Postprint: A Study on Optical Color Index Variations of Fermi Blazars

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Abstract

This study employs the method of adjusting the flux baseline to correct the optical band flux and color indices of 19 Fermi Blazars, and investigates the influence of the Doppler factor on the color index variability mechanism by comparing the correlation between color index and magnitude before and after correction. The results indicate: (1) Before correction, only 5 sources exhibit a clear BWB trend, while 2 sources exhibit a clear RWB trend; (2) After correction, 9 sources exhibit a clear BWB trend, 6 sources exhibit a weak BWB trend, and only 4 sources show no correlation between color index and magnitude; (3) Approximately half of the sources have their color variability mechanism affected by the Doppler beaming effect, and the correlation between color index and magnitude for these sources is enhanced after correction; (4) Variations in the Doppler factor may be responsible for the weakening of the BWB trend. By studying the correlation between color index and magnitude, the radiation mechanism of Blazars can be further elucidated.

Full Text

A Study on Color Index Variations of Fermi Blazars

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Abstract: This paper corrects the optical band flux and color index of 19 Fermi blazars using a flux base-level modulation method. By comparing the correlation between color index and magnitude before and after correction, we investigate the influence of the Doppler factor on the color index variation mechanism. The results show that: (1) before correction, only five sources exhibit a clear “bluer when brighter” (BWB) trend, while two sources show a clear “redder when brighter” (RWB) trend; (2) after correction, nine sources display a pronounced BWB trend, six sources show a weak BWB trend, and only four sources show no correlation between color index and magnitude; (3) the color variation mechanism of approximately half of the sources is affected by Doppler beaming, with the correlation between color index and magnitude strengthening after correction; (4) changes in the Doppler factor may be responsible for the weakening of the BWB trend. Studying the relationship between color index and magnitude can further elucidate the radiation mechanism of blazars.

Keywords: blazars; color index; Doppler factor; correlation; BWB trend

Introduction

It is well known that blazars constitute an extremely special subclass of active galactic nuclei (AGN), characterized by polarized emission in optical and radio bands, rapid and large-amplitude variability across all wavelengths, and non-thermal continuum radiation [1-2]. Based on emission line strength, blazars can be divided into two categories: BL Lacertae objects (BL Lacs), which lack or show only weak emission lines, and flat-spectrum radio quasars (FSRQs), which possess strong emission lines [3-4]. Blazar variability can be classified into three types according to timescale [5-6]: short-term variability (IDV, with flux variation timescales on the order of days), medium-term variability (STV, with timescales on the order of months), and long-term variability (LTV, with timescales on the order of years). S5 0716+714 is a BL Lac object exhibiting continuous variability, with optical variation timescales typically ranging from minutes to hours during short-term events, though the relationship between color index and magnitude is complex [7-9]. Villata [10-11] studied the light curves of 2200+420 and found a BWB trend when the source brightened, proposing that variations in the Doppler factor on a “convex” spectrum might explain the long-term variations and their subtle color changes. Dai, Yan et al. studied OJ 287 from 2005 to 2006 and identified a BWB trend [12]. Zhang et al. [13-14] conducted observational studies of OJ 287 in a low, faint state and found a BWB trend; they also performed long-term monitoring of the BL Lac object H0323+022, which similarly exhibited a BWB trend. Ikejiri et al. [15] observed 44 blazars and analyzed their color indices, finding that 88% showed BWB trends. Bindu et al. [16] discovered that BL Lacs typically display BWB trends, whereas FSRQs tend to show “redder when brighter” (RWB) trends. In a study of 86 sources, Hovatta [17] found that all flat-spectrum radio quasars are subject to Doppler enhancement effects, with FSRQs having higher Doppler boosting factors than BL Lacs. The Doppler beaming effect in blazars can shorten apparent timescales and dramatically enhance observed flux, which enables researchers to investigate the central engines of blazars through their flux variations [18]. Many researchers have studied blazar color indices, most commonly by examining the correlation between color index and magnitude to further interpret the radiation mechanisms of these objects. To investigate the impact of Doppler beaming effects on blazars, we collected B- and R-band magnitude data for 19 Fermi blazars from the SMARTS website for the following analysis.

2. Observation Data and Color Index Analysis

2.1 Observation Data

The data were obtained from the SMARTS website (http://www.astro.yale.edu/smarts/glast/home.php). To ensure robust analysis dependent on sample size, we selected sources with abundant observational data in both B and R bands, removing spurious data caused by observational timing gaps or telescope malfunctions. Ultimately, we acquired quasi-simultaneous B- and R-band data for 19 Fermi blazars: 3C 273, 3C 279, 3C 454.3, 0208-512, 0235+164, 0250-225, 0402-362, 0454-234, 0528+134, 0531-4827, 1004-217, 1144-379, 1406-076, 1424-41, 1510-089, 1622-297, 2052-474, 2142-75, and 2155-304. The longest observational coverage was for source 3C 454.3, spanning from Julian Date (JD) 2454640 to 2457964. Among the 19 sources, 0235+164 and 2155-304 are BL Lacs, while the remainder are FSRQs. After screening, we obtained 12,682 data sets from the SMARTS website, with 6,341 data points each for the B and R bands.

2.2 Color Index Analysis

We calculated the color indices for all 19 sources using the quasi-simultaneous data and computed the correlation between color index and magnitude. S5 0716+714 exhibits BWB behavior across microvariability, short-term, and long-term timescales; Mrk 501 shows a BWB trend on medium-term, short-term, and microvariability timescales [17]. The spectral index during outburst periods differs from that in quiescent periods [20], suggesting that color index variations may be related to the source's activity state and timescale. Additionally, the host galaxy, accretion disk component, and gravitational microlensing can produce apparent but spurious color variations [21-22]. Therefore, we employed the flux base-level modulation method to correct the flux and color index, comparing the differences in the color index-magnitude correlation before and after correction to investigate the effect of Doppler effects on blazar color indices.

The flux base-level modulation method [10-12, 23] proceeds as follows: (1) To mitigate the effects of dense sampling, fluxes were binned over 4-day intervals, after which cubic spline interpolation was applied to the binned data to obtain flux values with long-term trends removed. Since the SMARTS website provides observed magnitudes, we converted these to fluxes using the following formulas before calculation: $F_B = 4260 \times 10^{-0.4\times m_B} \times 10^3$; $F_R = 3080 \times 10^{-0.4\times m_R} \times 10^3$. (2) To study the impact of Doppler beaming on blazars, we assumed that baseline oscillations arise from variations in the relativistic Doppler factor ($\delta = [\Gamma(1-\beta\cos\theta)^{-1}]$), where Γ is the Lorentz factor and θ is the viewing angle. Corrections were applied by dividing each original flux by the ratio between the time-dependent spline interpolation and the minimum original flux ($C_{band}(t) = (F_{spl}(t), F_{om}$ represents the minimum original flux). Villata proposed this method to explore the relationship between the color variation mechanism and Doppler factor for 2200+420 [10-11]. Due to non-uniform observational sampling, data gaps exist in certain time periods; for example, source 0235+164 lacks observations from MDJ 2455893.65096 to 2456855.86900. To address this, we modified Villata’ s method by replacing the ratio between the time-dependent spline interpolation and its minimum value with the ratio between the time-dependent spline interpolation and the minimum original flux, yielding corrected fluxes from which we derived corrected color indices. The 4-day binning timescale was chosen because shorter timescales would demand excessively high sampling density, while longer timescales would smooth out flux variations during optimally sampled periods.

3. Research Results

We investigated the relationship between color index (B-R) and R-band magnitude (R) before and after correction. Assuming color index as Y and magnitude as X, the relationship follows $Y = a + b \times X$. Tables 1 and 2 present the correlations between magnitude and color index before and after correction, respectively, where a is the intercept, b is the slope, r is the correlation coefficient, p is the confidence level (with $p < 0.05$ indicating significance), and n is the sample size for each source. The linear relationships between color index (Y) and magnitude (X) are shown in Figures 1 [Figure 1: see original paper] through 19 [Figure 19: see original paper]. The results indicate that data points after flux base-level modulation are concentrated to the left of the original data points. Before correction, sources 3C 279, 0454-234, 0528+134, 1004-217, and 1144-379 exhibit clear BWB trends, while sources 3C 454.3 and 0402-362 show clear RWB trends. After correction, 15 sources display BWB trends, with only 3C 454.3, 0250-225, 1406-076, and 1510-089 failing to show BWB trends. Notably, all color correlations show considerable scatter.

Table 1 : The relationship between color index and magnitude before correction

Table 2: The relationship between color index and magnitude after correction

In Tables 1 and 2, SP denotes strong positive correlation, WP denotes weak positive correlation, SN denotes strong negative correlation, WN denotes weak negative correlation, and N denotes no significant correlation.

Figure 1 [Figure 1: see original paper]: Color index versus magnitude for 3C 273
Figure 2 [Figure 2: see original paper]: Color index versus magnitude for 3C 279
Figure 3 [Figure 3: see original paper]: Color index versus magnitude for 3C 454.3
Figure 4 [Figure 4: see original paper]: Color index versus magnitude for

0208-512
Figure 5 [**Figure 5: see original paper**]**:** Color index versus magnitude for 0235+164
Figure 6 [**Figure 6: see original paper**]**:** Color index versus magnitude for 0250-225
Figure 7 [**Figure 7: see original paper**]**:** Color index versus magnitude for 0402-362
Figure 8 [**Figure 8: see original paper**]**:** Color index versus magnitude for 0454-234
Figure 9 [**Figure 9: see original paper**]**:** Color index versus magnitude for 0528+134
Figure 10 [**Figure 10: see original paper**]**:** Color index versus magnitude for 0531-4827
Figure 11 [**Figure 11: see original paper**]**:** Color index versus magnitude for 1004-217
Figure 12 [**Figure 12: see original paper**]**:** Color index versus magnitude for 1144-379
Figure 13 [**Figure 13: see original paper**]**:** Color index versus magnitude for 1406-076
Figure 14 [**Figure 14: see original paper**]**:** Color index versus magnitude for 1424-41
Figure 15 [**Figure 15: see original paper**]**:** Color index versus magnitude for 1510-089
Figure 16 [**Figure 16: see original paper**]**:** Color index versus magnitude for 1622-297
Figure 17 [**Figure 17: see original paper**]**:** Color index versus magnitude for 2052-474
Figure 18 [**Figure 18: see original paper**]**:** Color index versus magnitude for 2142-75
Figure 19 [**Figure 19: see original paper**]**:** Color index versus magnitude for 2155-304

Our analysis of the correlations between color index and magnitude before and after correction reveals that: (1) before correction, only five sources show clear BWB trends and two sources show clear RWB trends; (2) after correction, nine sources exhibit pronounced BWB trends, six sources show weak BWB trends, and only four sources show no correlation between color index and magnitude; (3) the correlations for sources 3C 273, 0528+143, 0531-4827, 1406-076, 1424-41, 1622-297, 2052-474, and 2142-75 strengthen after correction, suggesting their BWB trends are influenced by the Doppler factor. In contrast, the correlations for sources 3C 279, 3C 454.3, 0235+164, 0250-225, 1144-379, and 1510-089 weaken after correction. For sources showing no significant change or decreased correlation, we conclude that the Doppler factor has minimal impact on their color indices or that these sources possess more complex radiation mechanisms. The shock-jet model provides a good explanation for the origin of BWB trends: when a large number of electrons radiate outward into a region with a strong magnetic field, the radiation from that region increases, causing high-frequency radiation to become immediately visible observationally while low-frequency radiation appears relatively later, resulting in the object gradually becoming bluer during flux rise. However, changes in the viewing angle alter the Doppler boosting factor, which can weaken the BWB trend in some blazars.

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