PROCEEDINGS OF SCIENCE

The 15–43-GHz Parsec-scale Circular Polarization of AGN

Denise C. Gabuzda*
Department of Physics, University College Cork, Republic of Ireland
E-mail: gabuzda@phys.ucc.ie

Vasilii M. Vitrishchak
Sternberg Astronomical Institute, Moscow State University, Moscow, Russia
E-mail: realvmv@yahoo.ie

Vitrishchak et al. [20] have recently published results of parsec-scale circular polarization measurements based on Very Long Baseline Array data for a number of radio-bright, core-dominated Active Galactic Nuclei obtained simultaneously at 15, 22 and 43 GHz. There are very few multi-frequency VLBI circular-polarization results to date, making these of considerable interest; we summarize these results here. The degree of circular polarization m_c as often rises as falls with increasing frequency between 15 and 22 GHz, while the degree of circular polarisation at 43 GHz is in all cases higher than at 22 and 15 GHz. This is somewhat surprising, since the degree of circular polarization from both synchrotron radiation and Faraday conversion of linear to circular polarization should *decrease* towards higher frequencies if the source is homogeneous. The increase in m_c at 43 GHz may be due to the presence of regions of both positive and negative circular polarisation with different frequency dependences (but decreasing with increasing frequency) on small scales within the core region; alternatively, it may be associated with the intrinsic inhomogeneity of a Blandford–Königl-like jet. There are several cases of changes in sign with frequency, usually between 22 and 43 GHz, and tentative evidence for transverse structure in the circular polarization of 1055+018 and 1334−127 that is consistent with their being generated by either the synchrotron mechanism or Faraday conversion in a helical magnetic field.

The 9th European VLBI Network Symposium on The role of VLBI in the Golden Age for Radio Astronomy and EVN Users Meeting
September 23-26, 2008
Bologna, Italy

*Speaker.

1. Introduction

The radio emission of core-dominated, radio-loud Active Galactic Nuclei (AGN) is synchrotron radiation generated in the relativistic jets that emerge from the nucleus of the galaxy, presumably along the rotational axis of a central supermassive black hole. Synchrotron radiation can be highly linearly polarized, to $\simeq$ 75% in the case of a uniform magnetic (**B**) field [17], and linear polarization observations can yield unique information about the orientation and degree of order of the **B** field in the synchrotron source, as well as the distribution of thermal electrons and the **B**-field geometry in the immediate vicinity of the AGN (e.g., via Faraday rotation of the plane of polarization).

Techniques for deriving circular-polarization (CP) information on parsec scales were pioneered by Homan and his collaborators [10, 6] using data taken on the NRAO[1] Very Long Baseline Array (VLBA). CP measurements for the first epoch of the MOJAVE project (monitoring of 133 AGN at 15 GHz with the VLBA) were published in [7]. The MOJAVE results confirmed previously noted trends: the CP is nearly always coincident with the VLBI core, with typical degrees of polarization m_c being a few tenths of a percent. No evidence was found for any correlation between m_c and any of 20 different optical, radio and intrinsic parameters of the AGN [7]. Interestingly, five of the 34 AGN displayed CP in their *jets*, well outside the VLBI-core region, suggesting that the mechanism generating the CP is capable of operating effectively in optically thin jet regions.

The two main mechanisms that are usually considered to be the most likely generators of the observed CP are the synchrotron mechanism and the Faraday conversion of linear to circular polarization [13, 12, 2, 21]. Although the intrinsic CP generated by synchrotron radiation may be able to reach a few tenths of a percent at 15 GHz for the magnetic-field strengths characteristic of the observed VLBI cores of AGN (typically $\simeq$ 0.4 G [14, 16]), the highest observed m_c values seem too high to plausibly be attributed to this mechanism. This suggests that Faraday conversion plays a role, possibly the dominant one, since it is expected to be more efficient at generating CP than the synchrotron mechanism for the conditions in radio cores [12].

Faraday conversion [12, 11] occurs because the component of the linear-polarization electric vector parallel to the conversion magnetic field, $E_{\|}$, gives rise to oscillations of free charges in the conversion region, while the component orthogonal to this magnetic field, $E_{\perp}$, cannot (the charges are not free to move orthogonal to the magnetic field). This leads to a delay of $E_{\|}$ relative to $E_{\perp}$, manifest as the introduction of a small amount of circular polarization. There is some evidence that the CP in AGN may be generated by Faraday conversion in helical jet magnetic fields [5].

Although knowledge of the spectrum of m_c can potentially provide very useful constraints on the CP-generation mechanisms, there have been very few multi-frequency VLBI circular-polarization studies to date; one exception is the recent study of 3C279 [8]. We summarize here the recent 43+22+15 GHz results of Vitrishchak et al.; full information about the data used, data reduction and results obtained can be found in [20].

[1]The National Radio Astronomy Observatory of the USA is operated by Associated Universities, Inc., under cooperative agreement with the US NSF.

PoS(IX EVN Symposium)003

2. Results of 43+22+15 GHz CP Measurements

2.1 Consistency with Previous MOJAVE Measurements

A comparison of the 15-GHz results of [20] and the first-epoch 15-GHz MOJAVE results [7] indicates that, in all 8 cases when CP is detected at 15 GHz in both studies, the sign of the CP for the two datasets agree. Vitrishchak et al. [20] did not detect 15-GHz CP in 1510−089, but the sign of CP detected at 22 GHz agrees with the sign of the MOJAVE measurements. In several other sources, detections made in [20] are consistent with the MOJAVE upper limits. This all shows the reliability and consistency of current VLBA CP measurements, and demonstrates that a self-consistent picture is emerging from the accumulating data, despite the difficulty of these measurements.

2.2 Location of Detected CP in the VLBI Core Region and Inner Jet

In most cases, the CP detected at all frequencies is been coincident with the I peak, i.e., close to the position of the VLBI core, as is also true of virtually all previous CP measurements (e.g. [7]). It is important to bear in mind when interpreting these measurements that the “core” as the optically thick base of the jet [3] is a theoretical concept, and will correspond to the observed “core” only for observations with sufficient resolution; the observed VLBI “core” will actually correspond to a combination of the genuine optically thick core and optically thin emission from the inner jet. Thus, the detection of CP coincident with the observed VLBI “core” does not necessarily mean that the V signal arises predominantly near the $\tau = 1$ surface. This view is supported by the direct detection of jet CP in nine AGN [7, 19, 20].

2.3 Spectra of the Degree of Polarization

There is no clear universal trend for the frequency dependence of the degree of circular polarization m_c, although a few patterns can be noted. When CP is detected at 43 GHz, the degree of CP at this frequency is higher than m_c at the lower frequencies for that same source. In addition, the average value for $|m_c|$ for the 15-GHz measurements is 0.42 ± 0.03, while the average $|m_c|$ at 22 GHz is 0.49 ± 0.06, and the average $|m_c|$ at 43 GHz is 1.00 ± 0.01. Thus, the average degrees of CP at 15 and 22 GHz essentially coincide, while the average degree of CP at 43 GHz is appreciably larger. This demonstrates that, treated as a group, as well as on a source-by-source basis, the 43-GHz $|m_c|$ values are systematically higher than the $|m_c|$ values at the lower two frequencies. In contrast, the $|m_c|$ values are as often higher as lower at 22 GHz compared to 15 GHz.

The nominal spectral index expected for intrinsic CP from a homogeneous source in the optically thin regime is $m_c \propto \nu^{-0.5}$, while the nominal spectrum expected for CP generated by Faraday conversion in a homogeneous source is substantially steeper $m_c \propto \nu^{-3}$. Neither of these frequency dependences describes the 43+22+15-GHz results well, indicating that some other factors are coming into play.

One way in which it might be possible to obtain a wide range of CP spectral indices for the core region is if there are several regions of CP contributing to the observed “core” CP. If we are observing the sum of two or more CP components, possibly having different signs and somewhat different spectra, this could lead to a fairly wide range of both positive and negative values for

α_c, as is observed. Both intrinsic CP and CP generated by Faraday conversion in a helical **B**-field geometry can also have comparably strong regions of CP of different signs in different regions of the jet (e.g. on different sides of the jet; see Fig. 6 of [5], which could be blended in the observed "core."

It is also quite possible that the frequency dependence for the observed CP is associated to a considerable extent with the intrinsic inhomogeneity of the jets. Wardle & Homan [21] discuss the approximate frequency dependences that might be expected for a Blandford–Königl jet under various conditions, and suggest that the spectrum for CP generated fairly near the optically thick base of the jet is likely to be fairly flat, or even inverted, $m_c \propto \nu^{+1}$. This counter-intuitive result essentially comes about due to the characteristic fall-offs in the magnetic field and electron density with distance from the jet base, combined with the shift of the location of the $\tau = 1$ surface closer to the true jet base with increasing frequency and the assumption that the dominant contribution to the CP is made by regions roughly in the vicinity of the $\tau = 1$ surface.

Thus, it is not easy to definitively distinguish between the synchrotron mechanism and either Faraday-rotation-driven or helical-field-driven Faraday conversion based purely on the observed m_c spectra. This leaves the observed degrees of CP as a possible means of constraining the mechanism at work. It has been argued in previous studies (e.g. [9] that intrinsic CP has trouble explaining the highest observed degrees of circular polarization, and in any case, Faraday conversion should generally be much more efficient at generating CP than the synchrotron mechanism under the conditions expected for AGN jets[12]. Overall, it seems likely that the observed CP is predominantly generated by Faraday conversion, and that the observed values of α_c are determined by effects associated with the intrinsic inhomogeneity of the jets, as well as the possible presence of several regions of CP of either one or both signs contributing to the observed "core" CP.

2.4 Sign Changes with Frequency

It has long been known that the sign of the CP in a particular AGN is usually stable over years, or even decades [10]. In contrast, little is known about the frequency dependence of the CP sign. Vitrishchak et al. [20] detected CP at more than one frequency in 10 AGN. All but one of the 9 AGN for which CP was detected at both 15 and 22 GHz show the same sign at these two frequencies, while 4 of the 6 AGN for which CP was detected at both 22 and 43 GHz show sign changes between these two frequencies. This appears to suggest optical depth effects, i.e., that the regions being sampled are optically thin between 22 and 43 GHz, but optically thick between 15 and 22 GHz, but there is no evidence that this transition occurs in this frequency range from the total-intensity spectral indices. Thus, at present, the nature of the frequency sign changes between 22 and 43 GHz remains unclear.

2.5 Transverse CP Structures

At least tentative evidence for transverse CP structures has been found in 1055+018 and 1334−127 at 43 GHz. Transverse CP structures such as those observed for these two objects could come about naturally if the CP is generated in helical jet **B** fields, independent of whether the CP is due to the synchrotron mechanism or helical-field-driven Faraday conversion. Gabuzda et al. [5] considered a simple model in which the CP in AGNs is generated by the latter mechanism; the sign of the CP is determined essentially by the angle between the **B** fields at the far side and near side of the jet relative to the observer, which changes across the jet. Whether the CP is dominated by a single sign throughout the jet cross section or includes contributions of both positive and negative CP on opposite sides of the jet is determined by the pitch angle and viewing angle. In this context, it is interesting that the *linear* polarization structures of 1055+018 and 1334−127 both correspond to the pitch-angle regime that is expected to give rise to the observed transverse CP structure. 1055+018 displays a "spine+sheath" linear polarization structure, with predominantly orthogonal inferred **B** field along the jet ridge line and longitudinal **B** field at the jet edges [1, 18]. This type of polarization structure will arise naturally if the jet has a helical **B** field, if the pitch angle is relatively high and the viewing angle is not too far from 90° in the jet rest frame [15]; the more symmetrical the CP structure, the closer to a viewing angle of 90° in the jet rest frame. This is precisely the combination of pitch angle and viewing angle that is required in the helical-field CP model to obtain roughly symmetrical regions of positive and negative CP on opposite sides of the jet, as is reported in [20]. 1334−127 is one of a minority of AGN classified as BL Lac objects whose inner-jet **B** fields are predominantly longitudinal, indicating that, if its jet has a helical field, the pitch angle is not greater than about 45° (i.e., the longitudinal component of the helical field is stronger than the toroidal component). Furthermore, the field is predominantly longitudinal in the VLBI core: quasi-simultaneous optical and 15+22+43-GHz VLBA polarization observations showed that the optical and Faraday-rotation-corrected VLBI core polarization angles were aligned to within 5°, with both being orthgonal to the jet direction [4]; since the optical emission is clearly optically thin, this implies a longitudinal core **B** field. Thus, the observed transverse CP structure in 1334−127 is also consistent with its linear polarisation structure: the simple helical-field CP model of [5] predicts that CP of a single sign that is displaced toward one edge of the jet should be observed for jets whose helical fields have pitch angles somewhat less than $\simeq 45°$ and are viewed at angles not too different from $\simeq 90°$ in the jet rest frame.

Thus, the 43-GHz CP images for 1334−127 and 1055+018 provide tantalizing evidence that a self-consistent picture of the observed intensity, linear polarisation and circular polarisation structures may be beginning to emerge. While this is somewhat speculative at the moment, these results certainly indicate the value of further high-resolution CP measurements, as well as the development of further techniques for testing the reality of tentatively detected transverse structures.

References

[1] Attridge J. M., Roberts D. H. & Wardle J. F. C. 1999, ApJ, 518, L87

[2] Beckert T. & Falcke H. 2002, A&A, 388, 1106

[3] Blandford R. D. & Königl A. 1979, ApJ, 232, 34

[4] Gabuzda D. C., Rastorgueva E. A., Smith P. S. & O'Sullivan S. P. 2006, MNRAS, 369, 1596

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

[6] Homan D. C., Attridge J. M. & Wardle J. F. C. 2001, ApJ, 556, 113

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

[8] Homan D. C., Lister M. L., Aller H.D., Aller M. F. & Wardle J. F. C. 2009, ApJ, in press

[9] Homan D. H. & Wardle J. F. C. 2004, ApJ, 602, L13

[10] Homan D. C. & Wardle J. F. C. 1999, AJ, 118, 1942

[11] Jones T. W. 1988, ApJ, 332, 678

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

[13] Legg M. P. C. & Westfold K. C. 1968, ApJ, 154, 499

[14] Lobanov A. P. 1998, A&A, 330, 79

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

[16] O'Sullivan S. P. & Gabuzda D. C. 2009, these proceedings

[17] Pacholczyk A. G. 1970, *Radio Astrophysics. Non-thermal Processes in Galactic and Extragalactic Sources* (San Francisco, Freeman)

[18] Pushkarev A. B., Gabuzda D. C., Vetukhnovskaya Yu. N. & Yakimov V. E. 2005, MNRAS, 356, 859

[19] Vitrishchak V. M. & Gabuzda D. C. 2007, Astronomy Reports, 51, 695

[20] Vitrishchak V. M., Gabuzda D. C., Algaba J.C., Rastorgueva E. A., O'Sullivan S. P. & O'Dowd A. 2008, MNRAS, 391, 124

[21] Wardle J. F. C. & Homan D. A. 2003, in *Circular Polarisation from Relativistic Jet Sources*, Astrophys. Space Sci., 288, 143