PROCEEDINGS OF SCIENCE

Multi-Epoch Observations of BL Lac Objects on Decaparsec Scales.

Redmond Hallahan[*][†]
University College Cork
E-mail: rhallahan@mars.ucc.ie

Denise Gabuzda
University College Cork
E-mail: gabuzda@physics.ucc.ie

We present 18cm Very Long Baseline Array (VLBA) polarisation observations of the 4 BL Lac objects 0735+178, 0954+658, 1803+784 and BL Lac at two epochs $4\frac{1}{2}$ years apart (Jul 1999 and Jan 2004). These results are part of an ongoing analysis of 18cm VLBA observations of the 34 1–Jy BL Lac objects in the complete sample defined by Kühr & Schmidt[4]. The 2004 observations were made at four distinct wavelengths between 18 and 22cm, allowing for the investigation of the intrinsic Faraday rotation in each source. The 4 sources each display a spine-sheath polarisation structure in the VLBI jet, consistent with the presence of helical magnetic (**B**) fields [2]. The jet morphology, polarisation structure and degree of linear polarisation are compared for the two epochs and shown to be very stable on the scales probed by these observations. Some rotation measure (RM) maps from the 2004 data display transverse gradients in the inner jet, interpreted as further evidence for the presence of helical **B** fields in the jet. The fractional polarisation maps also display gradients increasing away from the core and towards the jet edges, again consistent with helical jet **B** fields [5].

Workshop on Blazar Variability across the Electromagnetic Spectrum
April 22-25, 2008
Palaiseau, France

[*]Speaker.
[†]supported by the Research Frontiers Program of Science Foundation Ireland.

PoS(BLAZARS2008)040

1. Introduction

The first BL Lac object was discovered in 1929 and like many Active Galactic Nuclei (AGN), was originally classified as a faint variable star. They are a subclass of the Blazar class, together with optically violent variable quasars (OVV's), and are believed to have FRI host galaxies. They are distinguished by an absence of strong optical emission lines and often strong variability on parsec scales. In the AGN unification paradigm, BL Lac objects (and other compact radio loud AGN) eject bipolar jets with relativistic velocities from a central engine, thought to consist of a black hole and accretion disk. Blazars emit over many orders of magnitude of the EM spectrum, with the bulk of the emission attributed to synchrotron radiation emitted by electrons accelerated to relativistic speeds. Due to the high velocity of the emitting region, radiation emitted isotropically in the rest frame of the electrons appears to be confined to a cone of angle $\frac{1}{\Gamma}$ in the observer frame, where Γ is the Bulk Lorentz factor, a measure of the velocity of the jet relative to the speed of light. Therefore one jet is 'boosted' towards the observer, while the other appears diminished or obscured completely. In BL Lacs the jets are believed to be aligned close to our line of sight, leading to strong beaming and high Doppler factors. At larger scales the jets are slowed due to interaction with the external medium and appear less variable than on parsec scales, which probe closest to the central engine. Synchrotron radiation is linearly polarised and by measuring the degree of polarisation, constraints may be placed on the degree of ordering of the magnetic field in the emitting region. The observed synchrotron radiation usually follows a power law spectrum in optically thin regions, $S \propto \nu^{\alpha}$, where α is the spectral index. This turns over at lower frequencies due to synchrotron self absorption (the plasma becomes opaque to it's own radiation). The jets of BL Lac objects display a number of properties that are consistent with their jets having helical **B** fields, including gradients of the Faraday rotation measure (RM) across the jet, which is due to the systematic change in the line–of–sight component of the helical field [2, 3, 6].

Relatively few Very Long Baseline Interferometry (VLBI) polarization observations of AGN have been carried out at 18 cm. Such observations provide information about intermediate scales between the more common VLA (typically ∼kiloparsec) and shorter-wavelength VLBA (∼ parsec) scales. Thus, 18cm VLBA observations link these two scales, extending our picture of VLBI jets. Our sample consists of the 34 BL Lacs from the Kühr & Schmidt sample [4]; we present results for four objects here. Our observations sometimes display surprisingly different structure at these low frequencies when compared to higher frequency VLBI or VLA images.

2. Observations and Analysis

The images considered here were made from 18cm VLBA data obtained on December 13 1999 and January 16–17 2004. The 2004 observations were made at 4 distinct wavelengths between 18 and 22 cm. We also have 13cm data for the 1999 epoch, currently being analysed. The data were calibrated and imaged in the NRAO AIPS. package using standard techniques, with Los Alamos as the reference antenna. Natural weighting was used where extended emission was observed. This had the effect of increasing the beam size and reducing spurious features near the noise levels.

The D–term (instrumental) calibration for the 2004 data was carried out using the compact sources 0745+241 for 16 January and 0851+202 for January 17, solving simultaneously for the source and antenna polarisation. The D–term calibration for the 1999 data was performed using the radio galaxy 3C84, which is unpolarised at 18cm. The electric vector position angle (EVPA) calibration for the 2004 data was carried out using VLA integrated polarisation measurements for 0851+202 (OJ287) made ∼1 month after the VLBA observations. Simultaneous VLA observations were not available for the 1999 data so the same EVPA calibration was initially applied. Note that EVPA calibration for a given reference antenna is typically stable over intervals as long as several years (see the MOJAVE[1] website [9]).The polarisation images for the 4 sources were very similar to the 2004 images, but showed a clear systematic offset of 15° in the EVPAs of optically thin jet regions, consistent for all 4 sources. The EVPA calibration for the 1999 data was corrected in accordance with this 15° offset.

2.1 Faraday Rotation

When analysing 18cm data, it is essential to take into account Faraday rotation of the plane of linear polarisation, which occurs when electromagnetic radiation passes through a magnetised medium. It is characterised by a linear relationship between the EVPA rotation and the square of the observing wavelength, with the coefficient of proportionality called the Rotation Measure (RM). The rotation is given by $\Delta\chi \propto \lambda^2 \int N_e B_{||} dl$, i.e., the integral of the line of sight magnetic field, $B_{||}$, times the electron density, N_e, along the line of sight. There are two sources of this rotation that must be considered separately: Faraday rotation occurring in or near the AGN and Faraday rotation occurring somewhere between the source and observer. The latter is usually dominated by the interstellar medium of our own Galaxy. The EVPAs for all sources were corrected for this Galactic Faraday rotation using the integrated RM values of Pushkarev [8]. No correction was made to 0735+178, whose integrated RM is zero within the errors. Any remaining Faraday rotation we assumed to be intrinsic to the source.

3. Results and Discussions

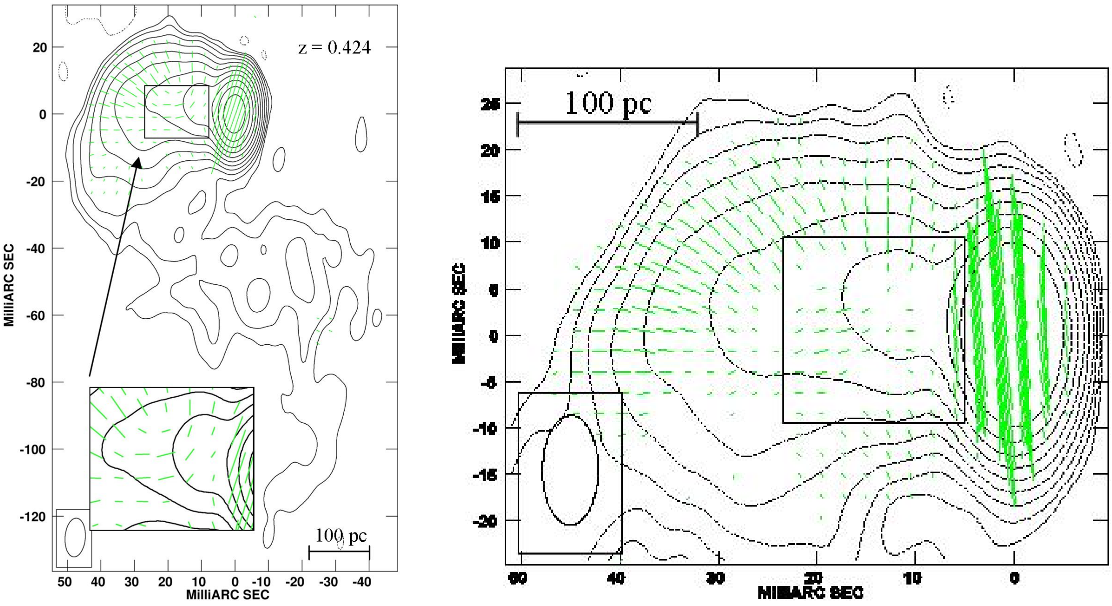
We find that the decaparsec scale jets of BL Lac objects are highly stable structures, displaying very little variation outside of the VLBI core over the course of our ∼ 4 year observational period. Changes in the core EVPAs of all objects were observed, as is to be expected for this partially optically thick and unresolved region, where the effect of emerging components may alter both the observed EVPA and intensity. The jet polarisation of all 4 sources shows signs of a spine–sheath structure, with a central region of transverse B field surrounded by regions of longitudinal B field, consistent with the jets having helical fields [1, 5]. Recall that the observed EVPA is orthogonal to **B** in optically thin regions such as the VLBI jet and parallel to **B** in optically thick regions. Distance measurements for all sources were calculated using the redshifts indicated below, taken from [8].

3.1 0735+178 (z = 0.424)

This was the only one of the 4 objects to show appreciable changes in jet polarisation between our two epochs (see boxes in Fig. 1). The observed change in polarisation is consistent with a

[1]**M**onitoring **O**f **J**ets in **A**ctive galactic nuclei with **VLBA** **E**xperiments is a long–term program to monitor jets associated with AGN in the northern sky.

PoS(BLAZARS2008)040



(a) (b)

Figure 1: 0735+178: 1999 (a) and 2004 (b) intensity maps with EVPA vectors superposed, showing that slight changes in polarisation can occur on decaparsec scales.

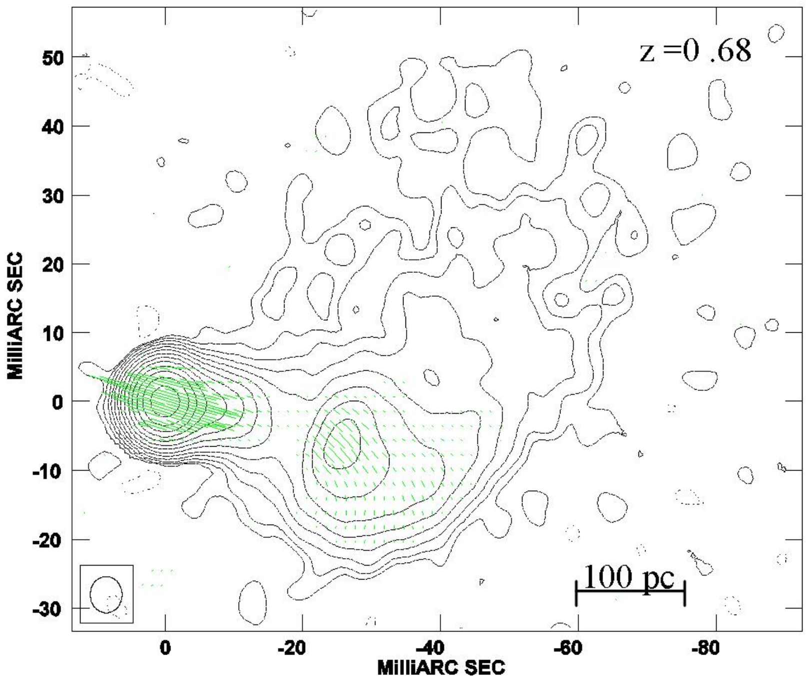


Figure 2: 1803+784: 1999 Intensity map with EVPA vectors superposed. The dominant jet **B** field is transverse.

decrease in the strength of a longitudinal **B**–field component (or conversely, an increase in the strength of a transverse **B**–field component) roughly 10 mas from the core. The degree of polarisation increases towards the northern side of the jet (Fig. 3(c)). The jet extends to over 120 mas from the core, ∼0.6kpc.

3.2 0954+658 (z = 0.368)

This object has a compact polarisation structure at these scales, but shows a nice RM gradient across the inner jet (Fig. 3(a), 3(b)), confirming the results of O'Sullivan & Gabuzda [7] and Mahmud & Gabuzda [6]. The jet polarisation increases toward the northern edge of the jet.

3.3 1803+784 (z = 0.68)

The dominant jet magnetic field is transverse throughout the jet, with some indication of a longitudinal field at the southern edge of the jet (Fig. 2). The degree of polarisation in the jet increases with both distance from the core and proximity to the edge of the jet.

3.4 BL Lac (z = 0.068)

A clear sheath–like polarisation structure can be seen, with the degree of polarisation increasing toward the jet edges (Fig. 3(d)). An area of low polarisation in the jet appears to be due to a superposition of orthogonal "spine" and "sheath" fields, combining to produce depolarisation.

4. Summary and Future Work

The rich intensity and polarisation structures in the images presented here are fairly typical of the other BL Lacs in the Kühr & Scmidt 1Jy sample [4]. The four objects display polarisation structure consistent with helical jet **B** fields, in particular spine–sheath structures with orthogonal **B** field near the jet ridge line and longitudinal near the jet edges with respect to jet direction.

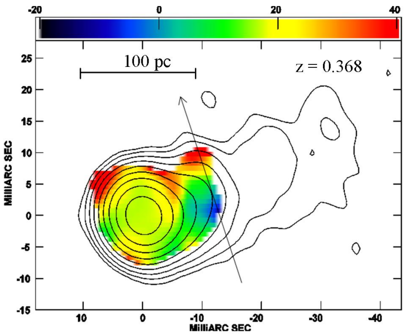
Data are also available for December 1999 at 13cm. Reduction of these data will enable us to construct tentative 2–wavelength RM maps for this epoch, making it possible to study the evolution of the distribution of thermal plasma and magnetic fields in the VLBI jets. Data reduction for the complete sample for January 2004 is now complete and we are proceeding with our analysis of the polarisation and rotation measure maps for all sources.

The transverse RM gradient observed in 0954+658 is a tell–tale sign of a helical jet B-field: the gradient in the Faraday rotation is due to the systematic change in the line–of–sight **B**–field across the jet. Such transverse RM gradients have also been observed for a number of other BL Lac objects at 2cm–6cm [2, 3, 6].

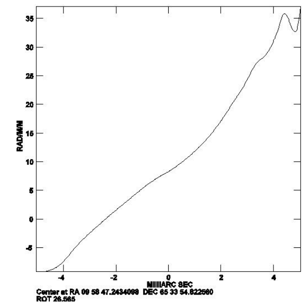
This publication has emanated from research supported by the Research Frontiers Program of Science Foundation Ireland. We thank P. Veres for his work on the initial calibration of the 2004 data. The National Radio Astronomy Observatory is operated by Associated Universities Inc.

References

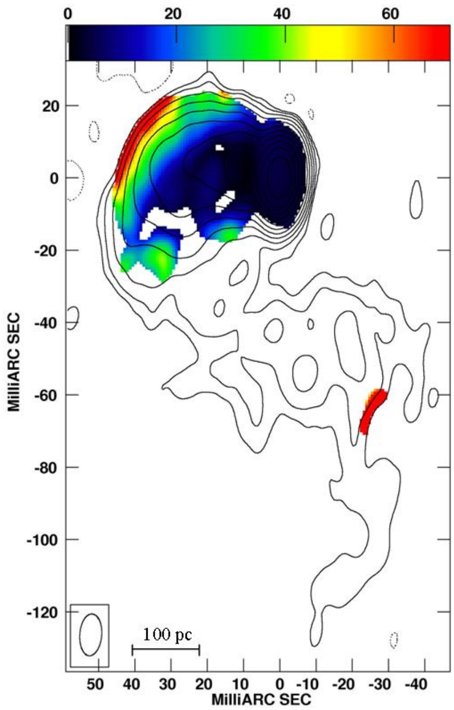
[1] Gabuzda, D. C., 2006, Proc. 8^{th} EVN Symposium, Ed. A. Marecki, http://pos.sissa.it//archive/conferences/036/011/8thEVN_011.pdf



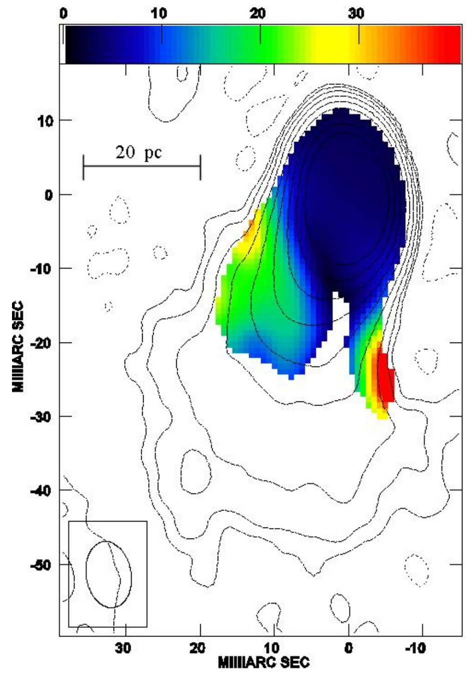
(a) **0954+658:** 2004 RM map scaled from -20 to 40 Rad / M^2, displaying a clear gradient across the inner jet.



(b) **0954+658:** 2004, Slice across the gradient shown in figure (a), see arrow.



(c) **0735+178:** 1999 fractional polarisation map scaled from 0 to 70%.



(d) **BL Lac:** 1999 fractional polarisation map scaled from 0 to 40%.

Figure 3: Gradients in the rotation measure and fractional polarisation maps are consistent with the presence of helical magnetic fields in the jets of AGN.[1, 5]

[2] Gabuzda, D. C., Murray, E. & Cronin, P. 2004, MNRAS, 351, L89

[3] Gabuzda, D. C., Vitrishchak, V. M., Mahmud, M. & O'Sullivan, S. P. 2008, MNRAS, 384, 1003

[4] Kühr, H. & Schmidt, G. D. 1990, AJ, 99,1

[5] Lyutikov, M.; Pariev, V. I. & Gabuzda, D. C. 2005, MNRAS, 360, 869

[6] Mahmud, M. & Gabuzda, D. C. 2008, in "Extragalactic Jets: Theory & Observation from Radio to Gamma Rays", Ed. Travis A. Rector & David S. De Young, ASP Conf. Series, 386, p494

[7] O'Sullivan, S. P. & Gabuzda D. C. 2008, IJMPD, in press

[8] Pushkarev, A. 2001, Astron. Rep., 45, 667

[9] M.O.J.A.V.E Program website, http://www.physics.purdue.edu/MOJAVE/