Astrophysical Phenomena Revealed by Space VLBI
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Multi-Frequency VSOP Polarization Observations of the BL Lacertae Object 1803+784

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Abstract

Very Long Baseline Interferometry (VLBI) polarization observations provide information about the magnetic-field structures of the parsec-scale jets in active galactic nuclei. Comparison of polarization observations obtained nearly simultaneously at different frequencies can reveal the presence of Faraday rotation due to thermal plasma along the line of sight from the source to the observer or mixed in with the non-thermal emitting plasma. VLBI polarization observations at 5 and 1.6 GHz were obtained of the compact BL Lacertae object 1803+784 on successive days in July 1998 with global ground arrays plus the orbiting HALCA antenna. The 5 GHz image revealed a smoothly bent jet structure, with the magnetic field transverse all along the jet. This may indicate the presence of a series of relativistic shocks, but more likely reflects the toroidal component of a helical magnetic field associated with the VLBI jet. Comparison of the 1.6 GHz VSOP image and 5 GHz ground-only image suggests that the rotation-measure distribution of 1803+784 is non-uniform on milliarcsecond scales.

1 Introduction

BL Lacertae objects are active galactic nuclei with weak, sometimes undetectable, optical line emission and strong variability in total intensity and linear polarization over a broad range of wavelengths from ultraviolet to radio. Their arcsecond-scale radio structures are compact, and their integrated radio spectra are flat or inverted. It is believed that synchrotron radiation is the dominant emission mechanism virtually throughout the spectrum. The origin of the relative low luminosity of their optical line emission is not clear.

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VLBI polarization observations of a complete sample of 1 Jy radio-selected BL Lacertae objects have shown a tendency for the dominant magnetic fields in the parsec-scale jets of these sources to be transverse to the local jet direction (Gabuzda, Pushkarev, & Cawthorne 1999, 2000). This has usually been interpreted as evidence for the presence of relativistic shocks that compress an initially tangled **B** field so that the dominant field lies in the plane of compression, perpendicular to the direction of propagation of the shock (Laing 1980; Hughes, Aller, & Aller 1989). It has seemed natural to associate transverse **B** fields in the jets of AGN with shocks, since these jets are obviously very energetic, and the components in which these transverse fields are detected are usually compact.

The BL Lacertae object 1803+784 has a redshift $z = 0.68$ (Witzel et al. 1988). The VLBI jet extends nearly directly west (Witzel et al. 1988; Gabuzda et al. 1992), though 5 GHz and 8.4 GHz VLBI polarization images suggested motion near the core in position angle about $-60°$ (Gabuzda et al. 1994; Gabuzda & Cawthorne 1996). The total intensity structure shows a remarkably persistent stationary feature roughly 1.2 mas west of the core, which has been detectable in VLBI images at centimeter wavelengths for more than a decade. Based on analyses of centimeter-wavelength P images, it was proposed that this feature was associated with a transverse shock.

2 Results at 5 GHz – Evidence for Toroidal Fields

The ground array for the 5 GHz VSOP observations of 1803+784 on July 21, 1998 included nine VLBA antennas (all but Brewster) plus the 100-m Effelsberg dish. Figure 1 shows the resulting (u, v) coverage; the HALCA baselines provided about a factor of three increase in resolution East–West and a factor of 1.5 North–South. The 5 GHz data reduction and results are described by Gabuzda (1999). We summarize these results below.

Figure 2 shows the 5 GHz VSOP total intensity (I) image with polarization vectors χ superimposed. We can see that, unlike previous centimeter-wavelength ground-based VLBI images, the brightest feature is not at the easternmost edge of the source emission: there is a weaker feature to the east of the brightest component, which is at the phase center. This suggests that the brightest feature is actually a knot in the innermost VLBI jet, rather than the core. Without spectral in-

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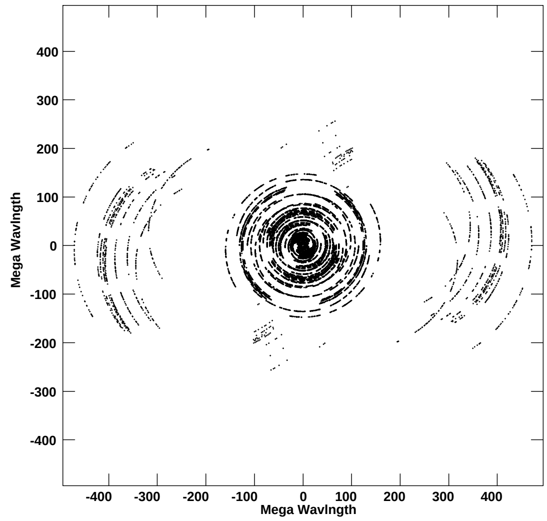

Figure 1: (u, v) coverage obtained for the 5 GHz VSOP observations of 1803+784 on July 21, 1998. The coverage for the 1.6 GHz observations one day earlier is very similar.

dex information, it is impossible to conclusively determine whether the easternmost feature is the 5 GHz core (optically thick) or a counterjet (optically thin). However, the fact that this feature is only modestly polarized, $\sim 3\%$, suggests that it is probably the core.

The well-known stationary jet feature is clearly visible to the west at a distance of ~ 1.3 mas from the phase center. The extra resolution provided by the HALCA baselines shows that the jet curves northward and then southward between the easternmost feature (which we take to be the core) and the bright feature at the western end of the jet. The χ vectors clearly follow this bending of the jet, remaining aligned with the local jet direction as the jet curves. The degree of polarization in the jet ranges from 5% to nearly 20%, indicating that the associated emission is optically thin. Thus, the χ distribution implies that there is a transverse **B** field all along the observed VLBI jet.

This type of magnetic-field structure could, in principle, be due to a series of shocks propagating along the VLBI jet, with each shock compressing the local **B** field so that it is transverse to the local flow direction. However, this explanation seems somewhat contrived. In addition, the polarized emission is relatively smooth, and is not concentrated only in the brightest and most compact features. This suggests that another

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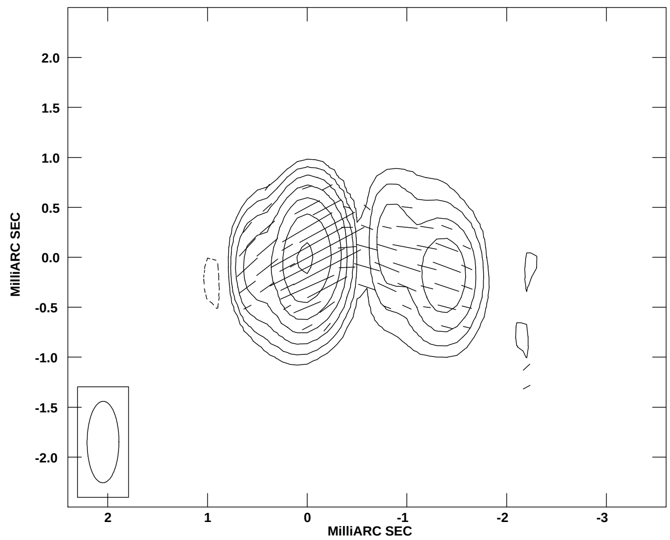

Figure 2: 5 GHz total intensity image for 1803+784 on July 21, 1998. The bottom contour is ±1.4% of the peak flux density of 1.07 mJy/beam, and the contours increase in multiples of 2. The sticks show superposed χ vectors for the linear polarization distribution.

interpretation is more likely: we are seeing the dominant toroidal component of a helical **B** field associated with the VLBI jet. This does not preclude the possibility that some of the knots of jet emission are associated with shocks; but it does provide a natural explanation for the fact that the observed jet **B** field remains transverse even as the jet bends fairly severely. The images presented here provide the first clear and direct evidence for the presence of toroidal magnetic fields on parsec scales.

3 Results at 1.6 GHz – Evidence for Non-Uniform Faraday Rotation

The ground array for the 1.6 GHz VSOP observations of 1803+784 on July 20, 1998 included the ten VLBA antennas, the phased VLA, and the 70-m Goldstone dish. The (u, v) coverage is similar to that in Figure 1.

The resolutions of the VSOP 1.6 GHz images and the ground-only 5 GHz images from the following day are very nearly the same. Figure 3 shows the two sets of I and P images of the inner-jet region; the 1.6 GHz structure actually extends much further from the core, and will

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be considered in more detail in a separate paper. At both frequencies, the structure observed in this region is very simple, and is dominated by a double roughly corresponding to the core and the nearly stationary feature to the west. This enables a relatively straightforward comparison of the images at the two frequencies.

Most surprising is the different behavior shown by the polarization position angles for the two features. In the simplest case in which the polarization of each of the components is subject to the same amount of Galactic (foreground) Faraday rotation, and this is the only Faraday rotation present, we would expect to observe the same rotation in χ between 1.6 and 5 GHz for both of the components. Even a cursory inspection of the images in Figure 3 shows that this is not the case.

This indicates a more complicated frequency dependence for the χ angles than is expected for a uniform foreground Faraday screen. Unfortunately, we cannot test for the λ^2 dependence expected for Faraday rotation, since we have data at only two frequencies. However, one obvious possibility is that there is Faraday rotation *local* to 1803+784, which is different for the two features.

We would like to derive reliable estimates for the separate rotation measures for the two components in the 1.6 GHz VSOP and 5 GHz ground images, in order to remove their effect from the higher resolution 5 GHz VSOP image. However, this is not so straightforward: rotation measure estimates are subject to $n\pi$ ambiguities, which can only be removed reliably when data are available at three or (preferably) more frequencies. In the case of our two-frequency 1803+784 data, even if we limit our consideration to χ ambiguities of $\pm 180°$, there are two possible differences in the 1.6 GHz and 5 GHz polarization angles for each component, which cannot be distinguished based on the available data. These imply two possible rotation measures for each component, of comparable magnitude but opposite sign: roughly +25 or –85 rad/m^2 for the core region and –50 or +60 rad/m^2 for the western component.

The corresponding rotations at 5 GHz are $+5°$ or $-17°$ for the core region and $+10°$ or $-12°$ for the western component. The two possible rotation measures for the core region imply the same general χ behavior: either way, χ remains aligned with the direction of the inner VLBI jet. The choice of rotation measure for the western component could affect our interpretation: if the rotation measure is close to +60 rad/m^2, the derotated χ vectors will align even better with the local direction of the downward curving jet; if the rotation measure is close to –50 rad/m^2,

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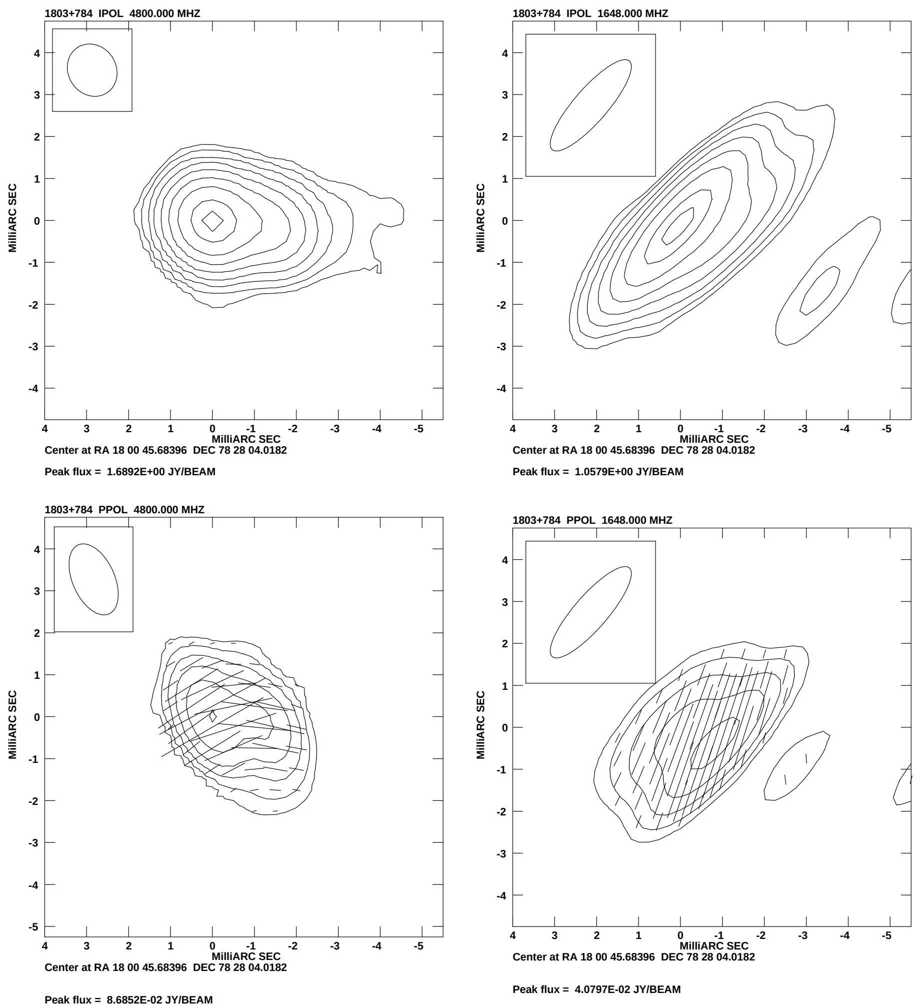

Figure 3: 5 GHz ground-only I (top left) and P (bottom left) images of the inner jet of 1803+784 on July 21, 1998 and 1.6 GHz VSOP I (top right) and P (bottom right) images of the same region on July 20, 1998. The bottom contours for the 5 GHz I and P images are ± 0.5 and $\pm 3\%$ of the peak flux densities of 1689 and 87 mJy/beam; the bottom contours for the 1.6 GHz I and P images are $\pm 1\%$ and $\pm 5\%$ of the peak flux densities of 1058 and 41 mJy/beam. The contours for all images increase in multiples of 2. The sticks show superposed χ vectors.

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the derotated χ vectors will be aligned nearly east–west, so that they will lie at an oblique angle to the local jet direction.

Formally, we cannot distinguish between these two possibilities. Since we cannot verify that the χ values for the two regions of emission obey a λ^2 law, we cannot exclude another physical origin for the frequency dependence of the polarization angles. One obvious possibility is the presence of polarized subcomponents that have different χ's and make different contributions to the total polarizations at 5 and 1.6 GHz. However, the high-resolution 5 GHz image in Figure 2 suggests that the polarized emission within each of the two regions in Figure 3 has fairly uniform χ values, making it unlikely that subcomponents with very different polarizations are giving rise to the anomalous frequency dependence of the χ values in Figure 3. We feel that the most natural explanation for our observations is that the two regions of emission experience different Faraday rotations, but we are unable to unambiguously determine the corresponding local rotation measures using our two-frequency data.

Due to this uncertainty, we have not applied any rotation measure corrections to the 5 GHz χ vectors in Figure 2. VLBA polarization images of 1803+784 at 1.3 cm and 7 mm, where we would expect the effects of the proposed rotation measures to be negligible, show that χ in the region of the stationary component clearly aligns with the direction of the jet channel curving downward from the north (Gabuzda and Chernetskii, in preparation; Marscher et al., in preparation). For this reason, we believe that our result, based on Figure 2, that the inferred **B** in the curved VLBI jet is everywhere transverse is on firm ground.

4 Conclusion

These first polarization images made from data obtained as part of VSOP General Observing Time have yielded two unexpected and potentially quite important results. The 5 GHz VSOP I and P images provide compelling evidence for a toroidal magnetic field in the curved VLBI jet of 1803+784 (Gabuzda 1999), as is, in fact, expected in many theoretical models of relativistic jet flows. Comparison of the 5 GHz ground-only and 1.6 GHz VSOP polarization images suggest that the rotation-measure distribution of this source is non-uniform on parsec scales. The implied rotation measures are not large – some tens of rad/m^2 – but it is surprising to find appreciable differences in the rota-

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tion measures of regions separated by only $\sim 1-2$ mas ($\sim 5-10$ pc at the redshift of 1803+784). This indicates the presence of thermal plasma in the immediate vicinity of the BL Lacertae object, and demonstrates that applying integrated rotation measures equally to all VLBI components can lead to erroneous results in some cases.

A more complete analysis of these data is in progress. We are also in the process of analyzing multi-frequency VLBA data for 1803+784, which we hope will enable us to study the toroidal **B** field in this source in more detail and better constrain values for the local rotation measures on parsec scales.

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