Circular polarization of AGNs on the parsec VLBI scales

V. M. Vitrishchak[1], *I. N. Pashchenko*[2], *D. C. Gabuzda*[3]

[1]Sternberg Astronomical Institute, Moscow State University, Universitetsky pr., 13, 119992, Moscow, Russia
[2]Astro Space Center of Lebedev Physical Institute of RAS, Profsoyuznaya st. 84/32, 117997, Moscow, Russia
[3]University College Cork, College Road, Cork, Ireland
vmv@pisem.net

Faraday effects possibly plays the major role in generation of circular polarization observed on Very Long Base Interferometry scales. Multi-frequency circular polarization measurementrs can become the desired breakthrough in understanding the active galactic nuclei jet physics and the only possibility to estimate some of their vital parameters. We review the possible mechanisms of circular polarization generation and their connection to the jet parameters. We throw a glimpse on the methods of data reduction and finally discuss our current observational progress and its possible interpretation.

Introduction

Since the begin of the Very Long Base Interferometry (VLBI) epoch in observations of active galactic nuclei (AGNs) lots of types of data became available. Mapping with the highest resolution up to tens of microseconds, simultaneous multi-frequency observations, high temporal resolution techniques, linear polarization and rotation measure studies give us terabytes of information on AGNs. Still, even the key properties and parameters of these sources remain unknown or uncertain (e. g., jet plasma composition, magnetic field geometry, mechanism responsible for jet generation etc.). These problems are not only technical, but sometimes principal. For example linearly polarized (LP) emission from the source to the observer is experiencing very significant impact of external effects, such as an external Faraday rotation of the polarization plane and the related effect of external depolarization. By observating LP and full intensity alone it is very difficult or even impossible to separate the external and internal propagation effects [2] and thus to study the physics of AGN jets. On the contrary, the influence of external effects on the circular polarization component can be neglected [1]. Thus, the observed circular polarization is related solely to the internal processes of the AGN emission. Since the signal circular polarization (CP) is dependent on a number of emission parameters — composition of matter, properties of the magnetic field, the presence in the energy spectrum of the low energetic relativistic particles, etc. it opens the new possibility of estimating these parameters with the help of CP observations.

Circular polarization

Circular polarization studies are the latest trend of astrophysical VLBI observations of AGNs. Data processing in this case is complicated because the degree of CP in AGNs even at linear scales of the order of parsecs rarely reaches 1%. Despite its low degrees, CP can become a new key for estimating various vital AGN parameters, which cannot be obtained otherwise. There are two mechanisms of CP generation which likely dominate in AGN jets [12]:

a) direct synchrotron emission, and
b) conversion from linear polarization (LP), which can have 2 modes:
b.1) conversion in changing perpendicular B-field, and
b.2) conversion driven by internal Faraday rotation.

In synchrotron emission each charged particle gyrating around magnetic field line radiates elliptically polarized electro-magnetic waves. Emission of full ensemble of particles is highly linearly polarized, but small amount of circular component is also emitted [8]. Direct synchrotron emission of typically observed CP levels requires strong ordered magnetic fields in radiating regions (CP $\sim B_{||}^{1/2}$, e.g. 10^{-2} G is needed to generate 1% CP in the homogeneous source) and only works in normal e^-–p^+ plasma as electrons and positrons emit the same CP signal with opposite signs.

In Faraday conversion mechanism, initially linearly polarized emission is being converted into circularly polarized and vice versa when passing through magnetized media with transverse magnetic field component. We can split our emission into two orthogonal modes — one parallel and one perpendicular to the transverse (to the wave propagation vector) projection of the magnetic field vector. The parallel linear mode is delayed as it accelerates charged particles which then reemit the waves, while the perpendicular mode is left unchanged as charged particles cannot freely move perpendicular to magnetic field lines and thus are not accelerated in this direction by the passing emission. The resulting emission on the exit of the medium is generally elliptically polarized. Faraday conversion (or Cotton-Mutton effect) works in electron-positron plasma as electrons and positrons contribute to the effect with the same sign.

Note that if only one of the modes was initially present in the linearly polarized wave (that is only parallel or perpendicular to the transverse projection of the B-field in the medium) no conversion would take place. As long as synchrotron emission is highly linearly polarized with the polarization plane perpendicular to the local generating magnetic field, intrinsic conversion of linear polarization inside the emitting synchrotron source itself can only happen if the polarization plane or/and transverse projection of the magnetic field are changing along the wave path. In the first case Faraday rotation can do the job, requiring normal electron-proton plasma and longitudal B-field component to be present. In the second case the direction of transverse B-field should be changing inside the source still remaining ordered (there will be no conversion but only depolarization in totally random unordered field).

Due to extremely low radiative transfer coefficients in interstellar medium [7], CP is immune to propagation effects (which, on the contrary, can totally distort linear polarization on the way from the source to the observer). This property along with the strong dependence of CP on the intrinsic parameters of the source (like jet plasma composition, density, particle energy distribution, magnetic field properties etc.) makes CP a good mean of estimating these parameters. Details can be found in [5].

Data reduction

As it was mentioned above, the typical degrees of CP in AGNs on the parsec scales rarely exceed 1% which makes it a real challenge to detect and measure CP signal from these sources. First results in this direction were obtained in 1999 [6]. The proposed gain transfer method [3] followed by separate “RR/LL calibration” [9] is the most fruitful technique of CP calibration so far, giving up to 30% CP detection rate for AGN objects with the 2σ criteria. Only two major CP parsec-scale AGN surveys exist up to date (see [4, 9, 10].

Current progress

According to current observational data [4, 9, 10] typical CP degrees in the VLBI core region are usually less then several tenths of a percent (0.86% in 3C279 is maximum so far). CP degrees on the jet edges (if observed) reach several percents. If CP is generated directly via synchrotron emission, very strong B-fields (~ 1 G) are required to create such high degrees. In most cases CP is observed in the optically thick VLBI core. CP peak is sometimes shifted from the full intensity peak towards the supermassive black hole — to even more optically thick regions. This is consistent with all CP generation mechanisms and states that intrinsic depolarization is weak and thus highly ordered B-field presents in the jets. Internal Faraday rotation is small or absent (which is more likely). It favors e^-–e^+ jet plasma composition and thus enabling only the mechanism of CP generation through Faraday conversion in changing B-field. Prolonged CP structures stretching from optically thick VLBI core to optically thin inner jet are detected for several sources. It shows that CP generation works within wide range of plasma parameters also favoring e^-–e^+ jet plasma composition as internal Faraday rotation working only in normal e^-–p^+ plasma is very sensitive to the intrinsic source parameters. Anti-symmetric CP structures with high degrees and different signs of CP on the different edges of jet were detected in some of the sources. Toroidal B-field component (typical for toroidal or spiral B-field geometries) should be present to explain such polarization pictures which also means that (at least) CP generation via conversion in changing B-field works for sure.

For all the sources observed at several epochs the sign of CP persisted throughout the epochs. For most of the sources CP degree persisted as well (within the error limits). This states that jet parameters responsible for CP generation (e.g. ordered B-field geometry) are persistent on the timescales of at least several years. For several objects changes in CP signal correlat with the major changes in the total source flux between the epochs. It can related to the CP variability, blazar activity and emerging of a new jet component. No obvious common CP frequency dependence was found so far. Only few sources have shown the $V_{peak} \sim \nu^2$ dependence (typical for direct CP generation via synchrotron emission), also stating that conversion mechanism(s) dominate in most of the sources. Various sources show sign changes with frequency that can also be explained by conversion mechanism. Difference in CP degrees was found for quasars and BL Lacertae type objects; the latter shows the lack of objects with high ($> 0.4\%$) CP degrees which can be explained by various reasons concerning the physical differences between these two classes of objects [11].

Conclusions

Generated CP signal is sensitive to many internal parameters of AGN jets: plasma composition, particle energy distribution and acceleration mechanism, magnetic field properties etc. Together with the other data, CP can be used to estimate these parameters. The most likely mechanism of CP generation is conversion from the linear polarization while propagating through the medium with changing transverse B-field along the line of sight. While some important qualitative conclusions can be made even now (like the evidence of toroidal magnetic field component in AGN jets), it is clear that the most promising way lies through numerical modeling of AGN jets, solving the radiation transfer problem and comparing the results with real observations. AGN CP database is still in its stone age and needs lots to be done to effectively use it in statistical studies.

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