

Article

High-Frequency Polarization Variability from Active Galactic Nuclei

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Abstract: The linear polarization of non-thermal emission encodes information about the structure of the magnetic fields, either from the region where the emission is produced (i.e., the intrinsic polarization angle) and/or from the screens of magnetized plasma that may be located on its way towards Earth (i.e., the effect of Faraday rotation). In addition, the variability timescale of the polarized emission, or its Faraday rotation, can be used to estimate the size of the region where the emission (or the Faraday rotation) originates. The observation of polarized emission from active galactic nuclei (AGN) and, in particular, its time evolution, also provides information about the critical role that magnetic fields may play in the process of jet launching and propagation. In this paper, we review some recent results about polarization variability from the cores of AGN jets, including observations at high spatial resolutions and/or at high radio frequencies.

Keywords: polarization; quasars; blazars; gamma rays; general



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1. Introduction

According to the current paradigm of a relativistic outflow from an active galactic nucleus (AGN), a fraction of the matter being accreted by the supermassive black hole (SMBH), located at the AGN's central engine, is ejected from the innermost part of the accretion disc in a direction roughly aligned to the rotation axis of the system, instead of falling into the deep gravity well of the SMBH. The large amount of energy needed to escape from the SMBH gravitational potential may come from different sources. On the one hand, the energy could be extracted from the dynamics of the accretion disc itself (the Blandford–Payne mechanism [1]), via the action of Lorentz force from magnetic fields that permeate the disc. This mechanism produces relatively wide and slow jet streams. On the other hand, a larger amount of energy could be tapped from the rotating SMBH (the Blandford–Znajek mechanism [2]), via the action of poloidal magnetic fields on the plasma that is orbiting inside the ergosphere. This mechanism produces narrower and faster streams.

Regardless of the dominant mechanism that boosts the plasma into the jet stream, magnetic fields are a key ingredient to produce the jets that are observed in radio-loud AGN. In the presence of such strong magnetic fields, the energetic plasma particles radiate non-thermal (synchrotron) emission, which can reach very high brightness temperatures (as high as 10^{10-13} K; e.g., [3,4]), especially in the compact core regions close to the jet base. Synchrotron emission can be strongly polarized, with an electric-vector position angle (EVPA) either perpendicular (in optically-thin media) or parallel (in media with high opacities) to the local magnetic field. Hence, by studying the distribution and strength of the polarized emission brightness in AGN jets, it is possible to probe the structures of the magnetic fields (as well as the physical conditions of the plasma) in those regions.

One of the main limitations of the observational studies of magnetic fields at the jet-launching regions of AGN (i.e., where the plasma is boosted into the jet stream) is the

strong opacity to the emission at long (centimeter) wavelengths. The plasma density and the magnetic-field strength in a jet decrease with distance from the SMBH (e.g., [5]). Given that higher plasma densities and stronger magnetic fields imply higher opacities to the radio emission [6], radio images of AGN jets will depend on the observing frequency. In particular, the lower the observing frequency, the farther the brightness peak will be from the jet base (an effect known as “core-shift” [7]).

Because of opacity, the only way to obtain information about the magnetic field at the base of an AGN jet is to observe the polarization at radio-frequencies sufficiently high to overcome the synchrotron self-absorption. Typically, AGN jets become fully optically thin in the range of millimeter/sub-millimeter wavelengths (e.g., [8]), where relatively fast polarization variability has been reported (timescales as short as intra-hour; refs. [9–11]). However, the capability to observe rapid polarization variability at these short wavelengths has been limited, until very recently, by the sensitivity of the telescopes. The emergence of new receiver backends (with bandwidths of several GHz) and the advent of the Atacama Large mm/submm Array (ALMA), effectively the most powerful radio telescope in the world at (sub)mm wavelengths, have opened a new window to the study of accretion and jet formation in AGN from time-resolved polarization observations. In addition, the extremely high spatial resolution achievable with very long baseline interferometry (VLBI) at mm-waves, chiefly with the event horizon telescope (EHT), allows us to image the fine structures of magnetic fields in the accretion discs on event horizon scales (within a few Schwarzschild radii or R_{Sch}) for the SMBHs with the largest apparent sizes in the sky [12] as well as at the base of jets on sub-pc scales for other AGNs.

In this article, we review some recent observational results of AGN polarimetry at mm/submm wavelengths, focusing on the time variability of the signals, and discuss the implications for the current state-of-the-art models of AGN jets. In Section 2, we briefly describe the geometry of the plasma and magnetic-field distribution in the region close to an AGN core. We discuss how different components of the AGN system may affect the polarization intensity and Faraday rotation, according to the current AGN models. In Section 3, we discuss how time-resolved polarization observations can help us to constrain the models described in Section 2, and review some key observational results. In Section 4, we summarize our conclusions.

2. Simplified Model of the Jet Base of an AGN

A simplified model of the jet-launching region of an AGN is sketched in Figure 1 (left). The figure includes several features that may (or may not) be present in all the AGN jets, but whose existence has been suggested from several observations targeting specific sources. In the following, we will focus our description on three features depicted in Figure 1: the jet (blue to red gradient and gray colors), the magnetic field (black lines), and the disk-like accretion flow (dark and light magenta).

The sketch in Figure 1 displays a “stratified” jet model, including an inner region, the so-called “jet spine”, and an outer boundary layer, the so-called “jet sheath”. In the jet spine, the plasma speed is relativistic and particles might be accelerated either via the Blandford–Znajek or the Blandford–Payne mechanism; in the jet sheath, the particle propagation is only mildly relativistic and might be associated either to outer winds and/or to the Blandford–Payne mechanism. Such a kinematic stratification has been detected, for instance, in the M 87 galaxy [13], although the association of the (faster) central jet stream to the spine is not conclusive, since the higher Doppler boosting in the spine predicts a ridge-brightening of the jet downstream from the core, which is not observed. A possible explanation to this issue is that the true emission region is located at the interface between the spine and the sheath (where Fermi particle acceleration may be more efficient), hence producing a lower brightness contrast in the jet stratification [14].

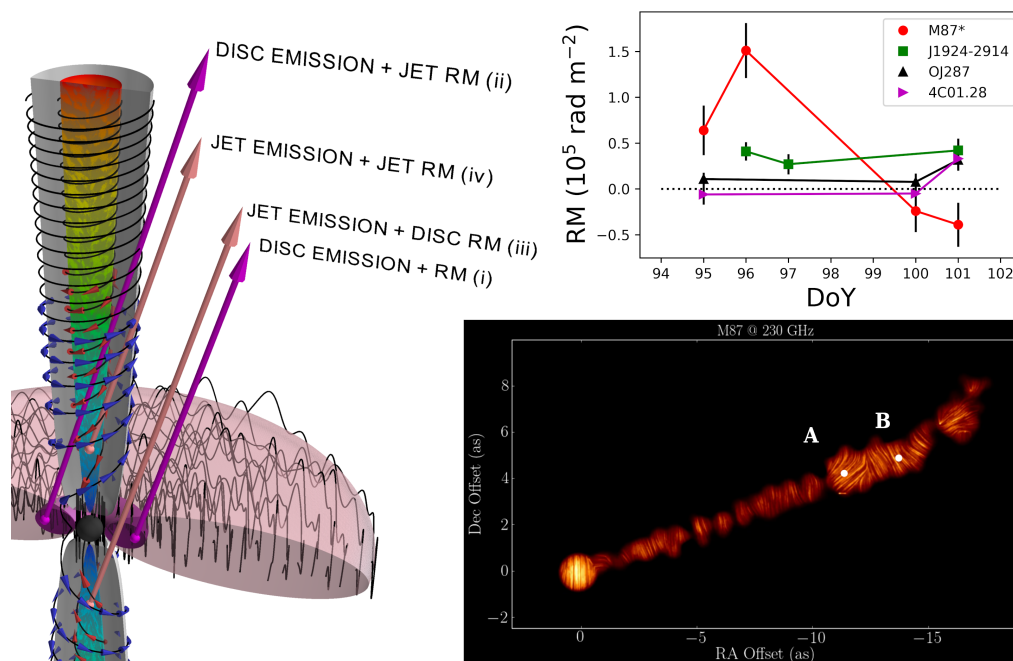


Figure 1. (Left) sketch of the core region of an AGN. Black lines represent the magnetic field (the blue arrow heads indicate the \vec{B} direction in the outer jet; the red arrow heads indicate the \vec{B} direction in the inner jet). The jet spine is colored representing synchrotron self-absorption (i.e., colors corresponding to higher frequencies come from regions closer to the SMBH) and is surrounded by a jet sheath (in gray). The accretion flow is shown in light (outer part) and dark (inner part) magenta. The thick arrows indicate the possible paths followed by non-thermal emission on its way towards Earth. Figure not to scale. (Top right) time evolution of the RM measured for several AGN observed with ALMA in 5–11 April 2017 [15]. (Bottom right) ALMA image of M87 at 230 GHz in full polarization [15], plotted using the algorithm used in [12] (see their Figure 7). The location of the A and B jet knots is marked with white points.

Regarding the structure of the magnetic field in the jet, there is strong observational evidence of helical structures in many AGN jets (e.g., [16]), in agreement with most of the theoretical models of electromagnetic jet launching (e.g., [17]). In Figure 1, we have sketched the jet magnetic field with two nested helical components wrapping around the jet. This specific configuration is inspired by the so-called “cosmic battery” model. Such magnetic structures are expected to be caused by differential rotation in the accretion disk based on the Poynting–Robertson effect [18], where the outer part always produces an outward electric current, whereas the inner part always produces an inward current. We notice that the nexus between the two nested helical components does not have to correspond to the interface between spine and sheath (as it is suggested by Figure 1, left). In addition, the longitudinal jet structure may not be smooth (as also suggested by the sketch). Shocks may develop along the jet stream, due to recollimation of the flow (caused by the pressure gradient in the ambient medium) or to MHD effects (e.g., [19]). In these shocks, the \vec{B} structure can change dramatically (e.g., the A/B knots in the M87 jet, Figure 1, bottom right). In some cases, efficient particle acceleration may take place in the shocks, producing emission from radio up to γ -rays [20], as we briefly discuss in Section 3.2.

Finally, the accretion disc (shown as light and dark magenta in Figure 1, left) is also permeated by a magnetic field. The actual shape of the disc and the spatial distribution of \vec{B} strongly depend on the accretion state of the SMBH. For instance, if the disc is radiatively inefficient, there is a high radiation pressure and the disc becomes geometrically thick; this is often described in terms of adiabatic accretion flows (ADAF) [21]. However, if the disc is geometrically thin, the timescale for dissipating (via radiation) the energy delivered by the viscous stress may become shorter than the accretion timescale, resulting

in a radiatively efficient (hence cooler) disc [22]. The structure of the magnetic field will depend on the role of the magnetic flux in the dynamics of the accretion flow. The two possible scenarios are the Magnetically Arrested Disc (MAD) and the Standard and Normal Evolution (SANE) (e.g., [23]). The former produces more ordered \vec{B} configurations (i.e., with higher power on the larger spatial scales), whereas the latter is more dominated by turbulence at smaller scales. The different geometries of accretion discs and the spatial structures of their associated magnetic fields may result in very different polarization imprints in the light that is crossing these regions, due to Faraday rotation.

3. Polarization Variability and AGN Jet Models

3.1. Faraday Rotation

Rotation Measure (RM) is a frequency-dependent rotation of the EVPA, produced by the propagation of light along the magnetic-field lines in an ionized non-relativistic plasma (the RM is heavily suppressed in relativistic plasmas, ref. [24]). The regions of low energy plasmas in AGN, where the RM can be naturally produced, are the accretion flow and the jet sheath. Rapid variability in the rotation measure (RM) at millimeter wavelengths may be interpreted in different ways depending on the relative location of the emitting and Faraday rotating sources. The sketch in Figure 1 showcases four possible origins of the emission and Faraday rotation in an AGN: (i) the emission and the Faraday rotation are both produced in the accretion flow; (ii) the emission is produced in the accretion flow and the Faraday rotation occurs in the jet sheath; (iii) the emission is produced in the counter-jet (i.e., the jet receding from the observer) and the Faraday rotation occurs in the accretion flow; (iv) the emission is produced in the approaching or forward-jet and the Faraday rotation occurs in the jet sheath.

Let us first consider a scenario where the disc is geometrically thick (i.e., radiatively inefficient, as in the ADAF) and strongly magnetized. In this case, the emission coming from the counter-jet (and/or from the inner side of the disc) may be affected by Faraday rotation from the disc (cases (i) and (iii) above). Since the RM is proportional to the amount of plasma (and \vec{B} strength) along the line of sight (LOS), measuring the RM in this case is a probe of the disc density (provided that we know its size along the LOS) and, hence, of the accretion rate. This is a simplified reasoning that assumes a dynamic timescale for the plasma much shorter than that of \vec{B} . Under such an assumption, the timescale of the RM variability would be related to the dynamical time of the orbiting material, which sets strong constraints on the size of the accreting magnetized medium that is responsible for the Faraday rotation. More rigorous analyses of RM variability should account for turbulence and magnetic-field structure variations in the accretion flow, based on realistic simulations [25]. This strategy has been applied to Sgr A*, where the RM variability has been used to probe the magnetized accretion flow on scales from tens of R_{Sch} (on timescales of hours) out to the Bondi radius $\sim 10^5 R_{Sch}$ (on timescales of months) [26].

In an alternative scenario, the RM can be dominated by the slow wind around the jet (the contribution of relativistic plasma to the RM is negligible [27]), whilst the polarized emission can come either from the disc or from the jet itself (cases (ii) and (iv) above). In this case, the RM variability may be related either to structural changes in \vec{B} and/or to changes in the wind density. This case applies to AGN with smaller viewing angles (e.g., [9,28]), where the disc contribution to the RM is expected to be small (even for geometrically-thick discs) as compared to that from the jet. There are even cases of RM sign reversals detected in some AGN jets [29], which could be explained by changes in the relative strength of two nested \vec{B} helical components. In such a model, the outer helical field, with poloidal magnetic field component oriented in the observer's direction, would produce a positive RM while the inner helical field, with opposite magnetic field direction, would produce a negative RM, and the sign of the total (measured) RM will depend on which component dominates.

Finally, for sources with intermediate viewing angles with respect to the jet direction, either the disk or the jet/wind can dominate the RM and its variability. A good example is

the AGN in M87 [15]. On the one hand, if it originated in the disc, the RM would in principle be usable to probe the accretion rate, as long as the disc is radiatively inefficient [30]. However, the rapid variability of the RM observed on timescales of days ([15], see also Figure 1), implies that the RM should occur at distances to the SMBH much smaller than the Bondi radius (i.e., the expected size of the accretion flow), which would in turn imply that the RM cannot be used to probe the conditions of the accretion flow [15]. In an alternative scenario, an inhomogeneous Faraday screen might be located further away from the disc; in such a case, the RM variability could be due to rapid changes in the emitting source structure. All these different scenarios are discussed in [15].

3.2. Polarization and High-Energy Emission

Regions where the magnetic field is turbulent and/or has large spatial gradients (as it happens in magneto-hydrodynamic, MHD, shocks) are the perfect loci for efficient particle acceleration (e.g., [6]). This in turn can result in high-energy γ -ray emission due to Compton upscattering (e.g., [31,32]). The study of correlations between the time-varying polarization and γ -ray emission from AGN can thus provide valuable information about the rapid MHD effects (e.g., shocks) that are taking place in the magnetized plasma of a jet. Despite being a powerful probe of the physics in relativistic jets, the radio-to- γ -ray correlation has not been fully exploited yet (e.g., [33,34]).

A rather particular source where sub-millimeter polarimetry has been studied in connection to the high-energy emission is the gravitational lens PKS 1830–211. This lens generates two different AGN images (named NE and SW), with a time delay of about 26 days (NE leading, ref. [35]). It is worth noting that (since the AGN is a variable γ -ray emitter) this time delay has also been detected from the γ -ray variability [36].

ALMA observations of PKS 1830–211 allowed us to accurately detect the radio counterpart of a γ -ray event in the year 2013 [37]. Later, these ALMA data revealed polarization variability (and a high RM) related to that same γ -ray event [9].

In spring 2019, a record-breaking γ -ray flare took place in PKS 1830–211. By serendipity, ALMA scheduled full-polarization observations at 230 GHz very close to the peak of γ -ray activity [11]. Even though the observations took place close to the peak of the flare, the SW image is delayed by about 26 days, so that it reflected the status of the AGN just at the beginning of the flare (see Figure 2, right). The variability analysis of the ALMA data showed two very different behaviors for NE and SW (Figure 2, left and center). On the one hand, NE shows very low polarization variability, with a hint of a decrease in Q. On the other hand, SW shows a very clear linear drift in the Q-U plane during the very short duration of the experiment (about 2 h). A clear conclusion is that the region responsible of this variability in the AGN was relatively compact and strongly dynamic during the onset of the γ -ray flare. Then, close to γ -ray peak, the polarization variability was much weaker. Models of γ -ray emission from AGN jets should take into account this behavior.

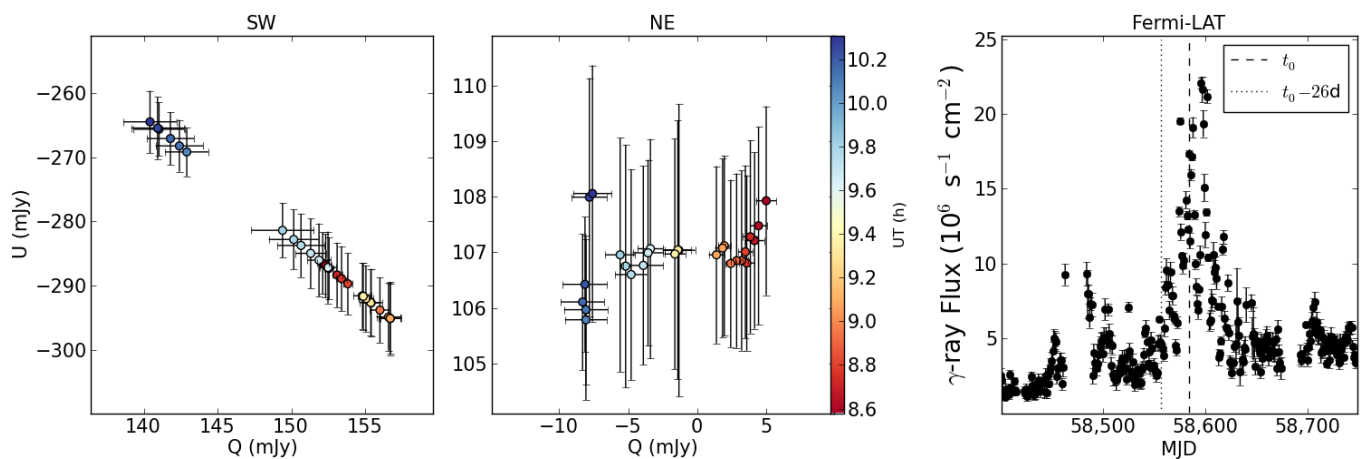


Figure 2. Left and center panels, Q vs. U plots for the SW and NE images of PKS 1830–211, as observed by ALMA at 230 GHz. Colors encode the observing time (only one epoch with a duration of 2 h). Right panel, lightcurve in γ -rays as observed by Fermi-LAT. The observing time (t_0 , which corresponds to the NE image) is marked as a dashed line and the delayed time (i.e., $t_0 - 26$ days, which corresponds to the SW image) is marked as dotted line.

4. Summary

The high sensitivities of modern mm/submm telescopes, chiefly ALMA, allow us to study the time-variable polarization of the non-thermal emission originated at the jet-launching regions of AGN, which are optically thin at these short wavelengths (blending effects within the finite telescope beam may add contributions from more extended components of the AGN jets, though the signal will be dominated by the core). These observations encode information about the magnetic fields and plasma densities in the strong gravity regime at the vicinity of SMBHs. Polarization observations can be used to probe the accretion of matter onto the AGN and the mechanisms responsible for the jet formation, acceleration and collimation. Polarization time variability can also be used to estimate the size of both the emitting source and the Faraday-rotating screen, and to study the role of magnetic fields in the process of efficient particle acceleration (and γ -ray production) within the jets.

Finally, observations at the highest spatial resolutions, now possible with the EHT and other mm VLBI arrays, may allow us to directly probe the structure of the hot magnetized plasma in the accretion disc and/or at the jet base in the immediate vicinity of SMBHs. These efforts combined hold the promise to address one of the main open questions in modern astrophysics concerning the launching mechanisms of astrophysical jets.

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Abbreviations

The following abbreviations are used in this manuscript:

AGN	Active Galactic Nucleus
ALMA	Atacama Large mm/submm Array
EHT	Event Horizon Telescope
EVPA	Electric-Vector Position Angle
LOS	Line of Sight
MAD	Magnetically Arrested Disc
MHD	Magneto-Hydrodynamics
NE	North East
RM	Rotation Measure
SANE	Standard Furthermore, Normal Evolution
SMBH	Supermassive Black Hole
SW	South West
VLBI	Very Long Baseline Interferometry

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