THE ASTROPHYSICAL JOURNAL, 347:701–712, 1989 December 15

THE MILLIARCSECOND POLARIZATION STRUCTURE OF SIX BL LACERTAE OBJECTS

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Received 1989 March 9; accepted 1989 June 17

ABSTRACT

Milliarcsecond resolution total intensity and linear polarization maps at 5 GHz are presented for the BL Lacertae objects 0235+164, 0454+844, 1749+096, 1823+568, and 2200+420 (BL Lac). Maps of 1807+698 (3C 371), which has in the past been classified either as a BL Lacertae object or an N galaxy, are also presented. Appreciable polarization structure is found in 0454+844, 1823+568, and BL Lac; in each the polarization position angle in the knots lies within $\sim 10°$ of the structural direction of the VLBI jet, suggesting that plane perpendicular shock waves may be common in these objects. The polarization of 3C 371 is weak, and is quite atypical of BL Lacertae objects. Comparison of our results with earlier observations by others suggests superluminal motion in 1823+568 at $\beta_{\rm app} h \simeq 2.5$. Similar comparison for 0454+844 over four epochs confirms proper motion at $\mu \simeq 0.14$ mas yr^{-1}; the redshift of this object is unknown.

Systematic differences in the VLBI polarization structures of BL Lacertae objects and quasars rule out the possibility that a significant fraction of BL Lacertae objects are gravitationally microlensed quasars.

Subject headings: BL Lacertae objects — gravitational lenses — interferometry — polarization — radio sources: galaxies

I. INTRODUCTION

VLBI polarimetry has begun to emerge as an effective new tool for exploring the magnetic field structure, thermal particle environment, and kinematics of compact radio sources (Cotton *et al.* 1984; Wardle *et al.* 1986; Roberts, Gabuzda, and Wardle 1987; Cawthorne and Wardle 1988; Wardle and Roberts 1988; Gabuzda, Wardle, and Roberts 1989*a*, *b*). One application of this technique is to explore the relationships among the various classes of extragalactic sources whose optical properties and/or arcsecond radio morphologies have similarities, such as the BL Lacertae objects and the radio loud quasars. In this paper we present VLBI polarization maps of six objects that have been classified as BL Lacertae objects, discuss their milliarcsecond polarization properties as a class, and contrast these properties with those of compact radio sources of different optical classes.

BL Lacertae objects form one subset of the strongly polarized class of extragalactic objects known as "blazars" (Angel and Stockman 1980). Some of their distinguishing features are (i) weak or absent line emission, (ii) strong and variable optical, infrared, and radio polarization, with most of the luminosity being radiated in the infrared, (iii) compact, flat-spectrum radio structure, and (iv) generally pointlike optical structure, though a number have been found to lie in the centers of luminous elliptical galaxies (Angel and Stockman 1980; Miller 1981). The radio emission and much of the optical emission is believed to be synchrotron radiation.

The first studies of the milliarcsecond-resolution polarization structure of BL Lacertae objects were of OJ 287 (Roberts, Gabuzda, and Wardle 1987; Gabuzda, Wardle, and Roberts 1989*a*) and 0735+178 (Gabuzda, Wardle, and Roberts 1989*b*). OJ 287 was shown to have a triple structure (core plus two knots), in which the inner knot was quite highly polarized (K2), the outer knot was weakly polarized, and both knots appeared to be expanding from the core with the "slow" superluminal speed of $\beta_{\rm app} h \simeq 3$ ($H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$). In the knots the electric vectors of the linearly polarized component of the radiation were closely aligned with the structural axis of the source. Cawthorne and Wardle (1988) were able to place useful kinematic constraints on the jet in OJ 287 based on the observed transverse motion and the polarization of K2. They showed that the modest superluminal speeds observed in the knots were consistent with the high degree of polarization of the knot K2, and with the large Doppler shifts implied by the extreme radio variability and by the X-ray data, if K2 were associated with a plane shock in a relativistic outflow. In the case of OJ 287, the shock must be travelling outward with a lower velocity than the emitting material, and be viewed at an angle that is significantly less than Γ^{-1}, where Γ is the Lorentz factor of the shock. Observations of 0735+178 demonstrated an interday polarization variation in the VLBI core of this source, without a comparable fractional change in the total intensity. One interpretation of this result yields an apparent brightness temperature of a varying component in the VLBI core with $T_b \gtrsim 4.8h^{-2} \times 10^{15}$ K, suggesting relativistic motion with a Doppler factor of at least ~ 15. Alternatively, a variation of this sort could occur if the opacity of the VLBI core changed by a relatively small amount on a time scale of days, leading to larger fractional changes in polarized flux than in total flux. Observations of 0954+568 (Gabuzda *et al.* 1989) showed a double structure (core plus knot), with the polarization position angle (the direction of the electric field **E**) in the knot within $\sim 20°$ of the structural axis.

In this paper we present the VLBI polarization structures of five additional BL Lacertae objects—0235+164, 0454+844, 1749+096, 1823+568, and BL Lac—and of 3C 371, which has in the past been classified either as a BL Lacertae object or as an N galaxy. We find that, in those sources displaying appreciable polarization structure, the electric field in the polarized knots lies close to parallel to the VLBI structural axis joining the core and knots. The fractional polarization of the knots ranges from less than 2% to greater than 10%. The polarization of the cores is moderate ($\sim$3%–5%) and the electric vectors randomly oriented. The alignment of the structural

TABLE 1

FRACTIONAL *I* AND *P* VISIBILITIES OF BL LACERTAE OBJECTS

		I (Jy)		*p* (mJy)		χ (degrees)		VISIBILITY	
SOURCE	EPOCH	VLA	VLBI	VLA	VLBI	VLA	VLBI	γ_I	γ_P
0235+164	1981.92	2.26	2.14	42.[a]	30.	+43[a]	+39.	0.95	0.72[a]
	1982.93	1.93	1.68	21.	19.	+107.	+109.	0.87	0.90
	1986.45	1.80	1.57	37.	...[b]	+30.	...[b]	0.87	...[b]
0454+844	1984.78	0.63	0.51	23.	20.	−18.	−13.	0.81	0.87
1749+096	1982.93	1.88	1.76	105.[a]	81.	+58.	+49.	0.94	0.77[a]
3C 371	1984.23	1.69	0.99	40.	7.	+54.	+4.	0.59	0.18
1823+568	1984.78	1.28	0.91	56.	52.	+31.	+31.	0.71	0.93
BL Lac	1984.23	3.02	2.25	84.	100.	−41.	−42.	0.75	1.19

[a] Integrated measurements interpolated from Aller *et al.* 1985.
[b] VLBI polarization information not available.

axes and the polarization of the knots suggests that the knots are associated with plane shocks that have compressed a tangled magnetic field, resulting in an observed magnetic field perpendicular to the plane of compression (Laing 1980; Aller, Aller, and Hughes 1985, 1988; Hughes, Aller, and Aller 1985). In contrast, the milliarcsecond polarization structures of quasars have very weakly polarized cores (typically $\lesssim 1\%$), and knots in which the electric field is predominately perpendicular to the VLBI structural axis (Wardle *et al.* 1986; Wardle and Roberts 1988; Roberts *et al.* 1989; Brown *et al.* 1989). As we discuss in § IV*c*, these systematic differences between the VLBI polarization characteristics of BL Lacertae objects and quasars rule out the hypothesis that most BL Lacertae objects are gravitationally microlensed quasars (Ostriker and Vietri 1985; Ostriker 1989).

II. OBSERVATIONS

Polarization-sensitive VLBI observations of several bright extragalactic sources, including a number of BL Lacertae objects, were carried out at 5 GHz ($\lambda = 6$ cm) in 1981 December and 1982 December using the Haystack (37 m, "K"), Green Bank[1] (43 m, "G"), and Owens Valley (40 m, "O") antennas, and the phased-up Very Large Array[1] (27 × 25 m, "Y"). Similar observations made in 1984 March, 1984 October, and 1986 June included the Effelsberg (100 m, "B") and Fort Davis (26 m, "F") antennas in addition. For the first two experiments, left circular polarization (LCP) was detected at all stations while right circular polarization (RCP) was detected only at Green Bank and the VLA. For the later experiments, both RCP and LCP were detected at all stations. The calibration of these data was performed as described by Roberts *et al.* (1984) and Wardle *et al.* (1986). Hybrid maps of the distribution of total intensity *I* were made using a self-calibration algorithm similar to that described by Cornwell and Wilkinson (1981). Maps of the linear polarization $P(P = pe^{2i\chi} = mIe^{2i\chi}$, where $p = mI$ is the polarized intensity, *m* is the fractional linear polarization, and χ is the position angle of the electric vector on the sky) were made by referencing the cross-hand fringes to the parallel-hand fringes using the antenna gains determined in the hybrid mapping, Fourier transforming the cross-hand fringes, and performing a complex CLEAN. In this way, registration of the *I* and *P* maps to within a small fraction of a fringe spacing is assured.

[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

III. RESULTS

Results for the six sources are discussed below. For each map, the beam is shown as a cross in a corner. For linear polarization maps, the contours are those of polarized intensity *p*, and the plane of the electric vector is indicated by the polarization position angle vectors that are superposed; the electric vectors have been corrected for the source rotation measure when appropriate. Models for several sources were derived by fitting the *I* and *P* visibilities that come from the hybrid mapping process with a small number of point components, as described by Roberts, Gabuzda, and Wardle (1987) and Gabuzda, Wardle, and Roberts (1989*b*).

A list of integrated (arcsecond resolution) *I* and *P* fluxes is given in Table 1. Most of these were obtained by us at the VLA during the VLBI sessions. Because no VLA polarization information was obtained during the 1981 December observing session, we have estimated *P* for 0235+164 and 1749+096 by interpolating the data of Aller *et al.* (1985) to our epoch. This is more reliable for 1749+096 than for 0235+164 since the latter was significantly more variable in late 1981. For each source we have estimated the fractional visibilities in *I* and *P*, γ_I and γ_P, respectively, by dividing the total VLBI flux (the sum of the fluxes in our models of the VLBI structures) by the integrated fluxes. Except for the two sources noted above, the major uncertainty in γ_I lies in the amplitude calibration of the VLBI data, which we estimate to be accurate to 10%. It is comforting that none of the values of γ_I exceeds unity. The interpretation of γ_P is more complex. The linearly polarized VLBI data are subject to the same amplitude calibration uncertainties as the *I* data. In addition, since *P* is a complex quantity, it is possible for γ_P to exceed unity if there is polarized flux that is resolved out by VLBI but not by the VLA, and that has a significantly different value of χ than does the flux detected by VLBI. This is apparently the case for BL Lac (see § III*f*). It is well known that BL Lacertae objects have high fractional visibilities in *I* at 5 GHz (Weiler and Johnston 1980); our results show that they also have high fractional visibilities in *P*.

a) *0235+164*

AO 0235+164 was first identified as a red BL Lacertae object by Spinrad and Smith (1975). During a strong outburst it was found to have strong optical absorption lines at $z_a = 0.524$ and 0.851 (Burbidge *et al.* 1976; Rieke *et al.* 1976), the first of which was also detected in the redshifted $\lambda = 21$ cm line of neutral hydrogen (Roberts *et al.* 1976; Wolfe, Davis, and Briggs 1982). Emission lines at redshift $z_e \simeq 0.94$ have recently been discovered (Cohen, Smith, and Burbidge 1986). There is an optical extension about 3″ to the south that displays absorption and emission lines at a redshift of 0.525 (Smith, Burbidge, and Junkkarinen 1977); presumably this is the nucleus of an active galaxy that lies by chance near our line of sight to AO 0235+164.

AO 0235+164 is a radio, infrared, and optical variable on time scales of weeks to around a year; especially energetic outbursts occurred in 1975 (MacLeod, Andrew, and Harvey 1976; Ledden, Aller, and Dent 1976; Rieke *et al.* 1976) and in 1979 (Pollock *et al.* 1979). The polarization of this object is rapidly variable at both optical and radio wavelengths (Rieke *et al.* 1976; Altschuler and Wardle 1976). Weiler and Johnston (1980) and Ulvestad, Johnston, and Weiler (1983) found no evidence for extended radio structure. Hybrid maps made from data taken at several epochs between 1979 March and 1982 December have been dominated by a compact core with faint extensions to the northeast (Bååth *et al.* 1981; Bååth 1984; Jones *et al.* 1984). The structural position angle of these extensions varies considerably, though structure has consistently been detected generally to the northeast.

AO 0235+164 was observed in 1981 December (KGYO), 1982 December (KGYO), and 1986 June (BKGFYO); no cross-hand fringes were recovered for the 1986 June observing session. The source showed no *I* or *P* VLBI structure at any of the three observing epochs, and we therefore do not show maps. In 1981 December the VLBI core was ~1.4% polarized at $\chi = 39°$; in 1982 December it was ~1.2% polarized at $\chi = 110°$. We use 0235+164 as a polarization position angle calibrator, because of its very compact VLBI structure and high γ_I and γ_P.

b) 0454+844

0454+844 was identified as a BL Lacertae object by Argue and Sullivan (1980); no emission or absorption redshift has been determined. It is extremely compact; no extended radio emission on VLA scales has been observed even at high dynamic range (Antonucci *et al.* 1986; Perley 1982). The radio emission is variable (Seielstad, Pearson, and Readhead 1983) and ~3% polarized (Perley 1982). At milliarcsecond resolution, the object displays double structure along position angle ~146° (Eckart *et al.* 1986, 1987; Pearson and Readhead 1988; Witzel *et al.* 1989).

Total intensity and linear polarization maps of 0454+844 are shown in Figure 1. 0454+844 was observed in 1984 October (BKGFYO) as part of our survey of the VLBI polarization properties of the Pearson-Readhead (1981, 1984, 1988) sample of bright northern compact sources. It is well-modeled at our epoch as a double with separation $r = 1.28$ mas at position angle PA = 152°; model parameters are given in Table 2. The double structure is more conspicuous in the polarized flux map, since the two components are more nearly equal in strength. The northern component is ~2.5% polarized at −5°, while the southern component is ~8.5% polarized at $\chi = -20°$; it seems natural to suppose that the brighter and more weakly polarized component is the core, and in what follows is assumed to be so. Since the rotation measure for 0454+844 is −10 rad m^{-2} (Rusk 1987), a correction of only +2° need be applied at 5 GHz, and **E** in the knot is nearly parallel to the source axis.

Because of the source's simple structure, it is possible to trace its evolution using the results of Eckart *et al.* (1986, 1987), Pearson and Readhead (1988), Witzel *et al.* (1989), and our own model fitting. Each of these groups of investigators has found the source to be double, at nearly the same position angle. A plot of the separation versus epoch is shown in Figure 2; a linear fit shows that the components are separating at a speed of 0.14 ± 0.04 mas yr^{-1}. This value agrees with the proper motion reported by Witzel *et al.* (1989), based on only two epochs. While the formal error on the four-epoch slope is not appreciably smaller than that on the two-epoch slope, the data presented here clearly show that a single knot has been moving linearly outward from the core over a period of at least ~6.5 yr. It is not possible to convert this proper motion into an apparent transverse speed since the redshift for this source is not known. Witzel *et al.* (1989) have pointed out that this proper motion is superluminal if $z \gtrsim 0.16$.

c) 1749+096

1749+096 has been identified with a slightly red lineless stellar object (Browne, Crowthier, and Adgie 1973; Strittmatter *et al.* 1974). Its optical polarization has been found in the range 3%–20% (Kinman 1976; Wills *et al.* 1980; Smith *et al.* 1987), but there are too few data to tell if there is a preferred position angle. The object 1749+096 has a flat radio spectrum (Andrew and Kraus 1970; Condon and Jauncey 1974) and has been found to be a variable at radio wavelengths (Medd *et al.* 1972; Altschuler and Wardle 1976), both in total intensity and in linear polarization. Weiler and Johnston (1980) found no evidence for extended radio emission on arcsecond scales. Cohen and coworkers, using a VLBI network that included substantial north-south baselines, found the source to be elongated along PA ≃ 19° (Cohen 1988). Integrated total intensity and polarization changes at centimeter wavelengths have been successfully fitted with models in which a piston drives plane shocks down a relativistic jet (Aller, Aller, and Hughes 1988).

1749+096 was observed in 1981 December (KGYO). The total intensity map is shown in Figure 3. The *u*-*v* coverage for both the parallel-hand and the cross-hand data were quite poor. The source is dominated by a point component, although an extension toward the east can be seen in the lower contours. Because of our lack of resolution and poor *u*-*v* coverage, the position angle of this structure is not well determined. The *P* visibility amplitudes give some indication that the *P* map is resolved toward the north; given the inadequacy of the *u*-*v* coverage, it is difficult to tell whether or not this structure is

TABLE 2

POINT DOUBLE MODEL FOR 0454+844, 1984 OCTOBER

Component	α[a]	δ[a]	I(mJy)	p(mJy)	χ_0(deg)[b]	m(%)	r(mas)[a]	PA(deg)[a]
Core …………………	…	…	377	9.6	−3	2.5	…	…
Jet ……………………	+0.60	−1.13	137	11.6	−18	8.5	1.28	152

[a] Positions, separations, and structural position angles with respect to the core.
[b] Corrected for a rotation measure of −10 rad m^{-2} (Rusk 1987).

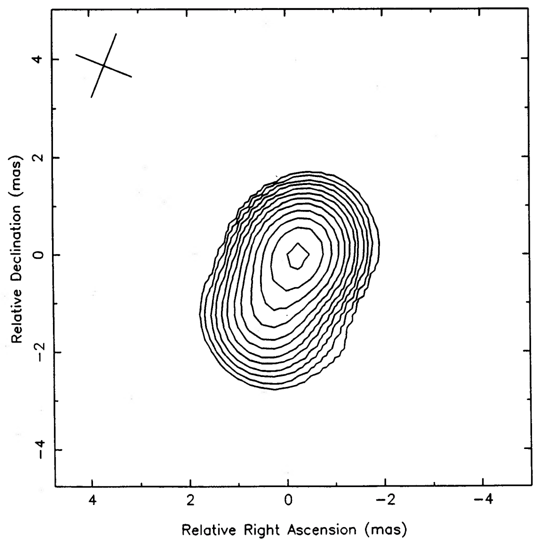

FIG. 1*a*

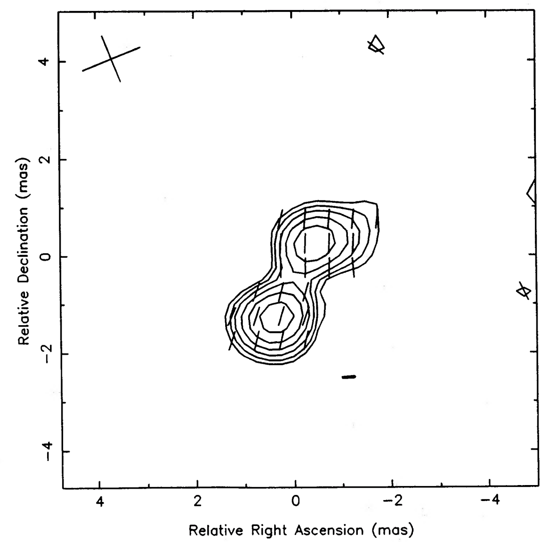

FIG. 1*b*

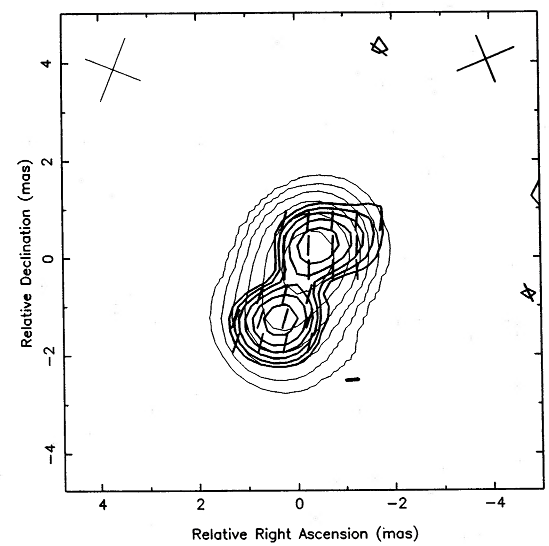

FIG. 1*c*

FIG. 1.—VLBI hybrid maps of 0454+844 at 5 GHz, epoch 1984.78. (*a*) Total intensity, with contours at −2.0, 2.0, 2.8, 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightness of 0.39 Jy per beam. (*b*) Linear polarization, with contours of polarized intensity at 14, 20, 28, 40, 56, and 80% of the peak brightness of 11 mJy per beam, and χ vectors (corrected for a rotation measure −10 rad m^{-2}) shown as sticks. (*c*) Superposition of the linear polarization map (*bold*) over the total intensity map, using only alternate *I* contours.

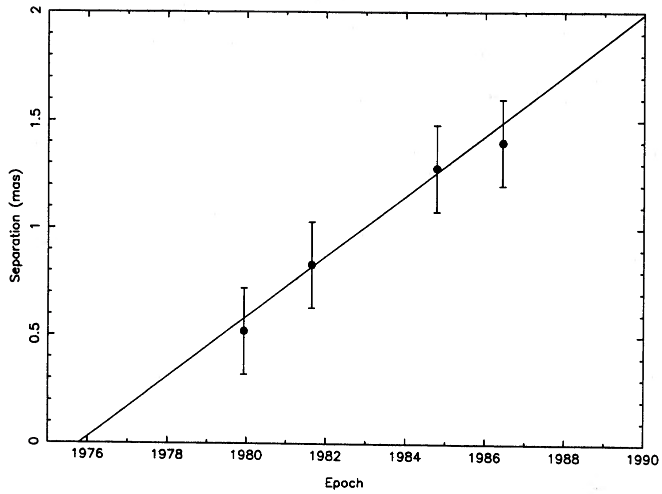

FIG. 2.—Proper motion in 0454+844. Plot of double separation versus epoch, based on the results of Eckart *et al.* (1986, 1987), epoch 1979.93; Pearson and Readhead (1988), epoch 1981.64; Witzel *et al.* (1989), epoch 1986.44; and this paper. Error bars for the earliest and latest points were given by Witzel *et al.* as ± 0.2 mas, and for the purposes of this plot, we have assigned error bars of this size to all four points.

real, although it is possible that it corresponds to structure in the direction detected by Cohen. We find the core to be $\sim 4.7\%$ polarized at $\chi = 48°$. Rudnick and Jones (1983) determined the rotation measure of this source to be $+105$ rad m^{-2}, which implies a rotation correction of $-22°$ at 5 GHz. Applying this

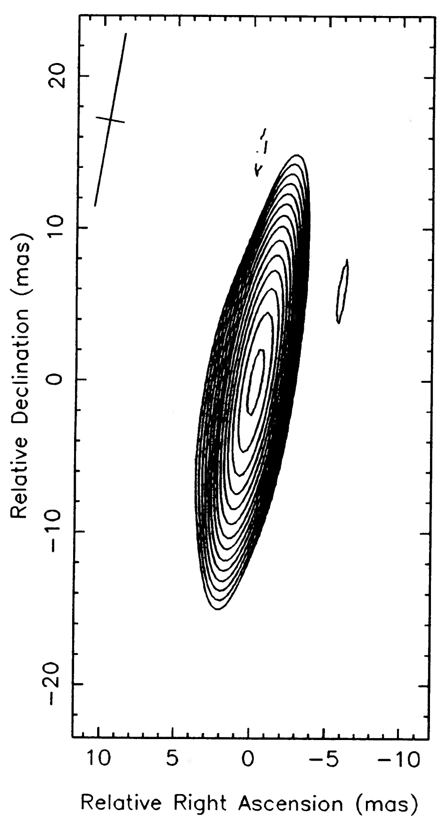

FIG. 3.—VLBI total intensity hybrid map of 1749+096 at 5 GHz, epoch 1981.93. Contours are -1.0, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightess of 1.62 Jy per beam.

to the observed polarization position angle renders an intrinsic position angle of $\sim 26°$, which is close to parallel to the direction of the elongation found by Cohen. Because of our lack of north-south resolution for this source, it is possible that the component we observe as the VLBI core may be a blend of the core and a knot (or knots) that we cannot yet resolve. We therefore know that in some component, the electric field direction is close to parallel to the structural axis found by Cohen, but we cannot tell if this component is the core itself or a knot.

There is a prominent peak in the integrated polarized flux at epoch ~ 1982.0 that immediately followed a optically thick burst in total intensity (Aller *et al.* 1985). This outburst pattern and the alignment of the VLBI core polarization position angle with the structural axis were indicative of the birth of the knot K3 in OJ 287 (Roberts, Gabuzda, and Wardle 1987; Gabuzda, Wardle, and Roberts 1989*a*); it is possible that a similar event was also occurring in 1749+096 at about the epoch of our observations. Further observations of this object currently under reduction may help address this possibility.

d) 1807+698 = 3C 371

In the literature, this object has been described either as an N galaxy or as a BL Lacertae object in the center of an elliptical galaxy (Miller, French, and Hawley 1978; Miller 1981). The variability and high optical polarization of its compact nucleus suggest that this object is related to the BL Lacertae objects. Its emission spectrum is similar to those seen in N galaxies, while the strength of the emission lines is intermediate between that typically found in BL Lacertae objects and in N galaxies (Miller 1975). Sandage (1966) found the redshift of 3C 371 to be $z_e = 0.050$.

The degree of optical polarization of 3C 371 varies within the range 0%–12%; there seems to be a preferred range of position angles of about $85 \pm 35°$ (Angel and Stockman 1980). Perley (1982) found the polarization at 5 GHz to be 2.7% at $\chi = 61°$. The data of Aller *et al.* (1985) show that over about 5 yr the degree of polarization at 8.0 GHz and 14.5 GHz ranged from $\sim 0\%$–8%; at 5 GHz, the degree polarization was quite constant at $\sim 2\%$, while χ was fairly constant at $\sim 40°$. 3C 371 has a flat radio spectrum at centimeter wavelengths (Angel and Stockman 1980; Perley 1982). The arcsecond scale structure is a one-sided jetlike structure at position angle $\sim 240°$ (Perley, Fomalont, and Johnston 1980; Browne *et al.* 1982). VLBI observations have shown a long (~ 15 mas), complex jet at structural position angle $\sim 260°$ (Pearson and Readhead 1981; Readhead, Pearson, and Unwin 1984; Lind 1987; Pearson and Readhead 1988). Wrobel (1987) has shown that the VLA core component is subject to a large rotation measure (between $+200$ and $+300$ rad m^{-2}), while that of the arcsecond jet is substantially less ($+16$ rad m^{-2}).

3C 371 was observed in 1984 March (BKGFYO). Our total intensity map, shown in Figure 4*a*, shows a jet extending toward the west. Our linear polarization map is shown in Figures 4*b* and *c*. The polarization in this source is very low; the map only contains ~ 7 mJy of polarized flux at $\chi = 4°$. Because the jet does not appear to be separated into distinct knots, we have not tried to model fit this structure. The peak on our linear polarization map may be associated with knot "A" on Lind's maps (1987).

This source is clearly distinguished from the other objects considered in this paper by the low polarization ($m \lesssim 0.3\%$) of its core and by its low visibility (see Table 1). Such a low polarization is uncharacteristic of BL Lacertae objects, supporting the classification of this source as a "transitional object" between BL Lacertae objects and emission line objects, which generally show much lower core polarizations than do BL Lacertae objects (Wardle *et al.* 1986; Wardle and Roberts 1988; Kollgaard *et al.* 1989; Brown *et al.* 1989). These results suggest that 3C 371 may be related to 3C 120, which also has a complex one-sided VLBI jet (Walker, Benson, and Unwin 1987), low polarization on milliarcsecond scales, and a low fractional visibility (Wardle and Roberts 1986).

We estimate the degree of polarization in the jet at the position of the polarized flux peak to be $m \simeq 15\%–20\%$. The total polarized flux contained in the VLA core of 3C 371 at this epoch was ~ 40 mJy at $\chi = 54°$. Thus the rotation measure of the VLA core determined by Wrobel (1987) is not determined primarily by the polarized flux shown in Figure 4*b*, but rather by the $\sim 85\%$ of the polarized flux that is missing from our map. Therefore we cannot apply the integrated rotation measure measurements to the VLBI jet, and the intrinsic polar-

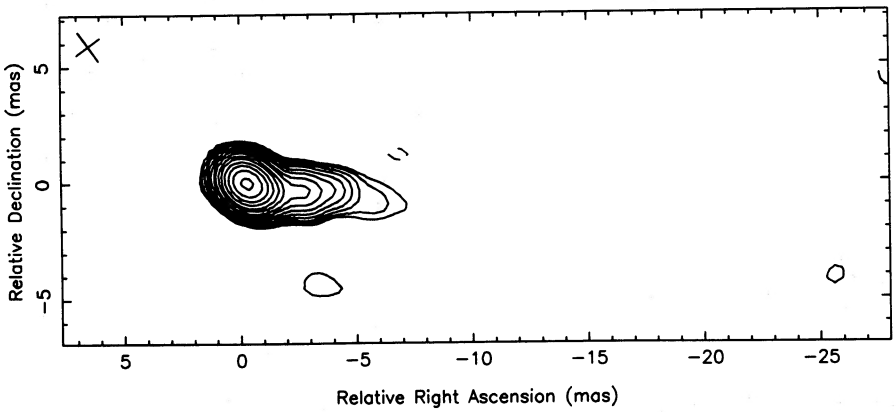

FIG. 4*a*

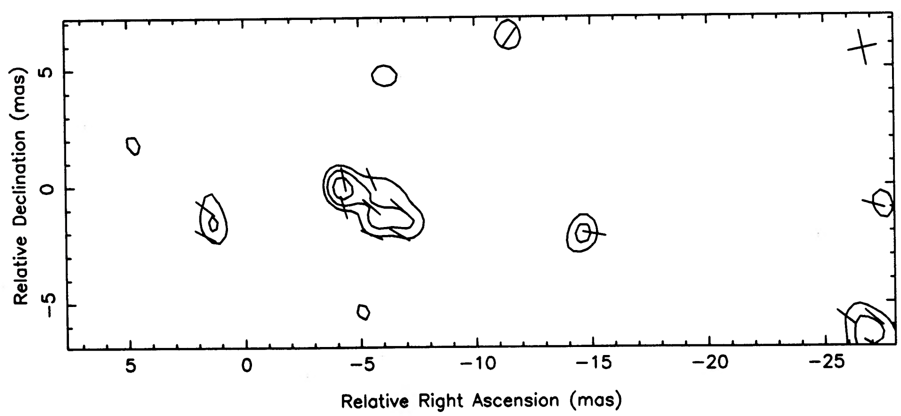

FIG. 4*b*

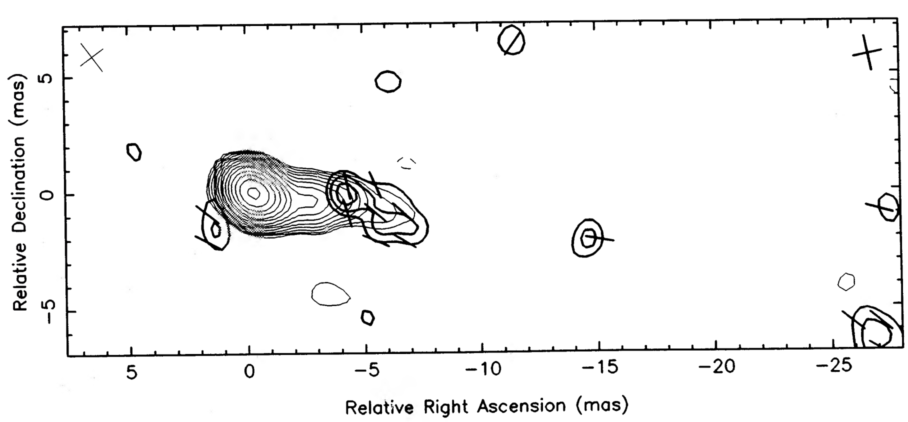

FIG. 4*c*

FIG. 4.—VLBI hybrid maps of 3C 371 at 5 GHz, epoch 1984.23. (*a*) Total intensity, with contours at −1.0, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightness of 0.75 Jy per beam. (*b*) Linear polarization, with contours of polarized intensity at 40, 56, and 80% of the peak brightness of 6.5 mJy per beam, and χ vectors shown as sticks. (*c*) Superposition of the linear polarization map (*bold*) over the total intensity map.

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TABLE 3

POINT TRIPLE MODEL FOR 1823+568, 1984 OCTOBER

Component	α[a]	δ[a]	I(mJy)	p(mJy)	χ_0(deg)[b]	m(%)	r(mas)[a]	PA(deg)[a]
Core	0.00	0	746	37.4	30	5.0	...	...
K2	−0.24	−0.81	101	12.1	11	12.0	0.84	197
K1	−0.52	−1.84	58	5.4	4	9.2	1.91	196

[a] Positions, separations, and structural position angles with respect to the core.

[b] Corrected for a rotation measure of +37 rad m^{-2} (Rusk 1987).

ization position angle for the polarized features in the VLBI jet remains unknown.

e) 1823+568

This object has been considered a BL Lacertae object by some authors because of its stellar appearance (Cohen *et al.* 1977), nearly featureless spectrum (Lawrence *et al.* 1986), and high and variable polarization (Perley 1982; Aller *et al.* 1985). Lawrence *et al.* (1986) have determined a tentative redshift of $z_e = 0.664$. VLA observations at 5 GHz have shown a jet extending toward the east (O'Dea, Barvainis, and Challis 1988). A 5 GHz VLBI map made by Pearson and Readhead (1988) at epoch 1979.92 shows a core-jet structure with the jet extending toward the south; they model the source as a double with separation $r = 1.35$ mas at structural position angle PA $\simeq$ 197°.

1823+568 was observed in 1984 October (BKGFYO). The total intensity and linear polarization maps, shown in Figure 5, each show an extension to the south. We have successfully modeled the source as the sum of three point components; parameters of this model are given in Table 3. The polarization position angles have been corrected for a rotation measure of +37 rad m^{-2} (Rusk 1987). Each of the knots in the jet is at structural position angle ~197° and has fractional polarization $m \simeq 10\%$ with **E** close to parallel to the jet axis.

At epoch 1979.92, Pearson and Readhead (1988) detected a knot with a separation from the core of 1.35 mas and structural position angle of 197°. If the knot we label K1 is the same knot, the two observations are consistent with proper motion of $\mu \simeq 0.12$ mas yr^{-1}, corresponding to $\beta_{app}h \simeq 2.5$. The fact that Pearson and Readhead found only two components is also consistent with such speeds in 1823+568, for if the inner knot that we detected (K2) is traveling at a similar speed it could not have been resolved from the core at the epoch of their observation.

f) 2200+420 = BL Lac

BL Lac was originally known as a variable star and was identified with the radio source VRO 42.22.01 by Schmidt (1968). It lies at the center of a giant elliptical galaxy; weak emission lines at a redshift of 0.069 were detected by Miller, French, and Hawley (1978). It is violently variable in the optical and infrared, significant changes in brightness and polarization position angle in the range ~10°–40° (Angel and Stockman 1980; Brindle *et al.* 1985; Sitko, Schmidt, and Stein 1985; Smith *et al.* 1987). Impey *et al.* (1984) observed the infrared polarization to be erratic, though the position angle was comparatively stable at $\chi \simeq 10°$. There is no obvious correlation between optical and radio variations (Pomphrey *et al.* 1976).
comparatively stable at $\chi \simeq 10°$. There is no obvious correlation between optical and radio variations (Pomphrey *et al.* 1976).

BL Lac is highly variable at radio wavelengths on time scales as short as a few days; the radio polarization is comparatively high, varying from ~0% to 10% (Altschuler and Wardle 1976; Aller *et al.* 1985). Aller, Hodge, and Aller (1981) observed a rotation in polarization position angle at centimeter wavelengths of substantially more than 180° in 1980 May and June, near the peak of a prolonged outburst. More recently, a series of flux and polarization outbursts in ~1980–1984 have been successfully fitted with models in which a "piston" drives plane shocks down a relativistic jet (Aller, Aller, and Hughes 1985; Hughes, Aller, and Aller 1985). High dynamic range VLA maps by Antonucci (1986) show an extended halo-like structure containing ~30 mJy of flux and an angular extent of ~40 arcseconds. VLBI maps show structure along position angle ~180°, and superluminal motion along this position angle has been observed at $\beta_{app}h \simeq 2.4$ for a number of components (Mutel and Phillips 1984; Phillips and Mutel 1988).

Our observations of BL Lac were made in 1984 March (BKGFYO). Total intensity and linear polarization maps are shown in Figure 6. With the resolution available at 5 GHz the structure is rather amorphous, but from the higher frequency observations of Mutel and Phillips we know that this source has core-jet structure, with the jet extending to the south. Inspection of the CLEAN components of our I map indicates that the total intensity structure is dominated by three components. The linear polarization distribution is well-represented by a point double whose two components may clearly be identified with the two northernmost I components. Model-fitting parameters are given in Table 4. The north-

TABLE 4

POINT TRIPLE MODEL FOR BL LACERTAE, 1984 MARCH

Component	α[a]	δ[a]	I(mJy)	p(mJy)	χ_0(deg)[b]	m(%)	r(mas)[c]	PA(deg)[c]
C	+0.25	+1.02	800	31	−30	3.8	...	...
K2	...	...	822	89	+9	11	1.05	194
K1	−0.08	−0.91	623	...	...	...	1.96	190

[a] Positions with respect to K2.

[b] Corrected for a rotation measure of −205 rad m^{-2} (Rudnick and Jones 1983).

[c] Separations and position angles with respect to C.

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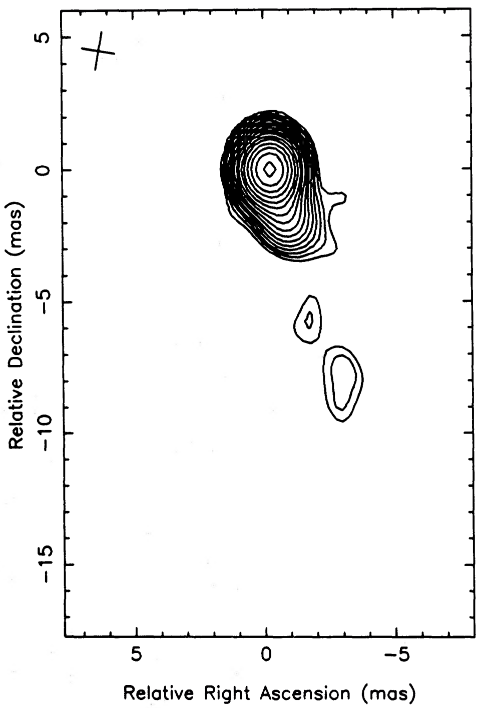

FIG. 5a

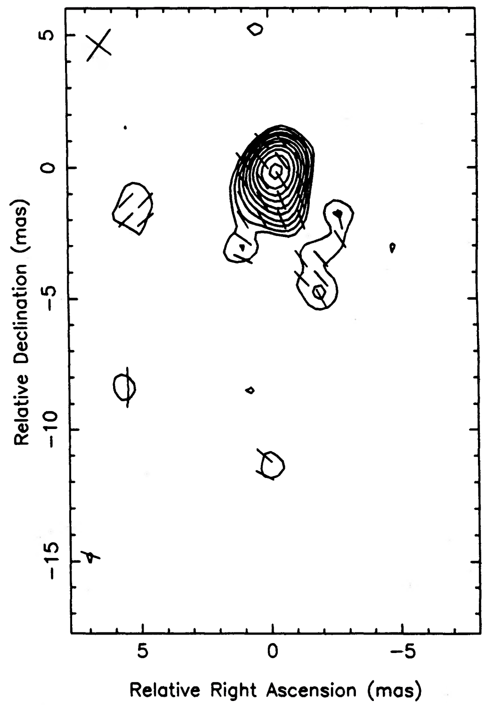

FIG. 5b

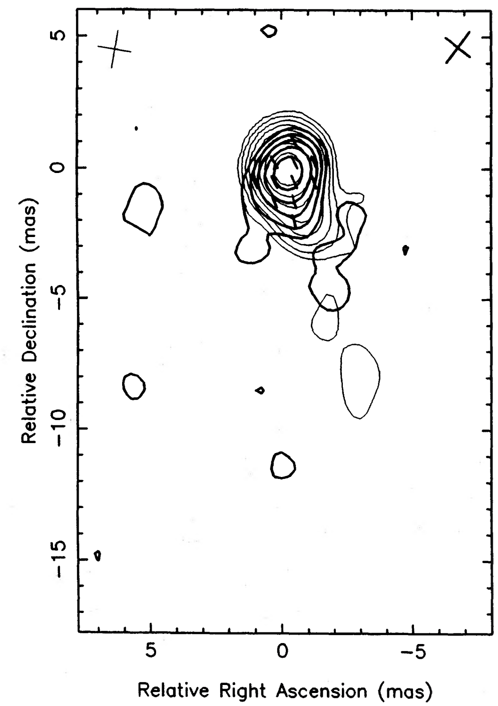

FIG. 5c

FIG. 5.—VLBI hybrid maps of 1823+568 at 5 GHz, epoch 1984.78. (*a*) Total intensity, with contours at −0.5, 0.5, 0.71, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightness of 0.79 Jy per beam. (*b*) Linear polarization, with contours of polarized intensity at 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightness of 39 mJy per beam, and χ vectors (corrected for a rotation measure of $+37$ rad m^{-2}), shown as sticks. (*c*) Superposition of the linear polarization map (*bold*) over the total intensity map, using only alternate I and p contours.

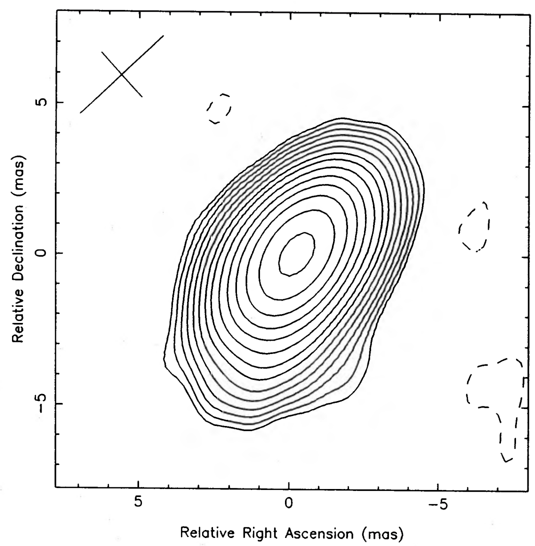

FIG. 6*a*

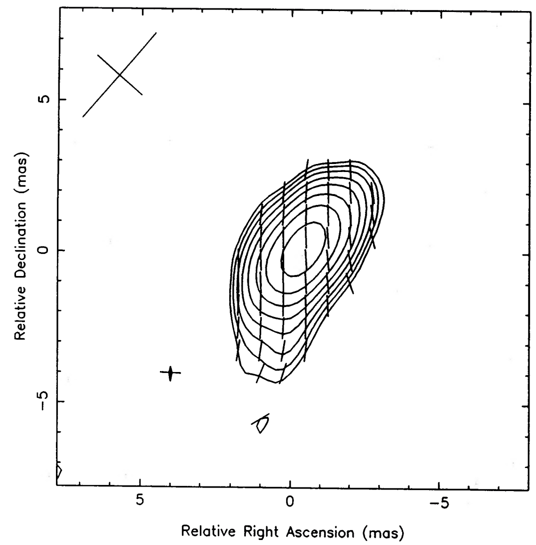

FIG. 6*b*

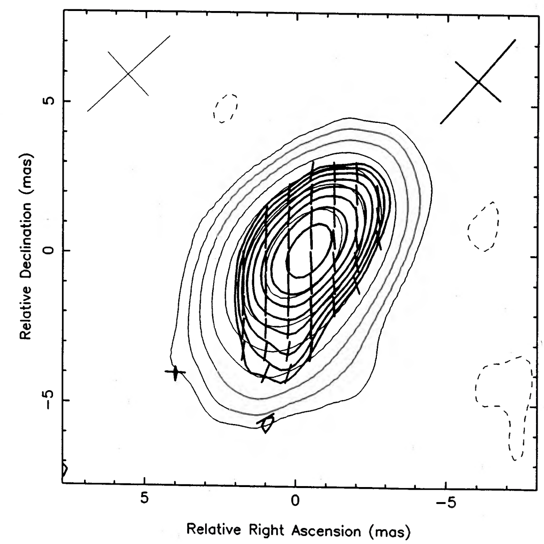

FIG. 6*c*

FIG. 6.—VLBI hybrid maps of BL Lac at 5 GHz, epoch 1984.23. (*a*) Total intensity, with contours at −1.0, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11.0, 16.0, 23.0, 32.0, 45.0, 64.0, and 90.0% of the peak brightness of 1.72 Jy per beam. (*b*) Linear polarization, with contours of polarized intensity at 7.1, 10.0, 14.0, 20.0, 28.0, 40.0, 56.0, and 80.0% of the peak brightness of 93 mJy per beam, and χ vectors (corrected for a rotation measure of -205 rad m^{-2}) shown as sticks. (*c*) Superposition of the linear polarization map (**bold**) over the total intensity map, using only alternate *I* contours.

ernmost component (C) is ~3.8% polarized at $\chi = -72°$, while the middle component (K2) has $m \simeq 11\%$ at $\chi = -33°$. The southernmost component (K1) is weakly polarized, with $m \leq 2\%$.

The brightest feature on our *I* map (K2) is apparently not the core, but an inner knot. The presence of *I* flux north of the brightest component at epochs was noted by Mutel and Phillips (1984), who suggested that the brightest *I* component in BL Lac is not always the core. The small polarization of C compared to that of K2 verifies that this is the case at our wavelength and epoch; the VLBI cores in BL Lac objects are only moderately polarized ~3%–5%, whereas knots may be polarized much more strongly. We therefore identify the northernmost component as the core, and the two southern components as knots in the jet. At epochs surrounding the observations of BL Lac presented here, at 10.8 GHz, Phillips and Mutel (1988) observed a component at a separation of ~1.5 mas that had previously been moving outward from the core, stagnate and fade. It is unclear which of the knots detected by us may be identified with this component.

Rudnick and Jones (1983) determined the rotation measure for BL Lac to be -205 rad m^{-2}, implying a rotation of $-42°$ at 5 GHz. Rudnick *et al.* (1984) confirmed this result and suggested that the rotation measure is constant in time and is due primarily to our Galaxy. Thus the rotation measure may be applied to the VLBI components, and the intrinsic polarization position angles for C and K2 are $-30°$ and $+9°$, respectively. The jet axis lies along position angle ~190°, so that E for K2 is nearly parallel to the structural axis.

Comparison of the VLA and VLBI *P* data for BL Lac suggests that γ_P for BL Lac exceeds unity, while the polarization position angles measured by the VLA and by VLBI agree quite closely (see Table 1). Taken at face value, this suggests that on scales too large to be imaged by our VLBI experiment there is about 15 mJy of linearly polarized flux, with an electric vector that is very nearly perpendicular to that of the polarized flux that we do image. The inferred magnetic field in this region would be parallel to the axis of the VLBI jet. However, this result must be regarded as tentative since the determination of γ_P is subject to flux calibration errors, and because the orientation of any linear structure on scales of ~10–300 mas in BL Lac is unknown. It is possible, for example, that the jet itself turns to the east or west; the VLA structure determined by Antonucci (1986) is too amorphous to decide. Both high dynamic range VLBI images and polarization-sensitive MERLIN maps are needed to determine the larger scale structure of the magnetic field in the jet in BL Lac.

IV. DISCUSSION

a) Are Plane Perpendicular Shocks Common in BL Lacertae Objects?

Each of the three sources considered here that has appreciable polarization structure (0454+844, 1823+568, and BL Lac) has one or more knots in which the electric field is nearly parallel to the structural axis, indicating a mean projected magnetic field nearly perpendicular to this axis. This is the same relationship between magnetic field direction and source morphology found previously for OJ 287, 0735+164, and 0954+658 (§ I). In Table 5 we show the polarization and structural properties of these six BL Lacertae objects. The angle between the structural axis (PA) and the electric field orientations of the core and knot components (χ_C and χ_K) are denoted

TABLE 5

RELATIVE ELECTRIC FIELD-STRUCTURAL AXIS ORIENTATIONS IN BL LACERTAE OBJECTS

Source	Epoch	χ_C(deg)	χ_K(deg)	PA(deg)	Δ_C	Δ_K
0454+844	1984.78	−25	−31	152	3	3
0735+178	1982.93	5	54	67	62	13
OJ 287	1981.92	−27	76	−100	73	4
	1982.93	−86	72	−100	14	8
0954+658	1987.41	−10	75	−82	72	23
1823+568	1984.78	35	20	−163	18	3
BL Lac	1984.23	−44	8	−175	49	3

Δ_C and Δ_K. *It is clear from even these limited data that there is a tendency for the electric field directions in the knot (jet) components of BL Lacertae objects to be aligned with the structure of the source.* Based on polarization measured from arcsecond scale maps, Rusk (1988) found a similar but somewhat weaker tendency. This is as expected, since his results were unavoidably contaminated by the polarization of the VLBI cores, which for BL Lacertae objects can contain considerable polarized flux, and which can vary (with time) quite widely in position angle.

The most likely explanation for this correlation of jet structure and magnetic field orientation is that the knots are associated with plane shocks that propagate down the jet. In this model, an initially random magnetic field is compressed by the shock, so that the projected magnetic field is perpendicular to the plane of compression, i.e., perpendicular to the jet (Laing 1980). This picture has been used successfully to model integrated polarized outbursts in BL Lac and 1749+096 (Aller, Aller, and Hughes 1985; Hughes, Aller, and Aller 1985; Aller, Aller, and Hughes 1988) and the VLBI polarization structure and kinematics of OJ 287 (Cawthorne and Wardle 1988). Our observations suggest that such shocks are common in BL Lacertae objects.

b) BL Lacertae Objects and "Slow" Superluminal Motion

A comparison of our data with those of Pearson and Readhead (1988) suggests superluminal motion in the knot K1 in 1823+568, with apparent speed $\beta_{\rm app} h \simeq 2.5$. This result is clearly tentative, since it is based on only two epochs that are fairly widely separated in time. Nonetheless, it is interesting to note that if this result proves sound, it will increase the number of known superluminal BL Lacertae objects to four, and that all of these sources display speeds on the order of 2–3*c* (BL Lac: $\beta_{\rm app} h \simeq 2.4$, Mutel and Phillips 1984; 0735+178; $\beta_{\rm app} h \simeq 2.8$, Bååth 1984; OJ 287: $\beta_{\rm app} h \simeq 2.4$ (K1), 3.2 (K2), Gabuzda, Wardle, and Roberts 1989*a*).

One possible reason why the apparent speeds observed so far in BL Lacertae objects are slower than those seen in core-dominated objects as a whole (Porcas 1987) is that while their intrinsic speeds are comparable to those in quasars, BL Lacertae objects are typically viewed at small angles ($\theta \ll \Gamma^{-1}$, where Γ is the Lorentz factor of the shock) to the direction of the jet axis. This is compatible with the idea that the extreme variability of BL Lacertae objects arises because they are strongly beamed and was suggested by Roberts, Gabuzda, and Wardle (1987) and by Cawthorne and Wardle (1988) for OJ 287. Gabuzda, Roberts, and Wardle (1989*a*) argued against this explanation for the slow speeds in BL Lacertae objects in general, on the assumptions that (i) BL Lacertae objects with measured redshifts are drawn from a similar redshift population to those with none. In this case all of the BL Lacertae objects in which proper motion has been observed (including those without redshifts) are "slow." (ii) The prominence of the core relative to any extended structure on arcsecond scales is a measure of the degree of relativistic enhancement of the core radio emission. Several of those sources that are *inferred* to be "slow" have relatively prominent extended structures and are thus not highly beamed if this assumption is correct. Such sources are therefore unlikely to be "slow" as a result of highly relativistic motion ($\Gamma \gg 1$) at a sufficiently small angle to the line of sight ($\theta \ll \Gamma^{-1}$); more likely they are a result of mildly relativistic motion so that modestly superluminal apparent speeds are seen over a fairly wide range of core dominance. While these assumptions are reasonable, both may be called into question; the most pressing need is to obtain redshifts for more BL Lacertae objects that have measured proper motions.

c) *BL Lacertae Objects and Microlensing*

Some authors (Ostriker and Vietri 1985; Ostriker 1989) have suggested that several distinctive characteristics of BL Lacertae objects could be understood if these objects were images of more distant quasars microlensed by stars in intervening elliptical galaxies. These characteristics include the lack of line emission (the lensing would amplify the optical continuum, but not emission from the larger line-emitting regions, so that any emission lines would be "buried"), the large and rapid variability seen in these objects (intrinsic variations would be amplified by the lensing), the low redshifts of most BL Lacertae objects compared to quasars (the measured redshifts would be those of the foreground galaxies), and the tendency to find BL Lacertae objects in elliptical host galaxies (Ostriker and Vietri argued that elliptical galaxies were the most likely lenses). One attractive aspect of this idea is that it can naturally explain the apparently slow superluminal speeds observed in BL Lacertae objects: the redshifts that had been determined for the BL Lacertae objects would actually be those for the foreground galaxies in which the lensing was taking place and would therefore be too small, causing the speeds deduced from proper motions to be too small.

In this picture the radio emission, even on VLBI scales, is not microlensed because it is not sufficiently compact; in order for a region to be lensed by a few solar mass star it must be typically hundredths of a parsec or less in linear size (Gott 1981). In this paper we have established that one characteristic of BL Lacertae objects is that the linear polarization in VLBI knots is polarized with **E** parallel to the structural axis, indicating a magnetic field structure perpendicular to this axis. On the other hand, VLBI polarization maps of quasars (Wardle *et al.* 1986; Wardle and Roberts 1988; Brown *et al.* 1989; Roberts *et al.* 1989) show that **E** in the knots of quasars tend to be perpendicular to the VLBI structural axis, indicating a magnetic field structure parallel to this axis. There is thus a systematic difference in the magnetic field structures of quasars and of BL Lacertae objects on milliarcsecond scales, ruling out models in which a significant fraction of BL Lacertae objects are gravitationally microlensed quasars. Other systematic differences between BL Lacertae objects and of quasars that conflict with the microlensing picture include, for instance, differences in their arcsecond-scale radio morphologies (Antonucci and Ulvestad 1985; Antonucci *et al.* 1986; O'Dea, Barvainis, and Challis 1988; Kollgaard, Wardle, and Roberts 1989) and in their X-ray spectral indices (Worrall 1989). It is still possible that certain individual sources are microlensed images of more distant squasars; however, this cannot explain the "slow" superluminal speeds observed in BL Lacertae objects thus far, since all of these objects have been mapped with polarization sensitivity and have been found to have **E** parallel to the jet axes.

V. CONCLUSIONS

This paper presents VLBI polarization observations of six compact radio sources that have been identified with BL Lacertae objects, and brings to nine the number for which such observations have been analyzed and published. One of these presented here, 3C 371, has also been identified as an N galaxy, and its VLBI polarization structure is indeed more characteristic of an emission line object than of a BL Lacertae object. Of the remainder, those that were resolved show the properties that appear to be characteristic of BL Lacertae objects and to which no exceptions have yet been found: (i) the VLBI I and P visibilities are quite high, (ii) the degree of polarization of the VLBI cores is $\sim$3%–5%, and (iii) the polarization (electric field) in the knots lies closely parallel to the projected direction of the jet. It seems likely that the alignment of the jet and the polarization in the knots arises because knots occur where plasma containing a tangled magnetic field is compressed in a plane perpendicular to the jet, for example by shock waves that propagate along its axis.

The apparent difference between the radio VLBI structures of BL Lacertae objects and quasars rules out models in which the optical appearance of a member of the former class is a consequence of microlensing the nuclear regions of a member of the latter.

The tentative report of $\beta_{\rm app} h = 2.5$ for 1823+568 lends weight to the view that the moving components in BL Lacertae objects are more mildly superluminal than those in core-dominated objects as a whole.

This work has been supported by the NSF under AST-84-18636 (J. F. C. W.) and AST-85-19529 (D. H. R.). The US VLBI Network stations, and astronomy operations of the Haystack Mark III correlator, are also supported by the NSF.

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