EVIDENCE FOR TOROIDAL B-FIELD STRUCTURES IN BL LAC OBJECTS

D.C. Gabuzda É. Murray P. Cronin

Department of Physics, University College Cork, Cork, Ireland

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Abstract. If the transverse jet B fields observed in BL Lac objects on parsec scales represent the toroidal component of the jet B fields, this should give rise to rotation-measure gradients across the jets, due to the systematic change in the line-of-sight component of the jet B field. We have found evidence for such rotation-measure gradients in one-third to one-half of the 1 Jy BL Lac objects we have analyzed. We present and discuss these new results, together with some of their implications for our understanding of the parsec-scale jets of AGN.

Key words: Use the key words from the A&A thesaurus

1. INTRODUCTION

BL Lac objects are highly variable, appreciably polarized Active Galactic Nuclei that are observationally similar to radio-loud quasars in many respects, but display systematically weaker optical line emission. VLBI polarization observations of radio-loud BL Lac objects have shown a tendency for the dominant magnetic (B) fields in the parsec-scale jets to be transverse to the local jet direction (Gabuzda, Pushkarev, & Cawthorne 2000 & references therein). This has often been interpreted as evidence for relativistic shocks that enhance the B-field component in the plane of compression, perpendicular to the direction of propagation of the shock (Laing 1980; Hughes, Aller, & Aller 1989).

It has been suggested more recently that the transverse jet B fields of BL Lac objects often correspond to the toroidal B-field component of the jet itself (e.g., Gabuzda 1999, 2003; Gabuzda & Pushkarev 2002). Such fields could come about as a result of the
“winding up” of an initial “seed” field with a significant longitudinal component by the rotation of the central accreting object (e.g. Nakamura, Uchida, & Hirose 2001; Lovelace et al. 2002; Hujeirat et al. 2003; Lynden-Bell 2003; Tsinganos & Bogovalov 2002). It is therefore of interest to identify robust observational tests that can distinguish between transverse $B$ fields due to a toroidal field component and due to shock compression. One possibility is to search for rotation-measure (RM) gradients across the jets, which should arise in the case of a toroidal $B$-field structure due to the systematic change in the line-of-sight magnetic field across the jet. Asada et al. (2002) claim to have detected such a gradient across the VLBI jet of 3C273. We present and discuss here evidence for transverse RM gradients in a number of BL Lac objects.

2. OBSERVATIONS AND RESULTS

Our analysis was based on polarization observations of the 34 BL Lac objects in the complete sample defined by Kühr & Schmidt (1990) carried out in February 1997 (1997.11, 24 sources) and June 1999 (1999.46, six sources) at 6, 4 & 2 cm using the NRAO Very Long Baseline Array. After eliminating sources that did not clearly show polarization outside the core at all three wavelengths, we were left with 22 sources suitable for rotation-measure mapping. A brief description of the data analysis is given by Gabuzda & Murray (2003), and more complete information will be given in a future paper.

We found clear RM gradients transverse to the VLBI jets in six of the objects, probable RM gradients in two more sources, and tentative RM gradients in three more. The figure shows the 6-cm
VLBI I image of 0820+25 with its parsec-scale RM distributions superposed in grey scale. The accompanying plots show the observed polarization position angles, $\chi$, as a function of the observing wavelength squared, $\lambda^2$, for individual locations in the VLBI jet. In all cases, the observed $\chi$ values are in good agreement with the $\lambda^2$ law expected for Faraday rotation.

3. DISCUSSION

It is natural to interpret the observed transverse RM gradients as reflecting a toroidal or helical B field associated with these VLBI jets. In this case, the gradients are due to the systematic change in the line-of-sight B field component across the jet. The fact that we detected transverse RM gradients in one-third to one-half of the sample sources studied suggests that they are quite common in BL Lac objects. In two cases for which RM maps are available at multiple epochs (Mrk501: Croke et al., these proceedings; 1803+784: Zavala & Taylor 2003), the independent RM maps show transverse RM gradients in the same sense, providing evidence that the phenomenon is stable over time scales of one to several years.

A helical B-field could come about via the “winding up” of a seed field threading the central accretion disk by the joint action of the rotation of the accretion disk and the jet outflow (e.g., Nakamura, Uchida, & Hirose 2001; Lovelace et al. 2002; Hujeirat et al. 2003; Lynden-Bell 2003; Tsinganos & Bogovalov 2002). It is intriguing that a B field with a predominant toroidal component would also come about if a non-zero current flows along the jet (e.g., Pariev, Istomin & Beresnyak 2003; Lyutikov 2003). Indeed, if we are seeing a dominant toroidal B-field component, basic physics demands that there must be currents flowing in the region enclosed by the field.

If we view a toroidal or helical B field at $90^\circ$ to the jet axis in the rest frame of the source and the distribution of thermal electrons is approximately uniform, we would expect to observe a rotation measure close to zero along the jet axis (since the line-of-sight B-field component there is close to zero) and RMs of opposite sign on either side of the axis. When the B field is viewed at some other angle to the jet axis, there will still be a systematic gradient in the RM across the jet, however the gradient “peak” will be shifted, and the RM will not necessarily pass through zero. Note that photons emitted at $90^\circ$ to the jet axis in the source frame will be observed in
the observer’s frame to propagate at an angle $\theta = 1/\gamma$ to the jet axis, where $\gamma$ is the Lorentz factor for the jet’s motion.

The results of our search for rotation-measure gradients transverse to the VLBI jets of BL Lac objects yield firm evidence for such gradients in several sources, lending strong support to earlier arguments that the “transverse” $B$ fields that are often observed in these objects are associated with toroidal or helical structure of the intrinsic jet $B$ fields. This underlines the view of these jets as fundamentally electromagnetic structures, and suggests that they may well carry non-zero currents. It also suggests that the jets may be Poynting-flux dominated, which is of cardinal theoretical importance.

A version of this paper with a colour figure can be found at astro-ph/0309668.

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