

THE ARC SECOND RADIO STRUCTURE OF 12 BL LACERTAE OBJECTS

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ABSTRACT

Twelve BL Lacertae objects have been mapped with the Very Large Array (VLA) to study their extended radio structures. All are dominated by flat-spectrum cores, but a number of them show significant extended emission on scales ranging up to hundreds of kiloparsecs. Although diffuse emission is common, the one-sided structures often seen in core-dominated quasars occur infrequently. Some of the extended structures are similar to those found in elliptical galaxies but no "classical" double sources are found in the BL Lac objects. There is an indication that the BL Lac sources can be divided into two variability classes on the basis of their radio structures. Those which are unresolved by the VLA tend to be highly variable at centimeter wavelengths, while those with extensive diffuse emission exhibited little or no radio variability in their cores on a 2 yr time scale. Such a difference might be understood from the relativistic beaming model if the highly variable objects have their beams more nearly aligned along the line of sight than do the more extended, less variable sources.

Subject headings: BL Lacertae objects — galaxies: nuclei — interferometry — quasars — radio sources: extended — radio sources: variable

I. INTRODUCTION

BL Lacertae objects (or "Lacertids") comprise one class of extragalactic radio sources which has been studied extensively in recent years. The BL Lac sources are often found to be highly variable, although most do not change their centimeter-wavelength flux densities by more than $\sim 25\%$ over a period of ~ 6 months (Weiler and Johnston 1980, hereafter WJ; Altschuler 1982). As expected from their variability, the bulk of the BL Lac objects are dominated by compact radio cores; these cores often show a high degree of linear polarization. The cores themselves have been studied in numerous very long baseline interferometry (VLBI) experiments and often contain jets or one-sided structures reminiscent of those in radio galaxies and in quasars (e.g., Bååth *et al.* 1981).

The pointlike optical continuum sources in the BL Lac objects show little or no line emission. However, careful spectrophotometry often shows some evidence for emission and/or absorption lines in the nebulous fuzz surrounding the compact sources (e.g., Miller, French, and Hawley 1978). Generally, the emission lines are interpreted as indicators of cosmological distance, while the absorption lines are thought to be due to intervening material which may or may not be associated with

the BL Lac objects themselves. Analysis of the optical continuum in the nebulosities has shown a radial light distribution characteristic of that found in galaxies (see, e.g., Weistrop *et al.* 1981), supporting the hypothesis that the BL Lac phenomenon is a manifestation of activity in the nuclei of otherwise "normal" galaxies. J. S. Miller (1981) finds that nearby BL Lac objects occur in the centers of highly luminous ("first-ranked") elliptical galaxies.

Although the radio morphology of most BL Lac objects is dominated by emission from a compact core, sources such as 0219+428 (Stannard, Edwards, and McIlwrath 1981), 1101+384 (Kapahi 1979), and 1400+162 (Hintzen and Owen 1981) have shown substantial extended structure as well. In their survey, WJ found a significant fraction of BL Lac objects to contain some flux density on scales greater than an arc second. In order to study this extended structure in more detail, we have mapped a number of the more promising sources with NRAO's Very Large Array (VLA). Throughout this work, we use a cosmological model having $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.1$.

II. OBSERVATIONS

Twelve BL Lacertae objects were observed at two frequencies, 4885 MHz (6 cm) and 1465 MHz (20 cm), with the nearly completed VLA on 1980 June 14-15. At that time, 24 antennas were available with spacings ranging from 50 m to 24 km. The antennas on the

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TABLE 1
CALIBRATION SOURCES

NAME	ASSUMED POSITION		ASSUMED FLUX DENSITY (Jy)	
	α (1950)	δ (1950)	S(6 cm)	S(20 cm)
0202+319	02 ^h 02 ^m 09 ^s .660	+31°58'10".55	1.36	0.97
0235+164	02 35 52.617	+16 24 04.04	2.47	2.04
0735+178	07 35 14.115	+17 49 09.02	2.20	2.02
1308+326	13 08 07.570	+32 36 41.00	2.32	1.63
1323+321	13 23 57.900	+32 09 43.55	2.40	4.51
1328+307	13 28 49.657	+30 45 58.64	7.41	14.51
2200+420	22 00 39.363	+42 02 08.57	6.63	3.34
2227-088	22 27 02.330	-08 48 17.40	1.23	...

southwest arm of the array were essentially in the high-resolution arrangement of the A configuration (Thompson *et al.* 1980), while the antennas on the other two arms were in a more compact, hybrid configuration. Typical full-resolution beam sizes were $\sim 0''.6$ (FWHM) at 6 cm wavelength and $\sim 2''.0$ at 20 cm.

Most of the objects observed were selected because of interesting large-scale structure found on visibility plots by WJ, while a few sources such as 2200+420 (BL Lac) were observed because of their importance as well-studied members of the BL Lac class or to help calibrate the data. Individual BL Lac objects were observed an average of ~ 10 – 12 times for ~ 4 minutes at each frequency. The integrations were spaced in hour angle so as to optimize coverage of the (U , V)-plane. Unresolved calibration sources having radio positions accurate to $0''.1$ and four BL Lac objects with highly dominant cores were used to make the initial calibration of the data (Table 1). All program sources were observed at both frequencies except 2223-052 (Brown *et al.* 1981), which was observed at 2 cm (14,985 MHz) instead of 20 cm. A 50 MHz bandwidth was used for all observations.

Although corrections for large atmospheric phase errors introduced some uncertainty, all positions agreed to within a few tenths of an arc second with those listed by WJ. The flux densities were normalized to the scale of Baars *et al.* (1977) by means of observations of 1328+307 (3C 286). This source was also used to calibrate the instrumental polarization, with 33° assumed as its polarization position angle. Since the program sources are dominated by compact components, the self-calibration algorithm devised by Schwab (1980) was used to greatly increase the dynamic range of the final maps, which were CLEANed by using Clark's (1980) algorithm. The dynamic range of the full-resolution maps depends on source strength and declination. It ranges from ~ 50 to 1 for 2155-304 to ~ 1000 to 1 for 2200+420, with a typical value of 300–400 to 1.

III. RESULTS

Visibility plots were generated for each of the sources observed, and maps were made with various visibility tapers to emphasize the source structures on different angular scales. In some cases, particularly at 6 cm, even heavily tapered maps failed to account for all the flux estimated by extrapolation of the visibility curves to zero baseline. This is apparently due to the presence of low-surface brightness features of large angular extent. For objects whose maps are missing some flux, total source flux densities were estimated from the visibility curves.

The linear polarization of the compact cores was measured for each BL Lac object. Corrections to the polarization position angles were made by estimating the rotation measure due to material in the Galaxy. These estimates were made from published polarization measurements of quasars within $\sim 15^\circ$ of each BL Lac source (Wardle and Kronberg 1974; Gardner, Whiteoak, and Morris 1975; Kronberg and Wardle 1977; Simard-Normandin, Kronberg, and Button 1981). It was assumed that the intrinsic direction of polarization of

TABLE 2
PROPERTIES OF UNRESOLVED SOURCES

IAU NAME (1)	OTHER NAME (2)	α (1950) (3)	δ (1950) (4)	6 CENTIMETERS				20 CENTIMETERS				α (13)
				S_v (Jy) (5)	d (6)	χ_{obs} (7)	χ_{int} (8)	S_v (Jy) (9)	d (10)	χ_{obs} (11)	χ_{int} (12)	
0219+428	3C 66 A	02 ^h 19 ^m 29 ^s .98	+42°48'29".7	0.572	2.2%	+59°	+77°	0.895	2.1%	+42°	+63°	-0.37
		02 19 30.07	+42 48 25.4	<0.005	...	...	...	~ 0.03	...	...	...	...
0235+164	...	02 35 52.63	+16 24 03.9	2.50	2.0%	+31°	+36°	2.05	1.0%	+119°	+171°	+0.16
0735+178	...	07 35 14.13	+17 49 09.2	2.22	<0.2%	...	...	2.05	<0.2%	...	...	+0.07
1101+384	Mrk 421	11 01 40.57	+38 28 43.0	0.526	<0.2%	...	...	0.514	1.0%	+167°	+3°	+0.02
1215+303	...	12 15 21.15	+30 23 40.0	0.381	4.7%	+54°	+54°	0.345	4.1%	+56°	+52°	+0.08
1308+326	...	13 08 07.57	+32 36 41.0	2.33	3.7%	+93°	+94°	1.61	$\sim 0.3\%$	+177°	+10°	+0.31
	...	13 08 07.58	+32 36 52.2	<0.005	...	...	...	0.014	...	...	...	...
1514-241	AP Lib	15 14 45.28	-24 11 22.7	2.91	5.4%	+38°	+8°	2.53	3.0%	+36°	+64°	+0.12
1538+149	4C +14.60	15 38 30.23	+14 57 21.9	1.59	5.3%	+142°	+133°	1.30	2.1%	+43°	+118°	+0.17
1652+398	Mrk 501	16 52 11.73	+39 50 25.2	1.28	2.1%	+152°	+144°	1.35	1.1%	0°	+89°	-0.04
2155-304	...	21 55 58.35	-30 27 54.5	0.278	1.3%	+9°	+14°	0.234	<0.2%	...	...	+0.14
2200+420	BL Lac	22 00 39.36	+42 02 08.6	6.74	1.4%	+4°	+23°	3.39	1.2%	+128°	+157°	+0.57
2223-052	3C 446	22 23 11.09	-05 12 17.9	2.40	4.6%	+4°	+0°	...	...	...	...	...

TABLE 3
PROPERTIES OF TOTAL SOURCES

IAU NAME (1)	z (2)	6 CM FLUX (Jy)		20 CM FLUX (Jy)		DIAMETER		EXTENDED STRUCTURE (9)
		Unresolved (3)	Total (4)	Unresolved (5)	Total (6)	Angular (") (7)	Linear (kpc) (8)	
0219+428.....	~ 0.4	0.572	0.935	0.895	1.52	100	460	Secondary + diffuse
0235+164.....	0.852	2.50	2.50	2.05	2.05	< 0.2	< 1.3	Unresolved
0735+178.....	0.424	2.22	2.22	2.05	2.05	$< 3?$	$< 14?$	Barely resolved?
1101+384.....	0.031	0.526	0.55V	0.514	0.720	200	120	Diffuse component
1215+303.....	...	0.381	0.43V	0.345	0.496	50	...	Diffuse component
1308+326.....	0.996	2.33	2.33	1.61	1.68	11	75	Secondary + extension
1514-241.....	0.049	2.91	2.91	2.53	2.67	20	18	Extended to east
1538+149.....	...	1.59	1.66V	1.30	1.48	4	...	Small diffuse component
1652+398.....	0.034	1.28	1.32V	1.35	1.45	60	37	Diffuse component
2155-304.....	0.17?	0.278	0.32V	0.234	0.333	210	540?	Diffuse component
2200+420.....	0.070	6.74	6.74	3.39	3.39	< 0.2	< 0.3	Unresolved
2223-055.....	1.404	2.40	3.95	...	...	0.15	1.1	Secondary

each quasar is independent of wavelength in the spectral region of interest, with deviations from that wavelength independence caused by Faraday rotation in the Galaxy. Individual quasars showing apparent rotation measures highly discrepant from others in their vicinity were not used because of the likelihood that the above assumption was breaking down.

The basic observational results for the BL Lac objects are summarized in Tables 2 and 3. Table 2 refers only to the compact-core and nearby secondary components. Columns (1)–(4) give source names and radio positions. Columns (5)–(8) and (9)–(12) give flux density, degree of polarization, measured polarization direction, and estimated intrinsic polarization direction at 6 and 20 cm, respectively. Finally, column (13) gives the spectral index between the two wavelengths ($S \propto \nu^{+\alpha}$). Flux densities for the compact cores are estimated to be accurate to better than 2%, while *intrinsic* polarization angles are highly uncertain.

In Table 3, properties of the extended radio structure are given for each program source. Column (1) lists source names, while column (2) gives measured redshifts (see WJ and Hewitt and Burbidge 1980 for references). Columns (3)–(4) and (5)–(6) give unresolved and total flux densities at the two main observing frequencies. Angular and linear diameters are listed in columns (7) and (8), while column (9) contains comments on the structures. Extents or total flux densities followed by the letter *V* are quantities estimated from the visibility plots.

A search was made for secondary components at large distances from the BL Lac cores. For each of the 11 sources observed at 20 cm, a large-scale map was produced after applying a 1 km (5000 wavelength) taper to the visibility data. In each map, a $20' \times 20'$ field was searched for distant secondary components. Eight additional sources having derived flux densities above 10 mJy were found and are listed in Table 4. Three of these sources are in the field of 1652+398 and two are near 2200+420, but there is no evidence that any of the extra sources is associated with a BL Lac object.

Integrating the source counts given by Willis *et al.*

(1977) gives an expected value of ~ 22 sources above 10 mJy in the 11 20 cm fields. Thus the BL Lac fields do not show any excess of radio sources. Part of the apparent deficiency may be caused by differences in limiting flux densities among the observed fields. However, the major effect is loss of correlation across the 50 MHz bandwidth for positions more than a few arc minutes from the field centers.

Figures 1–6 show maps of some of the resolved sources. Individual BL Lac objects are discussed below.

a) 0219+428 (3C 66 A)

This object appears to be in the center of a distant cluster at $z \approx 0.4$ (Butcher *et al.* 1976; Miller, French, and Hawley 1978). WJ found the radio source to have a compact core surrounded by an extended halo approximately $10''$ in size. Stannard, Edwards, and McIlwrath (1981) found a similar structure but estimated the diffuse emission to be greater than $10''$ in extent.

The radio source in 0219+428 shows an interesting progression in the position angles of its elongation when following the structure from the smallest to the largest angular scales. Bååth *et al.* (1981) found the VLBI source to be elongated in P.A. $\approx 135^\circ$. Our full-resolution 6 cm map (Fig. 1a) is extended in P.A. $\approx 155^\circ$

TABLE 4
BACKGROUND SOURCES IN BL LACERTAE FIELDS

Source	$\alpha(1950)$	$\delta(1950)$	$S_{20}(\text{Jy})^a$
0219 B1 ^b	02 ^h 20 ^m 02 ^s .9	+42°46'01".0	2.88
1101 B1	11 00 50.7	+38 31 53.0	0.05
1538 B1	15 38 02.5	+14 48 17.0	0.02
1652 B1	16 52 16.1	+39 55 06.0	0.01
1652 B2	16 52 32.7	+39 54 51.0	0.04
1652 B3	16 52 48.6	+39 45 16.0	0.01
2200 B1	22 00 20.1	+42 09 44.0	0.03
2200 B2	22 00 23.9	+41 59 09.0	0.02

^a Flux densities may be underestimated because of bandwidth smearing.

^b 0219 B1 = 3C 66 B.

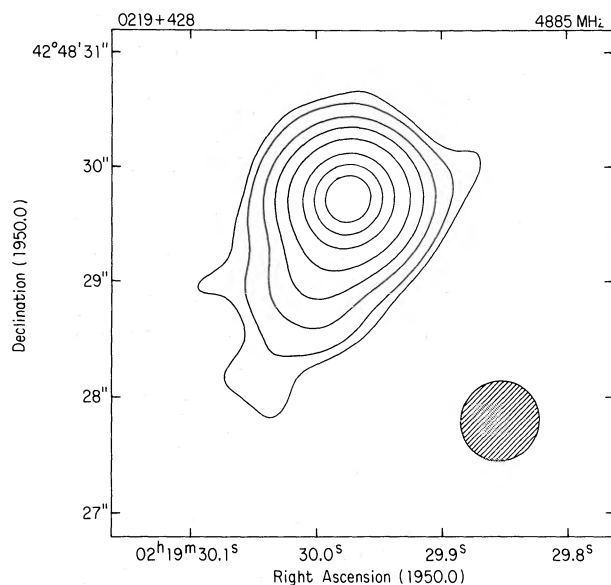


FIG. 1a

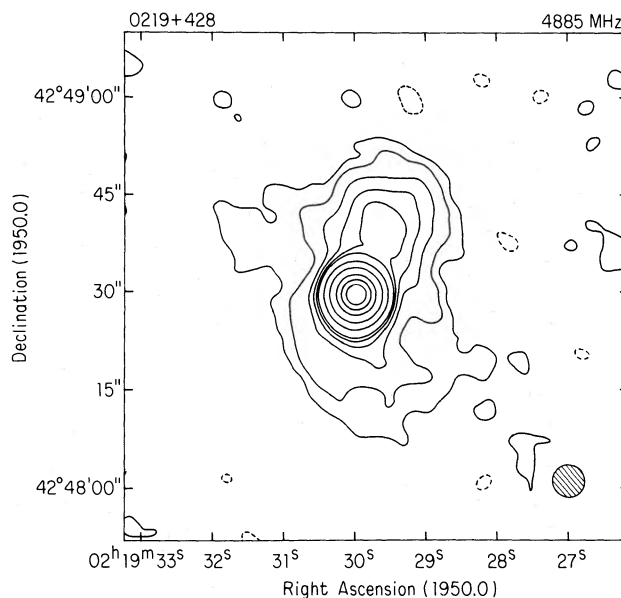


FIG. 1c

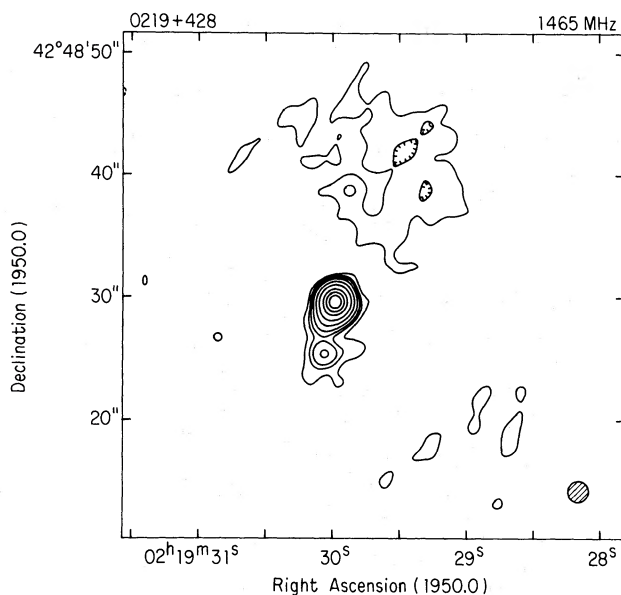


FIG. 1b

FIG. 1.—(a) 0219+428 at 6 cm, full resolution. Contours are at 1, 2, 5, 10, 20, 40, 60, and 80 percent of the peak of 0.526 Jy per beam area. (b) 0219+428 at 20 cm, full resolution. Contours are at 1, 2, 3, 5, 10, 20, 40, 60, and 80 percent of the peak of 0.878 Jy per beam area. (c) 0219+428 at 6 cm, 2 km taper. Contours are at -0.5 (dashed), 0.5 , 1, 2, 3, 4, 5, 10, 20, 40, 60, and 80 percent of the peak of 0.628 Jy per beam area.

on a scale of $1''.5$ (7 kpc), while the full-resolution 20 cm map (Fig. 1b) shows this extension to curve back to a secondary component $4''.4$ (20 kpc) from the central core in P.A. $\approx 167^\circ$. Finally, low-resolution 6 cm (Fig. 1c) and 20 cm (not shown) maps reveal diffuse emission stretching progressively more to the west with increasing distance from the central core. One possible interpretation of the curving morphology in the

southern part of the radio source is that it is caused by a jet which has been bent by ram pressure or by a static pressure gradient in an intracluster medium. Figure 1c shows the diffuse radio emission in the north to bend more toward the west with increasing distance from the central component, supporting the suggestion that a weak counterjet may exist and be bent by an external medium. The total extent of the diffuse radio source at 20 cm is approximately $100''$ (460 kpc).

b) 0235+164

AO 0235+164 underwent a radio and optical outburst during 1979 (Balonek and Dent 1980), but its flux density had returned to a lower level by the time of the VLA observations in mid-1980. Maps with dynamic ranges of better than 500 to 1 show no evidence for any emission outside the unresolved core. This agrees with the results of WJ, who found almost 85% of the flux density within a 0.5 milli-arcsec core and no evidence for extended structure. In particular, there is no radio emission greater than 5 mJy at either observing frequency at the position of the faint nebulosity $2''$ south of the BL Lac object (Spinrad and Smith 1975; Smith, Burbidge, and Junkkarinen 1977).

c) 0735+178

This flat-spectrum, compact radio source has been interpreted as a superposition of four peaked components, with the largest having a size of $\sim 0''.3$ and a flux density of ~ 210 mJy at 2.7 GHz (Cotton *et al.* 1980). The VLA observations show a dominant point source of size $\leq 0''.2$ with the possibility of very weak extensions contributing less than 0.5% of the total flux density on a scale of $1''$ – $3''$. The compact radio source is polarized only very weakly or not at all at the VLA observing frequencies; Perley (1982) finds a weak polarization of $\lesssim 1\%$ at 6 cm and at 20 cm.

d) 1101 + 384 (Markarian 421)

This BL Lac object is located in the center of the galaxy Mrk 421, which has an optical extent of $30'' \times 40''$ and is in a Zwicky cluster at $z = 0.03$ (Ulrich *et al.* 1975; Ulrich 1978a). The radio source was known previously to be quite extended, having a size of $\sim 2'$ at 2.7 GHz (Margon, Jones, and Wardle 1978) and $\sim 3.5'$ at 1.4 GHz (Kapahi 1979). We confirm these results, finding a radio source of diameter $\sim 200''$ at 20 cm (Fig. 2). The radio halo's extent of ~ 115 kpc is much greater than the apparent size of the optical galaxy.

e) 1215 + 303

WJ found a size of $36''$ for this object in their early observations made with one arm of the VLA. The current observations show $\sim 30\%$ of the total 20 cm flux density to be contained in an extended component $\sim 50''$ in size and elongated in P.A. $\approx 75^\circ$. The low-surface brightness halo does not show up well in any of the low-resolution maps, but its presence is evident from the visibility plots and the slight extensions in the radio maps.

f) 1308 + 326

This BL Lac object has an emission-line redshift of 0.996 (Miller, French, and Hawley 1978). Assuming isotropic emission, it had a luminosity greater than 10^{48} ergs s^{-1} during its outburst in the spring of 1978 (Moore *et al.* 1980). WJ found evidence for a bright compact VLBI core and complex arc second extended structure. The 20 cm map displayed in Figure 3 shows a secondary component located $11''$ north of the compact-core source; that core source is accompanied by some extended emission to the southeast in P.A. $\approx 110^\circ$. The

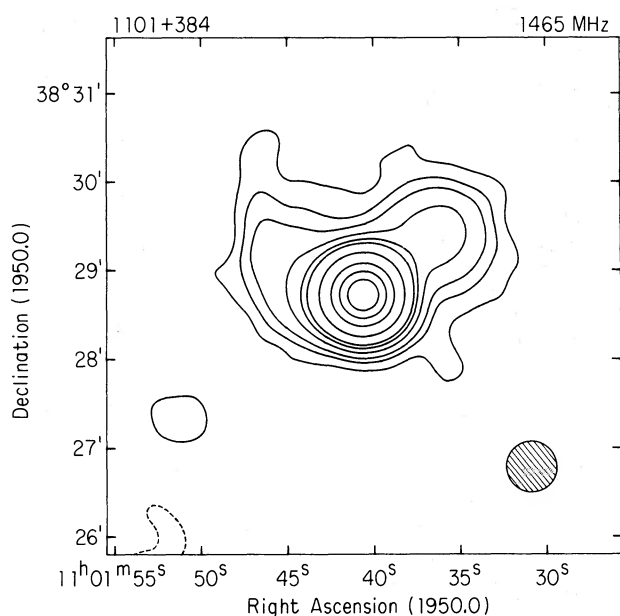


FIG. 2.—1101+384 at 20 cm, 1 km taper. Contours are at -1 (dashed), 1, 2, 3, 5, 7.5, 10, 20, 40, 60, and 80 percent of the peak of 0.564 Jy per beam area.

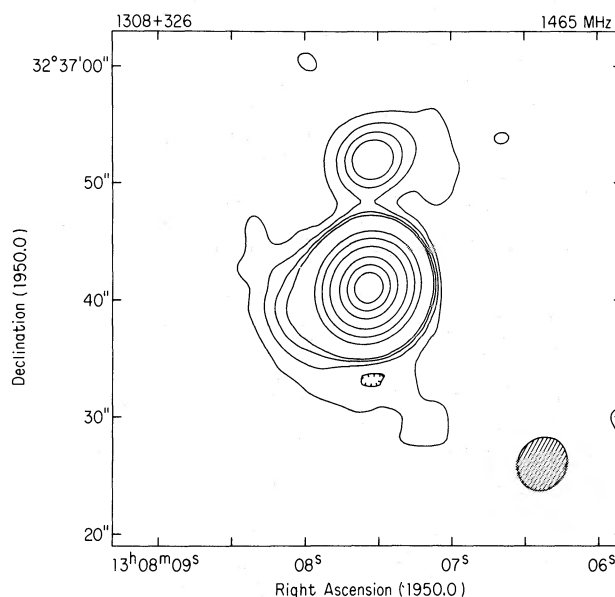


FIG. 3.—1308 + 326 at 20 cm, 8 km taper. Contours are at 0.25, 0.5, 0.75, 1, 3, 5, 10, 20, 40, 60, and 80 percent of the peak of 1.61 Jy per beam area.

alignment between the core and the northern component is not far from the 10° position angle WJ found for the elongation of the VLBI source. The northern component is not detected at 6 cm and thus has a spectral index steeper than about -0.9 .

g) 1514 - 241 (AP Librae)

Conway and Stannard (1972) found this source to consist of two components at 408 MHz, a compact radio core at the position of the optical object and an extended (greater than $10''$) component $\sim 20''$ east. Their inferred flux ratio of ~ 3 to 1 was used along with Fomalont's (1967) nondetection of the extended source at 1425 MHz to suggest a spectral index at least as steep as -0.8 for the eastern component. A low-resolution 20 cm VLA map (Fig. 4) definitely establishes the presence of a weak extended component to the east of the optical object, but its flux density and size cannot be determined accurately from the present data.

h) 1538 + 149 (4C + 14.60)

WJ estimated an extent of $1''.8$ for this source at 6 cm. The new observations confirm this size at 6 cm and show $\sim 15\%$ of the 20 cm emission to occur on a slightly larger scale of $\sim 4''$. This extended emission appears to be concentrated on the northern side of the compact source.

i) 1652 + 398 (Markarian 501)

This source is another case of a BL Lac object embedded in a Markarian galaxy (McGimsey and Miller 1978; Maza, Martin, and Angel 1978). The galaxy has a redshift of $z = 0.0337$ (Ulrich *et al.* 1975). Sramek and Tovmassian (1976) found the radio source to have a diameter of less than $1''$ at 2.7 GHz. Although an unresolved source does dominate the radio emission, there

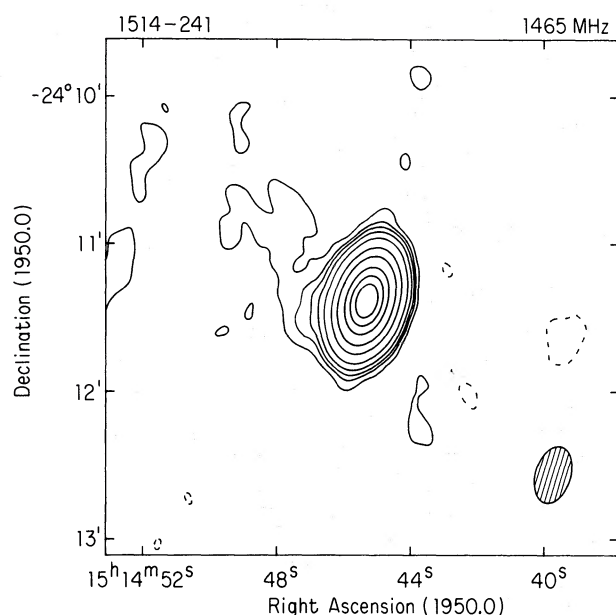


FIG. 4.—1514–241 at 20 cm, 2 km taper. Contours are at -0.4 (dashed), 0.4, 0.8, 1.2, 2, 4, 10, 20, 40, 60, and 80 percent of the peak of 2.52 Jy per beam area.

is evidence for a diffuse component of diameter $\sim 60''$ at 20 cm (Fig. 5). This extended emission, which contains less than 10% of the total flux density at 20 cm, is elongated along P.A. $\approx 45^\circ$. That direction is roughly perpendicular to the direction of optical polarization (P.A. = 149°) found by Puschell and Stein (1980).

j) 2155–304

This southern radio source was discovered as a BL Lac object on the basis of its X-ray emission (Agrawal and

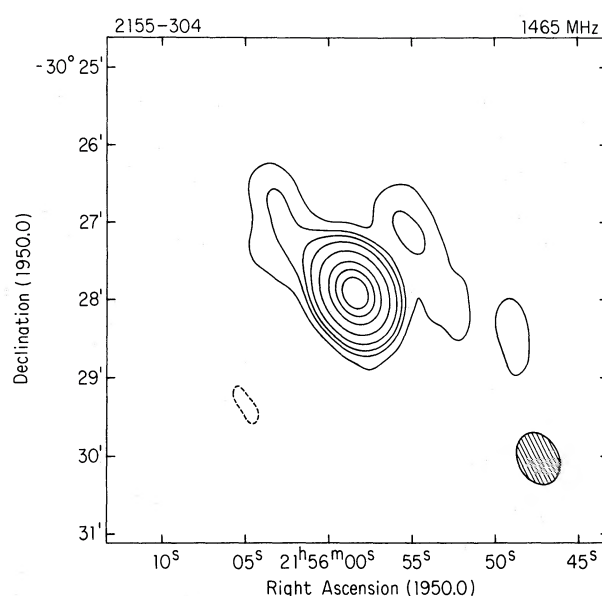


FIG. 6.—2155–304 at 20 cm, 1 km taper. Contours are at -2 (dashed), 2, 4, 6, 10, 20, 40, 60, and 80 percent of the peak of 0.276 Jy per beam area.

Riegler 1979; Griffiths *et al.* 1979). Although its redshift has been suggested to be $z = 0.17$ (Charles, Thorstensen, and Bowyer 1979; Maraschi *et al.* 1980), this suggestion was not confirmed by the spectrophotometry of Snyder *et al.* (1980). Urry and Mushotzky (1982) have used X-ray and radio data to deduce the presence of relativistic beaming in the BL Lac object. The heavily tapered 20 cm map displayed in Figure 6 shows a point source within a diffuse component of total extent ~ 3.5 . Approximately 30% of the total flux density is in the extended component, which has a linear diameter of ~ 540 kpc if the proposed redshift is correct.

k) 2200+420 (BL Lacertae)

The prototype of the BL Lac sources has been observed extensively in the past. We confirm its unresolved nature on the arc second level, with a dynamic range of close to 1000 to 1 at 6 cm and ~ 600 to 1 at 20 cm.

l) 2223–052 (3C 446)

This optically violently variable object (e.g., H. R. Miller 1981) at $z = 1.404$ (Miller and French 1978) has been observed at high resolution by Brown *et al.* (1981). Because of its small angular size, it was observed at 2 and 6 cm rather than 6 and 20 cm. The 6 cm map does not resolve the source fully, but the visibility curve shows gradual resolution of $\sim 40\%$ of the flux density on a scale of less than an arc second. At 2 cm, the compact core is found to contain 5.0 Jy, with another 0.5 Jy in a secondary component $0''.15$ (1.1 kpc) to the east (P.A. = $90^\circ \pm 30^\circ$). The resolution is not sufficient to provide highly accurate results. However, the compact core definitely contains an inverted spectrum between 2 and 6 cm, while the strength of the secondary falls off rapidly with decreasing wavelength.

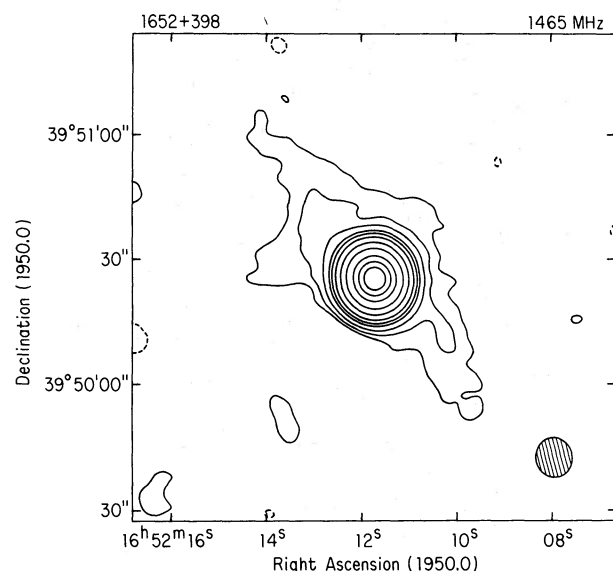


FIG. 5.—1652+398 at 20 cm, 4 km taper. Contours are at -0.25 (dashed), 0.25, 0.5, 1, 2, 3, 5, 10, 20, 40, 60, and 80 percent of the peak of 1.35 Jy per beam area.

IV. DISCUSSION

a) *Relativistic Beaming*

Blandford and Rees (1978) and Scheuer and Readhead (1979) have suggested that BL Lacertae objects might be sources in which relativistic beams of emitting material point almost directly along the line of sight. Beaming scenarios could account for observational data such as the dominance of compact radio cores, rapid variability, and apparently extreme luminosities during outbursts. We find our observational results to be consistent with the occurrence of relativistic beaming in the BL Lac radio cores.

If the BL Lac cores are relativistically beamed, the extended radio emission might be due to classical double sources seen nearly end-on. Browne *et al.* (1982) suggest such a model for core-dominated quasars, while Stannard and McIlwrath (1982) support a similar picture for BL Lac objects. Perley, Fomalont, and Johnston (1982) found core-dominated quasars to have highly asymmetric radio emission outside the cores; they could not distinguish between relativistic motion and intrinsic asymmetry as causes for such a morphology. In contrast to their quasars, we find the BL Lac objects to have relatively symmetric diffuse emission. Such structure makes it unlikely that relativistic geometrical effects are important outside the cores of the BL Lac sources studied in this work.

The intrinsic relative strengths of core and diffuse emission can be compared for a given amount of Doppler boosting in the core. For 2200+420 (BL Lacertae), Phillips and Mutel (1982) find apparent "superluminal" expansion with $\gamma \approx 5$. The standard formula for the flux density enhancement gives $[\gamma(1 - \beta \cos \theta)]^{-3+\alpha} \approx 260$ for beaming exactly along the line of sight. Since the VLA maps of 2200+420 display values greater than 600 (20 cm) to 1000 (6 cm) for the observed ratio of core to diffuse emission, the minimum *intrinsic* value for that ratio is ~ 3 to 1. This numerical result depends sensitively on the value of the Lorentz factor, which is not determined unambiguously for the complex VLBI source in 2200+420. But if the core is boosted by relativistic expansion at a rate near $\gamma = 5$, 2200+420 cannot be a *typical* double source seen end-on, since objects such as Cygnus A have core/diffuse flux density ratios near 10^{-3} (cf. Perley, Fomalont, and Johnston 1982).

The data listed in Table 3 show that four of the BL Lac sources have observed 20 cm values of 2.5 or less for the ratio of core to diffuse flux density. If the radio cores of these sources are relativistically enhanced as is hypothesized for 2200+420, their intrinsic values for this ratio are much closer to those found in many radio galaxies. Certainly, either their intrinsic properties or their orientations must differ significantly from 2200+420. The lack of strong asymmetries in the extended radio emission argues against relativistic beaming outside the unresolved cores. Only two sources have sizes much greater than 100 kpc on the sky plane, and one of these has a highly uncertain measured redshift. Therefore, the possibility that the extended

emission is comprised of material moving nonrelativistically near the line of sight cannot be ruled out because of excessive deprojected radio source sizes.

If the BL Lac cores are beaming toward us, strong and rapid core variability would be expected, as is found for some sources. Ideally, the radio flux densities would be monitored at short intervals for periods of 10 yr or more. A few of the sources discussed in this work have been followed in such a manner (Medd *et al.* 1972; Andrew *et al.* 1978). But since many of the more recently identified BL Lac objects have not been monitored for extended periods, all sources cannot be compared over the same long time baseline.

Ten of the 12 BL Lac objects discussed in this work were observed by WJ in 1978 March with the 100 m Effelsberg telescope. Comparison of the 6 cm flux densities at that epoch with those from the VLA observations in 1980 June gives an indication of the amount of variability present in each object. A variability index can be defined: $\text{VAR} = |S_2 - S_1|/(S_1 + S_2)$, where S_2 is the core flux density in 1980 June, and S_1 is the core flux density at the earlier epoch. Since 2155-304 and 2223-052 were not observed with the 100 m telescope, their respective first-epoch flux densities come from the 1971 July observations by Shimmins and Bolton (1974) and the 1979 July measurement by Brown *et al.* (1981). The core flux densities have been found by subtracting the diffuse emission (assumed constant) found in this work (Table 3) from the total flux densities. Given the $\pm 14\%$ errors on the 100 m results (WJ), values of $\text{VAR} \leq 0.08$ are consistent with a lack of variability.

For each source, Table 5 lists the variability index at 6 cm along with the fraction of emission in an unresolved core and the absolute powers of core and extended emission at both 6 and 20 cm. The sources with more than 20% of their total 20 cm emission in a resolved component all have $\text{VAR} \leq 0.08$, with three having VAR between 0.06 and 0.08 because of apparent flux density decreases over 27 months. These decreases may have been caused partly by loss of correlation across the 50 MHz bandwidth in the large-scale emission during the 1980 VLA observations. Taking this possibility and the uncertainties in the Effelsberg flux densities into account, we find the data to be consistent with *constant* core flux densities for all the sources having large fractions of their flux densities outside the unresolved cores. In contrast, many of the objects with greater core dominance show stronger variability. Further, many of the most dramatically varying BL Lac sources were not observed in this work because WJ found them to have no significant extended components. Including such sources would strengthen the likelihood of a relation between radio structure and variability.

A division of the BL Lac sources into two variability classes receives some support from Altschuler (1982), who found that many BL Lac objects did not vary significantly when monitored at monthly intervals for almost six months. Our data suggest that this dichotomy may be connected with the direction of relativistic out-

TABLE 5
RESOLUTION AND VARIABILITY

SOURCE	VAR	6 CENTIMETER			20 CENTIMETER		
		f_{core}	P_{core} (W Hz ⁻¹ sr ⁻¹)	P_{ext} (W Hz ⁻¹ sr ⁻¹)	f_{core}	P_{core} (W Hz ⁻¹ sr ⁻¹)	P_{ext} (W Hz ⁻¹ sr ⁻¹)
0219+428	0.08	0.61	1.9×10^{25}	1.2×10^{25}	0.59	3.0×10^{25}	2.1×10^{25}
0235+164	0.09	1.00	5.1×10^{26}	$< 1.0 \times 10^{24}$	1.00	4.2×10^{26}	$< 8.4 \times 10^{23}$
0735+178	0.15	1.00	8.5×10^{25}	$< 2.8 \times 10^{23}$	1.00	7.9×10^{25}	$< 2.6 \times 10^{23}$
1101+384	0.06	0.96	7.9×10^{22}	3.6×10^{21}	0.71	7.7×10^{22}	3.1×10^{22}
1215+303	0.07	0.89	...	...	0.70	...	...
1308+326	0.02	1.00	7.0×10^{26}	$< 2.8 \times 10^{24}$	0.96	4.8×10^{26}	2.1×10^{25}
1514-241	0.11	1.00	1.1×10^{24}	$< 3.7 \times 10^{21}$	0.95	9.7×10^{23}	5.3×10^{22}
1538+149	0.18	0.96	...	...	0.88	...	...
1652+398	0.10	0.97	2.3×10^{23}	7.3×10^{21}	0.93	2.5×10^{23}	1.8×10^{22}
2155-304 ^a	0.02	0.87	1.4×10^{24}	2.2×10^{23}	0.70	1.2×10^{24}	5.0×10^{23}
2200+420	0.73	1.00	5.4×10^{24}	$< 5.4 \times 10^{21}$	1.00	2.7×10^{24}	$< 4.5 \times 10^{21}$
2223-052	0.04	0.61	1.7×10^{27}	1.1×10^{27}	...	...	...

^a Redshift is uncertain.

flow. Those objects with beams pointing directly along the line of sight would be more rapidly variable, and greater Doppler boosting would give them a higher ratio of core to diffuse flux density. Thus low variability and substantial diffuse emission would go together, as found above. One would expect the more highly variable sources to have cores which are systematically more powerful than in the less variable sources. Such an effect is *not* present in our data, although selection effects and the small sample size may account for its absence. Extensive monitoring of BL Lac sources with and without substantial extended components would be necessary to confirm the suggested relation between radio morphology and variability.

b) Large-Scale Emission from Elliptical Galaxies

Double sources seen end-on were mentioned above as a possible explanation of the large-scale radio emission in the BL Lac sources. However, many "normal" elliptical galaxies show extended emission similar to that found around the BL Lac objects (R. D. Ekers, private communication), although they generally do not exhibit strong, flat-spectrum cores. For example, the extended radio morphology of 1652+398 (Fig. 7) is similar to that of the normal elliptical galaxy NGC 3665 (Kotanyi 1979) but is an order of magnitude more powerful. As J. S. Miller (1981) points out, all nearby BL Lac objects seem to be at the centers of elliptical galaxies. Thus the extended emission in some sources may be a property of the host elliptical galaxy which is largely unrelated to ejection directly along the line of sight.

For the weak diffuse emission in a few sources such as 1652+398 and the low upper limit in 2200+420, we find that the extended sources are not much more powerful than those found in normal elliptical galaxies. The extended radio emission in these sources has a total luminosity of $\sim 10^{41}$ ergs s⁻¹ and a minimum energy content of $\sim 10^{57}$ ergs. But the radio powers in the

extended emission range up to those of objects such as 0219+428, which has a luminosity in excess of 10^{44} ergs s⁻¹ and an energy content above 10^{60} ergs in the volume outside its core. These values are comparable to those found in radio galaxies. Indeed, the morphologies of the sources with the most luminous large-scale emission (e.g., 0219+428 and 1308+326) resemble those found in some radio galaxies. Hence, the extended emission in the BL Lac objects may represent the upper tail of the luminosity function for elliptical galaxies, with the radio sources initially generated by the active galactic nuclei.

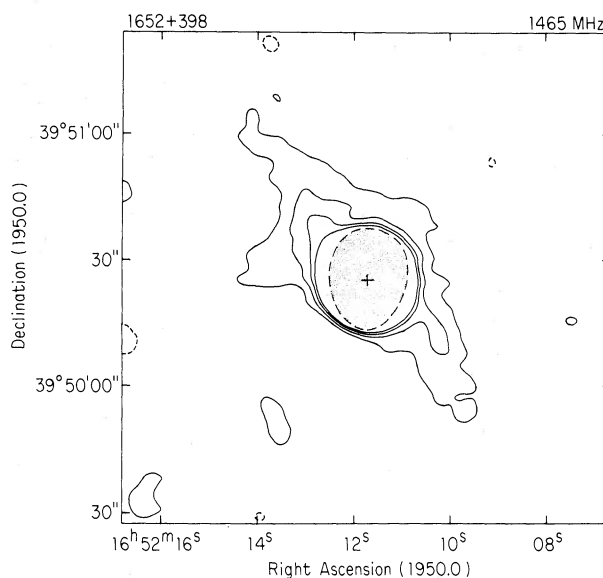


FIG. 7.—Radio map of 1652+398 overlaid on outline of the optical galaxy as shown by Ulrich (1978b). The extent of the optical galaxy is indicated by the stippled region, and the position of the radio core is indicated by the cross. The radio map is the same as that shown in Fig. 5, with contours at 0.25, 0.5, 0.75, and 1 percent of the peak displayed.

One possibility is that the large-scale emission, rather than representing end-on double sources, is the remnant of earlier activity when energy outflow from the cores was not directed along the line of sight.

c) Polarization

The radio cores of most of the BL Lac objects are linearly polarized, with values of the polarization ranging up to $\sim 5\%$ at both 6 and 20 cm. In general, the polarization position angles at the two wavelengths are not aligned either before or after correction for galactic Faraday rotation, indicating the presence of rotations within the extragalactic sources themselves. The range of polarizations is similar to that found by Perley (1982) for a large set of compact radio sources studied with the VLA.

We have five sources in common with Perley, who obtained 6 cm data in 1980 November and 20 cm data in 1981 February, five and eight months after the observations reported in this paper. Two of the sources, 0235+164 and 2200+420, are known polarization rotators (Ledden and Aller 1979; Aller, Hodge, and Aller 1981). Thus the lack of agreement between our observations and Perley's in these cases is not surprising. Both sets of 6 cm observations of 2200+420 do agree with the independent observations of Aller, Hodge, and Aller (1981), who monitored the source during 1979 and 1980; this leads us to believe that neither set of VLA polarization data contains any gross errors. For the other three sources, we find a lower degree of polarization than Perley but good agreement in position angle for the two objects in which we detect significant polarization. The polarized flux density changes considerably in these highly core-dominated sources, regardless of whether the total flux density increases, decreases, or stays the same. Since Perley did not study the BL Lac objects containing substantial extended emission, it is not clear how their polarization variability compares with the sources mentioned above. If they are less strongly beamed than the objects showing little diffuse emission, as suggested in § IVa, they might be expected to display less polarization variability.

In several sources, small-scale morphologies have been derived from VLBI data. Comparison of the orientation with our measurements of polarization position angles is meaningless for the polarization rotators. But in 0219+428 (Bååth *et al.* 1981) and 2223-052 (Brown *et al.* 1981; present work), the 6 cm polarization position angles are perpendicular to the sub-arc second elongations. This may indicate a tendency for the magnitude fields to be parallel to small-scale "jets," as seen in the inner parts of many large-scale jets in radio

galaxies (e.g., Fomalont *et al.* 1980; Bridle 1982). It should be mentioned, however, that if the jets are pointing nearly along the line of sight, projection effects may be important in the apparent alignment.

V. SUMMARY

We have mapped 12 BL Lac objects at centimeter wavelengths using the VLA. The observations show that extensive diffuse emission exists in some sources. That diffuse emission is much stronger at 20 cm than at 6 cm and is often fairly symmetric. One-sided sources probably occur less frequently than in core-dominated quasars. No classical double sources were found, although 0219+428 bears some morphological resemblance to triple sources seen in some radio galaxies.

The data are consistent with the presence of relativistic Doppler boosting of the radio source cores. Objects containing substantial fractions of their flux densities in extended radio emission may have less variable cores than the more highly core-dominated sources, which vary rapidly in both total and polarized flux density. Such an effect might be understood if the sources with the highest ratios of core to diffuse emission are beaming most nearly along the line of sight. VLBI monitoring of the cores of several BL Lac sources would provide a test of this hypothesis, since the objects beaming closest to the line of sight are the most likely to exhibit apparent "superluminal" motion. Effective monitoring of the core morphologies is probably not possible with present telescopes, but it might be accomplished with a dedicated array of VLBI antennas.

The powers of the extended radio sources in the BL Lac objects range upward from those characteristic of normal elliptical galaxies to those of powerful radio galaxies. The morphologies of the extended emission are also similar; sources with weak extended emission resemble normal elliptical galaxies, while objects with more powerful large-scale radio sources look more like radio galaxies. Thus the extended radio emission could be a manifestation of the "typical" energy supply processes from the central engines of elliptical galaxies rather than being directly related to relativistic line-of-sight beaming in the cores. Interpretation of all the diffuse sources as end-on double sources seems overly simplistic. At least some may be remnants of past activity when energy could have been supplied at angles to the line of sight that were different from those implied by the properties of the cores.

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REFERENCES

- Agrawal, P. C., and Riegler, G. R. 1979, *Ap. J. (Letters)*, **231**, L25.
 Aller, H. D., Hodge, P. E., and Aller, M. F. 1981, *Ap. J. (Letters)*, **248**, L5.
 Altschuler, D. R. 1982, *A.J.*, **87**, 387.
 Andrew, B. H., MacLeod, J. M., Harvey, G. A., and Medd, W. J. 1978, *A.J.*, **83**, 863.
 Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
 Bååth, L. B., Elgered, G., Lundqvist, G., Graham, D., Weiler, K. W., Seielstad, G. A., Tallqvist, S., and Schilizzi, R. T. 1981, *Astr. Ap.*, **96**, 316.
 Balonek, T. J., and Dent, W. A. 1980, *Ap. J. (Letters)*, **240**, L3.

- Blandford, R. D., and Rees, M. J. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 328.
- Bridle, A. H. 1982, in *IAU Symposium 97, Extragalactic Radio Sources*, ed. D. S. Heeschen and C. M. Wade (Dordrecht: Reidel), p. 121.
- Brown, R. L., Johnston, K. J., Briggs, F. H., Wolfe, A. M., Neff, S. G., and Walker, R. C. 1981, *Ap. Letters*, **21**, 105.
- Browne, I. W. A., Orr, M. J. L., Davis, R. J., Foley, A., Muxlow, T. W. B., and Thomasson, P. 1982, *M.N.R.A.S.*, **198**, 673.
- Butcher, H. R., Oemler, A., Jr., Tapia, S., and Tarengi, M. 1976, *Ap. J. (Letters)*, **209**, L11.
- Charles, P., Thorstensen, J., and Bowyer, S. 1979, *Nature*, **281**, 285.
- Clark, B. G. 1980, *Astr. Ap.*, **89**, 377.
- Conway, R. G., and Stannard, D. 1972, *M.N.R.A.S.*, **160**, 31P.
- Cotton, W. D., Wittels, J. J., Shapiro, I. I., Marcaide, J., Owen, F. N., Spangler, S. R., Rius, A., Angulo, C., Clark, T. A., and Knight, C. A. 1980, *Ap. J. (Letters)*, **238**, L123.
- Fomalont, E. B. 1967, *Pub. Owens Valley Radio Obs.*, Vol. 1, No. 3.
- Fomalont, E. B., Bridle, A. H., Willis, A. G., and Perley, R. A. 1980, *Ap. J.*, **237**, 418.
- Gardner, F. F., Whiteoak, J. B., and Morris, D. 1975, *Australian J. Phys., Ap. Suppl.*, **35**, 1.
- Griffiths, R. E., Tapia, S., Briel, U., and Chaisson, L. 1979, *Ap. J.*, **234**, 810.
- Hewitt, A., and Burbidge, G. 1980, *Ap. J. Suppl.*, **43**, 57.
- Hintzen, P., and Owen, F. 1981, *A.J.*, **86**, 1577.
- Kapahi, V. K. 1979, *Astr. Ap.*, **74**, L11.
- Kotanyi, C. G. 1979, *Astr. Ap.*, **74**, 156.
- Kronberg, P. P., and Wardle, J. F. C. 1977, *A.J.*, **82**, 688.
- Ledden, J. E., and Aller, H. D. 1979, *Ap. J. (Letters)*, **229**, L1.
- Maraschi, L., Tanzi, E. G., Tarengi, M., and Treves, A. 1980, *Nature*, **285**, 555.
- Margon, B., Jones, T. W., and Wardle, J. F. C. 1978, *A.J.*, **83**, 1021.
- Maza, J., Martin, P. G., and Angel, J. R. P. 1978, *Ap. J.*, **224**, 368.
- McGimsey, B. Q., and Miller, H. R. 1978, *Ap. J.*, **219**, 387.
- Medd, W. J., Andrew, B. H., Harvey, G. A., and Locke, J. L. 1972, *Mem. R.A.S.*, **77**, 109.
- Miller, H. R. 1981, *Ap. J.*, **244**, 426.
- Miller, J. S. 1981, *Pub. A.S.P.*, **93**, 681.
- Miller, J. S., and French, H. B. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 228.
- Miller, J. S., French, H. B., and Hawley, S. A. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 176.
- Moore, R. L., et al. 1980, *Ap. J.*, **235**, 717.
- Perley, R. A. 1982, *A.J.*, **87**, 859.
- Perley, R. A., Fomalont, E. B., and Johnston, K. J. 1982, *Ap. J. (Letters)*, **255**, L93.
- Phillips, R. B., and Mutel, R. L. 1982, *Ap. J. (Letters)*, **257**, L19.
- Puschell, J. J., and Stein, W. A. 1980, *Ap. J.*, **237**, 331.
- Scheuer, P. A. G., and Readhead, A. C. S. 1979, *Nature*, **277**, 182.
- Schwab, F. R. 1980, *Proc. 1980 Internat. Opt. Computing Conf.*, **231**, 18.
- Shimmins, A. J., and Bolton, J. G. 1974, *Australian J. Phys., Ap. Suppl.*, **32**, 1.
- Simard-Normandin, M., Kronberg, P. P., and Button, S. 1981, *Ap. J. Suppl.*, **46**, 239.
- Smith, H. E., Burbidge, E. M., and Junkkarinen, V. T. 1977, *Ap. J.*, **218**, 611.
- Snyder, W. A., et al. 1980, *Ap. J. (Letters)*, **237**, L11.
- Spinrad, H., and Smith, H. E. 1975, *Ap. J.*, **201**, 275.
- Sramek, R. A., and Tovmassian, H. M. 1976, *Ap. J.*, **207**, 725.
- Stannard, D., Edwards, M. R., and McIlwath, B. K. 1981, *M.N.R.A.S.*, **194**, 919.
- Stannard, D., and McIlwath, B. K. 1982, *Nature*, **298**, 140.
- Thompson, A. R., Clark, B. G., Wade, C. M., and Napier, P. J. 1980, *Ap. J. Suppl.*, **44**, 151.
- Ulrich, M.-H. 1978a, *Ap. J. (Letters)*, **222**, L3.
- Ulrich, M.-H. 1978b, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 192.
- Ulrich, M.-H., Kinman, T. D., Lynds, C. R., Rieke, G. H., and Ekers, R. D. 1975, *Ap. J.*, **198**, 261.
- Urry, C. M., and Mushotzky, R. F. 1982, *Ap. J.*, **253**, 38.
- Wardle, J. F. C., and Kronberg, P. P. 1974, *Ap. J.*, **194**, 249.
- Weiler, K. W., and Johnston, K. J. 1980, *M.N.R.A.S.*, **190**, 269 (WJ).
- Weistrop, D., Shaffer, D. B., Mushotzky, R. F., Reitsem, H. J., and Smith, B. A. 1981, *Ap. J.*, **249**, 3.
- Willis, A. G., Oosterbaan, C. E., Le Poole, R. S., de Ruiter, H. R., Strom, R. G., Valentijn, E. A., Katgert, P., and Katgert-Merkelijn, J. K. 1977, in *IAU Symposium 74, Radio Astronomy and Cosmology*, ed. D. L. Jauncey (Dordrecht: Reidel), p. 39.

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