Polarimetric observations of blazars at Belogradchik Observatory

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Abstract. With the use of a simple polarimeter, recently introduced at the 60cm telescope of Belogradchik observatory, we obtained our first results on blazar polarimetric variability. Practically all objects we studied showed significant and variable linear polarization as expected from synchrotron emission in a relativistic jet. Observational methods used and some of the first results are presented and discussed.
Key words: blazars, polarization, variability

1. Introduction

Belogradchik Observatory (NW Bulgaria) operates a 60cm Zeiss telescope and has been primarily used for photometric CCD observations of variable objects, among which various classes active galactic nuclei (AGNs) and interacting binaries (Strigachev & Bachev 2011). Most of the observing time, however, has been dedicated to blazar monitoring. As blazars are classified those AGNs, whose emission appears significantly *Doppler*-boosted towards the observer, as being generated in a highly relativistic jet via non-thermal (synchrotron) processes. The synchrotron jet emission, often peaking in the IR-optical region is known to be linearly polarized, with a polarization degree of up to 75% (Rybicki & Lightman 1985). Therefore, studying blazar polarization variability, in addition to the photometric one, can reveal much more information needed to better understand jets' physics. For example, the polarization degree (p) can be connected with the number of the independent emitting regions within the jet. The polarization angle (PA), if stable, can reveal the jet direction in the sky and if it changes – details about jet curvature or possible helical jet structure, shock fronts, etc. (Marscher & Jorstad 2021). For that purpose, from September 2020 we started polarimetric observations of blazars, using a simple linear polarimeter.

2. The Polarimeter

Using an existing double-barrel filter wheel we constructed a simple linear polarimeter with three polarizing filters, oriented at fixed position of 0, 60 and 120 degrees in one of the wheels (keep in mind the $n \times 180$ degree ambiguity of the PA, as it is a plane, not a vector). This 3-filter approach still allows determination of the polarization parameters, even though the standard Stokes parameters cannot be directly measured, as they require 4 orientations – at 0, 45, 90 and 135 degrees (4 filters in our case). Such a setup is a simple and cheap alternative to rotating platforms and retarding plates, and can be successfully used for smaller instruments, even though half of the light (the observing time) is being lost due to the use of simple polarizers (e.g. Berdyugin et al., 2019). Since a double-barrel has been used, the polarization filters could be combined with any of the remaining standard filters (i.e. UBVRI) to obtain the polarization in different colors of the source of interest. For the filter material XP42 plastic was used[1]. Filters from this material transmit less than 0.004% when crossed (with about 42% transmission of a single polarizer) for $\lambda < 700$ nm but the crossed transmission rises rapidly after that wavelength ($\sim 0.6\%$ at 750 nm and $\sim 3.7\%$ at 800 nm). Therefore, it should perhaps not be used for near IR observations (e.g. with I-filter, yet R-band should be fine). In order to extract the polarization parameters (p, PA) one needs to solve three equations for the source intensities, obtained in each of these 3 filters. It is convenient to consider that the intensity of the source consists of two constituents – a completely polarized and a non-polarized one. Note that the polarizing filter always cuts half ($\cos^2(\theta)$, integrated over 360 degrees) of the non-polarized light, leading to the losses, mentioned above.

$I_0 = \frac{1}{2}I_{\rm np} + I_{\rm p}\cos^2\theta$
$I_{60} = \frac{1}{2}I_{\rm np} + I_{\rm p}\cos^2(\theta - 60)$
$I_{120} = \frac{1}{2}I_{\rm np} + I_{\rm p}\cos^2(\theta - 120)$, where
$p[\%] = 100\frac{I_{\rm p}}{I_{\rm np}+I_{\rm p}}$, and $EVPA = \theta$.

We solve these equations numerically to get p and PA. The relative magnitudes of the object of interest with respect to the nearby (presumably unpolarized) stars are converted into fluxes (intensities) and used in the equations. The errors of the polarization parameters are estimated via Monte-Carlo simulations of the measured intensities within their respective photometric errors, which requires obtaining numerous solutions to the system above for a single observation. Note that these polarization errors are neither Gaussian nor even symmetric (at least for p), these are just the standard deviations of the distributions. As the polarization parameters do not depend on the intensity scale (but just on the intensity ratios) only two magnitude differences are required to extract them, e.g. $m_{60} - m_0$ and $m_{120} - m_{60}$, where each m is the arbitrary magnitude of the source of interest with respect to unpolarized nearby stars. Fig. 1 presents simple graphs to asses approximately the polarization parameters, knowing these magnitude differences.

The PAs indicated in the left panel are correct in case that the m_0 filter is oriented vertically in the sky (North-South), m_{60} – 60 degrees to the left (East) and m_{120} – 120 degrees to the left (East) as the astronomical polarimetry convention requires. Due to the specific orientation of the light-gathering setup at the Belogradchik telescope, to get the true orientation of the polarization plane with the Belogradchik m_0, m_{60} and m_{120} filters, one should add/subtract 90 degrees and flip vertically (which is done in parentheses in the legend of Fig. 1, right).

Using presumably unpolarized nearby stars for comparison has, however, a known disadvantage. The interstellar dust dichroic extinction, due to the magnetic field alignment of the dust grains introduces artificial polarization of all objects and is proportional to their extinction along the light-travel path. Typically, $p_{\rm dust} \leq 9.3E_{\rm (B-V)}$ [%] (e.g. Siebenmorgen & Peest 2019), meaning

[1] https://www.edmundoptics.com/document/download/493651

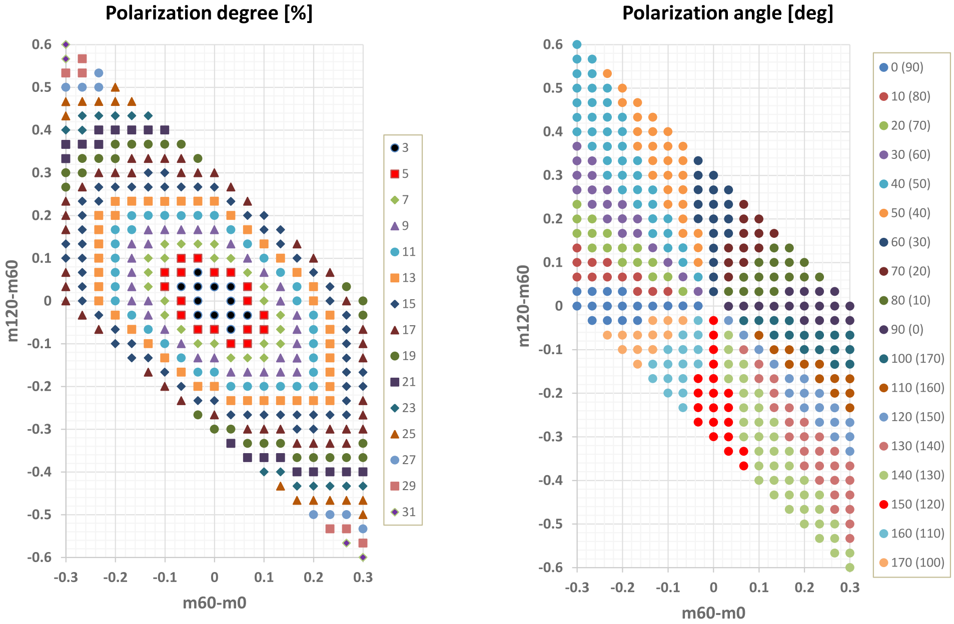

Fig. 1. A graph designed for rough estimates of the polarimetric parameters of a polarized source using the magnitude differences in 3 polarization filters (0, 60 and 120 deg). The left panel shows the polarization degree ($\pm1\%$) and the right one – the polarization angle (±5 deg). The first value of the legend of the right panel is to be used with the specific Belogradchik setup and the value in the parentheses is for a true 0, 60, 120 degree orientation (from North to East).

that the polarization measurements can be affected in a heavily absorbed directions. The problem can be avoided somewhat if the comparison stars are not very close in distance and are subject to the same absorption as the extragalactic object, provided the overall absorption in that direction is after all significant.

To verify the reliability of our polarimetric measurements we observed high polarization standards[2]. Among objects measured were BD +64 106, BD +59 389, HD 19820, HD 25443, Hiltner 960, VI Cyg 12, etc. The comparison between our results and the published ones was very good, except for BD +64 106, for which we measured significantly lower polarization degree than reported. We should note, however, that all these standards are very bright and lack comparison stars of similar brightness in the field, which makes their differential photometry difficult and respectively – their polarimetry somewhat prone to systematic errors. Yet, based on this comparison, we can estimate the (systematic) errors of our polarization parameters: $\sigma(p) \leq 0.5$ [%] and $\sigma(PA) \leq 1$ [deg]. As can be seen below, many blazars show much more sig-

[2] Compiled here: https://www.not.iac.es/instruments/turpol/std/hpstd.html

nificant polarimetric changes, even on intra-night time scales. For objects of ~ 14 magnitude or weaker the photometric errors of the measurements start to be more significant in determining the polarization accuracy than the systematic errors of the polarimeter. Reliable polarimetric measurements can be performed, based on our experience, for up to 16 magnitude (R-band) objects, but even there longer exposures / higher number of exposures may be required.

3. First results

For the first three years of observations, since 2020, we have measured repeatedly the polarization of a number of blazars, among which BL Lacertae, S4 0954+65, S5 0716+714, Mkn 501, 3C 66A, PKS 1420-01, PG 1553+115, 4C 29.45, 4C 38.41, OW 154.9, B2 1420+32, OJ 287, PKS 0735+178, 3C 279, Mkn 421, 4C 01.02, J1430+2303, B2 1308+32, 4C 27.50, etc. Virtually all objects showed significant changes in both – PA and p on time scales starting from one hour. Here we will share some initial results about the polarization variability of the most frequently studied objects, the details, however, were or will be published elsewhere (e.g. Bachev et al., 2023). All polarimetric measurements were performed in R-band (no filter was used in a few occasions). Some of the objects were monitored during pointings of *IXPE* X-ray satellite to measure the X-ray polarization (Mkn 421, Mkn 501, S4 0954+65, BL Lacertae, etc.).

BL Lacertae

This blazar has been intensively monitored on both intra-night and long-term time scales during its unprecedented 2020 – 2022 maximum. The object showed significant polarimetric parameter variations on intra-night time scales that did not seem to correlate significantly with the flux changes or with each other (details in Bachev et al., 2023). On longer time scales, however, the polarization angle tended to group between 10 and 20 degrees (32% of observations, for a total of 28 nights) and between 5 and 30 degrees (72%), yet practically any PA was observed. About 20 degrees is the direction of the radio jet of this object (Raiteri et al., 2023). The average p was about 10% with a log-normal distribution. Figure 2 shows the polarization dependence on the orientation, indicating that the highest polarization occurs when the optical polarization is aligned with the radio jet.

S5 0716+714

For a total of 33 nights of polarimetric measurements, the blazar showed PAs grouped around 90 degrees (30% between 80 and 90, 67% between 70 and 100). This PA, however, does not seem to coincide with the parsec-scale radio jet. The polarization degree was about 7% on average, again, with a log-normal distribution (18% was the highest observed value). Some small-scale polarimetric changes could be traced even on intra-night time scales.

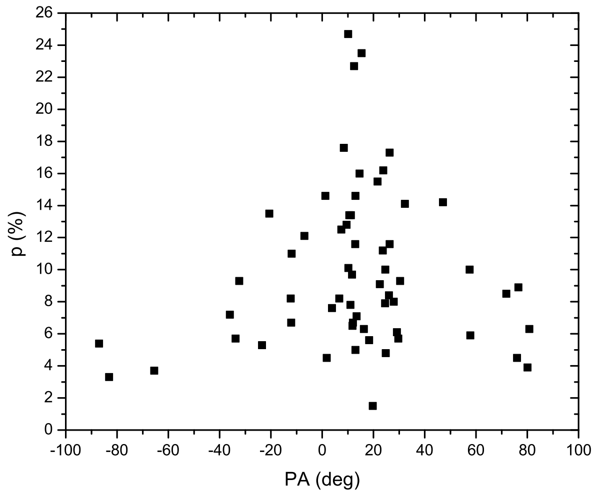

Fig. 2. The polarization degree of BL Lacertae as a function of the position angle. One sees that the highest polarization occurs when the optical polarization is aligned with the radio jet ($\sim$ 20 deg).

S4 0954+65

This blazar showed (during 33 nights) both significant intra-night and long-term flux and polarization variations (Pandey et al., in prep. No clear grouping in the PAs was evident (57% between 70 and 120 degrees) and no definite distribution of the polarization degree values was found to be statistically significant. The polarization degree was $\sim$ 15% on average, but occasionally reached up to 40% (Bachev, 2022).

OJ 287

This object was predicted to show an outburst in 2022, based on a theory of the presence of a companion black hole that presumably interacts with the accretion disk of the primary one and thus explaining an apparent periodicity of the light curve (Sillanpaa et al., 1988). For one reason or another, the predicted outburst did not happen. An alternative to the quasi-periodical injection of relativistic electrons to the jet is the binary-induced jet precession (Britzen et al., 2023; see also Bachev, 2018). Despite of the apparent low state, we monitored OJ 287 during 8 nights around the predicted outburst. The average p was about 18% with slowly changing PA, from -30 (150) to 30 degrees.

4C 29.45

The polarimetry parameters of this blazar were measured during 14 nights with $< p >\simeq 12$ %, but reaching up to 36%. The PAs were distributed rather uniformly, with night-to-night changes reaching up to 60 degrees.

B2 1308+32

This object was observed polarimetrically during a very high outburst (starting 2022, June) for 12 nights. It showed $< p >\simeq 15$ % and PAs between 0 and 90 degrees.

PG 1553+113

This object was observed during 28 nights as a part of a large international campaign, supplemented with observations by *MAGIC* and *TESS*. During about 30% of the nights only upper limits for the polarization were established, typically $p < 2$ %. For all remaining cases we obtained $p \simeq 3 - 6$ %, with PA between 90 and 110 degrees in 58% of the observations.

Mkn 501

This TeV emitting blazar was observed polarimetrically over 13 nights, during most of which we were able to determine only upper limits for the polarization. This is not surprising as the significant contribution from the unpolarized host dilutes the nuclear synchrotron emission. For the few remaining cases we obtained $p \simeq 2 - 3$ %, with PA always between 130 and 160 degrees. No correction for the host galaxy was attempted.

Finally, we show recent intra-night flux and polarimetric observations for 3 of the most studied objects (Fig. 3). One clearly sees that the changes of the polarization can occur even on intra-night time scales. No sifnificant correlation between the flux and the polarization was found.

4. Conclusions

Even though objects like blazars, whose emission is dominated by non-thermal processes are often highly polarized in the optical, polarization observations are still rare world-wide. In a recent paper (Jorstad et al., 2022), presenting blazar monitoring results of a large international campaign, only ∼5 out of ∼40 telescopes performed optical polarimetry (including the Belogradchik telescope). Yet, the polarization variability can be of essential significance to understand better the processes in a relativistic jet. Here we conclude that even small telescopes with relatively modest equipment can significantly contribute to studying the polarized sources, at least the relatively bright ones.

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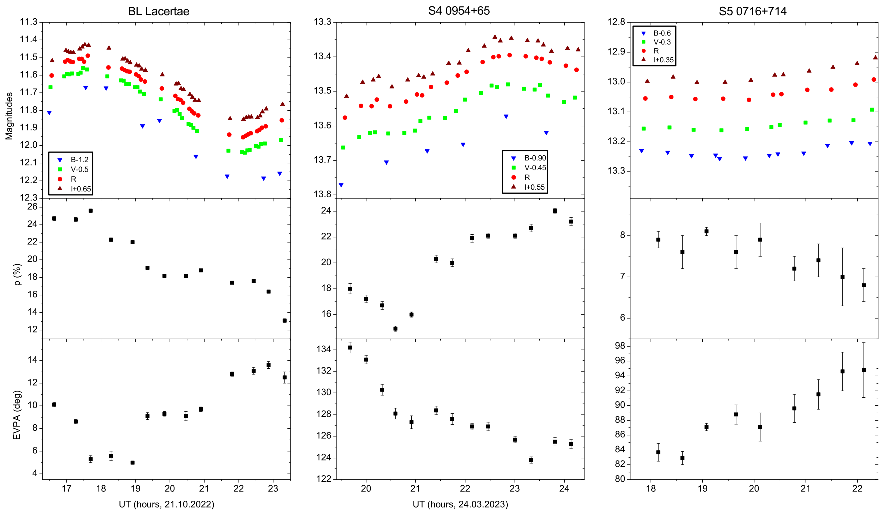

Fig. 3. Intra-night polarimetric observations for 3 of the most studied objects (BL Lacertae, S5 0716+714, S4 0954+65). Significant polarization changes can be traced for as short as a few hours in all objects.

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