In Search of Evidence for Toroidal B Fields Associated with the Jets of AGN

Denise C. Gabuzda and Éamonn Murray

Physics Department, University College Cork, Cork, Ireland

Abstract. Evidence is mounting that many of the transverse jet B fields observed in BL Lac objects on parsec scales represent the dominant toroidal component of the intrinsic jet B fields. If this is the case, this may give rise to rotation-measure (RM) 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 RM gradients in several BL Lac objects. We discuss these new results, together with some of their implications for our understanding of the pc-scale jets of AGN.

1. Introduction

BL Lac objects are a subset of Active Galactic Nuclei that are observationally similar to radio-loud quasars in many respects, but display systematically weaker optical line emission. BL Lac objects are also characterised by strong and variable polarisation at ultraviolet through radio wavelengths. The radio emission and much of the higher-frequency emission is almost certainly synchrotron radiation.

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 would come about naturally, for example, as a result of “winding up” of an initial “seed” field with a significant longitudinal component by the rotation of the central accreting object (e.g. Ustyugova et al. 2000; Nakamura, Uchida, & Hirose 2001).

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

We are engaged in an ongoing study of the 34 sources in the complete sample of northern BL Lacertae objects defined by Kühr & Schmidt (1990). As a first step in a search for transverse RM gradients in these sources, we initially concentrated on several sources that seemed to be good candidates for such studies, because their jets were rich in intensity and polarization structure and relatively well resolved in the transverse direction.

The observations considered here were carried out in February 1997 (0820+225, 1652+398 (Mrk501), 1749+701), April 1997 (1219+285, 1308+326, 1803+784), and May 2001 (1749+701, 1823+568) at 6, 4 & 2 cm using the NRAO Very Long Baseline Array. The total intensity ($I$) and linear polarization ($P$) calibration and imaging were done in AIPS using standard techniques. We then made 2, 4 and 6-cm matched-resolution (corresponding to the 6-cm beam) images of the Stokes parameters $I$, $Q$ and $U$ for each of the sources. The $Q$ and $U$ images were combined to make maps of the polarized flux and polarization position angle, $\chi$.

After subtracting the rotation corresponding to the known integrated (assumed to be largely Galactic) rotation measures (Pushkarev 1999) at each wavelength, the $\chi$ maps at each of the three wavelengths were then used to derive the RM distributions using the AIPS task RM.

3. Results

We included 0820+225 in this initial study because its curved jet is well resolved and very rich in $I$ and $P$ structure, extending tens of milliarcseconds from the core (Gabuzda, Pushkarev, & Garnich 2001). Although a comparison of the 4-cm and 6-cm polarization angles indicates the presence of a transverse RM gradient beyond the westward bend of the jet (Fig. 1), we did not attempt to obtain a three-wavelength RM map for this source, since the 2-cm emission was weak beyond the innermost jet.

We found reasonable to good evidence for transverse RM gradients in all the remaining sources except for 1308+326. Fig. 2 shows our RM map of 1652+398 as an example, together with plots of the observed polarization position angles $\chi$ as functions of the square of the observing wavelength, $\lambda^2$, for the two opposite sides and the center of the VLBI jet. These plots show that the $\chi$ values display the linear dependence on $\lambda^2$ expected for Faraday rotation.

4. Discussion

Of the seven sources investigated, we found clear systematic RM gradients transverse to the VLBI jets in 1652+398 and 1823+568, with $\lambda^2$ laws being obeyed well in both cases. Some indications of transverse RM gradients were also found in 1219+285 and 1749+701. A comparison of the 4 cm and 6 cm polarization-angle distributions for 0820+225 shows a clear transverse gradient in the RM
Figure 1. 6-cm total intensity contours of 0820+225 superposed on the two-wavelength rotation-measure distribution obtained by comparing the polarization angles at 4 cm and 6 cm.

Figure 2. 6-cm total intensity contours of 1652+398 superposed on the rotation-measure distribution derived using our 2 cm, 4 cm and 6 cm polarization data. Also shown are plots of the polarization angle versus $\lambda^2$ for opposite sides and the center of the transverse RM gradient.
distribution, but we were not able to verify this on the basis of data obtained at more than two wavelengths. Finally, although our own RM map of 1803+784 did not show convincing evidence for transverse RM gradients, the RM map of this source recently presented by Zavala & Taylor (2003), based on six wavelengths in the VLBA 2 cm and 4 cm bands, clearly shows a transverse RM gradient about 4 mas from the VLBI core. Thus, we consider this initial search for transverse RM gradients to have been successful.

It is natural to interpret the observed transverse RM gradients as reflecting the presence of a toroidal or helical $B$ field associated with these VLBI jets. In this case, the origin of the gradients is the systematic change in the line-of-sight $B$ field component across the jet. The fact that we detected transverse RM gradients in several of the sources considered in this initial study suggests that they may be common in BL Lac objects.

A helical $B$-field structure could come about in a natural way as a consequence of “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., Ustyugova et al. 2000; Nakamura, Uchida, & Hirose 2001). 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., Istomin & Pariev 1996). Indeed, one can turn the problem around, and assert that the presence of a substantial toroidal $B$-field component requires that there be a non-zero current in the jet!

In the simplest case when we are viewing a toroidal or helical $B$ field “from the side” (i.e., 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. This is roughly the behavior shown by the RM distribution in Fig. 2, where the RM is positive on the southwestern side of the jet and negative on the northeastern side of the jet. 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 viewing the jet at $90^\circ$ to its axis in the rest frame of the jet is equivalent to viewing the jet at an angle of $\simeq 1/\gamma$ in the rest frame of the observer, where $\gamma$ is the Lorentz factor of the bulk motion of the jet flow. Thus, since we know the jets of AGN such as BL Lac objects make relatively small angles to the line of sight, of order $\theta \simeq 1/\gamma$, it may be that we should expect to see such relatively symmetrical transverse RM distributions in these sources fairly often.

5. Conclusions

The results of our initial search for rotation-measure gradients transverse to the VLBI jets of BL Lac objects have yielded good evidence for such gradients in several sources. This lends further support to earlier arguments that the “transverse” $B$ fields that characterize the jets of 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.

The occurrence of Faraday rotation requires both a non-zero line-of-sight B-field component and the presence of free electrons in the medium through which the linearly polarized radiation propagates. This complicates searches for systematic behavior of the RM distribution across jet structures, since the density of free electrons is likely to drop off with distance from the core (e.g., Taylor 1998, 2000; Reynolds, Cawthorne, & Gabuzda 2001; Gabuzda & Chernetskii 2003). Higher resolution can be attained by moving toward observations at shorter wavelengths, but such observations will be less sensitive to Faraday rotation, since the rotation measure increases in proportion to $\lambda^2$. It appears that the use of multiple wavelengths within the VLBA 2 cm, 4 cm and 6 cm bands represents the best available approach for such studies in terms of providing both good resolution and good sensitivity to Faraday rotation. We have recently acquired such data for 0820+225, 1219+285, 1652+398, 1749+701, and 1803+784 in order to confirm the presence of transverse RM gradients across their VLBI jets and to study the properties of these gradients in more detail.

Acknowledgments. We would like to thank Patrick Cronin for help in the preparation of the figures presented here.

References

Asada, K. et al. 2002, PASJ, 54, L39
Gabuzda, D. C. 1999, New Astronomy Reviews, 43, 695
Gabuzda, D. C. 2003, The Physics of Relativistic Jets in the CHANDRA and XMM Era, New Astronomy Reviews, in press
Gabuzda, D. C. & Chernetskii, V. A. 2003, MNRAS, 339, 669
Gabuzda, D. C. & Pushkarev, A. B. 2002 in Particles and Fields in Radio Galaxies, R. Laing and K. Blundell, Editors, ASP Conf. Ser., 250, 180
Gabuzda, D. C., Pushkarev, A. B., & Cawthorne, T. V. 2000, MNRAS, 319, 1109
Gabuzda, D. C., Pushkarev, A. B., & Garnich, N. N. 2001, MNRAS, 327, 1
Hughes, P. A., Aller, H. D., & Aller, M. F. 1989, ApJ, 341, 68
Istomin, Ya. N. & Pariev, V. I. 1996, MNRAS, 281, 1
Kühr, H. & Schmidt, G.D. 1990, AJ, 90, 1
Laing, R. 1980, MNRAS, 193, 439
Nakamura, M., Uchida, Y. & Hirose, S. 2001, New Astronomy, 6(2), 61
Pushkarev A.B. 2001, Astronomy Reports, 45, 667; astro-ph/0307176
Reynolds, C.R., Cawthorne, T.V., & Gabuzda, D.C. 2001, MNRAS, 327, 1071
Taylor, G.B. 1998, ApJ, 506, 637
Taylor, G.B. 2000, ApJ, 533, 95
Ustyugova, G. V. et al. 2000, ApJ, 541, L21
Zavala R.T. & Taylor G.B. 2003, ApJ, 589, 126