type object, PKS 0735+17. The weights have been optimized for best signal-to-noise ratio in the region of FeII$\lambda\lambda$2586, 2599 lines. The instrumental wavelength response has not been removed.

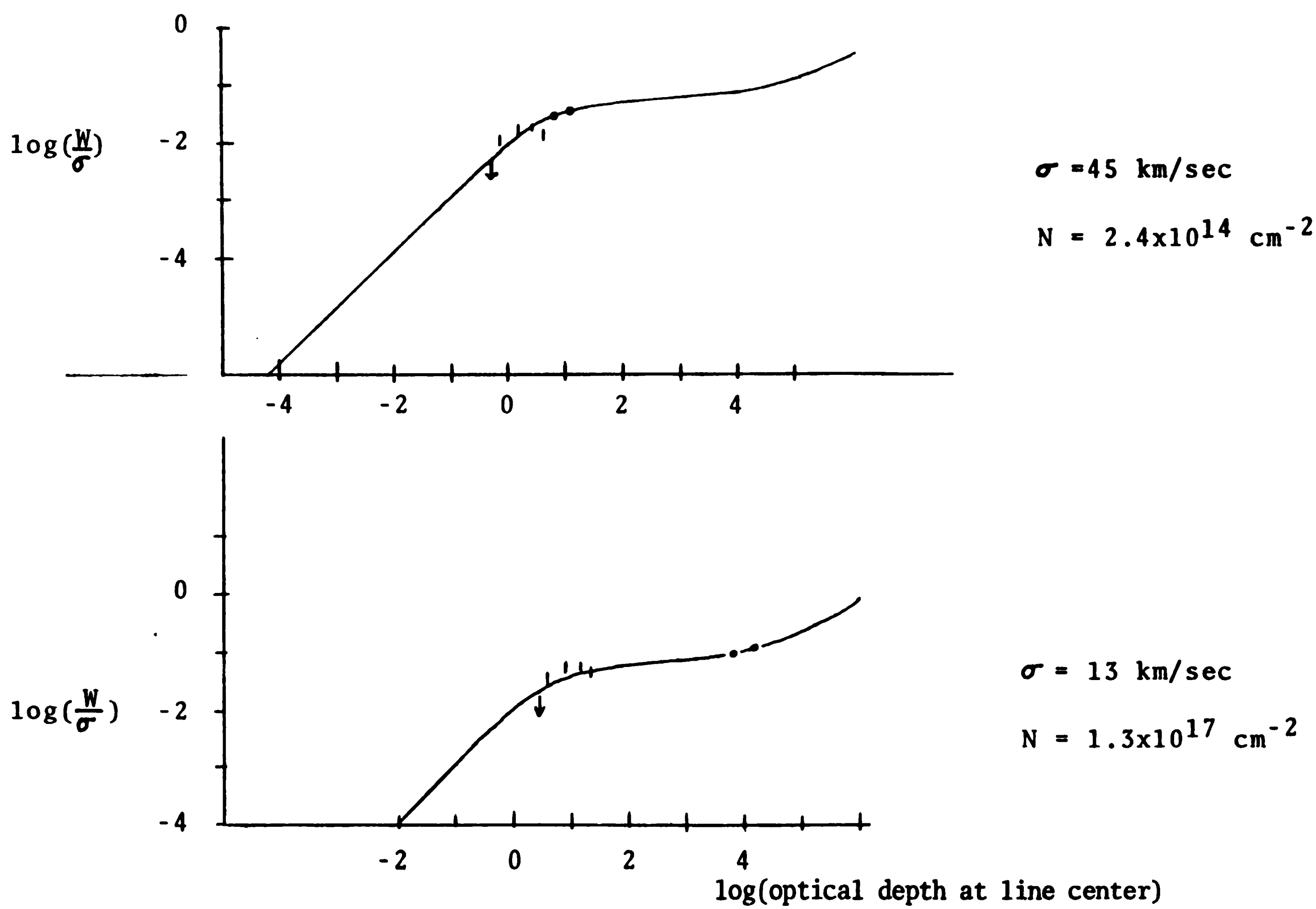

Fig.2 Curves of growth for the $z = 0.424$ absorption line system of PKS 0735+17 showing the two most likely solutions (see text). The MnII upper limits are not shown.

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DISCUSSION

A. WOLFE:
On the 0735+178 question, if you neglect *a priori* assumptions about abundances relative to hydrogen and construct an empirical curve of growth, it appears to me that the high column density solution fits the data better than does the low column density solution, at least with respect to the FeII lines.

B. WILLS:
I haven't made any *a priori* assumptions about abundances. I'll tell you why I don't think the high column density solution is better. (I think the error bars have got bigger on the Xerox reproduction.) The best observed iron line is FeII $\lambda2599$ which lies $>2\sigma$ above the curve and there is also an upper limit to the equivalent width of FeII $\lambda2372$, a 2.5σ upper limit which lies just below the curve shown. I feel that these are incompatible with the high column density solution.

A. WOLFE:
It appeared to me that the four FeII lines of similar oscillator strength had about the same equivalent width indicating that they lie on the flat portion rather than the linear portion of the curve of growth.

B. WILLS:
One can't shift the four FeII lines further into the flat portion because of the FeII $\lambda2372$ upper limit. Anyway, the single-cloud model used is probably too much of an approximation to the truth

to be able to distinguish between the two kinds of solutions in this way. I've noticed in a few objects the equivalent widths of the individual FeII lines scatter about the curve of growth systematically in the same direction. I don't know whether anyone else has noticed it.

M. BURBIDGE:
I am very interested in this object (AO 0827+24) in which the absorption redshift is much larger than the emission redshift.* In a sample of high redshift QSOs that we have been looking at, we find a candidate, which certainly needs confirmation, absorption redshift that is also much higher than the emission redshift.

J. PERRY (To M. Burbidge):
Margaret, you should point out that the percentage difference in redshift is the same in yours and in B. Will's object.

B. BURKE (to M. Burbidge):
What is the name of the object?

M. BURBIDGE:
OF 097, it is a centimeter excess radio QSO that comes from the Ohio Survey. It has another name which is 0457+024.

G. BURBIDGE:
This redshift occurs along with many other absorption redshifts in the same object that are lower than emission redshift.

*[*Ed.: In her talk Dr. Wills reported tentative evidence for an absorption redshift in AO 0827+24 that significantly exceeded its emission redshift. However, this absorption system has not been confirmed by a recent, more thorough analysis of the data (Wills, B.J. 1978, Private Communication).*]

REDSHIFTED 21 cm. ABSORPTION LINES IN BL LAC OBJECTS

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I. INTRODUCTION

I have been studying 21 cm. absorption lines both in QSOs and BL Lac objects. Today I will present results of two separate investigations. The first is a progress report of a continuing search for 21 cm. lines in optical redshift systems found in objects selected for their radio brightness. The second is a preliminary report of a theoretical investigation into the response of an HI cloud to flux variations of a nearby source of 21 cm. continuum radiation.

How can studies of 21 cm. absorption lines further our understanding of BL Lac objects? The detection of a 21 cm. absorption feature with a reasonable optical depth ($\tau > 0.1$), velocity width ($\Delta v \sim 3 - 50$ kms^{-1}), and spin temperature ($T_s \sim 100$K), indicates an HI column density of $N(HI) > 10^{20}$ cm^{-2} which resembles the column density perpendicular to the disk of a late-type spiral galaxy (velocity widths of $\Delta v \sim 50$ kms^{-1} are considered "reasonable" because gain variations that persist across the passbands of current paramp receivers make it difficult to detect features that are much broader). The discovery of an intervening galaxy in front of a BL Lac object has obvious implications for the distance to the BL Lac, which is a major theme of this conference. 21 cm. absorption lines are also sensitive indicators of local excitation conditions, which help to determine the distance separating the absorbing cloud from the BL Lac object. The high spectral resolution, $\Delta v < 1$ kms^{-1}, obtainable with radio autocorrelation spectrometers in addition to the high spatial resolution, $\sim 0\overset{''}{.}001$, achieved with VLB interferometers enables one to construct detailed maps of the absorbing gas. Consequently, 21 cm. lines provide a sensitive probe of the absorber, which should reveal its location along the line of sight.

BL Lac objects are prime candidates for 21 cm. absorption because they are associated with compact radio sources. Extended radio sources are undesireable because even a galactic-sized, optically thick absorber would only blot out a small fraction of the emitting area and therefore cause little decrease in line flux. Since most compact radio sources are variable, the 21 cm. absorption lines in BL Lac objects can also be studied for the effects of time variability discussed in §II. To date two 21 cm. absorption lines with prominent redshifts have been detected; one in a QSO, 3C 286 (Brown and Roberts 1973), and the other in a BL Lac object, AO 0235+164 (Roberts et al. 1976). In §II I will discuss attempts to find new 21 cm. lines in other BL Lac (or BL Lac-type) objects, and in §III I will discuss preliminary results of a program to monitor line variability in AO 0235+164.

II. 21 cm. Absorption Properties of MgII and FeII Optical Redshift Systems

The method used to search for 21 cm. absorption lines is the same for BL Lac objects and QSOs. The trick is to select an optical absorption system that is likely to be an HI region with significant 21 cm. opacity. This is straightforward for systems with absorption redshifts

$z_a \geq 1.8$ because Lα is shifted to wavelengths accessible to optical scanning devices. The appearance of Lα absorption does not, however, guarantee a finite 21 cm. optical depth. The reason for this is that the optical depth ratio is given by

$$\frac{\tau(L\alpha)}{\tau(21)} \approx 2 \times 10^8 \left[\frac{T_s}{100K} \right] \qquad (1)$$

where the spin temperature T_s is the effective Boltzman temperature that describes the hyperfine level populations in the ^1S state of hydrogen. Thus if $T_s \sim 100K$, the temperature commonly observed in galactic HI regions, then $\tau(L\alpha) > 10^8$ if $\tau(21)$ is of order unity. The signature of such an enormous optical depth is significant opacity in the damping wings of the line profile, and consequently an equivalent width $W_\lambda > 30$ Å in the rest frame of the absorber. The heavy element absorption spectrum should exhibit resonance lines usually observed in HI regions such as CII(λ1335), MgII($\lambda\lambda$2800), and FeII(λ2300-2600). Because of their lower abundances the heavier elements produce lines of lower optical depth, which should lie on the flat part of the curve of growth where W_λ typically equals about 1 Å if the velocity dispersion, σ, of the absorbing material equals the 30-50 kms^{-1} usually observed (cf. Boksenberg and Sargent 1978).

After you find a redshift system like this you then search for 21 cm. absorption at a frequency $\nu = 1420.4/(1+z_a)$ MHz if the background optical object is associated with a radio source. I know of only two redshift systems that satisfy all of these requirements; the two clouds at $z_a \approx 1.78$ in 1331+170 (Carswell et al. 1975), and the $z_a = 2.81$ cloud in 0528-250 (Jauncey et al. 1978). M. M. Davis and the author are currently investigating the 1331+170 system for 21 cm. absorption.

At lower redshifts where Lα is inaccessible one is confined to systems showing only MgII and FeII absorption. High resolution studies of various QSOs and BL Lac objects have revealed some 40 or more MgII and FeII redshifts (cf. Roberts et al. 1978). Whether or not these lines arise in clouds with $\tau(L\alpha) \sim 10^8$ is not at all clear. The absorbing cloud could be an HI region with $\tau(L\alpha) << 10^8$, but with enough column density so that $\tau(\text{MgII}) \geq 1$. Alternatively it could be an HII region with sufficient Mg^+ and Fe^+ to form observable absorption lines. Despite these provisos it is worthwhile investigating clouds with MgII and FeII lines since they are present in both redshift systems that absorb 21 cm. radiation (Burbidge et al. 1976; Spinrad 1978).

Table 1 summarizes the results of recent experiments carried out on the 305m telescope at Arecibo with the University of Pittsburgh parametric amplifier at the front end. The observations are the result of a joint effort with F. Briggs and M. M. Davis. The 3C 446 data was obtained with the 91m telescope in Green Bank with F. Briggs, J. J. Broderick, R. L. Brown, and K. J. Johnston. The 21 cm. measurements of 3C 286 and the lower z system in AO 0235+164 are included for comparison. These results indicate (a) that the 21 cm. optical depth in each of the recently investigated systems is exceedingly small; and (b) the absence of any correlation between 21 cm. optical depth and resonance-line equivalent width. This brings to mind the conclusion of Wolfe et al. (1978) who found that the clouds producing most of the resonance-line equivalent width at $z_a = 0.524$ in AO 0235+164 produce little 21 cm. absorption. Whether this actually holds for the other systems, can be investigated through use of the curve of growth.

Table 1
21 cm. Results

Object	Z_{abs}	$\tau(21)^{*}$	$(\Delta v)_{21}^{**}$	$(\Delta v)_{opt}^{+}$
AO 0235+164 (BL)	0.524	0.002 - 0.7	110(6)	∿250
	0.852	<0.03	5	∿ 30
PKS 0735+178 (BL)	0.424	<0.005	6	∿150
AO 0827+24 (Q-BL)	0.525	<0.008	7	∿300
3C 446 (Q-BL)	0.849	<0.01	5	-
3C 286 (Q)	0.692	<0.1	8.6	∿ 10

PKS 0735+178: $N(HI) < 10^{19}$ $(T_s/100)$ cm^{-2} if $\Delta v \sim 20$ kms^{-1}

*Upper limits are 3-σ values

**21 cm. velocity widths (FWHM) in kms^{-1}. In redshift systems without 21 cm. absorption entry is resolution used to derive upper limit on $\tau(21)$. 110(6) in first row stands for 110 kms^{-1} velocity range in absorption and 6 kms^{-1} width of individual components.

+FWHM of optical absorption line in kms^{-1}

The results of curve-of-growth analyses of the z_a = 0.525 and 0.852 systems in AO 0827+24 and AO 0235+164, while not unique, show that the data are <u>consistent</u> with absorbing clouds with MgII optical depths, $\tau(\mathrm{MgII}) \sim 1$. These should be compared to clouds with $\tau(\mathrm{MgII}) \sim 10^3$ in the z_a = 0.524 and 0.692 systems in AO 0235+164 and 3C 286 (Wolfe and Wills 1977; Spinrad 1978); i.e., the two redshift systems exhibiting 21 cm. absorption. If we make the reasonable assumption that Mg^+ is the dominant ionization stage of Mg in an HI region and that the abundance ratio $[Mg/H] \lesssim [Mg/H]_{\theta}$, then $\tau(L\alpha) \sim 10^8$ in the systems that are opaque to 21 cm. radiation and $\tau(L\alpha) \sim 10^5$ in the systems that are transparent to 21 cm. radiation. So the absence of 21 cm. absorption in table 1 appears to be simply a matter of column density: the transparent systems in AO 0235+164, AO 0827+24, 3C 446, and PKS 0735+178 have enough column density to be optically thick in MgII and FeII resonance transitions, but not enough to be thick in the 21 cm. line. In each case the equivalent widths are set by the velocity field internal to the absorber rather than by its optical depth. In addition, the spin temperature in each of the thin systems can equal the T_k = 100K kinetic temperature of the HI region without violating any physical constraints.

The problem with deducing ionic column densities from the curve of growth is that the high velocity-dispersion clouds dominate the low velocity-dispersion clouds in their contribution to resonance-line equivalent widths (cf. Nachman and Hobbs 1973). Thus the inclusion of a few "thick" clouds with velocity dispersion $\sigma < 10$ kms^{-1} and

$\tau(MgII) \sim 10^3$ in the "thin" systems would not alter the shape of the curve-of-growth (cf. Wolfe and Wills 1977), but would alter the explanation for why they are transparent to 21 cm. radiation. Since the "thin" systems now contain components with $\tau(L\alpha) \sim 10^8$, we would then conclude from eq. (1) that $T_s > 5000K$ if say $\tau(21) < 0.01$. There is no a priori reason to rule out $T_k \sim 10^4K$ in an HI region unless it is excluded by the velocity width of the absorption-line profile; individual components in some absorption features suggest that $T_k < 10^3K$ (Wolfe 1978). If in fact $T_s >> T_k$, we then have to assume that 21 cm. radiation emitted from the background source determines the hyperfine level populations (cf. Wolfe 1978). This would be an important result because it would indicate that the absorber is in the vicinity, say <10 kpc, of the emitter. The $z_a = 0.86$ absorber in PKS 0454+039 (Burbidge et al. 1977) provides an ideal test of these ideas because (i) the background QSO is a compact radio source as indicated by its very flat spectrum, and (ii) it has a curve-of-growth similar to the two 21 cm. systems in that $\tau(MgII) > 10^2$ as shown in Fig. (1). The failure to detect 21 cm. absorption in this system could imply a high spin temperature.

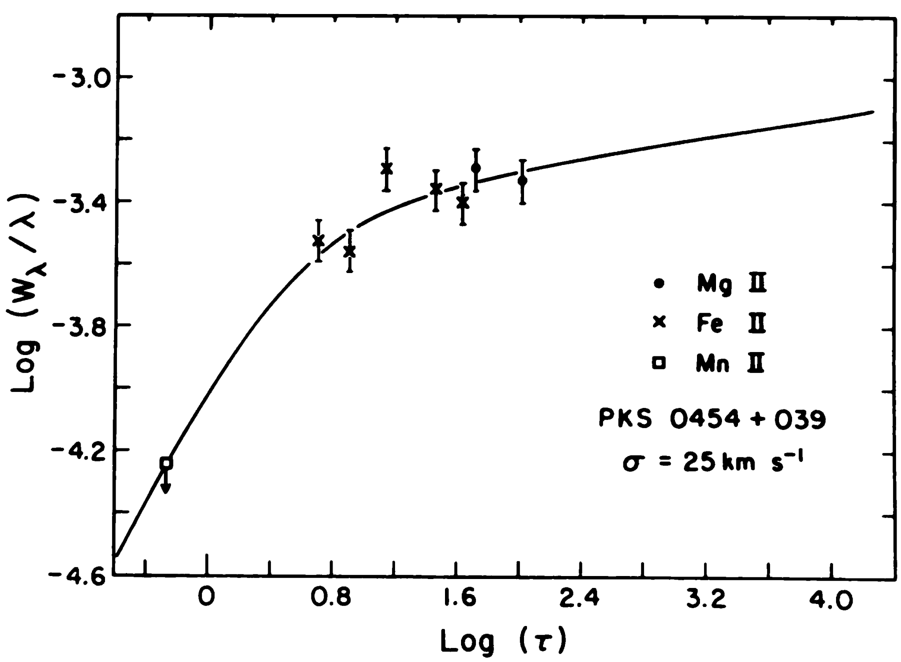

Fig. 1. Curve of growth for $z_a = 0.86$ absorber in 0454+039. W_λ is the equivalent width in the absorber frame, σ is the radial, rms velocity dispersion, and $\tau\cdot(\pi)^{-1/2}$ is the central optical depth. Equivalent widths are taken from Burbidge et al. (1977).

Unless studies of the optical absorption spectra of the "thin" systems at high spectral resolution suggest otherwise, I will henceforth assume that they do not contain "thick" clouds and therefore have normal spin temperatures. As to the nature of the absorbers, it is clear that these are _not_ HI clouds found in the population I disks of late-type galaxies like our own. Investigations of 21 cm. absorption in our Galaxy indicate that HI clouds with $\tau(21) < 0.01$ are rarely found in the plane, but are sometimes detected at high galactic latitudes, far out of the plane (cf. Hughes _et al_. 1971; Payne _et al_. 1978). So it is possible that the lines-of-sight through each "thin" system traverses a hypothetical, turbulent galactic halo at the absorption redshift. The turbulence is needed to produce the resonance-line equivalent widths in 0827+24 which are ~ 300 kms^{-1}, while in 0235+164 a smaller velocity range, $\lesssim 30$ kms^{-1}, is required. This general picture is supported by recent observations of 21 cm. and CaII absorption in the QSO/galaxy pair 4C 32.33/NGC 3067. In this case a weak, $\tau(21) \sim 0.03$, and narrow, $\Delta v \sim 4$ kms^{-1}, 21 cm. line (Haschick and Burke 1975; Haschick and Wolfe 1978) forms at the same redshift as the optical lines with $\Delta v \sim 90$ kms^{-1} (Boksenberg and Sargent 1978). The inclination of the NGC 3067 rules out the possibility that the optical lines are broadened by differential rotation in the disk of this galaxy.

Since we cannot determine a unique location for the "thin" systems along the line of sight, it is also possible that these are HI zones in turbulent clouds that have been ejected from the background QSO or BL Lac object. In this case one would expect higher ionization stages of common elements, such as C^{+3}, N^{+4}, etc. to form in the HII zone of the cloud that is ionized by and faces towards the emitting object. This hypothesis can be tested with UV spectroscopy from the Space Telescope.

III. A 21 cm. Probe of AO 0235+164

The parameters characterizing the $z_a = 0.524$ 21 cm. absorption line in AO 0235+164 are listed in table 1. Although the presence of gas in front of the radio source makes it less susceptible to interstellar scintillation experiments (see paper by Condon in this volume), it does provide a means of estimating the distance to this very interesting BL Lac object. This is essential if we are to understand the mechanism responsible for the 1975 outburst during which (i) a detailed and unique correlation between optical and radio variability was observed (Ledden _et al_. 1976; Rieke _et al_. 1976); (ii) a systematic rotation in the 8 and 14.5 GHz polarization position angle occured (see paper by Ledden and Aller in this volume); and (iii) AO 0235+164 was one of the most luminous objects in the Universe.

Distance of AO 0235+164

Since stellar absorption lines are neither observed in the optical continuum radiated by the BL Lac object nor in radiation emitted by the faint "fuzz" that is displaced from it by 2 arc sec (Smith, Burbidge, and Junkarinnen 1977), there is no direct evidence linking AO 0235+164 to a galaxy of stars. As a result an undisputed determination of its distance cannot be made (see paper by J. Miller in this volume). However, a distance _limit_ may be estimated if one could show that either absorption redshift, 0.524 or 0.852, is dominated by cosmological expansion. The recent detection of $z = 0.524$ emission lines in the "fuzz" suggests that the entire $z = 0.524$ system is a galaxy (Smith _et al_. 1977) because (1) the "fuzz" which resembles a galactic nucleus, is separated by ~ 20 kpc from the absorbing material in AO 0235+164; (2) the N(HI) $\sim 10^{21}$ cm^{-2}

column density of the absorber (Roberts et al. 1976) resembles that of a spiral arm; and (3) the Mg^+, Fe^+, and Mn^+ ions detected in absorption are also found in HI clouds in our Galaxy. If instead, the $z = 0.524$ redshift arose from ejection by the $z \geq 0.852$ BL Lac object, then the ejected gas would have a bulk velocity of $u \geq 0.2c$ and an internal velocity range of $\Delta u < 100$ kms^{-1} across 2 arc sec. This leads to a minimum distance of 350 kpc separating the $z = 0.524$ system from AO 0235+164 and a momentum requirement that the non-thermal energy source is unable to meet (Wolfe et al. 1978). It is therefore highly unlikely that the $z = 0.524$ system has been ejected from the BL Lac object.

The strongest argument against the galaxy interpretation for the $z = 0.524$ system is unrelated to its internal properties, but rather stems from the assumption that it is intervening, i.e., not associated with the Lac object. Smith et al. (1977) show that the Hα luminosity emitted by the "fuzz" is a factor of ten greater than that emitted by luminous ScI galaxies, implying that the $z = 0.524$ galaxy is a rarely occurring active galaxy. The probability of detecting two $z < 1$ galaxies, one of which is unusual, along the line of signt is $<10^{-5}$. These objections against an intervening galaxy led us (Wolfe et al. 1978) to suggest that AO 0235+164 might be physically associated with a galaxy at $z = 0.524$. We proposed that AO 0235+164 was ejected from an active galactic nucleus in the "fuzz" with a positive radial velocity that is large enough to explain the $z > 0.852$ redshift of the BL Lac object which presumably accelerates the $z_a = 0.852$ absorber towards us. The BL Lac object is ejected $\lesssim 10^5$y before the outburst, observed by us in 1975, to account for its projected distance from the nucleus. That the nuclear emission lines at the time of the outburst are not as broad as those normally found in active galactic nuclei could result from the ejection process consuming most of the energy and momentum normally reserved to drive bulk motions in the gas. The only indication of previous activity would then be the unusual strength of Hα.

This hypothesis or, for that matter, any intrinsic gas hypothesis can be tested by examining the effects of the bright non-thermal continuum on the nearby absorbing cloud. For example the strong IR continuum emitted by AO 0235+164 can populate the excited $J = 7/2$ fine-structure level in the ground term of FeII. By comparing the $J = 7/2$ and zero-volt $J = 9/2$ level populations in the $z_a = 0.524$ absorber, Wolfe and Wills (1977) were able to show that the distance d between BL Lac object and absorbing gas exceeds 0.45 kpc. Alternative estimates of d that consider UV excitation of the $J = 7/2$ level, or that combine collisional excitation of this level with the observed state of ionization inferred from the MgII/MgI ratio are not applicable in this case (see Wolfe and Wills 1977). Thus we are left with a rather unrestrictive limit on the absorbing geometry.

Effects of a Steady-State 21 cm. Flux on the Spin Temperature

A more sensitive measure of d can be made by considering the effects that the bright 21 cm. continuum has on the absorber (cf. Bahcall and Ekers 1969; Wolfe 1978). If the absorber is close to the BL Lac object, radio-frequency radiation redshifted to $\lambda = 21$ cm. in the absorber rest frame will compete with collisions in determing the $F = 0$ and 1 hyperfine level populations in the hydrogen ground state. Because of the exceedingly small energy - $h\nu_{10}/k = 0.07$K - separating these two levels, the 21 cm. continuum cannot alter the population ratio appreciably. Instead, it alters the population difference which is defined as

$$\Delta n \equiv n_o - (g_o/g_1)n_1 \; ; \tag{1}$$

or in terms of the more familiar spin temperature T_s,

$$\Delta n = n_o(h\nu_{10}/kT_s) \; . \tag{2}$$

This is important because Δn governs the stimulated emission correction to the 21 cm. opacity; that is, the net optical depth which is the difference between actual absorption and stimulated emission processes is

$$\tau_\nu = \underset{\sim}{k}_\nu \ell \cdot (\Delta n/n_o) \tag{3}$$

rather than $\tau_\nu = \underset{\sim}{k}_\nu \ell$, where $\underset{\sim}{k}_\nu$ is the opacity due to pure absorption and where ℓ is the line-of-sight dimension of the cloud. Thus a cloud in which $\tau_\nu \sim 1$ actually contains $n_o/\Delta n$ absorption mean-free-paths along the line-of-sight. Consequently the transfer of 21 cm. radiation is a multi-stage process in which absorption and stimulated emission occur in $\sim$1500 steps (if $T_s \sim 100K$), and which preserves the direction and phase of the incident radiation.

When the absorber is close to the source, the mean intensity of 21 cm. continuum radiation J_ν is so high that the radiative de-excitation rate $B_{10}J_\nu$ dominates the collisional de-excitation rate C_{10}. The net result is a decoupling of T_s from its usual collision-dominated value, $T_s = T_k$ (where T_k is the gas kinetic temperature), in the sense that $T_s > T_k$. Simultaneous solutions to steady-state transfer and population rate equations show that, in this case, the incident radiation is attenuated less steeply than the usual exponential decline with optical depth. Put another way, the observed optical depth of the absorber $(\tau_\nu)_{obs} \equiv -\ell n [I_\nu(\ell)/I_\nu(0)]$ is less than the "unbleached" optical depth $\tau_\nu(T_k) \equiv \underset{\sim}{k}_\nu \ell (h\nu_{10}/kT_k)$ (cf. Wolfe 1978). Therefore a measureable difference between these two depths or between T_s and T_k is an indication of proximity between absorber and radio source.

It is possible to measure T_s in a cloud that exhibits both 21 cm. and Lα absorption. Because stimulated emission can be neglected in Lα transport, the ratio of Lα to 21 cm. optical depth determines a unique value of T_s (see eq. 1) which together with limits on T_k, set by the narrow 21 cm. line widths (typically $T_k < 1000K$), should reveal whether or not $(\tau_\nu)_{obs} = \tau_\nu(T_k)$. Unfortunately L$\alpha$ absorption at $z_a = 0.524$ is unobservable. So unless one infers the Lα optical depth by combining heavy-element column densities with <u>a priori</u> assumptions about element abundances (as in §II), the spin temperature in low z absorbers that are in front of non-variable radio sources remains an elusive quantity.

21 cm. Line Variability

Now we consider what happens when the 21 cm. continuum incident on an HI cloud varies with time. If the cloud is close enough to the BL Lac object so that initially $B_{10}J_\nu \sim C_{10}$, the subsequent variation in J_ν will change the radiative contribution to the spin temperature, which induces a change in the population difference. This change is observable in principle because the 21 cm. optical depth is proportional to Δn (eq. (3)). Whether or not this change can be detected depends on (a) the time delay observed between outburst and change in Δn; and (b) the magnitude of this change. As long as $d >> r$, where r is the source dimension, the time delay is not the light-travel time d/c between source and absorber, but rather the characteristic response time of Δn to the change in J_ν (see Fig. (4a) in Wolfe (1978)). Previous order-of-magnitude estimates (Wolfe 1978) indicated that the response time is

$$t_s \approx (4B_{10}J_\nu)^{-1} \tag{4}$$

and that

$$\Delta\tau_\nu/\tau_\nu \approx (\Delta S_\nu/S_\nu)\cdot[1 + (C_{10}/B_{10}J_\nu)]^{-1} \; . \tag{5}$$

Soon after the 1975, November outburst D. Shaffer and the author began to monitor the 932 MHz line and continuum of AO 0235+164 with the 91m telescope at Green Bank. In 1976, December a 932 MHz feed was installed at the focus of the 305m telescope at Arecibo, and from that time to the present, M. M. Davis and the author have continued the 932 MHz monitor at Arecibo with the aid of the Pittsburgh receiver. These observations will be published elsewhere but preliminary indications are that (i) the 932 MHz continuum has decreased by 25% in $\sim$0.5y; (ii) the line depths of the stronger features have changed by less than 5%; and (iii) the ratio of the line depths has changed by less than a smaller amount, perhaps $\sim$2%. The fact that the 21 cm. optical depths remained constant while the continuum changed prompted a theoretical investigation to which we now turn.

The problem is to simultaneously solve the coupled time-dependent transfer equation

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial x} = -k_\nu\,(\Delta n/n_o)I_\nu \; , \tag{6}$$

and the population rate equation

$$\frac{1}{4}\frac{\partial}{\partial t}(\Delta n) = -[B_{10}\cdot(\Omega/4\pi)I_\nu + C_{10}]\Delta n + C_{10}\cdot\Delta n(T_k) \; . \tag{7}$$

Scattering of 21 cm. photons is negligible compared to thermal emission because the condition $C_{10} >> A_{10}(n_o/\Delta n)$ that is obeyed in clouds considered here (density $>> 10^{-4}$ cm^{-3}) implies that almost all the absorbed photons are lost by collisional de-excitation; but thermal emission, which has a maximum brightness temperature T_s, is negligible compared to the attenuated continuum with a brightness temperature T_b, since $T_b >> T_s$ throughout the cloud. Therefore we need only consider absorption and stimulated emission of radiation propagating along the direction from the source which subtends a solid angle Ω at the cloud. We assume that I_ν and Δn are given by steady-state solutions to eqs. (6) and (7) prior to the outburst at $t = 0$; the finite intensity guarantees that Δn will be smaller than its thermal value $\Delta n(T_k)$. Then after $t = 0$, $I_\nu(0,t)$ changes in a prescribed manner along the inner -towards AO 0235+164 - face of the cloud. The pair of non-linear, partial differential equations was solved by a numerical difference technique to be described elsewhere, along with other details of the calculation.

Let us first consider a case which illustrates most of the essential physics. Figure (2) shows an input "pulse" with a time scale resembling the 0235 outburst in the rest-frame of $z_a = 0.524$ absorber. In Fig. (3) the attenuation of I_ν with distance in a cloud across which the light

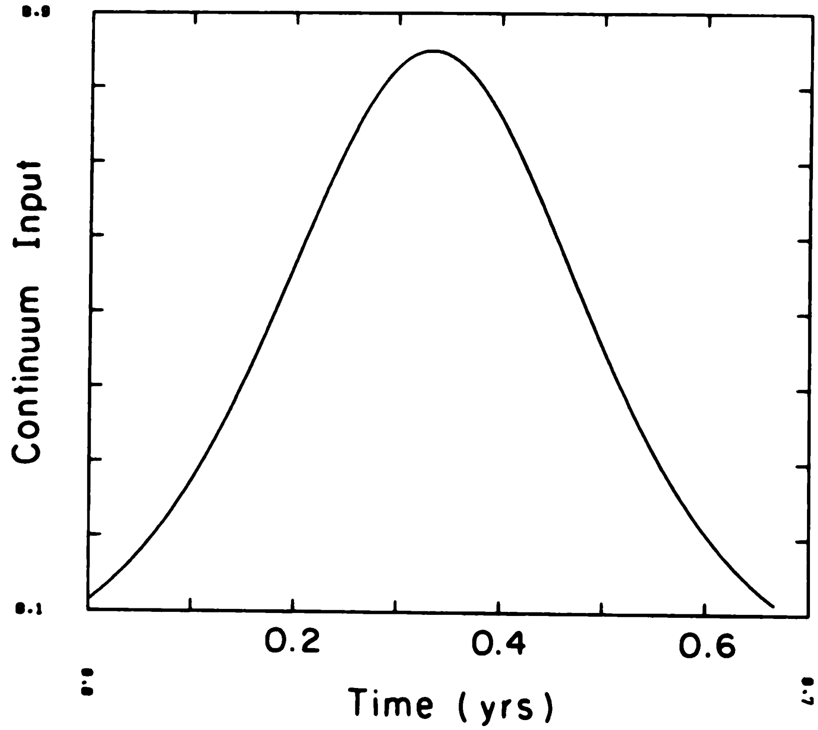

Fig. 2. Intensity variation $I_\nu(0,t)$ on inner face of the absorber. $I_\nu(0,t)$ is normalized to equal 0.85 times its present value at maximum.

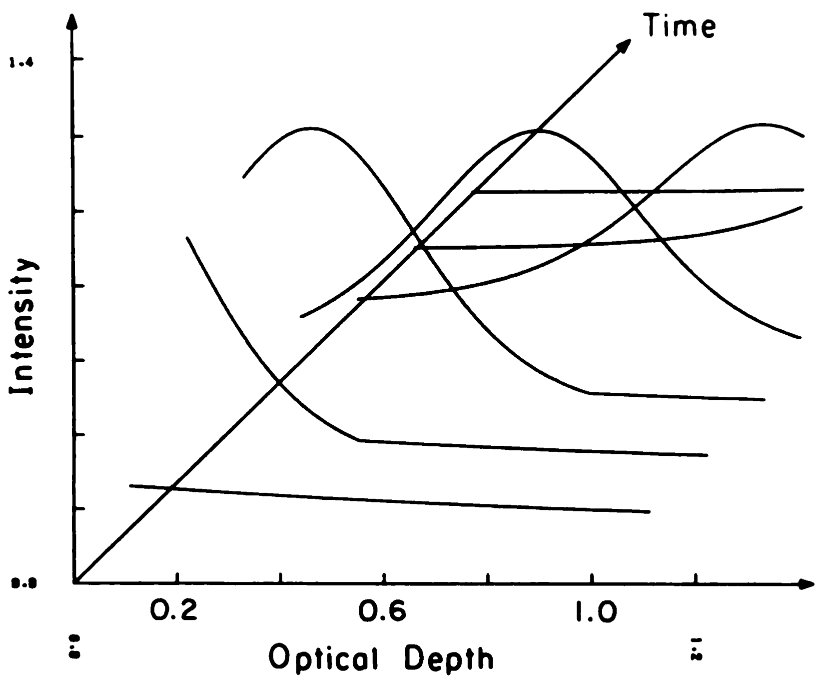

Fig. 3. Time-dependent propagation of pulse in Fig. 1 through a cloud with d=10 kpc, n(HI)=200 cm^{-3}, and total Optical Depth $\tau_{\nu_0}(T_k)=1$. The curves show intensity attenuation for successive times.

travel-time is comparable to the outburst time-scale is shown at various times subsequent to the onset of the outburst. This illustrates the causal propagation of the pulse across the cloud which occurs with the speed of light. What is not so obvious in this figure is how the response of the medium affects its absorption properties. A pulse of resonance line radiation would propagate similarly, and yet would not alter the absorption properties of the medium. However, the difference between a 21 cm. and resonance-line pulse is contained in Fig. (4) which shows the time-dependent response of the cloud detected by the observer.

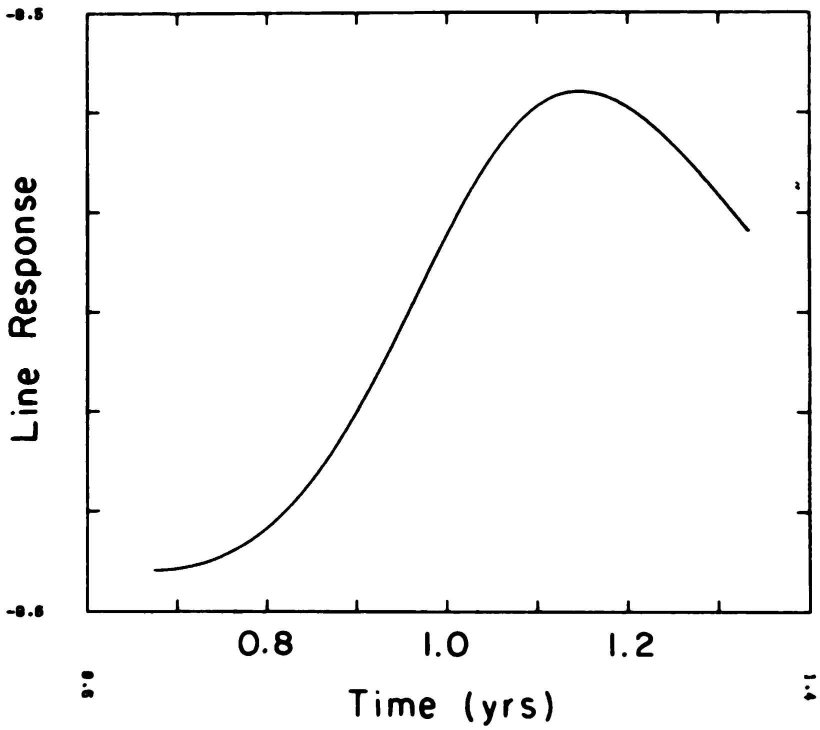

Fig. 4. Time-dependent behavior of relative line depth (see text) along outer face of the absorber. Time units are the same as in Figs. 2 and 3. The "zero-point" of the absorber response is actually t=0.6y since this is when the pulse first reaches the outer face.

In this case the ordinate is relative line depth; i.e., $[I_\nu(\ell,t)/I^c_\nu(\ell,t)]-1$, where I^c_ν is the intensity of the 21 cm. continuum. If we were considering the propagation of resonance radiation through a cloud of suitable two-level atoms, the observed line depth would not change because insignificant stimulated-emission correction to the net opacity implies that the net optical depth is independent of intensity in this case. The line depth of the 21 cm. line, is however, anti-correlated with continuum strength. Therefore we predict that the magnitude of the line depths should increase as a result of the observed continuum decrease if the $z_a = 0.524$ absorber is near AO 0235-164.

The lack of any measureable response of the 21 cm. line depths to continuum variations indicates that the level of excitation is controlled by collisions. This will occur in a cloud of high density, or in a cloud that is far from the continuum source (since $J_\nu \propto d^{-2}$). I have calculated lower limits on the density n(HI) at a given distance d according to the following prescription: First, a steady-state model satisfying observational constraints on the line depths is constructed; i.e., a unique "unbleached" optical depth $\tau_\nu(T_k)$ is found that together with n(HI) and d produces the observed line depth, say ~ 0.4 (see eq. (10) in Wolfe 1978). Then eqs. (6) and (7) are solved as described above. If the resulting line depth varies in time more than observed, n(HI) is increased until it no longer does; this yields a critical n(HI) for each d which is given in table 2. While these results are preliminary, they already produce a lower limit d > 18 kpc unless n(HI) > 50 cm^{-3} which is a

Table 2
Density and distance limits set by 21 cm. Variability*

d(kpc)	0.45	1	3	5	10	15	18
n(HI)cm^{-3}	>5(+5)	>1(+5)	>1(+4)	>5(+3)	>1(+3)	>2(+2)	>5(+1)

*Limits set by absorption from FeII fine-structure levels are d > 0.45 kpc and n(HI) < $10^6 cm^{-3}$

density larger than normally encountered in the interstellar medium. These are much more restrictive than the d > 0.45 kpc and n(HI) < $10^6 cm^{-3}$ limits previously set by observations of FeII fine-structure lines (Wolfe and Wills 1977). Of course they are not as stringent as the d > 350 kpc limit set in an ejection scenario; but they have the added virtue of being independent of geometry and kinematics. There is, however, an important proviso. If n(HI) is small enough to make the effective collision time $(4C_{10})^{-1}$ much larger than the continuum time-scale, the line depth will not change as the continuum decreases, independent of how large $4B_{10}J_\nu$ is. This is because stimulated emission and absorption processes alone cannot <u>reduce</u> the spin temperature of the gas (spontaneous emission is irrelevant because of its $\sim 10^7$y time-scale). Thus it is possible that the z_a = 0.524 absorber is a low density, n(HI) << 1 cm^{-3}, cloud located quite close to the source. Note that even this possibility would be ruled out if the line depths did not respond to an <u>increase</u> in the 932 MHz continuum because stimulated emission and absorption alone can <u>increase</u> the spin temperature.

Normally, the distance separating an absorption-line cloud from a background continuum source is deduced from observations of UV absorption lines arising from an excited fine-structure level and the zero volt level in either CII, SiII, or FeII (Bahcall and Wolf 1968). The simplest technique is to infer the mean intensity of exciting UV or IR radiation from the observed excitation level, and use that to find d (Bahcall 1971). More recently some authors (Williams and Weymann 1976;

Goldreich and Sargent 1976) assume that fine-structure excitation is due to collisional excitations by a gas with electron density n_e, and then combine n_e with the observed ionization equilibrium in the cloud to find d. Wolfe and Wills (1977) point out that limits previously set on d using UV excitation are applicable only when the absorber is optically thin in the resonance transitions. When the absorber is optically thick, as is almost always the case, the limits on d should be reduced. Furthermore Weymann and Williams (1978) have called attention to major uncertainties of the ionization equilibrium method; one must extrapolate the observed radiation field by a factor of $\sim$10 in frequency. This leaves direct IR excitation which depends on uncertain values of infrared fluxes.

In contrast, the new method outlined here makes use of exciting radiation that is directly observable, and that is not subject to opacity effects that weaken the limits on d. Moreover since radio fluxes and line depths can be measured with high precision, the limits on distance promise to be quite significant.

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DISCUSSION

P. CRANE:
What assumptions have you made that allowed you to ignore the effect of the Lyman continuum emitted by the BL Lac object?

A. WOLFE:
First of all it is extremely weak. The optical spectrum falls off like ν^{-4} and curves over even more steeply as you go into the UV. If you extrapolate it, there are very few ionizing photons.

M. BURBIDGE:
How do you know how to extrapolate it?

A. WOLFE:

Yes, if the spectrum suddenly flattens out then my statement would be incorrect. I have just extrapolated the ν^{-4} power law beyond the Lyman limit to obtain my result. But the slope would have to flatten to the minus one power to make a significant difference.

J. FELTEN:

I didn't hear you say whether there is any way to determine the particle density independently, and thereby put a definite limit on the distance.

A. WOLFE:

That's a good question. I think the best way to do that is with the Space Telescope so you can measure UV lines arising from excited fine-structure levels in CII and SiII; they are more sensitive indicators of density than the FeII lines. If these observations lead to limits similar to those found in other QSO absorption systems, say $n < 100 \text{ cm}^{-3}$, then the cloud would have to be further than 20 kpc. from the BL Lac object. I didn't have time to explain the physics. As the density goes up the magnitude of the response gets small for a given distance.

PHYSICAL CONDITIONS IN THE EMISSION-LINE REGIONS OF BL Lac OBJECTS AND QSOs

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ABSTRACT

BL Lac objects have weak emission lines because of the absence of even a small amount (~ 1 $M_\odot$) of gas at high densities. The large [N II]/Hα intensity ratio of BL Lac indicates that a substantial mass ($\gtrsim 10^3$ $M_\odot$) of gas is present, with a high nitrogen abundance. The broad line profiles of QSOs and Sy 1 galaxies are difficult to understand in terms of infall or orbital motion, but are consistent with outflow possibly resulting from radiation pressure. The asymmetries of the line profiles is a natural consequence of self-absorption in the outflowing clouds. Over a wide range in luminosity, the radius of the broad line region adjusts itself so that the incident flux $L/4\pi R^2$ is the same; the regulation mechanism may involve the evaporation of refractory grains. The ratio of radiation flux to gas density also is constant over a wide range of luminosity, and this can be understood in terms of radiation pressure. The absence of strong emission lines in BL Lac objects may be related to the geometry of an accretion flow that fuels the luminosity.

I. EMISSION LINES FROM BL Lac OBJECTS

The striking fact about the emission lines of BL Lac objects is their weakness in comparison with QSOs and Seyfert galaxies. This weakness is usually attributed either (1) to a lack of ionizing radiation or (2) to a lack of gas in the nucleus of the host galaxy. The first explanation is motivated by the tendency of BL Lac objects to have steeper continuum slopes than QSOs, but the effect is insufficient. If $L_\nu \propto \nu^{-\alpha}$, then $\langle\alpha\rangle \approx 2$ for BL Lac objects and $\langle\alpha\rangle \approx 1$ for QSOs (Stein, O'Dell, and Strittmatter 1976). A larger value of α gives a smaller number of ionizing photons relative to the continuum at the frequency of Hβ. The equivalent width of Hβ varies as

$$W(H\beta) \propto Q(H^o)/L_\nu(4861) \propto (912/4861)^{-\alpha} \cdot (\alpha^{-1}), \quad \text{(I-1)}$$

where $Q(H^o) = \int_{\nu_H}^{\infty} L_\nu(h\nu)^{-1}\,d\nu$. Thus $W(\alpha=2)/W(\alpha=1) = 10^{-1.0}$. Given that Seyfert galaxies have $W(H\beta) \approx 100$ Å, we might expect BL Lac objects to have $W(H\beta) \approx 10$ Å. In fact, the emission lines of BL Lac objects are much weaker than this. For example, from the spectrum of BL Lac by Miller and Hawley (1977), I estimate $W(H\beta) \approx 10^{-1}$ Å. Furthermore, some BL Lac objects have $\alpha \approx 1$ and nevertheless have weak lines.

The absence of strong emission lines may be attributed to an absence of gas in the nucleus, but one must remember that line emission depends strongly on the density of the gas as well as the mass. The broad emission-line regions (BLR) of Seyfert galaxies have electron densities $N \approx 10^{9\pm1}$ cm^{-3}. The mass of emitting gas is given by

$$M_B \approx (10^{0.9}\ M_\odot)\ L_{42} N_9^{-1}, \qquad \text{(I-2)}$$

where $L_{42} = L(H\beta)/10^{42}$ erg s^{-1} and $N_9 = N/10^9$ cm^{-3}. Thus, a very luminous Seyfert galaxy requires only ~ 10 $M_\odot$ of ionized gas to produce the broad lines. Many BL Lac objects do have weak, narrow emission lines. The presence of [N II] $\lambda 6584$ emission in the spectrum of BL Lac indicates that $N_e < 10^5$ cm^{-3}. The above estimate of $W(H\beta)$ corresponds to $L(H\beta) \approx 10^{39.1}$ erg s^{-1}, for a cosmological redshift of 0.07 (Oke and Gunn 1974). The required mass is $\sim 10^{1.3}\ M_\odot N_5^{-1}$. For $N \approx 10^2$ cm^{-3}, for example, $M \approx 10^4\ M_\odot$. This is enough to make a broad line region. The real issue therefore is, why do BL Lac objects lack even a tiny amount of gas at high density?

The weakness of emission lines from BL Lac objects is also interesting in the light of the promise held by accretion models of active nuclei (Lynden-Bell 1969). BL Lac luminosities typically correspond to accretion rates $\gtrsim 10^{-1}$ $M_\odot$ yr^{-1}. If the activity lasts $\gtrsim 10^6$ years, then large masses of gas are involved. This suggests that the difference in emission-line properties between QSOs and BL Lac objects may involve the geometry of the accretion flow.

From the spectrum by Hawley and Miller (1977), it appears that BL Lac has [N II]/Hα > 1. This is typical of galactic nuclei (Burbidge and Burbidge 1967), and it probably reflects high nitrogen abundances near the nuclei of galaxies. The strength of [N II] in BL Lac indicates that the gas in its nucleus is native to the nucleus. This argues against the model for active nuclei suggested by Gunn (1977), in which the activity is fueled by intergalactic gas clouds.

II. ORIGIN OF THE BROAD EMISSION LINES OF SEYFERT GALAXIES

Sy 1 galaxies have permitted emission lines of H, He, O I, and Fe II with wings extending up to ~ 10^4 km s^{-1} from line center. The line widths are attributed to Doppler shifts resulting from the bulk motions of the emitting gas. Several studies have shown that the line intensities are consistent with photoionization. My purpose here is to assess the relative merits of models in which the observed high velocities represent orbital motion around a central massive object, radial infall, random motions, or systematic outflow.

a) Disk Models

i) Possible geometries

One can imagine two basic geometries for the case in which the broad line emitting gas is in essentially circular Keplerian orbit around a central mass (see Figure 1): (1) Central illumination. There is a point source of ionizing continuum coinciding with the central mass. The broad line region is a thick disk composed of clouds extending to fractional height $h/r \gtrsim 10^{-1}$ above the midplane; such a thickness is required for the gas to intercept a fraction $\Omega/4\pi \approx 10^{-1}$ of the ionizing continuum (Oke 1974). A model of this nature has recently been discussed by Osterbrock (1978). (2) External illumination. The gas is confined to a thin ($h/r < 10^{-2}$) disk, as predicted by the α-model of accretion disks for appropriate values of the central mass M_H and accretion rate (Shakura and Sunyaev 1973; Shields 1977). In this case, the ionizing continuum must be emitted from a height z above the plane of the disk, comparable with the radius at which the circular velocity v_ϕ equals the observed line widths, so that the appropriate velocity region of the disk intercepts a large fraction of the ionizing continuum. The broad line region then consists of a photoionized skin on the surface of a relatively cool accretion disk. (A physically plausible model is that the nonthermal continuum is emitted from "beams" or "jets" ejected along the rotation axis by electrodynamic processes or radiation pressure.)

In either model the Keplerian velocity at distance R from the central mass is

$$v_\phi = c(R/R_g)^{-1/2} = (10^{4.07}\ \text{km s}^{-1})\ M_8^{1/2} R_{16}^{-1/2} \qquad \text{(II-1)}$$

where $M_8 \equiv M_H/10^8\ M_\odot$, $R_{16} \equiv R/10^{16}$ cm, and

$$R_g = G\ M_H/c^2 = (10^{13.17}\ \text{cm})\ M_8. \qquad \text{(II-2)}$$

M_H can be estimated from the Eddington limit,

$$L_{Ed} = (10^{46.1}\ \text{erg s}^{-1})\ M_8. \qquad \text{(II-3)}$$

For a fairly luminuous Seyfert such as 3C 120, with a luminosity $L \approx 10^{45}$ erg s^{-1}, one has $M_H \gtrsim 10^7\ M_\odot$. The radius having $v_\phi \approx 10^{3.5}$ km s^{-1} is therefore $r \approx (10^{16}\ \text{cm})\ (L_{Ed}/L)$.

ii) Observed line profiles

The basic shape of the broad line profiles is similar from object to object. Figure 2 shows the Hα line profile of 3C 120, derived by smoothing the observations by

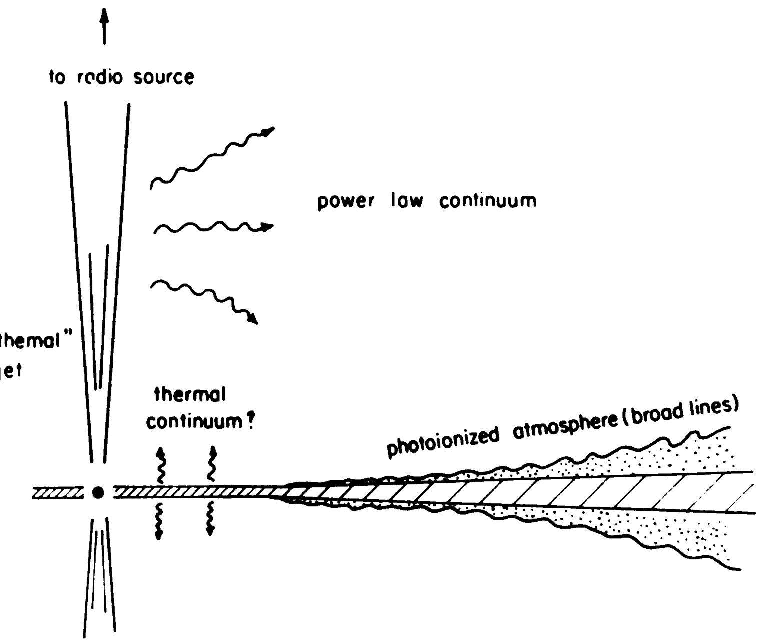

Fig. 1(a) -- Geometry of the "external illumination" disk model.

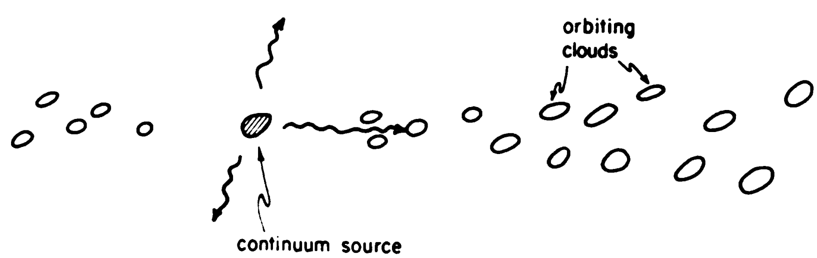

Fig. 1(b) -- Geometry of the "central illumination" model.

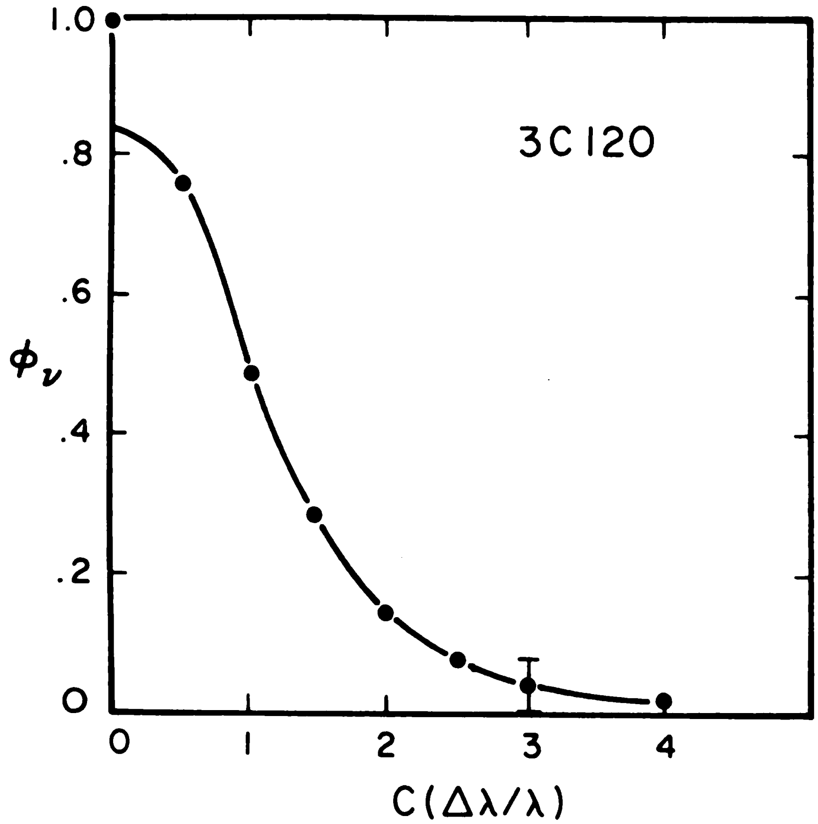

Fig. 2 -- Hα emission profile of 3C 120. Points are observed intensities; curve is disk model.

Osterbrock and Phillips (1975) and averaging the red and blue sides. The profile is characterized by a triangular core extending to $v = 1500$ km s^{-1} and wings extending beyond 4000 km s^{-1} with a shape $f_\nu \propto v^{-2.5}$, where $v = c\Delta\nu/\nu_o$, $\Delta\nu = \nu-\nu_o$, and ν_o is the line center.

iii) <u>The distribution of emission with radius</u>

The line profile of a narrow, rotating ring, radiating isotropically, is

$$f_\nu \propto (1-x^2)^{-1/2}, \tag{II-4}$$

for $x \equiv \Delta\nu/\Delta\nu_i < 1$, where $\Delta\nu_i = \nu_o(v/c)\sin i$ and $\sin i$ is the inclination. The profile peaks sharply at $x = 1$, and drops to a minimum (but not zero) at $x = 0$. This bears no resemblance to Seyfert line profiles. More generally, if there is emission from a range of radii (r_{min}, r_{max}) and corresponding velocities (v_{max}, v_{min}), then the intensity drops to zero for $\Delta\nu/\nu_o > (v_{max}/c)\sin i$, and has a central dip for $\Delta\nu/\nu_o < (v_{min}/c)\sin i$. Obviously, the observed profiles require that the emitting gas be distributed over a wide range of radii from $v_{max} \gtrsim 10^4$ km s^{-1} to $v_{min} \lesssim 200$ km s^{-1}. The latter value is motivated by the requirement that any central dip be narrow enough to be masked by instrumental broadening or by emission from the narrow line region. The emission thus extends over a factor $\gtrsim 10^3$ in radius.

Given the required spread in radius, the form of the line profile is determined by the radial variation of the line emission per unit surface area, $F(r)$(ergs s^{-1} cm^{-2}). If F varies as

$$F = F_o(r/r_o)^{-a} \tag{II-5}$$

over some fairly large range of r, then the observed profile is

$$\begin{aligned} 4\pi D^2 f_\nu &\approx 4f(a)r_\nu{}^2F(r_\nu)(\Delta\nu)^{-1} \qquad \text{(II-6a)} \\ &\propto (\Delta\nu)^{2a-5}, \end{aligned}$$

where

$$f(a) \approx \pi^{1/2}\Gamma(7/2-a)\ \Gamma(4-a) \tag{II-6b}$$

and $r_\nu/r_g = (\nu_o \sin i/\Delta\nu)^2$. This holds for $a<(5/2)$; for $a > 3$, there is too little emission from the outer disk to fill in the central dip.

Equation (II-6a) suggests that the wings of the 3C 120 profile, with $f_\nu \propto (\Delta\nu)^{-2.5}$, could be fit by having $a \approx 5/4$ whereas the core requires that the outer disk have $a \approx 5/2$. This is verified by numerical integrations. Figure 2 shows that a good fit is achieved for $a = 5/4$ for $v_\phi > 1700$ km s^{-1}, $a = 3$ for $v_\phi < 850$ km s^{-1}, and $a = 5/2$ at intermediate radii.

[The gentle maximum in the computed profile could be sharpened by further adjustments in F(r); on the other hand, there will be a weak contribution to the line peak by emission from the narrow line region.]

iv) Line profiles of different ions

Constraints on the physical conditions in the disk result from the observation that different ions have nearly identical line profiles in typical Seyferts and QSOs. For example, the similarity of the profiles of the He IIλ4686 and He I λ5876 implies that these ions exist in the same proportions at all radii. This automatically occurs in the external illumination model, because the photoionized layer is optically thick, and the relative thickness of the He^+ and He^{++} layers is fixed by the spectral index of the ionizing radiation (Williams 1971). On the other hand, the central illumination model might have individually optically thin clouds distributed through the general boundaries of the disk. In this case, an He^{++} Strömgren sphere would form at some radius; and the He II line profile would have a broad central minimum inside the corresponding velocity, whereas the He I line would have a sharp core but wings abruptly cutoff beyond this same velocity. Evidently, the central illumination model requires that the disk consist of discrete optically thick clouds at all radii. As suggested by Osterbrock (1978), the thickness of the disk might be governed by

$$h/r \approx (v_z/v_\phi)^2, \qquad \text{(II-7)}$$

where v_z is the random velocity dispersion of the clouds. However, Osterbrock appears to envision optically thin clouds, contrary to the foregoing argument.

A further important constraint is imposed by the requirement that for QSOs the line profiles of transition zone ions, such as C III] λ1909 and Mg II λ2800, are similar to those of C IV λ1550 and Lα λ1215. The relative intensities of these lines are governed by the ionization parameter

$$U \equiv \phi_i/Nc, \qquad \text{(II-8)}$$

where ϕ_i is the incident ionizing photon flux ($cm^{-2}\ s^{-1}$) and N is the gas density (cm^{-3}). Photoionization models for optically thick clouds (Davidson 1972) gives F(1909)/F(1550) $\propto U^{-1.0}$. If U were to vary systematically from the inner to the outer parts of the disk, then the lines would have different profiles. For example, if N were independent of R while ϕ_i varied as R^{-2}, then U would vary as $R^{-2} \propto v_\phi^{+4}$ Such a strong variation of U with v_ϕ would enhance the C III] core and suppress the wings, leading to a narrower profile than for C IV.

In order to put this on a quantitative basis, I have computed the line profiles of C IV and C III] under the assumptions that C IV has the same profile as Hα for 3C 120 and that U varies as $R^{\pm 0.2}$. The resulting profiles are shown in Figure 3. It is evident that even this gentle variation of U with radius is stronger than allowed by the observations of typical QSOs, such as the profiles for QSO 0736-06 by Weymann et al. (1977). Evidently, if the model is to succeed some mechanism must govern the gas density to vary as $N \propto \phi \propto R^{-2}$, to an accuracy

$$|d \log N/d \log \phi_i| \lesssim 0.1. \qquad \text{(II-9)}$$

Computations for the model with external illumination, with $\phi_i \propto F(H\beta) \propto F(C\ IV)$, lead to the same conclusion.

v) Radiation pressure and the gas density

Although equation (II-9) places a stringent requirement on the mechanism determining the gas densities, the relation $N \propto \phi_i$ is exactly what results if the density is determined by radiation pressure. For example, in the case of external illumination, the ionized gas is compressed against the underlying disk by the combined action of radiation pressure and the vertical component of the gravity of the central mass, $g_z = (GM_H/r^2)(h/r)$. For parameters of interest, the α-model for accretion disks gives $h/r \approx 10^{-2.5}$, so

$$g_z \approx (10^{-5.5}\ \text{cm s}^{-1})\ v_8^4\ M_8^{-1}, \qquad \text{(II-10)}$$

where $v_8 \equiv v/10^3$ km s^{-1}. For comparison, the radiative acceleration at a point in the ionized gas is

$$g_{rad} \approx (10^{-0.5}\ \text{cm s}^{-2})\ N_9 \qquad \text{(II-11)}$$

(Mathews 1974). Obviously, for $N_9 \gtrsim 1$ as required for suppression of forbidden lines $g_{rad} >> g_z$. Therefore, the density of the ionized layer is determined by radiation pressure, such that the pressure at the base of the ionized layer ("Strömgren surface") balances the momentum per unit area deposited by the ionizing radiation:

$$P \approx \phi_i \langle h\nu \rangle_i\ c^{-1}, \qquad \text{(II-12)}$$

where $\langle h\nu \rangle \approx 3h\nu_H$ is the mean energy of the ionizing photons. Taking $P = 2NkT$ with $T \approx 10^{4.1}$ K, as expected for photoionization, we have

$$N \approx \frac{\phi_i \langle h\nu \rangle_i}{2\ kTc} \approx (10^{8.8}\ \text{cm}^{-3})\phi_{18}, \qquad \text{(II-13)}$$

where $\phi_{18} \equiv \phi_i/10^{18}$ photons cm^{-2} s^{-1}.

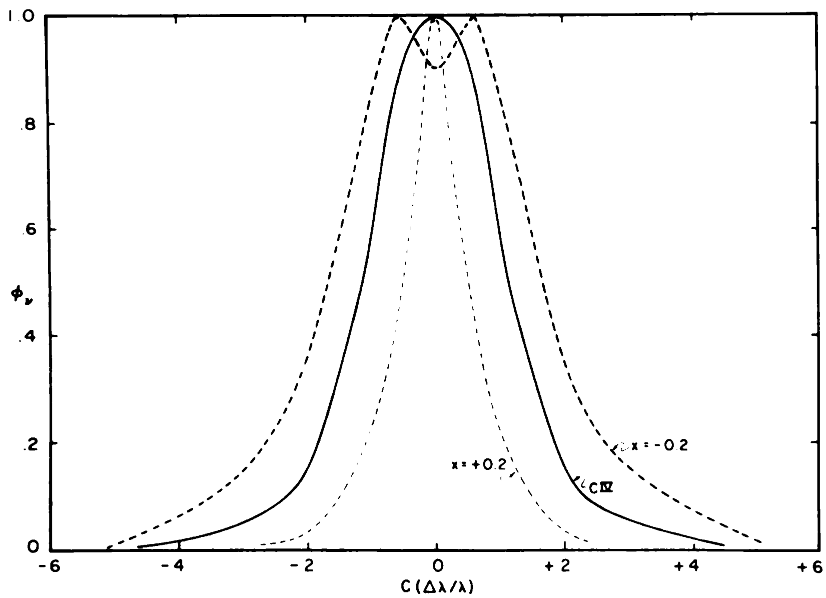

Fig. 3 -- Comparison of C III] and C IV line profiles for disk model with $U \propto R^{-x}$. Dashed curves are the C III] profile for $x \neq 0$.

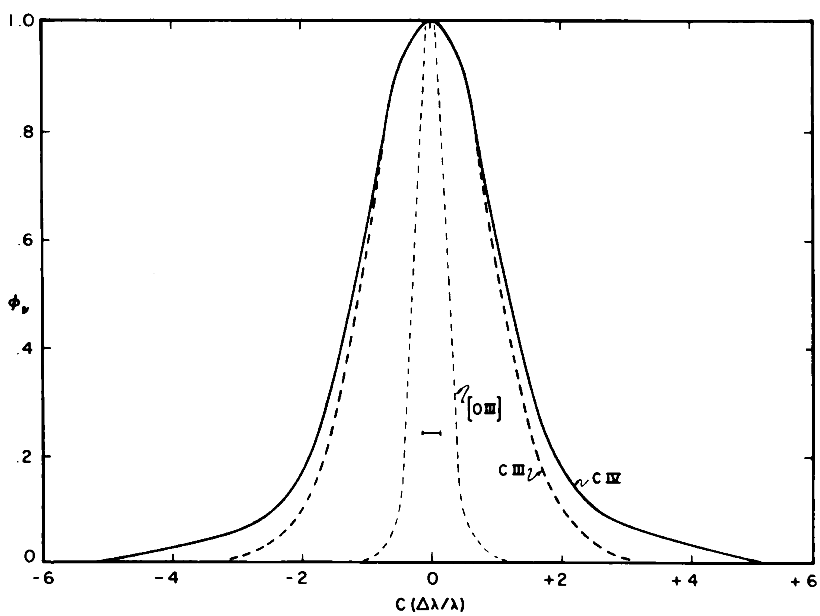

Fig. 4 -- Comparison of [O III], C III], and C IV profiles for in disk model with $N_e \propto R^{-2}$ and U independent of R.

For the external illumination model, we have

$$F(H\beta) = (\alpha_{42}/\alpha_B)\, h\nu\phi_i = (10^{-12.32}\ \mathrm{erg})\phi_i. \quad \text{(II-14)}$$

Equation (II-6) gives $F(H\beta)$ in terms of the observed line fluxes. For example at $v = 2000$ km s^{-1}, the line profile of Figure 2 and the Hβ flux of Shields, Oke, and Sargent (1972) give $F(r_\nu) = (10^{5.7}$ erg s^{-1} cm$^{-2})$ M_8^{-2}, where $r_\nu = (10^{17.5}$ cm) M_8 is the radius having $v_\phi = 2000$ km s^{-1}. Thus $\phi_i = 10^{18.1}\ M_8^{-2}$ and $N = (10^{8.9}$ cm$^{-3})$ M_8^{-2}. Thus, for $M_8 \lesssim 1$, radiation pressure succeeds in giving the correct range of gas densities in addition to the required constancy of U.

Radiation pressure may also govern the density in the central illumination model. Since the clouds must be optically thick, it is likely that the the total mass of a cloud (including the neutral zone) exceeds the mass of the ionized inner face by a factor $\gtrsim 2$. In this case, the inertia of the cloud is sufficient that the ionized layer is compressed against the rest of the cloud, and equation (II-13) still applies. Thus, for $\phi_i = Q(H^o)/4\pi r^2$, with $Q(H^o) = 10^{54.5}$ s^{-1} from L(Hβ), we have $\phi_{18} = 10^{-0.4}\ M_8^{-2}$ at the radius where $v = 2000$ km s^{-1}. Therefore $N \approx (10^{9.2}$ cm$^{-3})$ M^{-2} similar to the result for external illumination. This calculation also applies to clouds undergoing non-circular motion (e.g., outflow).

Does this mean that radiation pressure is a viable mechanism to determine the gas density? One might object that equation (II-13) leads to values $U \approx 10^{-1.3}$. However, photoionization models give a C III]/C IV intensity ratio much smaller than observed for this value of U, and a value $U \approx 10^{-2.5}$ is required to fit the observations (Davidson 1972).

I suggest that radiation pressure may nevertheless govern the density as given by equation (II-13), even in outflow models. (1) The weakness of C III] in photoionization models for $U = 10^{-1.3}$ is reminiscent of the well known "[O II] problem" in nebulae. When the density, radius, and ionizing stellar luminosity is known, thus determining U; but photoionization models usually give intensities of [O II], [N II] and similar "transition zone" ions much weaker than observed. Furthermore, ultraviolet observations of the planetary nebula NGC 7027 give C III]/C IV ratios stronger than predicted by models (Bohlin et al. 1975). These examples suggest that whatever mechanism causes the "O II problem" in nebulae may be capable of reconciling the C III] intensity of QSOs with the high value of U resulting from radiation pressure. (2) The C III]/C IV ratio shows little systematic variation with QSO luminosity, over several orders of magnitude in luminosity. This suggests that U is independent of luminosity, which is naturally explained by radiation pressure. (3) Observations of Fe II emission and x-ray absorption indicate that the broad line clouds have substantial neutral portions whose inertia will allow radiation pressure to compress the photoionized layer to the density of equation (II-13).

vi) The "[O III] Problem"

The rotation models now encounter a serious difficulty. The requirement $\phi_i/N \approx$ const implies that $N \propto R^{-2} \propto v_\phi^4$ for central illumination, and a similarly strong radial variation of density for external illumination. The trouble is that, for a range of a factor $\gtrsim 10^3$ in R (from the region contributing the wings to that contributing the sharp core), a variation by a factor $\gtrsim 10^6$ in N_e occurs. Thus if the outer disk is dense enough to suppress the forbidden lines (critical density $N_c = 10^{5.8}$ cm^{-3} for [O III] λ5007), then the disk is so dense that C III] λ1909 is suppressed. [Four-level calculations by Netzer (1978) give $N_c = 10^{9.5}$ cm^{-3} for a factor 2 suppression of λ1909.] Thus, there should either be strong, substantially broadened [O III] emission from the outer disk (if the density there is low), or else a sharp cutoff of the wings of C III], relative to C IV, at the velocity corresponding to the radius where $N = 10^{9.5}$ cm^{-3} (if the density in the outer disk is high).

This is illustrated by Figure 4, which gives the line profiles numerically integrated for the case of central illumination with $N = 10^9$ cm^{-3} at the radius where $v_\phi = 2000$ km s^{-1}. The comparison of C III] and C IV is shown with the peak intensities scaled to the same value. For [O III] λ5007 the flux f_ν is compared with that of Hβ on the same scale. For this, I have assumed $F(\lambda5007) = 15\ F(H\beta)/(1+N/N_c)$. where the factor 15 corresponds to I(5007)/I(Hβ) for power law photoionization models in the low density limit.

The truncation of the wings of λ1909 is evident, and is not observed in the profiles of 0736-06 or other QSOs. In the same model, the density drops low enough in the outer disk that [O III] λ5007 emission is strong. The [O III] emission has a width (FWHM) of 600 km s^{-1}, and a total flux $f(\lambda5007)/f(H\beta) = 0.70$. Such an [O III] contribution from the outer disk would not be marked by the observed [O III] from the narrow line region, which has a FWHM of 300 ± 100 km s^{-1}. The same problem occurs in the case of external illumination; quantitatively, it is slightly worse, since the fit to the 3C 120 profile has $N \propto \phi_i \propto v_\phi^5$ on the average between v = 200 and 4000 km s^{-1}, rather than $\phi_i \propto v_\phi^4$ as for central illumination.

One might try to relieve the [O III] problem by reducing M_H, thereby increasing the density of each value of v_ϕ in proportion to M_H^{-2}. However, this will result in more severe truncation of the C III] wings (i.e., at a smaller velocity), and conversely. Evidently, for any choice of parameters, one has either truncation of the C III] wings, or excessive broad [O III] emission, or both.

This "[O III] problem" is a general difficulty with the concept that the broad line material derives its velocities from Keplerian orbital motion. The following related points deserve mention: (1) Many Sy 1 galaxies have narrow line emission with $I(5007)/I(H\beta) < 0.3$, much weaker than for 3C120 (e.g. Osterbrock 1977). In such cases, the predicted [O III] from the outer disk contradicts the observations with regard to total intensity as well as width. (2) For some objects the narrow lines occur at a different redshift from that of the peaks of the broad lines. 3C 120 has z(broad) -z(narrow) = 0.007 = -2100 km s^{-1} (Osterbrock, Koski, and Phillips 1976). Any [O III] emission from the broad line region would appear as a separate feature to the blue of the observed narrow [O III] lines, and no such feature is observed.

b) Infall models

i) Line profiles

Let us now consider the case in which the broad line emitting clouds acquire their high velocities by falling radially toward the central mass. Such a picture has been suggested by Osterbrock (1977) to explain observed asymmetries in the line profiles. The velocity is

$$v_r = c(2R/R_g)^{-1/2} = (10^{4.22} \text{ km s}^{-1})\ M_8^{1/2}\ R_{16}^{-1/2}. \quad \text{(II-15)}$$

Because the velocity-radius relation is essentially the same, the discussion of disk models largely carries over to the case of infall. The profile of a thin shell is square, f_ν = const for $|\Delta\nu| \leq (v/c)\nu_0$. Again, the sharp line profile requires emission from a range $\Delta\log_{10} R \gtrsim 3$. Optically thick clouds and $N \propto R^{-2}$ are required to give similar line profiles; and moderately broad [O III] emission or else truncated C III] line wings are then expected. Evidently, the "[O III] problem" represents a general difficulty with models involving gravitational motions to explain the broad line profiles.

ii) The accretion rate

The mass flux corresponding to the hypothetical infalling broad line material is

$$\dot{M}_B = 4\pi R^2 (\varepsilon N m_H) v_r, \quad \text{(II-16)}$$

where ε, N, and v_r are the filling factor, number density, and infall velocity at R. The quantities ε and N are constrained by the observed luminosity. For a luminosity $L_\nu = 4\pi D^2 f_\nu$ at some frequency $\Delta\nu$, the mean emissivity (volume averaged) at the corresponding radius ($v_r/c = \Delta\nu/\nu_0$)

$$4\pi\langle j\rangle = \frac{dL}{4\pi R^2 dR} \simeq \frac{2^{-9/2}\ (v/c)^6}{\pi R_g{}^3} (L_\nu \Delta\nu) \left|\frac{d \log L_\nu}{d \log \nu}\right|^{-1} \quad \text{(II-17a)}$$

$$\approx (10^{-11.4}\ \mathrm{erg\ cm^{-3}\ s^{-1}})v_8^6\ M_8^{-3}\ \left(\frac{\nu_o}{\nu_{H\beta}}\right)L_{\nu 30},\ (\text{II-17b})$$

where $L_{\nu 30} = L_\nu/10^{30}$ erg s^{-1} Hz^{-1} and I have evaluated the numerical coefficient for the case of Hβ. For 3C 120, with $L_{\nu 30} = 0.05$ at $v_8 = 2$, we have $4\pi j \approx (10^{-10.9}$ erg cm^{-3} s^{-1}) x M_8^{-3}. From $4\pi\langle j\rangle = N^2\alpha_{42}h\nu$, we find $N_9^{\,2} = 10^{-3.9}\ M_8^{-3}$. Using this and v_r = 2000 km s^{-1} to eliminate R and ϵ from equation (II-16), we find $\dot{M}_B \approx (3M_\odot\ \mathrm{yr^{-1}})\ M_8^{-1}\ N_9^{-1}$. Photoionization models require $U \approx 10^{-2.5}$ and $N_9 \approx 10^{0.5\pm0.5}$ to fit the spectra of QSOs. For 3C 120, one finds $U \approx 10^{-1.9}\ M_8^{-2}\ N_9^{-1}$, whence $N_9 \approx 10^{0.6}\ M_8^{-2}$ and thus $M_8 \approx 1$. Substituting into the above expression for $\dot{M}_B$, we have $\dot{M}_B \approx 10^{-0.1}\ M_8 \approx 10^{-0.1}\ M_\odot\ \mathrm{yr^{-1}}$. This substantially exceeds the accretion rate needed to produce the luminosity of 3C 120, $\dot{M}_L \approx L/(0.1\ c^2) \approx 10^{-0.7}\ M_\odot\ \mathrm{yr^{-1}}$. If U is determined by radiation presure as in equation (8), larger values of U and M_B result. Evidently, it is not possible simultaneously to satisfy the constraints on N, U, and L without having an accretion rate much higher than implied by the total luminosity. Thus the accretion rate poses another difficulty for infall models of the broad line region.

c) Further Remarks on Gravitational Models

i) The Fe II - Radio Correlation

In spite of the foregoing difficulties with gravitational models, it seems worthwhile to mention a few more points to facilitate a balanced judgement. In this spirit, I note that a thick centrally illuminated disk model of the kind suggested by Osterbrock (1978) provides a possible explanation of the observed tendency of Sy 1 galaxies with strong Fe II emission to have weak radio emission, and vice versa (Osterbrock 1977). In this model, the disk thickness is described by equation (II-7), and large values of v_z/v are supposed to be associated with weak radio emission. Such a picture provides the following possible explanation of the radio - Fe II anticorrelation. It is often assumed that the Fe II emission results from continuum fluorescence, in which lines from the ground state absorb continuum photons around $\lambda \approx 2500$ Å, and alternative decay routes produce the optical lines (Wampler and Oke 1967). In order to produce the observed optical Fe II intensities, the various ultraviolet lines must absorb continuum intervals $\Delta\nu/\nu$ comparable with the observed line widths. This will not occur if the emitting material were in pure circular motion around a central continuum source, because the lines would not be Doppler broadened as seen from the continuum source. A random velocity component v_z would cause the continuum source to see a line width $\Delta\nu/\nu \approx v_z/c$. Thus the strength of the Fe II lines would increase with v_z/v linearly until the ultraviolet lines begin to overlap. The qualitative sense of the observed anticorrelation between radio and Fe II emission is reproduced.

e) Remarks on Outflow Models

The above difficulties with gravitational motions favor the alternative picture that the velocities represent an outward motion of the emitting clouds. In addition, there is the direct evidence for outflow in special cases, including the P-Cyni profiles of PHL 5200 (Scargle et al. 1970) and the blueshifted He I absorption features of NGC 4151 (Anderson and Kraft 1969; Cromwell and Weymann 1970). The arguments given above complement this evidence in that they refer directly to the emitting gas, rather than the absorbing material.

i) Asymmetries in the Line Profiles

Osterbrock (1977) has observed a general tendency for the broad line wings to extend further to the red side of the line peak than to the blue. Netzer (1978) has suggested that this could result from a gravitational redshift. However, the observed asymmetries, when present, are too large to be explained in terms of a gravitational redshift. Even for the relatively symmetrical Hα profile of 1217+02 (Baldwin 1975), the wings, at 0.08 of the maximum intensity, are centered $\Delta v \approx 600$ km s^{-1} to the red of the peak. Since the full width at this intensity is $2v = 12000$ km s^{-1}, this gives $\Delta v/v \approx 0.10$, much greater than the value $\Delta v/v \approx v/c = 0.02$ expected from a gravitational redshift. An extreme case is PHL 1093 (Baldwin 1975): for the intensity at which $2v = 5700$ km s^{-1}, the wings are centered at $v = +850$ km s^{-1}. Such a large value of $\Delta v/v$ as a result of a gravitational redshift, would require a nearly face-on disk with $\sin i \approx 0.09$, an occurence with a probability of only $\sim 10^{-2.5}$. Moreover, the actual rotation speed corresponding to the extreme ends of the wings ($2v \approx 10000$ km s^{-1}) would be $v_\phi = v/\sin i = 56000$ km s^{-1}, far greater than the width of any observed line profiles.

Evidently, the red-favoring asymmetries have another origin. A promising alternative explanation (Ferland, Netzer, and Shields 1978) involves Balmer self-absorption in optically thick clouds moving away from the continuum source. Line photons escape more easily from the side of a cloud that faces the continuum source, so that the clouds receding from the observer appear brighter. This process is observed to operate in novae, and PHL 1093 agrees well with the empirical relation between asymmetry and Balmer decrement for Nova Cygni 1975.

ii) Origin of the Outflow

Given that the broad emission lines are emitted by small dense clouds moving away from the energy source, what is the origin of these clouds and their velocities? One picture would be that the clouds condense in a radially outflowing wind moving at $v_W \approx 10^4$ km s^{-1}. The clouds would inherit the velocity of the wind, and might be further accelerated by some force such as radiation pressure. A difficulty with this picture is that the flow may be thought of as the sum of many thin spherical shells, each containing clouds moving at a particular velocity $v_r \geq v_w$. The line profile of emission from an expanding shell is square, f_ν = const for $|c\Delta\nu/\nu_0| \leq v_r$ and $f_\nu = 0$ otherwise. If clouds were to condense at $v_r = v_w$ and accelerate outward, the line profile would have a flat top of width $\pm\, v_w$, and wings falling off according to the details of the acceleration. The broad line profile of Seyferts and QSOs have peaks with widths $\leq$ 300 km s^{-1}. Thus $v_w \leq$ 300 km s^{-1}, which implies that the broad line widths cannot simply represent the velocities of clouds condensing in a wind and inheriting its velocity.

Evidently, the broad line clouds condense out of gas that originates near R_B or falls in from a larger radius. One possibility is that the clouds condense out of an accretion flow. For steady, spherical infall, the physical conditions in the flow can be estimated as a function of the accretion rate. The flow could in principle be slower than the free-fall velocity v_{ff} if the gas were near the virial temperature, so we write $v = \xi v_{ff}$ with $\xi < 1$. The density is then

$$N = \frac{\dot{M}}{4\pi r^2 v m_H} = (10^{4.3}\ \mathrm{cm}^{-3})\ \dot{M}_0 R_{18}^{-3/2}\ M_8^{-1/2}\ \xi^{-1}, \quad \text{(II-18)}$$

where $\dot{M}_0 \equiv \dot{M}/1\ M_\odot\ \mathrm{yr}^{-1}$. (Thus, for 3C 120, with $\dot{M}_0 \approx 10^{-}$, $M_8 \approx 10^{-1}$, $R_{18} \approx 1$, and $\xi \approx 1$, we have $N \approx 10^4$ cm^{-3}.) The flow must go into free fall if the cooling time is much shorter than the crossing time. Using the virial theorem in the approximate form $v^2 + c_s^2 \approx v_{esc}^2$, where c_s is the sound speed, one readily finds for bremsstrahlung cooling that

$$\tau_{br}/\tau_{cr} \approx 10^{-3.4}\ \dot{M}_0^{-1}\ M_0^{1/2} R^{-1/2} \xi^2 (1-\xi^2)^{-1/2}, \quad \text{(II-19)}$$

where $\tau_{cr} \equiv R/v$ is the crossing time. Thus $\tau_{br}/\tau_{cr} \ll 1$; additional cooling processes strengthen this condition. We must therefore take $\xi \approx 1$; and then for 3C 120 with $\dot{M}_0 \approx M_8 \approx 10^{-1}$ and $R_{18} \approx 1$ we find $N \approx 10^{3.8}$ cm^{-3}.

This density is sufficiently low that the flow can be completely photoionized by the power law continuum, and line emission from the flow is negligible. The value of U is very high ($\sim 10^3\ R^{-1/2}$) for 3C 120, and the gas is highly ionized. Of course, the infall could largely consist of clouds at some higher density filling relatively little of the volu in the absence of some outward force such as radiation pressure, such clouds would also be essentially in freefall.

Can the broad line emission result from some force that compresses and accelerates a portion of this infalling gas? The observed uniformity of the line ratios indicates that this mechanism is able to trigger cloud formation at densities $\sim 10^9$ cm^{-3} independent of luminosity. The luminosity independence of U then requires $R_B \propto L^{1/2}$, i.e., ϕ_i is independent of L. This is equivalent to saying that, for some reason, the broad line clouds choose to form at a radius such that the incident continuum flux, $L/4\pi R_B^2$, has some magic value, regardless of the value of L. This point seems sufficiently important that it is worth giving a second argument for constant flux. The O I $\lambda 8446$ line appears in Sy 1 spectra with quite uniform strength. The ratio $I(8446)/I(H\alpha)$ varies as $\tau_{H\alpha}$ (Netzer and Penston 1976), and $\tau(H\alpha) \approx 10^3 \phi_{18} (\Delta v_6)^{-2}$ according to equations (1-5) of Shields and Oke (1975). Since $I(\lambda 8446)/I(H\alpha) \approx 0.05$ for objects ranging in luminosity form NGC 4151 (Netzer and Penston 1976) to 3C 273 (Oke and Shields 1976), it follows that $\phi_i \propto L/R_B^2$ is constant to a factor ~ 2 or so over a luminosity range exceeding a factor 10^3!

What mechanism might regulate the radius of the broad line region to satisfy $R_B \propto L^{1/2}$? One possibility is that dust is involved. The temperature of dust is determined by the radiation flux. Therefore, if the broad line clouds form, say, at the radius where dust is destroyed in infalling gas, (or where it first condenses in outflowing gas) the constant-flux condition is precisely satisfied. Support for this idea comes from the expected grain temperature in the broad line region. For grains of radius $10^{-5} a_5$ cm with infrared emission efficiencies $\sim 0.1\ (2\pi a/\lambda)$, one finds an equilibrium temperature

$$T_D \approx (10^{3.0}\ \mathrm{K})\ \phi_{18}^{1/5}\ a_5^{-1/5}. \qquad \text{(II-20)}$$

Thus for $\phi_{18} \approx 1$ as inferred for the BLR, ($U \approx 10^{-2}$, $N \approx 10^9$ cm^{-3}), the radiation flux does indeed warm refractory grains just to their evaporation point. How this might trigger the formation of the dense BLR clouds is unclear. However, for infalling clouds with even a fraction of a solar abundance of refractory metals in the form of grains, radiation pressure on the dust has significant dynamical effects. Perhaps when the dust evaporates in the infalling gas, the instabilities associated with photoionization radiation pressure (Mestel, Moore, and Perry 1976; Mathews 1976) are able for the first time to cause dense clouds to form.

iv) Radiation Pressure and the Broad Line Velocities

Many workers have considered the role of radiation pressure in accelerating the emitting and absorbing regions of QSOs. Two physical pictures have been advanced to account for the magnitude of the broad line velocities. Shields, Oke, and Sargent (1972) envisioned optically thick clouds that have reached a terminal velocity in which the momentum flux of the ionizing continuum is balanced by the ram pressure exerted on the clouds by a surrounding medium, $\rho_m v_t^2 \approx \phi_i \langle h\nu \rangle c^{-1}$. In convenient units, this gives

$$v_t \approx (10^{3.5} \text{ km s}^{-1})\, Q_{55}^{1/2}\, R_{18}^{-1}\, N_{m_4}^{-1/2}. \qquad \text{(II-21)}$$

If we identify N_m with the accretion flow density of equation (II-18), then for 3C 120 at $R_{18} \approx 1$ we find $v_t \approx 10^{3.4}$ km s^{-1}, in agreement with the observed velocities. A further success of this picture is the weak luminosity dependence of v_t. If we take $\dot{M} \propto L$ and $M_H \propto L$ on the average, then $v_t \propto R^{-1/4} L^{1/4}$. The above requirement that $R \propto L^{1/2}$ then gives $v_t \propto L^{1/8}$. This agrees with the fact that the broad lines of dim Seyferts and bright QSOs all have $v_t \approx 10^4$ km s^{-1}.

Alternatively, Mathews (1974) has suggested that velocities of the observed magnitude can result from radiative acceleration of optically thin clouds experiencing little resistance. Given a confining pressure that falls off with radius, equation (II-11) gives a terminal velocity $v_t \approx \sqrt{2 g_{rad} R_B} \approx (10^{3.9} \text{ km s}^{-1})\, N_9^{1/2}\, R_{18}^{1/2}$. One can also estimate the luminosity dependence of v_t in this picture. For $R_B \propto L^{1/2}$ and $N \approx$ const, one has $v_t \propto L^{1/4}$. A weak increase in broad line width with luminosity is marginally indicated by the results of Baldwin (1976).

III. CONCLUSIONS

The lack of broad emission lines in BL Lac objects is attributable, not to a complete absence of gas in the nucleus, but to the absence of even a few solar masses of gas at high density. I have argued that the clouds emitting the broad lines of Seyfert galaxies condense at low velocity and are accelerated outward, rather than deriving their observed velocities from gravitational motion. Without a theory for the cloud formation mechanism, one can only speculate as to why the clouds fail to form in BL Lac objects. If the clouds condense out of a spherical accretion flow, then there may be critical accretion rate, for a given M_H, below which the flow density is too low for the unknown instability to operate. Alternatively, if in BL Lac objects the accreting matter has high angular momentum, it may enter an accretion disk before reaching the radius at which a broad line region would form. Yet another possibility may be that the clouds are formed and accelerated by the impact of a fast moving wind from the central regions, striking ambient or infalling gas at R_B. Objects shining well below the Eddington limit might not produce such a wind; then objects with $L/L_{Ed} \ll 1$ would be BL Lac objects whereas those with $L/L_{Ed} \gtrsim 1$ would be QSOs or Seyfert galaxies.

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DISCUSSION

E. CAPRIOTTI:

I think that's a brilliant idea; I've thought of it myself. I think that the model consisting of an expanding system of clouds can account for the double humped hydrogen line profiles that have been observed in a few cases (e.g., Disney, M.J. 1973, Ap.J. Letters, 181, L56). If dust is the attenuating agent in the individual clouds, then shadowing of clouds on the receding hemisphere of the system by clouds on the approaching hemisphere creats a depression in the line profile just redward of line center (as defined by the sharp component).

J. KROLIK:

I have two questions. First did I understand you to say that the ionizing radiation pressure confines the gas?

G. SHIELDS:

What I am saying is that you can get the right numbers if you assume that.

J. KROLIK:

Because typically there is always a sizeable region where the gas is optically thin to the ionizing radiation, and so it seldom gets a chance to "express" that pressure.

G. SHIELDS:

That is why it has to be optically thick. If you have a continuum source and a cloud that is optically thick, and don't ask me to defend the stability of this configuration [*Ed.: See Mathews, W.G., and Blumenthal, G.R. 1977, Ap.J., 234, 10.*], you will have a certain amount of radiative momentum per square centimeter per second, in the radiation flux. If you imagine a surface at the base of the ionized region, then momentum conservation demands that the pressure acting on the backside of that surface must equal the momentum flux in the radiation, since the ionizing radiation is being absorbed above that surface.

J. KROLIK:

But that fixes the pressure on the neutral gas.

G. SHIELDS:

No, the point is that it fixes the pressure at the base of the ionized gas, which cannot differ, if you have a hydrostatic situation, by more than a factor of ~ 2 from the average pressure in the ionized gas.

J. KROLIK:

My second question has to do with the asymmetry. Is it obvious that the neutral gas will have a substantial optical depth in the Balmer lines? You need this to excite atoms to the n=2 level of hydrogen.

G. SHIELDS:

You can get that. It is easy to get that if you assume individually optically thick clouds because the column densities of the clouds combined with the small velocity dispersion inside an individual cloud make the Lα photons scatter around enough to produce a significant Balmer optical depth.

J. KROLIK:

And they will diffuse far enough to penetrate into the neutral gas?

G. SHIELDS:

There is a region of sufficient size where the gas is partially ionized. Empirically, novae are observed to have large Balmer optical depths at times when the density and radiation flux are similar to those in QSOs.

J. PERRY:

Regarding radiation driving, we (Mestel, L., Moore, D.W., and Perry, J.J. 1975, Astr. and Ap., **44**, 123) have been working at it for some time. Williams (1972, Ap.J., **178**, 105) and others have shown that the clouds are unstable because of the "confinement problem." If you ionize clouds you automatically get recombination radiation which tears the cloud apart before it gets anywhere. We have done studies on radiation-driven winds and have shown that in the simple picture the winds are unstable to density perturbations and produce clouds when you have a flat optical spectrum like you have in QSOs. Kippenhahn has shown that propagating waves, superposed on the background wind, develop shocks that have small internal velocity dispersions, hence produce small internal line widths because you have a travelling signal instead of an individual cloud. The interesting point about the instability is that it does not occur when you have a steep optical spectrum like you have in BL Lac objects. You don't produce density perturbations due to a steep spectrum. This simplified picture can then explain why you get clouds only in the flat spectrum case. I think the picture is oversimplified and that the situation is actually more complex.

RADIO-FREQUENCY HEATING OF EMISSION-LINE GAS NEAR COMPACT EXTRAGALACTIC RADIO SOURCES

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ABSTRACT

High brightness temperature radio sources significantly heat by free-free absorption any nearby gas that has properties similar to those inferred for QSO emission-line gas. As a result, the outer layers of the gas clouds expand and their visible line emission decreases. Moderate heating enhances the collisionally excited ultraviolet line OVIλ1034. Stronger heating penetrates the entire cloud and extinguishes all lines. Strong enough radio fluxes cause a thermal instability by stimulated Compton heating that is only saturated by Compton cooling at very high temperatures. We speculate that BL Lac objects differ from quasars by having higher radio turnover frequencies, or lower gas pressures, or more violent variability, all of which make radio-heating more effective.

I. Introduction

In this paper we show that very bright compact radio sources can have profound effects on the optical line spectra of the regions in which they are imbedded. After explaining the physical mechanism and detailing just how the line spectra change, we will speculate that the radio properties of BL Lac objects differ from those of quasars in such a way as to naturally explain why one set of objects has very strong emission lines and the other set none, even though all their other characteristics are very similar. That is to say, we suppose that BL Lac objects (initially, at least) have dense gas at the same pressure and exposed to ionizing flux of the same intensity as in QSO's. We then suggest that the high frequency radio emission of BL Lac objects is so intense that it can drastically reduce or eliminate the line emission from the gas by heating it to very high temperatures.

II. Physics

We begin by adducing fiducial numbers by which to estimate various quantities. Burbidge, Jones, and O'Dell (1974) analyzed the energetics of a number of compact extragalactic radio sources by assuming that they were optically thick synchrotron emitters. Typically they found turn-over frequencies of a few to a few tens of GHz and brightness temperatures at that frequency of a few x 10^{11} to a few x 10^{12} ^{o}K. Those objects on their list whose sizes had been measured by VLBI observations ranged from 1/2 pc (the two Seyfert galaxies) to several tens of parsecs (the larger QSO components).

Conventional photoionization models of QSO emission line gas put its electron density between 10^8 and 10^{10} cm^{-3} and its temperature at 1-2 x 10^4 ^{o}K. They then place it roughly a parsec from the ionizing ultraviolet source (Davidson 1972, Krolik and McKee 1978, and many, many others). If the ultraviolet radiation and the radio radiation are more or less concentric, the emission line gas is at least very near the radio sources, and may perhaps even be inside it. What effect does such powerful radiation have on this gas?

The primary interaction between ionized gas and radio frequency radiation is free-free absorption. In a completely ionized hydrogen plasma the absorption coefficient is $1.32 \times 10^{-9}\ T_4^{-3/2}\ N_{e9}^2\ \nu_{10}^{-2}\ \mathrm{cm}^{-1}$ (Johnston and Dawson 1973) where T_4 is the gas temperature in units of $10^4\ {}^\circ\mathrm{K}$, N_{e9} the electron density in units of $10^9\ \mathrm{cm}^{-3}$, and ν_{10} the frequency in units of 10 GHz; we have assumed $h\nu \ll kT$. The free-free heating rate is then

$$G_{ff} = 4.06 \times 10^{-22}\ N_e^2\ T_4^{-3/2}\ S_{ff}\ \mathrm{erg\ cm^{-3} s^{-1}} \qquad (1)$$

where $S_{ff} = \Omega T_{n12} \nu_{n10} k_{ff}$. We define $k_{ff} = \int d(\nu/\nu_n) T_b(\nu)/T_b(\nu_n)$, Ω to be the solid angle the radio flux fills, T_{n12} the brightness temperature at the turnover frequency in units of $10^{12}\ {}^\circ\mathrm{K}$, ν_{n10} the turnover frequency in units of 10 GHz, and $T_b(\nu)$ the brightness temperature at frequency ν. S_{ff} may also be written in the form:

$$S_{ff} = 11.6\ k_{ff}\ R_{pc}^{-2} \nu_{n10}^{-1}\ \frac{F(\nu_n)}{1\mathrm{Jy}} \left(\frac{H_o}{50\mathrm{km\ s^{-1} M_{pc}^{-1}}} \right)^{-2} \times \frac{\left\{ zq_0 + (q_0-1)\ [-1+(2q_0 z+1)^{\frac{1}{2}}] \right\}^2}{q_0^2 (1+z)} \qquad (2)$$

Here ν_n and $F(\nu_n)$ are the quantities observed at Earth, and R_{pc} is the distance from the radio source to the gas in parsecs. By comparison, if we include the contribution to ionization energy, the photoionization heating rate in a plasma fully ionized by a power-law spectrum is:

$$G_{pi} \simeq 3\mathrm{x}10^{-23} N_e^2 T_4^{-0.4}\ \mathrm{erg\ cm^{-3} s^{-1}} \qquad (3)$$

A second interaction mechanism is stimulated Compton scattering (Levich and Sunyaev 1970). When the photon occupation number is large (i.e. $h\nu \ll kT_b$), and the electron temperature is much smaller than the radiation temperature, Bose statistics assure that photon-electron scattering will result in a net loss of energy to the photons and a corresponding gain to the electrons. Because the rate of scattering is proportional to the number of scatterers and to the number of photons in the final state, the heating rate is proportional to the square of the photon energy density:

$$G_{sc} = 3.3\mathrm{x}10^{-19}\ S_{sc}N_e\ \mathrm{erg\ cm^{-3}s^{-1}} \tag{4}$$

where $S_{sc} = \Omega^3 T^2_{n12}\nu^3_{n10}k_{sc}$ and $k_{sc} = \int d(\nu/\nu_n)(\nu/\nu_n)^{+2}[T_b(\nu)/T_b(\nu_n)]^2$. We have assumed $\Omega<<4\pi$ for the definition of S_{sc}; when $\Omega = 4\pi$, Eq.4 is still approximately correct. As compared to free-free heating, this process becomes important at high frequencies and low electron densities. Strictly speaking, single-particle scattering formulae only apply when the wavelength of the photons is short compared to the Debye length. Numerically, $k\lambda_D = 0.10T_5^{\frac{1}{2}}\ N_{e9}^{-\frac{1}{2}}\ \nu_{10}$. When $k\lambda_D<<1$, photons scatter off collective modes of the plasma, electrostatic Langmuir waves and ion sound waves, rather than single electrons. We will treat heating by those processes in another place (Krolik, et al. 1978).

Finally, anomalous resistivity in the plasma can cause absorption, rather than reflection, of frequencies below the electron plasma frequency $\nu_p = 300\mathrm{MHz}\ N_{e9}^{\frac{1}{2}}$. Since there is more energy to be absorbed in the next higher decade or two of frequency, this absorption, even if 100% efficient, is probably unimportant next to the free-free process. In fact, since anomalous resistivity depends on nonlinear wave-wave interactions, the small ratio of radiation energy density to thermal energy density probably also entails a high reflectivity.

The ratio of Equation 1 to Equation 3 shows that the local rate of heating from free-free absorption can outweigh that of photoionization. The reason is that ionizing photons destroy their own absorbers, and so self-limit the rate at which ionizing energy may be absorbed. Equivalently put, the local heating rate is determined by the product of absorption cross section and flux. Even if the cloud of gas is optically thick to radio frequencies and its average heating is due to photoionization, the localized radio heating can still dominate at the surface and have important effects.

To quantitatively determine the results of radio frequency heating, we propose a picture in which individual clouds of varying column densities are exposed to a radio flux in an optically thin external medium at some fixed pressure. Then, as the outer layer of a cloud heats, its density drops to maintain pressure equilibrium. One of us (C.B.T.) has performed numerical calculations of the radiative cooling function Λ of a photoionized gas with solar abundances as a function of temperature, but constrained to constant pressure (Fig.1); here $N_e^2\Lambda$ is the cooling rate per unit volume. In this case the ionization equilibrium and the cooling function depend on only two parameters, the photoionization parameter $\xi = L^{ion}/N_eR^2$ (where L^{ion} is the ionizing luminosity) and the temperature T. A given cloud is small compared to the distance R to the ionization source and is therefore characterized by a single value of

$$\Xi \equiv \xi/T = \frac{L^{ion}/R^2}{NT} = 1.05\times10^{-5}\,\frac{L^{ion}_{46}/R^2_{pc}}{(NT)_{14}} \qquad (5)$$

where $(NT)_{14} = NT/(10^{14}\text{cm}^{-3}\,{}^{\circ}\text{K})$.

The typical value inferred for Ξ from analyses of quasar emission lines (e.g. Davidson 1977) is about 10^{-5}; in Fig.1, Λ is plotted for three values of Ξ in this vicinity.

At high temperatures inverse Compton cooling becomes important (Levich and Sunyaev 1970); the cooling function is

$$\Lambda_{IC} = \frac{4\sigma_T ukT}{N_e m_e c} = 3.3\times10^{-40}(L^{tot}/L^{ion})\;\Xi_{-5}T^2\text{erg cm}^3\text{s}^{-1} \qquad (6)$$

where σ_T is the Thomson cross section and $u = L^{tot}/4\pi R^2c$ is the total energy density of the radiation. In Fig.1 we have arbitrarily taken L_{tot}/L_{ion}=3. Note that for non-relativistic, optically thin inverse Compton cooling as we are considering, the spectrum of the scattered radiation is similar to that of the incident spectrum; the hot electrons may well cool primarily in the infrared rather than in X-rays. The direct scattering of the radiation by the gas can also result in heating; the heating exceeds the cooling if $h\langle\nu\rangle > 4\ kT$, where $\langle\nu\rangle$ is the energy weighted frequency $\int u_\nu \nu d\nu/u$. The condition for direct Compton heating to exceed stimulated Compton heating is $S_{sc} < 0.30 \times (L_{46}^{tot}/R_{pc}^2) \times (h\langle\nu\rangle/1\text{keV})$.

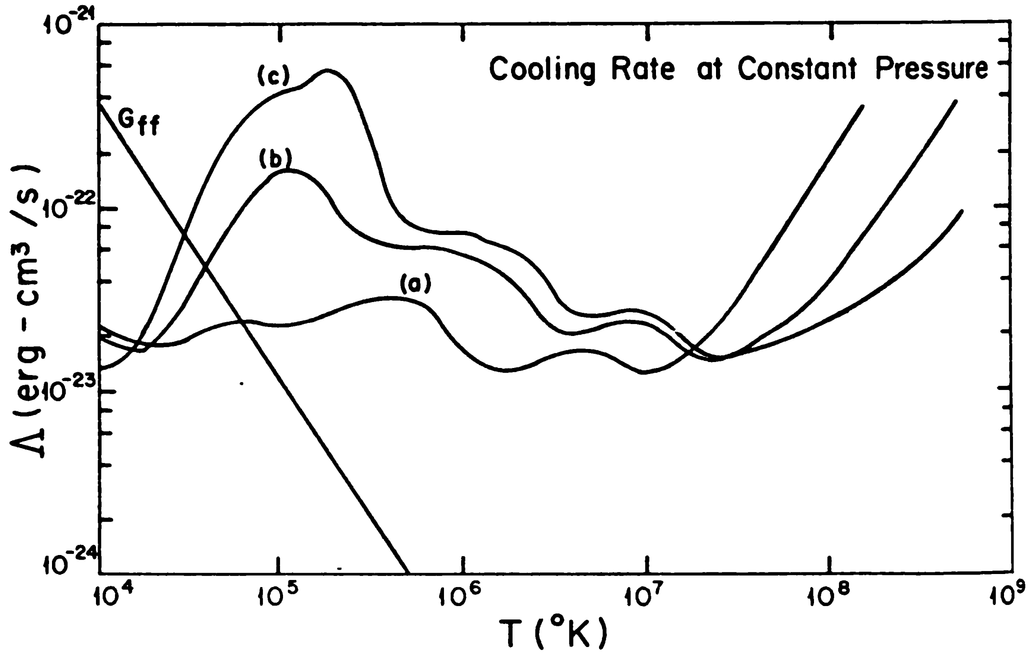

Fig.1. The isobaric cooling function Λ in units of erg cm^{+3} s^{-1} is plotted against temperature. Three values of the ionization-pressure parameter are illustrated: a) $\Xi=2\times10^{-4}$, b) $\Xi=2\times10^{-5}$, c) $\Xi=2\times10^{-6}$. The line labelled G_{ff} is the free-free heating function when $S_{ff}=1$.

The local equilibrium temperature T_{eq} for a given strength of radio flux (assuming no heat conduction or convection) is then found from the intersection of the total heating curve with the cooling curve at the desired pressure. Fig.2 shows the resulting T_{eq} as a function of radio flux at several values of Ξ. It makes use of the fact that $S_{sc}=k_{sc} \times S_{ff}^3/k_{ff}^3\ T_{n12}$ and assumes that $k_{sc}k_{ff}^{-3}\ T_{n12}^{-1}=1$. As can be seen, T_{eq} is significantly greater than the photoionization temperature for $S_{ff} > 0.1$.

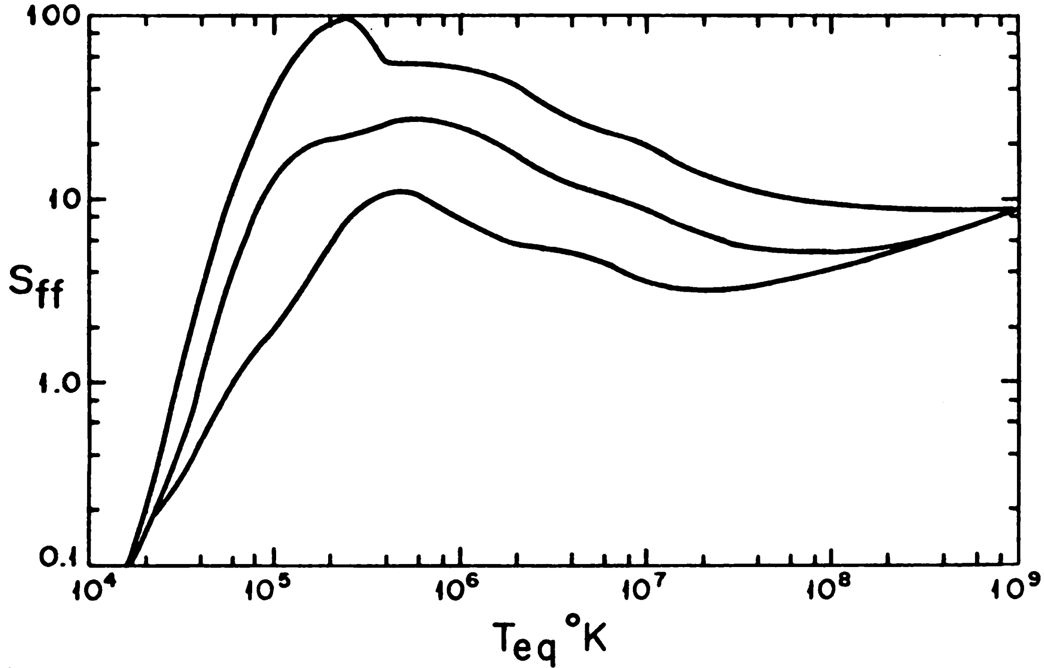

Fig. 2.

The equilibrium temperature in the radio-heated gas as a function of S_{ff} for the same three values of Ξ shown in Fig.1. See discussion in the text. The curves are, from top to bottom, c.), b), and a).

However, the most prominent feature of Fig.2 is the rapid rise in temperature with S_{ff} when $T \gtrsim 2\text{-}3 \times 10^5$ °K. This thermal instability is due in part to the pronounced maximum in the cooling curve at $T \simeq 1\text{-}2 \times 10^5$ °K found when $\Xi \lesssim$ few $\times 10^{-5}$ but primarily is due to stimulated Compton heating. Field (1965) showed that the condition for isobaric thermal instability is that the heating rate at constant pressure rise faster with temperature than the cooling rate does. Since $G_{ff}/N_e^2 \propto T^{-3/2}$, gas heated by inverse bremsstrahlung alone can be unstable only if $\partial \ell n\Lambda/\partial \ell nT < -3/2$. However, $G_{sc}/N_e^2 \propto T$; as Fig. 1 shows, from a few x 10^5°K up to the entrance of Compton cooling and bremsstrahlung emission above 10^7 °K, $\partial \ell n\Lambda/\partial \ell nT < 0$. The result is an unstable zone from $3\text{-}4 \times 10^5$ to 10^8 °K.

Fig. 2 demonstrates that for $2 \times 10^{-6} \lesssim \Xi \lesssim 2 \times 10^{-4}$, the critical S_{ff} for superheating is betwen 10 and 100. A cruder estimate may be obtained without detailed calculation of the shape of $\Lambda(\Xi, T)$ if its maximum value is known. The minimum of $G_{ff}+G_{sc}$ occurs when $G_{ff}=2/3G_{sc}$; if $G_{min} \geq \Lambda_{max}$, then the gas will be heated to the instability. Applying this technique to the case of $\Xi=2\times10^{-5}$, whose $\Lambda_{max} \simeq 1.8\times10^{-22}$ erg $cm^3 s^{-1}$, we find:

$$S_{ff}(\text{critical}) = 44\ (NT)_{14}^{3/11}\ T_{n12}^{3/11}\ k_{sc}^{-3/11} k_{ff}^{9/11} \qquad (7)$$

Since $\partial T_{eq}/\partial S_{ff} < 0$ in the unstable zone, a flare which temporarily provides a supercritical S_{ff} suffices to permanently heat the gas to $10^8\ {}^oK$ or more provided that it doesn't subside below $S_{ff} \sim 8$. In the stable high temperature regime, however, the cooling time is very long:

$$t_{cool} \simeq \frac{5m_e c}{4\sigma_T u} \simeq 2\times10^{10} R_{pc}^2 L_{46}^{-1}\ \ s \qquad (8)$$

Since the lifetime of QSO emission line gas is $R/v \sim 10^{10}$ sec $R_{pc}(0.01c/v)$, the gas may not have time to cool down to equilibrium whether the radio source is steady or not. Other forms of temporary heating, such as blast waves (Blandford and McKee 1976) may also lead to high, and perhaps unsteady, temperatures. If there is time to achieve equilibrium, the simple dependence of both the stimulated Compton scattering (of radio photons) heating and the ordinary Compton scattering (of optical photons) cooling on the radiation and electron densities leads to a simple solution for T_{eq}:

$$T_{eq} = 10^7 k_{sc} k_{ff}^{-3}\ T_{n12}^{-1}\ \left(\frac{L^{tot}/R^2}{10^9}\right)^{-1} S_{ff}^3\ {}^oK \qquad (9)$$

Thus, given sufficient time, there are two stable phases for photoionized and radio-heated gas: weak radio-heating and $T \sim 1\text{-}2\times10^4\ {}^oK$, and strong radio-heating with $T_{eq} \gtrsim 10^8\ {}^oK$.

Although an isolated gas cloud can be in one of two stable phases, the effects of thermal conduction may prevent the two phases from coexisting in physical contact in a quasar. An emission line cloud with a mean temperature of $1.5\times10^4\,{}^oK$ and a radius $\underline{a}$ evaporates in 0.06 $T_8^{1/2}\ a_{11}/F$ yr if it is embedded in a more massive hot cloud of temperature T (Cowie and McKee 1977). Here F is a factor which exceeds unity unless $T_8 >> 1$ or $a_{11}(NT)_{14} \gtrsim 10^3 T_8^3$; the characteristic radius of 10^{11} cm corresponds to the thickness of the Strömgren layer at $N \sim 10^{10}$ cm^{-3}. If the ambient hot cloud is much less massive than the emission line cloud, the former would cool and condense onto the latter in a similar time. Since the evaporation time is much less than the dynamical time $\sim 300\ R_{pc}(0.01c/v)$ yr, it follows that ionized emission clouds and hot gas with $T \sim 10^8$K cannot coexist in quasars. This constraint is removed if the clouds are large and mainly neutral or if $T >> 10^8$K. The analogous problem exists in the two phase model of the interstellar medium (Zel'dovich and Pikel'ner 1969), but there the evaporation time of order 10^8 yr is so long that evaporation and condensation are unimportant.

How far does the free-free heating penetrate? Since the free-free absorption coefficient is proportional to $N_e^{-2} T^{-3/2}$, the penetration length is proportional to $P^{-2} T^{+7/2}$, and the penetration column density to $P^{-1} T^{+5/2}$ for fixed pressure P. Therefore, as the outer layers heat, they also become more transparent, and deeper layers are heated.

A useful figure for comparison is the column density of the initial Strömgren layer. The ratio of heated gas to the maximum possible amount of gas ionized without radio-heating we will call M:

$$M \simeq 3\times10^{-4} [(T_{eq}-T_o)/10^4\ {}^oK]^{-5/2} (T_o/10^4\ {}^oK)^{-1.8} \nu_{10}^2 (L_{46}^{ion})^{-1} \times R_{pc}^2 \qquad (10)$$

T_o is the temperature without radio-heating. Of course, as the gas heats and expands, the neutral fraction drops, so its ionizing continuum opacity also falls. When $T_{eq} \simeq 2.6\times10^5 (T_o/10^4\ {}^oK)^{0.72} \nu_{10}^{-0.8} (L_{46}^{ion})^{0.4} R_{pc}^{-0.8}\ {}^oK$, all the gas that was initially ionized is heated to T_{eq}. It is a striking coincidence that this temperature is so close to the lower limit of the thermal instability zone.

III. Observational Consequences

What would the steady-state radio-heated gas look like?

The gas at very high temperatures radiates by Compton scattering the optical continuum and, to a lesser degree, by thermal bremsstrahlung. At 10^8 °K, electrons are still non-relativistic; consequently they do not change the energy of the photons they scatter by very much. Their thermal radiation, however, comes out mostly in X-rays. The two modes of radiation taken together do not provide much luminosity, for the power radiated per atom is $\Lambda N_e \propto \Lambda/T$.

The gas at moderately elevated temperatures ($2\text{-}20\times10^4$ °K) displays more complicated effects, and, of course, what cool gas remains still radiates as usual. To analyze the new line spectrum we divide the possible lines into two classes: the hydrogen and helium recombination lines, and the collisionally excited heavy element lines.

In the ionization conditions typical of quasars, hydrogen is almost completely ionized and helium is almost all HeIII, with some HeII mixed in (Davidson 1972). Heating, and expansion at constant pressure, only increases the HeIII/HeII ratio. Therefore, the HI and HeII recombination line fluxes are almost independent of the ionizing flux density. Their flux scales roughly as $PT^{-1.8}$ at constant pressure.

Table 1.

T_e (°K)	H_β	Lyα Collisionally Excited	CIVλ1549	OVI1034
10^4	1.0	0.016	0.60	0.0026
4×10^4	0.064	2.0	14.	18.
10^5	0.010	0.86	2.1	2.9
2×10^5	0.0025	0.26	0.13	1.2
4×10^5	6.4×10^{-4}	0.051	0.0024	1.1
6.3×10^5	2.5×10^{-4}	0.016	2.9×10^{-4}	0.12

Intensities are flux per mass relative to H_β at 10^4 °K, assuming a constant pressure $N_e T = 10^{14}$ °K cm^{-3}, and zero optical depth.

The Bowen OIII fluorescence lines, which are excited by HeII "Lyα" should scale in similar fashion, except that the OIII becomes converted to more highly ionized states as the density decreases.

The heavy element lines are much more sensitive to radio heating. The emissivity per unit mass of a collisionally excited line is proportional to $X(\xi,T)f(T)T^{-1}\exp(-h\nu/kT)$, where $X(\xi,T)$ describes the abundance of the ionic species as a function of ionizing flux and temperature, $f(T)$ is a slowly varying function arising from the average of the excitation cross section over that portion of the Maxwellian electron distribution above the threshold $h\nu$, and the exponential describes the fraction of electrons that have energy greater than $h\nu$. As Table 1 illustrates for the two strongest of these lines, CIVλ1549 and OVIλ1034, the threshold effect is most pronounced below 10^5 $^\circ$K (recall that kT of 10^5 $^\circ$K corresponds to a wavelength of 1440A$^\circ$). The ionization balance is more important at higher temperatures. OVI persists to much higher temperatures than CIV because its ionization potential (138eV) is twice as large as that of CIV ($64\text{eV} \simeq 7.5\times10^5$ $^\circ$K). Lyα is also collisionally excited at high temperatures, but collisional ionization limits its flux above 10^5 $^\circ$K. The strengths of coronal iron lines will be discussed elsewhere (Krolik, et al. 1978).

We see that the OVIλ1034 line is the line made most prominent by radio-heating. Its flux helps define two ratios that can be used as diagnostics of the emitting gas's physical conditions.

The first is the ratio of flux in the λ1034 line to that in H_β. To make use of this ratio one must either have both satellite and ground observations, or a large redshift and infra-red observations, or a large redshift and a satisfactory theory relating Lyα to H_β. Since virtually all the H_β flux arises in the cooler gas, the ratio of OVIλ1034 to H_β depends on how thick each cloud is. If we assume that the clouds are <u>always</u> ionization bounded, even after radio-heating, then the ratio of $\frac{\text{OVI}}{H_\beta}$ is simply M times the entries in Table 1. Osmer and Smith (1976) found that a sample of high-redshift QSO's had OVI/Lyα ratios ~ 0.1-0.35. If Lyα/H_β~3-4 (Baldwin 1977), OVI/$H_\beta \simeq$0.025-0.12. Radio-heating to T~3-5x10^4 ^{o}K would produce just such fluxes of OVI without invoking the separate, higher ionization, component that Davidson (1977) finds necessary.

The second ratio is what we will call the radio equivalent width. It is:

$$W_{OVI} = \frac{OVI}{L_{RF}\langle 1-e^{-\tau}\rangle} = \frac{j_{OVI}(T_{eq})}{\Lambda(T_{eq})}\left[1 + \left(\frac{T_{eq}}{T_0}\right) M^{-1}\frac{j_{OVI}(T_o)}{j_{OVI}(T_{eq})}\right] \tag{11}$$

where $\langle 1-e^{-\tau}\rangle$is the fraction of RF absorbed by the gas averaged over the entire surface of the radio source and j_ℓ(T) is the emissivity of line ℓ at temperature T. Because $\langle 1-e^{-\tau}\rangle \to 0$ as $M \to 0$, W_{OVI} formally diverges at small M. If the RF is beamed, W_{OVI} may be observationally uncertain. It is displayed in Fig. 3, for Ξ=2x10^{-5} and an initially ionization-bounded cloud.

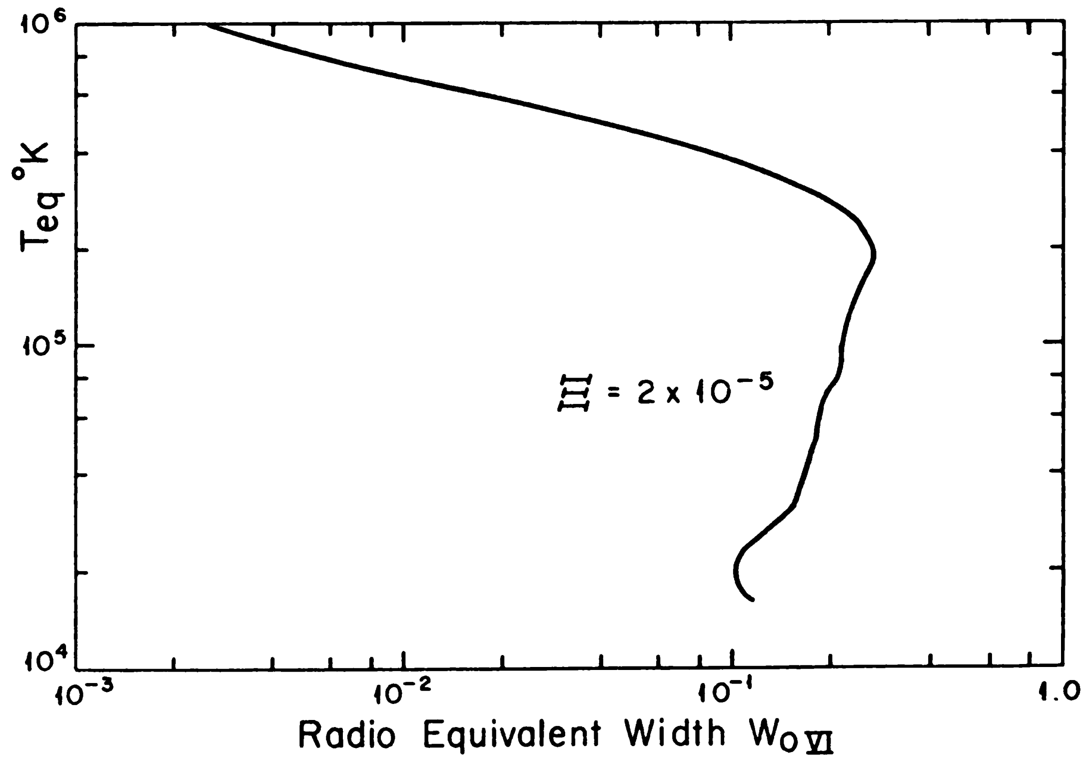

Fig. 3.

The radio equivalent width W_{OVI} as a function of temperature in the hot gas. Between 3x10^4 ^{o}K and 3x10^5 ^{o}K, roughly 20% of the radio energy absorbed is reradiated as OVIλ1034.

The column density is only relevant for T_{eq} less than 2.5×10^4 ^oK, in which case the heated fraction is so small that the OVI emission from the cold gas dominates. Above that temperature, W_{OVI} is steady at ~0.2 all the way up past 3×10^5 ^oK before it drops off. The physical interpretation of W_{OVI} is that it is the fraction of the cooling carried in the OVI line. Thus, so long as $T_{eq} \geq 2.5\times10^4$ ^oK, the OVI flux is a direct measure of the radio flux absorbed by the gas. If the total radio flux is known, we may then deduce the average covering fraction of the gas over the radio source.

Because W_{OVI} is so nearly constant, variations in the radio flux should be closely tracked by the λ1034 flux if the gas is closer to the radio source than the light travel distance during the time of the radio variation. However, it is the gas closest to the radio source which feels the greatest radio heating; furthermore, the velocity of the gas close to the central source may be systematically different from the gas further out. Consequently, the variations may be concentrated in one part of the line profile.

IV. BL Lac Objects and Quasars

Are the radio properties of BL Lac objects really sufficiently different from those of radio-bright quasars that we could predict their lack of visible emission lines from the strength of their radio heating? The crucial quantities are $S_{ff} \propto k_{ff} \nu_{n10}^{-1} R_{pc}^{-2} F(\nu_n) \propto k_{ff} \nu_{n10} \Omega T_{n12}$ and $\Xi \propto L^{ion} R_{pc}^{-2} N_{pc}^{-1} N_{e9}^{-1} T_4^{-1}$. Because VLBI measurements are extremely difficult to perform on objects that vary as rapidly as BL Lac objects do, there is little information on the sizes of their radio sources, and hence on their brightness temperatures. What information we do have is only by inference from spectral and variability properties. Altschuler and Wardle (1975) found that the spectra of BL Lac objects are characteristically either flat or slowly rising up to their maximum frequency of observation ~ 30GHz.

In the only observation at much higher frequency, Elias, et al. (1978) found that BL Lac itself has a spectrum that is essentially flat all the way up to 300 GHz. The presence of one or more components even smaller than the two found by VLBI to measure ~ 0.9_{pc} $(H_o/50 \text{ km s}^{-1}M_{pc}^{-1})^{-1}$ at 10.7 GHz by Shaffer, et al. (1975) is immediately suggested. The extreme variability is also consonant with the radiation coming from a small region or regions. An especially noteworthy fact about their variation is that its amplitude is characteristically much greater in the optical and UV than in the radio (Stein, et al. 1976). Quasars, by contrast, often possess flat spectra near a few GHz (Broderick and Condon 1975), but the small number that have been studied at a few hundred GHz (Elias, et al. 1978) show declining flux there. And, with only a few exceptions, quasars' luminosities are generally fairly stable.

We have seen that to heat the gas all the way through the initial Strömgren layer requires a temperature in the hot gas of $\gtrsim 2.6\text{x}10^5(T_o/10^4\ ^oK)^{0.72}(L_{46}^{ion}/R_{pc}^2)^{0.4}\ \nu_{10}^{-0.8}\ ^oK$. This temperature will also eliminate all the lines but OVIλ1034 from the spectrum of the hot gas. As Ξ increases from $2\text{x}10^{-6}$ to $2\text{x}10^{-4}$, the radio flux required to achieve this temperature decreases from S_{ff}=100 to S_{ff}=8. Coincidentally, if S_{ff} is slightly greater than the value necessary to raise T_{eq} to $2.6\text{x}10^5\ ^oK$, it triggers a thermal instability that pushes the temperature all the way up to ~ $10^8\ ^oK$. In such conditions, all lines are thoroughly destroyed. Because the cooling time at $10^8\ ^oK$ is so long, it is only necessary to heat each cloud once to keep it hot. Therefore, we suggest that BL Lac objects are essentially similar to quasars but for one of the following distinctions:

1). Their flat spectra betray the presence of small radio components of high brightness temperature. If their gas sees these as occupying the same fraction of the sky as quasar radio sources occupy in the sky of their clouds, then S_{ff} is sufficiently greater in BL Lac objects to evaporate their gas.

2). The critical S_{ff} for evaporation drops with increasing ratio of ionizing radiation pressure to gas pressure. BL Lac objects may have characteristically lower gas pressures than quasars; it doesn't take a large change to set off the instability.

3). BL Lac objects, almost by definition, are violent variables. A flare that temporarily raises S_{ff} or Ξ may suffice to lift all the neighboring gas to very high temperatures effectively forever. Because their optical and radio variations generally have much greater amplitude than their radio variations, a flare in the ionizing flux that suddenly makes the steady radio S_{ff} greater than critical is the most likely guess in this category.

V. Conclusions

We have shown that heating due to absorption of radio frequencies may be important in determining the physical properties and optical spectra of compact extragalactic radio sources. We have speculated that BL Lac objects may have radio spectra sufficiently brighter, and flatter, and more variable than quasars as to heat all nearby emission-line gas to the point that it is essentially invisible in the optical spectrum. Less strong heating strengthens collisionally excited optically thin ultraviolet lines such OVIλ1034.

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DISCUSSION

R. MUSHOTZKY:

At temperatures approaching 10^6 K wouldn't you get a fairly high soft X-ray flux?

J. KROLIK:

But the cooling here is mostly through the OVI λ1032 line.

R. MUSHOTZKY:

I'm saying that there is a lot of Bremsstrahlung emission at 0.25 keV.

J. KROLIK:

I think one way you can put a limit on that is that the amount of thermal re-radiation at X-ray wavelengths cannot be more than the radio frequency luminosity that was heating the gas in the first place. That is rarely more than 10^{44} erg/sec. And because these clouds will only intercept a fraction ($\sim$10%) of that and will radiate only a part of that as X-rays, the X-ray luminosity may be undetectable.

D. SHAFFER:

F. Owen could perhaps say more, but I don't think that BL Lac objects are unusual as compared to QSOs in having particularly flat spectra up to 3 mm. So if your mechanism suppresses line emission in BL Lac objects, it should do the same in flat spectrum QSOs. The flat spectra are not a distinguishing characteristic of BL Lac objects.

F. OWEN:

I think the point is how often are these large events maintained in the sub-millimeter wavelength region. These are the wavelength regions that are important in this model. I sort of got the impression that maybe they do occur more frequently in BL Lac objects.

W. DENT:

We only have 10 years of data and I don't think we can answer that question yet.

Absorption in BL Lac and Quasistellar Objects

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Introduction

To date absorption has been reported in the spectra of only two BL Lac objects. In AO 0235+164 both optical and 21-cm lines have been detected (Burbidge et al. 1976; Roberts et al. 1976; Wolfe and Wills 1977; Peterson et al. 1977); in PKS 0735+178 only optical lines have been found (Carswell et al. 1974; Peterson et al. 1977; Boksenberg et al. 1977; Galt 1977). Both objects have been subject to extensive analysis but, as is usual when discussing absorption in extragalactic objects, no definitive conclusions as to the nature or origin of the absorption have been reached. The optical absorption in both AO 0235+164 and PKS 0735+178 appears to be spectroscopically indistinguishable from the absorption at similar redshifts in several QSOs. Since there is such a large body of data on absorption in QSOs, I will primarily discuss that data in order to establish a framework for the discussion of the BL Lac absorption phenomenon.

Over 800 QSOs have, to date, been identified and had their redshifts measured (see the current update of the catalogue by Burbidge, Crowne and Smith 1977); some 30 to 40 BL Lac objects have been identified (the last complete list appeared in the review article by Stein, O'Dell and Strittmatter 1976). Optical absorption has been reported in the spectra of about 100 QSOs and in the two BL Lac objects listed above. Lines in about 70 QSOs have been identified and assigned to almost 250 different redshift systems. (For a summary of the situation as of 1 May 1978 see Perry, Burbidge and Burbidge 1978).

The information available on absorption is highly varied since a wide variety of instruments have been used to produce spectra of varied spectral resolution. Strong and broad absorption features are easily detected at the survey resolutions (typically about 400 Å/mm) with which the great majority of QSOs have been studied. High resolution spectra are, however, needed to reveal weak or very narrow absorption and only about 30 to 40 have ever been examined at 48 Å/mm or better. Since so few QSOs have been investigated in detail, the absorption discovered to date is clearly a lower limit on that which is actually present.

The only broad generalizations that can be made from this data are that absorption becomes ever more likely to be present as the emission line redshift increases, and that the majority of the > 800 QSOs do not show very rich absorption spectra or very strong lines. The richest known absorption-line object, PKS 0237-23, was found to have multiple absorption on the basis of low resolution objective prism surveys.

Whether the absorption is due to gas physically associated with the QSOs or BL Lac objects or whether it arises in intervening gas clouds or galactic haloes or galaxies has been the subject of a heated controversy ever since the initial discovery of the absorption lines in 1966. This controversy exists because the majority of the identified absorption-line systems in QSOs have redshifts significantly less than those of the emission lines. If all the redshifts are assumed to be of strictly cosmological origin then the absorption must arise in galaxies or gas clouds which are nearer than the QSOs. In this case, detailed spectroscopic studies of the absorption lines could provide information unobtainable by other means on the physical conditions, evolution, and space distribution of remote galaxies. If, however, the gas is physically associated with the QSOs then the redshift differences are presumably due to Doppler shifts caused by high velocity outflow: in some cases the implied velocities are as high as 0.3-0.6c. The study of intrinsic absorption could then yield information on the energetics, evolution and dynamics of the QSOs.

Clearly, if the great bulk of the absorption is due to intervening objects, the statistics and characteristics of the absorption must be identical for QSOs and the BL Lac objects - so long as these are at similar distances. If the absorption is primarily intrinsic, the differences in continuum and emission line properties of the two classes of object will presumably be reflected in differences in the absorption line properties. The absence of emission lines in the BL Lac object can be attributed either to an absence of gas (as is likely if they are nuclei of elliptical galaxies) or to the fact that what gas is present in the vicinity of the nucleus is uncondensed and/or too hot and too highly ionized to give rise to emission lines. In the latter case it is possible that condensations far from the nucleus may give rist to absorption lines similar to those in QSOs.

The Observations

With a few striking exceptions the majority of the absorption lines seen in the spectra of QSOs are very sharp. These are often at the limit of the spectral resolution, particularly at intermediate resolutions. When looked at with higher resolution, strong narrow lines often tend to split up into several components. The extreme narrowness of the lines implies very small internal velocity dispersions in the absorbing gas consistent with a few times the thermal velocity in a gas at a few 10^4 K. If the gas were intrinsic to the QSO this would imply that there is no dispersion in the velocity relative to the central source except for random thermal motions. Several, but not the majority, of the narrow lines are black implying, for those systems, total obscuration of the central source.

The broad line objects, PHL 5200, RS 23, Q 1246-057 and Q 0324-407 all have supernovae-like absorption profiles which are accepted to be clear evidence of very large scale mass outflow. In both PHL 5200 (Lynds 1967, Burbidge 1968, 1969; Scargle, Caroff and Noerdlinger 1970) and RS 23 (Burbidge 1970) the broad absorption troughs are adjacent to the emission lines. Sharp line structure is visible in the troughs in PHL 5200 and the troughs are not completely black, with the possible exception of the Ly-α trough. Q 1246-057 (Osmer and Smith 1977) is the most startling and significant of these objects. The broad absorptions, which stood out on the original low-dispersion discovery plates, are completely detached from the emission by $\sim$15,600 km/s, with the short wavelength edge standing at $\sim$0.1c with respect to the emission. Sharp line structure appears in the bottom of the troughs and a narrow line system at $z_a \approx z_e$ is also present.

Absorption appears to be a rare phenomenon in the spectra of QSOs with emission line redshifts below about 1.4, despite the fact that these comprise the majority of known QSOs and despite the fact that absorption systems with $z_a < 1$ appear in many high redshift QSOs. In fact, the fraction of QSOs in this redshift range which have confirmed absorption

(10 out of about 500) is less than that of the BL Lac objects (2 out of about 40). In the range $1.4 < z < 2$ the objects with reported absorption follow the general distribution of QSOs and represent about 1/3 of the sample. Above $z \sim 2.3$ all QSOs studied at moderate to high dispersion show some absorption, but with considerable variation in line density and strength. In these objects the spectra are exceedingly complex, with a vast number of lines shortward of Ly-α emission. The line density shortward of Ly-α is often 10 times that longward of Ly-α.

The identification of the absorption lines has proved to be an increasingly difficult task. 3C 191 ($z_e = 1.95$) was the first absorption-line object discovered. Its lines were all identified with resonance lines of moderately ionized common elements, at $z_a \approx z_e$. High resolution spectra have revealed that the absorption lines are split into two systems at z_a= 1.949 and 1.945. These two systems identify 22 out of 25 lines present; 3C 191 thus continues to have one of the best identified QSO absorption line spectra. The more common situation among objects with similar emission line redshifts is that up to 50% or more of the absorption lines remain unidentified, even after the application of sophisticated computer identification schemes (Bahcall 1968; Bahcall and Joss 1973; Colvin 1957; Aaronsen, McKee and Weisheit 1975; Joss and Ruffs 1977; Roberts and O'Dell 1978).

The large number of unidentified lines cannot be due primarily to lack of precision in measurement of wavelength, since in the few cases where the same object has been studied by different observers strikingly good agreement between wavelength lists is found. By and large (but not exclusively!) the unidentified lines lie shortward of the Ly-α emission. This fact led Lynds (1971) to suggest that most of these lines are Ly-α absorption in gas of small enough optical depth so that no other lines (such as CIV 1550) are strong enough to be seen. Boksenberg (1978) proposed that the absence of other lines in the "Ly-α" only systems is due to an underabundance of heavy elements - i.e. to the gas being "primordial". In some cases it has been possible to find Ly-α, Ly-β pairs, but in general the attempt has been unsuccessful.

The really troubling problem is the large number of lines <u>longward</u> of Ly-α which remain unidentified. Roberts <u>et al</u>. (1978) conclude that they can be neither the strong resonance lines usually identified, nor can they be Ly-α with $z_a > z_e$; they can also not be identified with features in our galaxy or its surroundings.

The natural suggestion for improvement of the identifications is to take spectra of yet higher resolution. Unfortunately, high resolution spectra have resulted not in finding more lines that fit any already established system but rather in finding yet new systems, or lines which fit no system at all.

It seems, therefore, that the number of redshift systems found so far are a lower limit to the number that really exist - or the identifications are seriously in error!

Accepting the identifications as correct - what then are the physical properties of the identified systems?

The most common lines identified are Ly-α and lines belonging to the ions C IV, Si IV, Mg II, N V, O VI and to C II, Si II & III, Fe II, N I, O I, AL II, and Mg I. The two BL Lac spectra contain lines of Mg II, Fe II, Mg I and Mn II as well as the one 21-cm line. Examination of a table of ions of all the abundant elements reveals that every ion which has a resonance lines in the observable window over the redshift range $0 < z < 3.5$ has been identified in at least some spectra. Unobserved ionic stages simply do not have lines which are detectable with present techniques: they may be presumed to be present. The absorption lines most frequently identified in the QSOs, those of C IV, SIV, and Ly-α, are also the most commonly identified emission lines.

Among the narrow-lined absorption systems no spectroscopic differences have been established between systems with $z_a \approx z_e$ and z_a very different from z_e. In part the sparseness of the data may account for this. There are three "types" of system known: those of low, intermediate, and high ionization. (For a detailed discussion, including a catalogue of all the systems and the lines identified in each see Perry et al. 1978). The pure low ionization systems show heavy-element lines of ions all having ionization energies $\chi_i < 30$ eV: (i.e. Ly-α, CII, SiII, FeII, MgI,II); the pure high ionization systems show lines of ions generally requiring at least $\chi_{i-1} > 30$ eV; (i.e. CIV, SiIV, OVI, NV). The mixed systems show several overlapping stages of ionization: (i.e.,SiII, III, IV, CII, III, IV, etc.). Material of very high ionization would be unobservable with present techniques. The frequency with which the various types occur can not be definitely established but there is the general impression that the mixed systems are most common. The differences are not due to selection effects: Perry et al. (1978) find that there are 3 objects, all with $z_e \approx 1.95$, which were observed at comparable resolution, over the same spectral window and which yet show clear examples of all three ionization types. In AO 0235+164 and PKS 0735+178 the absorptions are low ionization (although at these redshifts, high ionization lines are not observable).

Detailed curve-of-growth analysis is difficult, if not impossible, for most absorption line spectra; there are too many free parameters and too few data. In fact the only detailed curve-of-growth analyses which have been carried out have been for the absorptions in the two BL Lac objects. High resolution data, in both the optical and radio, on PKS 0735+178 made such an analysis by Pettini et al. (1978) and Boksenberg (1978) possible. The Mg II lines contain at least four components; the narrowest is less than 20 km/s wide and the whole complex spreads over 165 km/s. Two complex models, of seven clouds each, fit the Mg II line profile quite well; a choice was made between the two models by computing the equivalent widths of the FeII, MgII, and 21-cm lines and comparing them with the observations. Assuming normal relative abundances for the heavy elements, the model of seven clouds of low column densities ($N_{mg} \simeq 9.4 \times 10^{13}$ cm^{-2}) provides the best fit to the data.

The detailed analysis (Wolfe and Wills 1977) of the $z_a = 0.524$ system in AO 0235+164 also found a cloudy structure of normal relative abundances, and, in that case a MgII column density of 10^{16} cm^{-2}.

All our information on column densities in the absorbing regions of QSOs comes from estimates based on relative line strengths and degree of saturation of doublets (cf. Chan and Burbidge 1975). Based on such estimates the vast majority of systems seem to be consistent with normal heavy element abundances and column densities in neutral hydrogen of about 10^{17} cm^{-2}. For normal or low heavy element abundances, this column density is the minimum detection limit. There are several outstanding exceptions: the HI-like neutral systems in PHL 957 (Coleman et al. 1976), 1331+170 (Carswell, Hilliard et al. 1978; and the mixed ionization system in 0528-250 (Jauncey et al. 1978; Smith et al. 1978). These all have inferred column densities of neutral hydrogen of 10^{20}-10^{21}.

Only in QSOs with the highest values of z_e is the Lyman limit visible. Where the Ly-edge for an absorption system is visible, direct information on the optical depth in H^o is available. In OQ 172 (Baldwin et al. 1974) no drop is see at the Ly-edges. This is in contrast to OH 471 (Carswell, Strittmatter et al. 1975) where the continuum declines in stages at the Lyman edges corresponding to four absorption systems.

Although some hints of particular anomalies, such as a Mn underabundance (Burbidge et al. 1978) and a general heavy element underabundance in 0528-50 (Smith et al. 1978) exist, in general most abundance determinations (e.g. Wingert 1975) are consistent with normal relative heavy element abundances. Whether or not the heavy elements have solar or interstellar abundances with respect to hydrogen is more difficult to establish, since H is normally highly ionized and Ly-α is not seen in low redshift systems.

In principle important limits on the electron density can be set by the measurement of, or the determination of upper limits on, the excited fine structure lines or the lines due to transistions from metastable states (Bahcall and Wolf 1968). Where the ground state of an ion is split by fine structure, absorption lines out of the upper level can be observed if the level is populated. Since either collisions or photon absorption can populate such levels, the relative strengths of the ground state and excited lines can be used to determine either the density or the local flux of exciting radiation. When no lines of such ions are observed, upper limits on the density of flux cannot be established. Similarly, metastable states can be populated by collisions, but only at extremely high densities.

Of the ions usually observed in absorption, only CII, SiII and FeII have ground state fine structures; thus it is only in systems where lines of these ions are seen that such upper limits are obtainable. Despite the frequent claim that the zero volt line is commonly seen unaccompained by the excited fine structure line and that therefore an upper limit on the density of $< 10^2$ cm^{-3} is general, Perry et al. (1978) find that actually fewer than 40% of the identified systems contain identified CII, SiII or FeII lines, and that in about 20% of those that do, fine structure identifications are made. (Many of the spectra have been taken at resolutions too low to properly separate the two lines.)

In e.g. PHL 191 excited fine structure is observed; analysis by Bahcall, Sargent and Schmidt (1967) yielded $n_e \leq 10^3$ cm^{-3}, $r \geq 10^{2\pm1}$ pc. Further analysis, based on the assumption that photoionization is the excitation mechanism for the ionization structure- yielded values of $n_e \simeq 10^3$ cm^{-3}, $r = 10^4$ pc. This large inferred distance, (and thus the large implied Mass $\gtrsim 4\pi r^2 N_H$) has been used as an argument against the possiblity that the absorption is intrinsic, despite the fact that $z_a \approx z_e$.

In the $z_a = 3.066$ system in OQ 172 six fine structure lines of CII and SiII are positively identified, requiring an electron density in excess of 10^3 cm^{-3}. It is thus unlikely that this system arises in an intervening galaxy, yet its velocity relative to the emission-line gas, if the system is intrinsic, is 0.1c. A similar case is the $z_a = 2.3088$ system in PHL 957 where fine structure lines of CII, NII, III and SiII are identified and $\Delta v \sim 0.1c$.

Somewhat more extreme limits are often deduced for those objects where the excited lines are missing; then typically $r \geq 1 - 10$ kpc, based on Bahcall and Wolf's arguments alone. Less stringent limits ($r \gtrsim 0.45$ kpc) were deduced by Wolfe and Wills (1977) from the absence of FeII excited-level lines in AO 0235+164. If it is assumed that photoionization (by the nonthermal continuum extrapolated into the UV) is the excitation mechanism it can be shown that gas of densities $n \sim 10^2$ cm^{-3} must be at least a few thousand parsecs distant from a source of visual luminosity $\sim 10^{46}$ erg/s. Since there are difficulties with simple photoionization models particularly with optically thin ones, arguments based on such models are weaker than the purely observational ones based on the fine-structure lines alone.

In a new high resolution study of PKS 0237-23 Boroson et al. (1978) identified 45 redshift systems in the range $1.4 < z_a < 1.75$ based on the CIV doublet. In 21 of these systems no lines of SiII were identified; in 9 both the zero volt and the excited lines were found; in 9 only the zero volt and in 6 only the excited fine structure line was found.

Using the arguments given above, one would have to conclude that density differences of at least several hundred obtain between systems of very similar redshift and CIV column density. If the systems are intervening a galactic super cluster with a velocity dispersion of over 5000 km/s is required. Furthermore clouds with particle densities of 10^3 are known only in the disks of spiral galaxies; but these present cross sections too low to account for the large number of systems present (Boronson et al. 1978). If it is assumed that the material is intrinsic to the QSO (on the basis of the appearance of high-density systems) then, since these systems are distributed throughout the range $z_a = 1.4 \rightarrow 1.75$ it would be necessary to assume that there is a systematic structured outflow; it then seems unreasonable to use optically thin photoionization arguments to place a few intermediate systems at distances far in excess of their neighbors in velocity space. This observation, it seems to me, throws open the question of the reliability of the fine-structure identifications, or more likely, of the simplified photoionization arguments.

In any discussion of the origin of the absorption the distribution of the numbers of systems per object and as a function of redshift plays a crucial role. While no predictions have yet been made on the basis of the intrinsic hypothesis, definite predictions are made if the systems are to be intervening.

Unfortunately studies of complete samples are required to be able to determine distribution functions. No such studies have yet been published. On the basis of the limited data so far available the following can be said:

The distribution of numbers of identified absorption line systems per QSO is non-random. For redshifts below 1, well under 1% of QSO spectra show absorption; this percentage rises rapidly to almost 100% by $z \sim 2$. The distribution of z_a is also non-random, there being relatively few systems with $z_a < 1$; the number rises to a maximum between 1.6 and 2 and then decreases. The number of systems per object varies from 1 to probably well over 50. The distributions in number for the entire heterogeneous sample of all QSOs are given by Burbidge and his collaborators (Burbidge 1978). Analysis of this sample must account for the selection effects.

For objects with $z_e < 1.5$ there appears to be a striking deficiency of absorption lines. However, the significance of this deficiency is not easy to assess, since the only strong resonance lines in the visible part of the spectrum at $0.2 < z < 1.5$ are the low ionization lines MgII λ2798 and FeII λλ2300-2380 and λ2600. No highly ionized gas at redshifts in this range would be detected in absorption - in fact, the identification of the great majority of the high z systems depends on CIV λλ1548,1551. A possible key to the puzzle of the absorption lines lies in the frequency with which such low-ionization low redshift absorption systems appear in the spectra of, respectively, low and high emission redshift QSOs. Robert et al. (1978) find many $z_a < 1$ systems in objects with $z_e = 2.16 \rightarrow 2.97$. Similar systems must appear with at least as high a frequency in all QSOs with $z_e > z_a$ (where $z_a < 1$) if the absorption is due to intervening galaxies. Peterson and Strittmatter (1978) have examined a number of QSOs with low z_e and so far have found only 2 out of 7 cases with absorption lines; several previously reported cases of MgII absorption proved to be erroneous. Similar work, reported at this meeting by Dr. Miller, is being carried out by Miller and French. A statistically significant number of low-z_e QSOs without corresponding z_a, relative to the number of high-z_e QSOs with low z systems, would be strong evidence in favor of the hypothesis that the absorption is intrinsic. Miller reports in addition, that when low-z_a systems are found in objects of medium-to-low z_e, they seem to occur only in the optically violently variable (OVV) objects.

Weymann et al. (1977) studied the distribution function for z_a for a group of QSOs with $1.2 < z_e < 2.2$ and implied velocity differences, were the absorbing gas intrinsic to the QSOs, of less than 18,000 km/s. They find a distribution function for the relative velocity with the following characteristics: (a) a sharp cutoff for $V_{rel} \leq -3000$ km/s; (b) a steep decline in the number of systems for $V_{rel} \geq 5000$ km/s; and (c) a long tail in the distribution for $V_{rel} \geq 3000$ km/s, which is not present for $V_{rel} \leq 3000$ km/s. They obtain a good fit to their distribution function by the superposition of two distribution functions, one accounting for the sharp peak at $V_{rel} \sim 0$ with a width of 3000 km/s, and a long tail extending from $V_{rel} \sim 0$ out past 5000 km/s. They contend that the sharp peak is due to random motions in clusters of galaxies associated with the QSOs (3000 km/s is, however, a rather large random velocity for a cluster and that the long tail is due to Doppler shifts in material ejected from the QSOs; were the high relative velocities due to intervening material, the distribution should be flat rather than decaying at high V_{rel}.

If the absorption is due to intervening objects randomly distributed in space, then the number of absorption redshifts in individual QSOs should be Poisson-distributed, and the redshifts in individual objects should be, on average, uniformly distributed, provided the detection efficiency is constant (Bahcall 1978). Tests of this hypothesis can only be made, because of selection effects, on samples in a narrow range of z_e observed with comparable resolution and signal-to-noise ratios. Conflicting claims partially on the basis of as yet unpublished data, are often made. The question is far from settled and the reader is referred to Perry et al. (1978) and the references therein.

Any dependence of the absorption-line redshifts on the emission line redshift or any other intrinsic property of the objects would be very strong evidence in favor of the hypothesis that the absorption is intrinsic.

Quite early in the study of QSO absorption line spectra, it was noticed that in many QSOs the ratio of (1+z) between pairs of systems appeared to be in the ratio of the rest wavelengths of strong resonance lines, and that sharp absorption lines often appear in the wings of emission lines. After the reduction of the data it often appeared that different absorption lines in different redshift systems appeared at the same observed wavelength. (Lines of rest wavelength, λ_R^1 and λ_R^2, arising in gas of redshifts z_1 and z_2 respectively will appear to coincide in the observers frame if $\lambda_R^1/\lambda_R^2 = (1+z_1)/(1+z_2) = R$.) This numerical coincidence, called line locking, its statistical significance and possible explanation has long been the subject of heated controversy (cf. Mushotsky, Strittmatter and Solomon 1972; Scargle 1973; Burbidge and Burbidge 1975; Sargent and Boroson 1977; Drew 1978).

Occasional accidental coincidences are certainly to be expected. But the repeated occurrence of a single ratio corresponding to the pairing of strong resonance line and/or absorption edges, suggests an intrinsic physical phenomenon. An empirical study of absorption redshifts by the Burbidges (1975) made a case for several preferred values of R, in particular, R = 1.11. This work was criticized by Sargent and Boroson (1977). However, Drew (1978), using an independent selection of redshifts, has concluded that there is good evidence for the statistical significance of the R = 1.11 ratio.

Statistical significance alone is not sufficient; therefore, Perry et al. (1978) examined the physical properties of the R = 1.11 systems. They find that the 1.11 systems occur in objects with a high z_{abs} multiplicity and that the 1.11 systems are heavily saturated (which is not a common feature of the absorption line systems in general). It is noteworthy that the only two pure-HI -cloud-absorption of high column density ($N > 10^{21}$ cm^{-2}), the systems A in PHL 957 and B in 133+170, are R = 1.11 systems. The ratio R = 1.11 corresponds to an ejection velocity of 0.1c.

Interpretation

How are the observations to be interpreted on the assumption that the redshifts are all cosmological in origin, i.e. that the absorption is due to intervening objects along the line of sight to the QSOs and BL Lac objects? If the QSOs are at their cosmological distances one expects to see some such absorption. One must ask if the distribution of $N(z_{abs}$ $z_{em}))$ as it stand - surely an underrepresentation of reality - is compatible with any particular model for the distribution of absorbers in space, assuming a standard (i.e. $q_o \sim 0$, $H_o \sim 50$ $kms^{-1}Mpc^{-1}$). cosmology.

Wagoner (1967) computed, as a function of z_{em} the probability that the line of sight to a QSO would intercept an intervening normal spiral galaxy within its Holmberg radius. The number of absorption systems already detected exceeds his predictions by an order of magnitude. Thus the effective dimensions of intervening galaxies must be considerably greater than a Holmberg radius. Burbidge et al. (1977) recently redid

Wagoner's calculations for assumed galactic cross-sections corresponding to radii of 20, 40, and 100 kpc. They find that in order to observe as many multiple absorption systems as have already been found (which is surely an underestimate due to the incompleteness of the observations), radii of at least 100 kpc are required for the systems containing heavy elements and 300 kpc for the "Lyman-α only" systems.

However, it is then predicted that essentially every QSO must show at least one absorption system, a prediction at variance with the results for z_e objects, of Peterson and Strittmatter (1978) and Miller and French (1978) mentioned earlier. On the basis of more recent data on a sample of 6 high-z_{em} QSOs Roberts et al. (1978) found that yet larger cross sections - as large as 0.5 Mpc - would be required to get the high multiplicity of absorption found in their samples.

How compatible with the evidence about the sizes of galaxies is this? Large low-density galactic haloes were first proposed by Bahcall and Spitzer (1969), who pointed out that such haloes may be detectable more easily in absorption than in any other way. Observational tests, both optical and radio, have established the existence of some large haloes, but it is not yet clear what percentage of galaxies have haloes. (For reviews of the data from opposing points of view, see Boksenberg (1978) and Burbidge et al. (1977). One of the most striking new observations is that of Boksenberg and Sargent (1978), who found galactic CaII, H and K absorption lines in the spectrum of the QSO 3C 232, $z_{em} = 0.53$, at the same redshift as the neighboring galaxy NGC 3067 at a projected distance of 16.5 kpc. 21 cm line studies (Davies 1974) show extensive hydrogen regions in the M 81 group and around several other galaxies, including M 31. However, in a recent search for neutral hydrogen in the radio spectra of QSOs near spiral galaxies, Haschick and Burke (1975) found 21 cm absorption in only one case out of five, although their experiment was sensitive to column densities 10^{18} - 10^{19} cm^{-2} (more than adequate to produce optical absorption if the gas has normal abundances), and their impact parameters were less than the proposed size of the haloes being 16 - 58 kpc.

To be stable, large haloes must either be hot (>10^6 K) or have turbulent virial velocities ∿200 km/s. Since many systems are observed with lines as narrow as 30 km/s this may present difficulties for the intervening hypothesis. The $z_a = 0.424$ system in the BL Lac objects PKS 0735+178 has a complex structure of several narrow components (>20 km/s) extending over 165 km/s. Boksenberg (1978) suggested that this is due to individual clouds in a clumpy halo whose large scale velocities are of the order of 200 km/s.

The ionic species observed in QSO spectra are also observed in the interstellar gas (Boksenberg 1978), and Boksenberg argues that this fact coupled with the observations of 3C 232/NGC 3067 justifies the conclusion that the heavy element systems can be formed in massive enriched haloes.

However, studies of nearby spiral galaxies show that the heavy element abundances decrease rapidly with distance from the nucleus. This fact led Burbidge et al. (1977) to argue that although it is plausible to assume that some enriched material exists out to radii of 40 kpc, it is implausible that much larger haloes contain detectable levels of heavy elements.

Thus those who favor the intervening hypothesis argue that the QSOs show that there is far more absorbing gas, particularly at large redshifts than had ever been considered before (cf. Boksenberg 1978), while those who tend not to favor the hypothesis treat the contradiction between prediction from known phenomena and the observations as evidence against the intervening hypothesis.

The problem is compounded by the fact that we must account for the large amount of unidentified absorption which must occur somewhere.

In addition, peculiar peaks in the absorption redshift distribution in some individual objects (e.g. PKS 0237-23), if real, poses problems. Unless they can be completely explained by selection effects they require considerable variations in the absorption as a function of cosmological epoch.

In some cases galaxies or intergalactic clouds in rich clusters are invoked to explain many absorption redshifts lying close together in velocity space, and also to explain some of the values of z_a slightly greater than z_{em} (cf. Weymann et al. 1978). Velocity dispersions as high as 3000 - 5000 km/s are then sometimes required. However, no line of sight velocity dispersions in excess of about 1500 km/s have ever been measured in known clusters and values as high as this are only seen in clusters of ellipticals whose galaxies contain little or no gas (cf. Bahcall 1978). Consequently to argue that this kind of absorption would be due to clusters requires (a) that the velocity dispersions are much higher than those observed, and (b) large clouds of gas are present in the galaxies or between them.

The particular case of the BL Lac object AO 0235+164 which has two absorption line systems at $z_a = 0.524$ and 0.851 may be relevant to the question of galaxies as interceptors. The small-diameter highly variable BL Lac object, in which no emission lines have been detected, is accompanied by a fainter object or "nebulosity" 3 arc sec away which has emission lines at $z_e = 0.525$ (Smith, Burbidge and Junkkarinen 1977). If this "nebulosity" is an intervening galaxy producing the absorption, at $z_a = 0.524$. Smith et al. have shown from the strength of its emission lines that such a galaxy must be an active one whose central luminosity in Hα alone exceeds 2×10^{42} erg s^{-1}. Since lines of MgI, II, and FeII are observed in absorption, the degree of ionization corresponds to an ionization parameter $y < 10^{-12}$ (where $y \simeq L_{vis}/nm_pc^3r^2$, Kippenhahn et al. (1974)). Then at the presumed intercept distance of 20 kpc from the galaxy's nucleus we have $1.6 \times 10^{37} < (L_{vis}/n) < 1.6 \times 10^{41}$. Unless strong absorption of the ultraviolet continuum intervenes between the nucleus and the gas lying in the line of sight to AO 0235+164, $n > 13$ where $L_{vis} = \ell L_{H\alpha}$.

If the absorption is intrinsic and the emission-line redshifts are cosmological then large amounts of gas must be ejected from QSOs some with speeds as high as 0.5c and in some cases gas must be falling in. The direct evidence in favor of this hypothesis is the presence of the supernovae-like absorption in several objects which is generally agreed can be caused only by outflow. Many Seyfert galaxies, orders of magnitude less energetic than QSOs, also have well-documented narrow-like, high-velocity outflowing absorption-line systems. These include, among others, NGC 4151 (Anderson and Kraft 1968), where multiple absorption-line systems are identified with relative velocities of several hundred km/s and Mk 231 (Boksenberg, et al. 1977), where three spearate systems with mean outflow velocities of $\sim$6350, $\sim$4700, $\sim$200 km/s^{-1} have been identified. There is certainly no doubt that these systems must be intrinsic and are probably due to ejection. The kinetic energies associated with such ejected clouds are of the order of 10^{56} erg. Since the high relative velocity (>0.1c) absorption systems occur only in the brightest of the QSOs, $L_{vis} > 10^{47}$ erg s^{-1} (Perry and O'Dell 1977) - objects more luminous than Seyferts by at least four orders of magnitude - it is not unreasonable to assume that outflow kinetic energies might be similarly scaled to perhaps $10^{60} - 10^{62}$ erg.

Line-locking, based on the appearance of certain ratios R, particularly R = 1.11 in a number of QSOs, and coincidences in wavelength of lines from different elements in many cases in a few objects (cf. Roberts et al. 1978) is further evidence in favor of the intrinsic hypothesis. This evidence is, however, far from convincing to many.

Perhaps the most crucial evidence in favor of the intrinsic hypothesis may turn out to be the statistics of the absorption systems with $z_a < 1$. If, as is suggested by some new observations (discussed before) $z_a < 1$ systems are common in objects with $z_e >> 1$ but not in objects with $z_e > z_a, z_a < 1$, then it would seem fairly convincing to perhaps most that the absorption is primarily intrinsic.

The most striking feature of the systems which are the subject of controversy is their extreme narrowness. In the case of the highest velocity systems, velocity dispersions of $\Delta v/v_{rel} \lesssim 10^{-3}$ are implied. Similarly small velocity dispersions are often observed in novae (as has been pointed out by Strittmatter and Williams 1976).

The greatest difficulty associated with the intrinsic hypothesis are the large distances and therefore large masses and kinetic energies derived for many of the systems. From the observations it is possible to determine for any given object, only the absorption line redshift (and thus the relative velocities, $v/c = (R^2 - 1)/(R^2 + 1)$, $R = (1+z_e)/(1+z_a)$) the number of systems present, ionic column densities and a minimum set of consisting ions per system. The mass and kinetic energy in any given system are then, $M \sim 4\pi r^2\, m_p N_H$, and, $T \sim 2\pi r^2 m_p N_H v^2$ where N_H is the total hydrogen column density and r is the distance from the source of the nonthermal continuum. r cannot be determined directly from the observations but must be inferred from arguments based on the observed ionization degree. If it is further assumed that the observed nonthermal continuum can be extrapolated beyond the Lyman limit and that the system is optically thin, then the degree of ionization observed yields a relationship between L/n and r. For those systems where the density limits of $n < 10$ cm^{-3} can be set, it is generally found that they must lie further than a few hundred kiloparsecs from the source and contain, themselves, masses in excess of $10^9 M_\odot$ and have kinetic energies of perhaps $>10^{61} - 10^{62}$ ergs.

However, as was pointed out earlier, it is only in a minority of systems that the necessary lines of the singley ionized species are seen and, as illustrated by the data on PKS 0237-23, even when they are seen the situation is confused. Therefore for the majority of the systems no reliable density limits can be set. In view of the high density limits inferred for the permitted emission line region ($n_e = 10^6$-10^{10} cm^{-3}) and the similarity in the degree of the ionization of the supernovae-like outflow systems (which are clearly adjacent to the emission line region) to that of the majority of the absorption line systems it is not clear, a priori, which densities it is reasonable to assume, based on continuity and similarity arguments. If the densities are not known the masses and kinetic energies cannot be inferred.

We see then, that assuming that essentially all of the absorption is either intrinsic or due to intervening objects leads to what most people consider uncomfortably large objects. In the one case, narrow massive shells of gas of normal abundances must be ejected at almost relativistic velocities to great distances; in the other case, heavy element enriched galactic haloes must extend to hundreds of kiloparsecs. To reduce these numbers significantly seems increasingly difficult, even if one were to find a reasonable way to separate the absorption into two different groups, one intrinsic and one intervening. Unless the cosmological hypothesis for the emission line redshifts is rejected it would appear that the absorption lines are telling us that, in fact, particularly at large redshifts massive and very extended objects are common.

In what way then can the BL Lac objects aid in the resolution of the controversy? If the QSO absorption is due mostly to intervening objects, similar absorption must be detected in BL Lac spectra - if distant BL Lac objects can be found. Surveys such as that described earlier by Dr. Craine are therefore very important. (One indication that many of the BL Lac objects are at least more distant than $z \sim 0.6$ was discussed by Dr. Mushotsky who hypothesizes that the lack of detection X-rays from most BL Lacs requires minimum distances of this order.) Since most discovery programs are of necessity based on radio surveys it will remain difficult to find distant BL Lac objects without surveys at lower flux levels then are presently being carried out (see Dr. Condon's talk at this meeting.) Alternatively if the absorption is mostly intrinsic it would be reasonable to suppose that the general spectral differences between the two sets of objects will be reflected in the absorption spectra as well. The usual assumption that BL Lac objects are nuclei of elliptical galaxies and that QSOs are associated with spirals leads to the natural explanation that the spectroscopic differences reflect the difference in the gaseous content of the two galactic types. This assumption is supported by the high polarization of the BL Lac spectra which may indicate an absence of gas which could depolarize the continuum. It is thus essential to combine the radio and optical data on BL Lacs in order to determine the amount of gas actually present in their environs and to find a way of estimating their distance on the absence of emission lines.

In conclusion it seems fair to state that it is not yet possible to say where the absorption in the QSO spectra is occuring. Further, careful studies of BL Lac spectra, particularly "high redshift" BL Lac objects, if these can be found, may prove very important in sorting out this puzzle.

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DISCUSSION

A. WOLFE:

I just want to point out that if the $z = 0.52$ absorber in AO 0235+164 has been ejected, it has to be more than 400 kpc from the BL Lac object which places severe requirements on momentum and energy (see Wolfe et al. 1978, 222, 752).

J. PERRY:

That is very difficult to understand in terms of ejection and in fact, your suggestion in Wolfe et al. (1978) that the BL Lac object is ejected from the galaxy is an interesting possibility. No matter which way we turn, however, we run into large numbers and everybody prefers their own particular large numbers.

B. BURKE:

There is a recent possibility that has been raised by Lo and Sargent (1977, private communication), and that is that there may be small cloudlets of gas in small groups of galaxies. One can interpret these as being small galaxies since there always seem to be a few stars associated with the cloudlets: they may be small galaxies containing hydrogen. They may be the remnant of larger gas masses that have fried away due to a hot intergalactic medium. This would be a population that evolves in time, is more prevalent in former times, and doesn't have to be very close to a particular galaxy, but rather is spread around in between a few galaxies.

J. PERRY:

That is an interesting suggestion. However the intercept diameters required to explain the large multiplicity of the absorption redshifts must have been very large. You can't get away from the fact that you have a certain path length and that you have to have a certain minimum cross section and density to explain the number of redshifts that you see. The evolution of these cloudlets must then have been very strong between say $z \sim 1.6$ and 1.

B. BURKE:
This is an evanescent population of which there are a few left now, but which were much more common in early times.

G. BURBIDGE:
But you need a lot of them now, at $z < 1$, and you can't evoke evolution at that epoch so I think that this is an evanescent idea. [laughter].

M. BURBIDGE:
Along the line of sight to one particular object you have to find a number of these things between $z = 1.4$ and 1.7, and in other objects you must have an absence of these same things in order to explain the observed redshift distribution.

J. PERRY:
There is an object OQ 172 where you have an emission redshift of 3.5 and there are four absorption systems between $z = 2.5$ and 3.1 and there are no lower absorption redshifts (Baldwin, et al. 1974, Ap.J. 193, 513). The span in redshifts there corresponds to a velocity dispersion 0.1c so you cannot evoke a large cluster of galaxies. So the redshift distribution here is clearly inhomogeneous. There is also PKS 0237-23 (Boroson et al. 1978, Ap.J. 220, 772) which has 45 absorption redshifts in one small range and no low redshift systems. Yet, there are lots of other objects which do have plenty of low redshift systems so it seems that you require a large degree of inhomogeneity in the population of the universe which is rather difficult to explain. But of course the statistics are not good enough yet.

M. BURBIDGE:
I want to ask you about the mechanism for ejection of intrinsic gas. You spoke earlier about the breakup or instability in the outward flow of gas, could you say more about that?

J. PERRY:
Our model is a highly over-simplified version of what could actually be going on. We make the minimum assumptions about such objects: i.e. there is a gravitating mass at the center which emits non-thermal radiation and there is gas with normal chemical abundances in the environs. We then do a hydrodynamic calculation based on those assumptions. We then find continuous winds which are a function of central mass and the spectral index. (Kippenhahn, Mestel, Perry 1975, Astron. and Astrophys. 44, 123; Beltrametti and Perry 1978, in preparation). One finds that the continuous outflows can reach velocities close to those observed. If the spectrum of the driving radiation is flat then Figure 1 shows that as long as you can recombine, then the gravitational force is proportional to density and the radiative force is proportional to the square of the density. So an initial density perturbation absorbs momentum from the radiation field and instability develops (see Mestel, Moore, and Perry 1975, Astron. and Astrophys. 52, 203). Kippenhahn (1976, Astron. and Astrophys., 55, 175) shows that this could develop into a shock wave where the

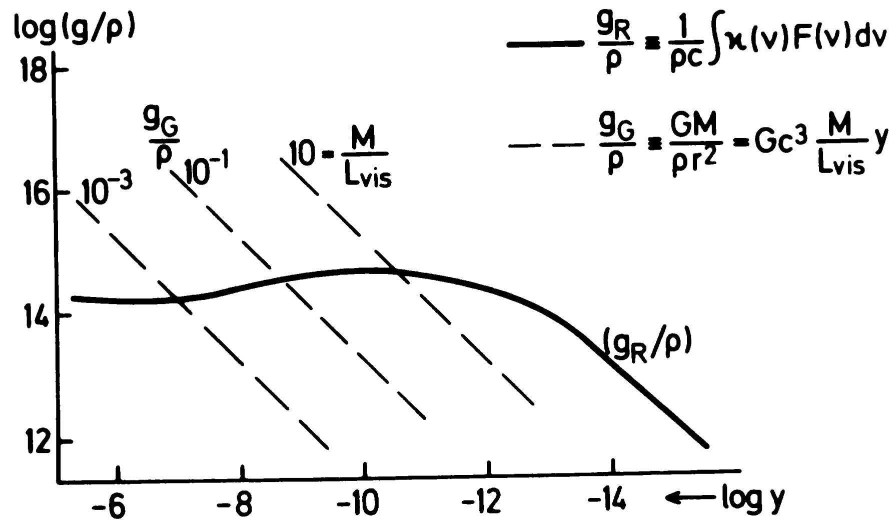

Figure 1

absorption occurs in the peak of the shock and a very narrow absorption line develops. The width of the absorption line is controlled by the kinetic temperature of the gas and furthermore the resonance lines don't disperse the gas. All of these calculations have to be carried into the non-linear regime, and one must account for the development and interaction with the ambient medium. John Dyson and I are studying this problem now.

One can plot the terminal velocities observed, assuming that the QSO redshifts are cosmological, as a function of the absolute visual luminosity. The theoretical terminal velocity reached by a continuous outflow (Beltrametti and Perry 1978) from sources of radius 0.01 pc, central gravitating mass 10^8, 10^9 and 10^{10} $M_\odot$ and mass loss rates $-\dot{M} \lesssim 5.10^{-20}$ L_{vis}, are shown as functions of luminosity superposed on the observed results in Figure 2: These results represent a good envelope for the observations. Of course it is still necessary to show how density condensations in such a wind develop, and at what radius.

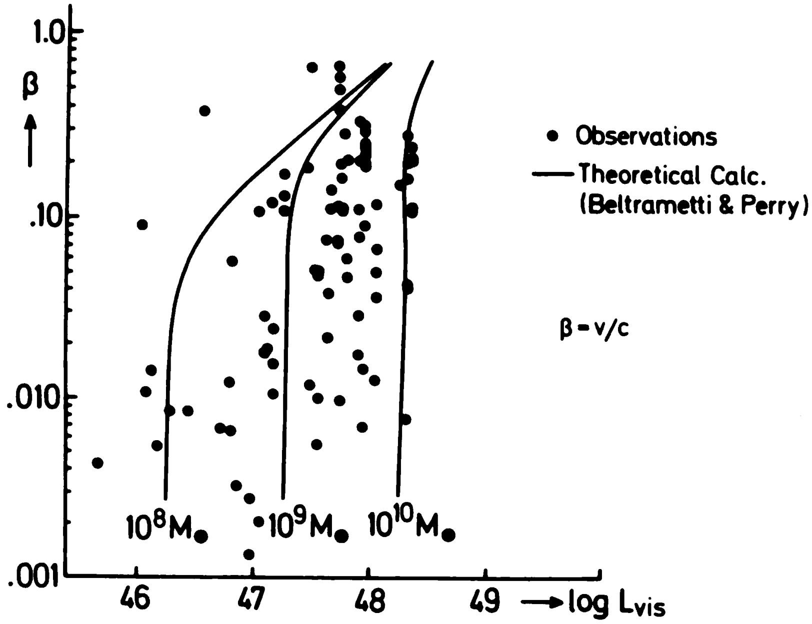
1.0
β
.10
.010
.001
46
47
48
49
→ log Lvis
• Observations
— Theoretical Calc. (Beltrametti & Perry)
β = v/c
10⁸M⊙
10⁹M⊙
10¹⁰M⊙

Figure 2

THE CONTINUUM RADIATION OF COMPACT EXTRAGALACTIC OBJECTS

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1. INTRODUCTION

Compact extragalactic objects - BL-Lac objects, quasars, class-1 Seyferts, and other "active galactic nuclei" - share one unifying characteristic: appreciable emission not attributable to normal stellar processes, originating in a volume small in comparison with that of a galaxy. Otherwise, they exhibit a variety of properties ranging from undetected to intense radio emission, from strong broad-lined to virtually featureless optical spectra, from unpolarized to highly polarized continuum radiation, and from approximately constant to highly variable flux. Notwithstanding the heterogeneous nature of compact extragalactic objects, it is generally believed (or hoped) that they all are powered by the same sort of central machine which converts gravitational energy into more visible forms of energy. If this proves to be the case, then BL-Lac objects possibly provide the most direct view of the effects of the central machine, unobscured by the emission (or absorption) of thermal gas.

In Section 2, I summarize the observed properties of BL-Lac objects and other compact extragalactic objects (particularly quasars). In Section 3, I review various emission mechanisms which might play some role in compact extragalactic objects. I discuss in Section 4 evidence for the presence of special-relativistic effects in many compact radio sources. Section 5 is a brief summary.

2. OBSERVED PROPERTIES

Several authors (Kinman 1975; Schmidt 1975; Kellermann 1976, 1978; Strittmatter 1976, 1978; Stein, O'Dell, and Strittmatter 1976; Neugebauer 1978; Giacconi 1978; O'Dell 1978) have reviewed various observational aspects of compact extragalactic objects. Here, I shall emphasize the more recent data. (For detailed bibliographies of data prior to mid 1977, see O'Dell 1978 and references therein.)

Since compact extragalactic objects (or "active galactic nuclei") constitute a highly heterogeneous class, it is difficult to label any object as "typical"; thus attempts to generalize may be misleading. It does appear, however, that many BL-Lac objects and optically-violent-variable radio-loud quasars (OVVs) exhibit the most extreme form of the (nonthermal) quasar phenomena: I shall, therefore, devote most of this observational review to these objects, in the belief that they best indicate the intrinsic character of nonthermal quasars, relatively unconfused by the effects of thermal gas.

(a) Radio Emission

Most quasars (~ 95%) do not emit radio waves at levels currently detectable (Katgert et al. 1973; Murdoch and Crawford 1977; Sramek and Weedman 1978). Thus, while some compact radio sources are extremely powerful with radio luminosities up to $\sim 10^{46}$ erg/s (under the assumption of cosmological redshifts and isotropic emission), most quasars and Seyfert nuclei must be much less luminous. Since the nucleus of our own Galaxy has a compact radio source of luminosity only $\sim 10^{33}$ erg/s (Kellermann et al. 1977), it is impossible to specify meaningfully a typical radio luminosity for compact radio sources.

The defining characteristic of compact radio sources is, of course, small (frequently complex) angular structure. Very-long-baseline-interferometry (VLBI) measurements indicate angular radii typically 0.1 to 10 milli-arcseconds, roughly proportional to observing wavelength. Since VLBI is sensitive primarily to angular scales $\theta \approx \lambda/b$ (with b the baseline), the size-wavelength correlation to some extent results from selection; but it also reflects the existence of a characteristic rest-frame brightness temperature ($\sim 10^{12}$ K),

$$2kT_b^* = I_\nu \lambda^2 (1+z) \approx \frac{F_\nu}{\pi\theta^2} \lambda^2 (1+z) \qquad ,$$

as required by the theory of incoherent-electron-synchrotron emission (Kellermann and Pauliny-Toth 1969; Burbidge, Jones, and O'Dell 1974). The absence of interstellar scintillation in all extragalactic sources examined further indicates that brightness temperatures $\gg 10^{14}$ K are not generally present (Condon and Backer 1975; Armstrong, Spangler, and Hardy 1977); however, it must be determined whether scattering by a two-phase intergalactic medium (if such exists) might sufficiently broaden images at the lower radio frequencies to obviate this argument.

The flux from many (if not most) compact radio sources is variable on time scales from a few weeks to decades, depending upon the source and the observing frequency. For a given source, the variability time scale is roughly proportional to wavelength, again reflecting the existence of a characteristic brightness temperature and the general presence of inhomogeneous structure (such as multiple components). In addition to flux variations, changes in angular structure over a period of years have been observed for several radio-loud quasars (Cohen et al. 1977). At distances corresponding to measured redshifts, the structural changes and in many cases the flux variations indicate relativistic motion or phase effects within the source (see Section 4).

Typically, compact radio sources are linearly polarized at $\lesssim 4\%$; but on occasions -- such as during some outbursts in BL-Lac objects -- the linear polarization can exceed 10% (see e.g. Altschuler and Wardle 1976). There is a tendency for sources to be more highly polarized at the higher frequencies (Rudnick et al. 1978). Often the linear polarization is variable in both degree and direction on a time scale comparable to that of changes in flux density. No general pattern of variations is yet discernible; nor is there obviously a relationship between polarization direction and the VLBI position angle (Altschuler and Wardle 1976).

Circular polarization appears to be present in some sources at a level $\lesssim 0.1\%$ (e.g. Roberts et al. 1975; Hodge and Aller 1977; Weiler and Wilson 1977); however, there is still some uncertainty (Ryle, O'Dell, and Waggett 1975). If present at $\sim 0.1\%$, circular polarization probably results from Faraday conversion of linear polarization (Sazonov 1969; Pacholczyk and Swihart 1974; Jones and O'Dell 1977a).

The effective spectral indices of compact radio sources

$$\alpha_{\text{eff}} \equiv \left\langle - \frac{d\ln F_\nu}{d\ln \nu} \right\rangle \lesssim 0.5$$

are flatter than those of extended radio sources, and are in some cases inverted. Such a spectral-flux distribution is usually attributed to self-absorption in an inhomogeneous (Condon and Dressel 1974; de Bruyn 1976; Marscher 1977) and/or relativistically evolving (e.g. Jones and Tobin 1977) synchrotron source.

(b) Infrared and Optical Emission

At infrared frequencies quasars tend to have rather steep continua with $0.8 \lesssim \alpha_{IR} \lesssim 2.1$ (Neugebauer 1978) while at optical frequencies, the average spectral slope is flatter with $0 \lesssim \alpha_{OPT} \lesssim 1.6$ (Oke, Neugebauer, and Becklin 1970). The OVV quasars and BL-Lac objects have rather steep continua $0.8 \lesssim \alpha \lesssim 2$ throughout the optical-infrared spectral domain (e.g. Tapia, Craine, and Johnson 1976; O'Dell, Puschell, and Stein 1977). A few BL-Lac objects in fact exhibit concave-downward continua, in contrast with many quasars (Baldwin 1975) and class-1 Seyfert nuclei (Neugebauer et al. 1976) whose continua are noticeably flatter at the shortest optical wavelengths. Concave-downward continua may result from contamination by starlight or by interstellar extinction, or it might be intrinsic to the nonthermal emission process; concave-upward continua might indicate an increasing relative contribution of thermal-gas emission. In contrast with these "typical" continua, some quasars have been found to be very red with $1.5 \lesssim \alpha_{OPT} \lesssim 4.5$ (Boksenberg, Carswell, and Oke 1976; and H. E. Smith, private communication): Previous selection procedures have discriminated against identification of quasars this red.

The OVV quasars -- which constitute $\sim 15\%$ of radio-selected quasars (McGimsey et al. 1975) -- and most known BL-Lac objects exhibit rapid, large-amplitude optical variations amounting to $|\Delta m| \approx 1$ over days and during giant outbursts $|\Delta m| \approx 5$ over weeks. On the other hand, the optical flux of most quasars and (class-1) Seyfert nuclei varies but moderately -- perhaps a few-tenths of a magnitude over months. During major outbursts, the optical-infrared spectral shape of the nonthermal continuum of BL-Lac objects and OVV quasars is usually approximately constant (e.g. Oke et al. 1970; Smith et al. 1975; Rieke et al. 1976), although short-term variations may occur (e.g. Visvanathan 1973; Craine, Johnson, and Tapia 1975; O'Dell et al. 1977).

The optical-infrared linear polarization of BL-Lac objects and OVV quasars is wavelength independent (Visvanathan 1973; Knacke, Capps, and Johnson 1976; Tapia et al. 1977), frequently variable in both degree and direction, and on occasions can reach $\sim 30\%$ (Kinman 1976; Tapia et al. 1977). On the other hand most quasars and class-1 Seyferts are at most only slightly polarized ($\lesssim 1\%$; Stockman and Angel 1978), suggesting that the observed optical emission from these objects may not be nonthermal. [One radio-quiet quasar PHL 5200 is polarized at $\sim 4\%$; however, this polarization probably results from resonance scattering in the same medium which produces the very deep and broad (P-Cygni-type) absorption profile (Stockman and Angel 1978).]

Although there is usually little convincing evidence for a correlation of optical and radio variability (Pomphrey et al. 1976) or polarization (e.g. Kinman 1977), the largest outbursts in BL-Lac objects and OVV quasars do appear at both radio and optical wavelength (Kinman et al. 1974; Rieke et al. 1976). This indicates that during such events, the optical-infrared and radio emission are closely related and that the synchrotron process probably produces the optical-infrared radiation (as well as the radio) from BL-Lac objects and the OVV quasars. In addition, the few observations of radio-loud quasars and BL-Lac objects, at intermediate (submillimeter) wavelengths indicate no departure from a sensible interpolation of the optical-infrared and radio spectral-flux distributions (Hildebrand et al. 1977; Elias et al. 1978).

For cosmological redshifts and isotropic emission, the optical-infrared luminosity of quasars and BL-Lac objects reaches as much as $\sim 10^{47}$ erg/s, or even higher during major outbursts. At the low end, some BL-Lac objects and class-1 Seyfert nuclei emit but $\lesssim 10^{42}$ erg/s, at which point contamination by starlight makes detection of the compact object difficult.

(c) X-Ray Emission

Current X-ray observations indicate that the (2-10 keV) X-ray luminosity of a given compact extragalactic object is comparable to or less than its optical-infrared luminosity; however, fewer than 10 BL-Lac objects and quasars (e.g. Ricketts et al. 1976; Forman et al. 1978; Ricker et al. 1978; White and Ricketts 1977) and 20 class-1 Seyfert galaxies (Elvis 1977a) are known X-ray sources. Furthermore, the available data on the spectral-flux distributions -- mostly for a few of the brighter class-1 Seyfert galaxies -- show a rather flat spectral index ($0 \lesssim \alpha < 1$) up to at least $\sim$ 100 keV (e.g. Baity et al. 1975; Paciesas, Mushotzky, and Pelling 1977; Ulmer 1977; Auriemma 1978) so that the total X-ray (or gamma-ray) luminosity is yet uncertain. Compact extragalactic X-ray sources are sometimes variable (e.g. Davison et al. 1975; Mushotzky et al. 1976; Mushotzky et al. 1978; Lawrence, Pye, and Elvis 1977), with time scales as short as $\sim$ 1 week (Winkler and White 1975) or perhaps even shorter (Elvis 1977b; Delvaille, Epstein, and Schnopper 1978).

At present the extragalactic X-ray sky is rather sparsely populated. During the next couple years, however, the X-ray data will increase dramatically with the use of the HEAO series of X-ray satellites.

3. EMISSION MECHANISMS

Although incoherent-electron-synchrotron emission can quite plausibly account for the radio emission of most compact extragalactic objects, this mechanism does encounter some difficulty in explaining the rapid variability observed in a few radio sources (e.g. AO 0235+164 and 3C 454.3). For this reason alternative radiation processes -- such as incoherent proton synchrotron (Jukes 1967), coherent electron synchrotron, coherent curvature (Cocke and Pacholczyk 1975), coherent plasma-oscillations emission with Compton upscattering (Petschek, Colgate, and Colvin 1976) -- have been proposed. While such models can in principle circumvent the time-scale problem imposed by the 10^{12} K brightness-temperature limitation on a nonrelativistically evolving incoherent-electron-synchrotron source, they generally introduce new problems of their own which render the models questionable (see, e.g., Jones, O'Dell, and Stein 1974; Benford 1977).

Since VLBI measurements show that a substantial fraction of the radio flux of objects originates in regions of brightness temperature $T \lesssim 10^{12}$ K and since the absence of interstellar scintillation indicates that little flux arises in components with $T > 10^{14}$ K, compact radio sources cannot usually contain regions of highly coherent emission. This statement, however, does assume the absence of substantial angular broadening in any intergalactic medium, and furthermore does not necessarily apply to the rapidly variable portion of the flux since

VLBI and scintillation measurements only rarely are coincident with major outbursts (but see, e. g., Scheuer 1976).

The other possible solutions to the time-scale problem are that the distances are less than indicated by the redshifts, or that the sources are evolving relativistically. For a few objects (such as BL Lac) which have been shown to lie in the nuclei of galaxies of stars (Oke and Gunn 1974; Miller and Hawley 1977), noncosmological redshifts seem not to be the solution. In the final section, I discuss evidence (some of which is independent of distance) for relativistic evolution in compact extragalactic objects.

While it is my view that the radio emission of compact extragalactic objects and the optical-infrared continuum of most BL-Lac objects and OVV quasars is synchrotron radiation from (in many cases) moderately relativistically evolving sources, other emission mechanisms also seem likely to be relevant at X-ray energies and, for most quasars and class-1 Seyfert nuclei, at optical wavelengths as well. Evidently, at optical frequencies, most quasars and Seyfert nuclei are not highly polarized, do not vary dramatically, and exhibit a rather flat spectral-flux distribution. These properties are in marked contrast with those of active BL-Lac objects and OVV quasars.

There are several plausible radiation processes besides synchrotron emission; however, it is not possible here to discuss any of them in detail. At infrared wavelengths, thermal reradiation by dust or by an optically-thick post-shock H I region (Daltabuit, MacAlpine, and Cox 1978) could contribute to a blackbody peak. Although such spectral-flux distributions do occur in the nuclei of many galaxies, they do not appear to be a common feature of compact extragalactic objects (Neugebauer 1978).

At optical and X-ray frequencies, the following mechanisms seem plausibly relevant to quasars and class-1 Seyfert nuclei:

(1) synchrotron self-Compton, in which synchrotron radiation is scattered by the (relativistic) synchrotron-emitting electrons;

(2) Compton scattering of non-synchrotron photons, such as thermal-emission from gas or dust, by relativistic electrons (e. g., Beall et al. 1978);

(3) partial Compton thermalization of (thermal or nonthermal) seed photons by a thermal gas (Katz 1976); and

(4) thermal bremsstrahlung by a hot gas.

For most quasars much of the optical and X-ray power may be thermal, and in some sense of secondary interest, since the gas might be heated by by a nonthermal photo-ionizing source. Other possibilities for heating of the gas are through shocks (e.g., Daltabuit et al. 1978) or turbulent viscosity in an accretion disk (e.g., Rees 1978). BL-Lac objects appear to be the purest form of the (nonthermal) quasar phenomenon, probably owing to a low concentration of gas.

4. RELATIVISTIC EFFECTS

Special relativistic effects appear to play a role in compact extragalactic objects. There are several lines of evidence which indicate that compact radio sources evolve at moderately relativistic rates:

(1) At their cosmological redshifts, the milli-arcsecond components of some radio sources are apparently expanding at superluminal velocities (Cohen et al. 1977), a phenomenon which might be explained in terms of models evoking relativistic phase effects and/or separation (Blandford, McKee, and Rees 1977).

(2) The time-scale for flux variations in many compact radio components is comparable to the light travel time across the component as derived from VLBI-determined angular sizes and redshift distances (Burbidge et al. 1974).

(3) Independent of distance (and contrary to observation), theoretically predicted synchrotron self-Compton spectral flux is greater than or comparable to synchrotron spectral flux unless moderately relativistic motion is present.

(4) Inversely proportional to the distance, the energy density in relativistic electrons exceeds that in the magnetic field (unless relativistic kinematic effects are present), which indicates that the relativistic gas will expand relativistically unless there is sufficient nonrelativistic matter or external pressure to retard the expansion.

(5) Independent of distance, the observed linear polarization in most compact radio sources implies that Faraday depolarization is not large, which restricts the density of cospatial nonrelativistic electrons to a small fraction ($\lesssim 10^{-3}$) of that of the (relativistic) synchrotron-emitting electrons -- unless the magnetic field is anisotropic on very small scales -- so that there appears to be insufficient nonrelativistic matter to prevent relativistic expansion (Jones and O'Dell 1977b; Wardle 1977).

While none of the above arguments is totally irrefutable, each points to the probable importance of relativistic motion (or phase effects) in compact extragalactic objects. Furthermore, some arguments do not rely upon any estimate of distance; and other arguments are independent of the assumed emission process.

In order to produce superluminal flux variations even in a relativistically evolving source, the distribution of emitting material must be concentrated in a shell or ejected anisotropically (Jones and Tobin 1977). Thin-shell geometries are in fact expected for relativistic expansion (Vitello and Pacini 1978) or blast waves (Blandford and McKee 1977); channelling of ejected material by anisotropic external pressures (as in a disk) also seems likely.

An external medium (if present) can retard expansion unless there is sufficient energy within the relativistic gas or blast wave to sweep up the ambient material at relativistic speeds. In terms of the observed variability time scale (t_o) and the Lorentz factor (γ_o) of the bulk motion or blast wave, the requisite energy (for spherical symmetry) is

$$U \approx (10^{51} \text{ erg}) \left[\frac{t_o}{\text{yr}}\right]^3 \gamma_o^{\;8} \, n_o \quad ,$$

where n_o is the density of the ambient gas (Jones and Tobin 1977). Unless the external medium is extremely rarefied or the expansion anisotropic, the energy requirements for even a single burst can be prohibitively large if highly relativistic effects are required. For most compact radio sources, only moderately relativistic motion is required; thus energy requirements are reasonable. However, if sub-GHz variability on a time scale as short as that observed in 3C 454.3 and CTA 102 (Hunstead 1972; Cotton 1976) are real (as they appear to be, Condon et al. 1978) and intrinsic to the sources, then the energy requirements can become quite high for a synchrotron source.

5. SUMMARY

BL-Lac objects and OVV quasars seem to represent the purest form of the nonthermal quasar phenomenon. Although the infrared-optical continua of BL-Lac objects and OVV quasars and the radio emission of all compact extragalactic objects may be explicable in terms of synchrotron radiation, other emission mechanisms are probably important in the optical continua of most quasars and class-1 Seyfert nuclei and in the X-ray emission from compact extragalactic objects.

Several arguments suggest that the dynamics of the most rapidly variable, compact radio sources are dominated by a relativistic gas and that the relative abundance of cospatial nonrelativistic gas is small. Furthermore, in BL-Lac objects, little ambient thermal gas (in clouds or filaments) seems to be present.

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DISCUSSION

A. WOLFE:
Are there any radio-quiet quasars strongly polarized at optical wavelengths?

S. O'DELL:
The radio-quiet quasar PHL 5200, which exhibits very wide and deep absorption lines, is polarized at about 4%; Stockman and Angel (1978, Ap.J. Lett., 220, L67) attribute this polarization to resonance scattering. With this exception, all quasars with high optical polarization are (steep optical continuum) OVVs.

A. WOLFE:
There is then no direct evidence for synchrotron emission from radio-quiet quasars.

J. COCKE:
During the 1972 outburst of 3C 454.3, flux-density variations at 400 MHz and at 30 GHz appear correlated, whereas no variations occurred at the intermediate frequency 2.7 GHz; thus two (or more) emission mechanisms may be at work. A. G. Pacholczyk and I have constructed a model for this object, wherein the 30-GHz radiation is small-pitch-angle synchrotron emission and the 400-MHz radiation is produced by the relativistic electrons scattering off long-wavelength irregularities in the magnetic field. While such a model works well for this outburst, the narrow range of acceptable parameters implies that similar events are fairly rare.

H. ALLER:
The quasar 3C 454.3 is an extremely complex object. There is obviously a lot of opacity at GHz frequencies and below. This opacity can effect a time delay in the appearance of a burst at short wavelengths and its appearance at longer wavelengths. Thus one may actually see at low frequencies an outburst shifted so that it appears correlated with a later high-frequency outburst: The delay time is so great that the identity of individual outbursts becomes confused. So here is one object for which we have good data but still don't understand what's going on.

F. OWEN:

Concerning the low-frequency variations, B. McAdam has suggested an alternative explanation - namely, a change in the opacity of circumnuclear material. If this change is triggered by a centrally located event, say in the nucleus of a larger radio source, then the variations of the larger source could (in principle) be as rapid as those of the central source. An example of this type of model would be an ultraviolet outburst from the nucleus which would ionize gas clouds surrounding the low-frequency source, thus increasing the opacity to free-free absorption. Under such circumstances, the flux from the low-frequency source would drop as the ionizing radiation increases, and then return to its original level as the plasma recombines. The variations of 3C 454.3 appear to exhibit this sort of behavior. There are two other of these low-frequency variables: 0736+01 and DA 406.

J. CONDON:

Thus far the change in DA 406 has been downward. Also, I have a couple comments concerning 3C 454.3 and other low-frequency variables. First, the optical depth at low frequencies does not seem significantly greater during the outburst than at any other time. I suspect that the various outbursts at decimetric and centimetric wavelengths are almost entirely independent, and that strong correlations would be absent in outbursts large enough to be detected at low frequencies. Concerning B. McAdam's absorption picture, the specific mechanism - namely, free-free-opacity changes - seems unlikely for the following reasons: If the flux is to return to its original value in a year, the emission measure along the line of sight must decline in that time, due either to recombination or expansion. Recombination in so short a time would require $n_e > 10^5$ cm^{-3}; expansion at the speed of sound (for T $\approx 10^4$ K) would indicate an even higher density. The necessary parameters are thus a shell optically thick to free-free absorption at decimetric wavelengths, a column density of about 10^{20} electrons cm^{-2}, and an electron number density of at least 10^5 cm^{-3}. Such a shell must be very thin, less than 0.001 pc thick, and would probably be unstable. In any case, it should show strong Ly-α and 21-cm absorption. Because the density is so high, kinetic collisions determine the spin temperature; thus the 21-cm absorption will not be destroyed by the high 21-cm continuum radiation temperature (see talk by A. Wolfe in this volume). In summary, I think that year-time-scale variations in decimetric flux cannot be explained in terms of changes in free-free opacity.

F. OWEN:

While the specific model proposed by B. McAdam may run into problems, the general mechanism - opacity changes initiated by a central outburst - still seems a possible explanation of low-frequency variability. There may be many alternative models based on this general concept.

G. SETTI:

As a contribution to the present discussion, I would like to report the following results obtained at Bologna at 408 MHz: Since 1975, BL Lac decreased from 3 Jy to about 2 Jy in approximately 6 months, remained constant until mid 1977, and then increased again to 3.2 Jy in about 6 months. Another BL-Lac object, PKS 0735+178, showed no variability over the three-year monitoring period. The 408-MHz flux density of the quasar 3C 454.3 decreased slowly in 1975 and part of 1976, remained constant until the beginning of 1977 when it decreased rather sharply in about 2 months, and again stayed constant until the beginning of 1978 when it increased sharply in about 2 months to its present value.

Some Comments on Radiation Mechanisms in Lacertids*

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I. INTRODUCTION

In this talk we would like to discuss two problems--possible implications of observations of rapid variability in Lacertids, and dynamical models for the November 1975 outburst of AO 0235+164. We shall assume that Lacertids lie at cosmological distances.

Several Lacertids and a few quasars are characterized by extremely rapid variability at optical wavelengths and strong linear polarization (reviewed by Drs. Angel, Craine and O'Dell in this volume). It is of general interest, and of some importance as far as the nature of the primary energy source is concerned, to ask what are the most general inferences that can be drawn from these observations.

The linear polarization provides the best argument that can be adduced in favor of conventional Compton-synchrotron models of these objects. Thermal mechanisms are unlikely to produce >10% polarization except in the most contrived geometrical models, and in practice the expected degree of polarization is much less.

In section 2 we set some general constraints on a compact non-thermal source resembling the emitting region of Lacertids: the electrons have lifetimes much less than the light travel time across the source; they must be repeatedly accelerated throughout the emitting volume; and the existence of polarization sets constraints on the electron scattering optical depth and on the internal Faraday rotation. These constraints are so severe--particularly for the ultraluminous sources--that they suggest the need to invoke relativistic expansion. In section 3 we develop a model along these lines for the prolonged outburst of AO 0235+164. This discussion is so far independent of the nature of the energy source. However the deep potential well near a massive accreting black hole is a plausible location for the efficient production of relativistic plasma; in section 4 we discuss some features of such models. Section 5 presents some conjectures on the relationship between "Lacertids" and other active nuclei. For a more general discussion of emission from active nuclei see Rees (1977) and references therein.

*Ed.: *Here Lacertid stands for BL Lac object.*

2. GENERAL CONSTRAINTS OF RAPIDLY-VARYING NON-THERMAL SOURCES WITHOUT RELATIVISTIC OUTFLOW

Let us grossly over-simplify the observations and look at a theorist's version of a typical rapidly variable non-thermal source. We characterize the observations by a power $10^{46}L_{46}$ erg s^{-1} emerging at frequency $10^{15}\nu_{15}$ Hz and varying on timescale t_{var}hr. (All these quantities are evaluated at the redshift of the source.) If we assume that the source is optically thin to Thomson scattering and synchrotron absorption--necessary to produce high polarization--and ignore the possibility of extremely relativistic motion (discussed in section 3), then we can estimate a lower bound to the radiation energy density and hence define a "Compton" magnetic field whose energy density equals this minimum value. Numerically we obtain

$$B_{Comp} \sim 8 \times 10^3 L_{46}^{1/2} t_{var}^{-1} \text{ G}. \tag{1}$$

If the optical radiation is produced by the synchrotron process, then in order to avoid excessive Compton losses (as discussed by Dr. O'Dell), $B > B_c$, and the Lorentz factors of the emitting electrons (or positrons) satisfy

$$\gamma < 300\nu_{15}^{1/2} t_{var}^{1/2} L_{46}^{-1/4} . \tag{2}$$

If the "signal velocity" associated with the energy supply in the source is βc, then the right hand sides of equations (1) and (2) must be multiplied by factors β^{-1} and $\beta^{1/2}$ respectively.

An electron accelerated to energy γ will cool in the synchrotron time

$$t_{synch} \lesssim 20 L_{46}^{-3/4} t_{var}^{3/2} \nu_{15}^{-1/2} \text{ ms}. \tag{3}$$

and in the absence of subsequent acceleration these electrons will cool to subrelativistic energies in the cyclotron time

$$t_{cyc} \lesssim 6 L_{46}^{-1} t_{var}^{2} \text{ s} . \tag{4}$$

For sources that vary significantly from month to month, we can conclude that $t_{cyc} < t_{var}$, and that most of the electrons spend most of their time in the emitting region with a non-relativistic energy.

To be quantitative, let us suppose each electron is accelerated N times in the light travel time across the source. (This argument is of course independent of whether or not the electrons are actually traversing the emitting region, although in practice they probably are so doing with speeds approaching c.) Provided that $N < t_{var}/t_{cyc}$, we can calculate the condition that the optical depth to Thomson scattering be $\lesssim 1$. This requires

$$t_{var} > 30 L_{46}^{5/6} \nu_{15}^{-1/3} N^{-2/3} \text{ hr} . \tag{5}$$

This means that a luminous source whose dimensions are $< ct_{var}$ can be optically thin only if the radiating electrons are "recycled".

The interpretation of (5) is as follows. The total energy radiated in time t_{var} is $L \cdot t_{var}$. The number of electrons present in the source must then be $L\, t_{var}/\gamma N m_e c^2$, γ being given by (2). These electrons spend most of their time "cold" (i.e., with Lorentz factor ~ 1) and contribute a Thomson optical depth $\tau_T \simeq \sigma_T L/\gamma N m_e c^4 t_{var}$. Note that $\tau_T > 1$ is not the condition for the inverse Compton catastrophe (Hoyle, Burbidge and Sargent 1966). This requires that the radiating electrons themselves (Lorentz factor γ) should intercept less than $1/\gamma^2$ of the synchrotron photons, and the condition $B > B_{Comp}$ ensures this. However, if $\tau_T > 1$, not only is the escape of photons inhibited, yielding a larger t_{var} for given source dimensions, but the high polarization characteristic of synchrotron radiation is destroyed.

If $N < t_{var}/t_{cyc}$, there will be enough non-relativistic electrons in the source for the plasma frequency to satisfy:

$$\omega_p > 10^{11} L_{46}^{5/8}\, t_{var}^{-5/4}\, \nu_{15}^{-1/4}\, N^{-1/2} \text{ rad s}^{-1}\ , \tag{6}$$

and the lower limit (1) on B then implies that the gyrofrequency is

$$\omega_g > 10^{11} L_{46}^{1/2}\, t_{var}^{-1} \text{ rad s}^{-1}\ . \tag{7}$$

In order to see high polarization we require not only $\tau_T < 1$, but also that the Faraday rotation of the electric vector on crossing the source be $\lesssim 1$ rad. For an electron-proton plasma where the rotation is $\gtrsim \omega_p^2 \omega_g^2 t_{var}/\omega^2$, this condition becomes

$$t_{var} \gtrsim 100\ L_{46}^{7/10}\, \nu_{15}^{-1}\, N^{-2/5} \text{ hr.} \tag{8}$$

These sources are observed not to display circular polarization (at the $\sim 0.3\%$ level). This requires

$$t_{var} \gtrsim L_{46}^{1/2}\, \nu_{15}^{-1} \text{ hr.} \tag{9}$$

Conditions (5), (8), and (9) are, on the face of it, simple model-independent conditions that must be satisfied by a rapidly variable electron-proton plasma synchrotron source. The most stringent is probably (8) which, unless $N > 10^3$, would seem to imply that in a source like OJ 287 or 3C 446, the optical radiation must be produced by another mechanism (unless we invoke relativistic effects: see section 3).

Some "escape routes"

Before accepting this inference, let us examine some of the assumptions that have gone into the above argument. The first point concerns what is meant by t_{var}. If this is derived from the time for the polarization to change, then it may lead to a substantial underestimate of the size of the source. As an illustration suppose that a source is composed of n 70%-polarized (consistent with the synchrotron hypothesis) but randomly oriented sub-units each radiating a power $\sim L/n$. The expected degree of polarization is $\sim 50/\sqrt{n}\%$. If we then add or subtract one sub-unit, the total intensity will change by a fractional amount $\sim 1/n$, and the expected swing in position angle is $\sim n^{-1/2}$ rad, while the change in the degree of polarization is $\sim 50/n\%$. So a 17% polarized source with n = 9 may change its polarization by $\sim 5\%$ and its position angle by $\sim 20°$ as a result of an outburst involving <10% of the emitting volume. In fact, with a small number of sub-units, the fluctuations will be large and we may select for special scrutiny just those outbursts where abnormally large polarization changes are occurring. Unless the derived values of t_{var} are averaged over a long period of observations the light travel times across the total source may thus be underestimated by factors typically >3, leading to a consequent weakening of inequalities (5), (8) and (9).

We have assumed that the polarized optical radiation is produced by the synchrotron process. It could also be produced by inverse Compton scattering of lower frequency synchrotron photons. (The degree of polarization is typically reduced by a factor ~ 0.5 for each scattering.) The brightness temperature T_B of the synchrotron photons is, however, limited to the kinetic temperature of the radiating (and scattering) relativistic electrons, i.e.,

$$\gamma \gtrsim \frac{kT_B}{m_e c^2} > \frac{\gamma^6 L}{32\pi^2 \, m_e \nu^3 \, t_{var}^2}$$

or

$$\gamma \lesssim 4 \, \nu_{15}^{3/2} \, t_{var}^{2/5} \, L_{46}^{-1/5} \quad . \tag{10}$$

We also know that the field must exceed B_{Comp} which implies that

$$\gamma < 20 \, \nu_{15}^{1/4} \, t_{var}^{1/4} \, L_{46}^{-1/8} \quad . \tag{11}$$

For extremely rapid outbursts, inequality (10) is the stronger and we see that the electrons producing the Comptonization are constrained to be no more than mildly relativistic, the injected photons being in the infrared. (The brightness temperature constraint prevents there being an adequate supply of radio photons unless coherent emission occurs.)

It seems inevitable that in a synchrotron model, $t_{cool} \ll t_{var}$ and so continuous acceleration throughout the emitting volume must be invoked. Two types of acceleration mechanisms can be distinguished. In "impulsive" processes individual electrons would be heated to some characteristic energy $\gamma_{acc} m_e c^2$ in a time short compared with t_{synch}. Thereafter, they would lose energy $\propto \gamma^2$. (The actual observed slope would depend on the distribution of γ_{acc}.) Possible impulsive acceleration mechanisms include magnetic reconnection processes and mildly relativistic shock waves. "Continuous" acceleration processes proceed on time scales long compared with t_{synch}. These include: stochastic acceleration mechanisms in which the particles gain energy in small steps, presumably at the expense of some background wave turbulence;

heating by ions which are hotter than the electrons; and electromagnetic accelerating processes in which large scale electric fields, possibly magnetically induced in the vicinity of a massive black hole or star, are maintained. The equilibrium value of γ is then given by balancing the acceleration with radiative loss. Constraints derived from Thomson scattering and Faraday rotation arguments really only apply if the acceleration is impulsive. In practice, though, a modified form of these constraints probably also applies to models with continuous acceleration, because the electrons are presumably either leaving or entering the acceleration region along the line of sight and are then able to cool to sub-relativistic energies.

Looked at at face value, then, these constraints seem to present a problem for the simplest types of model for a rapidly variable (t_{var} < 10 hrs), powerful (L_{46} > 1) and polarized (> 15%) Lacertid. We must find some way of evading conditions (5), (8), and (9). One attractive way of circumventing the circular polarization and Faraday rotation limits is to invoke an electron-positron plasma instead of an electron-proton plasma. (This is discussed in O'Dell's contribution to the conference.) We would still require that the Thomson scattering optical depth be less than unity for self-consistency, as otherwise the pairs would quickly annihilate. This is probably just about possible if we include geometrical beaming effects or allow each electron to be accelerated several (N > 5) times.

We next turn to dynamical inferences. For simple impulsive acceleration models, it is straightforward to show the ratio of the electron energy density U_e to the radiation energy density U_r is

$$\frac{U_e}{U_r} \sim (\ln\gamma)\cdot\frac{t_{synch}}{t_{var}} \ll 1 \quad . \tag{12}$$

As the field energy density $>U_r$ (to avoid Compton problems) we conclude that the source regions must be dynamically dominated by magnetic fields, or by a very large pressure in the relativistic protons which cannot cool in t_{var}. Ways in which this may occur in accretion models are mentioned in section 4.

An optically thick "Comptonized" model

If the emitting region is optically thick, then any observed polarization must be a secondary phenomenon, resulting from scattering in a non-spherical region, or from differential propagation or absorption effects for the two modes. Unless the electrons are all "cold", the spectrum would be determined by the effects of multiple scattering.

Katz (1976) has discussed this class of model and pointed out that any spectrum of "soft" photons injected from a central source can be transformed into a power-law. The mean electron temperature T_e must be such that $kT_e > h\nu$, and T_e must exceed the brightness temperature of the injected "soft" radiation. The process is then equivalent to Fermi acceleration of photons. If T_e is regarded as fixed, the resulting slope depends on the value of $\tau^2(kT_e/m_ec^2)$; but if one assumes that the Compton cooling represents the main drain on the electron energies, then there will be a feedback effect on T_e, with the result that the final spectral slope depends on the fraction of the total injected energy that goes into the emission of the "soft" photons.

A possible model for the optical continuum source would have $r \simeq 10^{14}$ cm, $B \simeq 10^4 B_4 G$ ($B_4 \simeq 1$) and $\tau_{es} > 1$. The synchrotron lifetime of relevant optical or infrared electrons ($\gamma \simeq 100$) is only $\sim 10^{-2} B_4^{-3/2}$ sec. They may therefore be continually reaccelerated. (If the acceleration involves a single relativistic blast wave, the thickness of the layer of radiating particles would be << r). If $\tau > 1$, only a small fraction of the electrons can be relativistic: the bulk must have $kT_e < \tau^2 m_e c^2$ to avoid complete Comptonization to a Wien spectrum.

The injected "soft" photons would be in the infrared or optical; at longer wavelengths, self-absorption would lead to an inadequate net production rate for the photons (cf. (10) and (11)). Changes in any of the source parameters would alter the slope of the emergent spectrum, and a model of this kind could naturally give rise to power-law spectra with steep and variable slopes. This suggestion is, in effect, a scaled-down version of the explanation given by Colgate and collaborators (see elsewhere in this volume) for quasar spectra.

3. DIRECTED RELATIVISTIC OUTFLOW: THE CASE OF AO 0235+164

The Lacertid AO 0235+164 (discussed elsewhere in these proceedings) is one of the most active and interesting of this class of objects. In November 1975, it underwent a violent outburst that was observed simultaneously at both optical and radio frequencies. As has been discussed by several authors, the radio brightness temperature derived assuming that the angular size is subtended by a source of size$\sim ct_{var}/(1+z)$ at a redshift $z = 0.85$; is $>10^{15}$K, far too high to be compatible with the Compton limit for a non-relativistic outburst. If the source emits more or less isotropically then the total power radiated at the peak of an outburst is $L > 2 \times 10^{48}$ erg s^{-1}. This energy is mainly in the infrared, the spectral index over the range $10^{14} - 10^{15}$ Hz being ~ 3. (If this steep spectrum is not intrinsic but due to external reddening, $>10^{49}$ erg s^{-1} may be involved.) This object therefore appears to be amongst the most luminous of extragalactic sources.

In these days of heightened energy consciousness it is important to find ways of reducing the total power consumption. One way of doing this is to make the emitting region move at relativistic speeds; Lorentz factors $\Gamma > 10$ suffice to bring the brightness temperature in the comoving frame down to $\sim 10^{12}$K, and if we just happen to be in the emission cone of a single object, a reduction of Γ^2 in L is possible. Furthermore, the Thomson optical depth of the emitting region is reduced because the transverse linear dimensions are larger by $\sim\Gamma$, and the total mass-energy required (for a given efficiency in the comoving frame) is reduced by Γ^4. These effects are of essentially kinematic origin. One way of realizing them dynamically is by means of a relativistic shock wave behind which the necessary particle acceleration and field amplification should naturally occur. Physical processes occurring in relativistic shock waves have been described by Drs. O'Dell and Marscher, and we shall not repeat their discussions. Instead, we develop this theme a little further and outline two new ways in which these relativistic shock waves might be created. The application of these ideas to the jet in M 87 and superluminally expanding compact double sources will be presented elsewhere.

VLBI studies of compact radio sources have told us that double (or, more generally, linear) structure is a common feature of active galactic nuclei. Assuming that small scale (< pc) structure is somehow associated with the large scale extended double structure found in many other sources, it is reasonable to suppose that the link is provided by two straight jets along which matter flows at supersonic and possibly relativistic speeds. What observations we have of these jets indicate that their opening angles are typically $\sim 10°$. Therefore, in a small fraction of sources (< 0.01) we should be looking directly along either jet. Perhaps this is what Lacertids are. In some quasar models the central powerhouse is surrounded by a dense optically thick and radiation-dominated atmosphere in which the jet is focussed parallel to the angular momentum direction of the whole system. Only when you look along the jet do you expect to see unscattered, and therefore rapidly variable and polarized, non-thermal emission directly.

We therefore hypothesize that in AO 0235+164 we are seeing emission from behind a shock wave moving relativistically in the jet towards the observer. As the inferred distance of the shock from the central object ($\sim \Gamma^2\, ct_{var}$) is typically $\sim$ 10pc, $\gtrsim 10^4$ times the Schwarzschild radius for any reasonable central mass, we must find some way of developing a shock at large distances without destroying the atmosphere that is responsible for the focusing close to the hole. Two possible methods are to steepen non-linear waves to form shocks and to place a blunt obstacle in the jet. We discuss these in turn.

<u>Non-linear sound wave</u>

Suppose that for some reason the speed of the jet fluctuates with time. Then this will appear to an observer moving with the jet as a nonlinear sound pulse. Suppose also that the Lorentz factor of the jet γ increases by $\Delta\gamma$ in a time t. (For simplicity, we confine out attention to ultrarelativistic flows.) Then the sound wave will steepen and break at a distance $r \sim \gamma^3 c\Delta t/\Delta\gamma$ to form a shock. Particle acceleration and field amplification can occur behind the shock, and the relative kinetic energy of the converging flows can be radiated away. If the radiative efficiency is $\gtrsim 0.5$, a distant observer lying in the emission cone who assumes that the observed flux is radiated isotropically will infer a total power $L \sim (4\pi/\Delta\Omega)(\Delta\gamma/\gamma)^3$ where $\Delta\Omega \gtrsim \gamma^{-2}$ is the solid angle occupied by the jet which has a total power L_{jet}. This will vary on a time scale $t_{var} \sim r/c\gamma^2 \sim \gamma\Delta t/\Delta\gamma$.

In the comoving frame, the relative velocity across the shock will be $\sim c\, \Delta\gamma/\gamma$ and therefore sub-relativistic for $\Delta\gamma < \gamma$. The mean radiation energy density behind the shock is given roughly by $\sim \gamma^{-6} L/4\pi c^3 t_{var}^2$, which is much smaller than the value that would be derived assuming a non-relativistic source varying in a time t_{var}. The Compton problem is thereby eased.

If, optimally, we choose $\Delta\Omega \sim \gamma^{-2}$, $\Delta\gamma \sim \gamma \sim 10$ then the total power required in the jet is only $\sim 10^{46}$ $ergs^{-1}$. From the observed variability timescale $t_{var} \sim 10^7$s., we then obtain $r \sim$ 10pc, $\Delta t \sim 10^7$s.

The energy density behind the shock is $\sim 10^{-4}$ erg cm^{-3} giving an equipartition magnetic field $\sim$0.05G. The corresponding brightness temperature at 10 GHz calculated by a distant observer who estimated the source size as ct_{var} would then be $\sim 10^{15}$K in rough agreement with the radio observations. Most of the power is observed at frequencies $\sim 3 \times 10^{13}$ Hz and so electrons of energy >5 GeV (measured in the comoving frame) must be accelerated behind the shock (which is only mildly relativistic). The observed frequency for which the cooling time equals the dynamical time is $\sim 4 \times 10^{12}$ Hz, roughly that at which a steepening of the spectrum may have been inferred. The synchrotron spectrum could have extended up to optical wavelengths and in addition a comparable power in higher frequency Compton radiation may have been generated.

Provided that efficient particle acceleration can occur in the manner hypothesized, it appears to be possible to account for the high apparent brightness temperature and the over-large total inferred power of AO 0235+164 during the outburst in terms of this simple model. Later outbursts can presumably also be interpreted in these terms, although the long term behavior of the radio source, produced by relativistic electrons which are not radiative, is very difficult to anticipate.

Blunt obstacle

An alternative dynamical model is this: suppose that a large obstacle (plasmoid) of mass M and size h is created in the jet. A strong bow shock will form ahead of the plasmoid behind which the shocked jet plasma can radiate. A strong shock will also be driven through the plasmoid with a speed $\sim (h_o L_{jet}/Mr^2c^3\Delta\Omega)^{1/2}$, bringing the plasmoid into pressure equilibrium with its surroundings. It can then be accelerated along the jet, presumably expanding as the ram pressure weakens.

If, for simplicity, the acceleration occurs over a length < r, we may treat the momentum flux in the jet as constant. As long as the Lorentz factor of the plasmoid Γ is less than that of the jet γ and its internal energy E is subrelativistic, we have

$$L_{rad} \propto \frac{Md\Gamma}{dt} \propto h^2 \frac{\gamma^2}{\Gamma^2} \propto \frac{E}{h} \propto \frac{h_o^{\,2}}{h^3} \tag{13}$$

where L_{rad} is the power radiated (assuming the radiating electrons are able to cool on the acceleration time scale) and h is the size of the plasmoid. We therefore obtain

$$L_{rad} \propto \Gamma^{-6/5} \propto t^{-6/11} . \tag{14}$$

If the observer makes an angle θ with the direction of motion of the plasmoid, the observed flux will increase and then decrease while the plasmoid is being accelerated.

Specifically $L \propto L_{rad} D^4$ where $D = \Gamma^{-1}(1- \sqrt{1-\Gamma^{-2}} \cos\theta)^{-1}$ is the Doppler factor, so

$$\begin{aligned} L &\propto t^{14/11} , \quad \Gamma < \theta^{-1} \\ &\propto t^{-26/11} , \quad \Gamma > \theta^{-1} . \end{aligned}$$

Of course spectral effects complicate the issue, but in general we expect the observed flux to be maximized when D attains its maximum value of cosec θ, and to decline very rapidly thereafter. As in the previous model, a Lorentz factor $\Gamma \sim 10$ and a source size $h \sim 1$ pc suffices to account for the radio and optical variability, although the details are somewhat different. (One important distinction is that until the plasmoid has been accelerated to $\Gamma \sim \gamma$, nearly all the energy flux in the jet can be radiated away. In the case of the sound wave, this is only true if $\Delta\gamma \sim \gamma$).

If we assume that the plasmoid is to be accelerated to a speed with $\Gamma \sim 10$ in a distance $r \sim 10$ pc, then $M \sim 10^{31}$g, $h \sim 1$ pc, $e \sim 10^{-4}$ erg cm^{-3} and the temperature within the plasmoid is marginally relativistic ($\sim 10^{13}$K). Unless the plasmoid contains magnetic field it will not radiate, however, and so should be able to retain sufficient pressure support to provide the necessary cross-section. The corresponding (comoving) particle density and field strength in the jet depend on its speed and are given by $\sim 10^{-23}\gamma^{-2}$g cm^{-2} and $\sim 0.2\gamma^{-1}$ G, respectively. For self-consistency we clearly require that $\gamma >> \Gamma$. Of course these calculations are only approximate but they do demonstrate that, with this scheme too, it is possible to reduce the total power radiated and satisfy the Compton limit in a model that reproduces the approximate flux variability.

What is the nature of the obstacle? Three possible answers spring to mind. Firstly, it might be a portion of the wall of the jet entrained into the flow as a result of nonlinear development of a Kelvin-Helmholtz instability. A second possibility is an ordinary HI cloud or filament that finds itself in the jet, perhaps as a result of a slight change in direction of the jet. A third idea is that a supernova actually goes off in the jet. (A star would be unaffected as it presents far too small a cross-section.) It turns out that in the present application this third option can probably be ruled out: the mass involved is only 0.01 $M_\odot$ and the ejecta would expand only out to a radius $\sim$0.1 pc if their explosion velocity were $\sim 10^9$ cm s^{-1}. Supernova remnants do, however, form ideal targets for other variable sources.

Note that the behavior of compact variable radio sources--and the kinematics of "superluminal" effects, etc.--may be sensitive to the density and distribution of gas encountered by the beams, and to the time-variability of the beam velocity. It would be interesting to relate this to the apparent dissimilarity between the VLBI characteristics of BL Lac and of other variable sources.

4. SPECIAL CASE OF ACCRETION MODELS

The foregoing discussion leads to various conclusions about the nature of the emission region. If the region has dimensions $\lesssim ct_{var}$, it must contain and energize a plasma that is devoid of the usual "thermal background" component: i.e., the mean kinetic energy per particle must be so high that at least the electrons are relativistic. Moreover, the electrons must be repeatedly reaccelerated on a timescale $< t_{var}$; and even then the high polarization raises a problem. Faraday rotation could be suppressed if the plasma contained similar densities of electrons and positrons, but the requirement that the electron scattering optical depth be $\lesssim 1$ in order that high linear polarization be observed is a constraint on interpretations of sources such as 3C 446.

Relativistic outflow with $\Gamma \gtrsim 10$ eases these problems, by allowing longer dimensions and lower opacities for a given t_{var}; if the outflow is directed preferentially towards us, the overall source energetics are greatly eased.

These influences follow straightforwardly from the observations, assuming only that the radiation mechanism is incoherent: they involve no particular assumption about the central energy supply. We now consider the specific hypothesis that this is a massive black hole powered by accretion from its surroundings.

A characteristic luminosity is the so-called "Eddington limit"

$$L_{edd} = \frac{4\pi GMm_p c}{\sigma_T} \simeq 1.3 \times 10^{38}(M/M_\odot) \text{ erg s}^{-1} \quad . \tag{15}$$

The Schwarzschild radius corresponding to mass M is

$$r_s = \frac{2GM}{c^2} \simeq 3 \times 10^5 (M/M_\odot) \text{ cm} \; . \tag{16}$$

The characteristic minimum dynamical timescales for motions involving a mass M are

$$\sim r_s/c \simeq 10^{-5}(M/M_\odot) \text{ s}. \tag{17}$$

The minimum periods for stable orbits around a black hole are a few times larger than this, the precise factor depending on the angular momentum of the hole. There is, of course, no reason why localized regions (e.g., shock-heated gas clouds near the hole) should not give rise to variability on timescales shorter than this; there are, however, other constraints which still operate if the luminosity is high.

If the efficienty is ε (so that $\dot{M} = 0.15\varepsilon^{-1} L_{46}$ solar masses per year), then the density of gas in free-fall accretion would be

$$n_{acc} \simeq 10^{11} \varepsilon^{-1}(L/L_{edd}) M_8 (r/r_s)^{-3/2} \text{ cm}^{-3}. \tag{18}$$

If the gas were not in free-fall the density, averaged over solid angle, would be higher by a factor $(V_{infall}/V_{free\ fall})^{-1}$. In addition, if the material were, for instance, in a disc, the density n in the relevant radiating region could be less, and we define a parameter $\mu = n/n_{acc}$, which may be << 1.

If the mass supply is sufficient to provide a luminosity L, then (for spherical accretion), the Thomson optical depth down to radius r is

$$\tau(>r) \simeq (L/L_{edd})(r/r_s)^{-1/2} \mu\varepsilon^{-1}\left(\frac{V_{infall}}{V_{free\ fall}}\right)^{-1} \; . \tag{19}$$

If $L \simeq L_{edd}$, this implies that there is an optical depth $\gtrsim \mu\epsilon^{-1}$ down to the region ($r \sim$ a few times r_s) when most of the energy is liberated. This means that we require $\mu << 1$ for a consistent model.

If a luminosity L is emitted from an effective "photosphere radius" r, then the effective temperature can be written as

$$\frac{kT_{eff}}{m_p c^2} \simeq (L/L_{edd})^{1/4} \ (M/M_c)^{-1/4} \ (r/r_s)^{-1/2} \ \eta^{-1/8} \ (m_e/m_p)^{1/2} \ \alpha^{-1}. \quad (20)$$

In this expression, η denotes the well-known large dimensionless ratio (hc/Gm_p^2), M_c is the "Chandrasekhar mass" $\eta^{3/2}M_p$, and α is the fine structure constraint. In "practical" units this is $\sim 10^8(M/M_\theta)^{-1/4}(L/L_{edd})^{1/4}(r/r_s)^{-1/2}$K. Note that for all compact objects of astronomical interest, T_{eff} is far below the "virial temperature" T_v, defined as

$$T_v \simeq \frac{m_p c^2}{k} (r/r_s)^{-1} \simeq 5 \times 10^{12}(r/r_s)^{-1} \text{ K}. \quad (21)$$

Provided that cooling is efficient enough to permit the radiating material to cool to $\sim T_{eff}$, this therefore means that <u>gas pressure</u> is dynamically negligible.

If $\dot{M} << \dot{M}_{crit}$ and the infall is radial, then the gas may be unable to cool by bremsstrahlung-type processes on the inflow timescale. It will then heat up ($T \simeq T_v$), the electrons all becoming relativistic near the hole. Other more efficient cooling processes can then come into play.

In other situations the radiative efficiency is so great that most of the gas spends most of its time at $T \simeq T_{eff}$. If the inflow is quasi-spherical, a "two-phase" structure develops, with dense clouds ($T \simeq T_{eff}$) embedded in material at $T \simeq T_v$ which emits the bulk of the radiation. In disc accretion, most of the matter remains at T_{eff} but inward spiralling material may--in a variety of ways--supply power to a rarified hot corona.

A possible geometry naturally yielding $\mu << 1$ would be an accretion disc when most of the energy was radiated in a corona. For instance, in the model of Blandford (1976) the energy is radiated by relativistic particles coupled to magnetic field lines anchored in the disc. This type of model--or that of Blandford and Znajek (1977)--has the property that energy is emitted from a region with the properties outlined in section 2.

The "Compton field," equation (1), can be re-expressed

$$B_{Comp} \simeq 3 \times 10^3 (\dot{M}/\dot{M}_{crit})^{1/2} M_8^{-1/2} \ (r/r_s)^{-1/2} \text{ G} . \quad (22)$$

The fields near the horizon are thus likely, when $\dot{M}/\dot{M}_{crit} \simeq 1$, to be strong enough for vacuum-breakdown to lead to the production of electron-positron pairs.

5. CONCLUDING CONJECTURES

The so-called Lacertids are all characterized by a high ratio of non-thermal to thermal luminosity. As such, they are peculiarly important because they provide relatively direct clues to the primary energy-production mechanism. But, though the individual objects in this category are interesting, it is debatable whether the name "Lacertid" is helpful: it is by no means obvious that the ultra-luminous systems such as 3C 446 and AO 0235+164 really fall into the same category as small redshift (and thus <u>low</u>-luminosity) systems such as BL Lac itself.

In accretion models, there is a natural tendency for non-thermal radiation to become more predominant as $\dot{M}$ decreases, because bremsstrahlung-type cooling mechanisms are then less efficient. This line of argument may explain the compact radio sources in the nuclei of some elliptical galaxies, and perhaps the low-redshift "Lacertids" as well. This interpretation obviously fails, however, for ultra-luminous systems. There are other ways (for instance those reported here by Dr. Krolik) in which emission lines can be suppressed in strong non-thermal sources even if gas is present; but the existence of high polarization (implying small optical depths) is still a problem, unless relativistic outflow occurs.

We would therefore like to propose the hypothesis that Lacertids (and perhaps also optically violent variable quasars) are active galactic nuclei where the continuum emission is enhanced by being beamed toward us. This may either occur because the emitting region moves relativistically outwards in the form of a jet, or because, unless an active nucleus is viewed along the symmetry axis, the emergent optical photons have been steadied, softened, and depolarized in their transfer through an optically thick gas cloud (see Fig. 1).

If Lacertids are objects where the "jet"--presumably fixed in space and related to the angular momentum vector of the central object--is pointing toward us, the probability $(\Omega/4\pi)$ of a suitable orientation may be as small as Γ^{-2}, where Γ is the bulk Lorentz factor for a relativistic jet. Observed jets in radio sources indicate that $(\Omega/4\pi) \simeq 10^{-2}$. Note, however, that this does not mean that observed Lacertids should be rare compared to other types of galactic nuclei, because there will be an obvious selection effect in favor of those objects with the special orientation. The quantitative details depend on the luminosity function, but a simple example illustrates the point. Suppose that active nuclei have a luminosity function $n(L)\, dL \propto L^{-q} dL$, and that the observed flux is enhanced by a factor X if we lie in the beam. Then "Lacertids" would actually <u>predominate</u> in surveys down to a given flux density if $X > (\Omega/4\pi)^{-1/(q-1)}$. (Observations suggest q in the range 2 - 2.5).

If the low luminosity Lacertids are to be explained in this way, the spatial density of their counterparts whose beams are <u>not</u> oriented toward us must be high--corresponding to active nuclei in ellipticals. (Maybe M 87 would have been classified as a Lacertid if its jet were pointing directly toward us.) An obvious consequence of this model is that extended double radio structure should be anticorrelated with the

Lacertid phenomenon, and that some Lacertids should show halo emission corresponding to a double source viewed along its symmetry axis.

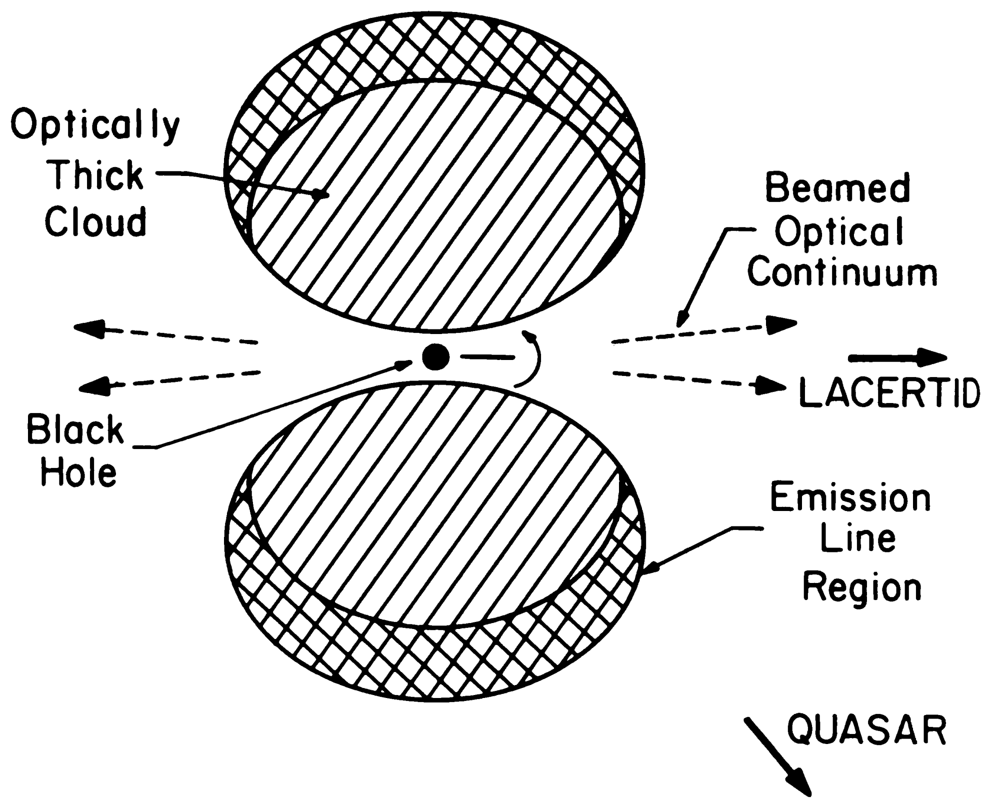

Fig. 1. Schematic representation of a geometrical interpretation of Lacertids. If the optical continuum is beamed along the symmetry axis, then the emission lines may be suppressed when the source is viewed from this direction.

Relativistic jet models seem capable of accounting for the major outburst in AO 0235+164, at least insofar as the gross observational features are concerned. It is of further interest to ask whether or not a cloud accelerated by the jet (or alternatively a portion of the jet that became thermally unstable and cooled) could be responsible for the $z = 0.52$ absorption features that are seen. The answer must surely be no, however, because (as remarked by several authors) the fact that the emission feature is located 2" away from the continuum source and yet shows less than $\sim$100 km s^{-1} redshift difference from the absorption feature puts a lower limit on the distance of the gas (typically $\gtrsim$ 300 kpc). In fact as a plasmoid is accelerated and convected it will cool, although it can be broken up by Rayleigh-Taylor instability and could presumably be responsible for absorption features in some other quasars. However, if the numbers derived here are any guide, then the column densities through the clouds at the cooling radius are very much less than the values $\gtrsim 10^{18}$ cm^{-2} necessitated by the observations.

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DISCUSSION

G. BURBIDGE:

I know that these models are incredibly ingenious and I feel continually exasperated that you won't approach the other way of looking at the problem, namely the distance. But given that you take this approach, what kind of predictions can you make and at what level would you concede that the observations cannot be fixed up in this way? Are there any real predictions of any of these theories which would lead us to conclude that these models might work or that they ultimately will not work?

R. BLANDFORD:

For instance, if the November 1975 outburst of AO 0235+164 is repeated, then the best prediction is that the angular size of the radio source should be $\lesssim$0.1 milliarc-sec. before it declines. Certainly you should see something that is extremely compact and that might even scintillate. However, that doesn't necessarily rule out some other variant on this sort of dynamics.

G. BURBIDGE:

No, but for example you argued that it must be a rare event and a rare phenomenon. If many more of these were found, would you say that that is the end of your explanation?

R. BLANDFORD:

Well this was a point that I didn't have time to make. [*Ed.: Included in the written text.*] There is an interesting hypothesis that is somewhat related to what you said; that is, what is happening in a BL Lac object is not so much that the emission lines are faint because there is no gas, but rather that the continuum is high. So I'd like to suggest the hypothesis that in fact what you are seeing is something like an elliptical galaxy where you look along the rotation axis. In only ~1% of all active elliptical galaxies would you look along the rotation axis. I think that this particular hypothesis can be tested on statistical grounds.

G. BURBIDGE (to R. Blandford):

Roger, is your model for AO 0235+164 an elliptical galaxy with a black hole at the center?

R. BLANDFORD:

I would say that it is either a galaxy or a proto-galaxy. As the continuum emission is proposed to originate in the central 10 pc, I don't think the nature of the surrounding object is particularly relevant to the model.

G. BURBIDGE:

Yes, but you do have to explain the absorption systems and that's a big problem ultimately.

R. BLANDFORD:

I agree.

G. BURBIDGE:

I am curious as to how you view this.

R. BLANDFORD:

My personal view is that the z = 0.524 system is at its cosmological distance. I find the kinematic argument against an intrinsic origin of this absorption system very convincing. [*Ed.: See Wolfe et al. 1978, Ap.J., 222, 752.*]

G. BURBIDGE:

And the 0.85 system?

R. BLANDFORD:

It seems to me that the simplest interpretation for the 0.85 system is that this is absorbing material associated with the object itself and that 0.85 is the actual redshift of AO 0235+164.

G. BURBIDGE:

So do you really believe that there is an intervening system or not?

R. BLANDFORD:

I believe that there is one intervening system responsible for the 0.524 redshift and that 0.85 is the actual redshift of the object. On the basis of present observational evidence I think that is the simplest explanation.

S. COLGATE:

You just touched on the observations of Wardle and Ledden which show that there is no Faraday rotation and the rather hideous constraints this places on the magnetic field and on the low-energy electron density. Do you see a way in which the electron density can be somewhere else in this system (AO 0235+164)? You need sufficiently few electrons within the model so that you don't violate the Faraday rotation observations. You need a low-energy electron density less than 10^{-4} to 10^{-5} of the relativistic electron density to explain them.

R. BLANDFORD:

In BL Lac objects there isn't necessarily much gas present so you don't have this problem with thermal plasma, but in QSOs you do need thermal plasma to make the emission lines.

S. COLGATE:

In their talks Wardle and Ledden imply that the cold electron density should be $\sim 10^{-4}$ times the relativistic electron density. While observations of emission-line regions suggest a cold electron density of $\sim 10^{8}$ cm^{-3}, the relativistic density is ~ 1 cm^{-3}. This is a confrontation of $\sim 10^{12}$. You can certainly separate line emitting regions from the continuum, but a factor of $\sim 10^{12}$ seems too large a separation. Do you see this separation as reasonable?

R. BLANDFORD:

If the line-emitting regions do not cover the source, then you expect little observable depolarization.

H. ALLER:

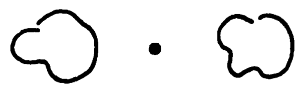
I just want to caution against saying that AO 0235+164 is a rare event. I think that it was serendipity that it was found. There is no guarantee that there are not many more of these objects going off. I think that what is unique about this object is that it is something which is intrinsically weak both at optical and radio wavelengths and that it flared up by a large amount and then went down. We just don't look at things like that very often.

R. BLANDFORD:

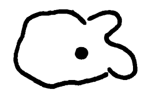
As you say, it may be a rare object rather than a rare event. I think that that statement is testable and you can answer your own question observationally.

J. CONDON:

If QSOs and BL Lacs differ only in orientation, shouldn't a complete sample of radio BL Lacs contain numerous luminous, extended sources, such as the classical 3CR quasars? (Of course they might not be doubles, but still there should be some with luminous (10^{45} erg sec^{-1}) extended halos or whatever.) For example, the following sketch illustrates my point.



3CR QSO



BL LAC OBJECT
[Double seen end-on]

R. BLANDFORD:

Yes, that's right. But perhaps what BL Lac would look like when seen from the equatorial plane would be a not too-bright elliptical rather than a quasar. The probability of a strong double being associated with a BL Lac object is then correspondingly lower. The question can really only be answered by a careful statistical study.

M. REES:

I guess that you would not expect to find typical classical doubles associated with BL Lac objects on this hypothesis. But I want to reiterate what Roger (Blandford) said about the rarity of these events. This hypothesis requires that they are rare per unit volume, but it doesn't necessarily require that they should be rare in a survey carried out to a given flux density, obviously, because the ones where the beam is squirted toward you are favored. The actual fraction of BL Lac objects in a survey down to a given flux density is going to depend on putting in the luminosity function because you are seeing a fainter part of the luminosity function in a favored orientation. If the luminosity function is rising very steeply towards the faint end, then that effect may compensate for the small angle factor. So to answer that question, one needs to feed in some assumption about the luminosity function.

D. SHAFFER:

That was my point, that the only ones we see are the weirdos because they are beamed at you.

M. BURBIDGE:

H. Aller's point, that events like the outburst in AO 0235+164 are not that rare, is a good one. It was just a chance that Arp happened to be at the telescope when the object he described yesterday (0846+51W1) flared. There might be many of these.

A. MARSCHER:

I noticed that you assume that you're looking along the beam in your particular model for the November 1975 outburst in AO 0235+164. Would you make a prediction as to the structure of this type of object? For example, would it have a double structure or would it simply have a single component coming out? Or can you preserve a double structure from burst to burst?

R. BLANDFORD:
This is model-dependent but as an example, take the accelerating plasmoid model. In the early phases you would see something that was more or less spherical, but in the late phases you could see a double develop or at the very least some linear structure, with constant position angle, develop. If you are looking at 5° to the velocity vector, the orientation is of course optimal for extremely super-luminal expansion.

A. MARSCHER:
Is it a double structure, in that one is going away from you and one is coming toward you?

R. BLANDFORD:
No, the only structure that you would see is associated with the one beam that is coming towards you.

A. MARSCHER:
Would the orientation stay the same from burst to burst?

R. BLANDFORD:
Yes, but the polarization may not because the polarization could be associated with the transverse field which could be uniformly distributed.

J. WARDLE:
It is not obvious that you would find many classical double radio sources associated with BL Lac objects because they have been selected mainly on the basis of their centimeter excess flux. We do have a few steep radio spectra for BL Lac objects. I have a map in my bag here of one such BL Lac object (1107+03) which is a classical double that is a minute of arc across. The reason I didn't show it during my talk is that there is a BL Lac object and a galaxy very close together in the middle and it is not clear which or either of them is the correct optical identification. Because we are strongly selecting BL Lac objects on the basis of their radio spectra you wouldn't expect to find many classical doubles. [*Ed.: See Hazard on p. 409 for a different interpretation.*]

M. DAVIS:
Can you say anything at all about the recurrence probability of a November 1975 type event on the basis of this model?

R. BLANDFORD:
No, that's like asking the question is there life elsewhere in the Universe? One just doesn't know enough yet.

T. JONES:
If the difference between BL Lacs and QSOs is orientation, how do you account for the difference in emission lines which don't care about orientation?

R. BLANDFORD:

I am just advancing the hypothesis, not necessarily defending it, that what is going on in BL Lac objects is not so much that the emission lines are faint, but that the continuum is brighter than in some cosmological objects that you are looking at from the side of the beam. Another way to throw out this hypothesis is to find some quantifiable difference between emission lines that you do see in BL Lac objects, when you look hard enough, and emission lines in active elliptical galaxies.

G. BURBIDGE:

Now what do you mean by that? There are such things obviously, people have measured emission lines in ellipticals.

R. BLANDFORD:

If you saw much different lines, say lines arising from much higher stages of ionization, in BL Lac objects than you might find in some objects like Cyg A.

M. BURBIDGE:

You don't.

R. BLANDFORD:

Well you don't see many emission lines at all in BL Lac objects yet. There are a couple of cases where things look like emission features and if in time you find more of these and if you find that they are associated with different stages of ionization, then that says there's something different about the emission lines.

M. BURBIDGE:

OK, but I am just saying that the things Joe Miller described in BL Lac objects were the same lines as in ellipticals but much weaker.

R. BLANDFORD:

Yes, apart from the relative strengths the lines are quite similar.

A. WOLFE:

What about 3C 446? How would you classify that?

R. BLANDFORD:

We've heard arguments that it is a BL Lac object. Somebody else said that it hasn't got centimeter excess. [*Ed.: 3C 446 exceeds 3 Jy at cm. wavelengths (Kellermann and Pauliny-Toth, 1971, Ap. Lett. 8, 153).*]

A. WOLFE:

I thought its radio spectrum was quite similar to AO 0235+164. What kind of emission line spectrum does it have?

M. BURBIDGE:

The emission lines are the ones normally seen in QSOs at that red-shift ($z \simeq 1.4$), i.e. the stronger features are CIV, CIII], and they seem to have the usual relative strengths.

T. CHUBB:

Could you say something about the nature of the obstacles in the jets?

R. BLANDFORD:

I was afraid someone might ask that. I can think of a few ideas. One possibility is if the jets have walls, then the walls themselves are Kelvin-Helmholtz unstable and material tears off, that is one possibility. The sort of masses that you need are about 0.01 $M_{\odot}$ in a parsec or so indicating densities of about 10^{-2} cm^{-3}.

D. DeYOUNG:

That's going to get blown away rather rapidly by the ram pressure of the relativistic beam.

R. BLANDFORD:

Yes, it gets blown away pretty rapidly. It gets accelerated over a distance of about 10 pc. so what one sees is a light-travel time over 10 pc. reduced by a factor of γ^2, reducing it to 3 months.

T. CHUBB:

What about in M87?

R. BLANDFORD:

In M87 you could either invoke an HI region or a supernova remnant as an obstacle.

J. MILLER:

I would like to make one more comment about this question of double versus compact radio sources for QSOs as opposed to BL Lac objects. I don't think that this is a selection effect. The only case where there is a double source is 1400+162. In a program that I am carrying out now in collaboration with G. Miley we compare Westerbork maps of large numbers of QSOs with their optical spectra. We are finding some very interesting things, but one thing we see in 1400+162 is that it doesn't look anything like the classical doubles around QSOs. The central source is much more dominant than you see in QSOs all of which do have some kind of a central source. In the case of 3C 446 you don't see a classical extended radio double. That is also a very compact source. In all the violently variable QSOs that I know about, that is the ones that resemble BL Lac objects, you again don't find classical double radio sources. So I don't think you will find one of these Mpc size double radio sources surrounding BL Lac objects.

A MODEL FOR RADIATION FROM COMPACT NON-THERMAL SOURCES

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ABSTRACT

In the framework of the spinar model for active galactic nuclei we have discussed the acceleration and the radiation of relativistic particles. We show that this model eliminates the difficulties associated with the short lifetime of the radiating electrons (in fact, a short lifetime guarantees a conversion efficiency of order 1) and allows a determination of the magnetic field, energy and number of particles in the emitting region.

For a typical source having $L \sim 10^{45}$ ergs/sec, size $R \sim 10^{15}$cm, synchrotron emission at $\nu \sim 10^{13}-10^{14}$ Hz the fitted parameters are $B \sim 200$ gauss, $\gamma \sim$ few hundreds, $N \sim 10^{50}$. As a consequence, most of the inverse Compton emission falls in the X-ra range with an intensity comparable to that of the primary emission and a cutoff is predicted in the sub-millimeter region.

We have considered the origin of the particles energy distribution and we find that under reasonable physical assumption the observed spectrum should be rather flat.

An extended version of this model is being prepared for th Astrophysical Journal.

RADIO EMISSION FROM
QUASARS AND BL LAC OBJECTS BY COHERENT PLASMA OSCILLATION
AND STIMULATED COMPTON SCATTERING

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ABSTRACT

We interpret the full radiation spectrum of quasars and BL Lac objects as due to a combination of a soft plasma oscillation source at $2\nu_P$ and bremsstrahlung. We extend our previous work of the plasma oscillation radiation into the radio part of the spectrum and show that the high brightness temperature observations of BL Lac objects [kT_b (100 MHz) $\tilde{=}$ 3×10^5 mc^2] are a reasonable consequence of a lower external plasma density and ejection as required for the observed lack of emission lines. We consider two extreme cases; the one where the plasma oscillations are suddenly extinguished and only stimulated Compton scattering remains and a second case of a constant source of plasma oscillations but a graded surface density. The first case gives a rapidly decaying brightness and the second gives 100 times too large a brightness temperature as well as 10 times too large a radius. We feel it is reasonable to invoke a combination of both processes to explain the observed radio spectrum. We predict a spectral flux $n_\nu\, d\nu \propto \nu^\alpha$, $\alpha = -7/5$. This model circumvents the self-Compton X-ray flux difficulty of incoherent synchrotron emission and predicts the observed lack of Faraday rotation.

INTRODUCTION

The confrontation concerning large redshift objects (quasars and BL Lac type objects) between observations of their variability, flux and spectra and the interpretation of their spectra in terms of incoherent synchrotron radiation has culminated most dramatically in the recent outburst of the BL Lacertae type object AO 0235+164. We suggest an extension into the radio part of the spectrum of a model based upon coherent plasma phenomena first designed to interpret the infrared and optical part of the spectrum and now extended to interpret observations of the radio spectrum, particularly the high brightness temperature.

Synchrotron Self-Compton X-ray Difficulty

A series of four papers by the University of California at San Diego group (Jones and Burbidge 1973; Jones, O'Dell and Stein 1974 I; Jones, O'Dell and Stein 1974 II; Burbidge, Jones and O'Dell 1974) has explored in depth the consequence of synchrotron radiation models for many of the known quasars and BL Lac type objects. These papers confirm and explore more deeply the difficulty of synchrotron self-Compton radiation originally pointed out by Hoyle, Burbidge, and Sargent (1966). Briefly, the difficulty revolved around the high brightness temperature inferred from the small size, $r < \Delta t\ c$, (Δt the fluctuation time) and the observed high flux. Since the equivalent Planck spectrum emissivity corresponds to a temperature (the brightness temperature) $\gg mc^2$, the electrons giving rise to the synchrotron radiation must have an equivalent temperature also $\gg mc^2$, or $\Gamma \gg 1$, $\Gamma = (1 - \beta^2)^{-1/2}$. These highly relativistic electrons will then scatter the radio photons to energies $\Gamma^2\ h\nu$ in the X-ray range, contradicting observations and requiring an unreasonable total energy. The difficulty of packing the radio source of high brightness temperature into the same region as the more energetic infrared and optical sources further exacerbates the problem although special geometries have been proposed (Rees 1966) where the radio flux is emitted from a highly relativistically expanding source $\Gamma_s \geq 5$ with weak magnetic fields. However, the low frequency flux must be created at the same place where a high magnetic field nonexpanding region is needed for the infrared and optical fluxes. Furthermore, Terrell (1977) and Vitello and Pacini (1978) argue against relativistic expansion producing the short pulse width (rise and fall) times because one always sees, after transparency, the opposite side. Beam models have been proposed (Cocke and Pacholczyk, 1977) but the angle is small, $\lesssim 10^{-3}$ radians. The problem appears so difficult that special objects of unusual brightness temperature may be considered local in origin whereas the major class is considered cosmological. However, one of the most dramatic confrontations between models using incoherent sources and observations occurs with the BL Lacertae object AO 0235+164 where the radio fluctuations and spectrum (MacLeod, Andrew and Harvey 1976, and Ledden, Aller, and Dent 1976) establish a brightness temperature $kT_b \cong 10^{15}$K, that is 1.7×10^5 mc^2, at 8 GHz and a flat spectrum, intensity spectral index $\alpha \cong -0.15$. The nearly simultaneous outbursts observed in the radio, infrared and optical (Rieke et al. 1976) force one to consider congruent sources. The option of postulating a local origin is unattractive in this case, because the absorption line redshifts, one probable at z = 0.852, but a second one certain at z = 0.524 (Burbidge et al. 1976) have been confirmed in the 21 cm. hydrogen line (Roberts et al. 1976). Finally the hydrogen line absorption at 21 cm. seen in QSO 3C 286 (Wolfe et al. 1976) excludes any possible source of absorption other than an intervening galaxy and a narrow absorption line at 21 cm. as observed in AO 0235+164 is an additional indication of a cosmological distance. We therefore suggest a coherent mechanism for the majority of the photons observed and interpret all such objects at their cosmological distance.

Coherent Emission

The possibility that a coherent emission mechanism could circumvent modeling difficulties has been pointed out repeatedly by the San Diego group, but usually with the disclaimer that a coherent mechanism implies emission at one frequency only. That this need not be the case is extensively considered in theory and experiments in laser fusion (Ott, Manheimer and Klein 1974; Albritton 1974; Lin and Dawson 1975) where coherent absorption takes place in regions where the laser frequency and the plasma frequency are quite different. This absorption is the inverse of our proposed emission process.

THE PLASMON-PHOTON SCATTERING MODEL

In a series of previous papers (Colgate 1967; Colgate, Lee, and Rosenbluth 1970; Jones and Kellogg 1972; Colgate, Colvin, and Petschek 1975) culminating in Petschek, Colgate, and Colvin (1976, hereafter PCC) a quasar model involving a coherent photon source is developed. A summary is given in Colgate and Petschek (1976).

In this model a quasar is assumed to have a mass $10^8\ M_\odot$, to emit radiation at $\cong 10^{47}$ ergs/sec necessarily about 10 times greater than its Eddington limit, and to eject gas at a rate of 10 to 100 $M_\odot$ per year. Burbidge and Perry (1976) independently come to the same conclusion from line emission arguments. If the optical surface is to satisfy $R_s \leq \Delta t\ c \cong 10^{17}$ cm then the outflow velocity must be $\geq 5 \times 10^9$ cm sec^{-1} and if radiation is to accelerate this matter by Compton scattering, then the luminosity becomes $10^{47}\ R_{17}$ erg s^{-1} where R_{17} is the nebula radius in units of 10^{17} cm. We call the most likely radius R_o. The kinetic energy of the outflow is just the Eddington limit $\dot{M}\ v^2/2 = 8 \times 10^{46}$ ergs s^{-1}. The condition that the radiation flux (greater than the Eddington limit) escape in steady state with the mass flux is that $v = c/(3\tau_c)$ where τ_c is the thickness of the nebula in Compton scattering mean free paths, or $\tau_c \cong 2$, $n_e \cong 3 \times 10^7$ cm^{-3} for $R_{17} \cong 1$. This is the hemostate that controls the electron density. If τ_c increases above $\cong 2$, the radiation is trapped and all the energy goes into PdV work to remove matter from the gravitational potential. If $\tau_c < 2$, the radiation escapes without removing matter and matter accumulates.

BL Lac Objects Versus Quasars

It is further assumed that a BL Lac object is a quasar that creates very much less gas and so by the above argument ejects less matter. Therefore there is very little matter far from a BL Lac object so that it does not emit line radiation excited at large radius in the lower (cooler) radiation flux.

Plasma Conditions

Our model depends upon photon emission from a plasma that is both hot ($kT_e \cong \frac{1}{2}\ mc^2$) and highly excited in non-thermal plasma oscillations. Both conditions are created if matter is released into the nebula at kinetic energies of 1 to 10 MeV per nucleon. This kinetic energy in 10 solar masses is needed to power a typical outburst of 10^{53}ergs. One can ascribe this to a stellar explosion or tidal breakup of a star by a Kerr black hole (Tsuruta 1977; Young, Shields, and Wheeler 1977). The radius and thickness τ_c determine a density. The mass of the nebular plasma is then = 100 $M_\odot$ so that the radius at which the mass of the explosion equals the fractional mass of the nebula is about 1/2 R_o or 5 x 10^{16} cm. The equilibrium electron temperature when purely collisional heating of the electrons by ion dynamic friction balances a radiation rate Γ_B times bremsstrahlung is $kT_e/mc^2 \cong 0.6\ (E_i/\Gamma_B)^{1/3}$ where E_i is the ion energy in MeV/nucleon. Therefore if the total emission rate is 10 times the bremsstrahlung rate the electron temperature is about 0.5 mc^2 in the region of interaction whose radius is $R_o/2$. The range of a 10 MeV/nucleon ion is also approximately $R_o/2$ at this electron temperature so that the dynamic friction interaction length is the same as the equal mass radius. We then have a self-consistent description of local high temperature low density ($n_e \cong 3 \times 10^7\ cm^{-3}$) regions heated by counter streaming ions.

Plasmon Temperature and Scattering

In PCC we showed how a very weak excitation of electron plasma waves ($E^2/8\pi \cong 10^{-3}$ of the thermal energy) led to an effective temperature of plasma oscillations $kT_{eff} \cong 10^{12}\ mc^2$ (6×10^{21}K). The non-linear breakup of strong ion waves created by counter streaming should lead to this level of Langmuir turbulence. The departure from thermal conditions is large despite the small absolute value of plasmon energy because the number of electrons per cubic Debye length is so large (about 10^{13}). Direct interaction between photons of frequency ν and plasmons of frequency ν_p is enhanced proportionally to kT_{eff}. This means the photons will be strongly confined by scattering. In addition, the photons will be heated by the plasmons if their mean energy is less than kT_{eff} and their intensity is not too great. If the photon intensity is very large then the plasmons will be heated to a higher kT_{eff}. This occurs in laser fusion experiments and is sometimes called stimulated Compton scattering. The photon scattering is stimulated by the collective plasma mode in that case. We reserve the term "stimulated scattering" for the process of photon scattering from individual electrons stimulated by other photons which in our case is dominantly important (Sunyaev 1971; Chapline 1975).

THE PHOTON SPECTRUM

A photon number density spectrum can be derived as follows: Initially an excess of photons is emitted at $2\nu_p \cong 10^8$ Hz reaching a limiting density determined by the Planck value at kT_{eff}. These photons diffuse in frequency by emitting or absorbing plasmons. This looks like a scattering process with a cross section per electron

$$\sigma_{PLS} = \sigma_{Compton}(\nu_p/\nu)^2(kT_{eff}/mc^2)$$

and leads to a diffusion along the energy axis with a coefficient given by the product of the square of the step size ν_p and the collision rate $n_e\,\sigma_{PLS}\,c$. With n_ν the photon density per frequency interval so that $n_\nu\,\nu^{-2}$ is proportional to the occupation per state and including a factor ν^2 for the area of the sphere in momentum space the flux becomes

$$\phi_{PLS} \propto -\,\nu_p^2\,n_e\,\sigma_{PLS}\,c\nu^2\,\frac{d}{d\nu}\,\frac{n_\nu}{\nu^2}$$

and drives photons to higher energies unless the occupation per state increases with ν. This plasmon scattering flux competes with a cooling rate for stimulated Compton scattering given by Kompaneets (1957). The exact formulation is given in PCC but an approximation valid when the photon density is superluminous, i.e., $n_\nu >> n_{Planck}\,(kT_e)$ is that $\phi_{stim} \propto (n_e\sigma_c c)n_\nu^2$. Since $\sigma_{PLS} \propto \nu^{-2}$, the steady state spectrum is $n_\nu \propto \nu^{-3}$ as given in PCC. This spectrum applies from $2\nu_p$ where $n_{2\nu_p} = \frac{8\pi}{hc^3}\,kT_{eff}\,2\nu_p$ to where $n_{\nu_{crit}} = \frac{8\pi}{hc^3}\,kT_e\,\nu_{crit}$. Here ν_{crit} is that frequency at which the steep spectrum crosses the Planck spectrum corresponding to a temperature T_e. Of course for photon number densities below the Planck values the effect of stimulated Compton scattering is comparable to normal Compton scattering. Since $n_{\nu_{crit}}/n_{2\nu_p} = (2\nu_p/\nu_{crit})^3$, and $n_{Planck} \propto \nu$ then

$$\nu_{crit} \cong 2\nu_p(kT_{eff}/kT_e)^{1/4}, \text{ or } 2 \times 10^{11} \text{ Hz}.$$

Above ν_{crit} the photon density is not superluminous and normal Compton scattering takes over. Since $kT_e \cong 0.5\ mc^2$, this raises the photon energy by a factor $(1 + 4\ kT_e/mc^2)$ per collision on the average. We can calculate a flux of photons at ν_{crit} and hence a "Comptonized" spectrum. The flux is just the number density of a Planck spectrum at ν_{crit} times the scattering rate, $n_e \sigma_c c$ times the step size 4 kT_e x ν_{crit}/mc^2. The upward bias is so strong that almost every scattering contributes to the upward flux.

This part of the spectrum has been calculated more accurately than PCC by Katz (1976), but Katz assumed a photon source ($\phi_{h\nu}$, ν_{crit}), electron temperature, and thickness all ab initio. When $\tau_c(kT_e/mc^2) \cong 1$, $n_\nu \propto \nu^{-1}$ for several (2 to 3) orders of magnitude as observed for the millimeter to infrared spectrum. In our model the process is energy limited in the sense that the thermal electrons are cooled by giving up energy to the photon spectrum. This occurs in the infrared in PCC in agreement with observation.

X-RAYS

The bremsstrahlung is similarly heated by Compton scattering, but since the scattering cross section falls when $h\nu > 100$ keV because of relativistic effects, it escapes the nebula more easily and so is subject to less Compton heating. Bremsstrahlung, the source of the X-ray photons, is entirely different from the soft plasmon photon source. The ratio of these two sources can be calculated directly. It depends upon the ratio of photon flux crossing ν_{crit} to photons created by bremsstrahlung. Both fluxes are Compton heated until they escape. The X-rays escape at roughly 100 keV and the plasmon photons escape at roughly 1 eV. Since the ratio of photon numbers is about 10^5, the total luminosity in X-rays should be roughly the same as in the infrared and optical. Our model so far gives qualitative agreement in absolute flux and spectrum from the far infrared through the hard X-rays.

THE RADIO SPECTRUM

In PCC we left open the question of the escape of photons in the radio part of the spectrum. Our problem is to demonstrate that some fraction of the effective high radio frequency photon density escapes from the nebula. The dilemma is that the high effective photon temperature is maintained by plasmon scattering. But the same plasmon scattering retains the photons within the nebula. We can illustrate this by the results of Sunyaev's (1971) analysis of induced Compton scattering modification of the low frequency spectrum of radio sources.

The photon spectrum below ν_{crit} is determined by an equilibrium between stimulated Compton scattering (SCS) and plasmon scattering (PLS). SCS removes energy from a photon at a rate dependent only upon the photon density. PLS on the other hand, causes a random walk along the energy axis. The equality of these two fluxes results in the spectrum $n_\nu \propto \nu^{-3}$. The radial escape probability of a photon is complicated by both processes. SCS reduces the energy of the photons but, if the angular distribution of photons is slowly dependent on energy it affects the free streaming only slightly. This is because stimulated scattering enhances scattering back into the more intense beam. PLS, on the other hand, both heats the photons and scatters them in direction. Hence if one wants the photons to escape easily, PLS must be extinguished, but then the heating will also be extinguished. The result will be a competition between escape and stimulated Compton cooling. Sunyaev (1971) has calculated this problem when the source of the photons (presumably but not necessarily synchrotron emission) is in steady state with stimulated Compton cooling. The result is that there is a sharp transition in frequency above which SCS is not important and below which SCS is always dominant. This results in an evergy density per frequency interval (i.e., n_ν) that rises to a transition frequency and falls according to the source function above the transition frequency.

In our case we can ask the following questions:

1. What spectrum escapes on the average in steady state between SCS and PLS with a sharp boundary?
2. What spectrum escapes on the average if we suddenly extinguish the plasmon source? This might occur in a sudden transition to stability of the counter streaming plasmas thereby allowing nearly free streaming photon escape.
3. What spectrum escapes from a boundary that is graded in density?

Sharp Boundary

Since photons are very rapidly produced (PCC), if we had a sharp boundary and if the plasmon excitation extended to the boundary uniformly distributed, we would expect to see the *in situ* photon distribution emerge. This would correspond to a brightness temperature of 10^{12} mc^2 at 100 MHz going down as ν^{-4} to 0.5 mc2 at ν_{crit}. The photon mean free path (mfp) would be that corresponding to the effective photon transport cross section. The PLS changes the photon frequency to $\pm\nu_p$ and the angle by ν_p/ν, so that to change the frequency of a photon from ν by $\pm\nu$, or its angle by one radian requires $(\nu/\nu_p)^2$ scatterings and thus $\sigma_{eff\ PLS} = \sigma_c(kT_{eff}/mc^2)(\nu_p/\nu)^4$. This has the proper limit such that at ν_{crit} we have just Compton scattering. This mfp at $2\nu_p$ is hence 10^{-11} R_o. Unless the transition at the boundary is narrower than 1 mfp, the sharp boundary model is inapplicable so we discard it.

Sudden Plasmon Extinction

Next we consider the case of a sudden extinction of the plasma oscillations. The full analysis will be published elsewhere, but we note that in this case SCS is so dominant at lower frequencies where kT_b is largest that the spectrum (at low frequencies) must be in quasi steady state (i.e., the divergence of the flux = 0) during cooling and escape. This means that $\partial n_\nu^2/\partial\nu = 0$, and so n_ν = constant.

Since SCS is proportional to n_ν^2 to ν^{-6}, there is a transition from the constant spectrum to the original ν^{-3} spectrum at a time-dependent frequency. The emission will be a superposition of spectra constant at low frequency and ν^{-3} at higher frequency with smaller values of the constant and higher transition frequencies as time progresses from the plasmon turnoff. The emission is superluminous only briefly and does not explain the observations at all.

Graded Boundary

A graded boundary case is that which is most likely to occur, but there the analysis has not been completed. If the plasma density, n_e, falls as $(R/R_o)^{-m}$, then m = 2 for constant streaming. One might expect m equal to 2 or 3 for the quasar case so that sufficient cold plasma mass would be present for line emission. Also we might expect $m \gtrsim 4$ for the BL Lac case. Then we can calculate n_ν and the mean free path, λ, as a function of n_e and hence R. If we assume the same fractional energy content in plasma oscillations as before, $\varepsilon = 10^{-3}$, then $kT_{eff} \propto n_e^{-1/2}$ and $n_\nu \propto kT_{eff}\ (\nu_p/\nu)^3 \propto n_e$ since $\nu_p \propto n_e^{1/2}$. Then the brightness temperature at a given frequency decreases as n_e at the depth at which photons of that frequency originate. On the other hand $\lambda \propto 1/(n_e\sigma_{PLS}) = n_e^{-1}(kT_{eff})^{-1}(\nu/\nu_p)^4 \propto n_e^{-5/2}$. For escape of our radio photons we want $\lambda \geq R/m$. We start with the condition $\lambda/R_o = 10^{-11}$, so that n_e must decrease by $(4 \times 10^{-11})^{2/5} = 10^{-4} = n_e/n_o$. The radius on the other hand will be larger by a factor $R_{escape} = R_o(n_e/n_o)^{-1/m} \cong 10 \times R_o$ if $m = 4$. The brightness temperature at the original plasma frequency,100 MHz, will be decreased $\propto n_e$, or $kT_b = kT_{eff}\ (n_e/n_o) = 10^8 \times mc^2$. This is roughly 100 times greater than observations. We therefore expect that some combination of plasma oscillation extinction that gives too low a value for kT_b and the graded density boundary with constant plasmon excitation that gives too high (x 100) a value of kT_b should explain the observations. The emitting surface radius is also too large for the high brightness case and both plasma oscillation extinction as well as an increased steepness of the nebula density gradient, i.e., a larger m, will bring the fluctuation times of radio, infrared, optical and X-ray closer. It is encouraging that the quasar radio fluctuation times are larger than those of the BL Lac objects as would be expected for greater gas emission as needed for the line spectra.

Radio Spectrum

We can calculate the spectrum expected for the graded boundary case. We have already noted that the effective plasmon temperature and photon number satisfy

$$kT_{eff} \propto \varepsilon\, n_e^{-1/2}(kT_e)^{5/2}, \tag{1}$$

and

$$n_\nu \propto T_{eff}\ (\nu_p/\nu)^3 \propto n_e\ \nu^{-3}. \tag{2}$$

However, the mean free path due to plasmon scattering, λ_{PLS}, is

$$\lambda_{PLS} = \frac{1}{n_e\sigma_{PLS}} \propto n_e^{-1}\ T_{eff}^{-1}\,(\nu/\nu_p)^4. \tag{3}$$

We see in a depth λ_{PLS} so that photon escape requires $\lambda \cong R/m$ for the density distribution

$$n_e = n_o(R_o/R)^m. \tag{4}$$

Then from 3 and 4

$$n_e = (m/R\varepsilon)^{2/5} \frac{\nu^{8/5}}{kT_e} .$$

Therefore from Eq. 2

$$n_\nu \propto \varepsilon^{3/5}(kT_e)^{3/2}(m/R)^{2/5} \nu^{-7/5} . \tag{5}$$

The flux of photons ϕ_ν leaving the nebula will be proportional to $n_\nu \times R^2$. We have already pointed out that if ε remained constant and m was of order 4, then the brightness temperature would be 100 times too large at 100 MHz and the radius would be $R \cong 10 R_o$. By reducing ε and kT_ε as the radius increases we can make R closer to R_o, and then $\phi_\nu \propto \nu^{-7/5}$ so we have a reasonable explanation of the observed, flat spectrum ($1 \leq$ spectral index ≤ 1.5).

Faraday Rotation

Wardle (1977) has shown that the mean Faraday rotation of the polarization vector as a function of frequency from BL Lac objects is amazingly small. A similar observation by Ledden (1978) shows one outstanding example in the 1975 outburst of AO 0235+164 where the plane of polarization at 3.75 and 8.1 cm tracked together within 5 degrees during a rotation of 130 degrees in 54 days. There is therefore no evidence of any finite Faraday rotation with an upper limit of ~ 3 radians per meter^2. We use the scaling

$$RM = 8.2 \times 10^5 \; n_e \, B\ell \text{ radians m}^{-2} \tag{6}$$

where n_e is the electron density in cm^{-3}, B is the magnetic field in Gauss and ℓ is the path length in pc. For typical BL Lac parameters: $B = 3 \times 10^{-2}$ and $\ell = 3 \times 10^{-2}$, this requires a cold electron density $n_e \leq 3 \times 10^{-3}$ cm^{-3}. This is to be compared to a relativistic electron density ($\Gamma = 10^3$) of $n_r = 2 \times 10^{-1}$ cm^{-3} for equal energies in field and particles. Thus the cold electron density must be $\cong 10^{-2}$ of the relativistic electron density which is a difficult constraint. On the other hand in the plasmon model the radio photons are emitted from a surface whose electron density will be of order 10^3 to 10^4 cm^{-3}. Then the magnetic field must be assumed small $B \leq 10^{-7}$ Gauss. This would seem to be reasonable if the object was made up of $N_s = 10^8$ stars with the typical magnetic flux of a neutron star, 10^{12} Gauss at a radius r of 10^6 cm. We then consider the average dipole field due to stars of radius r_θ at the average spacing s namely $\langle B \rangle = 10^{12}(r/s)^3\ (r_o/r)$ where $s = (4\pi R_o^3/3N_s)^{1/3}$ or 3.4×10^{14} cm. This yields $\langle B \rangle = 1.5 \times 10^{-9}$ Gauss.

CONCLUSION

We have reviewed the plasmon photon scattering model for the soft photon emission spectrum of quasars and BL Lac objects and shown how the spectrum above $\nu_{crit} = 2 \times 10^{11}$ Hz is produced by normal Compton scattering from a hot plasma $kT_e = 0.5\ mc^2$. The frequency of ν_{crit} is the frequency at which the photon spectral density produced by the competition between plasmon scattering and stimulated Compton scattering ($n_\nu \propto \nu^{-3}$) becomes equal to the Planck spectrum density at kT_e. The starting point of the steep _in situ_ spectrum is at a frequency twice the plasma frequency at a value corresponding again to the Planck density but this time at the plasmon temperature, $kT_{eff} \simeq 10^{12}\ mc^2$. This high temperature is presumably produced by weak $[(E^2/8\pi)/(n_e\ kT_e) = 10^{-3}]$ plasma turbulence. This high temperature ($kT_b = kT_{eff} = 10^{12}\ mc^2$ at 100 MHz) would be seen at a surface if the surface plasma gradient were infinitely steep. Since it is not, we consider two alternate ways of producing the escaping radio spectrum. First we assume that the plasmon source is suddenly extinguished; this produces a photon density or number flux that is roughly independent of frequency, but rapidly decaying in time. This cannot explain BL Lac objects. Next we consider a graded density $n_e \propto R^{-m}$ and no plasma oscillation extinction. Then $kT_b(100\ \text{MHz}) = 3 \times 10^7\ mc^2$, i.e., 100 times greater than observation, and for m = 4, the radio surface is roughly 10 times larger than that of the bulk of the plasma. It is evident that some reasonable combination of plasma oscillation extinction and graded surface density will lead to the observed $kT_b \simeq 3 \times 10^5\ mc^2$ at 100 MHz. We then predict a flux with spectrum $n_n \propto \nu^{-7/5}$.

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DISCUSSION

J. PERRY:
The observations of J. Miller seem to indicate that BL Lac objects are in elliptical galaxies, while there is no proof that the QSOs have an underlying (stellar) galactic component. Your model uses plasma oscillations in gas generated by stellar debris; if you can thus explain the BL Lac spectrum how do you account for the lack of a line spectrum in BL Lac's, and its presence in QSOs?

S. COLGATE:
In order to regulate the residual bound gas, I believe that for both QSOs and BL Lac's the luminosity, $L \geq 10$ times the Eddington limit so that both eject gas regulating the residual gas to $\tau_c \cong 2$. The BL Lac objects then become a case of less gas generation - perhaps $\leq 1\ M_\odot$ per year compared to 10 to 100 $M_\odot$'s per year for the QSOs. The large mass ejection then cools at larger radius - making clouds and hence line emission.

A. WOLFE:
What is the kinetic temperature of the gas?

S. COLGATE:
It is about 0.5 mc^2 which is determined by ion counter stream heating balanced by radiative cooling.

A. WOLFE:
But then you won't see emission lines.

S. COLGATE:
No, that's right in the core. In neither BL Lac objects nor QSOs should emission lines come from the core. But as soon as you go out by a factor of 100, then your effective radiation temperature drops by a large amount. Therefore the QSO emission lines must come from dense clouds at large radii, say $R \simeq$ several pc. That is why the variability of emission lines becomes one of the crucial measurements for this theory.

G. BURBIDGE:
What do you predict about the X-ray spectrum? Where will it cut off?

S. COLGATE:
The X-ray spectrum is just Comptonized bremsstrahlung from a plasma where the temperature is $\simeq 0.5\ mc^2$ and thickness $\tau_c \simeq 2$. This leads to a very flat spectrum, $\alpha \simeq -1$, and a cut-off around 50 to 100 keV due to the Klein-Nishina relativistic cross-section decrease. The total energy out to that point is about equal to the optical and infrared luminosity. The 50-100 keV region is a very crucial test in self-Comptonized models. Right now its ratio to the 10 keV region is quite correct in my model. You have very little lee-way in changing this ratio because the flux of photons in the optical and infrared is determined by the number density of the Planck value at $\nu_{critical}$ at 10^{11} Hz which in turn depends on only the 0.25 power of various variables. So you are very tightly constrained as to the ratio of the X-ray flux to the total flux in the optical and infrared.

G. BURBIDGE:
Absence of X-rays in these sources at the luminosity level of the optical radiation would be a difficulty again for your model, isn't that so?

S. COLGATE:
It is the absence of X-rays below that number predicted by this thing that is crucial. It is the ratio of photon fluxes.

G. BURBIDGE:
And they are comparable according to your model?

S. COLGATE:
No, the number flux is about a factor of 10^5 larger in the optical and infrared than in the X-ray. But the energy of each X-ray is about 10^5 larger, namely it is 10 keV, so that gives you about the same amount of energy flux in both wavelength regions.

T. CHUBB:
How does your theory produce 30% polarization of optical fluxes?

S. COLGATE:
We're only just beginning to start working on the polarization problem. Certainly the work of Jones and Kellogg (1972, Ap.J., **172**, 283) predicts that photons interacting with an oriented K vector plasma oscillation scatter off the plasma oscillation and become polarized. This is confirmed by laboratory measurements. The logical way to orient the K vectors is through an explosion.

J. FELTEN:

I thought I understood you to say that the stimulated scattering doesn't affect the photons; they just go right out.

S. COLGATE:

It doesn't affect the direction. If you know or if anybody here knows whether stimulated scattering changes the polarization properties, please tell me. As far as I know this problem has never been solved.

J. FELTEN:

Your statement is another way of saying that the number of stimulated scattering from photon state A to state B is equal to the number of scatterings from state B to state A. But I am wondering whether you've taken into account the electron recoil which changes the photon energy?

S. COLGATE:

Yes, the electrons are heated. This heating adds to the electron temperature. Therefore the plasmon-photon scattering enhances the dynamic friction between the counter streaming ions and the electron gas.

B. DENNISON:

Does your model require brightness temperatures at least as great as those implied by the observed variability? Shouldn't these high brightnesses produce interstellar scintillation?

S. COLGATE:

The highest brightness temperature is of the order 10^7 mc^2 or 10^{17}K. Such a source should scintillate. The lack of observed scintillation is the strongest confrontation to the theory; on the other hand, the effect of an intervening galaxy as in BL Lac makes this lack of scintillation problematic.

T. JONES:

In order to preserve the polarization produced in your model by scattering you need, don't you, a region almost completely devoid of magnetic field, because (a) you require high electron densities; and (b) you want to avoid forming a shock. Also, to get the larger degree of polarization sometimes seen at visual wavelengths ($\sim$30%) you presumably need your plasma K-vectors to be highly anisotropic. But then won't this reduce the efficiency of the initial scattering process and possibly alter the resulting spectrum?

S. COLGATE:

Yes, there should be no magnetic field, $B \lesssim 10^{-7}$ Gauss, to avoid Faraday rotation as discussed by Wardle and Ledden. We do not yet understand polarization; for example whether stimulated Compton scattering polarizes or depolarizes a given photon flux. I understand that besides Jeff Colvin and Albert Petschek, David Wilson of Cambridge is working on this problem. The K-vectors should be reasonably well oriented at the outside "surface" and so should only affect the "last" scattering of a photon thereby allowing polarization without compromising efficiency.

A THEORETICAL INTERPRETATION OF THE RADIO OUTBURSTS OF BL LAC OBJECTS AND OTHER RAPIDLY VARIABLE SOURCES

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I. INTRODUCTION

Among the most distressing observations which astrono-
ers have made in recent years are those of the extremely apid flux variations and apparent faster-than-light struc-ural changes in an increasing number of compact extraga-actic radio sources. If we assume that a given incoherent ynchrotron source cannot vary significantly over a time eriod shorter than the light travel time across the nitting region, then the brightness temperatures thus nplied often greatly exceed the theoretical limit of 10^{12} . Furthermore, our profound faith in special relativity oes not allow us to believe in physical speeds exceeding . We are therefore led to the brink of abandonment of the otion that the redshifts of such sources are caused by the xpansion of the universe. Yet we have recently been ombarded with seemingly strong evidence that at least some f these troublesome objects are indeed cosmologically istant (Miller, French, and Hawley 1978).

In the midst of these two profound problems, a major ifficulty with the commonly adopted description of the etailed nature of the flux variations of compact sources as also arisen. The early observations seemed to confirm ne validity of the expanding cloud model of Kellermann nd Pauliny-Toth (1968) and van der Laan (1966), in which ne flux peaks at a given frequency as the source under-oes an optically thick-to-thin transition. However, later onitoring studies of a large number of objects (Medd *et l.* 1972; Altschuler and Wardle 1976) reveal that only a nall percentage of the extragalactic variable sources ctually follow the predictions of this model (Altschuler nd Wardle 1977). Instead, the variations often seem to ave little to do with an opaque source becoming ransparent.

In no source are these troubles more evident than in ne BL Lac object AO 0235+164. In late 1975, the flux ensity at centrimetric wavelengths rose by a factor of bout ten in only a few months and then declined almost as apidly. The implied brightness temperature at 8 GHz was pproximately 10^{15} K (Ledden, Aller, and Dent 1976). urthermore, scintillation studies of later outbursts ndicate that this source expands superluminally (Scheuer 976; but see Condon and Dennison 1978). In addition, the bservational data of Ledden *et al.* clearly show that the lux variations were not due to optically thick-to-thin transitions. We now explore the above problems in detail and attempt to show how the difficulties can be explained through a rather simple relativistic blast wave model.

II. RELATIVISTIC KINEMATICS AND SUPERLUMINAL EFFECTS

We can come to grips with the brightness temperature problem stated above if we realize that, in every case in which the angular size of the source is directly measured, the brightness temperature is of the order of (or less than) the 10^{12} K limit. The difficulty only occurs when the size of the source is inferred from the time scale of the flux variations. The resolution of the apparent dilemma is then obvious: the source size is larger than c times the time scale of the variations. This necessarily implies that the observed source diameter should increase superluminally. Of course, faster-than-light separations of the components of several compact sources have been observed for some time using VLBI techniques. However, it was not until the recent scintillation experiments of Condon and Dennison (1978) that the superluminal expansions of the individual components of some sources were confirmed. We are now left to conclude that the excessive implied brightness temperatures and the observed superluminal structural changes can simply be considered to be different aspects of the same problem.

With this simplification in mind, we can now turn to the search for a model which can explain the creation of a variable radio source whose dimensions appear to increase faster than light. The most straightforward models (first studied by Rees 1967) are those which involve highly relativistic bulk motions of the emitting regions. The success of these theories directly depends on the manifestations of relativistic time dilation: those parts of a relativistically expanding source which have velocity vectors pointing almost directly at the observer appear to evolve much more rapidly than in their own rest frames. Furthermore, the well-known relativistic beaming effect, wherein the radiation emitted from a source moving at a speed near c is strongly focussed in the forward direction, provides an extremely strong selection effect against seeing those regions whose velocity vectors do not point almost directly at the observer. For a relativistically expanding sphere, we therefore selectively view those parts of the source which appear to evolve much more rapidly than in their rest frames. Jones and Tobin (1977) have recently shown that, because of light travel time effects, this statement can only be applied to a sphere whose emission mainly originates in the outer edges. Such a shell structure is expected from a blast wave, and it is for this reason that relativistic shock models have become so popular as of late (e.g., Blandford and McKee 1976, 1977; Marscher 1978a,b; Christiansen and Scott 1977; Christiansen, Scott, and Vestrand 1978).

Quantitatively, the time dilation allows phenomena which occur over a time period $\Delta\tau$ in the proper frame of an object with Lorentz factor Γ to last for a much shorter period

$$\Delta t \sim \Gamma^{-1}\Delta\tau \qquad (1)$$

in the observer's frame. If the expansion velocity of the source is nearly c in the proper frame, then the observer measures a speed

$$v_{exp} \simeq c\ \Delta\tau/\Delta t \sim \Gamma c \qquad (2)$$

and a size

$$r \simeq \Gamma c\Delta t\ . \qquad (3)$$

We therefore see that relativistic kinematics can, in a rather straightforward fashion, explain source sizes which are larger by a factor $\sim \Gamma$ than those obtained through naive light travel time arguments.

III. A RELATIVISTIC BLAST WAVE MODEL FOR THE FLUX VARIATIONS OF COMPACT SOURCES

Now that we have obtained a more than adequate resolution of the major controversies surrounding rapidly variable extragalactic radio sources, we can get down to the business of explaining their detailed observed behavior. We wish to apply the theory to the late 1975 outburst observed in the BL Lac object AO 0235+164 for two reasons. First, this event was so strong that there is little chance of flux contamination from previous outbursts. Second, the nature of the spectral variations are typical of those observed in other sources (Altschuler and Wardle 1977). The turnover frequency ν_m changed very slowly with time while the flux density rapidly rose and then fell at all frequencies simultaneously, as is shown in Figure 1 (data taken from Ledden et al. 1976). As is stated above, this behavior is not at all consistent with the notion of an expanding cloud of plasma which undergoes optically thick-to-thin transitions. Instead, we must develop a model that utilizes other means through which the source is allowed to vary. In light of the discussion in the previous section, we wish to incorporate the existence of an ultrarelativistic blast wave into our model.

We assume that at observer's time t=0 an explosion occurs which releases a large amount of energy in some form which, for our purposes, need not be specified (e.g., a highly relativistic plasma or a burst of low frequency electromagnetic waves). This "signal" is assumed to travel outward unimpeded until, at some large radius R_{scr}, it interacts with a shell or ring of gas (a "screen"). If the energy of the signal is high enough and the density of the screen low enough, the resultant blast wave propagates outward at highly relativistic speeds. This scenario is depicted in Figure 2, where three distinct stages of evolution are shown. Particle acceleration and magnetic field amplification occur at the shock front (Blandford and McKee 1976, 1977) and the consequent synchrotron emission is observed at radio and possibly even optical frequencies.

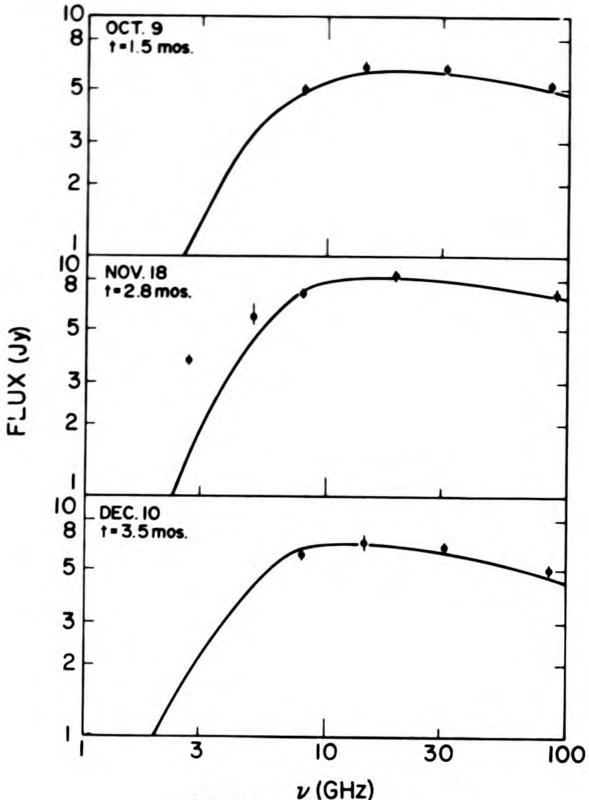

figure 1

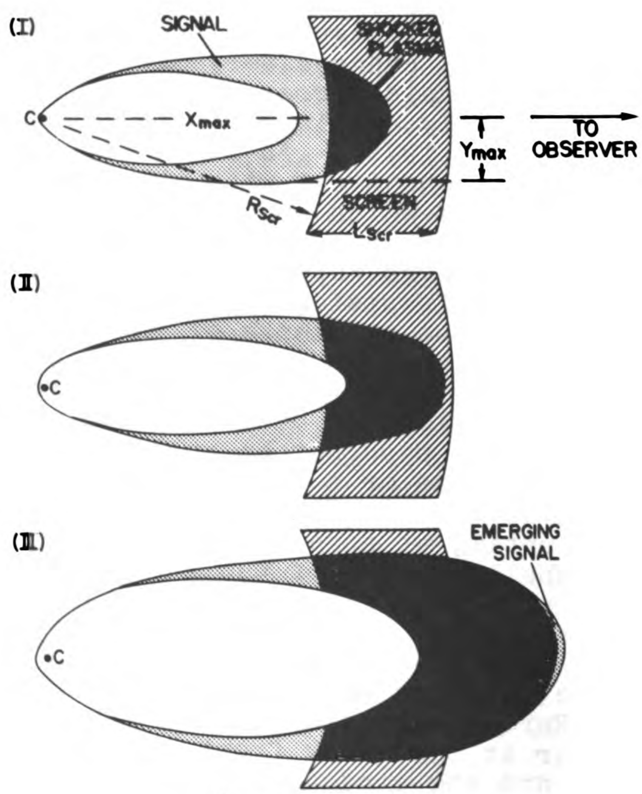

figure 2

The rise time of such a radio burst is given by Marscher (1978b) as

$$\tau_{rise} \sim 5\ (R_{scr}/1\ pc)(1+z)\ \Gamma^{-2}\ \ yrs, \qquad (4)$$

where z is the source redshift. The Lorentz factor of the expanding blast wave can be obtained from equation (3) and the requirement that the observed brightness temperature not exceed $\sim 10^{12}[\Gamma/(1+z)]^{1.2}$ K. For AO 0235+164 we find that $\Gamma\sim25$ and $R_{scr}\sim30$ pc (see Marscher 1978b). The turnover frequency remains virtually unchanged during the increase in flux. Also, this signal-screen model allows the source to be always optically thin at high frequencies, as is generally observed (Altschuler and Wardle 1977).

If the screen is thick enough, viz.

$$L_{scr} \gtrsim \Gamma^2 c\tau_{rise}(1+z)^{-1} \equiv L_{crit}, \qquad (5)$$

then the subsequent evolution of the spectrum is dominated by optically thick-to-thin transitions and the turnover moves to lower frequencies as the burst ages. While this behavior is in fact seen in some sources, we have already mentioned that the turnover frequency in a rapidly variable source typically changes quite slowly throughout the duration of any given outburst. However, if the screen is thin, $L_{scr} \lesssim L_{crit}$, then the blast wave breaks out of the screen before this stage has had a chance to develop. The expansion and radiative cooling of the shocked plasma causes the flux to decline, with the turnover moving rather slowly to lower frequencies. The results of the application of such a model to the late 1975 event in AO 0235+164 are shown as solid curves in Figures 1 and 3 (data again taken from Ledden et al. 1976). For this case the parameters used are $R_{scr} = 4L_{scr} = 35$ pc, total energy $E_{sig} \simeq 3\times10^{57}$ ergs, and density and magnetic field of the unshocked screen

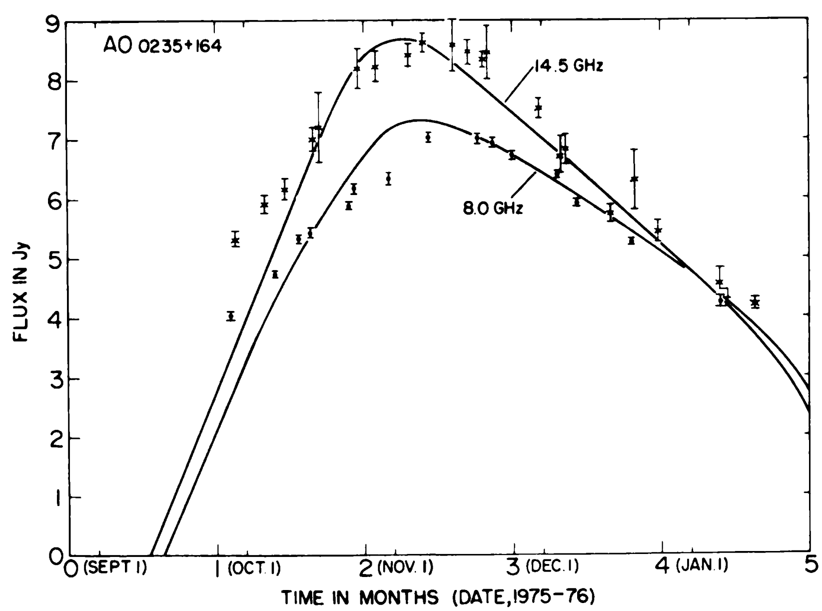

figure 3

$n = 10^{-3}$ cm^{-3} and $B = 10^{-4}$ gauss. We see that the model reproduces quite well the observed spectra except for one detail: the theoretical spectra are too steep below the turnover. However, this is more an artifact of the idealization of the problem, where the screen has been assumed to possess circular symmetry, than an inherent shortcoming of the model. Any clumpiness of the gas in the screen would cause the spectrum to flatten below the turnover without significantly affecting the nature of the flux variations (see Kellermann and Pauliny-Toth 1969). It would indeed be surprising if perfect symmetry could be maintained over size scales of tens of parsecs!

The screen is certainly totally disrupted by the action of the blast wave. Therefore, an essential nature of the screen must be its ability to regenerate itself in time for the occurrence of the next outburst, which can happen in less than one year. The most straightforward model which comes to mind is one which involves a relativistic outflow of gas from the central regions of the source. One such model is illustrated in Figure 4. Dense clouds are imagined to be created at some radius $R \sim 1$ pc. These are presumably the same filaments which radiate the broad emission lines observed in most objects of this type. In a separate study of the interactions between the explosive events and these clouds (Marscher 1978c) we have found that, once an unconfined filament expands, it is subject to dissipation and tremendous acceleration by one of these outbursts. As is shown in Figure 4, we thus expect a highly energetic explosion to leave in its wake a rapidly expanding shell of "evaporated" clouds. If the expansion velocity of this shell is a sizeable fraction of c, then we can expect it to reach a large radius before the next outburst overtakes it.

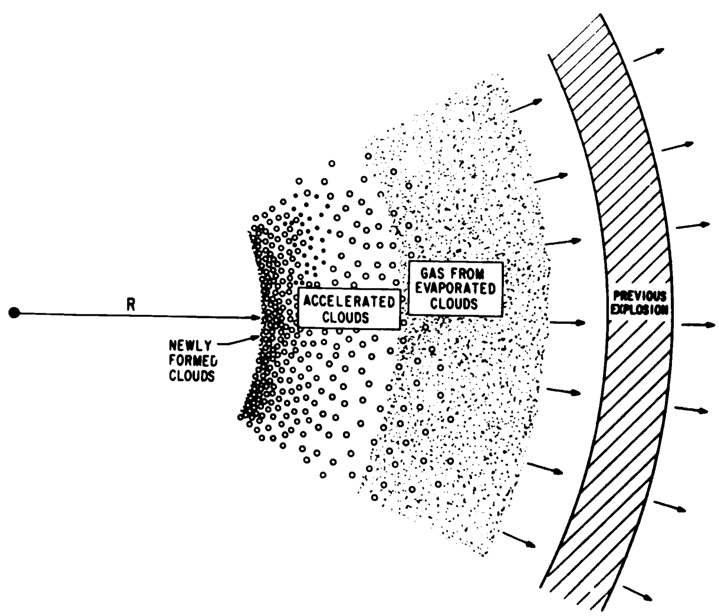

figure 4

Another observational detail which must be accounted for is the general double-lobed appearance of compact sources. As is fully discussed in our previous work (Marscher 1978a,b), such structure can be obtained from relativistic blast wave models if the screen is confined to lie in a thin disk. The two components are observed to separate with superluminal speeds, as is frequently seen.

The position angle of linear polarization expected from this model is, unfortunately, difficult to predict, especially if the screen is composed of evaporated clouds. It seems likely, however, that if the gas is flattened into a disk, the magnetic field is likely to be more closely aligned with the plane than with the axis of symmetry.

One final caveat is called for: While the model presented here is capable of explaining in detail the observed nature of variable extragalactic sources, we must consider the picture to be incomplete without a specification of the mechanism by which energies of up to 10^{58} ergs can be repeatedly released from the central regions of such sources. However, it may be possible to observationally verify the existence of such energetic outbursts through their X-ray, γ-ray, and neutrino emission. A theoretical study of this possibility is currently underway.

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DISCUSSION

G. BURBIDGE:

Are you arguing that it is only the interaction with the screen that generates the increase in the whole electromagnetic spectrum?

A. MARSCHER:

No, only the radio spectrum. The optical could have something to do with the outburst at point source C while the radio emission is produced at much larger radii. You have no trouble with simultaneity between the radio and the optical because they have the same time of flight, that is the radiation reaches the observer at the same time. This is because the pulse of energy travels at or near the speed of light, as do the optical photons. If the energy pulse is produced in the central region at the same time as the optical flare, near simultaneity at the various frequencies results.

G. BURBIDGE:

In other words you are not explaining the optical and infrared spectra.

A. MARSCHER:

I am not purporting to do that in this talk.

J. KROLIK:

If you are generating the magnetic field in the screen, is the smallest length scale of the field large enough to preserve the polarization?

A. MARSCHER:

My magnetic field is simply the ambient field in the "screen" whose tangential component is amplified by the shock. So the polarization sort of depends on the direction in which the magnetic field is pointing.

J. KROLIK:

Are you actually trying to generate the field?

A. MARSCHER:

No, I am assuming that the field is already present in the screen. The shock wave simply amplifies it.

W. DENT:

How do you explain the large rotation in the polarization position angle in AO 0235+164?

A. MARSCHER:

Unlike Dr. Blandford I wrote my talk before I came to the meeting, so I have no explanation to offer at this point. [laughter.]

J. FELTEN:

Why is your first figure an oval and not a sphere? In what frame of reference, and at what time, does this surface have this oval shape?

A. MARSCHER:

The first figure represents the surface of a relativistically expanding sphere as viewed by the observer. The oval shape is caused by the variation of time dilation with the direction of the bulk motion with respect to the observer. See the 1967 paper by Rees for more details (Rees, M.J., 1967, M.N.R.A.S., 135, 345).

A. WOLFE:

I guess one thing that worries me is all these emission line clouds. How do you explain the absence of emission lines in your model for AO 0235+164?

A. MARSCHER:

Well it's just far away for one thing. How do you explain the absence of emission lines in any BL Lac object?

A. WOLFE:

But you are invoking emission line clouds to make the screen.

A. MARSCHER:

Yes, there have to be emission line clouds in some BL Lac objects if you don't mind throwing out BL Lac itself as a BL Lac object. Joe Miller observes emission lines in various BL Lac objects.

A. WOLFE:

But this is an unusual case it seems to me. You said yourself that unusual conditions are needed to explain the outburst in this object.

A. MARSCHER:

Maybe so. There may not be enough emission line clouds for there to be a high enough emission measure to cause the emission lines.

M. BURBIDGE:

But you need them to make your screen.

D. SHAFFER:

Yes, how tenuous can your screen be?

A. MARSCHER:

I need to have some type of mass outflow.....

A. WOLFE:
You were saying something like 10 $M_\odot$.

A. MARSCHER:
I could reduce that by quite a bit because there is no need for the screen to be spherical.

A. WOLFE:
All you need is about 1 $M_\odot$ to make bright emission lines if the density is high enough and I guess that's what worries me.

A. MARSCHER:
Well in that case there might be a problem. [Added later: If the clouds are very dense, $n \sim 10^{10}$ cm^{-3} and large, $R \gtrsim 10^{14}$ cm, then they are optically thick to the Lyman continuum radiation and only a small fraction of the gas may be capable of producing emission lines.]

A. PALCHOLCZYK:
Wouldn't you have plenty of Faraday rotation because of the presence of your screen?

A. MARSCHER:
Possibly so at early epochs, but it depends on the details of the field configuration in the screen. I haven't considered the polarization properties in detail.

R. BLANDFORD:
There may be no magnetic field associated with the filaments for one thing. The other point is that the filaments might not cover the entire source.

A. MARSCHER:
But the screen that is being shocked presumably covers a lot of the source. The field and the density in the screen that lie ahead of the shock are too low to cause significant Faraday rotation.

SUPERLUMINAL EXPANSIONS: THE STRONG MAGNETIC DIPOLE MODEL

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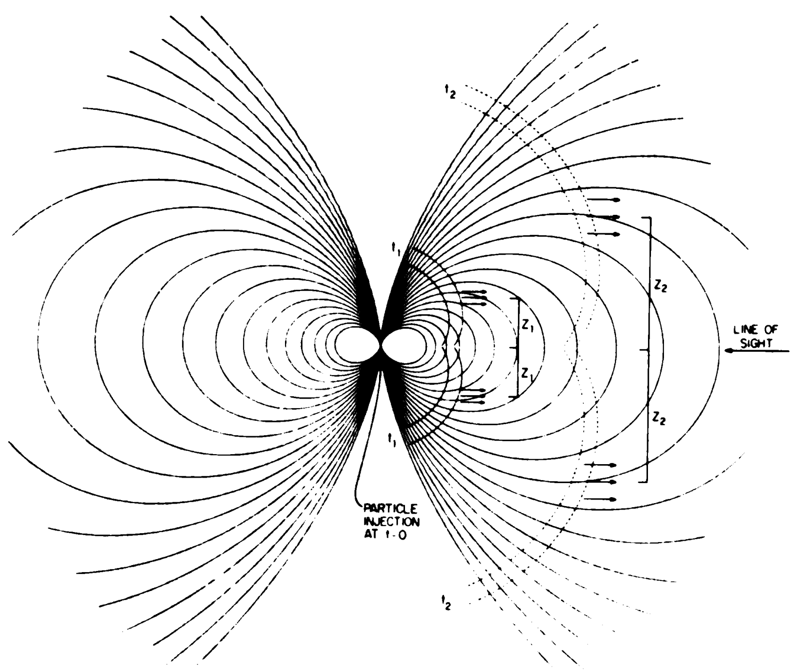
The strong magnetic dipole model (SMD) was suggested several years ago as one possible explanation for the observed superluminal separation of components in compact radio sources (Sanders 1974). The geometry of the model is illustrated in Figure 1. At some time, t_o, a burst of relativistic particles occurs at the center of the dipole.



The energy density in the magnetic field is assumed to be much higher than the energy density in relativistic particles, so the particles are confined to move out along field lines. The pitch angles of these particles will be very small primarily due to the rapid decrease of field strength in a dipolar field, given that $p_{\perp}{}^2/B$ is an adiabatic invariant of the particle motion ($p_{\perp}$ is particle momentum perpendicular to the magnetic field). Therefore, a sheet of relativistic particles moves out along the field lines at near the velocity of light, with the particles beaming their synchrotron radiation strongly in the direction of motion. The thickness of the sheet is determined by the duration of the initial burst at the dipole center.

We assume that an observer is viewing the dipole perpendicular to the dipole axis (this is a simplifying but not a necessary assumption). Due to the beaming, radiation from the sheet is seen by the observer only at those two points where particles are moving parallel to his line-of-sight. As time proceeds he will observe an apparent separation of two synchrotron spots, which, actually, at every epoch, is radiation from different particles. Therefore, the velocity of separation is a phase velocity. The apparent separation velocity, when a pure dipole field is viewed edge-on, is 4.4c for instantaneous injection at the dipole center. Milgrom and Bahcall (1977) have recently shown that 4.4c is the minimum separation velocity and that the observed separation velocity of the two components will be larger when the observer's line-of-sight does not lie in the equatorial plane of the dipole. Apart from these purely geometrical considerations, arbitrarily high separation velocities are possible if particle acceleration occurs first on the central or higher field lines and later on the lower field lines.

In their recent theoretical review, Blandford, McKee, and Rees (1977) present the following argument against the SMD model. The volume emissivity of synchrotron radiation is given by

$$P = C_o\ N\ B^2\ \psi^2\ \varepsilon^2$$

where N is the number density of relativistic particles, B is the magnetic field strength, ψ is the rms particle pitch angle, ε is the mean particle energy, and C_o is a constant (2.37×10^{-3} in cgs units). In the SMD model the magnetic field is dipolar in form which means that $B \propto z^{-3}$ and from the particle adiabatic invariant, $\psi \propto z^{-3/2}$. Since particles are confined to move along field lines, the particle density must follow the magnetic field strength, i.e. $N \propto B \propto z^{-3}$. Therefore, the dependence of the synchrotron volume emissivity on the projected distance of the synchrotron spot from the dipole center is

$$P \propto z^{-12}.$$

This certainly implies that the flux at all relevant frequencies decreases extremely rapidly with increasing separation, and that it is unreasonable to expect that the two components could be observed to separate by as much as a factor of ten, as they may do in 3C 120 (Cohen et al., 1977).

However, this argument is valid only if synchrotron self-absorption is unimportant; that is, only if the synchrotron emission regions are optically thin and we observe every radiating electron. Conversely, it must be true that the SMD model can only work if the synchrotron emission regions are optically thick during the entire period over which they are observed to separate. Whenever the spots become optically thin, they must, in effect, turn off due to the rapid decrease of volume emissivity with separation. Therefore, high optical depth in the emission regions is another basic constraint of the SMD model.

From the theory of synchrotron radiation and the constraints of the SMD model we may immediately write down three equations relating the physical parameters in a compact component at a projected distance of z_m from the dipole center. Assuming that the relativistic electrons are mono-energetic (with energy $\gamma\varepsilon_o$), the maximum frequency of radiation emitted by the spot is given by the usual expression for the synchrotron critical frequency:

$$\nu_c = C_1 \, B \, \psi \, \gamma^2 \, \varepsilon_o^{\,2} \tag{1}$$

where B is the field strength in the emission region and ψ is the rms pitch angle. (Here the notation of constants is taken from Pacholczyk, 1970; in particular $C_1 = 6.27 \times 10^{18}$). At some given projected distance from the dipole center, z_m, the optical depth of the emission region is

$$\tau_\nu = 3C_4 \, B^{3/2} \, \psi^{1/2} \, N_o \, K(u) \, \nu_c^{-5/2} \, z_m \tag{2}$$

where we have made use of straightforward source geometry to determine the depth of the emission region along the line of sight. N_o is the number density of relativistic electrons;

$$u = \frac{\nu}{\nu_c}$$

where ν is the frequency of observation; and

$$K(u) \approx 1.4 \, u^{-5/3}$$

where $u \lesssim 0.1$. We may write down one further condition which expresses the basic requirement of the SMD model: that the magnetic field energy density exceed the radiating particle energy density by some factor K_o:

$$\frac{B^2}{8\pi} = K_o \, N_o \, \gamma \, \varepsilon_o \quad . \tag{3}$$

Equations 1,2, and 3 relate physical parameters in the emission regions. The unknown quantities in this system of equations are the field strength, B, the energy of the electrons, γ, and the number density of particles, N_o. The other variables are either observed or constrained by the SMD model. The observed quantity is z_m, the projected distance of the emission region from the dipole center as observed at frequency ν. The constraints are that the pitch angle must be small, i.e. $\psi < 0.1$ radians; that the optical depth of the emission region must be large, $\tau_\nu > 1$; that synchrotron radiation must be produced at microwave frequencies, i.e. $\nu_c \approx 10^{11}$ Hz; and that the field energy density must considerably exceed the particle energy density, i.e. $K_o >> 1$. Therefore, we have a system of three equations for three unknown source parameters: B, γ, N_o.

Solving these three equations for the parameters of 3C 345, perhaps the most well-studied object, we find

$$B \approx 3G$$

$$\gamma \approx 860$$

$$N_o \approx 0.003 \text{ cm}^{-3} .$$

Here we have taken z_m to be 8 pc corresponding to the maximum observed separation of components in this source; we assume further that $\psi \approx 0.01$ and $K_o \approx 2 \times 10^4$. The quantity K_o is sufficiently large that even if the positive charges are protons with the same velocity or relativistic γ as the electrons, the field energy would exceed the particle energy by a factor of ten at the greatest observed separation of components. Thus, the constraints of the model are satisfied by a considerable margin.

In order to estimate total energies, we must assume a size for the equivalent current loop producing the dipole field. This is presumably the region where particle acceleration occurs, and it must be sufficiently small to assure that the dipole approximation is valid over the observed region of superluminal expansion (1-2 pc in the case of 3C 345). Thus we find that the total magnetic field energy and the relativistic particle energy associated with one outburst is

$$E_B \approx 10^{60} \text{ ergs}$$

$$E_p \approx 10^{56} \text{ ergs.}$$

These total energies are comparable to the usual estimates for microwave outbursts made on the basis of the expanding synchrotron cloud model (Kellermann and Pauliny-Toth, 1968), and the condition that $\tau_\nu > 1$ assures that the spots will be visible out to the maximum observed separation. It should be added that the total energy requirements over the lifetime of the source may be even less severe than for the synchrotron cloud model because it is not necessary, in the context of the SMD model, to recreate the magnetic field for every single outburst.

The detailed character of the flux variations predicted by this model depends upon two free parameters--or, at least, two parameters which are determined by the unspecified acceleration process: the electron energy distribution (actually a free function) and Δt_B, the duration of the burst of particle acceleration. For a mono-energetic distribution of electrons, it may be shown that the intensity of radiation in the separating spots is roughly constant. Therefore the variation of flux depends only upon the variation of the size of the separating spots and falls into four distinct phases:

1) The spots are emerging from the dipole center and are getting bigger. From considerations of source geometry it can be shown that the dependence of flux on time is $F_\nu \propto t^{1/2}$.

2) The spots have completely emerged from the dipole center. During this phase the spots are actually getting smaller due to the decreasing pitch angle, and it is possible to show that $F_\nu \propto t^{-1/2}$.

3) The spots have reached their maximum observed separation and are moving out of the $\tau_\nu > 1$ window. In this phase the flux falls almost linearly to zero: $F_\nu \to 0$.

4) The spots are outside of the $\tau_\nu > 1$ window and are no longer observed at frequency ν. They may still be seen to reach greater separation at lower frequencies.

The important point is that in phase 2, when the spots have emerged from the dipole center and are seen as distinct components, they may be observed to separate by as much as a factor of ten while their flux decreases by only a factor of three.

The model makes several observational predictions which should be readily testable as VLBI measurements accumulate and become increasingly sophisticated.

1) Superluminal motions in any given source should always occur along a line with the same position angle. This line, of course, corresponds to the projection of the dipole axis on the plane of the sky.

2) Whenever there is a strong anisotropy in the particle velocity distribution and the radiation field, with both the particles and the radiation moving in the same direction, the inverse Compton losses are considerably decreased (Woltjer 1966). Following Woltjer, it may be shown that the ratio of Compton to synchrotron losses is approximately

$$\frac{L_c}{L_s} = \left[\frac{T_b\ \psi}{10^{12}K}\right]^5$$

where T_b is the brightness temperature of a component, and ψ is the rms pitch angle. Since $\psi < 0.1$, the SMD model permits the brightness temperature of the components to be in excess of 10^{12}K without the necessity of invoking coherent emission processes.

3) The period of declining flux from a source component is not due to the decreasing synchrotron volume emissivity in an optically thin emission region, but rather to the decreasing surface area of an optically thick spot. Therefore, during a period of declining flux, individual components should actually become smaller.

4) Because the velocity distribution of the particles is highly anisotropic, we might expect the radiation from an individual component to be circularly polarized at some level. The actual percentage of circular polarization would depend upon the detailed distribution of particles with pitch angle but could be as high as 10%. However, because the magnetic field is oppositely directed in the two components, we would expect to observe an opposite sense of circular polarization in the radiation from the two components. Of course, we would see no circular polarization if the positive charge carriers were positrons. But if any circular polarization is observed, it should be in the opposite sense in the two components.

All of the above points will be discussed more completely in a forthcoming paper by Sanders and DaCosta (1978).

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DISCUSSION

D. SHAFFER:

In 3C 345 I don't think that we have enough information to tell what the component sizes are doing. In 3C 120, which is the best studied case, the separating components expand and fade away as they separate.

R. SANDERS:

It is possible to get around this difficulty. I should say that there are 3 or 4 phases of the separation. In the first place when the flux of the components is increasing, the components are emerging from the dipole center and actually getting bigger. But in this model if the flux is getting smaller, the components should be getting smaller and I don't see any way around that.

D. SHAFFER:
In 3C 120, towards the end of one of these expansion phases, we lost it because we actually lose the ability to detect the individual components. They get so big that they get resolved by the VLB interferometer.

R. SANDERS:
I don't mind that the components get bigger with time. This happens in the model, as the components emerge from the dipole center. But it's not clear to me if you can say that the flux in the components is decreasing with time, or that the components are getting too big to be seen with VLBI.

H. ALLER:
P. E. Hodge and I have made extensive observations of 3C 345 and other variable sources over a period of several years. In the case of 3C 345 the observed degree of circular polarization at 8 GHz is less than the order of 0.1%. This is much less than the 10% predicted by your model and would require a high order of symmetry between the two source components, so that the RH circular and LH circular polarizations cancel. This means that the dipole has to be oriented exactly perpendicular to the line of sight.

R. SANDERS:
I'll admit that this could be a serious problem for the model. One possible way around the difficulty of circular polarization is to assume that the positive charge carriers in the expanding sheet are positrons and not protons. This may not be so unreasonable- since particle acceleration takes place in a region at the dipole center which is probably quite dense - and thus susceptable to pair production.

B. DENNISON:
3C 273, which may not be applicable here, does not have circular polarization structure on a scale of milli-arc secs. This has been known for quite some time (Harwit, M.O. *et al*. 1974, Nature, **249**, 230). Barry Geldzahler may have more to say about it now.

R. SANDERS:
It would be interesting to see circular polarization measurements of the compact structure in 3C 345 where the structure is that of a simple double - with most of the flux in the two compact components. I gather that the structure of 3C 273 is more complicated. Again the absence of circular polarization may not be devastating for the model - because of the possibility of positrons as the positive charge carriers.

G. BURBIDGE:
In the calculations that we (Burbidge, Jones, O'Dell and Stein : cf. 1974, *Ap.J.*, **193**, 43) made some time ago based on observed parameters for compact sources, we always found that with one exception, NGC 1275, the particle energies are much greater than the magnetic energies. This has been invoked as one of the reasons why you might have relativistic expansion. But I don't

quite see how this squares with your assertion that it is the other way around.

R. SANDERS:
How have you derived the fact that the particle energies are much greater than the magnetic energies?

G. BURBIDGE:
From a straightforward calculation using the parameters of the model taking synchrotron self-absorption into account.

S. O'DELL:
I don't think that these constraints apply to Sanders' model.

S. COLGATE (To G. Burbidge):
If you want beaming Geoff, you've got to have it this way. If you don't want beaming, then you're correct.

G. BURBIDGE:
I am saying that these conclusions are based on the way compact sources did seem to be. I agree that the superluminal argument is based on a double structure.

R. SANDERS:
Derived source parameters depend critically upon the assumed isotropy of the electron velocity distribution. I would say that what you have derived, in the context of our model, is something more like the product of the magnetic field and the rms pitch angle ($B\Psi$). The derived magnetic field could easily be a factor of 100 larger.

K. KELLERMANN:
I also think that 3C 345 is optically thick.

R. SANDERS:
How do you know?

K. KELLERMANN:
Because of the shape of the spectrum. I want to ask W. Dent whether the primary in 3C 345 has increased in the last 3 or 4 years?

W. DENT:
That is a very complex source. The character of that source is different from one radio frequency to another. Many of the outbursts that you see at 4 cm. are completely gone at 9 mm. and especially at 3 mm.

J. COCKE:
I want to comment on the state of the theory of polarization expected for these small pitch angle sources. As far as I know, that is not worked out very well. I wouldn't worry too much about the fact that you appear to need so much symmetry between the two components to cancel possible circular polarization.

M. REES:
As long as the pitch angles are larger than $1/\gamma$ the theory is OK.

S. O'DELL:
If the transverse γ is small, then the circular polarization will also be small.

R. BLANDFORD (To J. Cocke):
Are you talking about the case where there is self absorption, because that might make it more complicated?

J. COCKE:
I don't recall right now what the details of the complexity are, but it's a very difficult problem analytically.

R. BLANDFORD:
No, if it's optically thin, it has already been worked out (see Epstein, R.I. 1973, Ap.J., 183, 593).

R. SANDERS:
This model requires optical thickness of the components.

K. KELLERMANN:
3C 345 is optically thick because of observations made from several centimeters down to 3 mm.

F. OWEN:
How do you interpret that as being optically thick?

K. KELLERMANN:
Because if it's optically thick, it's several times stronger at millimeter wavelengths than at centimeter wavelengths.

F. OWEN:
Well then it's partially optically thick.

D. SHAFFER:
I have two comments. There has been a VLB experiment by the MIT group (Menyuk et al. 1978, Ap.J. Lett., 220, L27) to detect circular polarization. It was not very sensitive but I think that the source structure of 3C 345 in two opposite circular polarizations is essentially the same down to around 5 or 10%. Secondly, if you believe our decomposition at several frequencies, we have observed the two individual components in 3C 345. I don't actually remember the results, but I think that at least one of them, which we were observing at 2 cm., was at a frequency higher than the turnover frequency. So we were in the optically thin region and it still looked like the same expanding double that one finds at 3 and 6 cm. So I think that the source is thin at frequencies where we see double structure.

R. SANDERS:

If a component of 3C 345 is really optically thin at 2 cm., then it shouldn't be visible much longer at that wavelength. This is an unavoidable consequence of the model. Also these arguments about whether the source is optically thin or thick are based on the appearance of the spectrum. They are a bit tricky, aren't they, because you assume rather standard particle energy distributions.

D. SHAFFER:

But you never get into any trouble by making those assumptions.

ON THE SPACE DENSITY OF BL LACERTAE OBJECTS

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In order to understand the relationship between BL Lac objects and quasars, it is important to establish their space density as a function of cosmic epoch. A lower limit to the local space density of BL Lac objects has been obtained by Setti and Woltjer (1977): $n_{BL} > 30$ Gpc^{-3}. (A Hubble constant Ho = 50 Km s^{-1} Mpc^{-1} is assumed). This should be compared with the local space density of quasars $n_0 \gtrsim 100$ Gpc^{-3} for $M_v < -23$ (Schmidt, 1970; Fanti et al., 1973). Also, noting that 6 out of 32 BL Lac objects listed by Stein, O'Dell and Strittmatter (1976) have redshifts $z \lesssim 0.07$, Setti and Woltjer pointed out that this is strikingly different from the situation presented by the quasars. It must indicate that the luminosity function of such objects is comparatively steep and, perhaps, their cosmological evolution comparatively weak.

In this paper I wish to present some results, obtained in collaboration with L. Woltjer, which bear on the cosmological evolution properties of the BL Lac objects.

In order to gain some insight into this problem, we have constructed a "tentative" optical number count relationship for BL Lacs, taking into account the fact that they are primarily selected by their radio emission properties.

At the faint end, our estimate is based on the Braccesi field, which contains 175 quasi-stellar objects with an ultraviolet excess U-B < -0.35 over an area of 37.2 square degrees (Braccesi, Formiggini and Gandolfi, 1970). This sample is claimed to be complete (Bracessi and Formiggini, 1969) down to a magnitude b = 19.4 which corresponds to a magnitude B = 19.3 (Setti and Woltjer, 1973). The Braccesi field has been partially surveyed with the Westerbork Synthesis Radio Telescope at 1415 MHz in an attempt to detect radio emission down to very weak flux densities (Katgert et al., 1973). By inspection of Table 5 of the paper by Katgert *et al.* (1973), we find that out of 99 objects which have been observed, only 80 have radio data good enough to insure their detection down to a flux density = 15 mJy. Of these 80 objects, 29 are quasars with measured redshifts and 1 is a star. The remaining 50 objects may all be considered potential BL Lacs and one has been detected with a radio flux close to the limit of 15 mJy. Since in the whole Braccesi sample there are 130 objects whose nature has still to be determined, we estimate the surface density of BL Lac objects with magnitudes B < 19.3 and radio flux densities >15 mJy to be $\lesssim 7 \times 10^{-2}$ (sq deg)$^{-1}$.

On the bright end, our estimate is based on all known BL Lac objects with a ratio between radio and optical powers such that they would still be detected at a flux density level >15 mJy (at 1415 MHz) down to a limiting magnitude B = 19.3 and with U-B colours satisfying the selec-

Table 1

The fractional time spent by each object at various magnitude levels. The objects are designated by their coordinates.

Magnitude B	<13	<14	<15	<16
0219+42			0.4	1.0
0521-36			0.3	0.5
0537-44		0.1	0.7	1.0
0735+17			0.2	1.0
0818-12		0.1	0.6	0.9
0851+20	0.4	0.8	0.9	1.0
1514+19				0.1
2200+42		0.4	0.8	0.8
Total	0.4	1.4	3.9	6.3

tion criteria of the Braccesi survey. The colours have been corrected for galactic absorption. To account for the optical variability of the objects, we have estimated from the published light curves the fractional time during which each object is brighter than any given magnitude. Our findings are summarized in Table 1. By applying a correction factor of 2 to account for completeness in the sky coverage for identifications, we estimate the surface density of objects brighter than B = 15 to be $\simeq 2 \times 10^{-4}$ (sq deg)$^{-1}$. This is likely to be an underestimate of the true surface density.

As a result, we find the ratio between the number of objects at the two limiting magnitudes considered above to be

$$\frac{N\ (B < 19.3)}{N\ (B < 15)} \simeq 350,$$

which corresponds to an increase of approximately a factor 4 per magnitude in the number of objects or, equivalently, to integral counts for a population of sources distributed uniformly in euclidean space (slope 1.5). Consequently, cosmological evolutionary effects, if at all present, must be weak.

By contrast, Green and Schmidt (1978) have determined a factor 8.5 per magnitude for the counts of optically selected quasars in the magnitude interval 15.7 < B < 18, indicating the presence of very strong cosmological evolution.

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DISCUSSION

P. VERON:
I don't think it's really fair to compare the volume density of the nearby BL Lac objects, that is the intrinsically faint ones, with the volume density of the QSOs which are more luminous than say $M_V = -24$. You should compare the density of BL Lac objects with the density of the Seyfert I galaxies which are QSOs with absolute magnitudes similar to the BL Lac objects.

G. SETTI:
Let me remind you that the density of 100 in 1 Gpc^3 given by Schmidt (Ap.J., 1970, 162, 371) really includes QSOs that are much fainter than an absolute magnitude $M_V = -24$, at least one magnitude below that.

P. VERON:
The BL Lac objects that you are using have absolute magnitudes $M_V =$ -19 or -20, for example Mk 421 has a very faint intrinsic luminosity.

G. SETTI:
But the bright end of a BL Lac luminosity function or even the average BL Lac absolute magnitude is about -23.

P. VERON:
But along side the brighter BL Lac objects you must consider fainter objects like Mk 421 and Mk 521 with $M_V = -19$ to -20.

G. SETTI:
What we have derived is a lower limit for the density of objects which present a BL Lac type phenomenon, and compared it with the density of quasars without pretending at this stage (and the state would not allow us to do so) to make any detailed comparison between the respective luminosity functions. It is true that only some (two, if I remember right) of the low redshift BL Lac's have an average luminosity comparable to that of quasars (-23), and in this respect our limit should be reduced by a factor 3, or so, for a more direct comparison. However it should also be noted that, because of the large variability intervals, most objects at their bright end fall in the luminosity class of quasars.

G. BURBIDGE:
I think what he (Veron) is saying is that you are looking at completely different volumes for the two classes of objects. If you compare the number of BL Lac objects with $z < 0.07$ to the number of QSOs in the same redshift range, you get an enormous ratio because

there are no QSOs there.

G. SETTI:

No, you mean that there are no very luminous QSOs in that redshift range. But some people would include things like Seyfert galaxies and N galaxies in their sample of nearby QSOs. You should also include objects detected in the Braccesi survey (Braccesi et al., 1970, Astr. Ap., 5, 264) because that includes objects that are intrinsically faint. The Braccesi field includes low luminosity QSOs and N galaxies as well.

P. USHER:

What are the color correction criteria that you used in your sample of objects?

G. SETTI:

All the objects have U-B < 0.35 in order that they be compared with the Braccesi objects. Of course the same color criterion has been applied to the bright BL Lac objects used in our derivation of the counts.

PANEL DISCUSSION

PANEL MEMBERS: M. Burbidge, C. Hazard, K. Kellermann, J. Miller and M. Rees

MODERATOR: A. Wolfe

A. WOLFE:
What observational programs do you think will lead to a better physical understanding of BL Lac objects?

M. BURBIDGE:
Just to start the ball rolling, it seems to me that we heard a lot about series of observations that did not overlap at radio and optical wavelengths at the same time. We need to get observations that are carried out at the same time at both of these wavelengths. When anything happens in the way of a flare or an outburst in an object, we need some mechanism to inform people who have access to radio and optical telescopes in order to get coordinated observations. This might solve the undersampling problem that was discussed previously.

A. WOLFE:
Does anybody have ideas about establishing a communications network to coordinate observations like this and communicate information rapidly?

K. KELLERMANN:
As somebody pointed out, the IAU telegram is a good way to do this.

M. BURBIDGE:
Yes, but we don't always receive these. A phone call from someone who has seen something that happened or a list of people that they knew would be interested would be another way.

A. WOLFE:
What type of time scales are we talking about? A day or less?

K. KELLERMANN:
Yes, unfortunately.

H. ALLER:
I want to report that we had a conference a number of years ago on variable sources and we set up an elaborate program. I think we had five chairmen who tried to communicate observing programs. It lasted for about 1 round only. When we had to write a report for the next six months people got tired, and said they hadn't done anything new since the last 6 months. It died on the vine. I think the network needs to be something very simple that doesn't take forever to keep going. I think it would be a very good thing to have a list of relevant phone numbers, a list of where you work and where you observe.

K. KELLERMANN:

I think the phone numbers might include observatories instead of the people because people can't get on the telescope in the necessary time scale unless they are already on.

M. REES:

In the past, unfortunately, this type of program has not led to anything very exciting because in general there has not been much correlation between the radio and the optical. In fact, apart from AO 0235+164, not a great deal has emerged from coordinated observations at different wavelengths. So maybe that particular outburst ought to have raised people's morale. It might make them feel it worthwhile to discuss continuing this type of program on the BL Lac objects.

B. ANDREW:

The difference with AO 0235+164 was that it was a reaction to something happening, whereas the others were pre-organized and we didn't know if anything would happen or not. It usually didn't.

C. HAZARD:

I think this situation is going to change soon. A search for BL Lac objects using purely optical techniques is now under way at Cambridge. Observations with Schmidt telescopes using broad and narrow band filters and objective prisms in combination with new high speed scanning machines permit programs which up to now have been impractical. A new scanning machine at Cambridge will take all the data off a Schmidt plate down to the plate limits in about 8 hours and it will be possible to compare easily Schmidt plates taken at monthly intervals. We have selected two regions to be monitored regularly for variability and hopefully we will be able to find out how frequent are these tremendous optical outbursts we have heard about earlier. Since the ones we know about have been detected in a random manner, I suspect they are pretty common. If we do find one, however, the problem will be to follow it up since the Anglo-Australian telescope to which we have access is scheduled 6 months ahead of observing time.

A. WOLFE:

Somebody mentioned that we should schedule a small undersubscribed telescope just for this purpose. In this way somebody can get on the telescope right away.

M. BURBIDGE:

A smaller telescope could certainly monitor things optically.

A. WOLFE:

That raises another question that we have been talking about. How unique is the outburst in AO 0235+164? As Martin Rees said "It's the only one that we know about in which the radio and optical variability are extremely well correlated."

K. KELLERMANN:

We could kick ourselves in the pants for not taking better advantage of that outburst; but of course there have also been many false alarms.

J. MILLER:
Did anything happen in 1308+32? Optically it went from 20.5 to 13.5 mag.

K. KELLERMANN:
We don't have any pre-outburst data at millimeter wavelengths. The fact that it is so strong at millimeter wavelengths means that it should also increase in flux at longer (cm.) wavelengths.

W. DENT:
It's not showing much variability at radio frequencies over the last year or so. However, 0420-01 is undergoing a very strong radio and optical outburst and this is an example of an outburst happening right now. I'm not aware of any infrared observations of 0420-01.

M. BURBIDGE:
What is that source?

J. MILLER:
It's behind the sun right now.

W. DENT:
Perhaps for a good reason. [laughter.]

B. WILLS:
IIIZw2 is also undergoing a radio outburst. [*Ed.: See Schnopper et al. 1978, Ap.J. Lett., 222, L91.*]

J. MILLER:
It's undergoing an optical outburst too. I observed it between the rain clouds a few weeks ago.

A. PACHOLCZYK:
A very crucial observation for the theoretician is a study of the size of the source during an outburst. I would say that it is very important to observe the interstellar scintillation of a number of objects at the time when each is undergoing an outburst.

A. WOLFE:
Has that been done?

B. DENNISON:
DA 406 has been looked at at low frequencies and did not show any scintillation.

J. CONDON:
It's a tricky business to do sensitive scintillation observations at Arecibo. But they probably could be done on short notice. If someone at Arecibo were to be told that source X is flaring, he could get at it. On the other hand, I think that outbursts at low frequencies are slow enough that the timing isn't quite so critical.

A. MARSCHER:

I would urge anyone seeing something spectacular happening to call R. Mushotzky at NASA so that he could point HEAO at it, or call anybody else who has an experiment on HEAO.

K. KELLERMANN (To J. Condon):

I think you just raised the trouble with scintillation observations. The reason that the outbursts are slow at low frequencies is that you don't see the low frequencies until the source is big; i.e. until it has expanded. So you have to do it at short wavelengths where the source is small, but then you can't see the scintillations.

J. CONDON:

But when the source is small, there wouldn't be a significant amount of low-frequency flux present.

K. KELLERMANN:

Yes, so I don't know how useful that type of observation is going to be.

D. SHAFFER:

But you can't see a source until it is big enough for its brightness temperature to be about 10^{12} K, and then it will not scintillate.

K. KELLERMANN:

His (Condon's) speculation is that the brightness temperature might be higher, that is the purpose of the observation.

J. CONDON:

Well it wasn't obvious until a few months ago how many low-frequency variable sources there actually were. We did the scintillation observations before we knew this, and because of the comments that have been made at this meeting, I think I will go back to Arecibo and try to do scintillation experiments on all the low-frequency variables.

J. MILLER:

In connection with flares I think that's also the way to look for new radio-quiet BL Lac objects. I think that the ones that have been found so far have been more by accident than through a concerted search. Eric Craine mentioned using photographic polarization plates. That's one approach. A simpler approach that anyone can do is just to take ordinary plates. I think anyone that has a small telescope or access to a Schmidt can take 10 to 20 selected fields at intervals of some weeks or months and also include some fields that have known BL Lac objects in them, and then ask a graduate student - not tell him which is which - to see if he can find the known objects as well as the additional ones. This would provide a control.

C. HAZARD:

When the new high speed scanning machine at Cambridge is available it will be a simple matter every month to pick out objects down to the plate limit, which have flared up by more than 0.5 mag. So the highly variable ones can be picked up quickly.

A. WOLFE (To C. Hazard):
Cyril, I know that you think there are no radio-quiet BL Lac objects. Would you say something about that?

C. HAZARD:
I think this is an important question. It is not at all clear what we are talking about when we talk about radio-quiet QSOs. I was fairly struck by talking to people here, by our own observations, and by listening to some of the talks that there does seem to be developing striking differences between the optically selected objects and radio selected objects. There are only indications rather than anything positive, but it's fairly certain now that the radio-quiet objects don't vary to the same extent as the radio-selected ones. Examination of recent observations taken by our group indicates a much higher incidence of absorption features among the radio-quiet QSOs. There is certainly no evidence at the moment that the radio-quiet ones are strongly polarized except in the cases where one has the absorbing gas producing the polarization (as in the case of PHL 5200), but not polarization due to synchrotron radiation. There is certainly strong evidence that the redshift distributions of the two classes are different. At least when you pick a radio object, you can be sure it has a non-thermal source associated with the radio object. In the optically selected ones we don't really know if there is a non-thermal source. All we do know is that it has the same spectral features as the radio object, that it has ionized gas.

A. WOLFE:
The emission line properties are the same in the two classes as far as I know.

C. HAZARD:
Yes, but the emission line properties can arise in various ways. The mechanism need not be the same in both cases. The question is whether the radio-quiet objects are fundamentally the same as the radio QSOs or quite different objects.

A. WOLFE:
You mean that the emission lines are not telling us very much about what is going on in the energy source.

C. HAZARD:
That's right. The point that was raised by G. Setti toward the end of the conference is also very important. What we do know about the radio objects is that they do evolve very strongly with time and therefore the density of QSOs at a redshift of two is much higher than locally by a factor of a 1000. Presumably the QSOs had massive objects in the middle at that time. Now where are these objects presently? The present density of radio-galaxies is too low to provide an explanation. So presumably there must exist among the local extragalactic population a large number of galaxies now hiding relatively quiescent massive objects in their interiors. Are these the BL Lac objects? That is why it is so important to find their local density. It could well be that the BL Lac objects are highly evolved QSOs which, though accretion during their active phases, now contain at their centers, objects

much more massive than the normal QSO. Perhaps the radio-quiet ones have very little to do with this evolutionary process. This is the reason why I think it is important to look for possible differences in the optical and radio selected objects, and why I feel the polarization observations are so important. I do not think it can be excluded that some of the radio-quiet QSOs are young galaxies in which the ionization is not from a non-thermal source but rather from a population of very young, hot stars. Perhaps the absence of variability in the radio-quiet objects can be explained this way and, if real, the absence of polarization. One thing does appear to be certain; namely, the radio-quiet QSOs are not an extrapolation of the radio QSOs down to fainter radio luminosities.

R. ANGEL:
Just a word of caution: In the published paper on 40 QSOs (1978, Ap.J. Lett., 220, L67) there was some difference in the optical polarization properties of the radio selected and optically selected QSOs. In the full sample of 100 QSOs, except for the OVVs there really is no significant difference in the optical polarization properties of the two types of QSOs.

C. HAZARD:
My point is simply that so far the strongly polarized ones come from radio selected samples.

R. ANGEL:
That's true.

C. HAZARD:
And you have no evidence at the moment that there is strong optical polarization in QSOs that come from optically selected samples. I'm not saying that there is necessarily a difference between the full samples but I think any possible differences should be investigated.

A. WOLFE:
Does anybody else on the panel want to comment on the space density of BL Lac objects?

M. REES:
I want to reiterate that one ought to explore the relationship, if any, between the BL Lac objects and the compact radio sources in the nuclei of ordinary elliptical galaxies. It could well be that BL Lac objects are fairly common. One should, as well as thinking of their relationship to the brighter end of the luminosity function, explore their relationship to the fainter end of the luminosity function of more common objects.

M. BURBIDGE:
I want to raise that again because in previous discussions some of the radio astronomers, I forget who, said that the radio sources in the centers of ellipticals and BL Lac radio sources were different kinds of beasts.

C. HAZARD:

We have looked at some of these objects found in the Molonglo survey. Many of the bright ellipticals that we have identified have very small angular sizes and flat spectrum point sources at the centers. We have looked at them with the AAT and optically they are indistinguishable from normal elliptical galaxies even though the radio sources are like the radio sources associated with QSOs. The galaxies show H and K, MgIb and NaD absorption. There is no evidence for non-thermal emission.

M. BURBIDGE:

But are they variable? Are these radio sources at the centers of ellipticals that you talked about variable and polarized?

K. KELLERMANN:

Even at the center of spirals such as M81 and our own Galaxy there are variable radio sources.

G. SETTI:

I think even Virgo A would look like a BL Lac object.

M. REES:

Yes, I think if you looked along the jet of M87 it would be like a BL Lac object.

J. FELTEN:

The nucleus of M87, that is the optical emission of the M87 nucleus, isn't non-thermal, am I not right?

K. KELLERMANN:

No, the optical nucleus is non-thermal in M87.

W. DENT:

There are several examples of radio sources at the centers of elliptical galaxies. In general they tend to be only slightly variable, nothing nearly as dramatic as the radio quasars.

A. WOLFE:

What about the BL Lac objects?

W. DENT:

The BL Lacs on the other hand show a tremendous range in variability from the extreme case of BL Lac itself to some that are virtually constant, very weak, radio sources. Some are very strong and very active and some hardly vary at all.

K. KELLERMANN:

The radio source in the elliptical galaxy NGC 1052 is quite variable, isn't it?

W. DENT:

I don't think it's quite that variable.

K. KELLERMANN:

It's weak but it varies by a factor of 2.

W. DENT:

NGC 1052 has a very long variability time scale, on the order of 8 years. It has just shown one small undulation during this time. We have been looking at Virgo A for a long time and we find no evidence for variability there, especially at millimeter wavelengths where the nuclear component becomes dominant. We find that the nuclear component doesn't vary by more than 10%.

K. KELLERMANN:

That's very interesting because it's one of the smallest radio sources known. It's only about a light month across and the flux doesn't vary and neither does the size.

W. DENT:

On the other hand Centaurus A, which is of comparable size, is extremely variable. In fact, its variability characteristics are similar to those of AO 0235+164 except that they are seen at millimeter rather than centimeter wavelengths.

J. FELTEN:

How large is the angular size of that Virgo A source and how far is it known to be displaced from the optical center of the galaxy?

K. KELLERMANN:

It's angular size is 0.25 milli-arc sec. and its location is known to be within a half a second from the optical nucleus. I don't know how well you can determine the location of the optical nucleus.

M. BURBIDGE:

Certainly not to a milli-arc sec. [laughter.]

K. KELLERMANN:

There is a point optical source there. I guess the agreement is good to within half a second.

T. CHUBB:

It seems that there is some longer term planning that could be done. Now that we have the space shuttle it is possible to put up satellites that could point to 10-20 specific active extragalactic objects and continuously monitor them in the X-ray and visible polarization. And that type of data could be accumulated just because it requires a long lead time to detect the type of variations that we have been talking about. The history of the spectral energy distributions of the hard part of the spectrum and the polarizations of the visible would be a good way of making progress on these objects.

K. KELLERMANN:

I want to say a word about radio observations. If you look at the graph on the wall of the total flux variations of BL Lac, put up by Bill Dent [*Ed.: See page 66*],the observations were taken about once a month or so. That is where the statement that defines the rapid variations during the early 70's comes from. Dave Shaffer showed some data that came from the total of about 15 epochs of VLB observations which involved perhaps 200 hours of telescope observing time and a similar amount of man hours. What came out of that is essentially one map of BL Lac in 1974 with a total of 6 or 8 picture elements which show that BL Lac is double. But, imagine that instead of just total flux variations as a function of time one had a picture of BL Lac taken every few weeks as a function of wavelength. The different components of BL Lac have different optical depths, so the structure is very wavelength dependent. If you observe this every week, you would see the structure vary with time. You saw the interesting polarization observations of AO 0235+164 presented by Ledden where the polarization position angle rotated with time. In the future we could obtain the polarization distribution across this source as a function of time. This type of thing could come in a few years. The VLA could be expanded into an ultra-large array with intercontinental baselines, even a super-large array with baselines extending out into space.

J. MACLEOD:
It is interesting to note that there are two different time-scales involved on that chart on the wall (p. 66). BL Lac has slowed down a lot in the last few years and just looking up the Algonquin observations of the elliptical NGC 1052 we find that although the percentage variation is not as great, the time-scale is about the same. We have seen two outbursts in three years in NGC 1052 and that's not very different from the latter time-scale in BL Lac shown on the chart.

K. KELLERMANN:
I don't understand Bill Dent's statement when he said that elliptical galaxies don't vary very much with the exception of Centaurus A.

W. DENT:
NGC 1052 changed only slightly at 15.5 GHz from 1971 to 1975. In 1975 and again in 1976 it experienced two weak outbursts with peak amplitudes of 0.4 and 0.2 Jy respectively.

A. WOLFE:
I was surprised that there was not much discussion about Ledden's observations (p. 60). I thought that the theoreticians would leap on them. Does anybody have any comments? Martin (Rees), I know I am putting you on the spot, but what do you think?

M. REES:
Stirling Colgate would like to say something. [laughter.]

S. COLGATE:
I just got some numbers from Ledden because of Tom Jones' question to me about what it implied in terms of the minimum magnetic field. For a model with about 1000 electrons per cubic centimeter in the surface layer, the field should be less than 10^{-7} gauss which seems reasonable in a model of the galactic nucleus that has been ejecting mass and has no dynamo.

A. WOLFE:
How do Ledden's observations jibe with your idea of many outbursts occurring randomly?

S. COLGATE:

That's the whole point. The evolution of a galactic nucleus of stars doesn't make a dynamo. When you don't have a dynamo, magnetic flux gets reconnected and destroyed especially if there is mass ejection. The magnetic field gets continually reduced unless you have a single massive object. If you have a single massive object all bets are off, but I think the existence of such an object is still an open question.

G. BURBIDGE:

Some people use ejection and shocks to amplify magnetic fields.

S. COLGATE:

At most by a factor of 2 with a shock wave and when you have an *in situ* magnetic field. Perhaps a factor of 4 or some number like that. It's not a dynamo.

G. BURBIDGE:

Do you think it's realistic to destroy magnetic fields to this level?

S. COLGATE:

Yes. I don't think its a question of destroying. If you take an ensemble average of the magnetic fields of stars in a galactic nucleus, you get a very small field. The stars comprise a tiny fraction of the total volume and the fields are oriented randomly so that the net amount is very small.

G. BURBIDGE:

The density of stars in a cubic light year is very high.

S. COLGATE:

Yes, I'm taking 10^8 solar masses in a cubic light year.

A. WOLFE (To M. Rees):

Martin, you wanted to say something.

M. REES:

Yes, my general impression was that the optical polarization observations are perhaps the most important recent clue to what is going on. I want to summarize what can be learned from them. The existence of high polarization at all, as has been emphasized by Angel and Stockman in their talks, does tell us that the emitting region is not surrounded by any cloud that is opaque to electron scattering and as Blandford explained this morning, this is quite a significant constraint if we have compact regions where we expect the densities and column densities to be quite high. As regards the radio polarization, this is a tremendously powerful constraint: it means that one either has an exotic electron-positron plasma, or a different radiation mechanism which doesn't involve a magnetic field at all, along the lines of Colgate's model. I think those are two areas of theoretical work that deserve more attention.

A. WOLFE:

The next subject I have here is the Mg and Fe absorption lines that are seen in some of the high redshift BL Lac objects. Some people mentioned that they were interested in discussing the possibility of detecting blueshifted absorption lines in the UV continua of nearby BL Lac objects. This would distinguish ejected clouds from intervening galaxies. Does anybody have any comments?

M. BURBIDGE:

That raises the question of what should be done with the new Space Telescope. The obvious observation is to look in the UV at any object that has low redshift absorption lines, particularly those in which 21 cm. absorption exists and those in which a good 21 cm. upper limit exists. We should look for Lyman α absorption in these objects. I was also struck by Penston's IUE observations in B2 1101+38 in which he found no Lyman α emission. I thought that whatever gas ought to be there, at least Lyman α ought to show up in emission. I wonder if he has been able to set any upper limits on the amount of gas present from the complete absence of Lyman α?

K. HACKNEY:

About your second point concerning Lyman α, could you say why it shouldn't be there.

M. BURBIDGE:

Either a high temperature or a low density gas could explain the absence of Lyman α.

K. HACKNEY:

These are very low redshift objects and Lyman α suffers from contamination with geocoronal Lyman α.

M. BURBIDGE:

No, Penston's observations were clear of geocoronal Lyman α.

A. WOLFE:

That brings up another question. R. Mushotzky emphasized how the lack of X-ray absorption demonstrates that there is no gas in BL Lac objects capable of producing observable emission lines. I don't think there was general agreement about his conclusions. Would anybody like to comment on this?

M. BURBIDGE:

I don't think it was a very strict limit.

A. WOLFE:

I agree, he had an upper limit of $N(H) < 3 \times 10^{22}$ cm^{-2}. I think you can make observable emission lines with a lot less gas than that.

J. KROLIK:

There does seem to be substantially less gas than X-ray astronomers are accustomed to seeing in Seyfert galaxies. But given the small covering fraction that the canonical model for QSOs requires, that's not a very tight upper limit for the amount of gas you need to produce emission lines.

A. WOLFE:

What is the canonical model to which you refer?

J. KROLIK:

Just the usual sort of argument that about 10% of the Lyman continuum being converted to Lyman α emission. That implies an effective column density of several times 10^{20} cm^{-2} which is right about at the limit derived from the 0.25 keV observation. If the ionization equilibrium is seriously different from what we are accustomed to, then that might cause the absence of observable emission lines.

A. MARSCHER:

In addition to that, Mushotzky made the implicit assumption that X-rays from Seyferts come from the same source as X-rays from BL Lac objects, that is, that they come from some compact region at the center. However, from the poor resolution of the X-ray observations, there is no way to know whether this is in fact the case. In Seyferts the X-rays could be coming from the gas itself. In BL Lac objects the X-rays could arise from inverse Compton emission.

A. WOLFE:

The spectra looked very different. The BL Lac X-ray spectra looked totally different from the Seyfert X-ray spectra.

M. REES:

The BL Lac spectra were much flatter than that of Seyferts and Mushotzky said that they were too flat to be thermal. Even a very high temperature Bremsstrahlung spectrum would fall off more steeply than he observed. I think that this discovery highlights that the X-rays are something else which, along with the optical non-thermal continuum, is coming from deep down near the central object. I personally think that it is still an open question whether the X-rays are thermal or non-thermal in origin. Obviously if one were to find a rapidly varying X-ray Fe line, this would be a very exciting result and I don't think that this can be ruled out at present. Another interesting result which I don't think is widely appreciated is that if the X-ray spectrum is so hard that it extends over 0.5 MeV, then one finds that pair-production - an X-ray hitting a gamma ray and producing an electron-positron pair - is probably a more important source of opacity then anything else for the hard X-rays. This means that if one has observations of gamma rays from the same small region one can set constraints on what is going on. Also of course this is another way of getting electron-positron pairs. So I think that to examine the spectrum of the X-rays up to the gamma rays and to look for variability is going to be very important.

J. FELTEN:

To return to this question of the possible relationship between BL Lac objects and compact objects in galaxy nuclei, and considering M87 in particular, my impression is that there is not much gas in the nucleus where you have a compact non-thermal source which I gather from K. Kellermann has a radio spectrum flat enough to be a BL Lac object. Have any of the optical observers considered the following question? If there were a typical BL Lac object in the nucleus of that particular galaxy with strong variations in total flux and polarization, would it be extremely difficult to detect the BL Lac in the nucleus of that galaxy?

J. MILLER:

I carried out a monitoring program of both the knots in the jet and the nucleus because I had some marginal evidence that the knots were varying at a 10% level. I have looked at plates taken over the past 10 years and have compared them all and there is no evidence of variations in the nucleus. The nucleus looks very stellar and sharp and it certainly has varied by less than a factor of 2, and probably by less than a factor of 50%.

J. FELTEN:

But those numbers are not very strong upper limits. I wonder how much better than that one can do. Of course there have also been recent observations at Steward Observatory [*Ed.: See Schmidt, G.D., Peterson, B.M., and Beaver, E.A. 1978, Ap.J. Lett., 220, L31*]. I don't think any of these people are here now, but I think they said that they did not see any significant polarization except in the jet. But I wonder if you actually had a typical BL Lac object in the nucleus of M87, how large would the variation have to be before you could actually detect it against the stellar background of the nucleus.

J. MILLER:

If you put the nucleus of BL Lac at the center of M87, there wouldn't be any question, since it would equal the magnitude of the entire galaxy.

J. FELTEN:

But how do the radio sources of BL Lac and the compact source of M87 compare?

K. KELLERMANN:

The radio source in M87 does not vary, that's the difference from the highly variable source in BL Lac.

P. CRANE:

The radio source in M87 is also weaker and there is no polarization that could have been detected by interferometer observations.

R. ANGEL:

We have mapped the optical polarization of the knots in the jet of M87. We also have pretty good seeing-limited polarization observations of the nucleus. We didn't detect any polarization in the nucleus at all and the upper limit must be something like 1% polarization.

A. SMITH:
We took a series of short UV exposures of the nucleus of M87 over a 2 year period. We took about 12 exposures in that 2 year period which took place around 1971 and 1972. We were not able to detect any variations although, as was pointed out, it is difficult to do iris photometry or even visual observations because of the galaxy background [*Ed.: See talk by Kinman in this volume*], but I am sure that we would have seen anything as large as 0.5 mag variations easily.

J. FELTEN:
Now the problem is to boil down all these numbers and come out with some conclusions.

J. MILLER:
Yes, that there are no BL Lac objects in M87, that's one possible conclusion.

C. HAZARD:
This comes back to the point as to what we mean by a BL Lac object. If we adopt the view that they are all highly polarized and strongly variable, are we not already prejudging the issue and perhaps selecting only the extreme members of a much broader population? It must be remembered that the identification of continuum objects is difficult. If an identification shows no prominent emission features, then the detection of polarization or variability is a good indication that the identification is genuine and it becomes worthwhile to spend a lot of time investigating it further. In the absence of polarization or variability the identification is suspect and observations will probably not be pursued further.

W. DENT:
I think that the reconciliation of this problem might be that the BL Lac objects are episodic in nature, that they go through phases of extreme activity where they draw a lot of attention and then they become quiescent just as BL Lac itself is now doing. It will be interesting to see what happens over the next 10 years. BL Lac may just hold steady or decrease to some insignificant flux level in which case it will resemble some of these other non variable BL Lac objects, or resemble the sources in the nuclei of some of the elliptical galaxies which we have been discussing.

C. HAZARD:
You may be right and it again raises the danger of searching only for objects with specified properties: until a few years ago all QSOs by definition had an ultra-violet excess and as we now know this led to serious redshift-dependent selection. Ideally we should search for all objects with non-thermal continua whether or not they show emission lines, are polarized, or are highly variable. Otherwise we could miss objects which in the past have shown or in the future will show extreme variability.

W. DENT:
I think it would be fruitful to again survey the whole sky at radio wavelengths. I think that we would find a substantially new population of radio sources. A lot of the ones that we are now

familiar with would be either gone or be very weak. This should be done at centimeter or millimeter wavelengths.

D. SHAFFER:
I have done, in some sense redone, that survey by looking at more than half of the sources that were discovered in Mike Davis' Green Bank 6 cm. survey (see Davis, M.M. 1971, A.J., **76**, 980).

K. KELLERMANN:
The point is that you haven't found any new ones.

D. SHAFFER:
Well by deliberately looking only close to the sources in the Davis catalog I found another new 100 mJy source,and half of the sources in the Davis catalog have changed in the sense that they have decreased in brightness. So if you look at the sources that you know, at a later time they have gone down. Presumably there must be a comparable fraction that have appeared, but they are in the part of the sky that has not been resurveyed.

M. DAVIS:
This is a very serious problem because we're losing...

W. DENT:
Yes, we're losing all of our sources. [laughter.]

C. HAZARD (To W. Dent):
Why don't you go to the multi beam survey at Arecibo?

K. KELLERMANN:
No, that's too long a wavelength for these purposes.

D. SHAFFER:
3C 273 and 3C 345, they will be gone.

K. KELLERMANN:
That's right. Where are the new ones? They all appeared 10 or 12 years ago.

M. DAVIS:
Yes, it's a very serious problem.

G. BURBIDGE (To W. Dent):
What do you mean by "episodic" Bill? BL Lac after all is a variable "star" and therefore the history at optical wavelengths has shown that it has been varying for a long time before you even thought about it. How far back does that go? Is there really any evidence at optical wavelengths that it has stayed constant for long periods?

W. DENT:
I don't know the answer to that. I was referring only to the radio characteristics.

G. BURBIDGE:
Presumably it's there because it has been in the catalog for a long time, it's been a regular variable.

W. DENT:
Yes, but it would go through active phases and then quiescent phases and active phases and so on.

G. BURBIDGE:
But has that really happened optically? I don't really know.

P. USHER:
My recollection of the 1970 to 1972 visual light curve of BL Lac is that it is very similar to this (radio curve of Dent's). It undergoes very spiky behavior over periods of years then calms down for a while. Of course the coverage is spotty, there are gaps in the records but my recollection is that it is very similar to the radio curve of Dent's.

H. MILLER:
B2 1101+38 very definitely shows spiked characteristics for over 70 years. From the Harvard plate collection material we have found that in the mid 1930's for example, it was violently variable on the time scale of a few days. But recently one half to one magnitude changes occur on time scales on the order of months as opposed to one to two magnitude changes on similar time scales during the 1930's.

M. BURBIDGE:
There are a few QSOs also that W. Liller picked out which had varied in the past, in the 1930's to 1940's, by high factors which have not been on anybody's list as current optically violent variables. They haven't been varying recently.

H. MILLER:
3C 279 went through a tremendous outburst. [*Ed.: See Eachus, L.J., and Liller, W. 1975, Ap.J. Lett., 200, L61.*]

G. BURBIDGE:
Yes, in 1976.

M. BURBIDGE:
Yes, that has done it recently but there were some more which have not varied recently.

ANONYMOUS:
Even 3C 273 which is not a real tremendous variable, optically, perhaps for several years has shown no significant variation in the optical.

ANONYMOUS:
Another object that Liller worked on was 1510-08 which underwent a 6 magnitude outburst. [*Ed.: See Liller, M.H., and Liller, W. 1975, Ap.J. Lett., 19, L133.*]

J. MILLER:
It's not doing anything now.

H. ALLER:
I think it is only a matter of things being studied longer in optical astronomy.

D. SHAFFER:
That brings up a question I was going to address at some point. Are you ready for that?

A. WOLFE:
Depends on what it is. [laughter.]

D. SHAFFER:
Those objects that vary optically vary by 4-6 magnitudes which is a factor of 100 in flux. The most violent radio variations occur in BL Lac, OJ 287, and AO 0235+164 which varies by a fractional factor of 5. So the radio variations which really require probably less energy than the optical variations are ten times weaker in terms of the total factor range of variation. I don't think a 50 year time scale would make a difference because we already have a ten year coverage on dozens of variable radio sources so I don't think we have missed the factor of 100 variations at radio wavelengths.

G. BURBIDGE:
Well that's not obvious. For example, have you ever surveyed the skies twice at a certain flux level and found more sources or new sources because they came essentially out of nothing and are now sources that are simply there. I don't think that's done in radio astronomy in general. You count them often. In terms of a one to one correspondence there has never been one survey that has been done the same way more than once.

K. KELLERMANN:
It doesn't have to be done the same way any more. We get the right answer no matter which way we do it. [laughter.] This is not Cambridge, 1955.

G. BURBIDGE (To K. Kellermann):
OK Ken, what is the answer?

D. SHAFFER:
The optical objects which have been found to undergo these five magnitude outbursts are in the 20 or so optical objects that have been studied. We have been studying a 100 or more radio sources so the number of objects times the numbers of years of observation is probably comparable. A hundred objects times 10 years versus 20 objects times 50 years.

K. KELLERMANN:
But it is true that there has been almost no resurvey at radio wavelengths.

D. SHAFFER:
But the point is that the five magnitude optical jumps have been found by going back and observing known BL Lac objects. We have observed known BL Lac radio sources with a comparable integrated length of years times objects and we don't see any factor of 100 radio outbursts.

K. KELLERMANN:
Except that there is every reason to believe that NGC 1275 and 3C 273 which are now at the 50 Jy level may very well have been down a factor of 50 or 100 about 10-40 years ago.

D. SHAFFER:
Yes, but it took them that long to come up too. They didn't go up overnight like some things go up 4 magnitudes.

G. BURBIDGE:
The tacit assumption in this argument is that if you did the 3C survey in 100 years it would look about the same.

K. KELLERMANN:
I think the 3C survey would. But not the centimeter wavelength surveys.

G. BURBIDGE (To K. Kellermann):
I'll leave it to you Ken. [laughter.]

K. KELLERMANN:
The 3C sources are big sources, hundreds of kiloparsecs to megaparsecs in size. You need relativistic gamma factors of 10^5 to explain variations in them. [laughter.]

G. BURBIDGE:
I wish you would not impose some interpretation on what the distance actually is. [laughter.]

K. KELLERMANN:
But the centimeter wavelength surveys, I agree, would be interesting to do again.

G. BURBIDGE:
Yes, anything that is basically compact. It's a reasonable possibility that it comes from below the sky level to something quite significant.

K. KELLERMANN:
The only point I was trying to make before was that it is not necessary for the same person with the same telescope to do the survey again.

M. REES:
Well suppose that Dave (Shaffer) is right, that they are not as variable at radio wavelengths as in the optical. Perhaps that isn't all that surprising because even though the luminosity is less in the radio, the energy reservoir needed may be higher. Also, self absorption sets a limit in the radio and not in the optical. So maybe it's not surprising that it's in the optical that you see the rapid large amplitude variation.

R. BLANDFORD:
There is an additional point too. The electrons emitting at radio wavelengths are not necessarily able to cool before the electrons emitting optical radiation.

D. SHAFFER:
Yes, it never gets cold enough.

W. DENT:
Also at radio wavelengths you tend to have a reasonably strong constant component that the source sinks to. This reduces the ratio of the variability so you don't see 5 magnitude changes. In AO 0235+164 where you don't have this constant component, it goes from a very small amount to a very large amount. It is not as large as a factor of 100, but it's substantially larger than most sources.

K. KELLERMANN:
That's a good point. If you took away the 2 Jy background source from BL Lac then a factor of 5 could be a factor of anything.

W. DENT:
The background source there, if you connect up all its minima, would show a gradual long term decline.

K. KELLERMANN:
That's a very good point.

W. DENT:
I think it's incorrect to think of these outbursts in terms of fractional variability.

A. WOLFE:
Let's go on now to another topic. Would anybody be so bold as to say what their definition of a BL Lac object is? [laughter.]

ANONYMOUS:
Perhaps we can have drawings of them. [laughter.]

M. BURBIDGE:
I can only give a phenomenological description. I think of them as certainly non-thermal and very compact objects. The evidence for this is strong polarization and variability and violently variable too. The question about presence or absence of emission lines may be important. What we heard on the first day about being able to see closer into the energy source in a BL Lac object than in a QSO is also important.

A. WOLFE:
How important do you think the absence of emission lines really is? Some people don't think that's very important.

M. BURBIDGE:
I think it is a phenomenological property, a way in which we have been linking them together.

K. KELLERMANN:
I don't think we should ever use the word (BL Lac) again. Just by inventing a new name every time a phenomenon looks slightly different quantitatively is confusing. The thing that's of interest is the stellar-type non-thermal phenomenon which is variable. It could have

gas around it with emission lines or absorption lines. The polarization is also interesting. Some of these properties apparently are correlated with other properties. For example, polarization with variability. I certainly have the impression the last few days that there is a consensus that we are dealing with basically the same phenomenon; that is, non-thermal emission from a very small object. We ought to invent a name for that, QSO is as good as any. Let's stick to that and not invent all the other words.

A. WOLFE:
Is it true or not that the extreme characteristics of this class of objects are in objects without emission lines?

K. KELLERMANN:
Yes, that very well may be. But that doesn't mean they should be called a separate object.

M. REES:
Clearly we cannot agree on theory or even interpretation but we at least ought to be able to agree on semantics so I am happy to accept Margaret's (Burbidge) definition of what we should call a BL Lac object. But on the other hand I agree with Ken (Kellermann) that maybe the term is not a useful one. It may indeed be timely to start thinking about a more sensible and rational classification scheme for all active galactic nuclei rather than carrying around historical baggage that isn't of great value now. So maybe it would be useful if some body, I won't suggest the IAU, would come up with a classification scheme.

C. HAZARD:
In principle I agree with that but I think a classification scheme could be dangerous without a better understanding of the relationship between the various types of objects and especially whether or not they form part of an evolutionary sequence. I think that most of us - Geoff (Burbidge) possibly excepted - think that the so called QSO phenomenon is a non-thermal source in the center of a galaxy. In the case of a classical QSO the non-thermal emission completely dominates over the stellar emission, hence the star-like appearance. In the BL Lac objects the non-thermal emission is apparently significantly less than for a QSO - except during a violent outburst. Part of the classification could therefore be based on what fraction of the total emission arises in a non-thermal component. There are obviously many complications. In the optically selected QSOs we don't even know if there is a non-thermal source. A most unsatisfactory aspect of the present situation is that we are dealing with a mixup of spectroscopic and morphological criteria and as a result we must be careful when comparing say the properties of QSOs and BL Lac objects. In the QSOs the non-thermal component dominates but at present we classify as BL Lac objects, a wide variety of optical types that range from objects where the non-thermal component is negligible to objects where it is comparable to the galaxy contribution. Secondly, there may be more than one type of QSO. Weedman (1977, Ann. Rev. Astron. Ap., **15**, 69) has argued that QSOs are simply very bright Seyfert galaxies implying that the embedding galaxies will be spirals. On the other hand the continuity argument linking the double radio-

source QSOs to the double radio-source radio galaxies is equally plausible; but this would imply that at least these QSOs are associated with ellipticals. Certainly no double radio sources seem to be associated with Seyferts or spiral galaxies. There is therefore at least a suggestion that we are dealing with two different populations of QSOs with different radio structures associated with spirals and ellipticals respectively. I do not think we can arrive at a satisfactory classification until we understand these matters better.

The characteristic features of the BL Lac objects are the strong polarization and variability, the polarization probably being the most significant. The centimeter excess in the radio appears to be equally characteristic and not simply a selection effect due to flat spectrum point sources being more easily identified. A number of BL Lac objects have been found in the low-frequency Molonglo survey and only later were they all found to have a centimeter excess. Whether or not these properties justify a special classification is, however, debatable since these same properties are found among the violently variable QSOs. I would not necessarily rate the absence of emission lines as a very important criterion as there could be a variety of reasons why spectral lines are not present or at least not seen: no ionizing photons, no gas, or simply that they are so broadened as to be difficult to detect except at very high signal-to-noise.

J. MILLER:

It's pretty hard for me to follow all the previous speakers in defining BL Lac objects. Let me repeat some of what I said yesterday. First,with the following proviso,I put optical criteria at the top. Certainly a radio astronomer may call some objects BL Lac objects that we (optical observers) would not and vice versa. I don't particularly care whether a given object is going to be called a BL Lac object and exists in a table with that name at the top. The importance of the phenomenon of BL Lac objects is certainly that they are quasi-stellar objects, they look stellar. There's no question about that. Also they have large luminosities. I disagree here with Cyril (Hazard) in that I think that their luminosities go up to a hundred times that of a giant elliptical galaxy in the nonthermal continuum. They are highly luminous objects and they are stellar. But the crucial property that they have called attention to, that most of the QSOs have not, is that they are very compact objects. The radiation we are seeing comes from a very localized region. This is the only way you can explain high polarization that varies very quickly on a short time scale, and a large light output that varies very quickly. To me the crucial and distinguishing feature is the high polarization. The BL Lac objects have called attention to something that is ordered and compact and producing an enormous amount of energy; and I think that's a clue to the radiation process. Once again I will repeat, since I'm the only one who has mentioned it, that the absence of optical light variations accompanied by very strong variations in polarization is perplexing. I think this phenomenon should be investigated as carefully as possible and I think it puts real constraints on any theoretical model. Just try to imagine what's happening that can produce 35% optical polarization that may change to 17% polarization without the total light changing.

Next comes the emission lines. Maybe there's a cause and effect thing going on here. Maybe it's the absence of emission lines which is related to the absence of gas that has allowed us to see the BL Lac objects. The fascinating thing, however, is the existence of objects that show the BL Lac phenomena that have strong emission lines such as 3C 446. Those may give us more clues because they have the emission lines, and their long term behavior is of considerable interest.

R. ANGEL:
What is the solid optical evidence for changes in optical polarization without any change in optical flux? This is something we haven't done at all.

J. MILLER:
It took a lot of looking through the literature and that means I have to take at face value what is in the literature, but Visvanathan has published a number of measurements on OJ 287 where the magnitude didn't vary by more than a few hundredths of a magnitude yet the polarization varied between figures like 5 and 15% (Visvanathan, N. 1973, Ap.J., 185, 145). Similarly in 3C 371 I observed the polarization to vary from 7% to 10% in 24 hours with less than three hundredths of a magnitude in light variation (Miller, J.S. 1975, Ap.J. Lett, 200, L55). Of course an optical astronomer doesn't normally look night after night at the same object. I think in some cases some of these objects should be followed for several nights. If this small sample has already produced such results, it should really be looked at more systematically.

J. FELTEN:
Without boring the public with further definitions of BL Lac objects I would just observe that according to some of the definitions given already, certain objects would be called both quasars and BL Lac objects and that I find an unsatisfactory situation. More work is needed! [laughter.]

D. SHAFFER:
J. Miller had one point: I don't think a radio astronomer would be prepared solely from radio observations to call anything a BL Lac object.

G. BURBIDGE:
Well they do.

D. SHAFFER:
I don't think so.

K. KELLERMANN:
J. Condon made the point that you cannot tell a quasar from a radio galaxy.

D. SHAFFER:
That's right. So the importance of some optical criterion is essential. Every object we have been discussing for the past three days has had some form of optical information so that it could be put into the BL Lac class.

A. WOLFE:

I want to ask Jim Condon a question. I remember you telling me about a VLBI survey that you did with John Broderick where you found that a larger fraction of QSOs had finite fringe visibilities than did galaxies.

J. CONDON:

Statistically you can tell the difference, especially if you had the redshift in addition to the radio data (but no optical morphology, spectroscopy, nor anything like that). I think that a useful distinction that a radio astronomer can make is whether or not the luminosity of the flat spectrum central component is more than about 10^{25} W/Hz or not. That seems to be the radio luminosity that corresponds to an optical non-thermal luminosity about equal to that of a giant galaxy. So if you have a radio source in which the absolute luminosity is more than 10^{25} W/Hz in the nucleus, you get something that's either going to be a QSO or a BL Lac object. You can guess that when the identification is actually made that there is going to be an optically stellar source there that is non-thermal.

K. KELLERMANN:

It could be a quasar or a galactic nucleus.

J. CONDON:

If the absolute luminosity is more than 10^{25} W/Hz it tends not to be a galactic nucleus.

K. KELLERMANN:

You don't know that unless, as you say, you have the redshift; but that's true for any radio source. If its more than 10^{25} W/Hz, it's not a galaxy.

J. CONDON:

Yes, that's at the heart of all the distinctions that the radio astronomers ultimately make between quasars and galaxies and so on.

K. KELLERMANN:

A radio astronomer observes a compact non-thermal radio source and that can be associated with a galactic nucleus or with a QSO. The QSO can have emission lines, absorption lines or nothing. Depending on whether it does or doesn't, we call it a quasar or a BL Lac object. The fact that the radio source does look the same all the time is certainly one indication that we are dealing with the same phenomenon. The fact that you can explain the optical properties with just the presence or absence of emitting or absorbing gas plus the non-thermal optical continuum is certainly consistent with the story that we are dealing with the same phenomenon which some properties enhance and others do not.

J. CONDON:

For whatever reason,nobody has yet seen a BL Lac object which has double components with a luminosity of 10^{45} erg/sec. I don't know why. I suspect that's a real effect and it is not likely that we are going to see much change in this in the near future.

A. WOLFE:

Don't some of the emission-line BL Lac objects, i.e., the OVVs, have double radio components?

J. MILLER:

3C 446 does not and 3C 279 doesn't.

M. BURBIDGE:

What about 3C 345?

J. MILLER:

I don't know.

J. CONDON:

It is sort of a funny thing that if you have an extremely luminous central component in the radio source, 10^{45} erg/sec, then it doesn't have a comparably luminous outer double.

K. KELLERMANN:

Well 3C 273 does in one direction.

J. CONDON:

But in most of these 3C sources that do have the very luminous doubles the central component is not as luminous for a reason that I do not understand.

G. BURBIDGE (To J. Condon):

But there is so much interpretation in almost everything that you have said. If you are going to have a definition, it's got to be a fairly simple observational definition so that we more or less understand, each of us, that if someone gets up and says this is a BL Lac object, we know what he means by it. It must be based purely on observed properties and not on what you interpret from this at all basically.

K. KELLERMANN:

If you look at the classical doubles hard enough they almost all have compact central components. If you look at the 1% level or even at the 10% level, you see the central component in nearly all cases.

C. HAZARD:

That would be different if you look at other frequencies.

K. KELLERMANN:

Of course you can't do it because the central component radiates mainly at the higher frequencies. But why BL Lacs do not contain doubles around the central component is something I don't understand.

W. DENT:

At the radio frequencies the original distinguishing characteristic of BL Lac objects was the very rapid fluctuation which you see virtually only in BL Lac itself.

K. KELLERMANN:
That's enough.

A. WOLFE (To W. Dent):
Would AO 0235+164 fit your definition?

W. DENT:
It's not as rapid as that. It has a time scale of several months whereas this has time scales of weeks. BL Lac is by far the fastest known radio source in any time in its history. Of course its slowed down now. The second object I want to talk about is one of the most rapid variables known, 3C 120. That used to be known as the second most rapid variable until AO 0235+164 was discovered. That's clearly not a BL Lac object. It's a Seyfert galaxy.

A. WOLFE:
Does everybody agree with that?

P. VERON:
Certainly not [*Ed.: That is, it is certainly not a BL Lac object*]! [laughter.]

A. WOLFE:
Would you care to elaborate on that?

P. VERON:
It has strong emission lines so it is not a BL Lac object.

A. WOLFE:
But we've heard people say that the emission lines make no difference.

P. VERON:
When you have broad emission lines, its either a Seyfert I galaxy or a quasar, but not a BL Lac.

J. MILLER:
But 1400+162 has broad Hβ which is not a sharp line. It has a type I spectrum.

P. VERON:
And you call it a BL Lac?

J. MILLER:
Yes (in answer to Veron).

Cyril (Hazard) got angry with me yesterday when I said that I didn't see galaxies when I looked at the QSOs at the same signal-to-noise used to observe the BL Lac objects. I was asking a very specific question: Does the same kind of galaxy that we see in BL Lac objects, that is luminous giant ellipticals, something like a first rank giant elliptical, exist in a class of QSOs which I selected for being no more than 2 magnitudes brighter than a first rank giant elliptical? If there were such a galaxy in those QSOs, would I have seen it? I have the signal-to-noise to say that I would have and I don't. So the conclusion that I draw from that is either there is a fainter elliptical galaxy there, or there may be no galaxy whatsoever, or maybe a spiral instead of an elliptical. But certainly the same kind of galaxy that surrounds BL Lac itself does not surround QSOs of the same luminosity in their non-thermal continuum.

A. WOLFE:
How many objects can you make that statement about?

J. MILLER:
About 15. There are three possible detections and the three that may show a galaxy are the ones that are known to be in clusters.

P. VERON:
What is the radio structure of these quasars?

J. MILLER:
Big.

P. VERON:
Double?

J. MILLER:
Yes, they are normal ones.

G. BURBIDGE:
Those people who want to assert that the quasi-stellars are in the centers of galaxies still have to provide proof.

J. MILLER:
About half of these objects are in the 3C catalog: 3C 323.1, 3C 215, 3C 277.1 and 3C 47. The optically selected one is PHL 1093. I cannot remember then all.

M. BURBIDGE:
What about 3C 48?

J. MILLER:
I didn't look at 3C 48 because it's too bright. I could not see a galaxy looking right at the center. For most of the objects in my program I couldn't use an annulus because there is no fuzz to look at so you have to look right at the center.

A. WOLFE:
Are any of these the violent variables or the highly polarized sources that Angel has looked at?

J. MILLER:
No, those (the OVVs) are not low luminosity objects.

A. WOLFE:
So these are not what we've been calling BL Lac-type QSOs.

ANONYMOUS:
What is the evidence or lack thereof for variability in the structure, of absorption or emission lines as a function of radio

or optical activity? Is it feasible within our lifetime to see if BL Lac will develop emission lines? Have we done accurate enough observations to see whether these features vary?

J. MILLER:
In some variable N galaxies the emission line strengths do vary. For example, in 3C 390.3, the Balmer lines do change (Osterbrock, D.E., Koski, A.T., and Phillips, M.M. 1976, Ap.J., **206**, 898). In some Seyfert galaxies, changes have been observed in the permitted lines but not in the forbidden lines.

ANONYMOUS:
But what would that do to our definition of BL Lac objects if in 10 years the emission or absorption lines looked totally different?

J. MILLER:
It would be wonderful. [laughter.]

ANONYMOUS:
Is this being looked for?

J. MILLER:
You are not going to spend a lot of time looking for this and hoping it will happen unless there is an indication that it will happen. I think that there is enough interest in BL Lac otherwise so that if strong emission lines suddenly appeared in BL Lac, I don't think it would be too long before someone would notice.

A. WOLFE (To M. Burbidge):
Margaret, have you looked for changes in absorption lines in some of the redshift systems?

M. BURBIDGE:
Yes, I have taken spectra of PHL 5200 which is super nova-like in that it has broad absorption. I hoped that it might eventually break up like a super nova shell, but the absorption spectrum has remained the same for 11 years. Of course now we have much better signal-to-noise than we had at the first observation. We do see some structure in the broad absorption troughs but we are not sure to what extent that structure was or was not there at the outset 11 years ago.

A. WOLFE:
I would like to put a plug in for absorption lines. The changes in absorption due to an outburst in the emitter do not depend on the light travel time between the emitter and absorber. The response time depends only on the intrinsic properties of the absorber and its distance from the emitter, whereas in the emission lines, changes are not observable before a light travel time between the emitter and the gas. So I would suggest that absorption lines are much more sensitive to variability.

D. SHAFFER:
Can't you change the character of the absorption line region if it heats up?

A. WOLFE:
If you have a blast in the QSO, the only time you have to wait for a response in the absorber is a characteristic relaxation time of the absorber. You don't have to wait a light travel time, unlike emission lines.

D. RICHSTONE:
I'd like to come back to the interpretation-free definition. If I understood what people said, it's polarization, rapid-variability in the radio and optical, and non-Planckian optical spectra and something about the flatness of the radio spectrum.

G. BURBIDGE:
Also weakness or absence of emission lines.

D. RICHSTONE:
That is why I said continuous optical spectrum.

A. WOLFE:
That hasn't been agreed upon yet.

D. RICHSTONE:
OK but let me come back to my question. Is that sufficient to specify a non-heterogeneous class of objects? Is there anyone of those characteristics that throws out, for example, the crab nebula pulsar?

K. KELLERMANN:
Maybe it should be included. [laughter.]

G. BURBIDGE:
But the crab pulsar is a regular variable. [laughter.]

K. KELLERMANN:
There is at least one other galactic supernova remnant that has a compact radio source with the same brightness temperature as a QSO or a BL Lac object. It's a classical supernova remnant with a diameter of 30 or 40 arc minutes and right in the middle it has a compact radio source with a diameter of a milliarcsecond and 10^{12} K brightness temperature.

A. WOLFE:
What is this object?

D. SHAFFER:
G127.1+0.5. It was reported in an article in the Monthly Notices by Caswell in December of 1977 (Caswell, J.L. 1977, MNRAS, **181**, 789).

K. KELLERMANN:
21 cm. absorption measurements will of course pin down whether objects like this are galactic or extragalactic so we don't have to worry about that ambiguity.

D. RICHSTONE:

Geoff (Burbidge) made a point that was good, and that is all you have to do is specify that it's irregular, which will destroy the crab pulsar example. But I still worry if we have objects mixed in with this class that aren't at all like most of them.

J. FELTEN:

Don't we want them to be extragalactic?

J. MILLER:

Yes.

A. WOLFE:

Yes, CL4 was thrown to the wind the first day of the meeting because of its galactic origin. [*Ed.: See comment by D. Wills on p. 35.*]

J. MILLER:

I also include luminous, we want them to be luminous objects.

G. BURBIDGE:

But that's not an observational criterion.

R. ANGEL:

The nice thing about optical polarization and irregular variability is that they divide objects into two very definite regions. There is very little overlap there. There are no objects that we have found that split that category. Either they are polarized and vary irregularly on time scales of days or they do neither. So there is one observational criterion that doesn't have any spots.

J. MILLER:

And where would you put 3C 446?

R. ANGEL:

I would put 3C 446, NGC 1275 and all the BL Lac objects in one bag and it's a very well defined bag.

B. WILLS:

It could be that at one time an object looks like a BL Lac object but at other times it doesn't.

R. ANGEL:

But we haven't seen that happen.

G. BURBIDGE:

But 3C 446 is a genuine quasi-stellar object according to the criterion in our book (Burbidge, G.R., and Burbidge, M. 1967, Quasi-stellar Objects (San Francisco: Freeman)). [laughter.]

C. HAZARD:

I think we are talking about a sub-grouping of the quasi-stellar phenomenon which has got strong polarization and rapid variability. I think these two properties define a sub-group of the QSO phenomenon.

G. BURBIDGE:
Not according to the definition that it's a quasi-stellar object.

C. HAZARD:
If you want to stick to that, a quasi-stellar object is a stellar appearing object in which all the emission comes from a star-like object. But now I am talking about a source that has a non-thermal continuum, strong polarization and variability. I think that this defines the group as Roger (Angel) said. This group sometimes includes objects which we now classify as QSOs, but I think that's irrelevant.

J. FELTEN:
But a QSO has a large redshift.

A. WOLFE:
So do some BL Lac objects, such as AO 0235+164 and PKS 0735+178.

J. FELTEN:
Some do but not all. So some BL Lac objects are not at all like QSOs.

J. MILLER:
Which BL Lac object has a real low redshift?

G. BURBIDGE (To J. Miller):
Anyone of the ones that you have been studying have lower redshifts than almost any of the QSOs.

J. MILLER:
But they are still outside the Galaxy.

C. HAZARD:
By high redshift you mean that they are extragalactic?

J. MILLER:
That they have non-thermal sources with luminosities comparable to giant galaxies.

S. COLGATE:
I am wondering if we could get beyond this definition business which doesn't seem to get us very far. If there is any possibility of learning anything special about the underlying galaxy, in the few cases where we can see it, will we learn more with the Space Telescope? Where will the critical measurements be?

M. BURBIDGE:
Yes, you can get 10 times the spatial resolution.

S. COLGATE:
Is that enough to see whether we are dealing with a galactic nucleus? Is that enough to see departures from what we call normal stellar densities in elliptical galaxies?

M. BURBIDGE:

If the object is less than 0.1 sec of arc it will be unresolved.

S. COLGATE:

Can we expect to see departures from the structure of a normal elliptical galaxy on the scale of 0.1 sec of arc?

M. BURBIDGE:

Yes, the luminosity profile for example.

S. COLGATE:

This seems to be a very crucial observation. We should crank up for the extreme case of the brightest underlying galaxy and have a program to look at the galactic structure of the closest analog normal elliptical and the underlying elliptical in BL Lac.

J. MILLER:

The question is if the BL Lac object disappeared would you know whether the galaxy was different from any other galaxy?

S. COLGATE:

Exactly.

J. MILLER:

And that's a very important question.

A. WOLFE (To J. Miller):

You were saying something about the metal abundances in the underlying galaxy in BL Lac.

J. MILLER:

Don't forget we are talking about distances of the order of kiloparsecs from the center. All I was saying was that there didn't seem to be any evidence from the spectra of the outer regions that there was anything unusual. But what is going in the center is another question.

J. WARDLE:

I wonder if anybody could say anything about the prospect for optical interferometry. It will be very valuable to see these things optically with milli-arc sec resolution.

P. MARTIN:

I don't know about the technical prospects but there is a proposal to link the UK telescope in Mauna Kea with the Canada-France Hawaii telescope which will give a baseline at optical and near infrared wavelengths of a milli-arc second. The two telescopes are almost in place but the technical problems of interferometry over that baseline at optical wavelengths have not been solved yet, although they are currently being worked on.

R. ANGEL:

Labeyrie is seeing fringes now down to less than 0.01 sec of arc, so the actual resolution is down to that.

K. KELLERMANN:

Even better than that, but there is a sensitivity problem, getting down to the magnitude where it becomes interesting to do this.

J. MILLER:

One thing you can do without interferometry that's never been done, as far as I know, is astrometry on the nuclei of some of the nearer active sources. With machines, you can measure the absolute position of the nucleus as it goes up and down to 0.005 arc sec. I've often wondered whether the photo-center will change as the light varies. That is something that a long focus refractor and a good measuring machine could do quite well. I know where it could be done. [laughter.]

D. SHAFFER:

Along those same lines, people have each been claiming for three days now that whatever they're doing, be it X-ray, infrared, optical and radio, they are looking at <u>the</u> nucleus of one of these objects. As J. Wardle points out, it is pretty obvious that the emission line region is not where the radio emission is coming from. The radio sources are as small as 1 parsec. That's why I asked G. Shields to draw where a parsec was on his picture yesterday. I think it's possible that there are separate regions where the optical emission and radio emission are coming from, at least lines vs. radio continuum. I don't know about the optical continuum. But that's the same type of problem in terms of absolute position measurement, structure, or whether things move around in that there may be several different regions down in the nucleus area each of which is responsible for different parts of the radiation spectrum.

A. WOLFE:

It seems clear that the radio radiation does not go through the emission line gas because of free-free absorption.

A. MARSCHER:

If relativistic effects are responsible for the rapid variability then along the line of sight the relativistic sources are quite large, larger than the emission line region because you have this factor of γ^2 times ct for the extent of the source. All the VLB measurements refer to the transverse extent. They don't measure the extent along the light of sight. In fact the energy could still come from the nucleus and the radio source. When you start to see it is when you have two blobs coming toward you, about 10 parsecs from the nucleus.

A. WOLFE:

How do you get the source expanding without affecting the emission line region?

K. KELLERMANN:

Are you suggesting that the source is larger along the line of sight than transverse to the line of sight?

A. MARSCHER:

Sure.

K. KELLERMANN:
No, that's not the way it looks in its own rest frame.

A. MARSCHER:
When you say it's a parsec, that two blobs are separated by a parsec, you are measuring the distance perpendicular to the line of sight. At that time...

K. KELLERMANN:
Which time?

A. MARSCHER:
At the time you observe it.

K. KELLERMANN:
It's probably gone by now. [laughter.]

A. WOLFE:
He means the time at which the world line of the source intersects our backward light cone.

A. MARSCHER:
At the time at which the source was at that distance, which would give you a perpendicular separation of 1 parsec, if it is moving relativistically along the line of sight you get another factor of γ.

A. WOLFE:
The important question is what is the size of the source in its own rest frame?

K. KELLERMANN:
Yes, it's spherical and it's a parsec in diameter.

R. BLANDFORD:
I think what he's saying is that it's a 1 pc object located 10 pc from the center of the nucleus.

A. MARSCHER:
Exactly.

A. WOLFE:
That would say that the optical and radio continuum sources are separate.

A. MARSCHER:
Yes, but the energy for both could come from the central region.

K. KELLERMANN:
We know that at radio wavelengths the centimeter and decimeter emission comes from different regions. 3C 273 for example, has these three compact regions which are separated and then there is a halo surrounding them. At longer wavelengths the emission comes from the region further away and the optical may well be off over here.

A. WOLFE:
Will we ever be able to tell where the optical source is relative to the radio?

K. KELLERMANN:
No, this is on a 0.01 arc sec scale.

A. WOLFE:
I meant ultimately.

K. KELLERMANN:
If you could do optical astrometry.

B. DENNISON:
But the optical line-emitting region could surround the radio source if the area filling factor is less than unity because the filaments would be black to free-free absorption so they would not impose any λ^2 effects nor would they impose any Faraday rotation restrictions because you just can't see through them.

A. WOLFE:
But nonetheless the area filling factor can't be too small since these clouds have to absorb a lot of Lyman continuum radiation. In the few high redshift objects where the Lyman limit is red-shifted to the visible about one half of the Lyman continuum is converted to Lyman α in emission.

H. MILLER (To K. Kellermann):
Ken, what can you say in particular about OJ 287 from the apparent strong correlation between optical and radio variability? If the radio and optical emitting regions are completely separate, doesn't it seem unlikely that the radio and optical would be so strongly correlated. In this case it looks like that they are in the same region.

K. KELLERMANN:
Yes, they have to be causally connected.

J. WARDLE:
No, all you've got there is that the polarization position angle is the same.

H. MILLER:
No, the total fluxes are also correlated over long periods of time.

J. WARDLE:
But the detailed, i.e., short, time variation do not correlate very well.

H. MILLER:
But the long-term, from time scales of months to years, do correlate very well in OJ 287.

W. DENT:

I have an unpublished result on this topic. In the case of 0420-01 I am convinced that there is definite evidence for time delay of 2 years between a very pronounced optical outburst that occured in 1975 and a radio outburst which occured again in 1977. In fact the emission patterns both optically and radio-wise are almost identical. The thing is both optically and radio-wise constant for about 8 years until 1975. In 1975 there is an abrupt change in the optical emission. The radio emission does not go up but remains flat until 1977 when it goes up, following the same pattern. It looks like a 2-year time delay. The simplest explanation is that this is a time of flight effect, that you have energy produced in association with the optical emission. The disturbance, whether it is photons or particles, travels out and then emits the radio radiation in some outer region maybe where there is some magnetic field present. Maybe there's a plasma screen. Who knows what it is?

ANONYMOUS:

I have a question about that. Does the second radio outburst go up almost as rapidly, or does it start going up immediately when you see the beginning of the optical outburst?

W. DENT:

It's a very abrupt increase at radio frequencies. It's unclear how fast it went up at optical frequencies because it occurred during that time in which the source was behind the sun. There are always 6 month gaps in the optical records so we don't know. We don't really know how long it took to go up and how long it took to come down in the optical.

K. KELLERMANN (To W. Dent):

Bill, what was the radio wavelength dependence? Was it simultaneous at mm. and cm. wavelengths?

W. DENT:

There is some evidence for time delay between those wavelengths.

J. MILLER:

It struck me that there is one other optical result that has been ignored by the theoreticians. That is the constancy of the optical spectral index over variations of factors of 10 in the light output. As I understand the radio observations there is a change in spectral index when the source brightens. 3C 371 is a good example; it went up and down by some two magnitudes with no change in optical spectral index (Oke, J.B. 1967, Ap.J. Lett, **150**, L5). It's a difficult observation because when it gets faint the galaxy contaminates the spectral index. If you do UBV photometry with the galaxy there you have a lot of interpretation to make of the data. With small apertures you have to be careful about light losses due to atmospheric dispersion.

K. KELLERMANN:
At optical wavelengths the sources are transparent to synchrontron self-absorption. So what you are saying is that in all these events the energy distribution of the synchrontron emitting electrons remains the same. The reason that you see variations in the spectral index of the radio sources is mostly due to changes in the opacity. The energy distribution might change a little too, but the effect is mainly due to opacity. The injection spectrum of the particles could very well be the same throughout the entire event.

A. WOLFE:
There is one case where the optical spectral index did change and that is in AO 0235+164.

S. O'DELL:
The change occurs on short time scales.

A. WOLFE (To S. O'Dell):
How do you interpret that?

S. O'DELL:
I don't. [laughter.]

A. WOLFE:
I want to finish up now by opening up a Pandora's box. Can we explain all these phenomena by conventional physics or must we abandon conventional physics and adopt new physical laws? [laughter.]

G. BURBIDGE (To A. Wolfe):
You know the answer by the reaction of the audience.

J. MILLER (To A. Wolfe):
Artie, a more conservative way of putting it is: Are the phenomena so baffling that it is worthwhile for people to spend 10% of their time thinking about an alternative view.

G. BURBIDGE:
I think it's fairly obvious that if everyone wants to make assumptions about the conventional model, they will go on pushing this argument just as hard as they can, getting more and more ingenious. Whether it's the right way to go I think is really still quite an open question. Unless some of the effort is devoted to thinking about things in a more radical way instead of just listening to Arp and then saying "that was a great presentation but let's move on fellows", we may very well be off on the wrong track. As you know I've been saying this for some time.

M. REES:
I completely agree with Geoff (Burbidge) that we might be off on the wrong track. But you can argue that even if one would bet odds-on that fundamentally new physics is needed, it might still make sense to spend essentially all one's time exploring the consequences of conventional ideas because it's not quite clear what we can productively do to devise a model on the basis of

physics that we don't know yet.

K. KELLERMANN:
That's what Ptolemy did. [laughter.]

G. BURBIDGE:
I think that the problem is that the effect that is caused by this now is that models which people work on, and are very unsure of, are getting into the textbooks. They are treated as facts and that leads some people to work on smaller and smaller pieces of the problem, and I still don't see any sign or evidence that this is correct.

M. REES:
Two comments on that: Obviously the model builders, if they achieve anything, might get the illusory satisfaction of a Ptolemaic astronomer who has just found another epicycle. It might be no more than that. But on the other hand such "theories" as we have consist of either very idealized models with special geometries, which are relevant to part of the problem, or just catalogs of general effects which might be relevant. That's as far as theory has got so far. It is true that most people have focused on a particular model. But, after all, isn't that the right way to go? The orthodox model, almost by definition, is the model on which the most serious work is being done which has not yet already been discredited, and only by refining it further can we either reinforce it or generate new ways of refuting it.

G. BURBIDGE:
Which model is that? [laughter.]

M. REES:
The general class of models involving infall onto a compact object or a spinar. I won't specify it further than that. So I would have thought it reasonable to use that model as a guide to what areas of theoretical work are now worthwhile regarding the radiation mechanism. But one should not expect too much yet because, after all, we haven't thought about these problems for very long and it's too much to expect an adequate model for what is certainly a multi-parameter problem involving the mass, the infall rate, the type of galaxy, the environment, etc. So we can't expect any simple model to fit observations accurately.

G. BURBIDGE:
Let's talk about another aspect of this problem. Why are people believing that there are relativistic effects present at all? They believe in these because they first of all make an assumption about distance. The radio astronomers would not believe that things were expanding relativistically--we hear the term superluminal getting into literature. What's it based on?

M. REES:
It's based on an assumption about distance.

G. BURBIDGE:
The only object for which there is any certainty about is NGC 1275. Here there is no evidence for superluminal expansion.

D. SHAFFER:
3C 120!

G. BURBIDGE:
3C 120, it has to be demonstrated that it is a galaxy.

D. SHAFFER:
Gene Harding told me two nights ago...

G. BURBIDGE:
Smith, Gene Smith!

D. SHAFFER:
Gene Smith swears that it is a galaxy.

G. BURBIDGE:
Yes, he's working on it very hard. [laughter.]

D. SHAFFER (To J. Miller):
Can you prove that 3C 120 is a galaxy so that Geoff (Burbidge) will quit hassling us about 3C 120?

J. MILLER:
It shows MgIb, and K of CaII - that is, features of a galaxy - but it shows more. It is not a giant elliptical galaxy.

G. BURBIDGE:
I'm usually told that it is a spiral galaxy. I was told that there is an excellent picture showing that it was a spiral galaxy, in fact Veron called it a Seyfert galaxy earlier today.

D. SHAFFER:
You said that you would accept that it was a galaxy if it showed H and K absorption lines.

G. BURBIDGE:
Yes, that's right at that redshift.

D. SHAFFER:
Joe (Miller) says that it has CaII K absorption...

M. BURBIDGE:
It has H and K.

J. MILLER:
And MgIb too.

D. SHAFFER:
We claim that there are double sources which separate at twice or three times the speed of light in 3C 120 at its redshift distance, so there are known to be relativistic effects in bulk motion.

G. BURBIDGE:
Let us wait and see. Let us see this information. I still have not seen anything published on this subject. I have been through this several times.

J. MILLER (To G. Burbidge):
Geoff, I feel I keep going to the telescope just for you. [loud laughter.]

A. WOLFE:
It's for a noble purpose. [laughter.]

M. BURBIDGE:
Let's change the subject. I think more theoretical work needs to go into this question of how to get these multiple absorption lines.

M. REES:
I agree, but one should not expect too much out of the theory because we don't necessarily have even the right general scenario. Even if we did, you wouldn't expect it to explain the observations in detail. Let me give an example. No one believes that one needs to invoke new physics to explain the solar cycle. And yet there is no detailed explanation for that. Even if there was, you wouldn't expect such a theory to predict the exact configuration of sun spots. So even if we did have the right explanation we couldn't explain all the details of the observations. So I don't think we've gotten to the stage...

K. KELLERMANN:
These are not details that we are trying to explain.

M. REES:
Right so maybe we haven't got to the stage where we know what the right general scenaro is.

K. KELLERMANN:
None of us are very concerned about the detailed distribution of sun spots.

M. REES:
Right.

M. BURBIDGE:
But we are concerned about the explanation for the absorption lines and I think that is a very important problem.

A. WOLFE:
One interesting thing we haven't talked about is this observation of B. Wills showing an absorption redshift much higher than the emission redshift. How can we explain that? [*Ed.: See footnote to talk by B. Wills on p. 242*].

G. SETTI:
Isn't there another object like that?

M. BURBIDGE:
It's one of a group of six high-redshift objects that we have been investigating, OF 097.

J. FELTEN:

As an ignoramous on the subject of BL Lacs I will nevertheless presume to follow up on Martin Rees'analogy of the solar cycle which I thought was an excellent one. The point is this: the parameters in this problem, like those in the solar cycle, are so many that the experts cannot even agree on the definition of the phenomena. We have failed so far to agree on a definition of BL Lac objects. In that situation, looking at this meeting as a man from Mars, I would say that it would be extremely presumptious if the meeting would conclude that although they don't know how to define this phenomenon, yet they are sure that the conventional theory is exhausted. [laughter.]

A. WOLFE:

The meeting is concluded.

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