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MILLIMETER AND SUBMILLIMETER POLARIZATION OBSERVATIONS OF BLAZARS

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ABSTRACT

Millimeter and submillimeter polarization observations of blazars from the James Clerk Maxwell Telescope are presented. The data are interpreted in light of recent results from centimeter wavelength VLBI polarimetry studies. Observations of the superluminal quasar 3C 279 at 1.1 and 0.8 mm give a degree of polarization in excess of 10% and imply that the magnetic field is aligned orthogonal to the milliarcsecond (mas) jet to within 6°. This magnetic field orientation is consistent with that expected to arise in a transverse shock. The high level of polarization suggests that the centimeter VLBI core is depolarized by Faraday rotation rather than by increased magnetic field disorder at the base of the inhomogeneous relativistic jet. Three BL Lacertae objects were observed at 1.1 mm and were found to be between 3% and 17% polarized with position angles either closely parallel or closely perpendicular to the mas jet. Although further observations are needed, these data favor a picture in which the position angles in the cores of BL Lac objects display a bimodal distribution as found by centimeter VLBI studies. The close relationship between the millimeter polarization position angle and the mas jet is surprising given the results of millimeter VLBI studies which show evidence for significant jet bending.

Subject headings: BL Lacertae objects: general — polarization — quasars: individual (3C 279) — radio continuum: galaxies

1. INTRODUCTION

By definition, blazars (BL Lacertae Objects and OVV/HP Quasars) are sources exhibiting high levels of optical and radio polarization. The continuum emission at these wavelengths is produced by the synchrotron process and is thought to arise in a relativistic jet that is oriented towards the observer. Flux and polarization monitoring studies of blazars have led to the development of models in which the variable emission arises in shocked regions which form near the base of the jet (e.g., Marscher & Gear 1985; Hughes, Aller, & Aller 1985, 1989a, 1989b).

Centimeter wavelength VLBI studies reveal knots of emission which emerge from a stationary core region and propagate outward along well defined paths at superluminal speeds. Such studies show that the knot emission is significantly polarized. For the BL Lac objects the implied magnetic field orientation is perpendicular to the jet flow, which is in turn consistent with the knots being transverse shocks (e.g., Gabuzda et al. 1989). For the quasars, however, the magnetic field is found to be ordered in a direction predominantly parallel to the jet (e.g., Cawthorne et al. 1993b). The difference in polarization properties may be due to the environments in which the jets propagate. For example, the optical spectra of quasars typically reveal broad emission lines, while those of BL Lac objects are usually featureless. The interaction of the quasar jets with the dense emission line gas may shear the underlying magnetic field parallel to the jet. For the BL Lac objects the relative paucity of gas suggests that the underlying magnetic field will be tangled. In this picture, the VLBI knots in quasars can still be transverse shocks but the perpendicular component of the magnetic field never dominates over the underlying parallel component (Cawthorne et al. 1993a).

Support for such a scenario comes from observations of the quasar 3C 345. First, centimetre flux and polarization monitoring data show that the magnetic field is orientated roughly along the jet during quiescent periods and that the effect of a radio outburst is to depolarize the total flux (Stevens et al. 1996). Second, VLBI observations show that the maximum fractional polarization occurs between the knots (Brown, Roberts, & Wardle 1994). These observations argue for an underlying magnetic field that contains both longitudinal and tangled components. Plane-parallel shock waves will compress the tangled component of the field orthogonal to the jet axis, thus decreasing the total polarization.

The VLBI polarization data for the cores of blazars are more difficult to interpret. The cores of quasars are found to be weakly polarized or unpolarized (Cawthorne et al. 1993a) while the cores of BL Lac objects exhibit levels of polarization comparable to those present in the knots (Gabuzda et al. 1992; Cawthorne et al. 1993a). The polarization of quasar cores is discussed further in § 4. It was originally thought that the distribution of core position angles in BL Lac objects was not correlated with the jet direction, possibly due to bends of the jet on milliarcsecond (mas) scales (e.g., Krichbaum et al. 1993). Subsequent work has hinted that this distribution is in fact bimodal, with the magnetic field ordered perpendicular to the jet during epochs when new knots are emerging and parallel to the jet at other times (Gabuzda et al. 1994). However, the effect of opacity and, to a lesser extent, Faraday rotation on the derived position angles is uncertain.

In this Letter we present millimeter and submillimeter polarization observations of blazars which were taken at the James Clerk Maxwell Telescope (JCMT). Emission at these wavelengths comes from the most compact regions of the relativistic jet, most likely from within the centimeter VLBI core, is typically optically thin and will be unaffected by Faraday rotation. The initial motivation behind this work was a comparison with simultaneous VLBI measurements. The results of that study, which incorporates a subset of the data presented here, will be published at a later date.

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TABLE 1

SUMMARY OF POLARIMETRY DATA

Source (1)	Date (1995) (2)	Class (3)	λ (mm) (4)	Flux (Jy) (5)	$p\%$ (6)	χ (7)	θ_{mas}[a] (8)	$\lvert\chi - \theta_{mas}\rvert$ (9)
1253−055 (3C 279)......	Aug 2	Q	1.1	7.6 ± 0.5	10.4 ± 0.6	76° ± 2°	−120°[b]	6°
1253−055 (3C 279)......	Aug 2	Q	0.8	5.3 ± 0.4	13.5 ± 1.4	76 ± 3	−120[b]	6
1803+784................	Aug 2	B	1.1	1.3 ± 0.1	5.5 ± 1.2	170 ± 6	−103	93
1823+568................	Aug 2	B	1.1	1.4 ± 0.1	9.4 ± 1.0	33 ± 3	−165	18
1823+568................	Sep 8	B	1.1	1.6 ± 0.1	17.1 ± 1.2	10 ± 2	−165	5
1823+568................	Sep 15	B	1.1	1.3 ± 0.1	16.7 ± 2.4	30 ± 4	−165	15
1823+568................	Sep 21	B	1.1	2.0 ± 0.2	11.3 ± 2.1	20 ± 5	−165	5
2200+420 (BL Lac).....	Aug 2	B	1.1	2.6 ± 0.2	3.0 ± 0.7	17 ± 7	171	26

[a] Values taken from Cawthorne et al. 1993b, except for 1253−055, which is from Cawthorne & Gabuzda 1996.
[b] This is the position angle of the innermost knot.

2. OBSERVATIONS AND DATA REDUCTION

The 15 m JCMT is situated close to the summit of Mauna Kea, Hawaii, at an elevation of 4092 m above sea level. Observations coincident with centimeter VLBI were taken on 1995 August 2 with the facility bolometer UKT14 (Duncan et al. 1990) and the Aberdeen/QMW Submillimetre Polarimeter (Murray 1991). Table 1 gives the dates of subsequent observations. The polarimeter consists of a fixed wire-grid analyzer and a rotatable half-wave plate which is stepped through 16 positions during one complete rotation. Normal photometry with a chopping secondary is performed at each position. An integration time of 16 s per position was employed that provides a compromise between adequate signal-to-noise and the need to complete the rotation before significant sky variation. Several rotations were averaged for each source in order to increase the signal-to-noise and to confirm detections. This latter point is important since spurious results can be obtained in the presence of sky noise.

The instrumental polarization (IP) which arises from the receiver, telescope, and membrane was subtracted to give the source polarization. The IP is determined with observations of the planets, which are assumed to be unpolarized at near-millimeter wavelengths. The 1.1 mm IP was determined on 1995 August 2 with observations of Uranus and was found to be consistent with previous measurements (≈1.7%). The 0.8 mm IP was determined during late July to be 0.7%, which is again as expected from previous work. These values were used on all subsequent dates.

The half-wave plate produces a polarization modulation at the fourth harmonic of the waveplate position. After despiking, the data were fitted with a sine function to give a least-squares estimate of the normalized Stokes parameters q' and u'. An example of such a fit for 3C 279 is shown in Figure 1. Each q' and u' was then corrected for IP, by subtraction of the normalized Stokes parameters for the unpolarized source, and for parallactic angle and elevation (see Murray 1991; Nartallo et al. 1996). Final estimates of the degree of linear polarization p and its position angle χ were obtained by averaging the corrected Stokes parameters q and u over several rotations of the waveplate. See Nartallo et al. (1996) for the relationship between q, u and p, χ.

3. RESULTS

3.1. *Results for Individual Sources*

The polarimetry results are summarized in Table 1. Column (1) has the source name(s); column (2) the UT date of the observations; column (3) the source classification, where B stands for BL Lac object and Q stands for quasar; column (4) the filter; column (5) the flux density; column (6) the percentage polarization; column (7) the polarization position angle (χ); column (8) the position angle of the mas jet; and column (9) the angle by which the polarization is offset from the mas jet direction. Note that the magnetic field direction is orthogonal to χ for optically thin synchrotron emission. No correction has been made to account for Faraday rotation, which is expected to be negligible at near-millimeter wavelengths.

1253−055 (3C 279).—This bright quasar has been monitored at the JCMT since about 1989. A recent set of light curves are presented by Litchfield et al. (1995). These data show that 3C 279 was in a low state at the time of the polarization measurements. Unpublished JCMT data show that the source underwent a rapid decline in flux density between 1995 July 1 (which corresponds to a peak in the emission from this period) and 1995 August 2. During this period the 1.1 mm flux fell from 12.8 ± 0.9 to 7.6 ± 0.5 Jy. Despite the low flux level, the percentage polarization is high (10%–14%; see Table 1). Further JCMT polarization measurements taken over a three year period (1991.4–1994.4) show that the 1.1 mm polarization varied between 7% and 15% with a mean of 10.5% (Nartallo et al. 1996). Single-dish polarization observations at centimeter wavelengths between 1965 and 1985 show the percentage polarization to vary between about 0% and 6% (Aller et al. 1985). Furthermore, the degree of polarization is typically higher at shorter wavelengths, possibly due to Faraday rotation (see also § 4). The 1.1 and 0.8 mm data are consistent with a constant level of polarization, although the errors are quite large.

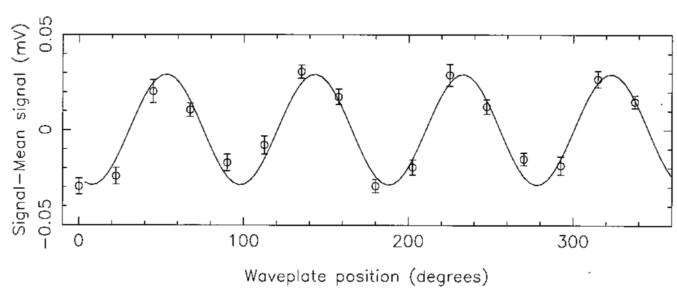

FIG. 1.—Sinusoidal modulation of the signal from 3C 279 produced during one rotation of the 1.1 mm waveplate. The mean signal level has been subtracted from each data point. The solid line is a fit to the data and allows extraction of the normalized Stokes parameters (see text).

The polarization position angle at both 1.1 and 0.8 mm implies that the magnetic field is aligned orthogonal to the centimeter VLBI jet[2] to within about 6°. The Nartallo et al. (1996) data show that this was the preferred magnetic field orientation over the 3 year monitoring period.

1803+784.—VLBI monitoring data for this BL Lac object at millimeter and centimeter wavelengths reveal strong evidence for jet bending on mas scales (Krichbaum et al. 1994). In fact, these observations suggest that the knots follow a helical trajectory as they expand outwards from the stationary core. Our 1.1 mm polarization measurement shows the magnetic field to be aligned within about 3° of the centimeter VLBI jet, which is perhaps surprising in light of the above finding. The degree of polarization is similar to the VLBI core polarization of 4% found by Cawthorne et al. (1993b), although the implied magnetic field directions are 70° different. This disparity may just reflect the nonsimultaneity of the observations. Unfortunately, no other 1.1 mm fluxes are available for this object, so it is impossible to determine whether the source was in a quiescent or higher level state at the time of observation.

1823+568.—This BL Lac object was observed on four occasions during a period of less than 2 months. During this time the degree of polarization varied between about 9% and 17%. Single-dish centimeter polarization observations taken between 1982 and 1985 show that the polarization at these wavelengths is typically 5%, although sometimes increasing to as high as 9% (Aller et al. 1985). Although the 1.1 mm flux rose from about 1.4 to 2.0 Jy over the period of observation, no trend of polarization with flux is apparent (Table 1). This suggests that the rapid variability of the polarization may be connected with turbulent processes (see Jones et al. 1985). In each case the position angle implies that the magnetic field is aligned orthogonal to the VLBI jet, in good agreement with Cawthorne et al. (1993b). At all four epochs the alignment was within 20° and was somewhat better ($\sim$5°) for the higher flux levels. Changes in position angle of about 20° are observed over timescales of 1 week. Millimeter monitoring data of this source at 1.3, 2.0, and 3.3 mm are available from the literature (Steppe et al. 1993). These observations, from the 30 m IRAM telescope, were taken over the period 1986–1993 and show that the 1.3 mm flux was as low as $\sim$0.6 Jy on a number of occasions. The 1.1 mm fluxes presented here thus represent a relatively high flux level.

2200+420.—BL Lacertae shows the smallest polarization of the sources described (3%). The five 1.1 mm polarization observations reported by Nartallo et al. (1996) all give higher degrees of polarization (the range is 7%–12%) for fluxes lower than our measurement of 2.6 Jy. The data presented here thus support the tentative anticorrelation of degree of polarization with total flux found in that study. Twenty years of monitoring data at centimeter wavelengths give a range of 0%–10% for the integrated polarization (Aller et al. 1985). The position angle at 1.1 mm is consistent with an orthogonal magnetic field, although the misalignment of 26° is the biggest in our sample. Similar position angles were found by Nartallo et al. (1996); range (−12°–48°). Long-term 1.1 mm monitoring data (Stevens et al. 1994) show that BL Lac was relatively bright at the time of observation and subsequent photometry on 1995 September 21 and 1995 October 14 showed that the 1.1 mm flux increased further to 2.95 ± 0.19 and 3.98 ± 0.30 Jy, respectively. This last measurement represents the highest level of 1.1 mm flux for BL Lac since monitoring at this wavelength began in 1989.

4. DISCUSSION

As is the case for quasars in general, a 6 cm polarization image of 3C 279 shows that the magnetic field follows the local jet direction (Cawthorne & Gabuzda 1996). At 1.1 and 0.8 mm, however, the magnetic field is found to lie perpendicular to the jet. This result is perhaps at first sight surprising but can be explained within the standard picture outlined in § 1. The underlying longitudinal component of the magnetic field in quasars is observed to increase in strength with distance from the core as expected if it is aligned by shear (Cawthorne et al. 1993a). Since the millimeter emission arises close to the base of the jet, probably from within the centimeter VLBI core, the longitudinal component is predicted to be less ordered than at 6 cm. Any perpendicular component of the magnetic field, such as that arising in a transverse shock, is thus likely to dominate at millimeter wavelengths. At centimeter wavelengths the parallel component will dominate and the shock will manifest itself as a decrease in the total polarized flux, as observed for 3C 345 (Brown et al. 1994; Wardle et al. 1994). Similar perpendicular magnetic field orientations are sometimes observed close to the cores of quasars, for example, 3C 454.3 at 6 cm (Cawthorne & Gabuzda 1996). However, in such cases it is not always possible to rule out the possibility that the emission is optically thick,[3] in which case the polarization information is consistent with a parallel magnetic field. The centimeter VLBI core is often found to be weakly polarized or unpolarized in quasars. For 3C 279 the core polarization was measured as less than 1.6% during 1987 (Cawthorne & Gabuzda 1996). There are two plausible explanations for this effect. Either the magnetic field is much less ordered close to the base of the inhomogeneous relativistic jet than further out or the emission is depolarized by Faraday rotation. Support for the latter hypothesis comes from the anticorrelation of fractional polarization at wavelength 2 cm with optical line-to-continuum ratio (Cawthorne et al. 1993a). This result suggests that the depolarizing gas resides in the emission-line regions of the quasar, as proposed by Burn (1966). No such trend is observed for BL Lac objects. The high 1.1 mm polarization of 3C 279 argues against an increase in magnetic field disorder and supports the Faraday depolarization hypothesis.

For the BL Lac objects the polarization position angle at 1.1 mm is found to be either closely parallel or closely perpendicular to the mas jet. Although the number of observations is small they are consistent with the bimodal distribution of VLBI core position angles proposed by Gabuzda et al. (1994). In this scenario a perpendicular magnetic field corresponds to a high level of core activity and hence to a high level of millimeter flux. The results for BL Lac and 1823+568 (see § 3.1) agree well with this picture. Insufficient long-term monitoring data for 1803+784 prevents comparison in this case; whether 1.3 Jy at 1.1 mm corresponds to a low flux level for this source awaits further observations. We note that the intrinsic nature of the position angle distribution is difficult to establish with single frequency VLBI observations alone since

[2] We take the position angle of the jet to be that of the innermost knot with respect to the core (see Table 1).

[3] For a typical power-law distribution of electrons the degree of polarization of an optically thick source has a theoretical maximum of $\sim$10%, and so, in some cases, single frequency VLBI observations can discriminate between optically thick and optically thin emission.

the polarization position angle rotates by 90° as the emission becomes optically thick. The observed distribution can thus be explained if the self-absorption turnover of the core typically occurs at around the observing wavelength of 6 cm for BL Lac objects. Since the millimeter radiation is optically thin this confusion is removed. Observations of larger samples are clearly required to establish (or refute) this result.

The tendency of the position angle to align either along or across the mas jet at millimeter wavelengths appears to contradict the findings of millimeter VLBI studies which show evidence for the jets to be significantly curved. Particularly surprising is the close alignment in the case of 1803+784, which shows perhaps the most convincing evidence for helical knot trajectories (Krichbaum et al. 1994). With only one observation, however, the position angle alignment could well arise by chance and further observations may reveal a smooth variation of position angle with time. More data are clearly required before firm conclusions can be made.

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