The Optical Variability Properties of TeV Blazars (Postprint)

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Date: 2024-10-08T00:00:00+00:00

Abstract

Variability is one of the typical observational properties of blazars and the spectral changes are usually associated with variability, although this kind of association is unclear yet. In this work, we used data from the Steward Observatory blazar monitoring program to investigate the optical variability properties including the short-term timescale, the brightness-dependent spectral property, the correlation between the the brightness variation and the polarization, and then estimate the Doppler factors based on the obtained short timescale to study the polarization property for a sample of 20 TeV blazars. Our analyses arrive at the following results: (1) The largest variation amplitude in R-band, ΔRM, covers a range from ΔRM = 0.29 mag (1ES 2344+514) to ΔRM = 4.66 mag (3C 279). (2) Intra-day variability was found from five sources with timescales from 0.14 day for S5 0716+714 to 0.98 day for PKS 2155-304. Sixteen sources show spectra that are bluer when they become brighter, suggesting a common bluer-when-brighter property. (3) The plot of the polarization versus estimated Doppler factor is consistent with the Doppler factor dependent formula of polarization. (4) The largest polarization is correlated with the largest optical variation, suggesting that the high polarization and high amplitude variation are both the indicator of beaming effect.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:095005 (10pp), 2024 September
https://doi.org/10.1088/1674-4527/ad6db4

The Optical Variability Properties of TeV Blazars

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Received 2023 December 4; revised 2024 July 29; accepted 2024 August 6; published 2024 September 4

Abstract

Variability is one of the typical observational properties of blazars, and spectral changes are usually associated with variability, although the nature of this association remains unclear. In this work, we used data from the Steward Observatory blazar monitoring program to investigate the optical variability properties of a sample of 20 TeV blazars, including the short-term timescale, brightness-dependent spectral properties, correlation between brightness variation and polarization, and Doppler factor estimation based on the obtained short timescales. Our analyses yield the following results: (1) The largest variation amplitude in the R-band, ΔR_M, ranges from ΔR_M = 0.29 mag (1ES 2344+514) to ΔR_M = 4.66 mag (3C 279). (2) Intra-day variability was found in five sources, with timescales ranging from 0.14 day for S5 0716+714 to 0.98 day for PKS 2155-304. Sixteen sources show spectra that become bluer when they brighten, suggesting a common bluer-when-brighter property. (3) The plot of polarization versus estimated Doppler factor is consistent with the Doppler factor-dependent formula of polarization. (4) The largest polarization correlates with the largest optical variation, suggesting that both high polarization and high-amplitude variation are indicators of the beaming effect.

Key words: galaxies: active –galaxies: jets –radiation mechanisms: nonthermal

1. Introduction

Blazars are an extreme subclass of active galactic nuclei (AGNs) with many special observational properties, such as rapid and large-amplitude variability, high and variable linear polarization, strong γ-ray emissions extending to TeV energies, and superluminal motion. These special properties arise from a beaming effect caused by a jet oriented at a small viewing angle with respect to the observer’ s line of sight (Wills et al. 1992; Urry & Padovani 1995; Ghisellini et al. 2014; Acero et al. 2015; Zhang & Fan 2018; Xiao et al. 2019; Abdollahi et al. 2020; Ajello et al. 2020; Otero-Santos et al. 2020; Zhang et al. 2020; Zhou et al. 2021; Chen et al. 2022, 2023; Pei et al. 2022; Yang et al. 2022; Yang et al. 2022a, 2022b, 2023; Fan et al. 2023).

Blazars are divided into two subclasses based on their emission line features: BL Lac objects (BL Lacs) and flat-spectrum radio quasars (FSRQs). FSRQs have strong emission lines with equivalent width (EW) > 5 Å, while BL Lacs show no or only weak emission lines with EW < 5 Å. Recently, Zhang et al. (2022) adopted the Gaussian Mixture Modeling clustering method to calculate the ratio of log L for a sample of 449 Fermi blazars with available emission lines and found that BL Lacs and FSRQs can be separated by log L. Pei et al. (2022) proposed that there is a changing-look region called the “appareling zone” with log L between -2.7 and -1.07, with sources falling into this zone being classified as changing-look blazars. However, it is also possible that the dividing line depends on the γ-ray luminosity (Xiao et al. 2022).

Padovani & Giommi (1995) proposed using the peak frequency log _p of the spectral energy distribution (SED) to classify BL Lacs into high-frequency peaked BL Lacs (HBLs) and low-frequency peaked BL Lacs (LBLs), separated by log _p = 15. Ghisellini (1998) proposed that there is a subclass of BL Lacs with synchrotron peak frequencies higher than those of conventional HBLs, called ultra-high-energy synchrotron peak BL Lacs (UHBLs; Costamante et al. 2001). By calculating the SEDs for a sample of 308 BL Lacs, Nieppola et al. (2006) classified BL Lac objects into LBLs, intermediate BL Lac objects (IBLs), and HBLs. Abdo et al. (2010) proposed that blazars can be classified as low synchrotron peak (LSP) sources if log _p < 14, as intermediate synchrotron peak (ISP) sources if $14 \leq$ log _p ≤ 15, and as high synchrotron peak (HSP) sources if log _p > 15. Recently, Fan et al. (2016) calculated the SEDs for a sample of 1392 Fermi blazars and proposed that a source would be classified as an LSP if log _p < 14.3, as an ISP if $14.3 \leq$ log _p ≤ 15.3, and as an HSP if log _p > 15.3 (Fan et al. 2016). Later, Yang et al. (2022) obtained log _p = 14.3 for LSPs, log _p = 14.8 for ISPs, and log _p = 15.7 for HSPs.

Variability across the entire electromagnetic spectrum is a typical observational property of blazars (Fan et al. 2002, 2021; Gu et al. 2006; Yang et al. 2017; Xiang et al. 2018; Zhang et al. 2018, 2023; Cai et al. 2022; Fang et al. 2022; Yuan et al. 2022; Lu et al. 2023; Otero-Santos et al. 2023). Fan et al. (2005) summarized the variability properties of blazars and pointed out that there are three types of variability based on timescales: short-term variability with timescales of minutes to days, which sheds light on the emission region size and black hole masses; middle-term variability with timescales of weeks to months that may be caused by spiral jets; and long-term variability with timescales of years, which may indicate the orbital period of a binary black hole system. The short-term variability timescale is also used to constrain the Doppler factor (Mattox et al. 1993; Cheng et al. 1999; Fan 2005; Fan et al. 2013; Pei et al. 2020). Observations show that it is common for the spectrum to change with source brightness. Generally, BL Lacs exhibit a bluer-when-brighter (BWB) phenomenon where the spectrum becomes harder when the source brightens, while FSRQs show a redder-when-brighter (RWB) phenomenon where the spectrum becomes softer when the source brightens, and some sources show more complicated patterns (Gu et al. 2006; Zheng et al. 2008; Xiong et al. 2017; Gupta et al. 2018; Yuan et al. 2023). Variability is also observed in the polarization of blazars (Feigelson et al. 1986; Mead et al. 1990), and polarization is found to be correlated with the core-dominance parameter (Wills et al. 1992; Fan et al. 2006), variation amplitude (Fan & Lin 2000), spectral index (Fan et al. 2008), and brightness (Mead et al. 1990).

As the successor to the Energetic Gamma Ray Experiment Telescope (EGRET; Hartman et al. 1999), Fermi/Large Area Telescope (LAT) has detected 3743 blazars and blazar candidates of uncertain type (BCUs) (Abdollahi et al. 2020; Ajello et al. 2020; Ballet et al. 2020). The γ-ray emission was also proposed to be one of the key observational properties of blazars (Fan et al. 2013).

Emissions have also been detected in the TeV band for blazars. From TeVCat (Wakely & Horan 2008), we can see that 81 blazars have TeV emissions, most of which are BL Lacs, particularly HSP BL Lacs. Compared to GeV blazars, the number of TeV blazars is only 3% that of GeV blazars. There have been many works on TeV candidate searches. Costamante & Ghisellini (2002) found that TeV BL Lacs occupy the region of both high radio and high X-ray fluxes and proposed that BL Lacs with strong radio and X-ray emissions are TeV candidates, obtaining 33 TeV BL Lac candidates. Massaro et al. (2013) found that TeV BL Lac candidates have similar infrared color index ranges (0.22 mag $<$ [3.4 m] - [4.6 m] $<$ 0.86 mag and 1.60 mag $<$ [4.6 m] - [12 m] $<$ 2.32 mag) and X-ray flux F__X $> 2.45 \times 10^{-12}$ erg cm^{-2} s^{-1} as TeV BL Lacs, predicting 95 TeV BL Lac candidates. Chang et al. (2017) proposed 1691 HSPs as TeV candidates. Very recently, Zhu et al. (2023) used machine learning methods and identified 40 high-confidence TeV candidates from 1459 blazars in 4FGL-DR2/4LAC-DR2. They calculated the SEDs for the 40 candidates and predicted that one source (4FGL J1058.6+5627) can be detected by the Large High Altitude Air Shower Observatory (LHAASO) (Zhu et al. 2023). More TeV BL Lac objects will provide us with opportunities to search for TeV emission mechanisms in BL Lacs and study the nature of TeV BL Lacs.

Lin & Fan (2016) made comparisons in observational properties between TeV BL Lacs and non-TeV BL Lacs. They found that (1) TeV BL Lacs are different from LSP and ISP BL Lacs but show similar properties to HSP BL Lacs, and (2) TeV HSP BL Lacs and non-TeV HSP BL Lacs exhibit differences in their $\alpha\{RO\}\ and\ \alpha\gamma$ but basically share other properties. Recently, Liang et al. (2023) investigated the mid-infrared properties of TeV blazars and non-TeV blazars and found that TeV BL Lac objects have stronger mid-infrared emissions than

GeV blazars and that TeV emissions are correlated with mid-infrared emissions. A statistical investigation of TeV BL Lacs in the optical band may also be interesting for understanding TeV BL Lacs.

However, most optical property studies have focused on individual TeV sources: 2344+514 (Cai et al. 2022), BL Lacertae (Gaur et al. 2019; Jorstad et al. 2022; Kalita et al. 2023; Raiteri et al. 2023; Yuan et al. 2023), OJ 287 (Gupta et al. 2019), 3C 66A, S4 0954+658 (Gaur et al. 2019), etc. There have been no statistical analyses for a sample of TeV BL Lacs.

Thanks to the Steward Observatory (SO) spectropolarimetric monitoring project (SPOL), we can analyze optical photometric and polarimetric data in both V and R bands for blazars. This motivated us to perform a statistical analysis of the optical properties for a sample of TeV BL Lacs. In this work, we investigate their optical variability properties based on the data of Smith et al. (2009). The paper is organized as follows: In Section 2, we describe the sample used in this work. The analysis results are presented in Section 3 with discussion, and our conclusions are provided in Section 4.

2. Sample and Results

In this work, we collected optical V and R band photometric observations and polarization measurements for a sample of 20 TeV blazars from the SO SPOL, which uses the 2.3 m Bok Telescope located on Kitt Peak and the 1.54 m Kuiper Telescope in Arizona (Smith et al. 2009) to monitor a sample of blazars, and listed them in Table 1 .

Fan & Lin (2000) obtained the de-reddened magnitude as follows. First, the Galactic latitude and longitude of each source were calculated. Second, the location of each source on the Burstein & Heiles H I maps (Burstein & Heiles 1982) was used to determine the proper reddening E(B - V). Third, the extinction A_λ was determined from the relation X( ) = A_λ/E(B - V), where   = 1/λ (see Seaton 1979), which was used to correct the observations to obtain the de-reddened V and R magnitudes. Now we can get magnitudes from the website. The corresponding values are listed in Column (3) and Column (4) for V and R bands in Table 1. Example light curves for four sources (3C 66A, 1ES 1959+650, BL Lac, and 1ES 2344+514) are displayed in the left panels of Figure 1 [Figure 1: see original paper]. Fifteen sources have V and R photometric magnitudes, and five sources (TXS 0506+056, VER J0521+211, S4 0954+658, S3 1227+25, PG 1554+113) have only differential photometric data between the source (V_S, R_S) and the comparison stars (V_C, R_C), namely V_S - V_C and R_S - R_C.

From our collection, we found that the greatest V variation amplitude ranges from ΔV = 0.32 mag in Mkn 501 to ΔV = 4.71 mag in 3C 279, and the greatest R variation magnitude ranges from ΔR = 0.29 in Mkn 501 to ΔR = 4.66 in 3C 279. The greatest variation amplitude in the V band tends to be larger than that in the R band, suggesting greater variability at shorter wavelengths. The maximum color index (V - R)*{max} ranges from 0.62 in TXS 0506+056 to 1.76 in BL Lac, while the minimum color index (V - R)*{min} ranges from -0.05 in TXS 0506+056 to 0.55 in BL Lac. In addition, it is also found that the color index is positively correlated with the greatest variation amplitude, following Δ(V - R) = (0.01 ± 0.07)ΔR + (0.22 ± 0.16) with a correlation coefficient of r = 0.05 and a chance probability of p = 8.3%, as shown in Figure 2 [Figure 2: see original paper].

2.1. Spectrum and Brightness Correlation

Based on the corrected magnitudes and the corresponding color indexes, we can investigate the relationship between magnitude and color index. The light curve examples for four sources (3C 66A, 1ES 1959+650, BL Lac, and 1ES 2344+514) are shown in the left panels of Figure 1. Examples of the spectrum-brightness correlations are displayed in the right panels of Figure 1. The results of the linear regression analysis for color index V - R and R magnitude are listed in Table 2 . We can see that 16 sources show positive correlations between V - R and R, or between ((V_S - V_C) - (R_S - R_C)) and (R_S - R_C) for those sources with only differential magnitudes, which indicates a BWB phenomenon. For the remaining four sources (TXS 0506+056, S4 0954+658, H1426+428, and PG 1553+113), more observations are needed for further investigation.

3. Discussions

Variability is a typical observational property of blazars and is observed across the entire electromagnetic spectrum (Caproni & Abraham 2004; Aleksić et al. 2011; Foschini et al. 2011; Graham et al. 2015; Wang et al. 2017, 2022; Xiong et al. 2017; Gupta et al. 2018; Liodakis et al. 2018; Zhang et al. 2018, 2020, 2023; Wang & Shi 2020; Fan et al. 2021; Jorstad et al. 2022; Yang et al. 2022a; Bachev et al. 2023). The rapid, large-amplitude variability is explained by the relativistic beaming effect. In this scenario, the observed timescale (Δt_{obs}) is shortened as Δt_{obs} = Δt_{int}/δ, while the observed flux density (f_{obs}) is boosted as f_{obs} = δ^(λ+α) f_{int}, where δ is the Doppler factor (boosting factor), λ stands for the jet morphology (λ = 3 for a moving sphere jet and λ = 2 for a continuous jet; see Lind & Blandford 1985), α stands for the spectral index (f_   ^(-α)), Δt_{int} is the intrinsic timescale, and f_{int} is the intrinsic flux density.

In this work, we obtained the V and R photometric data from the SO SPOL (Smith et al. 2009) and analyzed their variabilities and timescales as described in detail in the following subsections.

3.1. Correlation between the Spectrum and Brightness

Different spectral behaviors have been found for different sources. Gu et al. (2006) analyzed the BVRI band data of eight sources and found a clear anti-correlation between the color index and R magnitude, known as the BWB phenomenon. Zheng et al. (2008) analyzed the long-term optical monitoring of OJ 287 and found the same behavior. Liao et al. (2014) analyzed the long-term multi-band SED of 0716+714 and found that the SED peak frequency moves toward shorter wavelengths when the source gets brighter. Many sources including 0716+714, OJ 287, 3C 66A, BL Lac, and PKS 0420-01 (Gu et al. 2006), 3C 345 (Wu et al. 2011; Villata et al. 2006), and 3C 454.3 (Zhai et al. 2011) have been found to exhibit the same BWB phenomenon. On the other hand, the IR and optical spectra of some sources like Mkn 421 (Carnerero et al. 2017) and 0235+164 (Romero et al. 2000) remain unchanged when the sources brighten.

For the color index V - R and the R magnitude, we investigated their relationship and found strong correlations for 16 sources, suggesting a brightness-dependent spectral phenomenon as discussed in the literature (Gu et al. 2006; Zheng et al. 2008; Gupta et al. 2018; Li et al. 2021). For the 20 sources, four sources (TXS 0506+056, S4 0954+658, H1426+428, and PG 1553+113) do not have enough data, so we consider the other 16 sources. Among them, 3C 66A, J0521+211, S5 0716+714, OJ 287, Mrk 421, S3 1227+25, 3C 279, Mrk 501, 1ES 1959+650, PKS 2155-304, BL Lac, and 1ES 2344+514 show clear correlations between the color index (V - R) and the R magnitude, indicating BWB. Moreover, Ton 599, W Com, and PKS 1510-089 indicate that the spectrum becomes redder when the brightness increases, suggesting an RWB phenomenon. For OJ 287, our BWB result is consistent with that of Gu et al. (2006) but differs from that of Zheng et al. (2008). For 3C 66A, Mkn 421, and BL Lac, our BWB results are consistent with those of Gu et al. (2006) and Meng et al. (2018). However, the spectrum did not change in Carnerero et al. (2017). For S5 0716+714, our BWB results are consistent with those of Gu et al. (2006) and Poon et al. (2009). For 1ES 1959+650, our BWB result is consistent with the finding by Meng et al. (2018). For PKS 0736+01, we find no tendency for correlation between the color index (V - R) and R magnitude, for which a chance probability of p = 64% was obtained. It is clear that the brightness-dependent phenomenon is complicated and worthy of further study using a larger sample. Fortunately, the Chinese Space Station Telescope (CSST) will provide us with many simultaneous multiwavelength observations of AGNs, which will help astronomers study and understand the nature of the brightness-dependent phenomenon.

In addition, we also found that the color index variability Δ(V - R) and the variability amplitude ΔR are closely correlated, as depicted in Figure 2. This is understandable if the spectrum changes with brightness, so that the more violently a source varies, the larger the color index change. A similar phenomenon in the γ-ray band is discussed by Yang et al. (2022b) and Yu et al. (2024).

3.2. Doppler Factor

Observations indicate a double-bump structure for the SED of blazars (Urry & Padovani 1995; Abdo et al. 2010). The first bump extends from radio to X-ray bands with the peak in the IR to X-ray band, which originates from synchrotron emission of relativistic electrons in the jet. The second bump extends from X-ray to γ-ray bands with the peak in the X-ray to GeV γ-ray band, proposed to be from inverse Compton (IC) emissions. Shaw et al. (2012) and Paliya et al. (2021) show that FSRQs have richer seed photons from the external field than BL Lacs through emission line observations. The γ-ray emissions may be the combined result of synchrotron self-Compton (SSC) and external Compton (EC) processes for FSRQs, while SSC is the main mechanism for γ-ray emissions in BL Lacs (Ghisellini et al. 1998).

The variability and corresponding timescale are used to estimate the Doppler factor. Radio observations show that it is reasonable to define the equipartition brightness temperature (intrinsic brightness temperature) of blazars (Lähteenmäki & Valtaoja 1999; Hovatta et al. 2009). Savolainen et al. (2010) and Liodakis et al. (2018) estimated the variability Doppler factor for 1029 blazars based on long-term monitoring in radio bands and intrinsic temperature. Xie et al. estimated the optical Doppler factor based on the idea that the difference between the observed mass-energy conversion rate (_{obs}) and the intrinsic rate (_{int}) arises from the boosting effect. The Doppler factor in the γ-ray band can be constrained by the geometry of the radiation zone (Mattox et al. 1993; von Montigny et al. 1995; Cheng et al. 1999; Fan 2005; Fan et al. 2013, 2014; Pei et al. 2020; Zhang et al. 2020; Wang et al. 2022; Yang et al. 2022a).

Combining the IC mechanism and the variability timescale, one can also constrain the Doppler factor (Chen 2018). The SED calculations for the synchrotron component were carried out for released catalogs by Fan et al. (2016) for a sample of 2709 Fermi blazars. For the high-energy region, the SED calculations were performed by Yang et al. (2023) for 3743 Fermi blazars. Those calculations are useful for emission mechanism investigation and physical parameter constraints (Chen 2018; Fan et al. 2023).

According to properties of a soft photon, the Doppler factor in the Thomson regime can be estimated through SED parameters obtained by fitting a logarithmic parabola (Chen 2018):

δ_{SSC} = [(_p^{syn} L_p^{syn}) / (10^{45} erg s^{-1})]^(1/6) × [(10^{10} Hz) / _p^{syn}]^(1/3) × [(Δt / 1 day)]^(-1/3) × 10[1]

for the SSC process, or

δ_{EC} = [(_p^{ecn} L_p^{ecn}) / (10^{45} erg s^{-1})]^(1/6) × [(10^{10} Hz) / _p^{ecn}]^(1/3) × [(Δt / 1 day)]^(-1/3) × 10[2]

for the EC process. In this sense, given the synchrotron peak frequency (_p^{syn}), synchrotron peak luminosity (L_p^{syn}), and the curvature for the synchrotron component (b), the peak frequency (_p^{ecn}) and the corresponding peak luminosity (L_p^{ecn}) for the Compton component can constrain the Doppler factor using the obtained timescale (Δt).

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[1] (2-b)/6

[2] (2-b)/6

We obtained logarithmic parabola parameters for our sample from Yang et al. (2022, 2023). Using the timescale obtained in this work, we calculated the Doppler factors, $\delta\{SSC\}$ *(for the SSC process) and* $\delta\{\mathrm{EC}\}$ (for the EC process), and listed them in Columns (13) and (14) of Table 1, respectively. The Doppler factors from the SSC process range from $\delta\{SSC\} = 0.84$ *(1ES 1959+650) to* $\delta\{\mathrm{SSC}\} = 493.7$ (OJ 287), while those estimated from the EC process range from $\delta\{EC\} = 5.33$ *(1ES 1959+650) to* $\delta\{\mathrm{EC}\} = 31.93$ (OJ 287). Two other sources have Doppler factors greater than 100: 3C 279 ($\delta\{SSC\} = 224.79$*) and BL Lac (*$\delta\{\mathrm{SSC}\} = 114.08$).

We investigated the relationship between our Doppler factors and those from Liodakis et al. (2018). We found log $\delta\{SSC\} = 0.45 \, log \, \delta\{\mathrm{L18}\} + 0.29$ with r = 0.45 and p = 4.5%, suggesting a weak positive correlation as visible in the upper panel of Figure 3 [Figure 3: see original paper], and log $\delta\{EC\} = 0.33 \, log \, \delta\{\mathrm{L18}\} + 0.14$ with r = 0.33 and p = 15.3%, suggesting a positive correlation tendency as shown in the lower panel of Figure 3. It is clear that the sample is still too small, which results in a high chance probability. A larger sample will yield a result with higher confidence in the correlation analysis.

A large Doppler factor ($\delta > 100$) also appeared in Chen (2018). The reason may be that the physical parameters calculated for the two bumps are not very accurate. However, we can see that the Doppler factors estimated from the EC process are not as large as those from the SSC process. For OJ 287, its $\delta\{EC\} = 31.93$ *is close to the value* $\delta = 29.77$ *(Liodakis et al. 2018). For BL Lacertae,* $\delta\{\mathrm{EC}\} = 11.46$ is also close to the value $\delta = 12.17$ (Liodakis et al. 2018). Does this mean the EC process is responsible for the γ-ray emissions or that the EC process is the dominant mechanism for the γ-ray emissions? If this is the case, then one can determine which mechanism is more important for γ-ray emissions by comparing our Doppler factors with those in the literature.

Therefore, we suggest that the EC process is the main process for γ-ray emissions in TXS 0506+056, S5 0716+714, OJ 287, Ton 599, 3C 279, PG 1553+113, and BL Lacertae, while the SSC process is the dominant mechanism for γ-ray emissions in PKS 0736+01, 1ES 1959+650, PKS 2155-304, and 1ES 2344+514. Both processes are responsible for γ-ray emissions in 3C 66A, VER J0521+211, Mkn 421, Mkn 501, W Com, and PKS 1510-089. We believe that a larger sample with available variability timescales and physical parameters from the SEDs will enable us to investigate the correlation between the estimated Doppler factors and those from the literature, allowing us to study the γ-ray emission mechanism.

3.3. Polarization

In this work, the highest optical polarization values were also collected from Smith et al. (2009) and listed in Column (12) of Table 1. When linear regression analysis is performed for polarization and variation amplitude, a correlation is found with r = 0.81 and p = 1.03×10^{-5}, as shown in Figure 4 [Figure 4: see original paper]. This suggests that sources with higher polarization tend to have larger variation amplitudes, as observed in Fan & Lin (2000).

Fan et al. (1997) derived a relation between the observed polarization (P_{obs}) and the Doppler factor (δ):

P_{obs} = [(δ^(1+α) (1 + f) P_{int})] / [δ^(1+α) (1 + f) + (1 -)]

where P_{int} is the intrinsic polarization in the comoving frame, f is the ratio of emission in the jet to the unbeamed emission in the comoving frame, and   is the ratio of polarized emission to unpolarized emission in the jet. Following Fan et al. (1997), we choose   = 0.6, f = 0.1 or   = 0.11, f = 0.001 and obtain the corresponding P_{int} = 0.1% and 3.4%, respectively. The curves of P versus δ corresponding to f = 0.001 and f = 0.1 are displayed in Figure 5 [Figure 5: see original paper].

In this work, we used the collected maximum optical polarization listed in Column (12) of Table 1 and the estimated Doppler factor (δ{EC}*) to study their relationship. The result is shown in Figure 5. The observational data follow the same tendency as the theoretical curves, suggesting that polarization is an indication of the beaming effect or that high polarization arises from strong beaming in blazars. Most points are located between the two curves, and the parameters for the two curves suggest the intrinsic polarizations for our sample are P*{int} = 0.1% to 3.4%. In discussing Doppler factor-dependent polarization, it is difficult to get a theoretical curve to fit the Doppler factor well since the parameter f differs from one source to another, showing a 5 dex difference for BL Lacs (Fan 2003). However, we suggest the correlation can be tested using simultaneous polarization and the corresponding Doppler factor for a selected source or a sample of similar type. The high observed polarization suggests that TeV blazars have a strong beaming effect. For the 20 TeV blazars, 17 sources were given Doppler factors in the work by Liodakis et al. (2018), and nine sources have Doppler factors greater than 10, as listed in Column (15) of Table 1.

4. Conclusion

In this work, we collected optical V and R photometric observations and optical polarizations for a sample of 20 TeV blazars, of which 15 sources have V and R magnitudes and the remaining five sources have only differential magnitudes between the sources and their comparison stars. Their optical variability timescales were investigated and used to estimate the Doppler factor. The Doppler factors were also compared with known values from Fan et al. (2014), Liodakis et al. (2018), and Lähteenmäki & Valtaoja (1999). Our conclusions are:

(1) The largest variation amplitude was obtained for all 20 TeV blazars, with some showing intraday variability over timescales ranging from 0.14 day (S5 0716+714) to 0.98 day (PKS 2155-304).

(2) For the 16 sources with sufficient observations, 12 sources show bluer spectra when they are brighter, suggesting a BWB property in the optical band, three sources show the RWB phenomenon, and one source shows no brightness-dependent tendency.

(3) Doppler factors were estimated for those sources. The optical polarization and Doppler factor follow the Doppler factor-polarization relation, suggesting that polarization depends on the Doppler factor.

(4) The optical variation amplitude is correlated with the variation of color index, which is consistent with the BWB phenomenon.

(5) The optical variation amplitude is correlated with the optical polarization, suggesting both parameters can be regarded as indicators of the beaming effect.

Acknowledgments

This work is partially supported by the National Natural Science Foundation of China (NSFC, grant Nos. U2031201, 12433004, 11733001, U2031112, 12133004, and 12103012), and Guangdong Major Project of Basic and Applied Basic Research (grant No. 2019B030302001). We also acknowledge the science research grants from the China Manned Space Project with NO. CMS-CSST-2021-A06, and the supports for Astrophysics Key Subjects of Guangdong Province and Guangzhou City. The work is also supported by the Key Laboratory for Astronomical Observation and Technology of Guangzhou. The authors thank the referee for providing helpful comments and detailed remarks.

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