POLARIZATION DISTRIBUTIONS IN COMPACT RADIO SOURCES

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ABSTRACT. We present milliarcsecond-resolution 5 GHz polarization maps of several active galactic nuclei: one epoch each for the quasar 3C345, the galaxy 3C120, and the BL Lacertae object 0735+178, and two epochs for the BL Lacertae object OJ287.

1. INTRODUCTION

At the heart of the radio structures of active galactic nuclei is a compact (angular size mas, physical size pc) radio source coincident with the optical center of the object. At arcsecond resolution, these central components usually have flat radio spectra and a rather low degree of linear polarization. When observed at milliarcsecond resolution by VLBI, these sources often consist of a few discrete components with very high brightness temperatures ($\gtrsim 10^{10}$ K). In many cases the structures mimic those on the arcsecond scale, having an optically-thick "core" and an optically-thin "jet". The relationship of the millarcsecond jets to the arcsecond jets is not clear: Do the milliarcsecond jets "feed" the arcsecond jets, or do they have different origins? Are the same emission mechanisms and confinement processes involved? The low integrated polarization of the central components has been ascribed variously to a tangled magnetic field, a peaked electron energy distribution, optical thickness, internal Faraday rotation, or a non-synchrotron emission mechanism. Which, if any, is correct? The milliarcsecond jets must coexist with the optical line emitting gas; what is the effect of one upon the other? What are the kinematic and dynamical origins of the superluminal motions? And finally, what more can we learn about the "central engines" of active galactic nuclei by studying the radio structures on the smallest scales?

In order to further attack these questions, we have developed techniques of linear polarization measurement for VLBI and applied them to some of the brightest active galactic nuclei.

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2. POLARIZATION SYNTHESIS AT MILLIARCSECOND RESOLUTION

All of the data discussed below were taken using the Mark III VLBI system, recording seven 2 MHz channels of left circular polarization at four stations (Haystack=K, Green Bank=G, Phased VLA=Y, Owens Valley=O), and seven channels of right circular polarization at two (G,Y), at a frequency of 4984 MHz (λ6 cm). The data were correlated for all parallel- and cross-hand fringes at Haystack Observatory, and were reduced using our software on the VAX 11/780 and VAX 8600 computers at Brandeis.

The crucial step in a polarization synthesis is the determination and removal of the instrumental components of the cross-polarization response of the interferometer. The procedure for accomplishing this in the (non phase-coherent) VLBI case has been given by Roberts *et al.* (1984). The distribution of linearly-polarized radiation may be described by the complex polarization $P = Q + iU = p \exp(2i\chi) = mI \exp(2i\chi)$, where I is the total intensity, Q and U are the two Stokes parameters for linear polarization, $p = \sqrt{Q^2+U^2}$ is the polarized intensity, m is the fractional polarization, and χ is the position angle of the electric vector. Maps of P may be made from the decontaminated cross-fringes by several techniques (Cotton *et al.* 1984; Roberts *et al.* 1984; Roberts and Wardle, in preparation). The basic idea is to make an I-map from the parallel-hand fringes using one of the hybrid map-making techniques (Pearson and Readhead 1984), use the results to correct the cross-fringes for the antenna phases, transform the cross-hand visibilities, and perform a complex CLEAN on the resulting dirty P-map. The I-map and P-map are thus phase-referenced to each other, so there is no ambiguity about their registration.

3. THE SUPERLUMINAL QUASAR 3C345

The quasar 3C345 is one of the best-studied examples of the superluminal phenomenon. It consists of an opaque core denoted "D", and a series of rapidly-moving knots "C2", "C3", etc., which form a jet at position angle PA = −75° (Cohen *et al.* 1983a). Taking H_0 = 75 km/s/Mpc and q_0 = 0.5, for 3C345 (z = 0.595), 1 mas = 5.1 pc if we adopt the cosmological interpretation of the redshift.

Figure 1a shows a total intensity map of 3C345 made from limited data taken in December 1981 (Wardle *et al.* 1986). The clean beam used was 3.9 × 2.3 mas with major axis at PA = −18°. At this resolution, the inner (C3) and outer (C2) knots blend together to form the "bulge" to the west, and are separately visible only in the clean components. However, Figure 1a is consistent with the map of Unwin *et al.* (1983), which was based on observations a few months earlier than ours with twice the resolution. Figure 1b shows a polarization map, with E-field vectors superimposed on contours of polarized intensity. The position of the opaque core D (from Figure 1a) is shown by the cross. Because two of the VLBI stations detected only one polarization, the u-v coverage is somewhat poorer than that for the I-map, and the restoring beam here is 4.7 × 2.5 mas at PA = −25°.

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Comparison of Figures 1a and 1b shows that the polarized flux is associated with the jet rather than with the core, and that the two knots C2 and C3 are differently polarized. Summing the clean components of the I- and the P-maps, we find that the core is less than 1 % polarized, C3 is 11 % polarized at $\chi = 22°$, and that C2 is 6 % polarized at $\chi = 83°$. However, the maximum degree of polarization in the source is located on the side of C3 towards the core, and is about 20 %. While this is due in part to dilution by C2 (which has a different χ), it may represent actual polarization structure within C3. The total polarized flux in the map is 260 mJy at $\chi = 29°$, while the integrated polarized flux of 3C345 at this epoch (H. D. Aller, private communication) was about 370 mJy at $\chi = 33°$. Clearly there is some polarized flux associated with scales to which our observations are not sensitive. A lower resolution map made with a slight east-west taper reveals an additional weak component to the west of C2 (Wardle *et al.* 1986), but because of the paucity of short spacings in our data, we cannot be certain of its reality; it may be associated with the component C1 of Cohen *et al.* (1983b).

4. THE SUPERLUMINAL GALAXY 3C120

This galaxy provides the nearest ($z = 0.033$) example of superluminal motion, and is of great interest for the small scales which may be investigated (1 mas = 0.60 pc). An I-map made from data taken in December 1982 is shown in Figure 2a; this is in good agreement with interpolation between the maps presented by Walker *et al.* (1984). The opaque core and the knots called B, C, and D by these authors are all detected. The P-map in Figure 2b has a peak intensity which is only 2.3 % of that of the I-map; comparison of the two shows that the core is unpolarized, and the knots to have $m \approx 11$ %, 3 %, and 3 %, respectively. However, the correspondence of the I- and P-structures of the jet is not very tight. The total polarized flux in the map is 24 mJy at $\chi = -22°$, while the integrated flux measured by the VLA was 177 mJy at $\chi = 171°$ (corresponding to $m = 6.4$ %). Thus there is substantial polarized flux in an extended VLBI jet which we cannot map. These results are not unexpected, as Benson *et al.* (1984) have shown that 3C120 has structure on a continuous range of scales from milliarcseconds to arcminutes.

5. THE BL LACERTAE OBJECT 0735+178

This rather compact source ($z > 0.42$, > 4.4 pc/mas) has previously been studied at 6 cm by Baath (1984). The I-map in Figure 3a (epoch 1982.9) shows a bright core and two knots at PA = 72°. The polarization structure of 0735+178 is shown in Figure 3b; comparison of the maps shows a complete contrast to 3C345 and 3C120. Here the core is 3.6 % polarized, the inner knot (3 mas from the core) is unpolarized ($m < 1$ %), and the outer knot (5 mas) has $m = 6.5$ %. In this source 72 % of the integrated polarized flux appears in the VLBI map.

6. THE BL LACERTAE OBJECT OJ287

This source (z = 0.306, 3.7 pc/mas) has particularly strong and variable polarization at radio wavelengths. Previous VLBI observations have shown it to be very compact, and it is often used as a calibrator. Maps of OJ287 at two epochs a year apart are shown in Figures 4a, 4b, 5a, and 5b. While the total intensity maps show that the source is only slightly extended (in the south-west direction), the polarization structure is both striking and variable. Model fitting of the I-maps at each epoch is consistent with a simple double structure, with a separation of 1.9 mas and an intensity ratio of 8:1. At both epochs the P-map also shows a double structure, but with an intensity ratio much closer to unity. Because of the "interference" exhibited by close components with electric vectors roughly perpendicular to each other, the two components in Figure 4b (epoch 1981.9) are actually closer than they look. Model fitting shows the separation to be ~ 0.9 mas, with intensities (p = 120 mJy, χ = -19°) and (184 mJy, +83°) for the NE (core?) and SW (jet?) components, respectively. One year later the separation had increased to 1.4 mas, and the intensities were (124 mJy, -79°) and (96 mJy, +73°). Thus the NE component remained about 4 % polarized but underwent a rotation of position angle of <u>at least</u> 60 degrees, while the SW component fell a factor of two in polarized flux but held a roughly-constant position angle. <u>If</u> we identify the SW components of the I-maps with the SW components of the P-maps, the fractional polarization of this jet was as high as m = 50 % in 1981.9, and fell to 25 % a year later. A strict lower limit to the polarization of the SW component is 15 %.

7. ACKOWLEDGEMENTS

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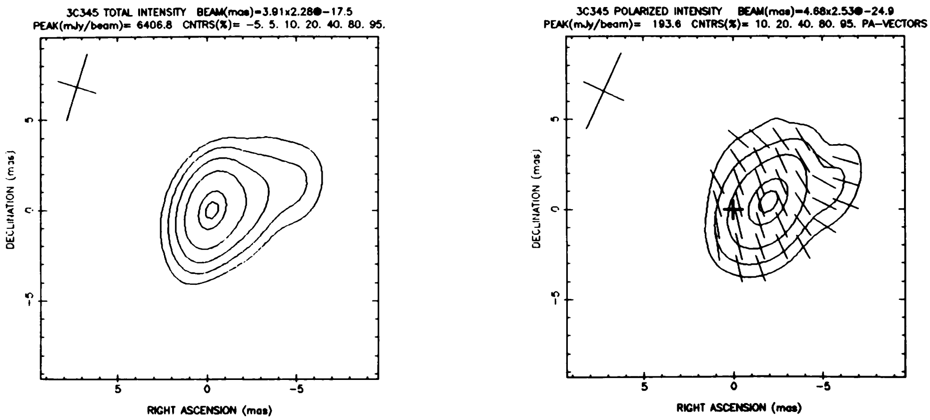
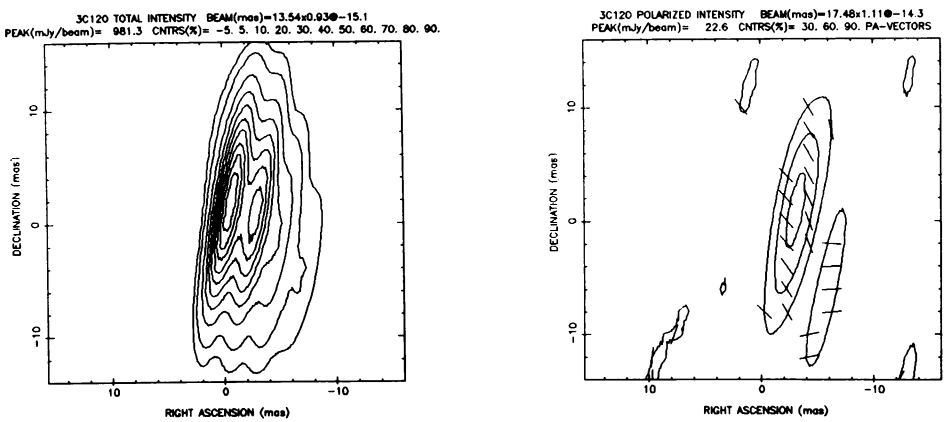
9. FIGURES



Figures 1a, 1b. I- and P-maps of 3C345, epoch 1981.9.



Figures 2a, 2b. I- and P-maps of 3C120, epoch 1982.9.

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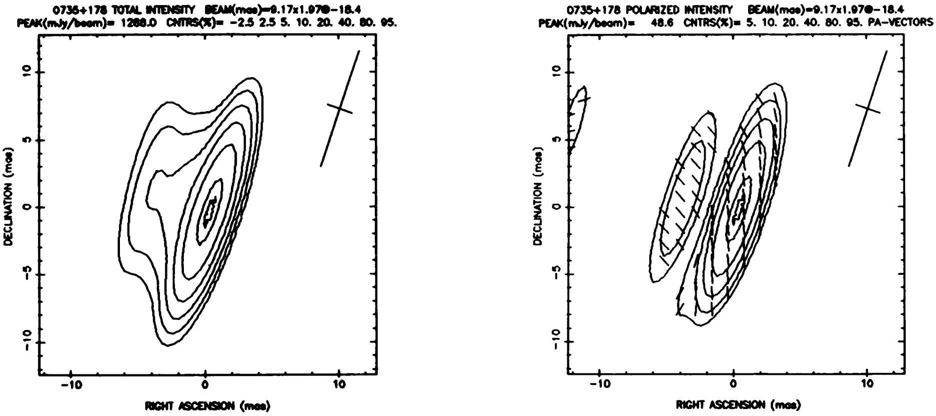
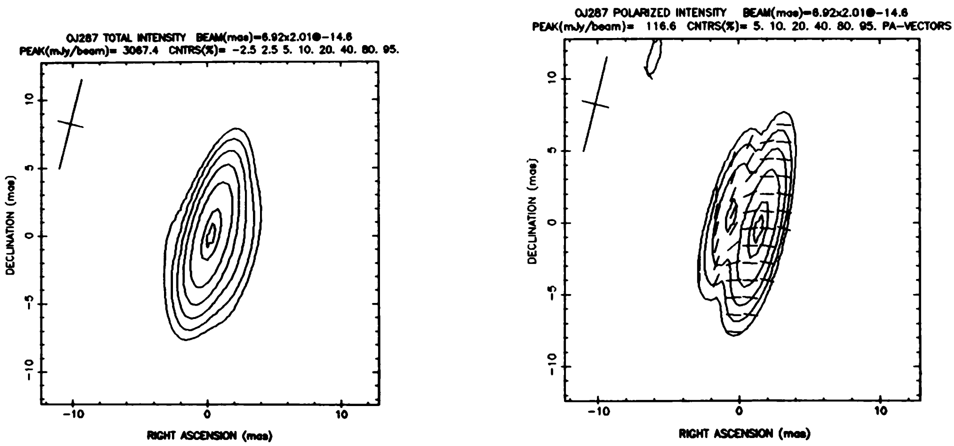
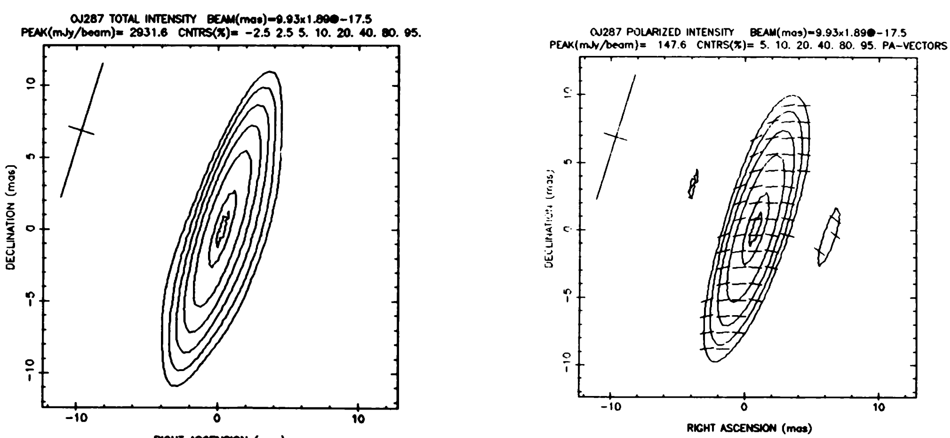


Figures 3a, 3b. I- and P-maps of 0735+178, epoch 1982.9.



Figures 4a, 4b. I- and P-maps of OJ287, epoch 1981.9.



Figures 5a, 5b. I- and P-maps of OJ287, epoch 1982.9.

DISCUSSION

Cotton : You interpreted the change in position angle as a change in the orientation of the magnetic field. Have you considered synchrotron opacity effects ? Five years ago we did a 13 cm VLBI polarization measurement of 3C454.3 in which the position angle rotated by 90°; we interpreted this as an opacity effect.

Roberts : I agree that a change in the orientation of B along the jet is not only possible explanation of swings in the plane of the electric vector. I would like to have multi-frequency polarization VLBI data in order to put better limits on any opacity effects.

Perez-Fournon : How do your results correlate with the unresolved polarization properties ?

Roberts : In some objects (0735+178, OJ287, and probably 3C345) the VLBI p-map contains most of the polarized flux seen with the VLA (ie, 50-90 percent). However, in 3C120 the milliarcsecond jet apparently has polarised flux on scales we are unable to map with our very limited u-v coverage, and we recover only ~ 14 percent of the arcsecond-scale polarized flux.

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" .... BL Lac is a BL Lac."

- Richard Porcas (p.139)