PROCEEDINGS OF SCIENCE

A Faraday rotation study of parsec-scale jet of BL Lac

Andrei Sokolov*
Centre for Astrophysics, University of Central Lancashire, Preston, UK
E-mail: asokolov@uclan.ac.uk

Tim Cawthorne
Centre for Astrophysics, University of Central Lancashire, Preston, UK
E-mail: tvcawthorne@uclan.ac.uk

Shane O'Sullivan
University College Cork, Cork, Ireland
E-mail: shaneosull@student.ucc.ie

We present the preliminary results of our study of the Faraday rotation structure of the parsec-scale jet of BL Lac. During the years 2002-2004 we obtained seven epochs of VLBA observations of BL Lac at 8, 15, 22, and 43 GHz. We constructed rotation measure maps across the core and jet regions of the radio image for each epoch. The observations were accompanied by phase-referencing on nearby radio sources to enable us to track the position of the core at different epochs. We study variability of the rotation measure and correlations between the rotation measure and other properties of the jet. We find evidence that the Faraday rotation in the core is external, possibly in a sheath, due to a correlation between polarized emission and rotation measure.

From planets to dark energy: the modern radio universe
October 1-5 2007
University of Manchester, Manchester, UK

*Speaker.

PoS(MRU)134

1. Introduction

BL Lac is one of a few active galaxies that appears to exhibit precession of the nozzle of the jet [1]. Due to its relative proximity it offers good prospects for studying properties of the relativistic jet on a parsec-scale observed with VLBI. The results of the phase-referencing study were reported recently in [3]. In the present paper we report the result of the rotation measure study of the parsec-scale jet of BL Lac. For a recent single-epoch study of the rotation measure structure in BL Lac see [2].

The objective of our observing programme was to obtain a sample of high resolution multi-frequency images of BL Lac for several consecutive epochs. This provides a uniform sample that can be used to track the evolution of the Faraday rotation structure. In conjunction with the phase-reference analysis of the core position we can place much more stringent constraints on the origin and properties of Faraday rotation than is usually possible. The implications of the precession and/or shifts in the position of the core along the jet affect the interpretation of the origin of Faraday rotation. The multi-epoch observations also allow us to investigate how the dynamical properties of the jet moderated by shock waves influence the rotation measure structure.

2. Observations and data reduction

The observations were carried out from October 2002 to July 2004. In this period we obtained seven epochs of VLBA observations, with roughly uniform time intervals between the epochs. The long gap between epoch B (Dec 2002) and C (Aug 2003) is due to bad weather during one of the epochs, which had to be discarded. BL Lac was the main observing target. Two nearby radio sources, 2151+431 and 2207+374, were observed for the purpose of phase-referencing. The sources 3C 454.3 and 1823+568, along with BL Lac itself, were used for calibrating D-terms and EVPAs. The phase-reference sources proved too faint to be used as polarization calibrators. All sources were observed in full polarization mode at four frequencies (8, 15, 22, and 43 GHz).

The basic data reduction was performed in AIPS, while imaging and self-calibration was done in Difmap. The D-terms established for BL Lac, 3C 454.3, and 1823+568 were averaged and applied to all sources. The EVPAs were then calibrated for some epochs using the VLA monitoring program at NRAO (http://www.vla.nrao.edu/astro/calib/polar/) as well as the UMRAO database (http://www.astro.lsa.umich.edu/obs/radiotel/). Unfortunately, direct calibration using these monitoring programs was not possible for most epochs due to large mismatch in time and/or polarized flux. A new method based on the D-terms (VLBA Scientific Memo 30 at http://www.vlba.nrao.edu/memos/sci/) was used to derive the corrections for the epochs for which direct calibration was not available.

Rotation measure maps were determined for two cases: 1) by imaging and combining maps at 8, 15, 22, and 43 GHz with the 8 GHz beam, and 2) the maps at 15, 22, 43 GHz with the 15 GHz beam. We used a modified version of the RM procedure for AIPS developed by C. Walker and R. Zavala. Good fits for the rotation angle χ vs λ^2 were obtained for most epochs. The calibration of the phase-reference sources and the relevant results are described in detail in [3].

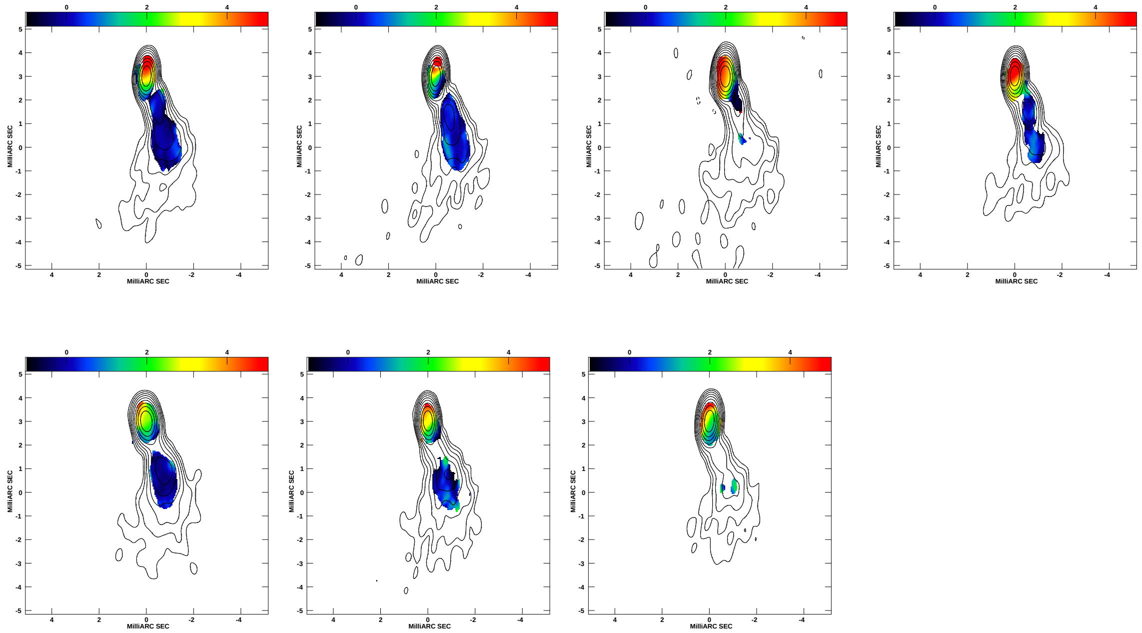

Figure 1: Radio maps of BL Lac at 15 GHz in contours with overlaid rotation measure maps in colour. The limits of the rotation measure scale are $-1000\ \mathrm{rad/m^2}$ and $5000\ \mathrm{rad/m^2}$. The rotation measure values with errors in excess of $500\ \mathrm{rad/m^2}$ have been flagged and are not shown. The rotation measure maps displayed here were determined on the basis of 15, 22, 43 GHz emission. The higher frequency maps were imaged with the 15 GHz beam for the purpose of calculating the rotation measure.

3. Results

The main results are shown in Figure 1. These rotation measure maps indicate high Faraday rotation in the core and relatively little rotation in the jet, typically within $\pm 200\ \mathrm{rad/m^2}$. A strong gradient in the rotation measure across the core is present at all epochs. There is also considerable difference in the orientation of the gradient from epoch to epoch. The structure of the rotation measure across the core region is generally consistent with the structure of polarized emission at higher frequencies, especially at 43 GHz. There is overall consistency with the rotation measure values determined with all four frequencies including 8 GHz. The rotation angle due to Faraday rotation exceeds 90° at 8 GHz in the core region. The fact that the rotation angle exceeds 90° implies that the origin of Faraday rotation is external (see [6]).

The phase-referencing technique that was employed in our observations allows us to determine the absolute position of the radio core on the plane of the sky. These results are shown in Figure 2. The position of the 8 GHz core is shifted downstream with respect to higher frequencies by about 0.2 mas. The most likely explanation of this is that the core component detected at higher frequencies is unresolved at 8 GHz, so that the “core” at 8 GHz actually corresponds to a component further downstream in the jet. The optical depth effects which become significant at lower frequencies should also be taken into account.

Examining the results for the highest frequencies, 22 and 43 GHz, suggests that the position

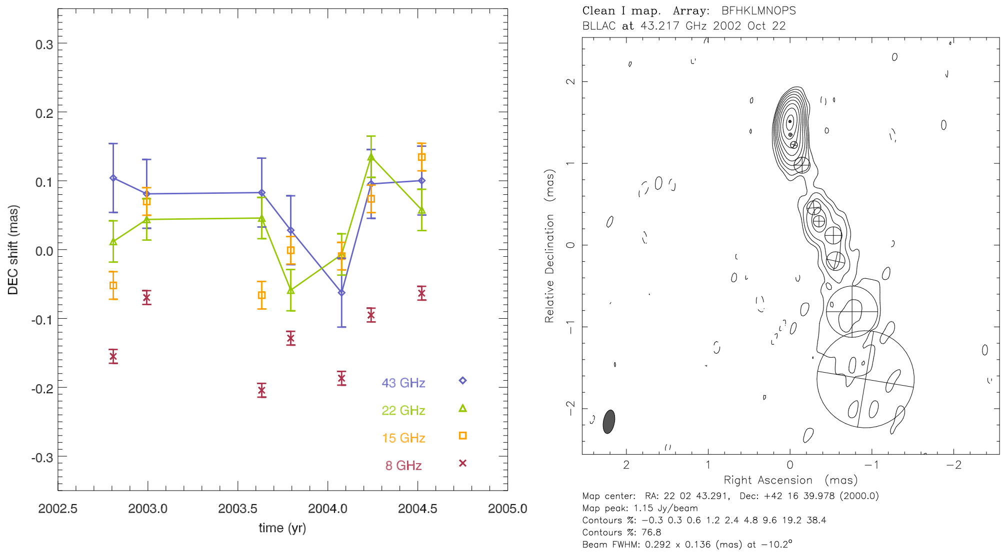

Figure 2: Left: the shift of the core position along declination for seven epochs and all four frequencies. The data points for 22 and 43 GHz are connected by lines to simplify the comparison for these two frequencies. The errors are derived by dividing the beam size along declination by the signal-to-noise ratio of the phase-reference component. The actual errors at 8 GHz are likely to be much higher since the structure of the phase-reference source seen at higher frequencies could not be resolved at 8 GHz. The shift along declination closely represents the shift of the core along the jet (the jet direction at the core is not known but it must be predominantly in the north-south direction as the rest of the parsec-scale jet). Negative values correspond to positions further downstream in the jet. Right: image of BL Lac at 43 GHz for one of the epochs in our experiment. Model components are shown. The core position is represented by the model component next to the peak of emission.

of the core is relatively stable over time, with a significant but temporary shift downstream in the second half of 2003. This downstream shift is likely to be caused by a flare that occurred in BL Lac in 2003. If the core at higher frequencies corresponds to a standing feature in the jet, it is plausible to assume that the flares are caused by a collision between a shock wave moving downstream in the jet and the standing structure corresponding to the core. This collision is expected to drag the standing feature downstream, with the original position of the standing feature being regained some time after the shock passes through (see [4]). There appears to be no correlation between this dramatic shift of the core's position and the rotation measure.

The relative stability of the core position over the other epochs perhaps indicates that variability in the rotation measure could not be caused by changing position of the radio core. This casts a shadow over the usual interpretation of the origin of the Faraday rotation in blazars. According to the usual interpretation the effect is caused by changes in the position of the core along the jet which is submerged in the stratified medium surrounding the nucleus on a large scale, such as the broad emission line region. This might explain why there is a strong gradient in the rotation measure along the core region and relatively little rotation further down the jet. This model, however, does not explain the changes in the rotation measure from epoch to epoch. On the other hand, there is a correlation between the rotation measure and polarized flux (see Figure 3). Apparently the

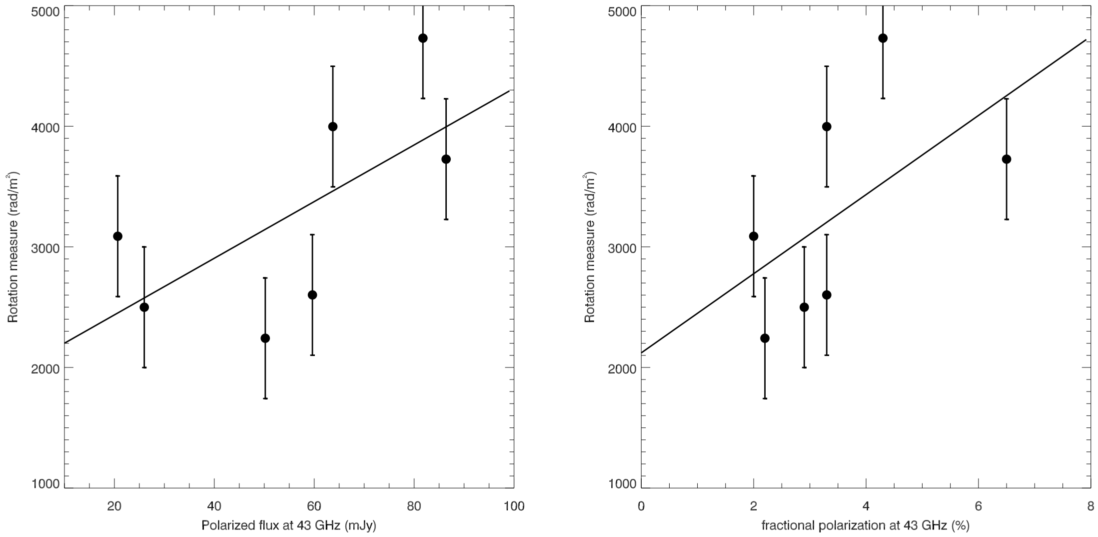

Figure 3: Rotation measure vs polarized flux at 43 GHz (left) and rotation measure vs fractional polarization at 43 GHz (right). All values are taken at position of the phase reference centre, which is roughly coincident with the position of the peak of total and polarized emission at higher frequencies. The error-bars correspond to 500 $\mathrm{rad}/\mathrm{m}^2$. Despite large errors there is a reasonable correlation betweeen polarized flux and rotation measure. Straight lines correspond to the least squares fit.

same mechanism that causes an increase in polarized flux also affects the rotation measure.

One of the explanations that can be offered is as follows. The flares seen in polarized flux are caused by the shock waves moving downstream in the jet. These shocks compress the medium in the jet and amplify the magnetic field. In the model of a stratified jet consisting of a fast spine and slow sheath (see [5]), the medium and the magnetic field in the sheath must be affected by the moving shock as well. The correlation arises naturally if the Faraday rotation is caused at least partially in the sheath surrounding the jet.

References

[1] Stirling, A. M. et al., 2003, MNRAS, 341, 405

[2] O'Sullivan, S. P., Gabuzda, D. C., 2007, arXiv:0710.0128

[3] Sokolov, A., Cawthorne, T., 2007, arXiv:0711.3564

[4] Gomez, J. L. et al., 1997, ApJL, 482, L33

[5] Laing, R. A., 1996, ASP Conf. Series, 100, 241

[6] Burn, B., 1966, MNRAS, 133, 67