International Workshop on Beamed and Unbeamed Gamma-Rays from Galaxies IOP Publishing
Journal of Physics: Conference Series **355** (2012) 012019 doi:10.1088/1742-6596/355/1/012019

Evidence for Helical Magnetic fields in Kiloparsec-Scale AGN Jets and the Action of a Cosmic Battery

D.C. Gabuzda[1], D.M. Christodoulou[2], I. Contopoulos[3], D. Kazanas[4]

[1]Physics Department, University College Cork, Cork, Ireland
[2] Department of Mathematical Sciences, University of Massachusetts Lowell, Lowell 01854
[3] Research Center for Astronomy, Academy of Athens, Athens 11527, Greece
[4] NASA/GSFC, Code 663, Greenbelt, MD 20771

E-mail: d.gabuzda@ucc.ie

Abstract. A search for transverse kiloparsec-scale gradients in Faraday rotation-measure (RM) maps of extragalactic radio sources in the literature has yielded 6 AGNs displaying continuous, monotonic RM gradients across their jets, oriented roughly orthogonal to the local jet direction. The most natural interpretation of such transverse RM gradients is that they are caused by the systematic change in the line-of-sight components of helical magnetic fields associated with these jets. All the identified transverse RM gradients increase in the counterclockwise (CCW) direction on the sky relative to the centers of these AGNs. Taken together with the results of Contopoulos et al. [7], who found evidence for a predominance of clockwise (CW) transverse RM gradients across parsec-scale (VLBI) jets, this provides new evidence for preferred orientations of RM gradients due to helical jet magnetic fields, with a reversal from CW in the inner jets to CCW farther from the centers of activity. This can be explained by the "Poynting–Robertson cosmic-battery" mechanism, which can generate helical magnetic fields with a characteristic "twist," which are expelled with the jet outflows. If the Poynting–Robertson battery mechanism is not operating, an alternative mechanism must be identified, which is able to explain the predominance of CW/CCW RM gradients on parsec/kiloparsec scales.

1. Introduction

It is widely believed that the physical mechanism that drives the jets of extragalactic radio sources is magnetohydrodynamical: the rotating active galactic nucleus (AGN) is threaded by a magnetic field organized on scales out to tens of kiloparsecs; the field is wound up by the rotation of the plasma (i.e., it becomes helical) and drives a collimated outflow (jet) above and below the symmetry plane of the nucleus. The asymptotic velocity attained by the jet material is of the same order as the rotational velocity at its base. It is now well understood that the galactic nucleus consists of two components, a rotating supermassive ($\sim 10^8 M_\odot$) black hole with its event horizon extending out to $\sim$1 AU, and a surrounding rotating accretion disk extending out to $\sim$1 pc. Therefore, extragalactic jets are also expected to consist of two components: an inner, relativistic, axial jet, and an outer, nonrelativistic, extended disk wind [17, 35]. The theoretical details of the jet launching mechanism have been well studied in the literature (e.g., [4, 10]; see also [37], and references therein), where it has been shown that the field is effectively wound up only beyond the Alfvén distance, which is ~10 times the radial extent of the outflow at its base. Thus, the theoretical models suggest that the magnetic field of the inner jet and the outer extended wind will develop significant toroidal components on distances beyond ~10 AU and ~10 pc, respectively, from the AGN centers.

In the past few years, a mechanism has been proposed that seems capable of generating strong, ordered, large-scale magnetic fields in AGN accetion disks and of providing the physical background needed to understand some of the most prominent features observed in magnetized jets. We call this the *Poynting–Robertson* (PR) *Cosmic Battery* because it relies on the PR drag on plasma electrons to generate large–scale azimuthal currents in the inner disks of AGN [6, 8, 9]. In the vicinity of a $10^8 M_\odot$ black hole, the PR battery can generate an equipartition field on timescales shorter than 100 million years [8]. But the most important feature of this mechanism is that the azimuthal electric current in the accretion disk always flows in the direction of rotation; thus, it supports and maintains a large-scale poloidal magnetic field that is inextricably tied to the rotation of the disk.

The PR battery solves the problem of large-scale field amplification via the continual (secular) generation of poloidal magnetic-field loops around the inner edge of the accretion disk surrounding the central supermassive black hole [9]. The outer footpoint of each loop resides well inside the accretion disk and diffuses outward on the disk's local diffusion timescale, provided that this is at least a factor of ~2 shorter than the local accretion timescale. The other footpoint is dragged inward by the accretion flow and eventually ends up near the black hole. This behavior was predicted in [8] and was demonstrated by the simulations of [6]. The inner and the outer section of the loop are both helically wound in the direction of rotation, but because the poloidal component of the inner (outer) loop is parallel (antiparallel) to the angular-velocity vector, the section in the inner jet (the "inner" field) develops a left–handed twist about the jet axis whereas the section in the outer wind (the "return" field) develops a right–handed twist about the jet axis, irrespective of the direction of the angular velocity [7].

The most important diagnostic tool of the above magnetic-field configuration is the predicted observation of characteristically oriented transverse Faraday RM gradients across the jets and lobes of at least some radio sources that are not too disturbed due to interactions with their environment or other factors. When an RM gradient is dominated by the contribution of the inner field, it should increase in the clockwise (CW) direction on the sky with respect to the AGN center. The opposite holds for a Faraday RM gradient that is dominated by the return field. These results are independent of the location of the observer [7].

With the above theoretical considerations in mind, we set out to search for transverse RM gradients on even larger scales in radio sources with jets extending over many kiloparsecs. The purpose of this study was essentially twofold: (i) to establish whether or not transverse RM gradients reasonably interpreted as reflecting the presence of helical jet magnetic fields are present on kiloparsec scales; and if present, (ii) to establish whether such RM gradients show any evidence for a preferred orientation. We have found clear, systematic, transverse RM gradients associated with kiloparsec-scale jets in 6 extragalactic radio sources, with tentative gradients identified in 4 more sources.

2. Transverse RM Gradients Across Kiloparsec-Scale Jets

Our extensive search for Faraday RM maps of extragalactic radio sources on kiloparsec scales published over the past 12 years produced 86 such maps [1–3, 5, 14–16, 20–24, 26, 30–32, 38, 40]. We were unable to reliably identify large-scale, systematic transverse RM gradients in most of these maps, because the jets appeared to be strongly influenced by their surroundings, the emission was patchy or limited to just a few pixels across the images, or the results were shown in gray scale that did not make the structures in the RM images sufficiently clear. We have focused specifically on objects in which we believe we have been able to identify gradients *transverse* to the jets; objects displaying RM gradients that were predominantly longitudinal were discarded from consideration.

In the end, we were able to identify 6 firm and 4 tentative objects with extended, monotonic, nearly transverse (to within $\sim 20°$ in most cases) RM gradients based on data at three or more wavelengths, listed below. We have made no attempt to measure the *magnitudes* of the RM gradients we have identified, and focus solely on the *presence* of clear transverse RM gradients and their *directions*—either CW or CCW on the sky—relative to the bases of the jets.

Firm transverse RM gradients:

0156−252 [CCW].—There is a clear RM gradient across the Eastern jet (Fig. 3 of [1]).

5C4.114 [CCW].—There is a clear, systematic, extended RM gradient across the entire Northern lobe of the radio structure. The RM distribution is extremely well resolved (Fig. 12 of [5]).

5C4.152 [CCW].—There are clear RM gradients present in both lobes (Fig. 15 of [5]). The gradient across the Southern lobe is fairly orthogonal to the jet direction, while the gradient across the Northern lobe appears to be offset from orthogonality as the jet bends toward the East just before the hotspot.

Cen A [CCW].—After subtraction of the overall mean RM (which is presumably foreground), the residual RM map shows a tendency for positive residuals along the Eastern side and negative residuals along the Western side of the entire Northern lobe (Fig. 7 of [15]). The Southern lobe is strongly bent; although local RM gradients can be identified, no systematic trends are obvious.

A2142A [CCW].—The RM distribution shows a clear tendency for RM values $\simeq -600$ rad m^{-2} along the Southern side of the jet and RM values $\simeq -200$ to -300 rad m^{-2} along the Northern side (Fig. 13 of [22]).

3C465 [CCW].—The Southern jet displays a systematic, extended transverse RM gradient that extends along most of this jet (Fig. 6 of [14]).

Tentative transverse RM gradients:

3C31 [CCW].—There is some evidence for an RM gradient across the Southern lobe (region SP3 in Fig. 2c of [30]); but an appreciable smaller-scale patchy component to the distribution makes it unclear whether a systematic component is present in the RM distribution.

5C4.74 [CCW].—An RM gradient is visible over an extended region in the Northwestern lobe, but it is hard to be sure of the monotonicity of this gradient due to the range of the color scale used (Fig. 11 of [5]). No RM gradient is seen in the Southeastern radio lobe.

5C4.127 [CCW, CW].—There are indications of RM gradients in the Western jet, however these are not very extended along the jet, and it is somewhat unclear whether a systematic component is present in the RM distribution (Fig. 13 of [5]).

A2065A [CW, CCW].—There are some regions with fairly clear transverse RM gradients at the bases of the lobes, but the overall RM distribution is fairly patchy, as is also noted by the authors of [22] (Fig. 14 of [22]).

3. Discussion

Reliability of the Detected Transverse RM Gradients.

In their critique of various parsec-scale Faraday rotation analyses, including that of [7], Taylor & Zavala [39] proposed four criteria for the reliable detection of transverse Faraday rotation gradients: (1) at least three "resolution elements" across the jet, (2) a change in the RM of at least three times the typical error σ, (3) an optically thin synchrotron spectrum at the location of the gradient, and (4) a monotonically smooth (within the errors) change in the RM from side to side. We have explicitly satisfied criteria (3) and (4) in our search, by retaining in our list only monotonic, smooth gradients in optically thin jet regions. Criterion (2) is also satisfied by the images selected here, sometimes with a very large margin; in some cases, the RM difference across the jet corresponds to tens of σ.

Criterion (1) reflects the desire to ensure that it is possible to distinguish properties between regions located on opposite sides of the jets, which are often quite narrow structures. However, the minimum of 3 "resolution elements" is proposed without any justification, and indeed without even defining what is meant by a "resolution element." In fact, quite a few cases are known in which imaged structures can be clearly resolved even when they are separated by distances of about one (or less than one) beamwidth; one such example is the detection of jet components less than 1 mas from the core in many sources in the MOJAVE VLBA monitoring project at 15 GHz, for which the beamwidths are typically about 1 mas (e.g. [27]). In addition, clear transverse polarization structure is often visible in the jets of this sample, even in parts of the jets with transverse sizes of 1–2 beamwidths [33].

Thus, we consider this to be an open issue, and further work is needed to address this question; see also the contribution to these proceedings by Murphy and Gabuzda. Most of the observed RM gradients considered here span 2–3 beamwidths; and those in 3C465, Cen A, and 3C31 are extremely well resolved, and extend across more than 10 beamwidths.

Importance of the Presence of Transverse RM Gradients on Kiloparsec Scales

The most fundamental implication of the above results is that transverse RM gradients—predicted to exist if the jets carry toroidal or helical magnetic fields and detected earlier in some AGN on parsec scales—are also present on kiloparsec scales. This identification of systematic transverse RM gradients on kiloparsec scales not only provides direct evidence that the jets of at least some of these objects carry helical magnetic fields; by inference, it also provides corroborative support to previous reports of parsec-scale helical magnetic fields.

In fact, it is easy to understand why it should be comparatively difficult to detect transverse RM gradients due to the presence of helical magnetic fields in kiloparsec-scale jets. There is an appreciable turbulent, inhomogeneous component to the thermal ambient media surrounding the jets on these scales, which superposes a more or less random pattern over the systematic pattern due to the helical fields. This random component in the RM distribution may dominate in the majority of cases. Thus, it is perfectly natural that most of the observed RM distributions appear random and patchy, but the overall pattern due to the helical fields sometimes comes through. This suggests that, on average, it may be easier to detect the systematic RM component due to helical jet magnetic fields on parsec scales, where the ordered inner field is more dominant, a result that seems to be borne out from the observations.

Predominance of CCW RM Gradients on Large Scales

Our results show a predominance of CCW RM gradients: namely, all 6 firm gradients are CCW. Based on a simple unweighted binomial probability function, the probability for 6/6 firm gradients to be CCW by chance is about 1.6%. This is not quite a 3σ result, and so must be considered tentative. However, we believe it to be significant, in light of the previous results collected and analyzed in [7] for parsec scales, as well as recent RM results for the jets of AGNs on scales of tens of parsec. In partiular, 3C120 [12], Mrk501 [13], 1749+701 [25], and 1633+382 [36] all display transverse CCW RM gradients on scales of tens of parsec in Very Long Baseline Array (VLBA) observations at four wavelengths between 18 and 22 cm.

This preponderance of CCW transverse RM gradients and the presence of helical magnetic fields on large scales can be explained naturally in the framework of the PR cosmic battery: the return helical field dominates the total observed Faraday rotation on relatively large angular scales on the sky, where the detected radio emission extends to fairly large distances from the jet axes. It is much less likely for such observations to be dominated by Faraday rotation due to the inner helical field, which is embedded in the outer layers of the jet itself. In contrast, as was shown by the analysis of [7], this "inner" region of helical field is more likely to dominate the RM measurements on parsec scales.

Königl [28] has argued that the CW RM gradients on parsec scales reported in [7] could be the result of ordered, large-scale, magnetic fields that were produced in the outer weakly-ionized accretion disks by Hall currents, and that were launched from the disks in centrifugally-driven wind outflows. This model could in principle also give rise to a predominance of CCW RM gradients on larger scales, if there is also a "return field". However, Hall currents are usually believed to be unimportant to AGN physics, because, unlike protostellar disks [29], the accretion disks of AGN have relatively higher ionization fractions near the central compact objects, where all the prominent magnetohydrodynamical phenomena are thought to take place (e.g., [18–19]). If, on the other hand, the magnetic field is brought in to the outer, cold, weakly-ionized part of the disk from outside [28], then different polarities are likely to undergo fast reconnection long before a strong toroidal field component can develop due to the much slower differential rotation of the outer disk. Therefore, we consider this model physically less plausible in AGNs than the PR battery model.

4. Summary

We have found 6 extragalactic radio jets across which monotonic RM gradients can firmly be identified on kiloparsec scales, providing direct evidence for the presence of helical jet magnetic fields. All of these RM gradients are monotonic and smooth, occur in optically thin jet regions, and correspond to RM differences of more than 3σ across the jets. Although some span only 2–3 beamwidths across the jets, others extend over dozens of beamwidths. We have also identified four additional cases, in which transverse gradients may be present, but are considered tentative because they could be due to random patchiness of the Faraday-rotating medium.

We find evidence for a preponderance of kiloparsec-scale gradients in which the RMs increase CCW on the sky. Although this result does not have an extremely high statistical significance, it is supported by (i) the tendency for parsec-scale transverse RM gradients to be CW [7] and (ii) the detection of transverse CCW RM gradients in several 18–22 cm VLBA RM images probing scales of tens of parsec. This result seems counterintuitive, since in the simplest models, one would expect transverse RM gradients associated with helical jet magnetic fields not to display any preferred orientation on the sky. The observed predominance of CCW transverse RM gradients essentially demands that the direction of rotation of the accretion disk and the direction of the initial poloidal seed field that is "wound up" by the rotation be coupled. Such a coupling can be provided by the PR cosmic battery.

The poloidal magnetic-field loops generated by the PR cosmic battery around the inner edge of the underlying accretion disk extend out to kiloparsec-scale distances and effectively establish an inner field embedded in the relativistic jet and a return field embedded in the outer extended disk wind. Faraday rotation observations of radio jets on relatively large scales can resolve the return-field sections of such poloidal loops that are not too disturbed by transverse motions, backflows, or turbulence. The associated Faraday RM gradients should increase in the CCW direction on the sky, independent of the orientation of the observer [7].

In the same physical picture, the Faraday RM gradients due to the inner sections of the poloidal loops should increase CW on the sky about the central sources, but such gradients are located much closer to the jet axes and cannot be observed in arcsecond-resolution images because the RMs on such large scales are dominated by the Faraday rotation in the outer extended disk wind. In turn, the "inner" CW RM gradients dominate on the parsec scales observed with VLBI, giving rise to the preponderance of CW transverse RM gradients found in the collected results analyzed in [7].

If the PR battery mechanism is not operating for some reason, another mechanism that can provide the required coupling between the direction of disk rotation and direction of the poloidal seed field must be found. The Hall-current mechanism of [28] may provide one alternative, although it remains unclear whether this mechanism is sufficiently efficient in the jet+disk systems of AGNs.

The results we have presented here must still be considered somewhat tentative; however, if confirmed by further studies, they will be of fundamental importance for our understanding of AGN jets. We are currently investigating ways to better quantify detected transverse RM gradients and to identify them in a more objective, automated fashion.

5. Acknowledgements

We acknowledge insights and assistance with data provided by Drs. Philip Best, George Contopoulos, Federica Govoni, Christian Kaiser, and Preeti Kharb.

[1] Athreya, R. M., Kapahi, V. K., McCarthy, P. J., & van Breugel, W. 1998, A&A, 329, 809
[2] Best, P. N., Carilli, C. L., Garrington, S. T., Longair, M. S., & Röttgering, H. J. A. 1998, MNRAS, 299, 357
[3] Best, P. N., Eales, S. A., Longair, M. S., Rawlings, S., & Röttgering, H. J. A. 1999, MNRAS, 303, 616
[4] Blandford R. D., & Payne, D. G. 1982, MNRAS, 199, 883
[5] Bonafede, A., Feretti, L., Murgia, M., Govoni, F., Giovannini, G., Dallacasa, D., Dolag, K. ,& Taylor, G. B. 2010, A&A, 513, 30
[6] Christodoulou, D. M., Contopoulos, I., & Kazanas, D. 2008, ApJ, 674, 388
[7] Contopoulos, I., Christodoulou, D. M., Kazanas, D., & Gabuzda, D. C. 2009, ApJL, 702, L148
[8] Contopoulos, I., & Kazanas, D. 1998, ApJ, 508, 859
[9] Contopoulos, I., Kazanas D., & Christodoulou, D. M. 2006, ApJ, 652, 1451
[10] Contopoulos, J. 1995, ApJ, 450, 616
[11] Contopoulos, J. & Lovelace, R. V. E. 1994, ApJ, 429, 139
[12] Coughlan, C., Murphy, R., McEnery, K., Patrick, H., Hallahan, R., & Gabuzda, D. C. 2011, Proc. 10th EVN Symposium, in press
[13] Croke, S. M., O'Sullivan, S. P., & Gabuzda, D. C. 2010, MNRAS, 402, 259
[14] Eilek, J. A., & Owen, F. N. 2002, ApJ, 567, 202
[15] Feain, I. J,. Ekers, R. D., Murphy, T., et al. 2009, ApJ, 707, 114
[16] Feretti, L., Dallacasa, D., Govoni, F., Giovannini, G., Taylor, G. B., & Klein, U. 1999, A&A, 344, 472
[17] Ferreira J., Petrucci P.-O., Henri G., Saugé L., & Pelletier G. 2006, A&A, 447, 813
[18] Gaskell, C. M. 2009, NewAR, 53, 140
[19] Gaskell, C. M. 2010, ASPC, 427, 68
[20] Goodlet, J. A., Kaiser, C. R., Best, P. N., & Dennett-Thorpe, J. 2004, MNRAS, 347, 508
[21] Govoni, F., Murgia, M., Feretti, L., Giovannini, G., Dolag, K. & Taylor, G. B. 2006, A&A, 460, 425
[22] Govoni, F., Dolag, K., Murgia, M., Feretti, L., Schindler, S., Giovannini, G., Boschin, W., Vacca, V., & Bonafede A. 2010, A&A, 522, 105
[23] Guidetti, D., Murgia, M., Govoni, F., Parma, P., Gregorini, L., de Ruitar, H. R., Cameron, R. A., & Fanti, R. 2008, A&A, 483, 699
[24] Guidetti, D., Laing, R. A., Murgia, M., Govoni, F., Gregorini, L., & Parma P. 2010, A&A, 514, 50
[25] Hallahan, R., & Gabuzda, D. C. 2008, Proceedings of Science, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=72
[26] Kharb, P., O'Dea, C. P., Baum, S. A., et al. 2008, ApJS, 174, 74
[27] Kellermann, K. I., Lister, M. L., Homan, D. C., et al. 2004, ApJ, 609, 539
[28] Königl, A. 2010, MNRAS, 407, L79
[29] Krasnopolsky, R., Li, Z.-Y., & Shang, H. 2011, ApJL, submitted
[30] Laing, R. A., Bridle, A. H., Parma, P., & Murgia, M. 2008, MNRAS, 391, 521
[31] Laing, R. A., Canvin, J. R., Bridle, A. H., & Hardcastle, M. J. 2006, MNRAS, 372, 510
[32] Laing, R. A., Canvin, J. R., Cotton, W. D., & Bridle, A. H. 2006, MNRAS, 368, 48
[33] Lister, M. L. & Homan, D. C. 2005, AJ, 130, 1389
[34] Murgia, M., Govoni, F., Feretti, L., Giovannini, G., Dallacasa, D., Fanti, R., Taylor, G. B., & Dolag, K. 2004, A&A, 424, 429
[35] Pelletier, G., Sol, H., & Asseo, E. 1988, Phys. Rev. A, 38, 2552
[36] Reichstein, A., Gabuzda, D. C., Coughlan, C., & Murphy, R. 2011, Proc. 25th Symposium on Relativistic Astrophysics, Proceedings of Science, in press
[37] Spruit, H. C. 2010, LNP, 794, 233
[38] Taylor, G. B., Govoni, F., Allen, S. W., & Fabian, A. C. 2001, MNRAS, 326, 2
[39] Taylor, G. B., & Zavala, R. 2010, ApJ, 722, L183
[40] Venturi, T., & Taylor, G. B. 1999, AJ, 118, 1931