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X-ray polarization from relativistic jets–the blazar 1ES 1959+650 seen by IXPE

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We present a summary of X-ray polarization measurements of blazars obtained with the Imaging X-ray Polarimetry Explorer (IXPE) during its first three years of operation. These observations reveal significant X-ray polarization in high-synchrotron-peaked (HSP) blazars, with degrees of polarization ranging from approximately 6% to over 30%, and polarization angles generally aligned with the projected jet direction. In contrast, low-synchrotron-peaked (LSP) blazars exhibit low or undetectable X-ray polarization except during flaring states dominated by synchrotron emission. We highlight recent results from 1ES 1959+650, which show variable X-ray polarization and rapid rotations of the polarization angle, indicating a dynamic, turbulence-influenced magnetic field structure. Overall, the IXPE findings support models in which X-ray emission originates from compact regions with partially ordered magnetic fields, embedded within a larger-scale turbulent jet environment. These results provide new insights into the geometry, dynamics, and particle acceleration processes in relativistic blazar jets.

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1. Introduction

High Synchrotron Peaked (HSP) blazars are a subclass of blazars characterized by radio to X-ray continuum emission peak occurring at high frequencies, typically in the ultraviolet to X-ray bands. These blazars are known for their rapid variability, strong polarization, and broad nonthermal spectra that result from relativistic jets pointed close to our line of sight. The synchrotron radiation that dominates the X-ray flux in HSP blazars is expected to be polarized. The degree of polarization, the polarization angle, and the dynamics of the polarized flux provide information about the level of order, the intensity, and the dynamics of the jet magnetic field in the radiation zone where the most energetic electrons in the jet cool. The high-energy emission in HSP blazars is thought to be dominated by synchrotron self-Compton processes, where photons are scattered to higher energies by the same population of electrons that produce the synchrotron radiation.

The Imaging X-ray Polarimetry Explorer (*IXPE*, [1]) is an X-ray observatory that was launched on December 9, 2021. Developed collaboratively by NASA and the Italian Space Agency (ASI), *IXPE* is the first mission dedicated to measuring the polarization of cosmic X-rays, providing insight into the extreme environments surrounding neutron stars, black holes, relativistic jets, and supernova remnants. Sensitive in the 2–8 keV energy range, *IXPE* employs three identical telescopes equipped with polarization-sensitive X-ray detectors [2]. The observatory's design includes a deployable 4-meter boom to achieve the necessary focal length for its Wolter Type-I X-ray optics.

The sensitivity of an instrument to characterize the polarization state of incoming X-ray photons is quantified by the *Minimum Detectable Polarization* (*MDP*). It represents the smallest degree of linear polarization that can be distinguished from statistical noise at a specific confidence level, which is commonly chosen as 99%. The *MDP* is given by [3]:

$$MDP_{99} = \frac{4.29}{\mu R_S}\sqrt{\frac{R_S + R_B}{T}}, \tag{1}$$

where μ is the modulation factor (indicating the instrument's efficiency in detecting polarization), R_S is the source count rate, R_B is the background count rate, and T is the total observation time. For bright sources with X-ray flux near 10^{-10} erg cm^{-2} s^{-1} in the 2-8 keV band, *IXPE* achieves $MDP_{99} \leq 8\%$ in 50 ksec of exposure [4].

IXPE has targeted a number of HBLs as well as other blazars during the first three years of its mission. A summary of the main results from these observations is shown in Table 1.

2. Observational properties of blazar jets

2.1 Degree of X-ray polarization

The X-ray degree of polarization Π_x observed in blazars with IXPE shows significant variance, ranging from values as low as 6–10% to extremes where $\Pi_x \leq 30\%$. HSP blazars, such as Mrk 421, Mrk 501, and PKS 2155-304, consistently exhibit measurable polarization, often above 10%, whereas low-synchrotron-peaked (LSP) sources like 3C 273 and 3C 279 only show upper limits. In LSP objects, the 2-8 keV radiation often attributed to Compton scattering, which under most scenarios it would be expected to be unpolarized. The only LSP object for which a significant degree of polarization was detected was during a flare of BL Lacertae in which the soft X-ray

Table 1: X-ray polarization properties of blazars observed with *IXPE*.

Source	Class	Reference	X-ray polarization	$\lvert\Psi_x - \phi_{jet}\rvert$
1ES 0229+200	HSP	[5]	18% ± 3%	40° ± 9°
S5 0716+714	ISP	[6]	< 26%	
Mrk 421	HSP	[7]	15% ± 2%	21° ± 11°
Mrk 421	HSP	[8]	15% ± 2%	21° ± 15°
			10% ± 1%	$\dot{\Psi}_x = 80 \pm 9°$/day
			10% ± 1%	$\dot{\Psi}_x = 91 \pm 8°$/day
Mrk 421	HSP	[9]	14% ± 1%	93° ± 14°
3C 273	LSP	[6]	< 9%	
3C 279	LSP	[6]	< 13%	
Mrk 501	HSP	[10]	10% ± 2%, 11% ± 2%	14° ± 13°, 5° ± 13°
Mrk 501	HSP	[11]	7% ± 2%, 9% ± 2%	14° ± 14°, 10° ± 14°
			6% ± 2%, 19% ± 2%	13° ± 14°, 17° ± 12°
PG 1553+113	HSP	[12]	10% ± 2%	46° ± 13°
1ES 1959+650	HSP	[4]	8% ± 2%, < 5%	15° ± 19°
1ES 1959+650	HSP	[13]	9% ± 2%, 12% ± 1%	70° ± 7°, 45° ± 3°
PKS 2155-304	HSP	[14]	31% ± 2%, 15% ± 2%	10° ± 30°
BL Lac	LSP	[15]	< 12.6%	
BL Lac flare	LSP	[16]	$22\%^{+6\%}_{-8\%}$	38° ± 10°
3C 454.3	LSP	[6]	< 28%, < 10%	

spectrum indicates emission temporarily dominated by synchrotron radiation, which yielded a polarization measurement of $\Pi_x = 22\%^{+6\%}_{-8\%}$.

2.2 Polarization angle

The last column quantifies the angular difference between the X-ray polarization angle (Ψ_x) and the projected direction of the radio jet on the sky (ϕ_{jet}). For most HSP blazars, this offset is relatively small, typically within 20° to 40°, indicating a general alignment between the X-ray polarization vector and the jet axis. An alignment between the X-ray polarization angle and the projected jet direction provides strong evidence for an ordered magnetic field structure within the jet. When the jet has a parabolic geometry, the magnetic field in the jet rest frame is assumed to be predominantly toroidal, appearing perpendicular to the axis of the jet projected on the sky. Since synchrotron radiation is polarized perpendicular to the magnetic field lines, this scenario would cause the polarization angle to closely align with the projected jet direction [17].

Notably, Mrk 421 shows consistent angles around 20° across different observations [7, 8], while showing an outlier in a later observation with a deviation as large as $\lvert\Psi_x - \phi_{jet}\rvert = 93° \pm 14°$ [9], suggesting significant dynamic changes or a misaligned magnetic field component during that epoch. Overall, *IXPE* observations of HSP blazars imply that X-ray polarization is often aligned with the jet, but transient deviations can occur.

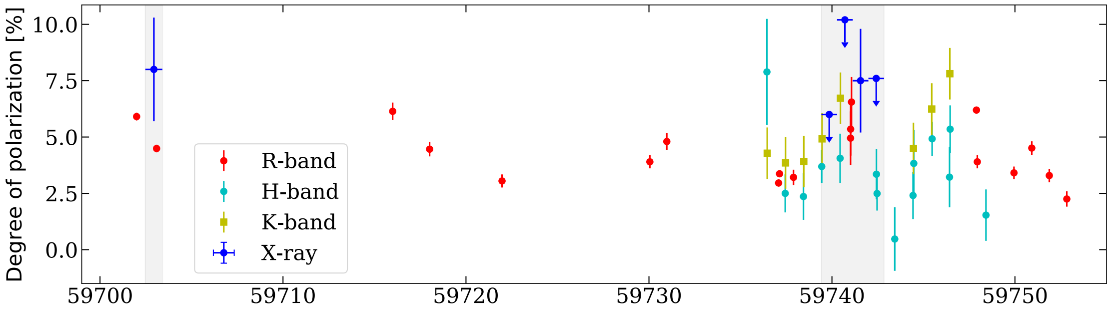

Figure 1: X-ray, optical, and IR light curves contemporaneous with the *IXPE* observations of 1ES 1959+650in May and June of 2022. Blue data points represent significant measurements of X-ray polarization, while blue downward-pointing arrows indicate 99% confidence level upper limits during time periods without a significant detection X-ray polarization. Grey vertical shaded areas indicate the two epochs of observation of *IXPE*.

2.3 X-ray polarization dynamics

The most notable dynamical feature in the polarization of the X-ray emission from a blazar that has been observed to date is the coherent rotation in the X-ray polarization angle observed in the blazar Mrk 421 over a 5-day period in June of 2022 [8]. The polarization angle was observed to rotate at with a rate in the range of $\dot{\Psi}_x \sim 90^\circ\ \mathrm{day}^{-1}$. The degree of polarization was more or less constant at $\Pi_x = 10\% \pm 1\%$.

3. X-ray polarization of the blazar 1ES 1959+650

IXPE conducted two campaigns on the blazar 1ES 1959+650in 2022, during its first six months of operations. The campaigns were conducted in May 3–4, 2022 (54 ks) and June 9–12, 2022 (200 ks). On May 3–4, a significant linear polarization degree of $\Pi_x = 8.0\% \pm 2.3\%$ was detected in the 2–8 keV band, with a polarization angle of $\Psi_x = 123^\circ \pm 8^\circ$. No significant polarization was detected during the June campaign, with a 99% upper limit of $\Pi_x < 5.1\%$ (Figure 1).

Simultaneous optical observations show a polarization degree of $\Pi_o \sim 5\%$. In the May epoch, $\Pi_x/\Pi_o = 1.8 \pm 0.5$, lower than the ratio measured in Mrk 421 (~ 5; [7]) but similar to Mrk 501 (~ 2.5; [10]). During the June epoch, $\Pi_x/\Pi_o \lesssim 1$, with the optical polarization angle appearing to swing during the *IXPE* observation window.

The detection of X-ray polarization from 1ES 1959+650confirms the synchrotron origin of the X-ray emission in HSPs. The measured Π_x value and Π_x/Π_o ratio suggest that in 1ES 1959+650, as in Mrk 501, the X-ray emitting region does not exhibit a highly ordered magnetic field such as that expected downstream of a standing shock [18]. Instead, the results are consistent with either magnetic reconnection or turbulence-dominated scenarios [19], where X-ray and optical polarization degrees are comparable and variable on short timescales.

Compared to prior *IXPE* observations of Mrk 421 and Mrk 501, 1ES 1959+650 shows somewhat lower X-ray polarization and a less pronounced X-ray/optical polarization ratio. The absence of strong chromatic trends in Π_x during the detected epoch and the variability observed between epochs imply that the jet of 1ES 1959+650 likely hosts a significant turbulent component with variability on sub-day timescales.

During a subsequent campaign in October of 2022, performed during an intermediate X-ray flux state, *IXPE* measured an average X-ray degree of polarization $\Pi_x = 9.4\% \pm 1.6\%$ and polarization $\psi_x = 53° \pm 5°$ [13]. The polarization variability analysis revealed the presence of a rotating component superposed on a constant component, with a rotation velocity $\dot{\psi}_x = -117 \pm 12$ deg day^{-1}. In contrast, during an August 2023 campaign, which followed a major X-ray outburst, the source displayed higher $\Pi_x = 12.4\% \pm 0.7\%$ with $\psi_x = 20° \pm 2°$. Crucially, this epoch exhibited a rapidly rotating polarization component with $\dot{\psi}_x = 1864 \pm 34$ deg day^{-1}, corresponding to ~5.2 turns per day. Such rapid rotations are consistent with either helical magnetic fields in the jet or stochastic processes in a turbulent plasma.

Collectively, these findings suggest that in HSPs like 1ES 1959+650, the subparsec-scale magnetic field is highly dynamic and often decoupled from the larger-scale jet magnetic structure. Optical emission appears dominated by a relatively stable component, while X-ray polarization traces fast-evolving regions potentially linked to shock fronts or turbulence in the jet. The presence of both stable and rotating X-ray components underscores the complexity of particle acceleration and magnetic field geometry in these sources.

4. Open questions

Does compactness of the emitting region alone explain the observed polarization in the synchrotron component of blazars?

The higher degree of X-ray polarization observed by IXPE, compared to optical measurements, suggests that the X-ray emitting regions are more compact and possess more ordered magnetic fields. In contrast, optical emissions originate from larger regions where magnetic fields are more turbulent, leading to depolarization.

This energy-dependent polarization can be explained by an energy-stratified emission model. In this scenario, high-energy electrons are accelerated in localized regions (e.g., shock fronts) and emit X-rays. As these electrons cool, they propagate downstream, emitting at lower energies (e.g., optical), where the magnetic field becomes more disordered, reducing the observed polarization degree [5].

The higher degree of polarization observed in the X-ray band measured by *IXPE* compared to results from optical polarization measurements can be explained by invoking a local particle acceleration site in the jet. This is opposite to a large-scale standing shock that would occupy most of the jet cross section and that has been invoked as a site of particle acceleration [e.g., 20]. Particles (electrons and positrons) would be locally accelerated and cool via synchrotron radiation on the local magnetic field, producing X-ray emission. As the particles cool, they would advect upstream and over a larger volume. In that larger volume, the ratio of random to ordered magnetic field would increase, thus reducing the observed polarization seen at lower synchrotron energies (e.g., in the optical band).

Are observations compatible with a toroidal or helical jet magnetic field?

The observed polarization properties are also influenced by the geometry of the magnetic field within the jet. Helical or toroidal magnetic fields can produce characteristic polarization signatures.

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For instance, a helical magnetic field can cause rotations in the polarization angle as the emitting region moves along the jet.

IXPE observations of blazars like Mrk 421 have shown such rotations in the X-ray polarization angle, supporting the presence of helical magnetic fields. These rotations are not simultaneously observed in the optical band, indicating that the X-ray radiation originates from regions with different magnetic field configurations than those producing the optical flux [8].

Can the chromatic polarization be explained without shocks?

A recent publication by Bolis et al. (2024) [17] provides an alternative explanation of the chromatic behavior of the polarized synchrotron flux, in which typically $\Pi_x > \Pi_o$, that does not depend on localized shocks. They examined synchrotron polarization from axisymmetric stationary jets with ordered magnetic fields, modeled within a Poynting-dominated regime. Their key findings are: the chromaticity of polarization arises naturally from the softening of the electron energy distribution, where X-ray emitting electrons have steeper spectra, enhancing polarization compared to optical-emitting electrons. The near-constancy of the polarization angle across bands is explained by the axisymmetric magnetic field structure, especially in nearly parabolic jets. The model predicts that the degree of polarization scales more steeply with the spectral index than expected in uniform magnetic fields, which accounts for why X-ray polarization can surpass optical polarization by factors of 2-7 without shocks. Crucially, the model indicates that the polarization signatures are more sensitive to the global magnetic field topology than to the particle acceleration mechanism.

5. Conclusion

Recent *IXPE* observations have significantly advanced our understanding of the magnetic field structure and particle acceleration mechanisms in blazar jets, particularly in the HSP subclass. The detection of substantial and variable X-ray polarization in sources like Mrk 421, Mrk 501, PKS 2155-304, and 1ES 1959+650 confirms that the X-ray emission is dominated by synchrotron radiation originating from compact regions with partially ordered magnetic fields. Observations of rapid rotations in X-ray polarization angle, without a similar rotation being observed in the optical band in the same epoch further suggest that the X-ray and optical radiation arise from physically distinct regions within the jet, each subject to different magnetic field dynamics. The alignment of the X-ray polarization angle with the projected jet direction in many HSPs also supports the presence of a globally-ordered toroidal or helical magnetic field structure, though transient deviations point to localized turbulence or could indicate reconnection events.

Although energy-stratified models involving the acceleration of shocks of particles remain a compelling explanation for the observed chromatic polarization behavior, alternative scenarios invoking ordered fields-ordered stationary jets also successfully reproduce the key polarization trends seen across bands. The growing body of *IXPE* results underscores the complexity of blazar jets, which likely involve an interplay between global magnetic field geometry, local turbulence, and dynamic particle acceleration processes. Future multiwavelength polarization campaigns, combined with time-resolved X-ray polarimetry, will be essential to disentangle these contributions and to refine our models of jet structure and evolution in these extreme astrophysical environments.

DISCUSSION

DEERAJ PASHAM: Did *IXPE* detect polarization from a blazar where the X-rays are produced via the inverse-Compton process?

MANEL ERRANDO: No. In low-frequency-peaked objects where the X-ray emission is dominated by Compton-scattered photons *IXPE* has only derived upper limits on the degree of X-ray polarization in the range of 10% to 30%. The only exception is an observation of a bright flare from BL Lacertae during which the X-ray spectrum did soften significantly, indicating a transient state in which the 2-8 keV flux was dominated by synchrotron radiation, and for which *IXPE* measured $\Pi_x = 22\%^{+6\%}_{-8\%}$ [16].

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