



Constraints on magnetic field and particle content in blazar jets through optical circular polarization

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ABSTRACT

Polarization offers a unique view in the physical processes of astrophysical jets. We report on optical circular polarization (CP) observations of two famous blazars, namely 3C 279 and PKS 1510–089, at high linearly polarized states. This is the first time PKS 1510–089 is observed in optical CP. While only upper limits can be extracted from our observing campaign, the non-detection of optical CP allows us to provide meaningful constraints on their magnetic field strength and jet composition. We find that high-energy emission models requiring high magnetic field strength and a low positron fraction can be excluded.

Key words: polarization – galaxies: active – galaxies: jets.

1 INTRODUCTION

Polarization is a powerful tool to understand the magnetic field structure and evolution in black hole jets (Blandford, Meier & Readhead 2019; Hovatta & Lindfors 2019). Here, we focus on a particular class of jets from supermassive black holes that are oriented towards the observer called blazars. Due to the synchrotron nature of their radiation, blazars are highly polarized and show variable, and often quite peculiar, polarization behaviour. This behaviour is connected to their high-energy emission (Blinov et al. 2018), the origin of which is still a mystery. The main mechanisms invoked to explain the high-energy emission in blazar jets are inverse-Compton scattering of relativistic electrons (also known as leptonic processes) by either internal (SSC) or external (EC) photon fields, and proton synchrotron, Bethe–Heitler pair production, pion decay etc. (also known as hadronic processes). Typically, the distinction between these processes is investigated through spectral energy distribution modelling (SED, e.g. Böttcher et al. 2013; Cerruti 2020). The Imaging X-ray Polarimetry Explorer will soon provide a new avenue of probing the origin of the high-energy emission in blazars through X-ray polarization (Liodakis, Peirson & Romani 2019). Here, we explore a third direction, that of optical circular polarization (CP).

The optical linear polarization (LP) degree in blazars can vary between 0 and >30 per cent within just a few days (e.g. Kiehlmann et al. 2016; Liodakis et al. 2020; Kiehlmann et al. 2021). A fraction of them shows rotations of the optical polarization plane that are most often accompanied by bright outbursts across the electromagnetic

spectrum (Marscher et al. 2008, 2010; Bottacini et al. 2016; Uemura et al. 2017; Raiteri et al. 2017a; Blinov et al. 2021b). While their optical and radio LP properties have been getting plenty of attention lately (e.g. Kovalev et al. 2020; Kravchenko et al. 2020; Event Horizon Telescope Collaboration et al. 2021; Blinov et al. 2021a; Goddi et al. 2021), their optical CP properties are unexplored. This is partly because of the scarcity of instruments capable of delivering CP measurements, but also because CP is expected to be low even in optimistic scenarios, requiring very sensitive instruments. Non-intrinsic CP can arise due to inverse-Compton scattering of low-energy radio photons, propagation effects, coherent radiation, accretion disc emission etc. (see Rieger & Mannheim 2005 for an overview). Measurements of intrinsic CP, however, are particularly important because if the jet is made up of a pure electron-positron plasma then the expected intrinsic degree of CP is zero. Any confident detection of CP would (assuming overall charge-neutrality) imply at least a small fraction of protons in the jet. Therefore, CP observations offer a unique view on jet composition, which is otherwise not accessible. This, of course, has implications for the origin of the high-energy emission, especially in light of recent results on possible astrophysical neutrino associations with blazar jets (IceCube Collaboration et al. 2018; Plavin et al. 2020; Hovatta et al. 2021). A few attempts have been made to measure CP in blazars (e.g. Valtaoja et al. 1993; Wagner & Mannheim 2001; Hutsemékers et al. 2010), however, there has not been a 3σ detection of optical CP in blazars to this day. Wagner & Mannheim (2001) reported a <2 per cent 3σ detection of CP in 3C 279 using the VLT, however, those observations suffered from linear-to-CP cross-talk which was not accounted for at the time (Bagnulo, Sterzik & Fossati 2011).

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CP of a few percent has been detected in several blazars at radio wavelengths (e.g. Homan, Attridge & Wardle 2001; Myserlis et al. 2018; Thum et al. 2018; Hovatta et al. 2019), however, it is most often attributed to Faraday conversion (which has a negligible effect in the optical bands) of the LP due to intervening magnetized plasma (MacDonald & Marscher 2018). Therefore, simultaneous measurements of CP in both radio and optical, can help constrain the properties of the Faraday screen. In this letter, we present optical CP observations of two well studied, and highly polarized blazars namely 3C 279 and PKS 1510–089. Assuming an intrinsic CP signal exists, we use the detected upper limits in combination with their LP degree to constrain their magnetic field strength and jet composition.

2 OBSERVATIONS & DATA REDUCTION

3C 279 and PKS 1510–089 are famous for their bright outbursts, high variable emission, extreme polarization behaviour as well as potentially multimessenger emission (Abdo et al. 2010; Marscher et al. 2010; Ackermann et al. 2016; Kreter et al. 2020; Blinov et al. 2021b). The sources were observed during the nights of the 2021 April 7, 8, 10, and 11, using the High-speed Photo-Polarimeter (HIPPO; Potter et al. 2010) on the 1.9-m telescope of the South African Astronomical Observatory. HIPPO measures polarization using two contra-rotating 1/2 and 1/4 wave-plates, rotating at 10 Hz and hence modulating the ordinary and extraordinary beams. The rotation speed is sufficient to effectively negate any errors due to atmospheric variations. Following Serkowski (1974), we estimate the amplitude and phases of the modulations using a least-squares fit algorithm to fit the 4th and 8th harmonics (LP) and the 6th harmonic (CP, Potter et al. 2008, 2010). Correction and efficiency factors are used to account for the fact that the modulated signal consists of a finite number of bins, instrumental polarization, position angle offsets, and a minor wavelength dependence due to retardance of the wave-plates. We estimated those factors by observing several polarized and non-polarized standard stars (Hsu & Breger 1982; Bastien et al. 1988). Background sky polarization measurements were taken immediately preceding every observation. In order to not introduce a random non-zero CP offset during sky subtraction, the circular polarized sky measurement was zeroed and only the unpolarized DC level was subtracted. The instrument is optimized for on-axis point source observations, hence it is not susceptible to linear-to-CP cross-talk. Table 1 lists the linear and CP parameters for both sources. Our results confirm the sources as high LP blazars and provide CP constraints at the level of ~ 1 per cent. Compared to archival observations, we find PKS1510–089’s LP to be higher than average and 3C 279 to be at a very high LP state, near historical maximum (Blinov et al. 2021a,b).

3 CONSTRAINTS ON THE MAGNETIC FIELD STRENGTH AND JET COMPOSITION

Synchrotron radiation is characterized by elliptical polarization, with a small fractional degree of intrinsic CP, $\Pi_c \propto \nu^{-1/2}$ (Legg & Westfold 1968; Melrose 1971). In the case of a pure pair plasma (electron-positron), the circular component cancels leaving only the linear component of the polarization. Here, we assume that the jet plasma is made up of an electron-positron-proton (pair-proton) composition. In order for the jets to be accelerated to the high observed velocities (Lorentz factor $\Gamma > 30$) at pc-scales (Liodakis et al. 2017, 2018), would require at least some population of ‘cold’ protons (Phinney 1987; Sikora et al. 1996a,b), however, those do not contribute significantly to the emission. In this scenario, we expect at least

some degree of intrinsic CP that depends on the LP, jet composition, strength of magnetic field, and Γ of the bulk flow. For a power-law emitting particle distribution with index $\sim (2-2.3)$, a perpendicular intrinsic magnetic field and an optically thin jet at a $\theta \approx 1/\Gamma$ angle to the observer, we can relate the (intrinsic) magnetic field strength to the degree of CP as,

$$B \approx 2 \times 10^7 \left(\frac{\nu_{\text{obs}}}{10^{15} \text{ Hz}} \right) \left(\frac{0.71}{\Pi_l} \right)^2 \left(\frac{1}{\Gamma^3(1-2f)^2} \right) \Pi_c^2, \quad (1)$$

where, B is in Gauss, ν_{obs} the observing frequency, Π_l the LP degree, f the fraction of positrons, and Π_c the CP degree (Rieger & Mannheim 2005). The term $(0.71/\Pi_l)$ describes the uniformity of the magnetic field which affects LP and CP equally (Jones & O’Dell 1977). In the $\theta \approx 1/\Gamma$ regime, $\Gamma \approx \delta$, where δ is the Doppler factor, $\delta = 1/[\Gamma(1 - \beta \cos \theta)]$. In Liodakis et al. (2021), we found that 3C 279 is decelerating in the GHz range, with δ peaking above 37 GHz and below 100 GHz. Therefore, we use $\delta = 18.3 \pm 1.9$ derived at 43 GHz (Jorstad et al. 2017). PKS 1510–089 does not show δ variations across the GHz range (Liodakis et al. 2018, 2021), hence for consistency we use $\delta = 35.3 \pm 4.6$ also found at 43 GHz. We discuss the choice of δ below.

To fully explore the parameter space of B , f , δ we uniformly draw random values in the range of $[1, 100]$ Gauss for B and $[0, 0.5]$ for f , where $f = 0$ is for a pure electron-proton plasma and $f = 0.5$ is for a pure electron-positron plasma. We also draw a random value for δ from a Gaussian distribution with mean and standard deviation δ and σ_δ , respectively. Using the observed Π_l , observing frequency and equation (1), we can estimate Π_c which we compare to the observed value. We repeat this process 10^6 times and record all B , f pairs that satisfy the observed 2σ upper limits for Π_c for each of the observing dates and sources. Fig. 1 shows the f versus B plane with the colorbar showing the fraction of accepted random δ draws given B , f . We have omitted the PKS 1510–089 observation at MJD 59315.631 since the low observed Π_l and high Π_c upper limit do not provide any constraints on B and f . We find a range of values for both parameters with the high B -field – low f parameter space to be excluded for both sources. Our best constraints come from MJD 59316.519 for 3C 279 and MJD 59312.645 for PKS 1510–089 (Table 1, Fig 1 top panels and bottom left hand).

4 DISCUSSION & CONCLUSIONS

Here, we presented measurements of the optical CP degree for two well-studied blazars, namely 3C 279 and PKS 1510–089. This is the first time an attempt was made to measure CP in PKS 1510–089. Although our measurements can only be considered as upper limits, they still provide meaningful constraints on the magnetic field and jet composition. Generally, we find that emission models requiring high magnetic field strengths and a low positron composition can be excluded. Leptonic models typically require $B < 5$ G while high B -fields (> 30 G) are often required in proton-synchrotron models (see Cerruti 2020 for a review). This is due to their low radiative efficiency which depends on B (Sikora et al. 2009). Specifically, SED hadronic modelling estimates for the magnetic field strength in 3C 279 and PKS 1510–089 are in the range of 50–150 and 10–50 G, respectively (e.g. Böttcher et al. 2013; Diltz, Böttcher & Fossati 2015; Paliya et al. 2018). Such values only allow for large positron fractions in 3C 279 ($f > 0.43$). In Liodakis & Petropoulou (2020), we estimated the minimum magnetic field strength in the context of a proton-synchrotron model to be about 43 G for 3C 279 and 9 G for PKS 1510–089. For 3C 279, this limits the range of compositions to $0.43 \leq f < 0.5$. This is consistent with Wardle et al. (1998) who

Table 1. Summary of observations for 3C 279 and PKS 1510–089. The columns are (1) name, (2) date of observations, (3) observing band, (4) LP degree (%), (5) polarization angle (degrees), and (6) CP degree (%). The uncertainties in columns 4, 5, and 6 correspond to the standard deviation of each measurement.

Name	Date	Band	Π_l	PA	Π_c
PKS 1510–089	59312.645	R	7.07 ± 0.51	5.0 ± 1.7	-0.52 ± 0.37
PKS 1510–089	59313.645	R	9.44 ± 1.45	4.6 ± 3.6	0.70 ± 1.02
PKS 1510–089	59315.631	R	3.65 ± 1.06	65.0 ± 11.7	-0.52 ± 0.76
3C 279	59316.519	R	31.46 ± 0.42	126.4 ± 0.3	-0.04 ± 0.30
3C 279	59316.526	B	32.72 ± 1.01	127.5 ± 0.6	-0.81 ± 0.73

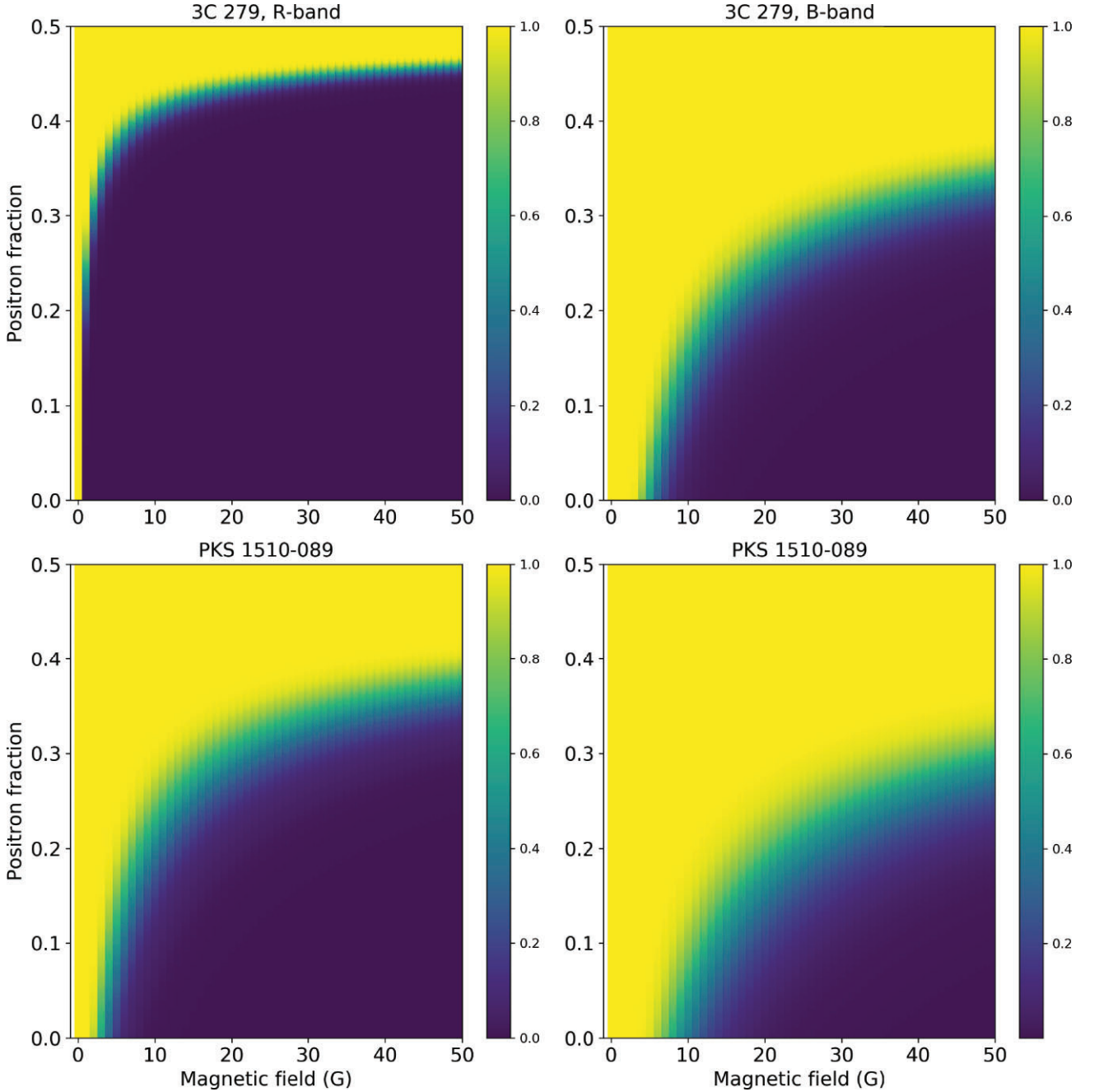


Figure 1. Constraints on the magnetic field strength and jet composition for both sources in different observing sessions. The top row shows the results for 3C 279 for the R-band (left) and B-band (right). The bottom row shows the results for PKS 1510–089 at MJD 59312.645 (left) and MJD 59313.645 (right). The colourbar shows the fraction of accepted random δ draws given B , f .

found through radio CP that the jet in 3C 279 is composed mainly from an electron-positron plasma. For PKS 1510–089, the low B estimate does not allow us to place any constraints on its positron fraction. However, we note that proton-synchrotron models typically assume a pure proton-electron plasma. A lower proton fraction would require even higher magnetic field strengths. In addition, in order for proton synchrotron to dominate the steady state high-energy emission, both sources require more than two orders of magnitude higher luminosity than the available Blandford–Znajek power of the jets, even in the MAD regime (Liodakis & Petropoulou 2020). Lepto-hadronic models or models with subdominant hadronic components are viable alternatives for low magnetic field strengths ($B < 10$ G, e.g. Mastichiadis, Petropoulou & Dimitrakoudis 2013; Petropoulou et al. 2015; Gao et al. 2019). Such field strength levels are often found through radio observations (Pushkarev et al. 2012). If the jets contain a significant fraction of protons, our results would be in favour of the aforementioned models, noting however, that their energetic requirements can often be greater than that of proton-synchrotron models.

Throughout this work, we have used as our limiting Π_c value the 2σ upper limit of each individual observation. In the case of 3C 279, using a 3σ limit has only a mild quantitative effect and does not change any of our conclusions. However, in the case of PKS 1510–089 for $\delta < 20$, we cannot exclude models requiring high B -fields and low positron fractions. One of our main assumptions is that all of the non-detected CP signal is intrinsic to the jet. If the observed CP limits include both an intrinsic and extrinsic contribution, our constraints on the f , B would improve. We have also assumed the δ of the optical emitting regions to be similar to the ones derived in radio. This is likely to be true for a number of blazars that do not show δ variations even at very high radio frequencies (Liodakis et al. 2021). While the δ estimate for 3C 279 is modest, PKS 1510–089 has a rather high value. However, we note that the $\sigma_\delta = 1.9$ for 3C 279 in Jorstad et al. (2017) is optimistic. The spread of the reported proper motions is rather large. In our study (Blinov et al. 2021a), we found that the ratios of δ for individual components can change up to a factor ~ 5 . Assuming a larger Doppler factor will only tighten the constraints on B and f . Therefore, targeting high linearly polarized – high- δ blazars, or during outbursts when δ could be amplified (Larionov, Villata & Raiteri 2010; Uemura et al. 2017; Raiteri et al. 2017b; Liodakis et al. 2020), would allow us to further constrain the B-field and jet composition in blazars.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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