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18-22cm VLBA Observations of Three BL Lac Objects

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VLBA polarization observations of the 135 AGNs in the MOJAVE-I sample have recently been obtained at four frequencies between 1.3 and 1.7 GHz. These observations are sensitive to compact radio emission on scales from a few to tens of parsecs from the VLBA core. VLBA observations at the same frequencies were obtained earlier for 34 BL Lac objects, enabling a multi-epoch study of the extended radio jets of these objects. As an initial step in this study, we have constructed new images for three BL Lac objects with rich jet structures: 0735+178, 1803+784 and 2200+420 (BL Lac), which are analyzed together with the previous results of Hallahan and Gabuzda (2008). We consider the morphology, polarization (magnetic field) structure and Faraday rotation distributions of these objects.

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1. Introduction

1.1 BL-Lac Objects

Bl Lac objects are a class of active galactic nucleus (AGN) whose synchrotron-emitting jets are aligned relatively closely to the line of sight of the observer. They are characterized by the presence of only weak absorption and emission lines in their spectra, substantial degrees of polarization in the optical through radio and rapid variability of both their intensity and polarization. For optically thin regions of the jet, the electric vector position angle (EVPA) of the polarized radiation is perpendicular to the magnetic field direction.

BL Lac objects show a tendency for their jet magnetic fields to be orthogonal to the jet direction (e.g., [1]). This was initially interpreted as evidence for transverse shocks in their jets, which enhanced the magnetic field in the plane of compression; more recently, it has been suggested that these orthogonal fields may represent the central part of a helical or toroidal field component. This latter idea is supported by the observation of spine-sheath polarization structures [2], [3] (see Fig. 1) and transverse Faraday-rotation gradients [4] - [7] (see below) in a number of BL Lac objects. Such fields would come about in a natural way as a result of the "winding up" of an initial "seed" field by the rotation of the central accreting objects (e.g. [8], [9]).

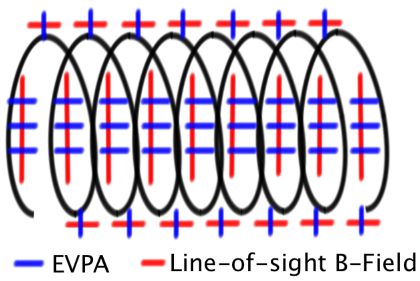

Figure 1: Schematic of the spine-sheath structure expected in the AGN jet in the presence of a helical magnetic field.

1.2 The MOJAVE Observations

*M*onitoring *O*f *J*ets in *A*ctive galactic nuclei with VLBA Experiments, or MOJAVE, is a long-term program to monitor the radio brightness and polarization distributions in jets associated with active galaxies visible in the northern sky with the VLBA. The MOJAVE-I observations (2002-2006), obtained at 15.3 GHz, were optimized for obtaining suitably high-dynamic range, full-polarization images on a sample of 135 sources at reasonable intervals for measuring superluminal motion. The MOJAVE-II observations (2006) extended the sample to 192 sources, and included polarimetric observations at 8.1, 8.4, 12.1 and 15.3 GHz. The MOJAVE-III observations (2007-present) are currently being carried out for the extended sample at 15.3 GHz only.

VLBA polarization observations of the 135 AGNs in the MOJAVE-I sample have recently been obtained at four frequencies between 1.36 and 1.66 GHz. These observations complement the previous MOJAVE observations by providing multi-frequency information about the jets on larger scales of tens or hundreds of parsecs. VLBA observations at these same four frequencies had been obtained earlier for the sample of 34 radio BL Lac objects defined in [10], enabling a multi-epoch study of the extended radio jets of the BL Lac objects present in both samples. We present here some first results from this multi-epoch study.

1.3 Faraday Rotation

An electromagnetic wave can be resolved into right-circularly polarized (RCP) and left-circularly polarized (LCP) components. If a polarized wave propagates through a medium with an ambient magnetic field B, the RCP and LCP components have different indices of refraction, meaning that they propagate at different speeds. This causes the value of χ to change by an amount $\Delta\chi$ (in cgs units):

$$\Delta\chi = \frac{e^3\lambda^2}{2\pi m^2 c^4} \int N_e B_{||} dl$$

where e is the electron charge, λ is the wavelength, m is the electron mass, c is the speed of light, N_e is the electron density of the plasma through which the wave propagates, $B_{||}$ is the component of the magnetic field parallel to the line of sight of the observer and RM is the Faraday rotation measure. Note that $\Delta\chi$ depends on the magnetic field component parallel to the line of sight toward the observer.

For a jet with a helical magnetic field, this field component changes systematically across the width of the jet, giving rise to a gradient in the RM (Fig. 2).

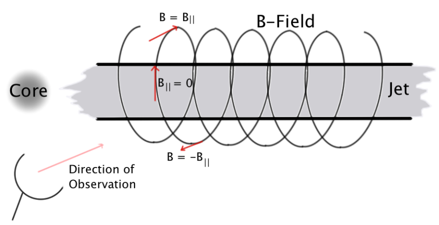

Figure 2: *Schematic describing how a helical magnetic field can cause a transverse RM gradient.*

2. Observations

The observations for this project were made with the VLBA in three 24-hour experiments on June 18, 2010 (0735+178), August 23, 2010 (BL Lac) and November 5, 2010 (1803+784). The observations were carried out simultaneously at 1358, 1430, 1493 and 1665 MHz (22.1, 21.0, 20.1 and 18.0 cm). The preliminary calibration, polarization (D-term) calibration and imaging were done in AIPS using standard techniques. In all cases, Los Alamos was used as the reference antenna. The polarization angles were calibrated using integrated (VLA) observations of compact polarized sources observed in the VLBA experiments. The RM maps were made in AIPS and CASA. Some further information about the observations and their calibration can be found in [11].

The intensity I, polarization P and Faraday-rotation images obtained for 0735+178, 1803+784 and BL Lac were compared to those obtained earlier using observations carried out in 2004 [12]. We consider the polarization structure, distribution of the fractional polarization and distribution of the Faraday rotation measure for each of these BL Lac objects below.

3. Results

Intensity maps for all three sources with sticks representing the EVPA orientation superposed are shown in Fig. 3, fractional polarization maps are shown in Fig. 4 and RM maps in Fig. 5.

0735+178. This source shows regions of longitudinal polarization along the upper and lower sides of its curved jet, and weaker transverse polarization near the jet ridge line (Fig. 3 top left). Thus, the polarization structure is reminiscent of a spine-sheath configuration, consistent with the possibility that the jet carries a helical magnetic field. The fractional polarization rises toward the edges of the jet (Fig. 4 top left). However, the appreciable bending of the jet and the fact that the polarization is stronger along the upper edge of the jet suggest that the polarization may include a contribution from curvature-induced polarization, with the longitudinal field enhanced at the outer edge of the jet bend. The polarization structure and fractional polarization distribution are virtually identical to those observed by [12] roughly six years earlier, showing that this structure is very stable. The distribution of Faraday rotation (Fig. 4 top right) is patchy, does not show any obvious systematic patterns.

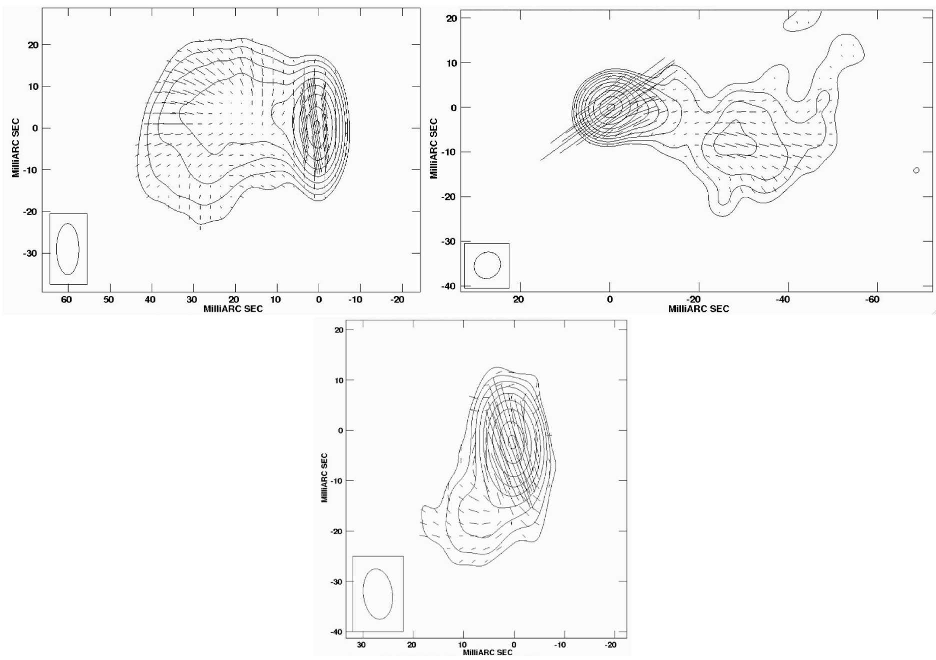

Figure 3: Total-intensity maps of 0735+178 (top left), 1803+784 (top right) and BL Lac (bottom) with EVPA sticks superposed. The EVPA sticks have been corrected for the integrated rotation measure.

1803+784. The jet is dominated by an orthogonal field component all along its length (Fig. 3 top right). The uniformity of the orthogonal field pattern all along the jet suggests that we are observing a helical or toroidal field component, rather than a series of closely spaced shocks. The degree of polarization is highest along the jet spine, and seems to increase at the end of the visible jet (Fig. 4 middle left). The polarization structure is very similar to that observed earlier by [12]. The distribution of Faraday rotation (Fig. 4 middle right) seems to show a pattern similar to that displayed by the fractional polarization map in the extended jet. If this is the case, it suggests that this Faraday rotation is associated with material in the immediate vicinity of the jet. The Faraday rotation distribution does not show any obvious systematic gradients.

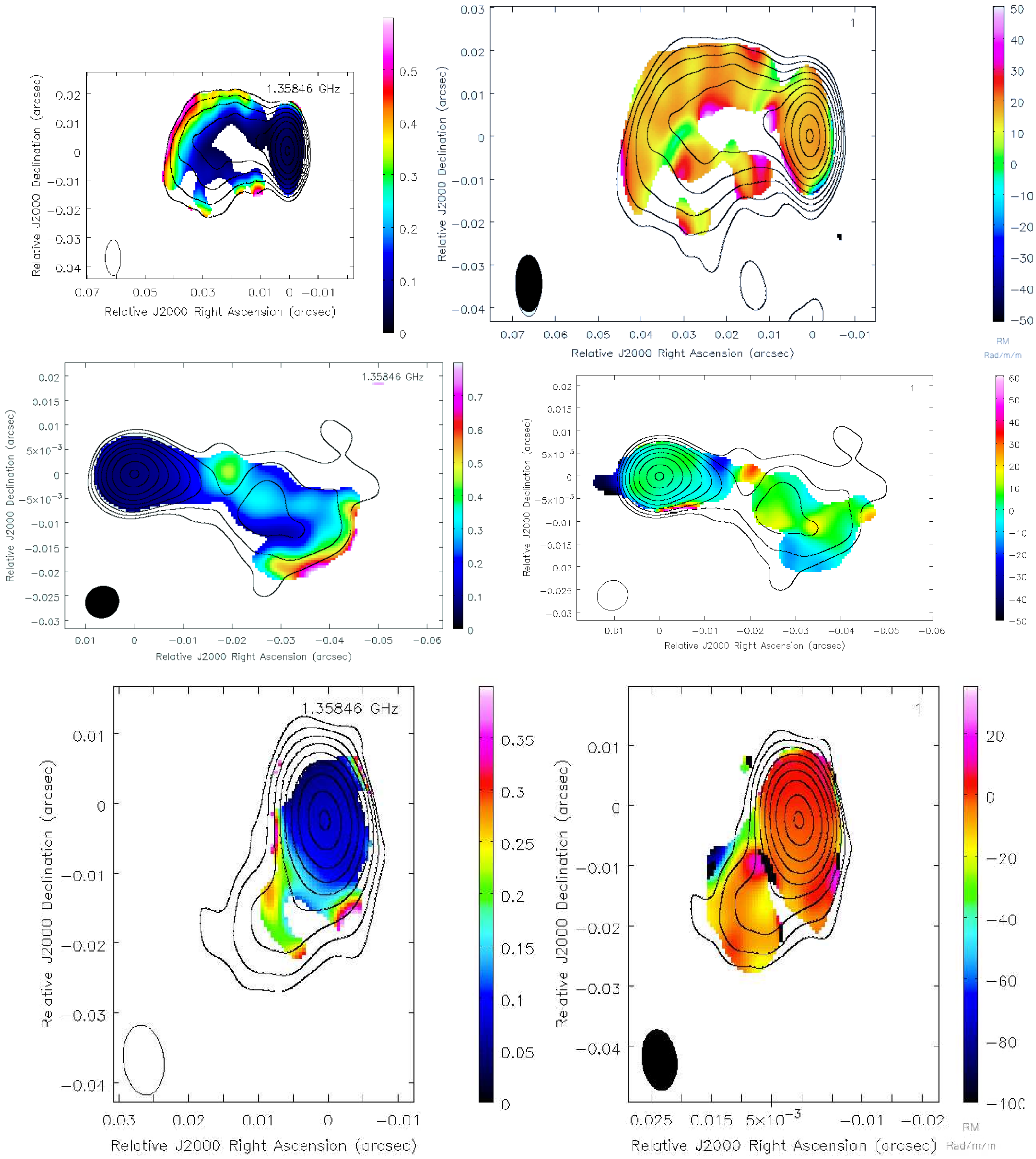

Figure 4: Fractional polarization (left) and rotation measure (right) maps of 0735+178 (top), 1803+784 (middle) and BL-Lac (bottom). The integrated (Galactic) Faraday rotation was removed before making the RM maps, so that the RM distributions correspond to thermal material in the vicinity of the AGNs.

BL Lac. The jet magnetic field is roughly orthogonal to the jet near the jet spine, and shows indications of a longitudinal component near the jet edges (Fig. 3 bottom). Thus, we see tentative evidence for a spine-sheath magnetic-field structure, suggestive of a helical jet magnetic field. The fractional polarization rises slightly toward both edges of the jet (Fig. 4 bottom left); this pattern is shown more clearly in the fractional polarization map obtained by [12]. The distribution of Faraday rotation (Fig. 4 bottom right) is patchy, and does not show any obvious systematic patterns.

4. Conclusions

The intensity and polarization structures of all three BL Lac objects considered here were strikingly similar at epochs separated by about six years (2004 and 2010), showing that the jet morphology and magnetic-field structure are quite stable on scales of tens of parsec. This is broadly consistent with our expectation that the jet structures should evolve more slowly with increasing distance from the central engine. The stability of the polarization structure can also provide a tool for the EVPA calibration of future observations at or near these frequencies. The polarization and fractional polarization structures of 0735+178 and BL Lac both are consistent with the possibility that these jets carry a helical field component, namely evidence for spine-sheath polarization structure and a rise in fractional polarization at the jet edges. It is possible that the longitudinal magnetic field at the upper edge of the 0735+178 jet has also been enhanced by the bending of the jet. The Faraday rotation maps for these two sources do not show any obvious systematic patterns or gradients. The polarization structure of 1803+784 corresponds to an orthogonal magnetic field all along the extended jet. In contrast to 0735+178 and BL Lac, the fractional polarization in 1803+784 is highest near the jet spine. Intriguingly, its RM distribution shows a pattern that seems to trace the pattern shown by the fractional polarization map; this suggests that the RM and fractional polarization patterns are somehow both related to the local magnetic field. Future work on this project will involve analysing the new 1.36-1.66 GHz data for other sources in the Kuhr & Schmidt sample of BL Lac objects obtained in 2010, and comparison with the results of the earlier observations in 2004. It will also be of interest to carry out model-fitting at both epochs for sources with well defined jet components, to try to obtain information about possible component motions on the scales probed by these observations.

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