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FAST VARIABILITY OF THE OPTICAL POLARIZATION IN BLAZARS: FIRST RESULTS FROM BELOGRADCHIK OBSERVATORY

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Abstract. Blazars are relativistic jet-dominated active galactic nuclei, whose emission in the optical region is mostly synchrotron in nature and is consequently polarized. We monitored several objects on night-to-night and long-term time scales in order to study their flux and polarization variability. Our primary goal was to study the variability of the optical polarization of blazars and its relation to the X-ray polarization, which had been measured for a number of objects with the newly introduced *IXPE* orbital observatory. Among the objects we studied were BL Lacertae, S4 0954+65, S5 0716+714, PG 1553+115, 4C 29.45, OJ 287, Mkn 421, Mkn 501, B2 1308+32, 1ES 1959+65, etc. Our first results suggest the presence of rapid changes in both – polarization degree and position angle in practically all the objects we studied. Such and similar polarization studies can facilitate the detailed modeling of the relativistic jet emission mechanisms.

1. INTRODUCTION

Blazars are among the most powerful and the highest-energy persistent sources in the Universe. They are a subclass of Active Galactic Nuclei (AGN), where the emitted energy is generated via accretion onto a supermassive black hole, located in the center of the galactic nucleus (Lynden-Bell, 1969; Rees, 1984). For the case of blazars, however, the observed electromagnetic energy is produced primarily as a results of non-thermal processes in a relativistic jet (Blandford & Rees, 1978), even though the primary energy driver can still be accretion onto a supermassive black hole. These jet-related processes may include synchrotron radiation, Compton scattering, particle cascades, etc. As blazars are classified those jet-dominated objects, whose jet is pointed almost directly towards the observer (Urry & Padovani, 1995). There are several distinctive features, making blazars unique objects in the Universe due to their significant *Doppler* boosting and the specific processes, taking place in their relativistic jets. These features include extremely powerful emission (as detected by the observer), extremely broad spectral energy distribution (SED), rapid flux and polarization variability (examples in Bachev 2015; Bachev et al. 2011, 2017, 2023 and the references therein), among others.

The blazar SED is almost entirely non-thermal in nature and consists primarily of two peaks. Depending on the location of these peaks the objects are classified as low- (LSP), intermediate- (ISP) and high-spectrum peaked (HSP), creating a sequence known as the "blazar sequence" (Fossati et al., 1998).

The low-energy peak (LEP), located in the optical-IR region, is most likely produced by relativistic charged particles (electrons) via synchrotron processes in a magnetic field. The synchrotron radiation is naturally linearly polarized up to 75% (Rybicki & Lightman, 1985) with a position angle (PA) perpendicular to the magnetic field of the corresponding emitting region. The overall polarization can be smaller if the magnetic field is too much disordered or if many independent emitting regions contribute to the total emission.

The energy production mechanisms for the high-energy peak (HEP), located in the X/gamma-ray region are less clear and can be broadly divided into *leptonic* and *hadronic* models (Bottcher et al., 2013).

The *leptonic* models include synchrotron-self Compton (SSC) processes, where the high energy (X/gamma-ray) photons are produced by inverse Compton scattering of the already produced IR/optical synchrotron photons off the same population of relativistic electrons that generates them (i.e. relativistic electrons generate both peaks via different processes). Since the seed photons are polarized, the SSC radiation will also be polarized after the scattering, yet at levels $P_{\rm HEP} \simeq 0.3 - 0.5 P_{\rm LEP}$ or less (Zhang et al., 2024). Another possibility is that the seed photons come from an external source as the accretion disk, broad line region or dusty torus, being scattered off the relativistic electrons in the jet (External-Compton process, EC). Since the seed photons are unpolarized in this case, then they remain unpolarized after the Compton scattering and $P_{\rm HEP} \simeq 0$.

The *hadronic* models include proton synchrotron mechanism and photo-meson processes/cascades (Bottcher et al., 2013). The proton synchrotron mechanism, however, requires much stronger magnetic field, than normally assumed (i.e 10–100G vs. 0.1–1G) and naturally produces polarized high-energy radiation, with a $P_{\rm HEP} \simeq P_{\rm LEP}$. The same is for photo-meson processes/cascades case, where $P_{\rm HEP}$ should again be high, as the cascades produce ultra-relativistic charged particles (pions, muons, electrons, positrons), moving in a magnetic field. The photo-meson cascade option is perhaps required for the neutrino production, as the first neutrino-emitting blazar, TXS 0506+056 (among other suspected) has been already identified in 2017 (IceCube collaboration, 2018a, b).

In short, while the leptonic processes can provide a wide range of HEP polarizations, for the hadronic models the polarization is always expected to be high. Therefore, studying the HEP polarization can help to constrain different mechanisms that are likely to produce the high energy emission. Recently a new window of opportunity in that respect was open with the introduction of the X-ray polarization explorer satellite (*IXPE*), making possible to probe the polarization of both SED peaks almost simultaneously, if combined with ground-based optical measurements.

The main objective of this work is to explore the optical polarization in a number of relatively bright blazars, trying to answer two questions:

(i) How variable is the optical polarization in terms of polarization degree and position angle for objects of different types?

(ii) How much is this optical polarization related to the X-ray polarization and what can we learn about the HEP energy production mechanisms?

2. OBSERVATIONS AND RESULTS

The optical polarization measurements of the objects we studied were performed with the 60-cm telescope of Belogradchik Observatory, Bulgaria, equipped with a CCD and standard UBVRI filters. Additional polarimetric filters were added in 2020 on a second wheel (Bachev et al., 2023; Bachev, 2024), allowing polarization measurements in any of the UBVRI bands. Some of the first results (as of 2024, August) are presented below and the most frequently observed objects are discussed individually.

BL Lacertae. This was the most frequently studied object, showing occasionally significant polarization variability, even on intra-night time scales (Bachev et al., 2023; Imazawa et al. 2023; Shablovinskaya et al., 2023). We obtained polarization measurements of this blazar during 98 nights, in 2% of which only upper limits of the polarization degree could be measured. The distributions of the polarization degrees and position angles are shown in Fig. 1. The average polarization was 9% (5% standard deviation) with a log-normal distribution, which cannot be rejected with more than 90% probability. The position angle was concentrated between 10 and 30 degrees (40% of all cases), which is close to the radio jet position angle (about 20 deg, Raiteri et al., 2023). The object was observed by *IXPE* (2022, November) and an X-ray polarization was detected with a high level of confidence ($P_x \simeq 22\%$; $PA \simeq 151$ deg; Peirson et al., 2023). The authors conclude that the SSC mechanism dominates over possible hadronic contribution. On the other hand, two other *IXPE* observations produced only upper limits of the polarization.

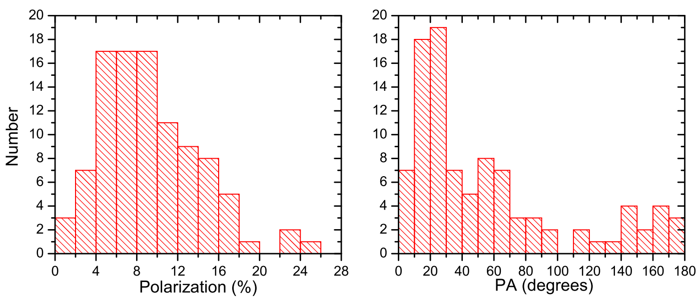

Figure 1: The distribution of polarization degrees (left panel) and position angles (right panel) of the R-band polarization of BL Lacertae (see the text).

S5 0716+714. This is another frequently observed blazar. During 54 nights (Fig. 2) we obtained average polarization $P_{opt} \simeq 7 \pm 4\%$ with only upper limits in 4% of the nights. The PA was concentrated between 70 and 100 deg (in 60% of all cases). *IXPE* observations set very loose upper limits for the X-ray polarization (Marshall et al., 2024).

OJ 287. This blazar was observed during 18 nights (Fig. 3) with $P_{opt} \simeq 17 \pm 5\%$ (with 6% upper limits) and PA concentrated between 140 and 160 deg for 82% of all cases. The object has not been observed with *IXPE* but should be a proper target, being bright enough and with high optical polarization.

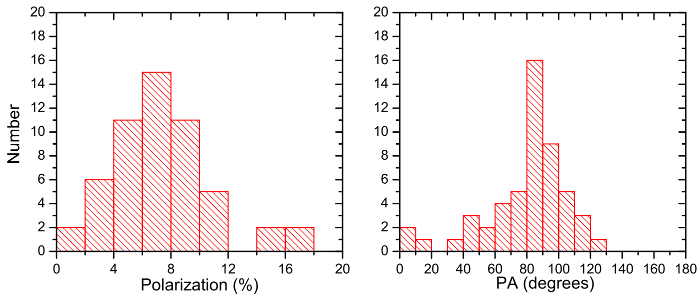

Figure 2: The same as Fig. 1 for S5 0716+714 (see also the text).

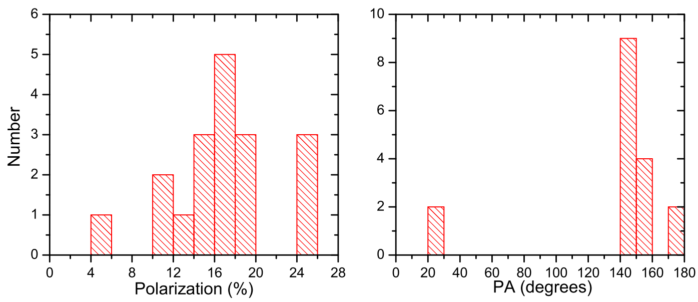

Figure 3: The same as Fig. 1 for OJ 287 (see also the text).

S4 0954+65. The object was observed during 59 nights with $P_{opt} \simeq 15 \pm 8\%$ (with 7% upper limits) and no apparent PA concentration (Fig. 4). *IXPE* has not yet observed this blazar.

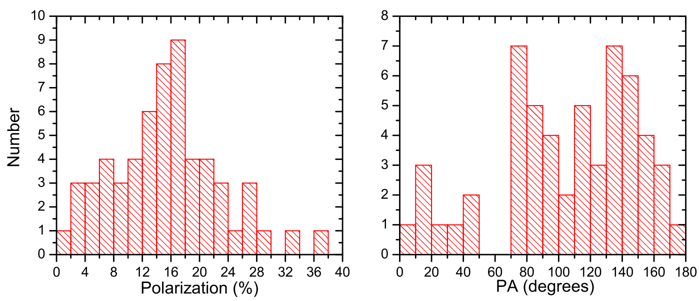

Figure 4: The same as Fig. 1 for S4 0954+65 (see also the text).

4C 29.45. This blazar was observed during 29 nights (Fig. 5) with $P_{opt} \simeq 17 \pm 5\%$ (with 21% upper limits as it was rather weak during some epochs) and PA concentrated between 10 and 30 deg for 56% of all cases. The object has not been observed with *IXPE*.

B2 1308+326. The object was observed during 27 nights with $P_{opt} \simeq 14 \pm 8\%$ (with 15% upper limits) and no apparent PA concentration (Fig. 6). *IXPE* has not yet observed this blazar.

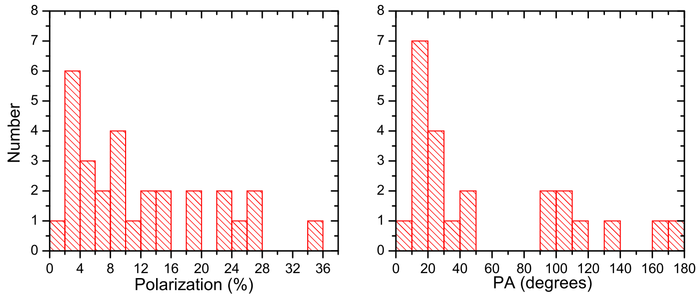

Figure 5: The same as Fig. 1 for 4C 29.45 (see also the text).

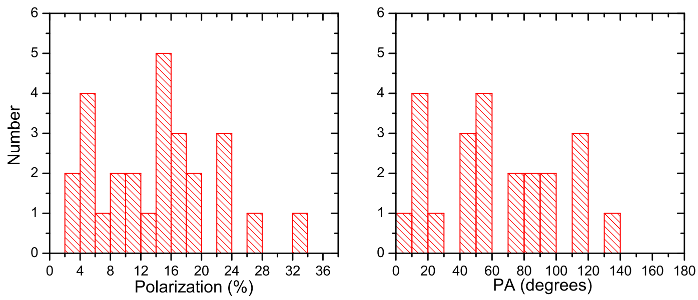

Figure 6: The same as Fig. 1 for B2 1308+326 (see also the text).

The blazars above are all classified as LSP/ISP. The blazars below, however, are all HSP with X-ray polarization measurements by *IXPE*. For these objects the X-ray polarization is typically much larger than the optical polarization.

PG 1553+113. We measured $P_{opt} \simeq 3.4 \pm 2\%$ (with 37% upper limits) during 38 nights (Fig. 7). The PA was concentrated between 90 and 120 deg (for 54% of the nights). *IXPE* observations (2023, February) showed $P_x \simeq 10 \pm 2\%$ and $PA \simeq 86 \pm 8$ deg (Middei et al., 2023). The radio jet of this blazar is positioned at about 50 degrees and does not seem to coincide with both – optical and X-ray polarization PAs.

Mkn 501. For most nights (29 in total) we obtained only upper limits for the optical polarization of this blazar (54%). When measured, $P_{opt} \simeq 1.8 \pm 0.7\%$ and PA was always between 120 and 160 deg (Fig. 8). *IXPE* observed this object on many occasions with P_x between 6 and 18% and PA between 100 and 140 deg. For this blazar the position angles of the optical polarization, X-ray polarization and the radio jet appear to coincide within certain limits (Marscher et al., 2024).

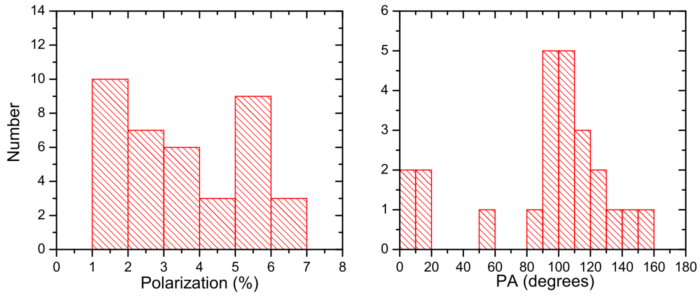

Figure 7: The same as Fig. 1 for PG 1553+113 (see also the text).

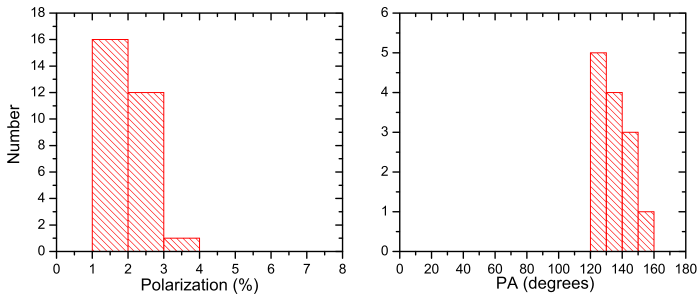

Figure 8: The same as Fig. 1 for Mkn 501 (see also the text).

1ES 1959+650. The object was observed during 7 nights with $P_{opt} \simeq 4 \pm 2\%$ (no upper limits) and PA always between 100 and 170 deg (Fig. 9). *IXPE* results showed $P_x \simeq 8 \pm 2\%$ and $PA \simeq 123 \pm 8$ deg and only upper limits during a second run (Errando et al., 2024). For this object the position angles of the optical polarization, X-ray polarization and the radio jet again appear to coincide within certain limits (Marscher et al., 2024).

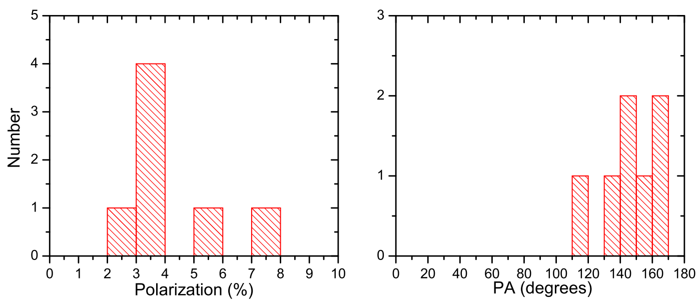

Figure 9: The same as Fig. 1 for 1ES 1959+650 (see also the text).

3. DISCUSSION AND CONCLUSION

The polarization results can be interpreted in terms of the processes, involved to produce the corresponding SED peak. The LEP polarization, which we measured in the optical region depends mostly on the level of disorder of the magnetic field and can reach typically up to 40 – 50%, but normally is about 10 – 20% for the most of the objects. What concerns the HEP polarization, however, the situation there is more complicated. The *IXPE* range, where the X-ray polarization is measured, can belong in principle to high-end of LEP (for HSP objects), low-end of HEP (for LSP objects) or be in the middle region (see Fig. 1 from Marscher et al., 2024). Therefore, the X-ray polarization, if present, should be interpreted with care as different processes might be involved in different (LSP/HSP) objects to produce the observed emission in these different peaks.

In addition, one should bear in mind that *IXPE* integration time is often in the realm of weeks, which reflects into detection as zero of any variable in position angle (but otherwise non-zero) linear polarization. Provided, of course, that the PA changes occur faster than the integration time.

Our preliminary results confirm the common understanding that the optical polarization can be moderate to significant for the LSP objects and is variable in both – polarization degree and position angle. The X-ray polarization for LSP objects (in the range of HEP for them) is usually not detected, perhaps suggesting the SSC/EC mechanism for the HEP emission generation. For the HSP objects we detected very low-level (if any) polarization in the optical. The X-ray polarization, however, which still covers the high-end of the LEP for these objects, appears to be significant, suggesting possible energy stratification caused by a standing or moving shock (Marscher et al., 2024). The shock orders the magnetic field and in the same time produces the highest energy photons close to the shock front, which causes only the high-energy X-rays to be polarized, while the low-energy optical photons, produced further out in a more disordered magnetic field – not that much. For the HSP blazars, X-ray polarization cannot help much to understand the HEP emission mechanisms, but hopefully the future gamma-ray polarization missions will.

To conclude, any high-energy polarization measurements should be supplemented by similar measurements in the low-energy (optical) range in order to successfully model the emission-production mechanisms. This is especially true when the optical polarization is highly variable in both – polarization degree and position angle, as our results suggest. Here, even small optical observatories, like Belogradchik observatory, if equipped with the proper instrumentation can contribute to further understand the highest energy phenomena in the Universe.

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