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Searching for Helical Magnetic Fields in BL Lac Objects

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Previously, a multi-wavelength (2-cm, 4-cm and 6-cm) polarization study by Gabuzda, Murray and Cronin 2004, showed systematic Faraday rotation gradients across the parsec-scale jets of several BL Lac objects, interpreted as evidence for helical magnetic fields — the gradients were taken to be due to the systematic variation of the line-of-sight magnetic field component across the jet. We present new results for the parsec-scale Faraday rotation distributions for a number of BL Lac objects, based on VLBA polarization data obtained from three separate sets of observations in August 2003, March 2004 and August 2004, at two wavelengths near each of the 2-cm, 4-cm and 6-cm bands. The rotation measure maps for several sources indicate gradients across their jets, as expected if these jets have helical magnetic fields. In at least one source (1803+784), we have found evidence for a change in the direction of the gradient across the jet with time, possibly suggesting the development of a kink in the helical magnetic field, that changed the direction of the helicity of the field.

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1. Introduction

BL Lac objects are a type of Active Galactic Nuclei (AGN) characterized by strong and variable polarization, rapid variability in luminosity, a featureless spectrum and weak optical line emission. The radio emission associated with BL Lac objects is a synchrotron emission that can be linearly polarized up to about 75% in the optically thin (jet) region, and up to 10–15% in the optically thick (core) region. VLBI polarization observations of BL Lac objects have shown a tendency for the polarization E vectors in the parsec-scale jets to be aligned with the local jet direction, which implies that the corresponding magnetic field is transverse to the jet, because the jet is optically thin (Gabuzda, Pushkarev & Cawthorne 2000). Although in the past, the dominance of the transverse magnetic field component was suggested as being the consequence of a 'shock model' where a series of relativistic shocks compress and enhance the transverse magnetic field component (e.g. Laing, 1980), it seems an improbable explanation for the transverse fields detected in extended regions in the jets of many sources. Instead, a helical magnetic field associated with the jet, with the toroidal component dominating over the longitudinal component (Gabuzda, Murray & Cronin 2004) would be a more plausible explanation.

2. Faraday rotation

When an electromagnetic wave passes through a region with free electrons and a magnetic field with a non-zero component along the line of sight, the plane of linear polarization gets rotated due to the difference in the propagation velocities of the right and left-circularly polarized components of the wave. This phenomenon is known as Faraday rotation. The degree of Faraday rotation is proportional to the integral over the line of sight from the source to the observer of the density of free electrons n_e, multiplied by the line-of-sight magnetic field component $B \cdot dl$, the wavelength squared, and various physical constants (Burn, 1966); the coefficient of λ^2 is called the Rotation Measure (RM):

$$\Delta\chi \propto \lambda^2 \int n_e B \cdot dl \equiv RM\lambda^2 \qquad (2.1)$$

The intrinsic polarization angle can be obtained from the following equation:

$$\chi_{obs} = \chi_0 + RM\lambda^2 \qquad (2.2)$$

where χ_{obs} is the observed polarization angle, χ_0 is the intrinsic polarization angle observed if no rotation occurred, and λ is the observing wavelength. The RM can easily be determined by measuring the polarization position angle at several wavelengths. Simultaneous multifrequency observations thus allow the determination of the RM, as well as identifying the intrinsic polarization angles.

For a helical magnetic field, due to the systematic change in the line-of-sight component of the helical field across the jet, we should observe a Faraday rotation gradient, and would expect a sign change in the RM across the jet, at least in some cases. The objective of this project is to search for new evidence for toroidal or helical magnetic fields associated with the jets of BL Lac objects by verifying and refining earlier results on transverse Faraday rotation gradients by using a wider range of frequencies, as well as identifying new sources with transverse Faraday rotation gradients.

3. Observations and reduction

VLBA polarization observations of 37 BL Lac objects were carried out in five experiments on 23 August 2003, 22 March 2004, 12 April 2004, 2 September 2004 and 11 August 2004, at six frequencies: 4.6 GHz, 5.1 GHz, 7.9 GHz, 8.9 GHz, 12.9 GHz and 15.4 GHz. Each source was observed for about 25-30 minutes at each frequency, in a ‘snap-shot’ mode with several scans spread out over the observing time period. Presented in this paper are the results for 5 sources: 1803+784, 0256+075, 1418+546, 0735+178 and 2155-152, obtained from the observations in August 2003, March 2004 and August 2004.

Standard tasks in AIPS were used for the amplitude calibration and preliminary phase calibration. Also, the imaging and RM determination was done with AIPS using standard techniques. The instrumental polarizations (‘D-Terms’) were determined using the observations of the sources J1159+29, 0235+164 and 1732+389 (one for each of the three experiments) with the task ‘LPCAL’. The Electric Vector Polarization Angle (EVPA) calibration was done using integrated polarization observations of 2200+420, obtained with the Very Large Array (VLA) on 13 Aug 2004, i.e. close in time to our observations on 11 Aug 2004, by forcing the EVPA for the total VLBI polarization of the source to match the EVPA for the integrated polarization of that source extracted from VLA observations. To refine the calibration, the calibrated maps of 1803+784 at all six frequencies were then used to compare the polarization vectors at the different frequencies in a region $\sim$ 1.5 mas from the core, where the observed polarization vectors were $\chi \sim 90^\circ$ at all frequencies, and where the RM is known to be zero. Several of the observed polarization angles showed deviations from the overall behaviour by 7–20°, and were rotated, so that all the polarization vectors in this specific region had the same orientation consistent with the known zero RM. This procedure improved the overall self consistency of the polarization and RM maps for virtually all of the sources observed. Due to the stability of the required EVPA correction for a given reference antenna over periods of several years (e.g. Reynolds et al. 2001), we were able to apply this refined EVPA calibration to all the epochs of our observations.

4. Rotation measure maps

4.1 Procedures

After the calibration for each wavelength, total intensity (I) and polarization images (distribution of Stokes parameters Q and U) were obtained. The Stokes parameters Q and U contain information about the linearly polarized flux: $p = \sqrt{Q^2 + U^2}$ and the polarization position angle: $2\chi = \tan^{-1}(U/Q)$. The polarization angle images were then combined to make RM maps after matching their parameters (beam size, image size, cell size). To choose between the most suitable beam parameters to be used for making the RM maps, different RM maps were made using the 4-cm and 6-cm beamsizes, and then compared to see which ones gave the most robust information, and to give a balance between resolution and sensitivity. In most cases, the 6-cm beam parameters were used. Before final RM maps were made, contributions from the known integrated (Galactic) Faraday rotation were subtracted at each wavelength (values obtained from Pushkarev 2001), so that any remaining Faraday rotation was due to regions in the vicinity of the source. The errors in the polarization angles in the final rotation maps were determined by propagating errors, taking

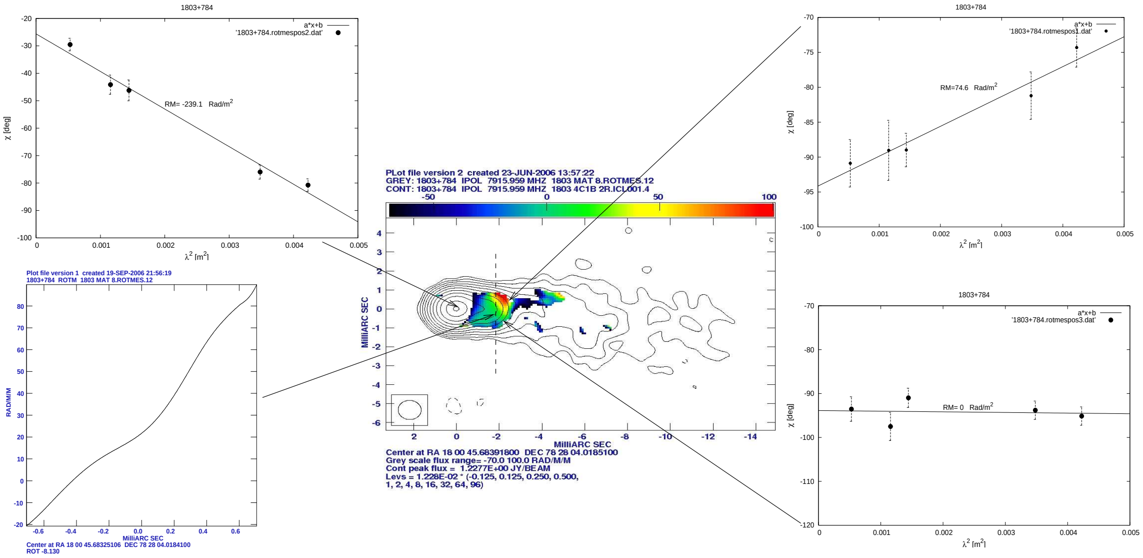

Figure 1: Rotation Measure Map for 1803+784, including a transverse RM slice across the jet showing the rotation measure values across the cross-section. Also shown are χ vs. λ^2 plots at three regions (3 × 3 pixels each) in the jet, showing a clear Faraday rotation gradient across the jet.

into account the uncertainty in the angle calibration ($\sim 2^\circ$), as well as finding the rms deviation from the mean value of a 3 × 3 pixel area at the desired region.

4.2 Results

Zavala & Taylor (2003), showed RM maps for 1803+784 (observed in June 2000) with RM values of -201 rad m^{-2} in the core, and 14 rad m^{-2} in the jet. Gabuzda & Chernetskii (2003), obtained similar results based on polarization model-fitting. A RM gradient (North-South, with the RM becoming more positive going South) is visible across the jet in the RM image of Zavala & Taylor (2003), although they did not make note of this in their paper. Our RM map of 1803+784 shows some interesting features as compared to Zavala and Taylor (2003). While confirming the core RM of about -200 rad m^{-2}, it shows a change in the direction of the transverse gradient observed in the jet. The RM gradient in our maps becomes negative going South, whereas Zavala & Taylor's map shows a gradient becoming positive going South. One possible explanation is that the gradient may have changed its orientation as a result of some sort of kink or distortion in the helical magnetic field, followed by a reconnection. This could change the direction of the helicity of the magnetic field and thus the sense of the RM gradient across the jet. Furthermore, we tentatively detect a RM gradient further along the jet ($\sim$ 5 mas), as well – see Figure 1. This source is a good example of how extending the frequency range used can confirm earlier RM determinations.

Several other sources in which transverse RM gradients have been detected for the first time include: 0256+075, 1418+546, 0735+178 and 2155$-$152 – see Figure 2. As seen in the figures, changes of the RM sign across the jet are often apparent in transverse RM slices across the jet. Since the RM values depend on the viewing angle θ, i.e. the angle the jet makes with the line of sight, as well as the pitch angle α, i.e. the angle that defines how tightly wound the helix is: the higher α, the more tightly wound the helix, different combinations of these angles can give different RM

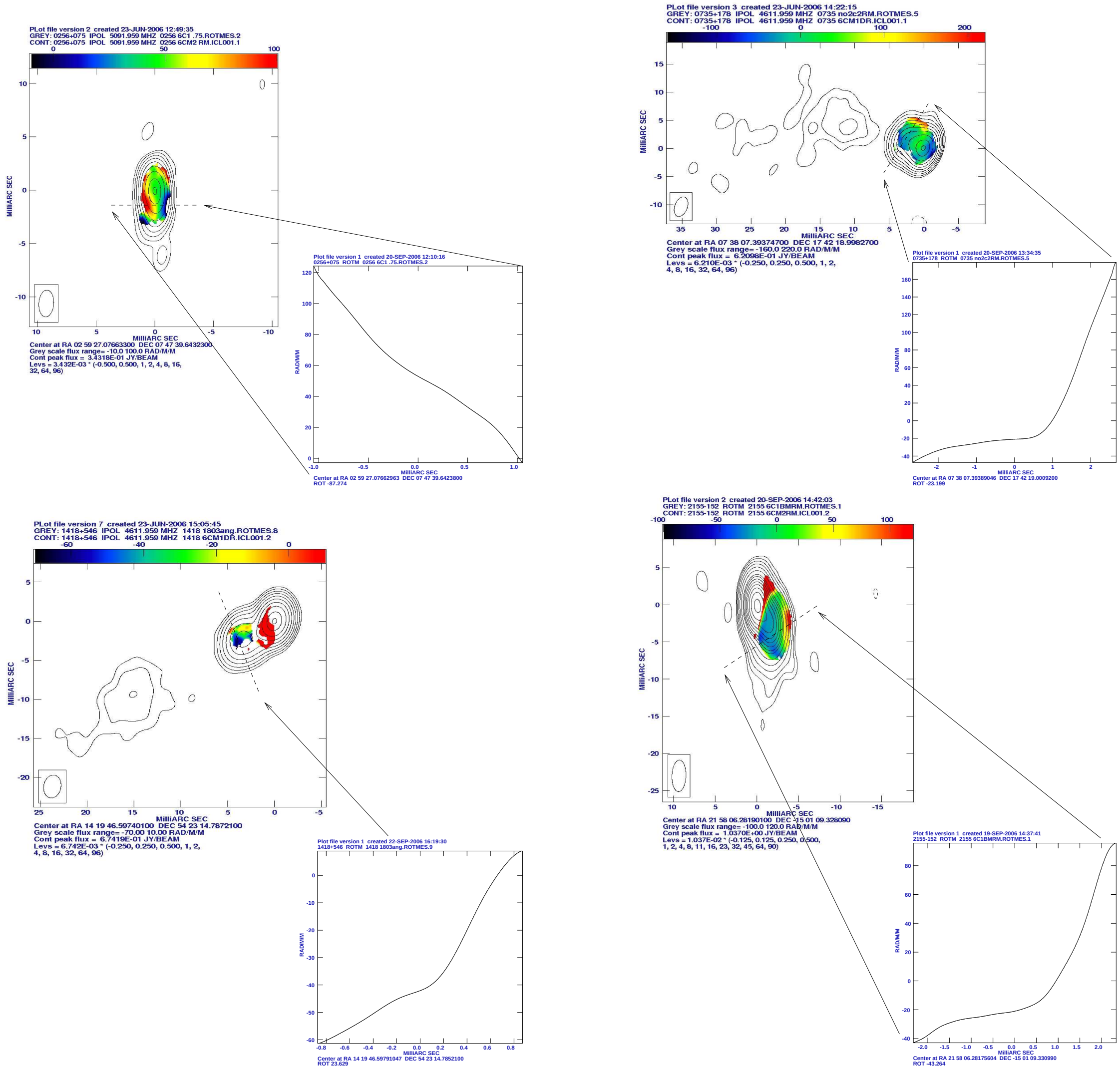

Figure 2: RM map of 0256+075, 0735+178, 1418+546 and 2155-152, including transverse slices of the RM values across the jets.

distributions, so that the RM sign change across the jet may not always be observed. For example, the change of the RM sign across the jet would be less obvious for a loosely wound helix, than for a tightly wound helix. Furthermore, different viewing angles will give rise to different RM profiles. Hence, it is not necessary to see a sign change in an RM gradient produced by a helical jet B-field, but an RM sign change across the jet is a clear indication of a helical field. It is also important to note that the transverse gradients observed were not isolated phenomena, and the gradients were systematic in different slices across the jet. Also, an interesting feature to note is the asymmetry in the systematic RM gradient across the jet. It is possible to have asymmetry in the sign change, due to either the combination of the viewing angle and the pitch angle, or possibly as a result of inhomogeneity in the density of the ambient medium, since the RM also depends on the density of thermal electrons.

5. Discussion

Like the RM map of 1803+784 made by Zavala & Taylor (2003), our new RM map displays a transverse rotation measure gradient across the VLBI jet. We have also found tentative evidence for an RM gradient further out in the jet. Furthermore, we have found evidence that the orientation of rotation measure gradients may change over time, possibly due to kinks in the helical B-field. New sources showing transverse gradients across their jets include: 0256+075, 1418+546, 0735+178 and 2155−152. The simplest explanation of these transverse rotation measure gradients is that they are produced by a helical magnetic field wrapped around the jet, where the changing line-of-sight magnetic field component causes the gradients.

Common features in the RM maps include an enhancement of the RM in the core (which could be a result of a higher electron density in the core), a sign change in the RM across the jet and an asymmetry in the transverse slices of the RM. The RM sign change is a clear indication of a helical B-field surrounding the jet, while the asymmetry in the transverse RM gradients could be due to the combination of the viewing and pitch angles, as well as variations in the density of the surrounding medium.

Further work will include identifying and studying spine–sheath structures (also associated with helical magnetic fields) as well as analysing other trends, such as RM gradients along the jets, that could further improve our understanding of the jet magnetic fields and jet collimation.

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