The RoboPol Program: optical polarimetric monitoring of blazars

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Abstract

Blazars are a subclass of Active Galactic Nuclei with relativistic jets pointing at us. For this reason the highly amplified polarized synchrotron emission from their jets dominates in the optical band. Typically, the electric vector position angle (EVPA) of the optical polarized emission in blazars varies in an erratic way. However, in rare cases the EVPA displays long, smooth and monotonic rotations. Being puzzled by this phenomenon missing a solid theoretical explanation, in 2013 we started an optical polarimetric monitoring program called RoboPol. After several years of operation this project has uncovered several key aspects of polarimetric rotations. The most important of these is that polarization properties of the synchrotron emission in the optical appear to be directly linked with γ-ray activity.

Novel polarimeter

We designed and constructed a two-channel polarimeter specifically for this program and the 1.3m telescope of the Skinakas observatory. Its main feature is that it splits every source image into 4 spots with different polarization states.

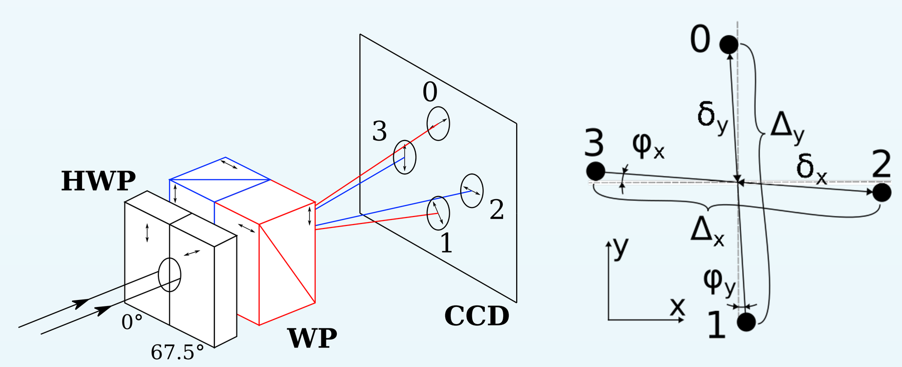

Fig. 1

This allows to measure I,Q,U Stokes parameters with one exposure. It increases efficiency, accuracy and simplifies operation (King et al., 2014; Ramaprakash et al., 2019).

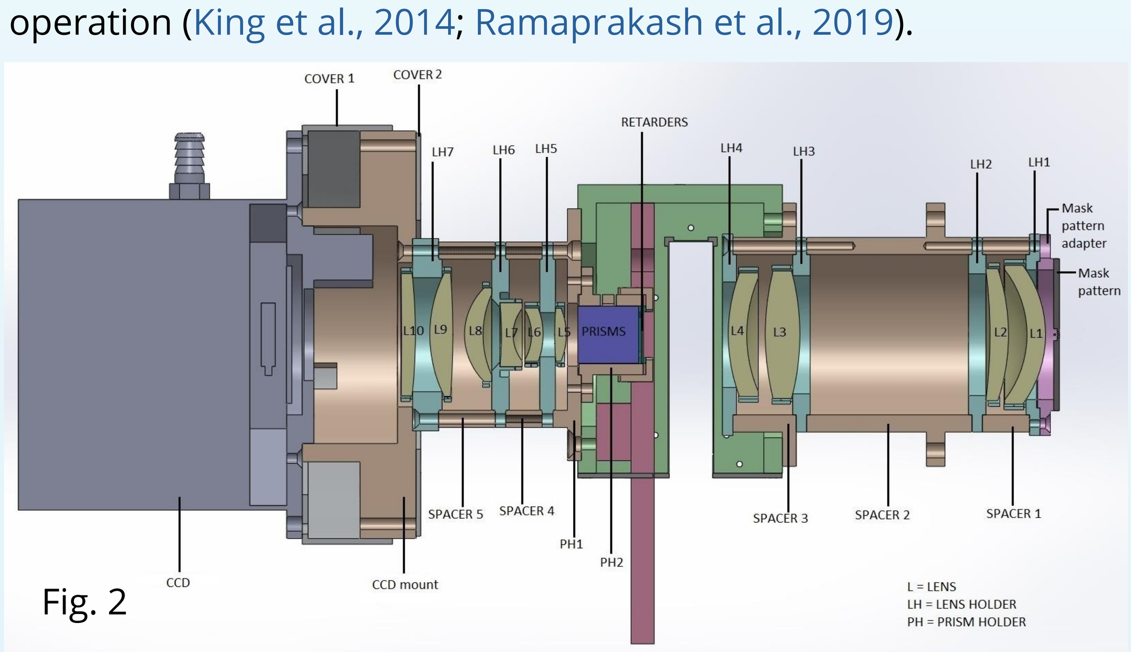
Fig. 2

Methodology

Contrary to other polarimetric monitoring programs we constructed a statistically meticulously defined sample of blazars for our monitoring (Pavlidou et al., 2014). The sample included:
- 65 γ-ray–loud blazars — the main sample
- 15 γ-ray–quiet blazar — the control sample
- 24 hand-picked sources of high interest that were not used in any further statistical analysis.

We monitored these sources for 3 seasons 2013 – 2015 with a median cadence of 6 days. In 2016 we monitored a sub-sample of 28 most active sources at a faster cadence to determine how a faster cadence would impact the results.
All monitoring data including **5068** observations of **222** AGN are publicly available https://dx.doi.org/10.7910/DVN/IMQKSE (Blinov et al., 2021)

γ-ray—loud blazars are significantly more polarized

Blazars of the **γ-ray–loud** sample **are significantly** (>4σ S.L.) **more polarized** compared to γ-ray–quiet. The corresponding mean intrinsic polarization is 9.2 ± 0.8 % and 3.1 ± 0.8 % (Pavlidou et al., 2014; Angelakis et al. 2016). This result implies that the magnetic field is more ordered in jets of γ–loud blazars compared to their γ–quiet counterparts.

Polarization variability correlates with sychrotron peak frequency

Variability of polarization **is correlated with the synchrotron peak position**. Low Synchrotron Peaked (LSP) blazars have higher average polarization and the range of its values is wider (Fig. 3) compared to High Synchrotron Peaked (HSP) sources. At the same time in HSPs the EVPA tends to have preferred value, while in LSPs it more uniformly distributed (Angelakis et al. 2016).

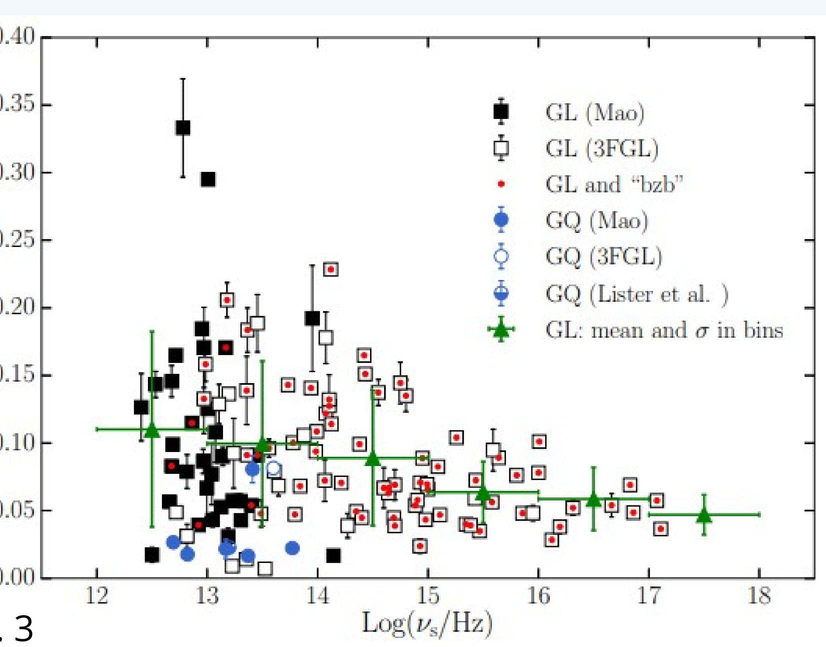

Fig. 3

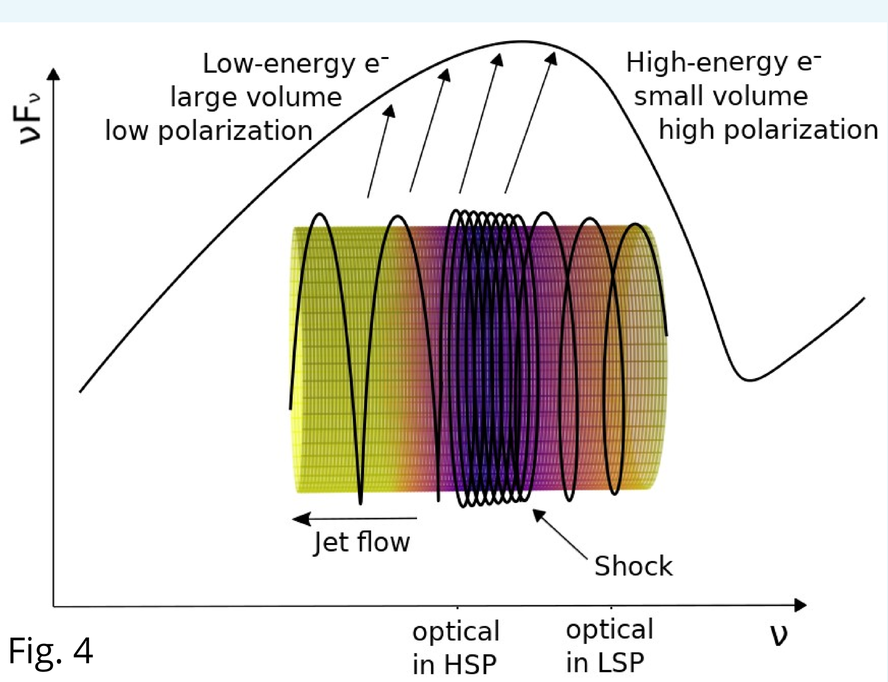

Fig. 4

This dependence of variability on the synchrotron emission peak frequency can be explained by a simple phenomenological model sketched in Fig.4. A mildly relativistic shock, causes efficient particle acceleration in a small volume, concentrated in the immediate downstream environment of the shock. Consequently, the highest-energy particles, responsible for the emission near and beyond the peak of the synchrotron SED bump, are expected to be concentrated in a small volume immediately downstream of the shock, where the shock-compressed magnetic field is expected to have a strong ordered component. Substantial degrees of polarization are thus expected near and beyond the peak of the synchrotron SED component. Due to progressive cooling of shock-accelerated electrons as they are advected downstream, the volume from which lower frequency synchrotron emission is received, is expected to increase monotonically with decreasing frequency. One therefore expects a lower degree of polarization with decreasing frequency due to de-polarization from the superposition of radiation zones with different magnetic field orientations (Angelakis et al. 2016).

There exists a rotator class of blazars

During the monitoring we detected 40 EVPA rotations in 24 blazars (c.f. with 16 rotations in 10 sources reported in the literature before). It has been found that it is **highly unlikely** ($p < 10^{-7}$) **that all blazars exhibit rotations of EVPA with the same frequency**. There is a subclass of sources (rotators) that demonstrates EVPA rotations ~10 times more frequent than others. The rotators have significantly higher γ-ray luminosity and γ-ray variability indices compared to non-rotators. Moreover, EVPA rotations tend to happen more frequently in LSP blazars (Fig.5), which can be explained by the same model as in "Result 2".

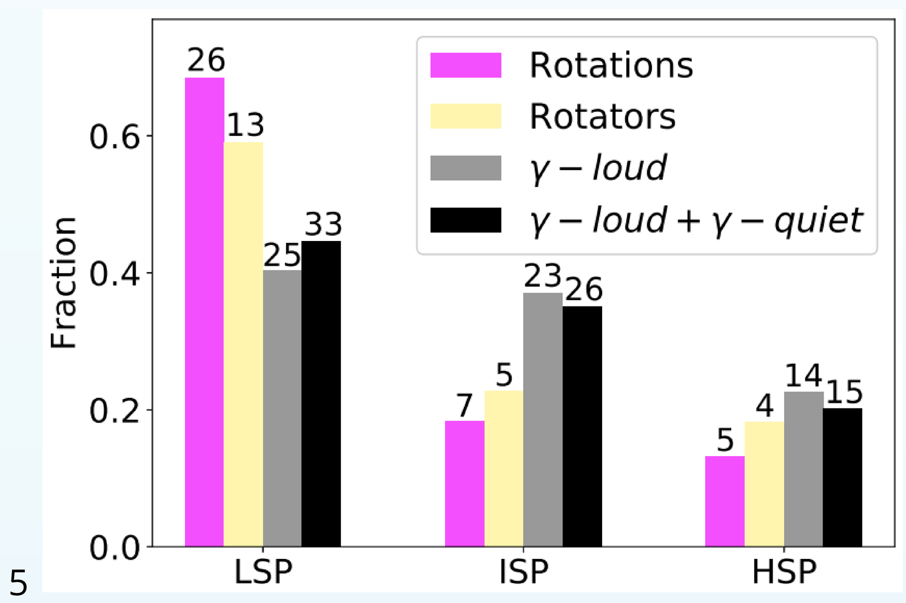

Fig. 5

EVPA rotations and gamma-ray flares are physically connected

The probability that the time lags between EVPA rotations and γ-ray are accidentally as small as we observe them is very low ($<7\times10^{-7}$), i.e. **there must be a physical connection between EVPA rotations and γ-ray flares** (Blinov et al., 2018).

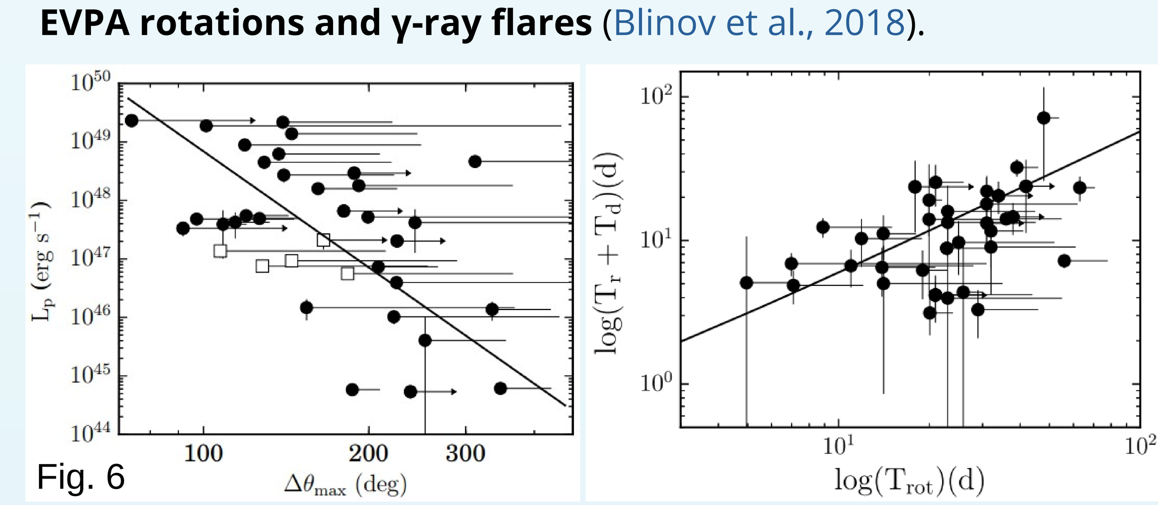
Fig. 6

The amplitudes of EVPA rotations ($\Delta\theta_{max}$) and adjacent γ-ray flares are correlated (Fig. 6 left panel), as well as the characteristic duration of these events (Fig. 6 right panel). The former correlation breaks down into two dependencies: the Lorentz factor is anti-correlated with $\Delta\theta_{max}$ and the jet viewing angle is positively correlated with $\Delta\theta_{max}$. In other words, the faster the jet and the smaller the viewing angle, the lower the amplitude of EVPA rotations that this blazar exhibits. The connection between parameters of EVPA rotations and γ-ray flares implies that these events are produced in the same region of the jet. Therefore, EVPA rotations can be used for localization of the γ-ray emission zone within the jet. Moreover, our these results strongly favour the deterministic nature of EVPA rotations. If a substantial fraction of these events was produced by a random walk of the polarization vector, then both amplitudes and timescales of rotations would be random quantities independent from corresponding properties of γ-ray flares. Moreover, we found that the γ-ray flares related to EVPA rotations do not show any distinctive properties in their amplitudes or characteristic timescales when compared to other flares that occurred during RoboPol observations. In principle, every gamma-ray flare could be accompanied by an EVPA rotation, and the absence of a recorded rotation in RoboPol data could be due to sparse sampling.

EVPA rotations are not random walks

The sample of **EVPA rotation events cannot be fully reproduced by a random walk model** (Kiehlmann et al., 2017). The model is capable of producing samples of rotations with parameters (amplitudes and durations) similar to the observed ones, but fails to reproduce distribution of the polarization fraction at the same time (Fig. 7).

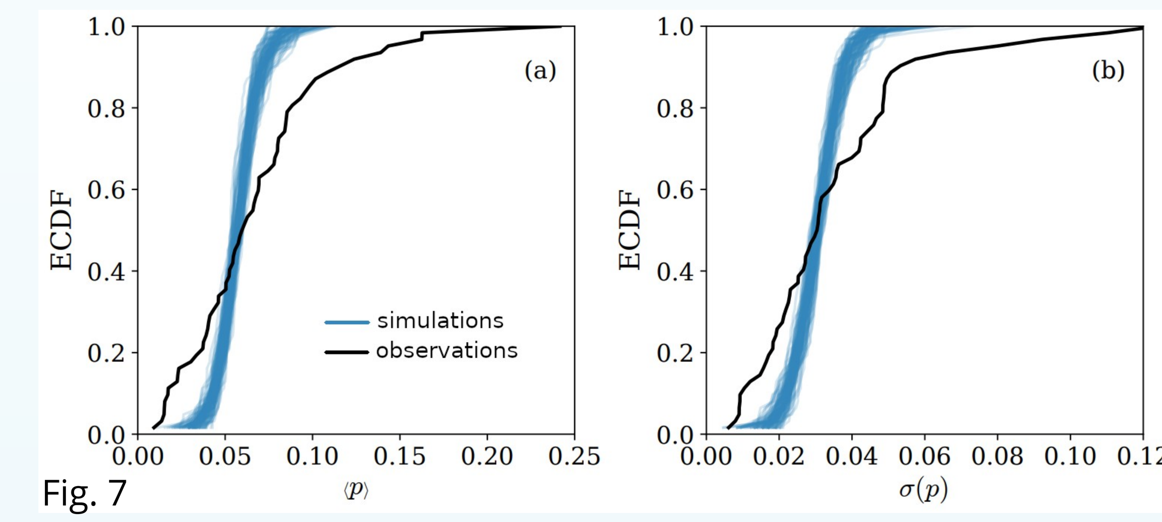

Fig. 7

Higher cadence is needed

The inherent 180° ambiguity in the measurements introduces significant difficulty in the interpretation of EVPA rotations. We show that at least daily observations are necessary to measure >96% of optical EVPA variability in the RoboPol sample of blazars correctly and that intra-day observations are needed to measure the fastest rotations that have been seen thus far. We estimated that 11% of the RoboPol data sampled with weekly cadence and the majority of the identified rotations are likely affected by the ambiguity. Daily cadence leads to a significant improvement, as only 4% of the data are affected. We caution that these results are specific for the studied sample and may differ for other samples of blazars. **We** clearly **need optical monitoring programs** of the same scope as RoboPol, but **with a cadence significantly faster than 1 day**, which requires multiple observing sites (Kiehlmann et al. 2021).

Conclusions

Optical polarization and γ-ray activity of blazars are tightly related in different aspects. For instance, optical polarization plane rotations and γ-ray flares in blazars are temporily linked and demonstrate correlations between their parameters. This implies a common physical mechanism behind these events.

Publications

Blinov et al. - MNRAS, 453, 1669 (2015)
Blinov et al. - MNRAS, 457, 2252 (2016)
Blinov et al. - MNRAS, 462, 1775 (2016)
Blinov et al. - MNRAS, 474, 1296 (2018)
Blinov et al. - MNRAS, 501, 3715 (2021)
Hovatta et al. - A&A, 596, A78 (2016)
Kiehlmann, Blinov, Pearson & Liodakis - MNRAS, 472, 3589 (2017)
Kiehlmann et al. - MNRAS, 507, 225 (2021)
King et al. - MNRAS, 442, 1706 (2014)
Liodakis, Blinov, Papadakis & Pavlidou - MNRAS, 465, 4783 (2017)
Liodakis & Blinov - MNRAS, 486, 3415 (2019)
Liodakis, Peirson & Romani - ApJ, 880, 7 (2019)
Pavlidou et al. - MNRAS, 442, 1706 (2014)
Ramaprakash et al. - MNRAS, 485, 2355 (2019)

and more at http://robopol.org