Circular Polarization as a Probe of Jet Physics

D. C. Homan[1] and M. L. Lister[2]

[1] Department of Physics and Astronomy, Denison University, Granville, OH, USA; homand@denison.edu
[2] Department of Physics, Purdue University, West Lafayette, IN, USA; mlister@physics.purdue.edu

Abstract

We discuss the use of parsec-scale circular polarization observations to constrain the magnetic fields and particle distributions of relativistic jets. We recap recent results from the MOJAVE study of a complete sample of AGN at 15 GHz, and we discuss work in progress regarding (1) the circular and linear polarization distributions of the MOJAVE sample, (2) variability of parsec-scale circular polarization in AGN, and (3) new multi-frequency observations of strongly polarized jets.

Introduction

Circular polarization (CP) in parsec-scale radio jets can be produced either as an *intrinsic* component of the emitted synchrotron radiation, or through a bi-refringence effect known as *Faraday Conversion* which converts linear to circular polarization (e.g. Jones & O'Dell 1977). If it is intrinsic to the emitted radiation, circular polarization implies both a strong component of uni-directional magnetic field along the line of sight, as well as a large imbalance in the signs of the emitting particles (i.e. a mostly electron-proton jet rather than electron-positron). Alternatively, if Faraday Conversion is the chief mechanism, jets must typically contain a significant population of low energy particles to perform the conversion.

Both emission mechanisms, but particularly Faraday Conversion, are complex to interpret, since multiple combinations of field structures and particle distributions can often yield the same circular polarization in a given jet. For this reason, we have embarked on a program to greatly improve the observational data available of parsec-scale circular polarization in an effort to better constrain the physical models for circular polarization production in AGN jets.

Polarization of a Complete Sample of AGN

We have used NRAO's Very Long Base Array (VLBA) to study the circular polarization of a complete sample of AGN as part of the MOJAVE program[1]. MOJAVE stands for **M**onitoring **O**f **J**ets in **A**GN with **V**LBA **E**xperiments, and the MOJAVE sample of 133 AGN is complete and flux limited on the basis of VLBA scale emission. Sources must have a total 15 GHz VLBA flux density of at least 1.5 Jy (≳ 2 Jy for sources below the celestial equator) at any epoch from 1994–2003.

Analysis of the first epoch linear and circular polarization observations from the MOJAVE program are complete and have been recently published (Lister & Homan 2005; Homan & Lister 2006), and Figure 1 shows the circular polarization distribution for the jet cores as a function of source type. We found strong circular polarization (≥ 0.3%) in about 15% of our sample. While we found a number of interesting results on individual sources (e.g. M87, 3C84, 3C273; Homan & Lister 2006), the sample as whole showed little correlation between core circular polarization and other source properties such as source type, redshift, EGRET detection, or even linear polarization. We speculated that 15% was simply not enough to detect subtle trends between circular polarization and other source properties. Another possibility is that perhaps even sub-milliarcsecond VLBA imaging is not sufficient to see where the circular polarization is being generated within the core region; however, we do note that the VLBA at 15 GHz does resolve the core region of most of our jets at least in some epochs (Kovalev et al. 2005).

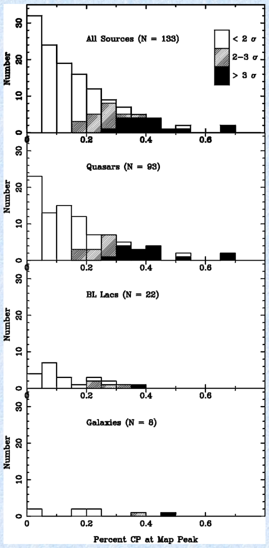

Fig. 1. Histograms of (absolute) fractional circular polarization at the location of the jet core for the first epoch MOJAVE observations. The significance of each measurement is indicated by open, hash, or solid fill styles for the histogram bars.

Multi-Epoch CP Observations

The MOJAVE program was designed to obtain at least four epochs of full Stokes images at 15 GHz of the parsec-scale structure of all sources in the sample. All of these data have been gathered and reduced, and we are currently analyzing them for circular polarization. Figures 2 and 3 show two of our epochs of the famous sources 3C273 and 3C279. These sources have consistently shown high levels of circular polarization over years and decades (see Homan 2005, and sources therein). The lack of correlation between circular polarization and other source properties in the first epoch MOJAVE data seems to stand in contradiction to the consistent nature of the circular polarization from 3C273 and 3C279.

By examining all four epochs for our sample as a whole, we hope to determine if changes in circular polarization are linked with other changes in the sources. Is it generally true that highly polarized sources stay polarized? Do they have a preferred sign of circular polarization in multiple epochs? The answers to these questions may help us determine the relative contributions of circular polarization due to stochastic favorable alignments of magnetic fields and that due to long standing structure in the jet magnetic field.

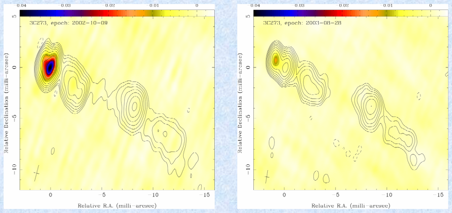

Fig. 2. Two epochs of 3C273 with circular polarization (color) superimposed on total intensity contours. The core has fractional CP of -0.67±0.10% and -0.28±0.14% in the 1st and 2nd epochs respectively. The first jet component is also polarized in the 1st epoch with -0.45±0.09%, but has < 0.28% in the 2nd epoch.

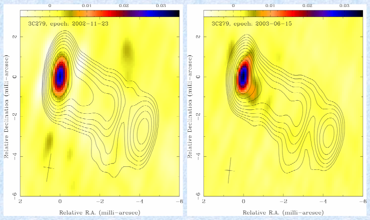

Fig. 3 Two epochs of 3C279 with circular polarization (color) superimposed on total intensity contours. The core has fractional CP of +0.30±0.08% and +0.40±0.09% in the 1st and 2nd epochs respectively.

Spectrum of Circular Polarization

Studying the spectrum of circular polarization from parsec-scale radio jets provides perhaps the best opportunity for distinguishing between competing models of circular polarization production and thereby constraining the jet magnetic field structure and particle distribution. Figure 4 illustrates this with a full-Stokes radiative transfer (e.g. Jones & O'Dell 1977) simulation that predicts the same polarization at one or two frequencies with quite different physical models; however, over a range of six closely spaced frequencies the models are distinct.

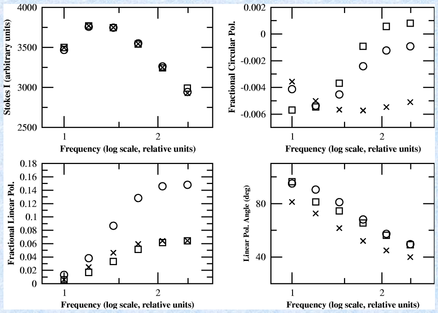

Fig. 4. Full-Stokes radiative transfer simulations of circular polarization in a synchrotron emitting plasma. Open symbols (circles and squares) are dominated by Faraday Conversion and crosses are dominated by intrinsic circular polarization. The circles have a low energy cutoff of $\gamma = 5$ and the squares have a cutoff of $\gamma = 100$. The simulation assumes a 30 x 30 x 30 grid of homogeneous cells. The cells share an ordered magnetic field (at a 45º angle to the line of sight) and an random component which varies from cell to cell. All cells have the same density and spectral index ($\alpha = 0.7$).

We (along with H. Aller, M. Aller, and J. Wardle) have recently observed four of the strongest circularly polarized jets from MOJAVE at six closely spaced frequencies from 8 to 24 GHz with the VLBA, and we are currently reducing those observations. We are also currently obtaining additional full-polarization VLBA images of all 133 MOJAVE sources at 8.1, 8.4, 12.1 and 15.3 GHz.

Modeling the Distribution of Polarization

D. Homan and students have begun a project to model the distribution of circular and linear polarization from the jet cores of the complete sample of AGN studied by the MOJAVE program. Our aim to find the types of magnetic field structures and particle populations that can explain the observed distribution of both linear and circular polarization from our complete sample of AGN jet cores.

We begin with a Monte Carlo simulation to produce the speeds and viewing angles of a population of radio jets consistent with our flux limited sample (Lister, in prep.). For each jet produced by this simulation, we use a full-Stokes radiative transfer code to find the circular and linear polarization emerging from the $\tau = 1$ region (assumed to be a cube for the purposes of the simplified model).

Each jet in this model is assumed to have the same intrinsic physical properties: magnetic field structure, brightness temperature, lower cutoff in the power-law particle spectrum, and lepton number. So far, we have only investigated a simple magnetic field model consisting of three components: (1) a tangled magnetic field, (2) a magnetic field along the jet axis, and (3) a possible shock transverse to the jet axis where unit length is shorted to length k.

While we have only done a coarse grid to date, we find that most model parameters give unsatisfactory results, producing either too much or too little circular and/or linear polarization on average, or giving distributions of these quantities that clearly don't match the observed distributions. As Figure 5 illustrates, we have been able to obtain a qualitative match to the observed distributions for at least one set of physical parameters. However, even this model is not a good match to the overall dataset, because it produces too much correlation between the linear and circular polarization (see Fig. 6).

There is still a wide range of parameter space to explore, and we also plan to study other magnetic field models such as helical fields.

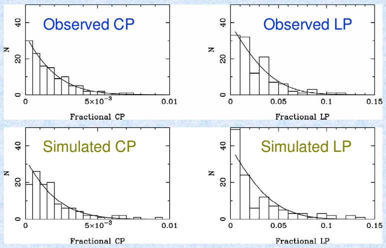

Fig. 5. Observed versus simulated distributions of circular and linear polarization. The solid lines are rough envelopes for the observed distributions. For the simulation we have assumed that each jet has about 20% of its field strength ordered along the jet axis (although less 1% of that is uni-directional), the rest of the field is tangled and shocked with a range of shock strengths where (1 – k) is Gaussian distributed from jet to jet with a mean of zero and a standard deviation of 0.2. The lower cutoff in the particle spectrum is $\gamma = 5$ for every jet in the simulation.

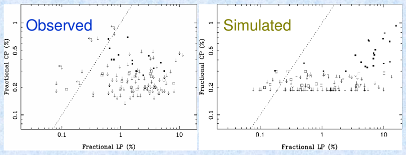

Fig. 6. Correlation between linear and circular polarization in our real observations and in the simulations shown above.

References

Homan, D. C. & Lister, M. L. 2006 AJ, 131, 1262

Homan, D. C. 2005, in ``Future Directions in High Resolution Astronomy: A Celebration of the 10th Anniversary of the VLBA", ASP Conference Series, vol. 340, p. 133

Jones, T. W. & O'Dell, S. L., 1977 ApJ, 214, 522

Kovalev, Y. Y. et al. 2005, AJ, 130, 2473

Lister, M. L. & Homan, D. C. 2005 AJ, 130, 1389

Acknowledgments

Denison students B. Welch and J. Ginter assisted in the simulations described above. We also thank the other members of the MOJAVE team: H. Aller, M. Aller, T. Arshakian, M. Cohen, M. Kadler, K. Kellermann, Y. Kovalev, A. Lobanov, E. Ros, R. Vermeulen, and A. Zensus. This work is supported by an award from Research Corporation. The MOJAVE program is supported by NSF research grant AST 04-06923 and a grant from the Purdue Research Foundation. The VLBA is operated by the National Radio Astronomy Observatory which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

---

[1] http://www.physics.purdue.edu/astro/MOJAVE