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Using Faraday rotation sign-reversals to study magnetic fields in AGN jets

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Most of detected variations in parsec-scale Faraday rotation in AGN have been associated with enhancement of the observed Faraday rotation measure (RM) in the region of the VLBI core, consistent with an increase in the density of free electrons with approach toward the centre of activity. Many of our multi-wavelength VLBA polarisation observations of 1 Jy BL Lac objects show this tendency, and also display higher RMs for the 7-mm/1.3-cm/2-cm cores than for the 2-cm/3.6-cm/6-cm cores, consistent with higher free electron densities being present on the smaller scales probed by the short-wavelength observations. However, in several sources, the signs of the core RMs determined from 7-mm to 2-cm and 2-cm to 6-cm data obtained at different epochs are different. This indicates that the orientation of the line-of-sight magnetic field associated with the Faraday rotation changes with either time or distance from the centre of activity. One possibility is that these RM sign reversals correspond to places where the helical magnetic field surrounding the jet undergoes a change in helicity due to a kink or reconnection. Another possibility is that a bend in the inner jet changes the side of the helical field with dominant polarisation, hence producing RMs with different signs in different lengths of the jet.

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1. Introduction

1.1 BL Lac objects

BL Lac objects are a subclass of Active Galactic Nuclei (AGN) that are highly variable in total intensity and polarisation. In many respects they are observationally similar to radio-loud quasars, but display systematically weaker optical line emission, whose origin is not clear. With the exception of the weakness of the optical line emission, these properties are shared by optically violently variable (OVV) quasars. Rapidly variable BL Lac objects and OVV quasars are sometimes referred to collectively as "blazars". In the unified model of AGN, blazars are thought to have relativistically moving jets pointing roughly towards us. Therefore, due to aberration, photons emitted at 90° to the jet axis in the source frame will be observed at an angle of $1/\Gamma$ to the jet axis in the observer's frame, where Γ is the jet Lorentz factor, so that we actually obtain a roughly side-on view of the jet. On parsec scales, we usually observe a one-sided core-jet structure, due to Doppler boosting of the jet coming towards us and Doppler de-boosting of the jet moving away from us.

1.2 Faraday rotation

Multi-wavelength VLBA polarisation observations can be used to study Faraday rotation in the immediate vicinity of AGN. Faraday rotation, also known as the Faraday effect, is defined as the rotation of the plane of polarisation due to the propagation of electromagnetic radiation through a magnetised plasma (Burn 1966). The intrinsic polarisation angle χ_0 is related to the observed polarisation angle χ_{obs} by the formula

$$\chi_{obs} = \chi_0 + RM\lambda^2 \tag{1.1}$$

where λ is the observed wavelength. Faraday rotation is thus identified through the linear relationship between χ and λ^2, where the slope of the line is the rotation measure (RM), defined by the formula

$$RM = \frac{e^3}{2\pi m^2 c^4} \int n_e \vec{\mathbf{B}}.\mathbf{d}\vec{\mathbf{l}} \tag{1.2}$$

which depends linearly on the electron density n_e and the integrated line-of-sight (LoS) magnetic (B) field component along the path length dl through the plasma.

1.3 Use of the rotation measure

Previous studies of parsec-scale Faraday rotation (Taylor 1998, 2000; Gabuzda, Pushkarev & Garnich 2001; Reynolds, Cawthorne & Gabuzda 2001; Gabuzda & Chernetskii 2003; Zavala & Taylor 2003, 2004) have mainly focused on enhancements in magnitude of the RM in the VLBI core compared to values in the VLBI jet. These enhancements can be interpreted as reflecting an increase in the density of free electrons with approach toward the central engine. Although it has not been considered in most studies, the sign of the RM is very useful because it indicates whether the LoS B-field is orientated towards the Earth (positive RM) or away from Earth (negative RM). There are several examples of RM gradients across the VLBI jet that have been found recently (Asada et al. 2002, Gabuzda et al. 2004, Zavala & Taylor 2005), with positive and negative RMs on opposite sides of the jets in some cases. These transverse RM gradients provide excellent evidence for the presence of helical magnetic fields around the jets of these AGN (Mahmud & Gabuzda, these proceedings).

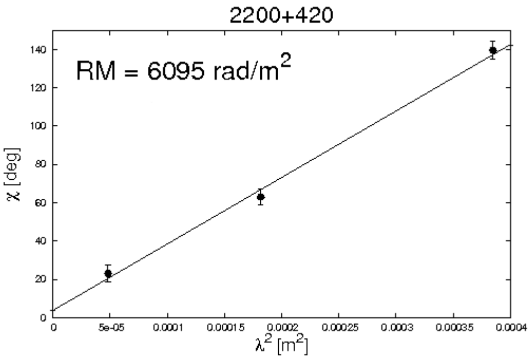

Figure 1: BL Lac core RM from 7-mm to 2-cm (Gabuzda et al. 2006)

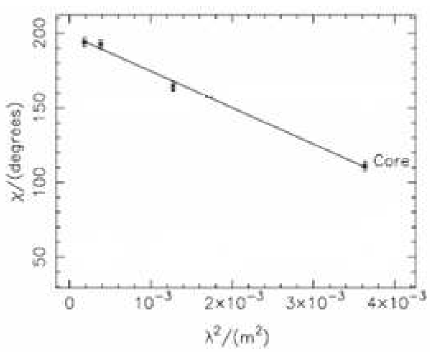

Figure 2: BL Lac core RM from 2-cm to 6-cm (Reynolds et al. 2001)

2. Discovery of core-RM sign reversals in AGN

We have recently published the results of VLBA polarisation observations of 12 AGN obtained simultaneously at 7 mm, 1.3 cm and 2 cm (Gabuzda et al. 2006), including parsec-scale RM maps for 6 of these sources. In line with previous observations, we found an enhancement in the magnitude of the RM in the core compared to the RM in the jet in many cases. This is consistent with an increase in the density of free electrons towards the centre of the AGN. We also observed that, in most cases, the core RMs measured at shorter wavelengths have larger magnitudes but the same sign as those measured at longer wavelengths, consistent with the higher resolution observations probing scales closer to the centre of activity of the AGN. However, we have also discovered several sources whose VLBI core components display RMs with *different* signs in our 7-mm to 2-cm maps and in the 1.3-cm to 6-cm results of Reynolds et al. 2001 and the 2-cm to 6-cm results of Gabuzda, Pushkarev and Bezrukovs (in preparation).[1]

Sources	Core RM (7-mm to 2-cm)	Core RM (2-cm to 6-cm)
0954+658	-740	+160
1418+546	+410	-960 or +480
1749+096	-675	+255
2007+777	+780	-200
2200+420	+6095	-430

Table 1: All RM values in units of rad/m^2

Table 1 shows four sources with unambiguous RM sign reversals. The most striking example is the core RM of BL Lac (2200+420), showing a very large positive RM in the 7-mm to 2-cm measurements and a moderate negative RM from 2-cm to 6-cm measurements. Fig.1 displays the VLBI core RM plot for BL Lac (2200+420) obtained by Gabuzda et al. 2006, yielding a core RM of $+6,095$ rad/m^2. Mutel et al. 2005 have also recently reported high core RMs for BL Lac, with values of up to $+8,200$ rad/m^2 being observed over nine epochs from 1998 to 2002. Fig.2 is from

[1] Data obtained in Feb 1997 and reduced in AIPS using standard techniques. For details see Gabuzda et al. 2001

Reynolds et al. 2001 giving a core RM of -430 rad/m^2 derived from observations at 1.3 cm, 2 cm, 3.6 cm and 6 cm. In both cases, the observed angles clearly display the λ^2 dependence expected for Faraday rotation but both the magnitude and the sign of the inferred RMs are different. The sources 0954+658, 1156+295, 1749+096 & 2007+777 all display similar behaviour.

The case of 1418+546 is unclear; depending on how we interpret the 2-cm to 6-cm polarisation angles, the core RM could be positive or negative. The black squares shown in Fig.3 represent the directly observed χ values and they clearly do not display a linear dependence on λ^2. However, when π is subtracted from $\chi = 88^\circ$ at 6 cm (represented by the hollow diamond) a good linear relationship is obtained giving a RM of -960 rad/m^2, signified by the dotted line. The value of $+480$ rad/m^2 is obtained if the polarisation angle at 2 cm is rotated by 90°, based on the hypothesis that the optically thick-thin transition occurred between 2 cm and 3.6 cm. The corrected polarisation angle is signified by the hollow circle, and the linear fit shown by the solid line produces the RM of $+480$ rad/m^2.

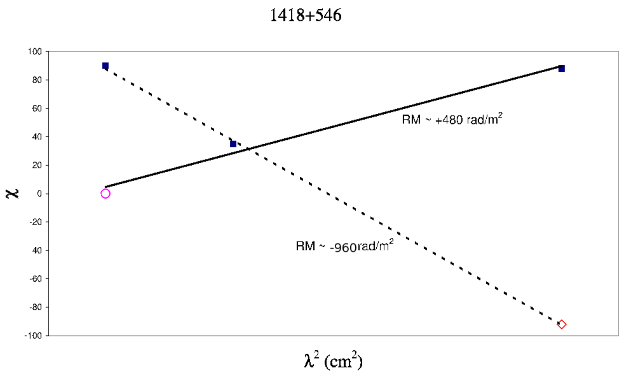

Figure 3: 1418+546 possible rotation measures

3. Discussion

There are two basic possibilities as to why the RM in the core region has different signs in the different datasets. The orientation of the LoS B-field in the core region must change with either (i) distance from the centre of activity or (ii) time.

3.1 Changes of the LoS B-field with distance from centre of activity

Based on growing evidence that the jets of many AGN have helical B-fields (Asada et al. 2002, Gabuzda et al. 2004, Zavala & Taylor 2005, Pushkarev et al. 2005, Mahmud & Gabuzda, these proceedings), we will consider ways in which a helical jet B-field geometry could give rise to different directions for the dominant LoS B-field in different stretches of inner jet.

3.1.1 Example 1: Bending of a jet with a helical B-field

As shown in Fig.4 (top), if a helical magnetic field surrounding a jet is viewed at 90° to the jet axis in the jet rest frame, then the observed polarisation will be equally strong on both sides of the

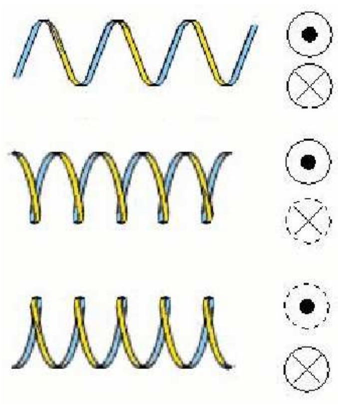

Figure 4: Helical field geometries

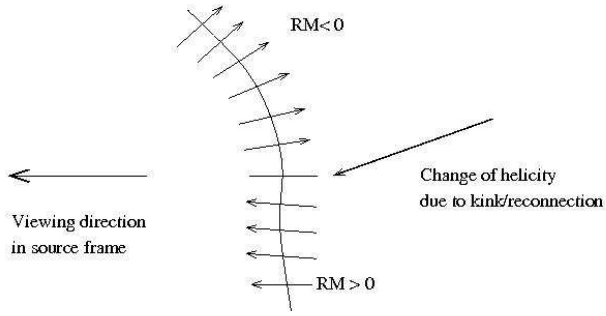

Figure 5: Change of helicity

jet. The solid and dashed circles to the right indicate the relative strength of the polarisations on the two sides of the jet. A black dot indicates that the LoS magnetic field is pointing towards us and a cross pointing away from us. If we view the jet at an angle θ different from 90° in the jet rest frame, the polarisation on one side will become stronger; which side has stronger polarisation will depend on whether we view the jet at θ slightly less than or greater than 90°, shown in Fig.4 (middle) & Fig.4 (bottom). Thus, if we are viewing the jet at roughly 90° in the jet rest frame and the jet bends away from us we will observe dominant polarisation from one side of the jet, producing a positive RM; if the jet bends towards us, we will observe dominant polarisation from the other side of the jet, producing a negative RM. Therefore, a change in the side of the jet with dominant polarisation due to a bend in the jet can yield changes in the sign of the observed RM in different lengths of jet. If all this is occurring on scales slightly smaller than the observed VLBI core, this could be manifest as core RMs with different signs in observations at different frequencies. The lower frequency observations have lower resolution and are also more sensitive to optically thin regions further from the centre of activity but contained within the observed VLBI core.

3.1.2 Example 2: Change in Helicity

In this case, we imagine we are viewing the jet at an angle slightly different from 90° to the jet axis in the jet rest frame, so that the polarisation from one side dominates. The direction of the dominant LoS B-field then changes because of a change in helicity, possibly due to a kink or reconnection in the helical B-field along the jet. In Fig.5 the top arrows indicate that the dominant LoS magnetic field is pointing away from us, hence a negative RM would be observed, whereas the arrows in the bottom half of the diagram, after the change in helicity, indicate that the LoS magnetic field is pointing towards us, hence a positive RM would be observed. Therefore, a change in the sign of the observed core RM could again be found in observations at different frequencies.

3.2 New observations

As stated previously, the orientation of the LoS B-field in the core region must change with either (i) distance from the centre of activity or (ii) time. A single set of simultaneous VLBA polarisation observations at 7 mm, 1.3 cm, 2 cm, 3.6 cm and 6 cm, obtained recently and awaiting reduction, will be able to discriminate between (i) and (ii), because if core RM sign reversals are detected for these 7-mm to 2-cm and 2-cm to 6-cm data it will mean that the sign reversals are not due to changes between observing epochs. There were observations at two wavelengths at each of the 2 cm, 3.6 cm and 6 cm bands. This is very important because it will enable us to make several RM maps providing resolutions on a range of different scales, each with a minimum of four wavelengths. This provides us with the ability to map out the RM distribution and its sign in the core region and out along the inner jet. Therefore, we can determine whether the sign of the RM in the core region is the same on all scales or if it changes at some points along the inner jet.

4. Conclusions - 3-D Structure of Jet

The presence of RM sign reversals in the innermost VLBI jets can yield information about the three dimensional path of a curved jet through space and we have obtained a set of VLBA polarisation data at 8 wavelengths from 7-mm to 6-cm to investigate this possibility. The interpretation of the RM sign changes will be aided by additional information provided by possible transverse RM gradients, the projected path of the jet in the plane of the sky, the distribution of linear polarisation and the distribution of spectral index. Theoretically, changes in the sign of the RM with distance from the centre of activity are possible, therefore, we should not neglect the opportunity to use the sign of the RM to investigate the direction of the LoS magnetic field.

References

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