THE BL LACERTAE OBJECTS

×2095

W. A. Stein
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

S. L. O'Dell
Department of Physics, University of California, San Diego, La Jolla, California 92093

P. A. Strittmatter
Steward Observatory, University of Arizona, Tucson, Arizona 85721

1 INTRODUCTION

Although discovered relatively recently, the class of objects of which BL Lac is the prototype is currently the subject of very active study. The peculiar character of these objects became apparent after the identification (Schmitt 1968) of the "variable star" BL Lacertae with the unusual radio source VRO 42.22.01 (MacLeod & Andrew 1968) and subsequent detections of rapid variations in the radio spectral flux (Biraud & Véron 1968, Andrew et al. 1969, Gower 1969) and linear polarization (Olsen 1969). In addition the optical radiation was shown to exhibit a continuous spectrum with neither emission nor absorption lines (Oke, Neugebauer & Becklin 1969; DuPuy et al. 1969) and a relatively high degree of linear polarization (Visvanathan 1969).

Subsequent optical, infrared, and radio observations by several investigators led Strittmatter et al. (1972) to suggest that objects similar to BL Lac comprise a class of quasi-stellar objects (QSOs) with some combination of the following characteristics: (*a*) absence of emission lines in the core source; (*b*) rapid variability at radio, infrared, and visual wavelengths; (*c*) nonthermal continuum with most of the luminosity radiated at infrared wavelengths; and (*d*) strong and rapidly varying polarization. Additional examples of this class investigated by Strittmatter et al. (1972) were OJ 287 (VRO 20.08.01), ON 231 (W Com), ON 325 (B2 1215+30), and PKS 1514–24 (AP Lib). The number of BL Lac objects known now exceeds 30 and is increasing rapidly (see Table 1; see also Kinman 1976).

Research on BL Lac objects has been concerned mainly with (*a*) documenting their properties, (*b*) investigating their relationship to QSOs and galaxies, (*c*) determining their distances in the absence of emission lines, and (*d*) accounting for the continuum emission within the constraints set by their rapid variability. A tacit hope has been that the apparently more rapid activity observed in BL Lac objects would lead to an understanding not only of these objects but also of QSOs. In this review we discuss progress made in this area up to approximately September 1975.

Table 1 Summary of data for BL Lac objects

(1) Object	(2) Name	(3) V	(4) $B-V$	(5) $U-B$	(6) $\alpha_{\rm opt}$	(7) Reference[a] (photometry)	(8) Reference[a] (spectroscopy)	(9) $P_{\max}$(%)
0048−097	OB 081	16v	0.48	−0.44	1.8	49	10	14
0219+428	3C 66A	15–16	0.33	−0.58	1.4v	15, 49, 52	52	14
0235+164	AO	14.5–19.5	0.96	+0.14	4.0	38, 46	9, 38	25
0340+046	3C 93	18–18.5	0.37	−0.52	1.3	27	41	5
0521−365		14–16	0.76	−0.28	2.7	20	44	
0537−441		13.5–15.5	0.46	−0.57	1.4	21	37	
0548−322		15.5	0.57	−0.30	2.3	18	18, 22	
0735+178		14.5–16	0.47	−0.58v	1.4	49	11	31
0808+019		17	0.38	−0.64	0.9	27	47	14
0829+046	OJ 049	16.5	0.70	−0.37	2.3	27	53	
0851+202	OJ 287	12.5–15.5	0.39	−0.64	1.1	27	28	29
0906+430	3C 216	18–19	0.55	−0.54	1.8	27	41	21
0912+297	OK 222	16v	0.37	−0.73	1.4	49	17	13
0957+226	4C 22.25	18	0.30	−0.66	0.8	49	42	4
1057+100		17.5	0.39	−0.74	1.3	49	47	10
1101+384	Mk 421	13.5v	0.51	−0.55	1.7	27	50	6
1147+245	OM 280	16	0.46	−0.57v	2.0v	49	47	13
1215+303	ON 325	15.5–16	0.46	−0.61	1.8	49	48	14
1219+285	W Com	16–17v	0.61	−0.54v	2.3	49	48	10
1225+206	4C 20.29	18	0.23	−0.72	0.6	27	42	4
1307+121	4C 12.46	18.5–19	0.53	−0.51	1.8	27	29	
1400+162	4C 16.39				1.5	3	3	14
1514+197		18.5–19	0.66	−0.45	2.3	27	47	9
1514−241	AP Lib	15v	0.80	−0.29v	2.7v	27	45	6
1538+149	4C 14.60	17.5v	0.52	−0.60v	2.0v	3, 15, 49	55	22
1652+398	Mk 501	13.8	0.74	−0.25	2.6	4, 27	50	3
1727+502	I Zw 186	16v	0.63	−0.52	1.9v	3, 15, 49	33, 34	6
1749+096	OT 081	16.5–17.5	0.83	−0.41	2.3v	3, 15, 49	47	9
2117+025	OX 029	18					16	8
2200+420	BL Lac	14.5v	0.97	−0.10v	2.4v	26, 27	19	19
2254+074	OY 091	16.5	0.66	−0.44	2.6v	3, 15, 49	47	21
2335+031	4C 03.59	17.5–18.5	0.68	−0.39	2.3	3, 15, 49	47	

[a] References:

1. Altschuler & Wardle (1975).
2. Argue et al. (1973b).
3. Baldwin, Hazard, Nordsieck & Wampler (1976) unpublished.
4. Blake (1970).
5. Bolton et al. (1965).
6. Browne (1971).
7. Browne & McEwan (1972).
8. Browne et al. (1973).
9. Burbidge et al. (1976).
10. Carswell et al. (1973).
11. Carswell et al. (1974).
12. Colla et al. (1975).
13. Condon & Jauncey (1974a).
14. Condon & Jauncey (1974b).
15. Craine et al. (1975a).
16. Craine & Warner (1976).
17. Crovisier et al. (1974).
18. Disney (1974).
19. DuPuy et al. (1969).
20. Eggen (1970).
21. Eggen (1973).
22. Fosbury & Disney (1976).
23. Hazard & Murdoch (1975) unpublished.
24. Hoskins et al. (1974).
25. Hoskins et al. (1972).
26. Kinman (1975a).
27. Kinman (1975b).
28. Kinman & Conklin (1971).
29. Lynds & Wills (1972).

Table 1 continued

Object	(10) b	(11) Reference[a] (identification)	(12) $B_{\min}^{(51)}$	(13) $\Delta B^{(51)}$	(14) $\alpha_{\rm rad}$	(15) Reference (radio spectrum)	(16) Comments
0048−097	−72	24	14.5	2.7	−0.4	1, 30, 42	
0219+428	−17	52			1.1, 0.3	32	
0235+164	−39	2	15.3	5.2	0.0	36	$z_{\rm abs} = 0.524$ (and 0.852)
0340+046	−38	40			0.8	14	4C 04.13, OE 069, NRAO 144
0521−365	−32	5	14.6	1.4	0.4	51	E $z = 0.055$
0537−441	−31	37	12.6	5.4	−0.7	51	
0548−322	−26	45			0.5	22	G $z = 0.069$ (cluster $z = 0.042$)
0735+178	+18	4	14.5	2.2	0.0	14, 30, 51	VRO 17.07.02, $z_{\rm abs} = 0.424$
0808+019	+18	7			−0.2	13	
0829+046	+24	53	15.0	1.9	−0.1	51	
0851+202	+38	4	12.4	4.0	−0.5	1, 14, 30	VRO 20.08.01, E?
0906+430	+42	39			0.7	30	
0912+297	+43		15.1	1.9	0.4	1, 51	B2
0957+226	+50	35			0.7	14	
1057+100	+58	25			0.9	31	
1101+384	+65	12	11.7	4.6	0.1	1, 12, 14	B2, G $z = 0.31$
1147+245	+76	24					
1215+303	+82	6	13.9	2.1	0.3	1, 14, 51	
1219+285	+83	6	13.2	4.0	−0.2	1, 14, 51	ON 231, E
1225+206	+69	35					
1307+121	+74	49			0.5	54	OP 112
1400+162	+70	23					OQ 100
1514+197	+56	8			0.0	14	
1514−241	+57	5	14.0	2.4	0.0	1, 51	OK−225, G $z = 0.049$
1538+149	+49	55	14.4	>2.8	0.0	14, 51, 54	
1652+398	+37	12			0.1	12	4C 39.49, B2, G $z = 0.034$
1727+502	+34	56	15.0	1.9	0.3	1, 51	OT 546
1749+096	+18	8			−0.1	14, 30	
2117+025	−31	16					II Zw 123
2200+420	−10	43	12.6	4.0	−0.5	1, 30, 51	VRO 42.22.01, E(G? $z = 0.07$?)
2254+074	−44	8	15.7	1.6	−0.3	14, 51	E
2335+031	−55	15			0.6	13, 14	E

30. Medd et al. (1972).
31. Murdoch & Hoskins (1973).
32. Northover (1973).
33. Oke (1967a).
34. Oke et al. (1967).
35. Olsen (1970).
36. Pauliny-Toth et al. (1972).
37. Peterson & Bolton (1972).
38. Rieke et al. (1976).
39. Ryle & Sandage (1964).
40. Sandage & Wyndham (1965).
41. Schmidt (1968).
42. Schmidt (1974).
43. Schmitt (1968).
44. Searle & Bolton (1968).
45. Shimmens & Bolton (1974).
46. Spinrad & Smith (1975).
47. Strittmatter et al. (1974).
48. Strittmatter et al. (1972).
49. Tapia et al. (1976).
50. Ulrich et al. (1975).
51. Usher (1975) [also Liller (1975) private communication].
52. Wills & Wills (1974a).
53. Wills & Wills (1976).
54. Wills & Bolton (1969).
55. Wills & Wills (1974b).
56. Zwicky (1966).

We call attention to recent reviews of observational data on BL Lac objects by Pollock (1975b), on their radio properties by Altschuler & Wardle (1975), and on their relationship to variable QSOs by Kinman (1975b).

2 SUMMARY OF KNOWN SOURCES

In Table 1 we list sources reasonably well established as members of the BL Lac class. The columns contain (1) the coordinate-type object designation, (2) other name, (3) V magnitude, (4) $(B-V)$ color, (5) $(U-B)$ color, (6) approximate optical spectral index (with $F_\nu \propto \nu^{-\alpha}$), (7) references to optical photometry, (8) references to spectroscopy, (9) maximum linear polarization in the optical (in per cent), (10) galactic latitude, (11) references to finding chart, (12) brightest B magnitude recorded on archival plates, (13) range B magnitude on archival plates, (14) approximate radio spectral index, (15) references to radio spectral index, and (16) comments. The letters E and G in the last column denote BL Lac objects associated with nebular extensions and galaxies, respectively. Although many other quasi-stellar radio sources appear to have continuous optical spectra, we have not included these in Table 1, because no additional property such as variability or polarization has yet been confirmed. The objects listed in Table 1 comprise a rather heterogeneous sample: Some objects (e.g. 1652+39) are clearly nuclei of galaxies, others (like BL Lac, or W Com) have faint surrounding nebulosity, possibly a galaxy, while the remainder (e.g. 0735+178) appear stellar. The range of mean apparent magnitude is fairly small (indeed comparable with the largest variations observed) and probably results from observational selection at fainter magnitudes. Not only is it more difficult, especially with photographic spectroscopy, to rule out the presence of weaker lines in faint objects, but polarimetry becomes time consuming, and historical records of variability are less frequently available.

3 DESCRIPTION OF SOME INDIVIDUAL SOURCES OF PARTICULAR INTEREST

Although many objects similar to BL Lac have been found, only a few have been studied in detail. In this section we summarize important properties of a few such objects, commencing with BL Lac itself. Our goal is to use these well-studied cases to illustrate important properties of the class rather than to provide an exhaustive review of the properties that each object has in common with other members.

3.1 *BL Lac*

Schmitt (1968) identified the "variable star" BL Lacertae with the radio source VRO 42.22.01 (MacLeod & Andrew 1968). Due to temporal variations in spectral fluxes, the shape of the radio spectrum at any one time is difficult to determine. Jones, O'Dell & Stein (1974b) derived the shape of the radio spectrum for the epoch 1971.75 using various published data. Interpreting the spectral-flux distribution requires care since it undoubtedly arises from the superposition of several components with different individual spectra. Under the canonical assumption of synchrotron self-absorption, the radio spectrum of BL Lac requires at least three compact components. Curiously, the radio-frequency data for BL Lac may at times be represented by an $F_\nu \propto \nu^{1/3}$ dependence, characteristic of synchrotron emission with a low-energy cutoff in the distribution of relativistic electrons; however, it is clear that superposition of compact components is the cause of the observed spectral form. The reasons for this conclusion are as follows:

1. Various theoretical considerations regarding the brightness temperature of synchrotron sources (Hoyle, Burbidge & Sargent 1966; Kellermann & Pauliny-Toth 1969; Burbidge, Jones & O'Dell 1974) require that the depth to self-absorption be of order unity for the observed parameters, thus supporting the self-absorption interpretation (Jones, O'Dell & Stein 1974a; Jones et al. 1974b).
2. The time scales for variations of spectral flux increase with increasing wavelength, indicating increasing linear dimensions for the emitting regions. The time scales are typically several weeks for $\nu \gtrsim 10$ GHz (Andrew et al. 1969, MacLeod et al. 1971, Hackney et al. 1972, Dent & Kojoian 1972, Medd et al. 1972, Dent & Hobbs 1973), a few months for $\nu \approx 1$ GHz (Gower 1969, Altschuler & Wardle 1975), and a few years for $\nu < 1$ GHz (Stannard et al. 1975).
3. Very long baseline interferometry indicates multiple components (Clark et al. 1973, Schaffer et al. 1975).
4. In general, the dependence of linear polarization upon frequency also may indicate complex source structure (e.g. Wardle 1971).

At radio frequencies, the linear polarization is typically a few percent and variable in degree and direction (Olsen 1969; MacLeod et al. 1971; Berge & Seielstad 1972; Ekers, Weiler & van der Hulst 1975; Altschuler & Wardle 1975) on a time scale shorter than that for variations in spectral flux. The circular polarization usually is undetectable or present at but a few tenths of a percent (Seaquist 1969; Seielstad 1969; Berge & Seielstad 1972; Seaquist et al. 1973; Seaquist 1973; Ekers et al. 1975); however, occasionally, usually only for a brief period near a maximum in spectral flux, circular polarization in excess of 1% has been detected (Biraud & Véron 1968, Biraud 1969, Seaquist 1973). It has been suggested that the conversion of linear polarization to circular polarization (Sazonov 1969, Pacholczyk & Swihart 1971, Pacholczyk 1973, Pacholczyk & Swihart 1974) quite possibly dominates the intrinsic contribution to circular polarization (Legg & Westfold 1968) near the spectral maximum. Continued monitoring of the radio-frequency circular polarization of rapidly variable compact nonthermal sources such as BL Lac thus seems to be a potentially fruitful program.

The structure of the radio source (VRO 42.22.01) associated with BL Lac has been deduced from VLBI measurements. At 8.4 GHz the source consists of two components elongated in the north-south direction by ~ 1 msec (Clark et al. 1973). The structure has been observed to change on a time scale of 1 msec yr^{-1}. If the redshift were $z = 0.07$ (Oke & Gunn 1974; Thuan, Oke & Gunn 1975; but also see Baldwin et al. 1975), this would correspond to an apparent expansion velocity of 6 c.

MacLeod & Andrew (1968) found a rotation measure consistent with BL Lac being extragalactic. Pigg & Cohen (1971) observed the 21-cm line in absorption against VRO 42.22.01, compared the results with those of 3C 438, and also concluded that they were consistent with BL Lac being extragalactic. However, the results set a lower limit to the distance of only 200 pc and, therefore, do not alone rule out a galactic origin of BL Lac. We are unaware of analogous studies in the optical using, for example, the interstellar Ca II lines, although such a project seems worthwhile.

Harvard archival plates indicate that BL Lac fluctuates between 14 and 16 visual magnitudes, with rare bursts to $V \lesssim 13$ (Shen & Usher 1970). Since the discovery of its peculiar nature, there have been many optical photometric observations of BL Lac (e.g. Bertaud et al. 1969, Milone 1972, Bertaud et al. 1973a, Milone 1974). Bertaud et al. (1973b) have given an excellent summary and bibliography. Kinman (Carswell et al. 1974) has carried out a long-term study, obtaining night-to-night variations of $\Delta m_{\mathrm{rms}} \approx 0.3$ mag for 1968–1970 and $\Delta m_{\mathrm{rms}} \approx 0.15$ mag for 1970–1972. Several other investigators (e.g. DuPuy et al. 1969; Bertaud et al. 1969; Racine 1970; Tritton & Brett 1970; Romano 1971; Cannon, Penston & Brett 1971; Epstein et al. 1972; Weistrop & Goldsmith 1973) have found comparable night-to-night variations. In this respect, BL Lac is apparently among the more active objects in the class. Bertaud et al. (1969), Weistrop (1973), and Weistrop & Goldsmith (1973) have reported variations of about 1 mag with a time scale of about an hour. In addition Weistrop (1973) obtained 0.5 magnitude changes in only a few minutes; however, Evseev, Kusminov & Tsarevsky (1973) detected no dramatic variations over so short a time scale, even though they observed BL Lac on the same night (1972 December 5) that Weistrop (1973) observed rapid changes. Racine (1970) reported flickers of 0.03 mag in a few minutes and fluctuations of 0.1 mag over a few hours. Since some of the claims to detection of variability on exceedingly short time scales involve only a few observations or very small amplitudes and lack independent confirmation, we consider conclusions based on such observations premature. It is, however, of considerable interest to determine the minimum time scale of variability and/or possible periodicities.

Oke, Neugebauer & Becklin (1969), using the Hale multichannel scanner and infrared photometers, have measured the ultraviolet-to-infrared spectrum of BL Lac. The optical and near infrared spectrum may be fitted by a power law, $F_\nu \propto \nu^{-\alpha}$ with $\alpha \approx 2.2$, which becomes steeper at optical wavelengths (redder) as the flux density decreases (Racine 1970). BL Lac has also been detected at wavelengths up to 10 μm, and the infrared flux varies with time (Oke, Neugebauer & Becklin 1969; Stein, Gillett & Knacke 1971; Epstein et al. 1972; Rieke 1972; Rieke & Kinman 1974). The spectrum (a continuum from ultraviolet to radio wavelengths) is such that most of the power is radiated in the infrared. At very short wavelengths, a search for X-rays from BL Lac proved negative, but furnished an upper-limit flux of 1.0×10^{-10} erg cm^{-2} sec^{-1} in the 2.5–7.5 keV energy range (Margon et al. 1976).

Visvanathan (1969, 1973a) has measured the optical polarization as a function of wavelength. Numerous broad-band measurements have also been obtained (e.g. Dombrovsky 1971, Strittmatter et al. 1972). The linear polarization, generally in the range 5–15%, is independent of wavelength and, evidently, of spectral flux as well.

In order to investigate the relationship of radio, infrared, and optical radiation from BL Lac through temporal variations, some groups have coordinated simultaneous observations at radio and optical wavelengths (Hackney et al. 1972, Andrew et al. 1974, Mikami et al. 1974) or with the infrared as well (Epstein et al. 1972). Hackney et al. found an isolated optical flare followed in 55 days by a radio flare; however, the observations could not be correlated using a constant radio-optical delay. Andrew et al. (1974) found similar time scales for optical and radio variations but no conclusive evidence for a correlation. As yet, there appears to be no obvious relationship between the short-term variations (weeks) at optical and radio frequencies for BL Lac. Wardle (1971) has pointed to a difference in polarization angle obtained at optical (Visvanathan 1969) and radio (3.75 cm; Olsen 1969) wavelengths as evidence against the observed optical and radio emission originating in the same source component of BL Lac (at least at that epoch for the wavelengths observed).

One of the most interesting and controversial aspects of the study of BL Lac has been the investigations of the nature of the diffuse optical emission surrounding the source. The object is nonstellar on the Palomar Observatory Sky Survey Prints (see also Arp in MacLeod et al. 1971; Penston & Penston 1973; Kinman 1975a). Adopting the composite model used by Sandage (1973) for N galaxies, Adams (1974) attempted to deduce the nature of the diffuse emission plus core using broad-band photometry. He assumed that the spectra of both constituents remained fixed during variations of core brightness and obtained the individual spectra by combining observations made at different brightness ratios. Assuming a standard galaxy spectrum for the nebulosity, he derived a redshift $z \sim 0.02$. Wlérick et al. (1974) used electrographic techniques to study the surface-brightness distribution in the nebula. Again assuming that the nebula was indeed an elliptical galaxy, they obtained a distance estimate of ~ 300 Mpc (or $z = 0.05$ for $H \approx 50$ km sec^{-1} Mpc^{-1}). Kinman (1975a) employed UBV photometry with different apertures, ranging from 7″ to 20″, to show that the distribution of surface brightness was consistent with an elliptical at $z = 0.07$, but not with one at $z = 0.02$. These methods should perhaps be viewed as indicative rather than definitive since they *assume* that the nebula is an elliptical galaxy and that it is "normal."

Oke & Gunn (1974) first attempted a direct determination of the nebular spectrum using the Hale multichannel scanner and an annular diaphragm to occult the central source. The data are of high signal-to-noise ratio but of low resolution. Oke and Gunn claimed to observe absorption features that would fit those corresponding to an elliptical galaxy at a redshift $z = 0.07$. The ultraviolet data were not consistent with that expected from an elliptical galaxy; however, an explanation was offered in terms of differential refraction from the central source around the occulting disk. Baldwin et al. (1975) tried to obtain a spectrum of the nebulosity using the Lick Observatory scanner. They observed only a portion of the nebula through a slit and made running checks on the amount of scattered light. The observations provided higher spectral resolution than those of Oke and Gunn and comparable signal to noise at *equal* wavelength intervals (obtained by subsequent numerical smoothing). They found that the continuum was similar to but slightly steeper than that of the nucleus, i.e. that there is an ultraviolet excess with respect to an E galaxy spectrum. This result is consistent with Oke's and Gunn's observations (but not their interpretation). Baldwin et al. were unable to confirm the presence of absorption features in the spectrum of the nebulosity. Subsequently, Thuan et al. (1975) repeated the original Hale experiment and obtained essentially the same result as on the first occasion. The problem is thus one of interpretation rather than photon statistics and is complicated by atmospheric refraction, scattering, and the presence of faints stars within a nebular radius. Although the redshift of BL Lac remains controversial, it is no longer so crucial, since other observations show that some other BL Lac objects are associated with galaxies (e.g. Ulrich et al. 1975; Disney, Peterson & Rogers 1974) and some can have much higher redshifts (Carswell et al. 1974). Further study of the nebulosity around BL Lac itself, however, is necessary in order to establish unambiguously the nature of the nebulosity (galaxy or nonthermal source) and, if possible, the distance to BL Lac. The latter would permit more profitable use of the wealth of data that has been accumulated for this source.

3.2 *OJ 287*

The source OJ 287 is very similar to BL Lac in many of its observed properties (Strittmatter et al. 1972). Archival records indicate four large optical bursts since 1894 with time scales of several months (Visvanathan & Elliot 1973). The optical spectrum is continuous (Kinman & Conklin 1971, Adam et al. 1972), and the light is highly linearly polarized (Nordsieck 1972), up to ~10% independent of wavelength (Visvanathan 1973b). It is variable in flux density by as much as a few tenths magnitude per day (e.g. Tsesevich 1972, Craine & Warner 1973, Goldsmith & Weistrop 1973, Véron & Véron 1975) and in linear polarization as well (e.g. Kinman & Conklin 1971, Strittmatter et al. 1972, Williams et al. 1972).

Various investigators have suggested possible periodicities in the temporal variations (~1 mag) of 30 days (Williams et al. 1972), 26 days (Tsesevich 1972), and 8 days (Kinman et al. 1974). Visvanathan & Elliot (1973) and Frohlich, Goldsmith & Weistrop (1974) have reported a possible very-small-amplitude (0.0065 mag) periodicity of 39.2 min. The longer-term periodicities were hypothesized after only one or a few periods or partial periods and lack confirmation. Power-spectrum analyses of two optical runs for OJ 287 do not confirm a 39-minute period (Kiplinger 1974). Substantiation of periodic variations in any extragalactic object would obviously be extremely important to our understanding of the physical processes; however, on the basis of the present data, we find no strong support for the existence of periodic variations.

The radio-frequency emission is linearly polarized at a few percent (at times, depending on the observing frequency) and variable (Berge & Seielstad 1972, Kinman et al. 1974, Altschuler & Wardle 1975). No circular polarization has yet been detected (Berge & Seielstad 1972) and upper limits are a few tenths of a percent. Here, as for BL Lac, the radio spectrum (Blake 1970) indicates two or more compact nonthermal components. Cohen et al. (1971) were unable to resolve the source at 3.8 cm (~0.5 milliarc seconds); however, Shaffer & Schilizzi (1975) found a diameter of 2.2 msec at 18 cm.

Several groups have coordinated simultaneous observations of OJ 287 in the radio and optical (Kinman & Conklin 1971, Kikuchi et al. 1973, Kinman et al. 1974), in the infrared and optical (Dyck et al. 1971, Rieke & Kinman 1974), and in the radio, infrared, and optical domains (Epstein et al. 1972). Here, as with BL Lac, there appears to be no evidence for a simple correlation between short-term (days) radio and optical variations; however, the long-term variations (months) do show evidence for correlation from radio through optical frequencies (Rieke 1972, Kinman et al. 1974). The correlation of infrared with optical and radio variations (Rieke 1972), as well as the apparently smooth continuation of the optical spectrum into the infrared (Strittmatter et al. 1972) suggests that for OJ 287 the radiation in all three frequency domains arises in the same source component and reflects the same (or at least related) physical process—namely, incoherent electron synchrotron radiation.

Unlike BL Lac, OJ 287 appears stellar on the sky-survey plates and even on higher-scale photographs, at least while the object was in a comparatively bright phase. According to Kinman (1975b), however, there may be a very faint extension toward the NNW, visible on plates taken with the 4-m Mayall telescope while OJ 287 was fainter than usual.

OJ 287 has provided an opportunity to study the spectral variation in BL Lac objects over a wide range of brightness. A large outburst took place in 1972 January, in which the visual magnitude reached ~ 12.2 (Visvanathan 1973b). The object subsequently declined to ~ 15 mag in two years with no long-term change in the relative flux densities at 10.5 and 0.44 μm (Rieke & Kinman 1974) or in the $U-B$ and $B-V$ color indices (Smith et al. 1975). At this peak brightness, OJ 287 was, for a time, one of the brightest known objects with QSO characteristics in the sky.

3.3 *AP Libra*

Less detail is known about the spectral-flux distribution and variability at radio, optical, and infrared wavelengths of AP Libra. Information available, however, clearly indicates that it is a member of the BL Lac class (Strittmatter et al. 1972). Rogers (1971) found the optical spectrum to be a pure continuum. AP Lib exhibits a diffuse halo surrounding the core, which is more easily discernible than for BL Lac. Indeed Bolton, Clarke & Ekers (1965) classified it as an elliptical galaxy, while Westerlund & Wall (1969) classified it as an N galaxy. Disney et al. (1974) investigated the nebulosity and suggested that the core source is surrounded by an elliptical galaxy at a redshift $z = 0.0486$. The result is based on a number of tracings of photographic spectra obtained over a period of three years. More recent scanner data obtained at the Anglo-Australian Telescope apparently confirm this result (B. A. Peterson, 1975, private communication). Disney et al. (1974) also suggested that emission lines are sometimes detectable in the object. If confirmed, this would be an important clue in understanding the absence of emission lines in BL Lac objects.

Optically, AP Lib varies both in flux density (Bond 1971, Biraud 1971) and linear polarization (up to $\sim 8\%$, Strittmatter et al. 1972). UBVRIJHKL photometry (Andrews, Glass & Howarden 1974) indicates a power-law spectrum, which steepens (reddens) when the core source is fainter. The optical spectrum continues into the infrared in a manner similar to those of BL Lac and OJ 287 (Rieke 1972, Andrews et al. 1974). Although Frye et al. (1971) reported the possible identification of an apparently variable γ-ray ($E > 100$ MeV) source with AP Lib, Margon et al. (1976) detected no X-ray emission from this source.

Nicolson (1971) found the 2295 MHz flux from AP Lib to be constant over a period of four years. Hunstead (1971) has also called attention to the lack of radio-frequency variability and to the displacement of the centroid of the 408-MHz source from the center of the optical object by 5″. Higher-resolution studies at the same frequency (Conway & Stannard 1972), however, reveal a compact component coincident with AP Lib and an extended component 20″ away, thus accounting for the displacement found at lower resolution. The linear polarization at centimeter wavelengths is a few percent and relatively constant over a year (Altschuler & Wardle 1975).

3.4 *PKS 0735+178*

Carswell et al. (1974) observed PKS 0735+178 in some detail at optical wavelengths. It is outstanding in its degree of variable optical polarization (5–30%) and flux variability ($\Delta m_B \sim 1$ mag) on time scales of less than one month (Wing 1973, Véron & Véron 1975). The spectrum exhibits no emission lines, but does contain two sharp absorption lines at 3981 and 3991 Å that have been identified with the Mg II $\lambda2798$ doublet (Carswell et al. 1974), implying a redshift $z = 0.424$. Adopting this redshift as an indication of its distance, one finds that 0735+178 is comparable in luminosity with the QSO 3C 273. The absorption could originate in ejected gas or intervening material so that the redshift of the continuum source could be greater, as is generally the case for QSOs. No nebular extensions have been reported for 0735+178, nor is there any obvious cluster of faint galaxies around the source on sky-limited red plates taken at the Steward Observatory 2.2-m telescope (P. A. Strittmatter, 1975, private communication). The spectral-flux distribution rises from the optical to the infrared, as in other BL Lac objects (Rieke & Kinman 1974). These observations of 0735+178 are especially significant in that they further illustrate the intimate connection of the BL Lac objects with quasi-stellar objects.

3.5 *AO 0235+164*

This BL Lac object is particularly interesting for several reasons. Other than PKS 0735+178, AO 0235+164 is the only BL Lac type object to exhibit spectral features. In fact, the spectrum of AO 0235+164 indicates two absorption redshifts (Burbidge et al. 1976, Rieke et al. 1976): the first ($z = 0.5239 \pm 0.0001$) is well established, with lines of Mg I, Mg II, Ca II, Mn II, and Fe II measured; the second ($z = 0.852$) is probable, with the Mg II doublet and a possible Fe II multiplet present. In addition to the optical absorption lines, the 21-cm line of atomic hydrogen has been detected in absorption at a redshift $z = 0.52385 \pm 0.00001$ (Roberts et al. 1976). Thus AO 0235+164 is the first extragalactic object for which a hyperfine transition, fine-structure splitting, and resonance lines have all been found at the same redshift.

The presence of the three types of atomic transitions at essentially the same redshift and the cosmological interpretation of the redshift place severe limits on temporal changes of three combinations of quantum electrodynamical constants. Wolfe, Brown & Roberts (1976) found the most restrictive of these limits to be $<2(10^{-14})$ per year!

The radio source AO 0235+164 was identified (Argue, Kenworthy & Stewart 1973b) with a red stellar object at $V \approx 19$ mag. Spinrad & Smith (1975) reported that the radio spectrum was flat ($\alpha \approx 0$) and variable, and found that the optical spectrum was steep ($\alpha \approx 4$) and featureless over the spectral range examined (0.70 μm $\gtrsim \lambda \gtrsim$ 0.43 μm) and that the apparent magnitude was variable ($17.5 \lesssim V \lesssim 19.5$ during 1972 to 1974). In late 1975 the object brightened dramatically to $V \approx 14.3$ (Kinman & Rieke 1975) and began to fade, with little change in spectral shape except at the longest ($\sim$10 μm) wavelengths (Rieke et al. 1976). It was at this time that several strong absorption features shortward of 0.43 μm were discovered (Burbidge et al. 1976, Rieke et al. 1976). These and several weaker features permitted the determination of the two redshifts $z = 0.542$ and $z = 0.852$.

Near maximum the optical flux was variable by as much as $\sim$0.2 magnitudes per day; the linear polarization varied between 25% and 5% (Rieke et al. 1976). The radio emission at 90 and 140 GHz reached a maximum at about the same time as did the infrared and optical flux; however, the radio maximum was less pronounced and its decline slower (Rieke et al. 1976).

There appears to be a faint extension, about 3″ in length, to the south of AO 0235+164 (Spinrad & Smith 1975). It is not clear whether this represents nebulosity physically associated with the core source, intervening material, or a faint foreground star. If the large column density of neutral hydrogen, evidenced by the 21-cm line at $z = 0.524$, is associated with dust at dust-to-gas ratios characteristic of interstellar material in the Galaxy, non-negligible extinction ($\sim$1 mag) would result (Roberts et al. 1976). It is thus important to establish to what degree the observed optical spectrum is attenuated and reddened by dust: If the observed steep and downward-curving optical continuum is intrinsic (rather than resulting from extinction), the absence of emission lines in this object—and, by analogy, in other BL Lac objects (presumably with smaller redshifts)—might be explained by absence of ionizing ultraviolet radiation.

3.6 *B2 1101+38 (Markarian 421) and B2 1652+39 (Markarian 501, 4C 39.49)*

These sources from the second Bologna catalog (Colla et al. 1973) have been identified as BL Lac objects by Ulrich (1973), Ulrich et al. (1975), and Colla et al. (1975). Each radio source is compact and exhibits a relatively flat spectrum (Colla et al. 1975) characteristic of inhomogeneous self-absorbed synchrotron sources. The spectral-flux distributions of these objects from radio to optical frequencies have been interpreted in terms of nonthermal radiation. The optical spectra exhibit no emission lines [see also Khachikian & Weedman (1974) with regard to Markarian 501]; however, a spectrum of the nebulosity surrounding B2 1652+39 (Markarian 501) shows stellar absorption lines at a redshift of $z = 0.0337$ (Ulrich et al. 1975, Wills & Wills 1974b). The spectrum of the nebulosity surrounding B2 1101+38 (Markarian 421) was more difficult to obtain, but the authors tentatively identified stellar absorption features at a redshift $z = 0.030$, which agrees with that of an irregular galaxy only 20″ away (Lynds in Colla et al. 1975). Archival records show this object to be strongly variable at visual wavelengths (H. R. Miller 1975).

These objects are of particular importance in that, like AP Libra, they demonstrate the existence of some BL Lac objects in the nuclei of galaxies—independent of the controversy that surrounds the nature of the nebulosity around BL Lac itself.

Recent X-ray observations by the *Ariel V* satellite show that B2 1101+38 lies within a $\sim\frac{1}{3}$ square-degree 90%-confidence error box of a variable X-ray source (Ricketts, Cooke & Pounds 1976). Since the X-ray emission flared by a factor ~ 2 over only a day, it is of considerable interest to verify that it is indeed associated with B2 1101+38.

3.7 *I Zw 186* (*1727+502*)

The object 1727+502 is barely distinguishable from equally bright (~ 16 mag) stars on plates obtained with the Hale 5-m telescope (Zwicky 1966). Oke et al. (1967), from visual inspection, found a diameter of 3″ with a pronounced central condensation. Optical spectra indicate a blue lineless continuum (Zwicky 1966, Oke et al. 1967, Sargent 1970). The object is optically variable by ~ 0.5 mag in a couple of months, becoming redder when fainter (Oke et al. 1967, Sandage 1967). Archival records document 2.1-mag variations (Hall & Usher 1973).

Warner (1972) identified this object with the radio source OT 546. [NB: The object should be I Zw 186, not I Zw 187.] Le Squéren, Biraud & Lauqué (1972) and Argue et al. (1973a) have confirmed the identification and found a spectral flux of slightly less than $0''.2$ Jy at centimeter wavelengths. The radio spectral distribution is relatively flat (Altschuler & Wardle 1975) and, as far as we know, has not been observed to vary. In view of the flat radio continuum and small angular size ($<0''.5$ at 5 GHz, Argue et al. 1973a), the radio emission is likely to represent self-absorbed synchrotron radiation from an inhomogeneous source structure.

The optical continuum of I Zw 186, unlike that of other BL Lac objects for which data are available, does not continue to rise steeply into the infrared (Oke et al. 1967). Possibly, this flattening at about 1 μm is related to the comparatively small spectral flux observed at radio frequencies. This object is of particular interest because it is but a weak radio source; in fact, it was discovered independently of its radio emission. Thus, its existence raises the possibility of (effectively) radio-quiet BL Lac objects.

4 OBSERVED PROPERTIES OF BL LAC OBJECTS AND COMPARISON WITH QSOs AND NUCLEI OF SEYFERT GALAXIES

Apart from the "defining" characteristic of an emission-line-free spectrum, the BL Lac objects have the following general observed properties, some of which are implicit in Table 1 or have been illustrated in the discussion of individual objects (Section 3).

4.1 *Distribution on the Sky*

It is clear from Table 1 that the BL Lac objects appear at all galactic latitudes with perhaps a tendency to avoid the galactic plane. With so small and heterogeneous a sample no detailed analysis of the distribution is possible; however, the evidence is consistent with an extragalactic origin for these objects.

4.2 *Visual Appearance*

BL Lac objects may appear in the nuclei of galaxies (e.g. B2 1101+38), may be associated with nebulosity (e.g. 2335+031), or may appear to be stellar even at high plate scale (e.g. 0735+178). A consistent interpretation of this sequence could be given in terms of increasing distance and/or increasing contribution from the nonthermal core relative to the surrounding nebula. Examples of BL Lac objects in elliptical galaxies are AP Lib, B2 1652+39, B2 1101+38.

4.3 *Spectral-Flux Distribution*

Broad-band colors and detailed spectrophotometric data indicate a mean power-law spectrum with index $\alpha \sim 2$ at visual wavelengths. Where sufficient infrared data exist, there is evidence for departure from a true power-law form in the sense that the local index α increases toward shorter wavelengths (Strittmatter et al. 1972, Rieke & Kinman 1974). There is also evidence (Rieke & Kinman 1974; Tapia, Craine & Johnson 1976) for short-term changes in spectral index, with perhaps most variability occurring at the shortest wavelengths. How far this can be accounted for by contributions from second components (e.g. a possible underlying galaxy) rather than by actual changes in the slope of the nonthermal component is a matter requiring further investigation. Over long time scales, the spectral index of OJ 287 (which is stellar, at least when brightest) remains essentially unchanged, while the intensity changes by more than an order of magnitude. On the other hand, the optical spectra of BL Lac and AP Lib (which are nebulous) redden as they become fainter.

The radio data present a less uniform picture owing to the contribution from several components. There is a considerable range of time scales for factor-of-two variations, ranging from weeks to at least several years. These data and their importance in analyzing the physical mechanisms involved in producing the nonthermal radiation are discussed further in Section 5.2.

No X-rays have yet been detected from a BL Lac object (Margon et al. 1976, Ulmer & Murray 1976), with the possible exception of B2 1101+38 (Ricketts et al. 1976).

Variability is a general characteristic of the BL Lac objects with apparently larger and more rapid changes occurring in the optical and near IR than at radio frequencies. At optical wavelengths, variations occur on a time scale $t = \langle L/\dot{L} \rangle \sim 10$ days. In addition, from archival plates, there appear to be "quiescent" phases and active periods, during which the object may brighten by as much as ~5 mag.

There appears to be a correlation between the amplitude of optical variations and the spectral index at centimeter wavelengths (Cannon, Penston & Brett 1971; Hall & Usher 1973; Pollock 1975a; Usher 1975) in the sense that the largest optical variations seem to occur for objects with the greatest centimeter excess. Evidently, this relation applies to QSOs and variable N galaxies as well. Such a correlation seems physically plausible, since, in terms of nonthermal compact components, a large centimeter excess and optical variations are both consequences of activity in the core source.

Tapia et al. (1976) have suggested that there may be a correlation between the presence of nebulosity around BL Lac objects and a steep spectral index. A subsequent search for nebulosity around four steep-index objects (4C 14.60, OT 081, OY 091, and PKS 2335+03) led to positive results in the latter two cases (Craine, Tapia & Tarenghi 1975b). The possibility that BL Lac objects may be ejected from galaxies (Craine et al. 1975b) perhaps receives some support from such a case as OX 029 (Craine & Warner 1976). However, in view of the wide range in character of the nebulosities involved, the hypothesis of ejection must be further explored.

4.4 *Polarization*

At visual wavelengths BL Lac objects show strong (up to 30%, though typically several percent) and highly variable linear polarization independent of wavelength. The time scales for changes both in degree and in direction appear to be somewhat shorter than those associated with brightness variations, but further observational work is required. No polarization measurements in the infrared ($\lambda \gtrsim 2$ μm) have yet been reported. The radio emission from BL Lac objects is polarized and usually variable, but the degree is more modest ($\lesssim 3\%$) and the time scale (particularly at long wavelengths) is frequently much longer than at optical wavelengths.

4.5 *Discussion*

It is obvious from the above discussion that, apart from the absence of emission lines, the BL Lac objects have many properties in common with QSOs and N-type and Seyfert galaxies. As Kinman (1975b) pointed out, these categories are not clear-cut, and it has long been our personal view that the BL Lac objects merely represent one limiting manifestation of the physical process that could give rise to QSOs and/or Seyfert galaxies (see e.g. Racine 1970, Penston & Penston 1973, Adams 1974). In this context the case of 3C 371 is of special interest.

J. S. Miller (1975) has pointed out the similarity of the "N galaxy" 3C 371 with $z = 0.05$ (Sandage 1966) to BL Lac objects. The object exhibits large and rapid variability of optical flux (Oke 1967b, Sandage 1967) and polarization (Visvanathan 1967). Stellar absorption lines of an elliptical galaxy are observed, as well as a nonthermal continuum. In addition, weak emission lines are present. Although this object could not strictly be called a BL Lac object (because emission lines are detected), Miller contends that if the nonthermal continuum were to increase significantly in brightness, then the emission lines would no longer be detectable. 3C 371 thus represents a possible link between the BL Lac objects and other emission-line galaxies and QSOs.

In comparing the BL Lac objects with QSOs, we note that many low-redshift QSOs show evidence of surrounding nebulosity, which has been attributed by Kristian (1973) to elliptical galaxies. The disappearance of such nebulosity at high redshifts would appear to be consistent with this hypothesis, which receives further support from observations of Ton 256 by Silk et al. (1973), who found colors consistent with those of an E galaxy. However, the elliptical-galaxy interpretation has been questioned recently by Wampler et al. (1975), who found that the nebulosity around 3C 48 is due mainly to emission-line radiation from a hot gas. The presence of such emission regions around high-redshift QSOs seems also to follow from a study of the absorption-line spectrum of 3C 191 (Williams et al. 1975): These emission regions, like elliptical galaxies, would also be unresolvable at higher redshifts (according to the cosmological interpretation). For the BL Lac objects it is a matter of definition that a significant hot gas component must be absent, although the intermediate case of 3C 371 is of particular interest in this context. Some BL Lac objects (e.g. 1101+384, 1514−241, and 1652+398), however, are associated with elliptical galaxies, while the nature of the nebulosity around BL Lac itself remains controversial. It is contended that the past brightness of some N galaxies provides support for the "continuity" argument relating QSOs and N galaxies (Oke 1967b, Sandage 1967); in particular, the N galaxies 3C 371 and 3C 390.3 would be called QSOs at their maximum luminosity, if they were more distant (Cannon et al. 1971) and if the emission lines remained detectable.

The continuous flux distributions of BL Lac objects and QSOs, although presumably both containing nonthermal components, differ significantly in spectral index. For "normal" QSOs, a mean spectral index $\alpha \sim 1$ is appropriate to the optical region, while the BL Lac objects listed in Table 1 have a mean index $\alpha = 1.8$. It is interesting, however, that the more variable QSOs (e.g. 3C 279, 3C 345, 3C 446, and 3C 454.3) have spectral indices that are significantly steeper than "normal" (Oke, Neugebauer & Becklin 1970) and rather similar to those of the BL Lac objects. These QSOs also tend to show strong and variable polarization (Visvanathan 1973a). Thus, it appears that the variability, polarization, and steepness of spectral index may be related (cf Nordsieck 1976). How this is linked to the absence of emission lines from BL Lac objects is uncertain (see discussion below).

In summary, the primary differences between BL Lac objects and QSOs and N galaxies seem to be the following:

1. By definition, BL Lac objects, unlike QSOs and N galaxies, exhibit no emission lines.
2. The nonthermal optical continuum of BL Lac objects is usually steeper than that of the average QSO; however, the optical continuum of the more variable QSOs also is steeper than average.
3. The brighter and more variable BL Lac objects are not associated with large extended radio sources, whereas many QSOs and N galaxies are.
4. While there exists considerable range of variability time scales in BL Lac objects and QSOs (including no observed variations), the most rapid variations observed have occurred in BL Lac objects.

The aforementioned differences are more quantitative than qualitative and have led to the suggestion that the more variable BL Lac objects are "young" QSOs (Altschuler & Wardle 1975, Pollack 1975a), which have not yet ejected much material from the core region. The nonthermal continua of BL Lac objects, QSOs, and N galaxies probably reflect the same physical process—namely, synchrotron radiation. This is certainly true in the radio domain, and is, at least frequently, the case in the infrared and optical as well.

Spectra of the nebulosities surrounding some BL Lac objects and N galaxies clearly demonstrate that nonthermal emission, both with and without detectable emission

1976ARA&A..14..173S

lines, occurs in the nuclei of galaxies of normal stars. Furthermore, the range of optical variations (as much as ~5 mag) observed in BL Lac objects, QSOs, and N galaxies (Liller 1975, private communication; Cannon et al. 1971) leaves no doubt that the nonthermal continuum from the core source may become so intense as to overwhelm the nebulous stellar contribution, thus causing the object to appear quasi-stellar and the emission to exhibit no evidence for a normal galaxy (e.g. Sandage 1967, Kristian 1973). As stressed by Burbidge (e.g. 1973, 1974), however, "nebulosity" $\not\equiv$ "galaxy of stars." The nebulosity surrounding 3C 48, due mainly to emission-line radiation from hot gas, clearly illustrates the danger of failing to make this distinction (Wampler et al. 1975).

5 THEORETICAL QUESTIONS RAISED BY THE BL LAC OBJECTS

5.1 *The Lack of Discrete Spectral Features*

As yet there is no satisfactory explanation for the absence of emission lines in the spectra of BL Lac objects. The suggested possibilities include the following:

1. The nonthermal continuum is of such strength that the flux at the emission-line center is small compared with the continuum emission (cf Searle & Bolton 1968). This hypothesis receives some support from observations of the QSO 3C 446 during its 1966 outburst. Both the broad-band measures (Sandage, Westphal & Strittmatter 1966) and spectrophotometric data (Oke 1967a) indicated that the line strengths remained constant, while the continuum level changed. The argument is, however, a time-dependent one: Ultimately the increase in continuum radiation should cause an increase in line emission if gas is present, so that current BL Lac objects should turn into QSOs or N galaxies. From our present knowledge of these latter objects, gas exists at distances greater than 10^{19} cm from the core source, and therefore time scales of 10–10^2 years are indicated. However, BL Lac objects have been observed at luminosities well below their peak values without any hint of line emission: This argues against such an explanation.

2. The lines are so wide that the contrast between line and continuum renders the former undetectable. Though difficult to test, this explanation may be criticized on the grounds that the continuum must have a substantial unpolarized thermal (line) component at minimum light; yet the polarization is often higher during this phase (Strittmatter et al. 1972). [Also a study of a small number of very-broad-line QSOs by Serkowski and one of us (P.A.S.) failed to reveal any continuum polarization, as might be expected if there were a continuity in these properties between QSOs and BL Lac objects.]

3. Ultraviolet radiation is insufficient to ionize and excite the surrounding gas. The observed steepness and spectral curvature (α increasing with frequency) in the spectral-flux distribution of many BL Lac objects tends to support this hypothesis; however, the question is one of degree. If a spectral-index difference $\Delta\alpha \sim 1$ applies between BL Lac objects and QSOs, not only in the observable spectral range but also down to the Lyman limit, then the equivalent width of Hβ would be reduced by a factor ~7 with respect to QSOs. The line should still be detectable with the

modern generation of linear detectors. Furthermore, the equivalent width of Lα should be reduced by a factor ~ 1.8. Thus, unless there is a dramatic cutoff in the ultraviolet of the primary emission, this explanation encounters some difficulty. While there is no indication of such a cutoff in the continuum of PKS 0735+178 ($z_{\mathrm{em}} \geqq 0.424$), the spectral flux of AO 0235+164 ($z_{\mathrm{em}} \geqq 0.852$) does fall rapidly into the ultraviolet. If this cutoff cannot be attributed to extinction due to intervening material, it seems possible to explain the absence of emission lines, for at least this BL Lac object, in terms of the severe ultraviolet deficiency of the continuum emission.

4. There is insufficient gas surrounding the nonthermal source (cf Silk et al. 1973). Although difficult to test, this hypothesis is consistent with observations. The tendency for BL Lac objects to occur in elliptical galaxies, in which little gaseous material is thought to be present, may be weak evidence in favor of the hypothesis; however, emission-line nuclei also occur in ellipticals. Also, the observation of Mg II $\lambda 2798$ absorption in PKS 0735+178 and the rich absorption-line spectrum of AO 0235+164 (unless due to an intervening galaxy) would argue for some material in BL Lac objects, although this probably occurs at fairly large distances (>1 kpc, Roberts et al. 1976) from the core source.

The explanation for the absence of lines is most likely some combination of (3) and (4) above. It also seems possible that a deficit of material may be correlated with a steep or "cutoff" spectrum. Calculations of steady-state, radiation-pressure-driven mass flow (Kippenhahn, Perry & Röser 1974; Kippenhahn, Mestel & Perry 1975) show that a cutoff in the far ultraviolet spectrum may result in high accelerations and terminal velocities. Although further study of the inner, nonaccelerating zone is required, such a mechanism might account for the lack of emission features in BL Lac objects.

5.2 *The Nonthermal Continuum*

It is generally believed that the nonthermal-emission process involved in the BL Lac objects (as in QSOs) is incoherent synchrotron radiation. In the radio domain, this interpretation seems quite secure (e.g. Jones et al. 1974b, Burbidge et al. 1974) in most cases; in the optical, the case is less clear, except in the few cases where extension from the radio into the infrared and optical is supported by temporal correlations.

It is important to understand why those objects with steeper optical spectra are systematically both more variable and more highly polarized than those with lower optical spectral indices. Building upon earlier work on synchrotron radiation in partially disordered magnetic fields (Korchakov & Syrovatskii 1962), Nordsieck (1976) provided a possible explanation for the spectral index–linear polarization correlation. A positive correlation between α and degree of polarization occurs because the power radiated by the electrons of the same energy in regions of higher field is not only greater but at a higher frequency. If the field directions in the two locations are different, a net polarization results, increasing as the observed radiation spectrum steepens. [Even for a homogeneous source, the degree of linear polarization increases with increasing spectral index (e.g. Ginzburg & Syrovatskii

1969); however, the enhancement due to the effect alone is small.] Although there would be a positive correlation between polarization and spectral index, the magnitude of the enhancement probably is not enough of itself to account for difference in the observed polarization, which ranges from about 1% to 30% (Korchakov & Syrovatskii 1962). Furthermore in some sources—e.g. 0735 + 178 and 0235 + 164—the linear polarization varies by a factor of four while the spectral index remains essentially unchanged (Carswell et al. 1974, Rieke et al. 1976). The more rapid variability observed in BL Lac objects suggests smaller linear dimensions: A smaller size may be associated with stronger and less disordered magnetic fields, which could result in more rapid radiative loss (and hence steeper spectra) and/or higher linear polarization.

Absence of distance determinations for BL Lac objects—not to mention the controversy over the distance-redshift relation for QSOs—has hampered detailed study of source characteristics. If observed redshifts are used to determine distances on the basis of a Hubble constant $H_0 \sim 50$ km sec^{-1} Mpc^{-1}, there are difficulties with an incoherent synchrotron interpretation for at least some BL Lac objects and QSOs (Jones & Burbidge 1973, Burbidge et al. 1974).

The essence of the problem was first stated by Hoyle, Burbidge & Sargent (1966) (see also Kellerman & Pauliny-Toth 1969), who pointed out that, in simple models, rapid variability of a very bright source implies a small volume containing the high-energy electrons and synchrotron radiation. A luminosity confined to a small volume implies a very large energy density of radiation, in which high-energy electrons rapidly lose energy through Compton scattering. This leads to short electron lifetimes and a large flux of Compton scattered photons—some of which would appear as X-rays. Since X-rays are not generally observed from BL Lac objects (Margon et al. 1976, Ulmer & Murray 1976), limits can be set on physical conditions in the source and lead to a conflict with the distance determination if the emission mechanism is accepted.

Various alternatives have been proposed to avoid these difficulties. In a study of the radio emission from compact nonthermal sources Jones et al. (1974a,b; see also Burbidge et al. 1974) examined alternative radiation processes. They concluded that such hypotheses as coherent synchrotron emission or proton synchrotron emission were not realistic alternatives in most cases. While a large number of independent radiating sources (Dent 1972, Andrew 1973) may account for "super-light" motions in some sources, it cannot explain large-amplitude variations of an object on a time scale appreciably less than the light-travel time across the source. The most plausible alternatives require relativistic motions such as relativistic expansion (Rees 1966, 1967; Rees & Simon 1968) or ejection (Ozernoi & Sazonov 1969, Andrew 1973) or electron streaming at small pitch angles along ordered magnetic fields (Shklovsky 1964, Woltjer 1966, Noerdlinger 1969, Ozernoi & Ulanovsky 1974). For most variable, compact, nonthermal radio sources, a consistent case for mildly relativistic motion ($\gamma_0 \beta_0 \approx 1$) may be made; however, the relativistic factors required for some sub-GHz variables (e.g. 3C 454.3 and CTA 102) seem excessive ($\gamma_0 \approx 20$). At a cosmological distance corresponding to the suggested value of $z = 0.07$, the variability of BL Lac requires a somewhat smaller factor ($\gamma_0 \approx 5$), as does that of 0735+178 (Jones 1974). There appears, however, to be good general agreement between theoretical and measured VLBI angular sizes provided that pitch angles of electrons are not extremely small and expansion is not ultrarelativistic. The resolution of this problem is clearly of fundamental importance to our understanding of compact nonthermal sources.

The investigations described above were concerned with the radio emission of compact nonthermal sources. The reason for this is that the presence of a spectral turnover (attributed to synchrotron self-absorption) and the direct measurement of angular size (through VLB interferometry) determine the physical parameters of the nonthermal source in considerably more detail than do the optical data alone. Care must be taken in applying physical parameters estimated from radio data to studies of the optical nonthermal continuum, since the optical and radio emission need not originate in the same volume. A further factor complicating analysis of the optical nonthermal emission is that even if the radiation is synchrotron, the standard relations between electron-energy index and spectral index may not apply: This is because the optical emission may come from that part of the electron distribution affected by radiative loss. Consequently, the spectral shape may reflect not only the intrinsic electron index, but also such processes as expansion, injection, and re-isotropization.

6 AREAS FOR FUTURE RESEARCH

On the theoretical side, the main requirements seem to be explaining the character and temporal evolution of compact nonthermal sources in general and accounting for the absence of lines in the optical spectra of BL Lac objects. Some fairly clear trends in the data are evident and these should provide useful leads to a better understanding of these sources.

On the observational side, measurements of polarization in the infrared (~2.2 μm) and in the ultraviolet would provide a key to the source geometry and emission mechanism. Further work on flux and polarization variations, especially on relative changes at different wavelengths, would also be useful in this regard. Measurements, even broad-band, of the far ultraviolet spectra of some BL Lac objects (preferably cases such as 0735+178 or 0235+164 where the Lyman limit must be shifted to at least ~1700 Å) might account for the absence of emission lines. Spectroscopic studies, particularly when a BL Lac object is faintest, would furnish important information on the amount of gas and may result in measurable redshifts.

Resolution of the controversy over the redshift of the diffuse emission surrounding BL Lac is especially important because it is the best-studied object of the class.

Finally investigation of the temporal dependence of VLBI angular size should continue. In particular, Is the source smallest when the flux increases significantly? A positive answer would substantiate explanations of difficulties based on multiple source components and lead to further information regarding possible source expansion.

7 CONCLUSIONS

Evidence on polarization, variability, and spectral-flux distribution indicates that BL Lacertae objects are a form of the QSO phenomenon; however, they do not exhibit emission lines. The physical explanation for the lack of spectral features is presently uncertain but evidence bearing on the question is available from objects such as PKS 0735 + 178 and AO 0235 + 164 (the spectra of which contain absorption lines). There is strong evidence that, in at least a few cases, these objects exist in, or as, the nuclei of elliptical galaxies. The possibility that they may be ejected from the nuclei of galaxies (e.g. OX 029) requires further study.

Problems of the physical conditions and distance as deduced from interpretation of nonthermal characteristics of these sources are not resolved by their association with galaxies. It is important to note that there is no conflict between distance as inferred from variability and nonthermal physics as compared with the direct measurement of redshift distance for Seyfert galaxies such as NGC 1275. However such a conflict does occur for 0735 + 178, a case where there is no observable evidence for a galaxy and hence no independent measurement of redshift and distance. A similar problem arises in the case of BL Lac if it is at the distance implied by the suggested $z = 0.07$. Thus, the determination of the redshift of BL Lac is especially important. These difficulties may possibly be explained by physical phenomena such as relativistic expansion.

ACKNOWLEDGMENTS

The authors wish to acknowledge communications with B. A. Peterson, M. Roberts, M. Schmidt, M. -H. Ulrich, E. J. Wampler, and A. Wolfe, as well as comments on the manuscript by G. R. Burbidge and H. E. Smith.

Literature Cited

Adam, G., Floquet, M., Marchal, J., Schneider, M. 1972. *C. R. Acad. Sci. Ser. B* 274:201
Adams, T. F. 1974. *Ap. J.* 188:463
Altschuler, D. R., Wardle, J. F. C. 1975. *Nature* 255:306
Andrew, B. H. 1973. *Ap. J.* 186:L3
Andrew, B. H. et al. 1974. *Ap. J.* 191:51
Andrew, B. H., MacLeod, J. M., Locke, J. L., Medd, W. J., Purton, C. R. 1969. *Nature* 223:598
Andrews, P. J., Glass, I. S., Howarden, T. G. 1974. *MNRAS* 168:7P
Argue, A. N., Kenworthy, C. M., Ryle, M., Shakeshaft, J. R. 1973a. *Nature Phys. Sci.* 241:139
Argue, A. N., Kenworthy, C. M., Stewart, P. M. 1973b. *Astrophys. Lett.* 14:99
Baldwin, J. A., Burbidge, E. M., Robinson, L. B., Wampler, E. J. 1975. *Ap. J.* 195:L55
Berge, G. L., Seielstad, G. A. 1972. *Astron. J.* 77:810
Bertaud, C., Dumortier, B., Véron, P., Wlérick, G., Adam, G., Bigay, J., Garnier, R., Duruy, M. 1969. *Astron. Astrophys.* 3:436
Bertaud, C., Wlérick, G., Véron, P., Dumortier, B., Bigay, J., Paturel, G., Duruy, M., deSaevsky, P. 1973a. *Astron. Astrophys.* 24:357
Bertaud, C., Wlérick, G., Véron, P., Dumortier, B., Duruy, M., deSaevsky, P. 1973b. *Astron. Astrophys. Suppl.* 11:77
Biraud, F. 1969. *Astron. Astrophys.* 1:156
Biraud, F. 1971. *Nature* 232:178
Biraud, F., Véron, P. 1968. *Nature* 219:254
Blake, G. M. 1970. *Astrophys. Lett.* 6:201
Bolton, J. G., Clark, M. E., Ekers, R. D. 1965. *Aust. J. Phys.* 18:627
Bond, H. E. 1971. *Ap. J.* 167:L79

Browne, I. W. A. 1971. *Nature* 231:515

Browne, I. W. A., Crowther, J. H., Adgie, R. L. 1973. *Nature* 244:146

Browne, I. W. A., McEwan, N. J. 1972. *Nature Phys. Sci.* 239:101

Burbidge, E. M., Caldwell, R. D., Smith, H. E., Liebert, J., Spinrad, H. 1976. *Ap. J.* 205:L117

Burbidge, G. R. 1973. *Nature Phys. Sci.* 246:17

Burbidge, G. R. 1974. *Nature* 250:181

Burbidge, G. R., Jones, T. W., O'Dell, S. L. 1974. *Ap. J.* 193:43

Cannon, R. D., Penston, M. V., Brett, R. A. 1971. *MNRAS* 152:79

Carswell, R. F., Strittmatter, P. A., Disney, M. J., Hoskins, D. G., Murdoch, H. S. 1973. *Nature Phys. Sci.* 246:89

Carswell, R. F., Strittmatter, P. A., Williams, R. E., Kinman, T. D., Serkowski, K. 1974. *Ap. J.* 190:L101

Clark, B. G., Kellermann, K. I., Cohen, M. H., Shaffer, D. B., Broderick, J. J., Jauncey, D. L., Matveyenko, L. I., Moiseev, I. G. 1973. *Ap. J.* 182:L57

Cohen, M. H. et al. 1971. *Ap. J.* 170:207

Colla, G. et al. 1973. *Astron. Astrophys. Suppl.* 11:291

Colla, G., Fanti, C., Gioia, I., Lari, C., Lequeux, J., Lucas, R., Ulrich, M. -H. 1975. *Astron. Astrophys. Suppl.* 20:1

Condon, J. J., Jauncey, D. L. 1974a. *Astron. J.* 79:437

Condon, J. J., Jauncey, D. L. 1974b. *Astron. J.* 79:1220

Conway, R. G., Stannard, D. 1972. *MNRAS* 160:31P

Craine, E. R., Johnson, K., Tapia, S. 1975a. *Publ. Astron. Soc. Pac.* 87:123

Craine, E. R., Tapia, S., Tarenghi, M. 1975b. *Nature* 258:56

Craine, E. R., Warner, J. W. 1973. *Ap. J.* 179:L53

Craine, E. R., Warner, J. W. 1976. *Ap. J.* 206:309

Crovisier, J., Le Squèren, A. M., Pollock, J. T., Usher, P. D. 1974. *Astron. Astrophys.* 30:175

Dent, W. A. 1972. *Ap. J.* 175:L55

Dent, W. A., Hobbs, R. W. 1973. *Astron. J.* 78:163

Dent, W. A., Kojoian, G. 1972. *Astron. J.* 77:819

Disney, M. J. 1974. *Ap. J.* 193:L103

Disney, M. J., Peterson, B. A., Rogers, A. W. 1974. *Ap. J.* 194:L79

Dombrovsky, V. A. 1971. *Astron. Tsirk.* 614:1

DuPuy, D., Schmitt, J., McClure, R., van den Bergh, S., Racine, R. 1969. *Ap. J.* 156:L135

Dyck, H. M., Kinman, T. D., Lockwood, G. W., Landolt, A. U. 1971. *Nature Phys. Sci.* 234:71

Eggen, O. J. 1970. *Ap. J.* 159:L95

Eggen, O. J. 1973. *Ap. J.* 186:L1

Ekers, R. D., Weiler, K. W., van der Hulst, J. M. 1975. *Astron. Astrophys.* 38:67

Epstein, E. E. et al. 1972. *Ap. J.* 178:L51

Evseev, O. A., Kusminov, B. U., Tsarevsky, G. S. 1973. *Soobshch. Spets. Astrofiz. Obs. Zelenchukskaya* 9:45

Fosbury, R. A. E., Disney, M. J. 1976. *Ap. J.* 207: In press

Frohlich, A., Goldsmith, S., Weistrop, D. 1974. *MNRAS* 168:417

Frye, G. M. Jr., Albats, P. A., Zych, A. D., Staib, J. A., Hopper, V. D., Rawlinson, W. R., Thomas, J. A. 1971. *Nature* 233:466

Ginzburg, V. L., Syrovatskii, S. I. 1969. *Ann. Rev. Astron. Astrophys.* 7:375

Goldsmith, S., Weistrop, D. 1973. *Ap. J.* 180:661

Gower, J. F. R. 1969. *Nature* 224:569

Hackney, R. L., Hackney, K. R., Smith, A. G., Folsom, G. H., Leacock, R. J., Scott, R. L., Epstein, E. E. 1972. *Astrophys. Lett.* 12:147

Hall, D. L., Usher, P. D. 1973. *Nature Phys. Sci.* 241:31

Hoskins, D. G., Murdoch, H. S., Adgie, R. L., Crowther, J. H., Gent, H. 1974. *MNRAS* 166:235

Hoskins, D. G., Murdoch, H. S., Hazard, C., Jauncey, D. L. 1972. *Aust. J. Phys.* 25:559

Hoyle, F., Burbidge, G. R., Sargent, W. L. W. 1966. *Nature* 209:751

Hunstead, R. W. 1971. *Nature* 233:401

Jones, T. W. 1974. *Ap. J.* 191:L15

Jones, T. W., Burbidge, G. R. 1973. *Ap. J.* 186:791

Jones, T. W., O'Dell, S. L., Stein, W. A. 1974a. *Ap. J.* 188:353

Jones, T. W., O'Dell, S. L., Stein, W. A. 1974b. *Ap. J.* 192:261

Kellermann, K. I., Pauliny-Toth, I. I. K. 1969. *Ap. J.* 155:L71

Khachikian, E. Ye., Weedman, D. W. 1974. *Ap. J.* 189:L99

Kikuchi, S. et al. 1973. *Publ. Astron. Soc. Jpn.* 25:555

Kinman, T. D. 1975a. *Ap. J.* 197:L49

Kinman, T. D. 1975b. *Variable Stars and Stellar Evolution*, ed. V. E. Sherwood, L. Plaut, p. 573. Boston: Reidel

Kinman, T. D. 1976. *Ap. J.* 205:1

Kinman, T. D., Conklin, E. K. 1971. *Astrophys. Lett.* 9:147

Kinman, T. D., Rieke, G. H. 1975. *IAU Circ. No. 2687*

Kinman, T. D., Wardle, J. F. C., Conklin, E. K., Andrew, B. H., Harvey, G. A.,

MacLeod, J. M., Medd, W. J. 1974. *Astron. J.* 79:349
Kiplinger, A. P. 1974. *Ap. J.* 191:L109
Kippenhahn, R., Perry, J. J., Röser, H. -J. 1974. *Astron. Astrophys.* 34:211
Kippenhahn, R., Mestel, L., Perry, J. J. 1975. *Astron. Astrophys.* 44:123
Korchakov, A. A., Syrovatskii, S. I. 1962. *Astron. J. USSR* 5:678
Kristian, J. 1973. *Ap. J.* 179:L61
Legg, M. P. C., Westfold, K. C. 1968. *Ap. J.* 154:499
Le Squéren, A. M., Biraud, F., Lauqué, R. 1972. *Nature Phys. Sci.* 240:75
Lynds, C. R., Wills, D. 1972. *Ap. J.* 172:531
MacLeod, J. M., Andrew, B. H. 1968. *Astrophys. Lett.* 1:243
MacLeod, J. M., Andrew, B. H., Medd, W. J., Olsen, E. T. 1971. *Astrophys. Lett.* 9:19
Margon, B., Bowyer, S., Jones, T. W., Davidsen, A., Mason, K. O., Sanford, P. W. 1976. *Ap. J.* 207: In press
Medd, W. J., Andrew, B. H., Harvey, G. A., Locke, J. L. 1972. *Mem. R. Astron. Soc.* 77:109
Mikami, Y., Kawano, N., Kawajiri, N., Ojima, T., Inoue, M., Konno, M., Tomino, K., Dashido, T. 1974. *Tokyo Astron. Bull. Ser. 2* 228:2633
Miller, H. R. 1975. *Ap. J.* 201:L109
Miller, J. S. 1975. *Ap. J.* 200:L55
Milone, E. F. 1972. *Publ. Astron. Soc. Pac.* 84:723
Milone, E. F. 1974. *Publ. Astron. Soc. Pac.* 86:899
Murdoch, H. S., Hoskins, D. G. 1973. *Aust. J. Phys.* 26:867
Nicolson, G. D. 1971. *Nature Phys. Sci.* 233:155
Noerdlinger, P. D. 1969. *Astrophys. Lett.* 4:233
Nordsieck, K. H. 1972. *Astrophys. Lett.* 12:69
Nordsieck, K. H. 1976. *Ap. J.* In press
Northover, K. J. E. 1973. *MNRAS* 165:369
Oke, J. B. 1967a. *Ap. J.* 147:901
Oke, J. B. 1967b. *Ap. J.* 150:L5
Oke, J. B., Gunn, J. E. 1974. *Ap. J.* 189:L5
Oke, J. B., Neugebauer, G., Becklin, E. E. 1969. *Ap. J.* 156:L41
Oke, J. B., Neugebauer, G., Becklin, E. E. 1970. *Ap. J.* 159:341
Oke, J. B., Sargent, W. L. W., Neugebauer, G., Becklin, E. E. 1967. *Ap. J.* 150:L173
Olsen, E. T. 1969. *Nature* 224:1008
Olsen, E. T. 1970. *Astron. J.* 75:764
Ozernoi, L. M., Sazonov, V. N. 1969. *Astrophys. Space Sci.* 3:395
Ozernoi, L. M., Ulanovsky, L. E. 1974. *Astron. J. USSR* 18:4
Pacholczyk, A. G. 1973. *MNRAS* 163:29P
Pacholczyk, A. G., Swihart, T. L. 1971. *Ap. J.* 170:405
Pacholczyk, A. G., Swihart, T. L. 1974. *Ap. J.* 192:591
Pauliny-Toth, I. K., Kellermann, K., Davis, M. M., Fomalont, E. B., Shaffer, D. B. 1972. *Astron. J.* 77:265
Penston, M. V., Penston, M. J. 1973. *MNRAS* 162:109
Peterson, B. A., Bolton, J. G. 1972. *Astrophys. Lett.* 10:105
Pigg, J. C., Cohen, M. H. 1971. *Publ. Astron. Soc. Pac.* 83:680
Pollock, J. T. 1975a. *Ap. J.* 198:L53
Pollock, J. T. 1975b. *Penn. St. Univ. Radio Astron. Obs. Sci. Rep. 029*
Racine, R. 1970. *Ap. J.* 159:L99
Rees, M. J. 1966. *Nature* 211:468
Rees, M. J. 1967. *MNRAS* 135:345
Rees, M. J., Simon, M. 1968. *Ap. J.* 152:L145
Ricketts, M. J., Cooke, B. A., Pounds, K. A. 1976. *Nature* 259:546
Rieke, G. H. 1972. *Ap. J.* 176:L61
Rieke, G. H., Grasdalen, G. L., Kinman, T. D., Hintzen, P., Wills, B. J., Wills, D. 1976. *Nature* 260:754
Rieke, G. H., Kinman, T. D. 1974. *Ap. J.* 192:L115
Roberts, M. S., Brown, R. L., Brundage, W. D., Rots, A. H., Haynes, M. P., Wolfe, A. M. 1976. *Astron. J.* 81: In press
Rogers, A. W. 1971. *Nature Phys. Sci.* 233:75
Romano, G. 1971. *Mem. Soc. Astron. Ital. Nuova Ser.* 42:57
Ryle, M., Sandage, A. R. 1964. *Ap. J.* 139:419
Sandage, A. R. 1966. *Ap. J.* 145:1
Sandage, A. R. 1967. *Ap. J.* 150:L9
Sandage, A. R. 1973. *Ap. J.* 180:687
Sandage, A. R., Westphal, J. A., Strittmatter, P. A. 1966. *Ap. J.* 146:322
Sandage, A. R., Wyndham, J. D. 1965. *Ap. J.* 141:328
Sargent, W. L. W. 1970. *Ap. J.* 160:405
Sazonov, V. N. 1969. *Astron. J. USSR* 13:396
Schmidt, M. 1968. *Ap. J.* 151:393
Schmidt, M. 1974. *Ap. J.* 193:605
Schmitt, J. 1968. *Nature* 218:663
Seaquist, E. R. 1969. *Astrophys. Lett.* 5:111
Seaquist, E. R. 1973. *Astron. Astrophys.* 22:299
Seaquist, E. R., Gregory, P. C., Biraud, F., Clarke, T. R. 1973. *Nature Phys. Sci.* 242:20
Searle, L., Bolton, J. G. 1968. *Ap. J.* 154:L101
Seielstad, G. A. 1969. *Astron. Astrophys.* 2:372
Shaffer, D. B., Cohen, M. J., Romney, J. D., Schilizzi, R. T., Kellermann, K. I., Swenson, G. W. Jr., Yen, J. L., Rinehart, R. 1975. *Ap. J.* 201:256
Shaffer, D. B., Schilizzi, R. T. 1975. *Astron.*

J. 80:753
Shen, B. S. P., Usher, P. D. 1970. *Nature* 228:1070
Shimmens, A. J., Bolton, J. 1974. *Aust. J. Phys., Astrophys. Suppl. 32*
Shklovsky, I. S. 1964. *Astron. J. USSR* 8:132
Silk, J., Smith, H. E., Spinrad, H., Field, G. B. 1973. *Ap. J.* 181:L25
Smith, A. G., Scott, R. L., Leacock, R. J., McGimsey, B. Q., Edwards, P. L., Hackney, R. L., Hackney, K. R. 1975. *Publ. Astron. Soc. Pac.* 87:149
Spinrad, H., Smith, H. E. 1975. *Ap. J.* 201:275
Stannard, D., Treverton, A. M., Porcas, R. W., Davies, R. J. 1975. *Nature* 255:384
Stein, W. A., Gillett, F. C., Knacke, R. F. 1971. *Nature* 231:254
Strittmatter, P. A., Carswell, R. F., Gilbert, G., Burbidge, E. M. 1974. *Ap. J.* 190:509
Strittmatter, P. A., Serkowski, K., Carswell, R., Stein, W. A., Merrill, K. M., Burbidge, E. M. 1972. *Ap. J.* 175:L7
Tapia, S., Craine, E. R., Johnson, K. 1976. *Ap. J.* 203:291
Thuan, T. X., Oke, J. B., Gunn, J. E. 1975. *Ap. J.* 201:45
Tritton, K. P., Brett, R. A. 1970. *Observatory* 90:110
Tsesevich, V. P. 1972. *Astron. Tsirk.* 688:7
Ulmer, M. P., Murray, S. S. 1976. *Ap. J.* 207: In press
Ulrich, M. -H. 1973. *Astrophys. Lett.* 14:89
Ulrich, M. -H., Kinman, T. D., Lynds, C. R., Rieke, G. H., Ekers, R. D. 1975. *Ap. J.* 198:261
Usher, P. D. 1975. *Ap. J.* 198:L57
Véron, P., Véron, M. P. 1975. *Astron. Astrophys.* 39:281
Visvanathan, N. 1967. *Ap. J.* 150:L149
Visvanathan, N. 1969. *Ap. J.* 155:L133
Visvanathan, N. 1973a. *Ap. J.* 179:1
Visvanathan, N. 1973b. *Ap. J.* 185:145
Visvanathan, N., Elliot, J. L. 1973. *Ap. J.* 179:721
Wampler, E. J., Robinson, L. B., Burbidge, E. M., Baldwin, J. A. 1975. *Ap. J.* 198: L49
Wardle, J. F. C. 1971. *Astrophys. Lett.* 8:183
Warner, J. W. 1972. *Astrophys. Lett.* 11:183
Weistrop, D. 1973. *Nature Phys. Sci.* 241: 157
Weistrop, D., Goldsmith, S. 1973. *Astrophys. Lett.* 14:225
Westerlund, B. E., Wall, J. V. 1969. *Astron. J.* 74:335
Williams, R. E., Strittmatter, P. A., Carswell, R. F., Craine, E. R. 1975. *Ap. J.* 202:296
Williams, W. L., Rich, A., Kupferman, P. N., Ionson, J. A., Hiltner, W. A. 1972. *Ap. J.* 174:L63
Wills, B. J., Wills, D. 1974a. *Ap. J.* 190:L97
Wills, B. J., Wills, D. 1976. *Ap. J. Suppl.* 31: In press
Wills, D., Bolton, J. G. 1969. *Aust. J. Phys.* 22:775
Wills, D., Wills, B. J. 1974b. *Ap. J.* 190:271
Wing, R. F. 1973. *Astron. J.* 78:684
Wlérick, G., Michet, D., Lelièvre, G. 1974. *C. R. Acad. Sci. Ser. B* 278:245
Wolfe, A. M., Brown, R. L., Roberts, M. S. 1976. *Phys. Rev. Lett.* In press
Woltjer, L. 1966. *Ap. J.* 146:597
Zwicky, F. 1966. *Ap. J.* 143:192