The Core-Region Rotation Measures of Active Galactic Nuclei and Unified Schemes

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Abstract

It has been known since the late 1990s that the parsec-scale cores of Active Galactic Nuclei (AGN) often display higher degrees of Faraday rotation than the parsec-scale jets. The work of Zavala and Taylor (2004) suggested that the core Faraday rotation measures of BL Lac objects tend to be lower than those of quasars, but the number of BL Lac objects in their sample was small, hindering definitive conclusions. We present parsec-scale core rotation measures for approximately 20 radio-loud BL Lac objects, increasing the number of such measurements by about a factor of three. These data demonstrate that the core rotation measures of BL Lac objects are, indeed, systematically lower than those of quasars. This reflects a lower density of free thermal electrons in the core regions of BL Lac objects, presumably due either to a reduced density of matter that can be ionised, or a reduced flux of ionising radiation from the region of the central accretion disk, or both.

Introduction

The physical relationships between various observational classes of Active Galactic Nuclei (AGN) has been a subject of discussion for many years. One example is the relationship between various types of core-dominated radio-loud AGN, such as flat-spectrum radio quasars (FSRQs), which have strong optical emission lines) and BL Lac objects (BLs, with weak optical emission lines). It is generally believed that the FSRQs and BLs are FRII and FRI radio sources, respectively, whose jets are viewed at small angles to the line of sight (e.g. Urry & Padovani (1995). This is consistent with the fact that, on average, FRII radio galaxies have higher optical line luminosities than do FRI radio galaxies of comparable radio luminosity (Baum, Zirbel & O'Dea 1995). This indicates that the intensity of the optical lines is an internal factor that depends somehow on the properties of the central engine.

Another question is the physical relationship between BL Lac objects discovered in radio surveys and X-ray surveys. Padovani & Giommi (1995) proposed to divide the general population of BLs according to the ratio of the X-ray and radio fluxes, parametrised by the radio to optical spectral index α_{ro}, which is strongly correlated with the frequency of the synchrotron-emission peak. This effectively divides the overall population of BL Lac objects into HBLs (high energy cutoff BLs) and LBLs (low energy cutoff BLs).

Based on estimates of the masses of the central supermassive black holes of samples of radio quasars and BL Lac objects together with various other results, Wang, Ho & Staubert (2003) proposed that the sequence FSRQ LBL HBL (and at larger angles of the jets to the line of sight, FRII FRI) can be understood as reflecting a change in the state of the accretion disk from standard, optically thick, geometrically thin disks in FSRQs to optically thin, advection-dominated accretion flows in HBLs. In this scheme for the unification of radio-loud AGN, two main parameters determine the observational properties of these AGN: the accretion rate (accretion regime) and (to a lesser extent) the angle of the jet to the line of sight.

We consider here the parsec-scale core Faraday rotation measures of FSRQs and BLs as a diagnostic of the relative abundances of ionised gas in the core regions of various AGN, which can provide important information about the accretion regimes acting in these sources.

Observations & Reduction

Multi-frequency VLBA polarisation observations of all 34 objects from the sample of 1-Jy Northern radio-loud BL Lac objects (nearly all LBLs) defined by Kühr & Schmidt (1990) were obtained at 5, 8.4 and 15 GHz in February 1997, April 1997 or June 1999. These data were calibrated and imaged in the NRAO AIPS package following standard techniques; previous rotation-measure results for several individual sources are presented by Gabuzda, Pushkarev & Garnich (2001); Gabuzda & Chernetskii (2003); and Reynolds, Cawthorne & Gabuzda (2001), where further details of the calibration can also be found.

Faraday rotation of the plane of linear polarisation occurs during the passage of an electromagnetic wave through a region with free electrons and a magnetic field with a non-zero component along the line of sight, and is essentially due to the difference in the propogation velocities of the right- and left-circularly polarised components of the wave.

The amount of rotation is proportional the integral of the density of free electrons n_e multiplied by the line-of-sight magnetic field $\mathbf{B \cdot dl}$, the square of the observing wavelength, and various physical constants; the coefficient of λ^2 is called the rotation measure, RM:

$$\Delta\chi \propto \lambda^2 \int n_e \, \mathbf{B \cdot dl} \equiv \mathbf{RM}\,\lambda^2$$

After matching the imaging parameters and beam sizes of the final images at all three wavelengths, we constructed maps of the rotation measure using the task RM in AIPS.

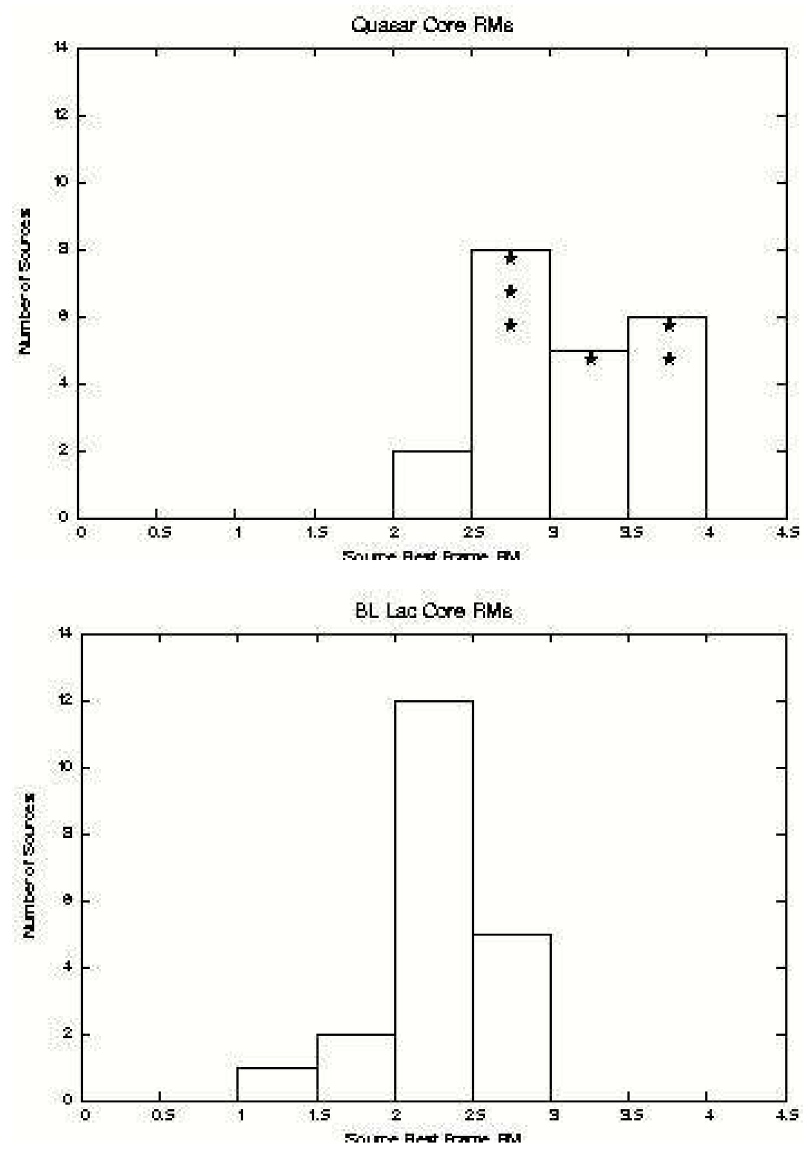
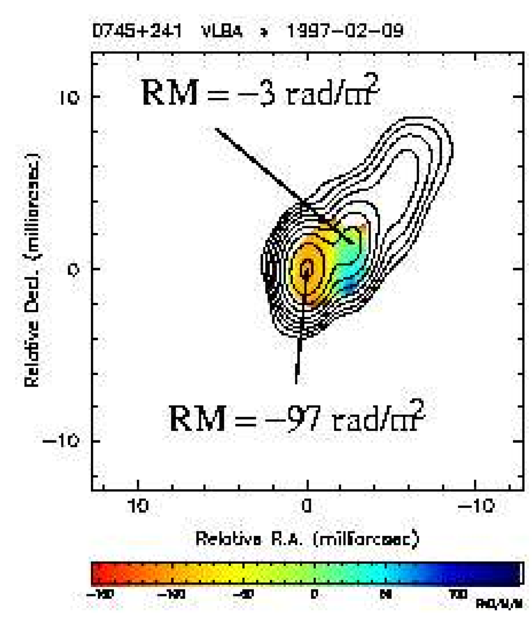
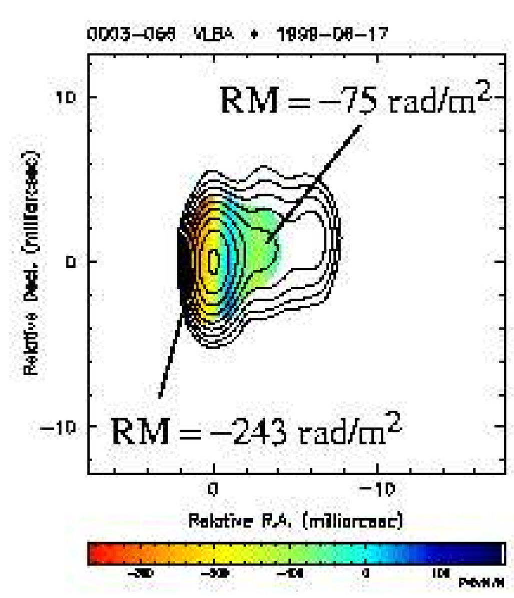
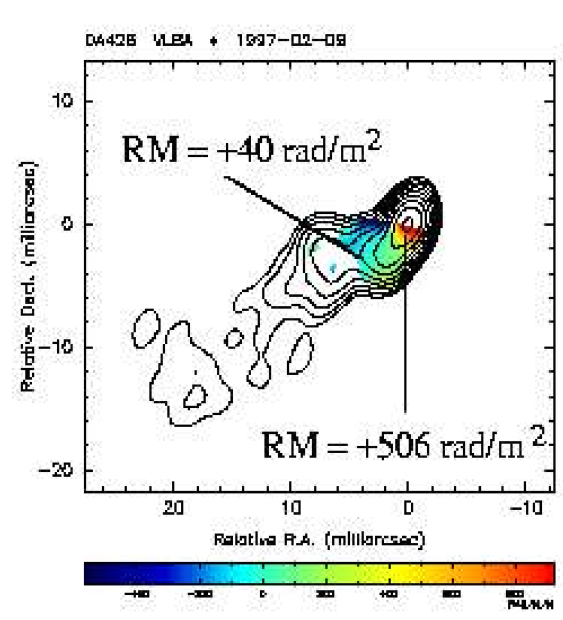
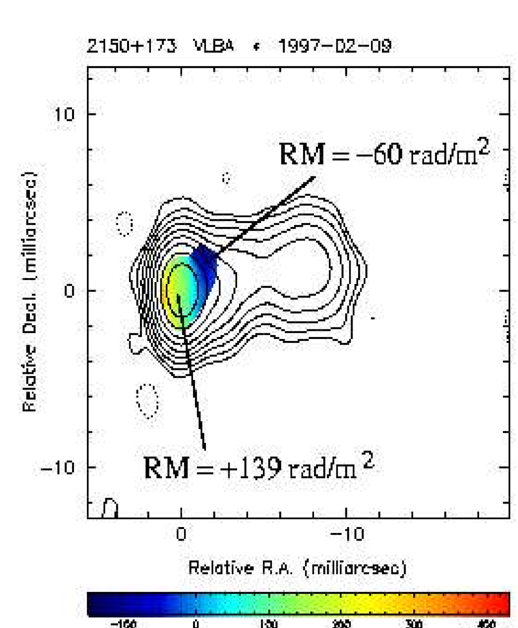


Fig. 1. Histograms showing the distribution of source rest-frame VLBI core rotation measures for flat-spectrum radio quasars (top) and low-energy peaked BL Lac objects (bottom). The integrated (predominantly Galactic) rotation measures have been subtracted from the observed RMs for all objects except for the quasars marked with a star, for which no integrated RMs are available. (It is clear that including these six "uncorrected" values has not skewed the overall distribution.) The resulting RM values were then multiplied by a factor of $(1+z)^2$ to reduce them to the rest frame of the AGN.









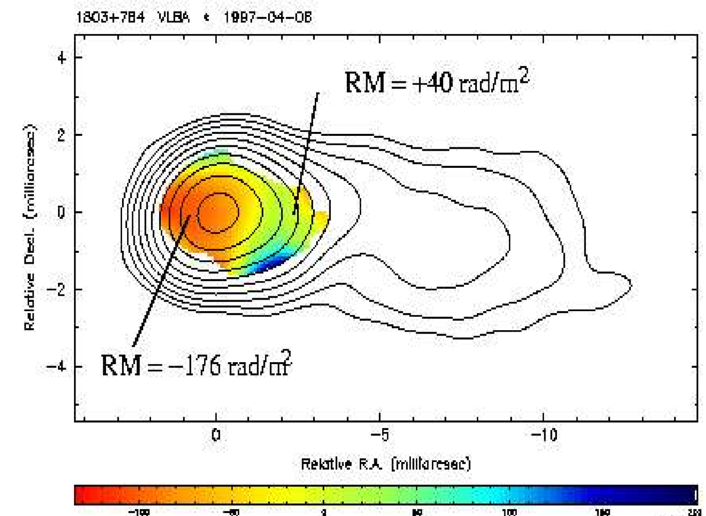


Fig. 2. Examples of BL Lac objects with enhanced Faraday rotation measures in their core regions. The integrated (predominantly Galactic) rotation measures have been subtracted from the RM distributions, so that the rotation measures shown should correspond to magnetic fields and free electrons in the immediate vicinity of the AGN.

Results & Discussion

Figure 1 summarises our results for the core rotation measures of 18 BL Lac objects from the Kühr & Schmidt (1990) sample for which polarisation was detected in the VLBI core at all three observing wavelengths and for which redshifts are available. A histogram of VLBI core rotation measures for about two dozen FSRQs presented by Zavala & Taylor (2004) are shown for comparison. In all cases except for the six marked quasars, the integrated (presumed Galactic) rotation measure derived from simultaneous 18-20 cm VLA data (Rusk 1988; Pushkarev 2001) has been subtracted off, and the rotation measure has then been reduced to the rest frame of the source by multiplying the observed values by a factor of $(1+z)^2$, where z is the redshift.

Our main result is immediately obvious: *the core-region rotation measures of the BL Lac objects are clearly lower, on average, than those of the quasars.*

Figure 2 shows several examples of the parsec-scale RM distributions, illustrating an enhancement of the rotation measure in the region of the VLBI core. This can naturally be understood as an increase in the density of free electrons toward the central regions of the AGN.

In this case, the lower core rotation measures in the BL Lac objects compared to FSRQs indicate a lower density of free electrons, in other words, of ionised gas. This can have two natural origins: a lower density of the thermal gas itself, or a lower flux of ionising photons from the vicinity of the central accretion disk. In addition, these two factors may be correlated (for example, the amount of thermal gas present may affect the accretion rate, which may, in turn, affect the ionising flux from the accretion disk).

This finding is fully consistent with the fact that the optical lines of BL Lac objects are less luminous than those of FSRQs, since lower optical line luminosity likewise requires a lower density of emitting gas and/or a lower incident flux of ionising radiation.

It is also qualitatively consistent with the scheme of Wang, Ho & Staubert (2003), in which FSRQs have optically thick, geometrically thin accretion disks with higher accretion rates than LBLs. Since the sequence proposed by these authors is FSRQ LBL HBL, we can thus make the prediction that, if this scheme is correct, the core rotation measures of HBLs should, in turn, be systematically lower than those of LBLs. We are in the process of analyzing new VLBA data for a sample of HBLs in order to test this hypothesis.

Although the redshift distributions overlap, on average, the redshifts of quasars extend to higher values than those of LBLs, which, in turn, reach higher values than those of HBLs. Thus, it is possible that the sequence FSRQ LBL HBL is at least partly evolutionary in nature.

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