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New VSOP Polarisation Images of BL Lac Objects

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Abstract. VSOP space-VLBI polarisation observations have proven very fruitful, both confirming some predictions based on earlier ground-based VLBI studies and providing fresh insight into the magnetic field structures of the jets of AGN. These new VSOP polarisation images of 0954+658 and 1418+546 make it possible to distinguish polarisation originating in the 6 cm VLBI core and the innermost VLBI jet, which are blurred together in the ground-array image. The images of both sources reveal the presence of longitudinal **B** fields in the innermost jets, with rapid reversals in the dominant field direction on scales of less than a milliarcsecond. In the case of 1418+546, the VSOP observations indicate the existence of a "spine" of transverse **B** field surrounded by a "sheath" of longitudinal field, with a rapid alternation between longitudinal and transverse fields in the inner 5 mas of the jet.

1. Introduction

Before the launch of the HALCA satellite, it was somewhat difficult to predict how much useful information could be obtained from VSOP polarisation observations of active galactic nuclei (AGN), due to the small size of the orbiting antenna and the ability to record only one circular polarisation for baselines to HALCA. However, in fact, such observations have been among the most interesting and informative of all those obtained by the VSOP project.

Even the modest increase in resolution provided by the baselines to the orbiting antenna has been enough to test certain hypotheses about the parsec- and subparsec-scale polarisation structures observed with lower-resolution ground-VLBI observations. One example is the confirmation that the polarisation ascribed to the ground-based 6 cm "cores" of BL Lac objects is typically dominated by the contribution of relatively highly polarised optically thin emission in the inner jet, as proposed by Gabuzda et al. (1994), with the core itself being much more modestly polarised than indicated by ground observations, $m \simeq 1 - 3\%$ (Gabuzda 1999, Gabuzda & Gómez 2001a,b). This is an important result, since it suggests that the resolution attained by 6 cm VSOP observations is beginning to be comparable to the size of the optically thick core region, enabling much more direct studies of the properties of this region at low frequencies than have been possible before. Another result that provided important confirmation of a widely accepted theoretical concept was the first direct observation of the theoretically predicted 90° flip in the core polarisation position angle in the transition from the optically thick to the optically thin regimes for OJ287 (Gabuzda & Gómez 2001a).

At the same time, VSOP polarisation observations have provided new insight into the nature of the magnetic (**B**) field structures on parsec scales. For example, they have yielded new evidence that the dominant transverse **B** fields in the VLBI jets of BL Lac objects may be associated with tightly wound helical **B** fields intrinsic to the jets themselves (Gabuzda 1999). This fundamentally changes our view of the **B** fields we are observing, since it suggests they may be primarily associated with the *global* magnetic field structure in the jets, rather than *local* phenomena such as shocks. In addition, somewhat unexpectedly, VSOP polarisation observations of OJ287 (Gabuzda & Gómez 2001a) revealed a region dominated by well ordered longitudinal fields in the inner jet, surrounded by regions of transverse **B** field in the core and further out in the jet (Gabuzda & Gómez 2001a).

I present here new results for two additional BL Lac objects: 0954+658 and 1418+546. These bring the total number of BL Lac objects for which VSOP polarisation results are available to five.

2. Observations

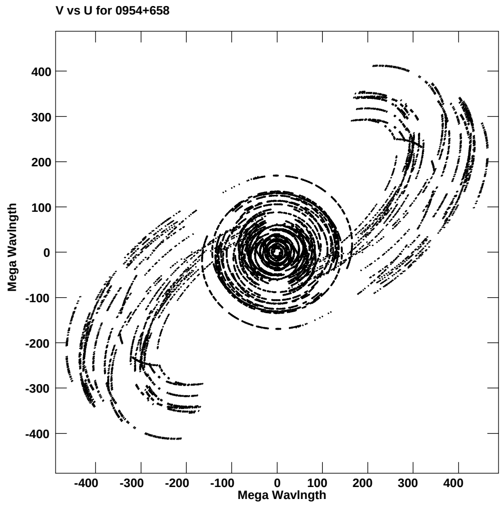
The 6 cm VSOP polarisation observations were obtained on October 21, 2000 (0954+658) and June 18, 2001 (1418+546). In both cases, the observing session lasted 8–10 hours, and the ground array included the ten VLBA antennas and the 100 m Effelsberg dish. The resulting *uv* coverages are shown in Fig. 1.

All antennas except for HALCA observed both right- and left-circular polarisation; HALCA observed only LCP. The ground antennas recorded using VLBA mode 256–4–2, and HALCA recorded in its standard mode – VLBA mode 128–2–2. Essentially, this was equivalent to HALCA recording in the same mode as the ground antennas, but without the two RCP channels. The data were correlated at the VLBA correlator in Socorro, New Mexico.

All calibration was performed in the NRAO AIPS package, as described by Gabuzda (1999). The polarisation calibration was done using the AIPS task LPCAL to find a joint solution for the instrumental polarisations of all antennas and for the source polarisation. Division of the source I distribution into separate regions for input to LPCAL was based on the distribution of the I CLEAN components, and was done by hand. The resulting instrumental polarisations for all ground antennas were $\sim 1-3\%$; the HALCA instrumental polarisation was estimated to be 1.8% on October 21, 2000 and 3.0% on June 18, 2001, similar to values derived for previous 6 cm VSOP polarisation observations of 0735+178 on January 30, 1999 (4%; Gabuzda, Gómez & Agudo 2001) and of OJ287 on April 4, 1999 (3%; Gabuzda & Gómez 2001a).

Absolute calibration of the polarisation position angles χ was performed by comparing the total polarisation detected in ground-only VLBI images of compact, appreciably polarised sources with integrated VLA measurements obtained at the NRAO, accessible on the web[1]. The sources used for this purpose were OJ287 and 1749+096; in both cases, integrated measurements were fortuitously available within 5–8 days both before and after the VSOP observations, and did not show evidence for variability between the integrated measurements. The absolute χ calibration is estimated to be good to within about 4°.

The 6 cm I images were made using the tasks CALIB (for self-calibration) and IMAGR (to perform the Fourier transform to make the dirty image and the CLEAN it). Maps of the linear polarisation[2] P were made by Fourier transforming the cross-hand fringes and performing a complex CLEAN using the AIPS procedure CXPOLN and task CXCLN. It was necessary to use a complex Fourier transform and CLEAN, since the uv coverage for the cross-hand correlations was not symmetric (the HALCA antenna did not record both right and left circular polarisation).



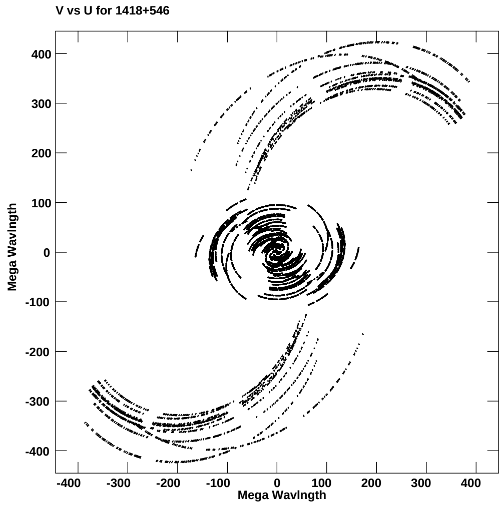


Fig. 1. uv coverage for VSOP polarisation observations of 0954+658 on October 21, 2000 (top) and of 1418+546 on June 18, 2001 (bottom). Note that the horizontal (u) axis is reversed from its usual definition.

3. Results

3.1. 0954+658

The ground-array image of 0954+658 (Fig. 2, top) shows the VLBI jet initially emerging in position angle $\simeq -45$ and then turning toward the west. The orientation of the polarisation position angles χ in the core region relative to the local jet direction is not clear. The relative orientation of the jet polarisation vectors about 2 mas to the northwest of the core is also not obvious, though it appears they may be perpendicular to the local flow direction, if the jet is already flowing toward the west at that location.

The full-resolution VSOP image (Fig. 2, middle) does not show any new features in terms of the overall jet structure. However, we can now distinguish polarisation from the 6 cm core ($m \simeq 3.8\%, \chi \simeq -68°$) and the inner jet ($r \simeq 0.5$ mas, $m \simeq 12\%, \chi \simeq +78°$). Thus, the core polarisation vectors lie roughly along the direction of the inner jet, while the polarisation vectors $r \simeq 0.5$ mas from the core appear to be rotating to become nearly transverse to the jet direction. If both the core and inner jet are dominated by optically thin emission, as is suggested by their relatively high degrees of polarisation, this suggests a transition from transverse to longitudinal **B** fields. The **B** field in the upper part of the jet appears to be longitudinal, although this remains somewhat unclear even in the higher-resolution VSOP image.

A comparison of the 6 cm VSOP polarisation map with a 2 cm VLBA polarisation map obtained in April 1997 (Fig. 2, bottom) shows striking similarity of the polarisation angles in the core and upper part of the jet. Of course, the source polarisation was very likely variable during the roughly 3.5 years between the VSOP and VLBA observations; nonetheless, these two maps suggest that the parsec-scale rotation measures are small, and not very different from the integrated value of -15 rad/m^2 (Rusk 1988). At the same time, the contrast between the polarisation at the two wavelengths in the inner jet is striking; since this

[1] http://www.aoc.nrao.edu/∼smyers/calibration/

[2] $P = pe^{2i\chi} = mIe^{2i\chi}$, where $p = mI$ is the polarised intensity, m is the fractional linear polarisation, and χ is the position angle of the electric vector on the sky

region is highly enough polarised to be optically thin, this must represent differing conditions in the flow structure in this region at different epochs.

3.2. 1418+546

The ground-array map in Fig. 3 (top) shows the extended VLBI jet in position angle $\simeq 135°$. The "core" polarisation vectors are clearly perpendicular to the jet, while the polarisation vectors in the inner 5 mas of the jet are first aligned with, then perpendicular to the jet direction. The polarisation vectors further from the core are clearly offset toward the northern side of the jet, and bear no clear orientation relative to the jet direction, similar to the behaviour seen in earlier 6 cm polarisation images (Gabuzda et al. 1999, Pushkarev & Gabuzda 1999).

The VSOP image (Fig. 3, bottom) enables us to zoom into the central few milliarcseconds of the source structure. Again, we can now distinguish the polarisation of the core ($m \simeq 1.5\%$) from polarisation in the innermost jet ($m \simeq 11\%$, $\chi \simeq 54°$), which can now be seen to be offset toward the southern edge of the jet. In contrast, the polarisation vectors about 2 mas from the core are well aligned with the jet direction and centred on the jet ridge line. These results are consistent with the idea that the jet of 1418+546 is comprised of a spine of transverse **B** field surrounded by a sheath of primarily longitudinal **B** field, as suggested by earlier VLBA images of this object (Gabuzda et al., in preparation).

Another interesting aspect of the VSOP image is that what would be taken as core polarisation in the ground image actually proves to correspond to a region of longitudinal **B** field in the innermost jet, as was also the case in the VSOP polarisation image of OJ287 presented by Gabuzda & Gómez (2001a). The alternation of longitudinal and transverse **B** field in the inner 5 mas of the VLBI jet is striking.

4. Conclusions

These new VSOP polarisation images display some of the same behaviour seen in previously analysed images of the BL Lac objects OJ287 (Gabuzda & Gómez 2001a), 1334–127 (Gabuzda & Gómez 2001b) and 1803+784 (Gabuzda 1999): what would be interpreted as the "core" polarisation in the ground-array image is dominated by the contribution of polarisation from the innermost jet. Since this has been the case for essentially all BL Lac objects for which VSOP polarisation observations have been analysed, it seems likely that this is characteristic of BL Lac objects as a class.

In both sources, the VSOP images provide evidence for regions of longitudinal **B** fields in the innermost milliarcsecond of the VLBI jets. In 0954+658, the origin of this roughly longitudinal field is not clear, but in the case of 1418+546, the corresponding polarisation is clearly offset toward the southern side of the jet, suggesting that it results from a shear interaction, as was proposed for the blazar 1055+018 by Attridge et al. (1999).

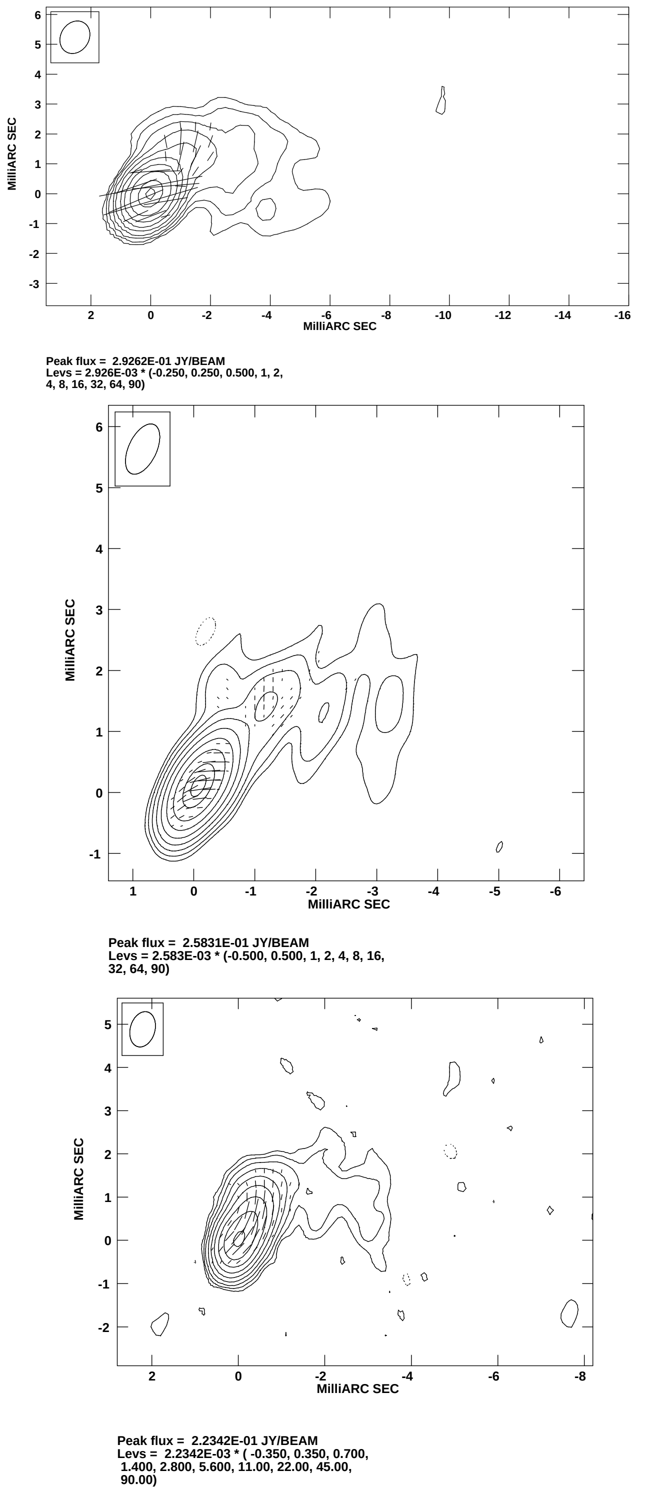


Fig. 2. 6 cm ground (top) and VSOP (middle) total intensity images of 0954+658 derived from VSOP data obtained on October 21, 2000, together with a 2 cm VLBA image derived from data obtained in April 1997 (bottom). χ sticks corresponding to the source polarisation are superposed. The beams are shown by the ellipses in the upper left-hand corners of the images.

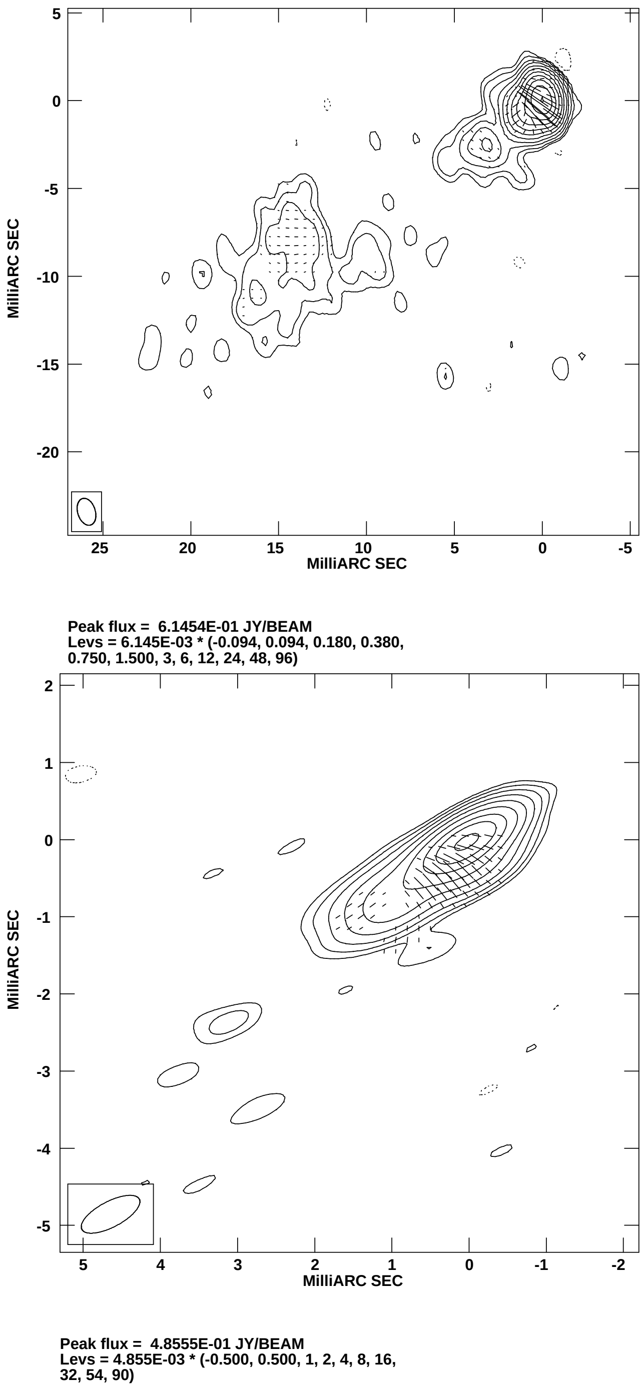


Fig. 3. 6 cm ground (top) and VSOP (bottom) total intensity images of 1418+546 derived from VSOP data obtained on June 18, 2001. χ sticks corresponding to the source polarisation are superposed. The beams are shown by the ellipses in the upper left-hand corners of the images.

The distinct alternating longitudinal–transverse–longitudinal **B** field structure observed in the inner jet of 1418+546 is reminiscent of the transverse–longitudinal–transverse **B** field structure displayed by the VSOP image of the core and inner jet of OJ287 (Gabuzda & Gómez 2001a). Although it is difficult to discern the core polarisation angle in the VSOP image of 1418+546, preliminary model fitting of the P data suggests this angle is $\chi \simeq -52°$, i.e. aligned with the inner jet, so that the alternation of magnetic field structures may originate on even smaller scales (if the observed VSOP core polarisation still includes a substantial contribution from optically thin jet emission on these smaller scales). Taking into account evidence that the jets of BL Lac objects may be characterised by helical **B** fields, it seems natural to associate such alternating **B** field structures with the global behaviour (oscillation? compression/rarefaction?) of these helical fields as the jet propagates from the core, in some cases interacting with a surrounding medium as well (as considered in the simulations of Aloy et al. (2000)). Further observations are required to test this possibility, for example, by searching for further regularities in the alternating **B** field patterns.

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