Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 1**, 247–252
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Multifrequency Polarization Properties of Blazars

S. Jorstad[1], A. Marscher[1], J. Stevens[2], P. Smith[3], J. Forster[4], M. Lister[5], A. Stirling[6], J. Gómez[7], T. Cawthorne[8], W. Gear[9] and I. Robson[2]

[1] Institute for Astrophysical Research, Boston University, 725 Commonwealth Ave., Boston, MA 02215, USA;
[2] Centre for Astrophysical Research, Science and Technology Centre, University of Hertfordshire, College Lane, Herts AL10 9AB, UK;
[3] Steward Observatory, University of Arizona, Tucson, AZ 85721, USA;
[4] Hat Creek Observatory, University of California, Berkeley, 42231 Bidwell Rd. Hat Creek, CA 96040, USA;
[5] Department of Physics, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907, USA;
[6] University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK;
[7] Insituto de Astrofísica de Andalucía (CSIC), Apartado 3004, Granada 18080, Spain;
[8] Center for Astrophysics, University of Central Lancashire, Preston, PR1 2HE, UK;
[9] School of Physics and Astronomy, Cardiff University, 5, The Parade, Cardiff CF2 3YB, Wales, UK

Abstract We report preliminary results of a 3-year multifrequency polarization campaign of 15 AGNs of blazar type, including bimonthly total and polarized intensity imaging at 7 mm with the VLBA. We find that the sources have two different dependences of degree of polarization on wavelength: sub-mm peaked or straight “polarization spectra”. The fractional polarization of the latter group increases with frequency. All sources with sub-mm peak polarization (6 objects) have similar degree of polarization in the optical region and in the VLBA core. In high-optically polarized sources (5 objects) the EVPAs at all frequencies align with the pc-scale jet direction within the 1σ uncertainties. This implies that the high frequency emission is co-spatial with the VLBI core and/or transverse shocks in the jet.

Key words: active — galaxies: quasars: individual (0420−014, 0528+134, 3C 273, 3C 279, PKS 1510−089, 3C 345, CTA 102, 3C 454.3) — galaxies: BL Lacertae objects: individual (3C 66A, OJ 287, 1803+784, 1823+568, BL Lac) — galaxies: individual (3C 111, 3C 120) — galaxies: jet

1 INTRODUCTION

Blazars, the most energetic class of active galactic nuclei (AGN), are characterized by short time scales of variability, highly relativistic radio jets, high linear polarization from radio to optical wavelengths and strong γ-ray emission. Most likely these phenomena are connected with each other, so that simultaneous observations of flux and polarization variability at different wavelengths along with the structural and polarization changes in parsec-scale jets should allow us to establish connections between different emission regions in the source. We have performed a 3-year program of polarimetric observations of 8 quasars, 5 BL Lac objects, and 2 radio galaxies at different frequencies. The program includes total and polarized intensity imaging of the jets at 7 mm with high resolution at 17 epochs (Jorstad et al. 2005). The images are accompanied at many epochs by simultaneous (within a week) measurements of polarization at 1.35/0.85 mm as well as less frequent optical polarization observations and polarization and flux measurements at 3 mm.

⋆ E-mail: jorstad@bu.edu

2 OBSERVATIONS AND DATA REDUCTION

The radio observations were obtained at 43 GHz at 17 epochs (from 25 March 1998 to 14 April 2001) with the Very Long Baseline Array (VLBA), which recorded both right and left circular polarization. The data analysis is described in Jorstad et al. (2005) and the total and polarized intensity images are presented there as well.

Observations at 3mm were carried out with the Berkeley-Illinois-Maryland Association (BIMA) array at Hat Creek Radio Observatory, CA. Measurements of parallel and cross-circular polarization were made by switching between pairs of 86 GHz quarter-wave plates oriented at $\pm45°$ relative to the linearly polarized feeds. Correction for leakage (from observations of 3C 273 and 3C 279) and derivation of Stokes parameters was done using the Miriad tasks GPCAL and IMPOL (Wright 1996).

Observations at 1.35 and 0.85 mm were performed at the James Clerk Maxwell Telescope (JCMT) using SCUBA (Holland et al. 1999) and its polarimeter (Greaves et al. 2003). Initial stages of the data reduction were performed with the standard SCUBA data reduction package, SURF. Subsequent analysis was undertaken with the SIT polarimetry reduction software. Flux calibration was achieved through observations of the planets and JCMT secondary calibrators. The instrumental polarization (of about 1%) was measured on each run by making observations of a compact planet, usually Uranus, which is assumed to be unpolarized at millimetre/submillimetre wavelengths.

Optical polarization and photometric measurements were obtained with the Steward Observatory 1.5 m telescope located on Mt. Lemmon, Arizona, using the Two-Holer Polarimeter/Photometer (Sitko et al. 1985). Data reduction of the polarimetry follows the procedure described in Smith et al. (1992). The observations have not been corrected for instrumental polarization, which is found to be $\leq$0.1%, but the degree of linear polarization has been corrected for statistical bias (Wardle & Kronberg 1974). Known polarized stars (Schmidt et al. 1992) were observed to calibrate the electric vector position angle (EVPA) on the sky.

3 DEPENDENCE OF FRACTIONAL POLARIZATION ON WAVELENGTH

We characterize each source by the maximum observed value of the fractional polarization at each wavelength. In the case of the VLBA observations the polarization level of the VLBI core at 7 mm is used.

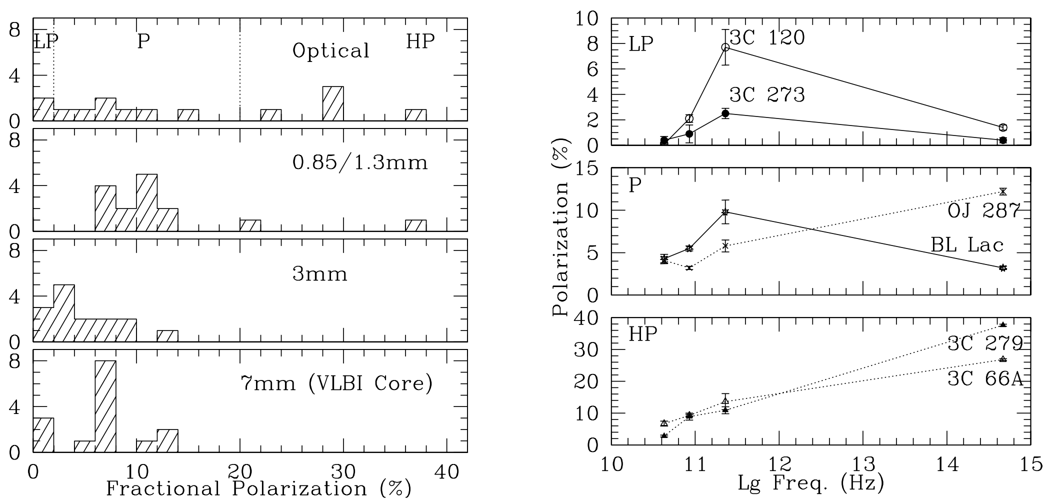

Fig. 1 *Left panel:* Distributions of maximum observed fractional polarization. *Right panel:* Examples of dependence of degree of polarization on frequency for nearly simultaneous observations.

Figure 1 (*left panel*) shows distributions of these values. These demonstrate that very high levels of polarization, m $\geq$20%, are seen only at short wavelengths, λ $\leq$1 mm, with the majority of such instances in the optical region. The peak of the distribution has lower polarization at longer wavelengths: 29% (opt), 11% (0.85/1.3 mm), 3% (3mm), and 7% (7mm). The distribution in the optical region has very large scatter, which suggests separation of the sources into three groups: LP (low-optically polarized, m <2%; these are 3C 120 and 3C 273), P (optically polarized, 2%≤ m <20%; these are 3C 111, 0528+134, OJ 287, 1510−089, 1803+784, BL Lac, CTA 102, and 3C 454.3), and HP (high-optically polarized, m ≥20%; these are 3C 66A, 0420−014, 3C 279, 3C 345, and 1823+568). Although we do not have optical measurements for the BL Lac object 1803+784, we include the source in group P according to previously published data (Impey et al. 1991).

For each source we plot level of polarization vs. frequency for nearly simultaneous (within a week) observations (some examples are shown in Fig. 1, *right panel*). We call this dependence the "polarization-spectrum." The sources in the LP group have sub-mm peaked polarization-spectra. However, in the optical region the blazar emission in 3C 273 and 3C 120 is noticeably diluted by unpolarized, non-synchrotron light (from the *big blue bump* in 3C 273 and from the host galaxy in 3C 120). This implies that optical polarization of the sources depends on the blazar contribution to the total flux, but this should not change the analysis of the objects as LP sources with sub-mm peaked polarization-spectra. All sources in the HP group have straight, steep spectra while sources in the P group have either sub-mm peaked spectra but with higher 7 mm fractional polarization than LP sources (1510−089 and BL Lac), or straight spectra but flatter than HP sources (3C 111 and 0528+134). Three P sources (OJ 287, CTA 102, and 3C 454.3) each show both types of spectrum. We stress that all sub-mm peaked polarization-spectrum sources display very similar (within 1σ uncertainty) levels of polarization in the optical region and in the 7 mm VLBI core when measured at nearly simultaneous epochs, although there are only a few such epochs.

4 CONNECTION BETWEEN POLARIZATION AND TOTAL FLUX

The relationship between fractional polarization and total flux is one of the criteria that can be used to assess a model for jet physics. In the case of the shock-in-jet model, one can expect an increase of polarization with an increase of brightness owing to ordering of the magnetic field in the shocked region. In electromagnetically dominated jets the reverse connection is likely if newly ejected plasma responsible for a rise in total flux has a chaotic magnetic field or one that is misaligned with the large-scale field.

Figure 2 shows distributions of linear correlation coefficients, r, between polarization and total flux at optical, sub-mm, and mm wavelengths. In the optical region r is calculated if at least 3 simultaneous photometric and polarimetric measurements have been obtained (there are only 6 such objects in our sample), at sub-mm wavelengths the number of points ranges from 5 to 14, at 3 mm it ranges from 5 to 20, and at 7 mm each source has been observed at 17 epochs.

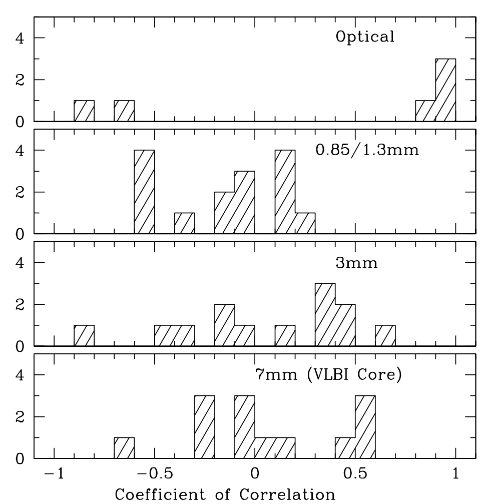

Fig. 2 Distribution of linear correlation coefficients between degree of polarization and total flux.

The distribution in the optical region appears essentially bimodal, with three HP quasars (0420$-$014, 3C 279, and 3C 345) and the BL Lac object OJ 287 showing very strong correlation between degree of polarization and total flux, while in two BL Lac objects (3C 66A and BL Lac) the reverse dependence occurs. According to Hagen-Thorn (1980), OJ 287 has a complex connection between degree of polarization and total flux ($\sim$ 50 measurements in B-band): polarization rises from 2% to 30% as the object brightens from $17^{\rm m}$ to $15^{\rm m}$ and falls to (8$\pm$4)% for brighter states. In addition, Hagen-Thorn et al. (2002) found a decrease in degree of polarization with increase of the total flux in BL Lac ($>$500 measurements). Therefore, despite the small number of optical coefficients of correlation that we have derived, they seem to represent global trends in the sources' behavior. The distributions at other wavelengths are not impressive when analyzed separately. Each distribution shows that $\sim$70% of sources in the sample have no significant connection between polarization level and total flux, $|r|$ $<$0.5. However, the linear correlation coefficient, $\bar{r}$, calculated over all epochs and sources, indicates some trend: at sub-mm wavelengths decrease of polarization with increase of total flux most commonly occurs ($\bar{r}$=$-$0.12, 139 points), while at mm wavelengths the degree of polarization tends to rise along with the total flux ($\bar{r} = 0.46$ at 3 mm, 157 points; $\bar{r} = 0.25$ at 7 mm, 217 points).

5 CONNECTION BETWEEN EVPA AND JET STRUCTURE

We calculate the average projected position of the jet, $\Theta_{\rm jet}$, for each source (see Jorstad et al. 2005) and compare the EVPA of the maximum observed polarization at each frequency with $\Theta_{\rm jet}$.

Figure 3 (*left panel*) shows distributions of the values $|EVPA - \Theta_{\rm jet}|$ for our sample. The distributions at $\lambda < 7$mm peak at EVPAs aligning with the jet direction within 10°. These are sources from the HP group, which also have similar EVPAs in the VLBA core, although the scatter is higher. This plus the straight polarization spectra of HP sources suggest that in these sources the emission at optical and sub-mm wavelengths originates in the mm-VLBI core, but occupies a smaller volume at higher frequencies. The optical emission, perhaps, comes from the region closer to a shock front or deeper in the jet where there is a higher ordering of the magnetic field in the transverse direction. Another explanation involves a helical magnetic field that has a toroidal component comparable to the poloidal field component in the jet frame, which should lead to strong dominance of the toroidal magnetic field in the observer's frame for highly beamed jets (Lyutikov et al. 2005).

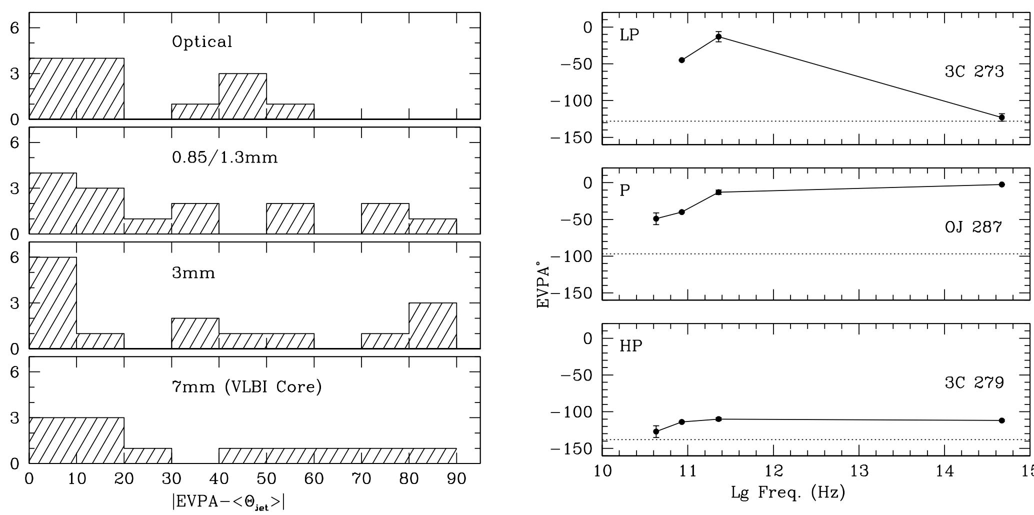

Fig. 3 *Left panel:* Distributions of the EVPA for maximum observed fractional polarization. *Right panel:* Dependence of the EVPA on frequency for nearly simultaneous observations (2000 April 3-5); dotted lines show direction of the inner jet.

Figure 4 plots Lorentz factor (Jorstad et al. 2005) vs. alignment between the electric vector at 7 mm for maximum observed polarization and the jet (in the case of 3C 111, 3C 120, and 3C 273 the EVPAs in the brightest polarized jet features are used) and shows that in our sample of blazar-like sources such a dominance is not apparent.

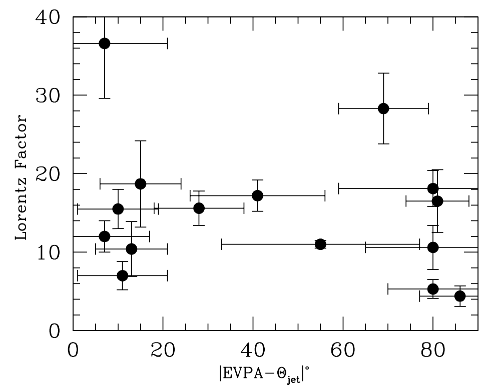

Fig. 4 Lorentz factor vs alignment between EVPA at 7 mm for maximum observed fractional polarization and jet direction.

The EVPAs obtained simultaneously at different frequencies for sources in the P group align more closely with each other than with the jet direction (see, e.g., OJ 287 in Fig. 3 *right panel*). This again suggests that the emission at different wavelengths is co-spatial. A weaker connection with the jet structure implies that either oblique shocks or less collimated sections of the jet are responsible for the emission, for example, the emission originates deeper in the VLBI core than in HP sources. The good correlation between EVPAs at different frequencies and jet direction in HP sources supports the idea that the jet is relatively straight up from the optical to mm scales, while the poorer correlation of the EVPAs with the jet position angle in P sources might result from non-ballistic trajectories on larger scales.

The statistics for the sources in the LP group are limited, although comparison of 9 measurements of the EVPA at 0.85/1 mm with the EVPA of the brightest polarized knots at 7 mm in 3C 273 shows a significant correlation between the values (coefficient of correlation 0.72). This suggests that the emission at sub-mm wavelengths in the LP group originates in the jet downstream the VLBI core, while the optical emission comes from the region close to the central engine and consists of a highly polarized blazar component with magnetic field perpendicular to the jet (see Fig. 3 *right panel* and also Impey et al. 1989) and an unpolarized or low polarized thermal component that significantly decreases the observed amplitude of the polarization.

Acknowledgements This material is based on work supported by the National Science Foundation under grants no. AST-0098579 and AST-0406865. The VLBA is a facility of the National Radio Astronomy Observatory, operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

References

Greaves J. S., et al., 2003, MNRAS, 340, 353
Hagen-Thorn V. A., et al., 2002, A&A, 385, 55
Hagen-Thorn V. A., 1980, Ap&SS, 73, 279
Holland W. S., et al., 1999, MNRAS, 303, 659
Impey C. D, et al., 1991, ApJ, 375, 46
Impey C. D, et al., 1989, ApJ, 347, 96
Jorstad S. G., et al., 2005, AJ, 130, in press
Lyutikov M., et al., 2005, MNRAS, 360, 869

Schmidt G. D., et al., 1992, AJ, 104, 1563
Sitko M. L., et al., 1985, ApJS, 59, 323
Smith P. S., et al., 1992, ApJ, 400, 115
Wright M. C. H., 1996, BIMA Memorandum 48
Wardle J. F. C., & Kronberg, P. P., 1974, ApJ, 194, 249

DISCUSSION

DANIELE FARGION: Is jet intensity correlated with polarization?

SVETLANA JORSTAD: When a new jet component is emerging from the VLBI core that increases the jet intensity, an increase of polarization at different frequencies is usually observed. However, there are cases when an increase of polarization at high frequencies is detected when the jet intensity is fairly low, so that there is no one to one correspondence.

SERGIO COLAFRANCESCO: Is there any evidence of increasing level of polarization with increasing frequency in your blazar sample? And do the E and B components behave differently with increasing frequency?

SVETLANA JORSTAD: Yes, all HP sources (these are the quasars 3C 279, 3C 345, and 0420$-$014 and BL Lac objects 3C 66A and 1823+568) display an increase of polarization with frequency. This can be explained if a more compact region with higher ordering of the magnetic field is responsible for the emission at shorter wavelengths. In HP sources the EVPAs at all frequencies closely align with the jet direction. In P sources some successive rotation of the EVPA is observed from optical wavelength to 7 mm (for example, $\sim 50°$ in OJ 287). This is difficult to explain by Faraday rotation since at 1.3 and 3 mm the effect should be negligible. Most likely this is the result of a change of the magnetic field structure in the VLBI core with its optical depth. We do not have circular polarization to investigate a difference in behavior of the E and B components.

HANS-JAKOB GRIMM: Can you estimate the kinetic energy of the jets?

SVETLANA JORSTAD: In general, it is possible, though difficult: we should know the Lorentz factor, magnetic field, composition and cross-section of the jet. Lorentz factor can be estimated from apparent speed; not many jets are resolved transverse to the jet direction, therefore the size of the beam is the simplest approximation for the jet cross-section; the jet can consists of electron-proton plasma, though electron-positron pairs are also possible, which changes the kinetic energy significantly; there are attempts to estimate the magnetic field that give B$\sim$0.1G on parsec scales.