Estimation of the Optical Doppler Factor for BL Lac Objects (Postprint)

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Abstract

BL Lacertae objects (BL Lacs) are a special class of active galactic nuclei (AGN) that exhibit extreme observational characteristics, such as high luminosity and polarization, rapid variability, superluminal motion, radio core dominance, and very high-energy radiation. These extreme observational properties may all be associated with jet effects, and the physical quantity that characterizes such jet effects is the Doppler factor. The Doppler factor facilitates understanding of the radiation physics and intrinsic properties of BL Lacs. Based on the unified model framework for BL Lacs and Fanaroff-Riley type I/Fanaroff-Riley type II (G) radio galaxies, it is proposed that the distribution of intrinsic apparent magnitude versus redshift (Hubble diagram) for BL Lacs should be similar to the distribution of observed apparent magnitude versus redshift for FRI/FRII (G) galaxies, and a method for estimating the optical Doppler factor of BL Lacs is presented. The Doppler factors estimated by this method exhibit good correlation with previously obtained optical Doppler factors, demonstrating that this method for estimating BL Lac Doppler factors in the optical band is reliable.

Full Text

Preamble

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Optical Doppler Factor Estimation for BL Lacertae Objects

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Abstract

BL Lacertae objects (BL Lacs) represent a distinct subclass of active galactic nuclei (AGN) that exhibit extreme observational characteristics, including high luminosity and polarization, rapid variability, superluminal motion, radio core dominance, and very high-energy emission. These extreme properties likely originate from relativistic jet effects, which are quantified by the Doppler factor (δ). The Doppler factor is crucial for understanding the radiation physics and intrinsic properties of BL Lacs. Based on the unified model framework for BL Lacs and Fanaroff-Riley type I/II (G) radio galaxies, we propose that the distribution of intrinsic apparent magnitude versus redshift (Hubble diagram) for BL Lacs should resemble the observed apparent magnitude-redshift distribution of FRI/FRII (G) galaxies, and we present a method to estimate the optical Doppler factor for BL Lacs. The Doppler factors estimated through this method show good correlation with previously published optical Doppler factors, demonstrating the reliability of this optical-band estimation technique.

Keywords: BL Lacertae objects: general, galaxies: active, galaxies: distances and redshifts, galaxies: jets

1. Introduction

Active galactic nuclei (AGN) are a special class of galaxies whose nuclei exhibit intense activity phenomena. Their observational properties can be explained by the "black hole + accretion disk + jet" model. Blazars constitute one subclass of AGN that display extreme observational features: high luminosity, rapid variability, high polarization, radio core dominance, apparent superluminal motion, and high-energy emission. Blazars are divided into two categories: flat-spectrum radio quasars (FSRQs), with emission line equivalent widths greater than 5 Å, and BL Lacertae objects (BL Lacs), with equivalent widths less than 5 Å.

In the black hole + accretion disk + jet model, the relativistic jets of blazars are oriented toward the observer. The observed flux density (F_{ob}) relates to the intrinsic flux density (F_{in}) through F_{ob} = δ^q F_{in}, where δ is the Doppler factor and q = 3 + α or q = 2 + α corresponds to spherical or continuous jet geometries respectively (for clarity, we denote spherical jets as q_1 and continuous jets as q_2), with α representing the spectral index. The relationship between flux density (F_) and spectral index (α) follows F_ ^(-α), where is frequency.

The Doppler factor (δ) is a fundamental physical parameter that depends on the jet viewing angle ( ) and relativistic velocity (β): $\delta = 1/[\Gamma(1 - \beta \cos\ )]$, where $\Gamma = 1/\surd(1 - \beta^2)$. Since and β cannot be directly obtained from observations, the Doppler factor cannot be measured directly and must be estimated indirectly.

Radio galaxies represent another AGN subclass. In 1974, Fanaroff and Riley conducted a detailed study of bright double-lobed radio galaxies, classifying them based on morphology and luminosity at 178 MHz. Radio galaxies with luminosity L_{178} MHz $< 2 \times 10^{25}$ $\mathrm{W \cdot Hz^{-1} \cdot sr^{-1}}$ and edge-darkened structure were designated Fanaroff-Riley type I (FRI), characterized observationally by narrow double-sided jets with poorly collimated large-scale structure. Those with L_{178} MHz $> 2 \times 10^{25}$ $\mathrm{W \cdot Hz^{-1} \cdot sr^{-1}}$ and edge-brightened structure were classified as Fanaroff-Riley type II (FRII), featuring hot spots with the highest luminosity and well-collimated single-sided jets. Based on optical spectral properties, FRII galaxies can be further divided into two subclasses: FRII (G), with optical spectra resembling normal galaxies, and FRII (Q), with spectra similar to quasars.

The optical nuclear radiation of radio galaxies is also influenced by jet effects. Arshakian et al. collected and analyzed 15 GHz radio and 5100 Å optical nuclear emission data for a sample of 20 radio galaxies, finding a close correlation and proposing that optical radiation in radio galaxies is affected by relativistic jets. Verdoes Kleijn et al. analyzed radio and optical nuclear emission from 21 nearby FRI galaxies, discovering strong correlations between these bands that likely originate from synchrotron radiation from internal jets.

Numerous studies of blazar and radio galaxy luminosity functions, extended radio emission, narrow emission lines, host galaxies, and environments have suggested that FRI galaxies are the most likely parent population of BL Lacs —when FRI jets point toward observers, they appear as BL Lacs—while FRII galaxies are the most likely parent population of FSRQs. However, some researchers have noted that certain FRII sources exhibit properties similar to BL Lacs, suggesting that a portion of FRII galaxies should also be considered part of the BL Lac parent population. For instance, Falomo et al. used Hubble Space Telescope optical imaging of 52 BL Lac host galaxies, finding that the average luminosity of BL Lac hosts lies between those of FRI and FRII galaxies, suggesting FRII galaxies could be part of the BL Lac parent population. Xie et al. and Fan et al. discussed unified models using redshift-apparent magnitude relationships in optical and infrared bands, finding that the Hubble diagram distribution of FRII (G) galaxies matches well with those of BL Lacs and FRIs, proposing that the BL Lac-FRI unified scheme could be extended to FRII (G) objects. Ye et al. collected extended 5 GHz radio luminosity data for 297 BL Lacs and 128 FRI/FRII (G) galaxies, using Wilcoxon rank-sum and Kolmogorov-Smirnov tests to support the notion that BL Lacs, FRIs, and FRII (G) galaxies belong to the same class of objects. Zeng et al. analyzed X-band extended spectral indices for 177 BL Lacs and 74 FRI/FRII (G) galaxies, finding similar average extended spectral indices, with Student' s t-test results supporting the inclusion of FRII (G) as part of the BL Lac parent population.

Due to jet orientation effects, the observed optical radiation of BL Lacs is amplified by relativistic effects, while FRI/FRII (G) jets are considered to be oriented away from observers with weaker beaming amplification, making their optical radiation essentially intrinsic. If BL Lacs and FRI/FRII (G) are indeed the same class of objects, the observed differences in optical radiation between them may be attributed to the Doppler factor. Therefore, based on unified model considerations, we propose a method to estimate the optical Doppler factor for BL Lacs by studying the Hubble diagrams of BL Lacs and FRI/FRII (G) galaxies.

2. Sample Description

From the works of Xie et al., Xie Zhaohua et al., Véron-Cetty & Véron, and Zirbel & Baum, we collected V-band magnitudes (m_V) and redshift (z) data for 491 BL Lacs and 95 FRI/FRII (G) galaxies, listed in Table 1 . Since observed magnitudes are increased by Galactic dust extinction, we obtained V-band Galactic extinction values from the NASA/IPAC Extragalactic Database (NED) for each object' s coordinates and subtracted these from the observed V magnitudes to obtain the true magnitudes.

The BL Lac redshifts range from z = 0.027 to 5.03, with a mean of z_{BL} = 0.461 ± 0.496. The redshift distribution is shown in Figure 1 [Figure 1: see original paper] (purple region). Most BL Lacs in our sample have z < 1, indicating they are primarily nearby galaxies. The FRI/FRII (G) redshifts range from z = 0.002 to 1.175, with a mean of z_{FR} = 0.16 ± 0.22 (Figure 1, deep yellow region). The majority of FRI/FRII (G) galaxies have small redshifts, likely because radio galaxies have weaker optical radiation, making distant objects difficult to detect with current optical telescope sensitivities.

The apparent magnitude distributions for the 491 BL Lacs and 95 FRI/FRII (G) galaxies are shown in Figure 2 [Figure 2: see original paper]. The BL Lac V-band apparent magnitudes range from m_V = 13.58 to 24.91, with m_V = 19.0 ± 1.42. The FRI/FRII (G) V-band apparent magnitudes range from m_V = 7.53 to 23.4, with m_V = 15.7 ± 3.12.

3. Methodology

Since BL Lac jets are oriented toward us, their optical radiation is amplified by relativistic effects, while FRI/FRII (G) jets have larger inclination angles with weaker beaming effects, making their optical radiation essentially intrinsic. Based on the unified model for BL Lacs and FRI/FRII (G), the intrinsic apparent magnitude-redshift relation for BL Lacs should match the observed apparent magnitude-redshift relation for FRI/FRII (G). We can therefore combine the FRI/FRII (G) Hubble diagram with the BL Lac beaming effect to study the jet properties of BL Lacs, quantified by the Doppler factor (δ).

Assuming the observed flux (F_{ob}) from a relativistically moving discrete gas cloud relates to its intrinsic flux (F_{in}) as:

$$F_{ob} = \delta^q F_{in}$$

where δ is the Doppler factor and q describes the jet geometry. We consider two cases: discrete spherical jets ($q_1 = 3 + \alpha$) and continuous jets ($q_2 = 2 + \alpha$), where α is the optical spectral index.

The relationship between optical V-band flux density and apparent magnitude is:

$$F_{ob} = F_0 10^{-0.4 m_{ob}}$$
$$F_{in} = F_0 10^{-0.4 m_{in}}$$

where m_{ob}^{BL} is the observed apparent magnitude of BL Lacs and m_{in}^{BL} is their intrinsic apparent magnitude, with F_0 being the constant for the optical V-band.

Substituting equations (2)-(3) into (1) and eliminating F_0 yields the relationship between observed and intrinsic magnitudes:

$$m_{ob}^{BL} = m_{in}^{BL} + 2.5 q \log \delta$$

Based on the unified model for BL Lacs and FRI/FRII(G), the intrinsic magnitude-redshift distribution for BL Lacs should match the observed magnitude-redshift relation for FRI/FRII (G):

$$m_V = (4.99 \pm 0.16) \log z + (21.40 \pm 0.21)$$

Combining this with equation (4) and accounting for Doppler boosting of BL Lac observed magnitudes, we derive a formula to estimate the Doppler factor:

$$\log \delta = \frac{m_{ob}^{BL} - 4.99 \log z - 21.40}{2.5 q}$$

Assuming an optical spectral index $\alpha = 0.72$ for BL Lacs, we estimate the optical Doppler factors for both spherical ($q_1 = 3 + \alpha$) and continuous ($q_2 = 2 + \alpha$) jet geometries using the V-band observed magnitudes and redshifts. The resulting Doppler factors are listed in columns (6)-(7) of Table 1.

In an expanding universe, for small redshifts, objects of the same class with similar absolute magnitudes should follow a magnitude-redshift relation with a slope of 5. For example, Fang Lizhi et al. collected a large sample of double-lobed radio-loud quasars, assumed they had identical absolute magnitudes, and obtained a statistical magnitude-redshift relation with slope 4.6. In our sample of 95 FRI/FRII (G) galaxies, the magnitude-redshift relation is:

$$m_V = (4.99 \pm 0.16) \log z + (21.40 \pm 0.21)$$

as shown in Figure 3 [Figure 3: see original paper]. The fitted slope of 4.99 ± 0.16 closely matches the theoretical value of 5, confirming that these radio galaxies have cosmological redshifts with similar optical absolute magnitudes, making them suitable standard candles. The 491 BL Lacs show a different magnitude-redshift relation:

$$m_V = (2.04 \pm 0.17) \log z + (19.57 \pm 0.10)$$

with a best-fit slope of 2.04 ± 0.17, significantly deviating from the theoretical value of 5. This discrepancy likely arises from strong jet effects in BL Lacs that amplify the observed optical radiation, making some objects appear brighter and producing a shallower slope.

4. Discussion

The extreme observational properties of BL Lacs likely result from relativistic jet effects that amplify their optical radiation, while FRI/FRII (G) galaxies exhibit intrinsic radiation characteristics. BL Lacs show significant variability across all wavelengths, and rapid variability can cause substantial changes in flux (apparent magnitude). Therefore, our method primarily describes the jet conditions in the optical band at the epoch of observation.

Based on the unified model for BL Lacs and FRI/FRII (G), we estimated optical Doppler factors for 491 BL Lacs. For spherical jets ($q_1 = 3 + \alpha$), δ ranges from 0.32 to 4.45 with $\delta = 1.21 \pm 0.56$. For continuous jets ($q_2 = 2 + \alpha$), δ ranges from 0.21 to 7.71 with $\delta = 1.36 \pm 0.94$. The distributions are shown in Figure 4 [Figure 4: see original paper]. When BL Lac jets move toward observers with small inclination angles, $\delta \quad \Gamma > 1$. Consequently, some BL Lacs in Figure 4 show $\delta < 1$, likely due to method limitations. When $\delta \quad 1$, $\beta \quad 0$, indicating weak relativistic effects; in such cases, Xie et al. adopted $\delta = 1$ for blazars with weak relativistic effects.

Xie et al. collected optical magnitudes and minimum variability timescales for 23 BL Lacs to calculate observed energy conversion efficiencies (_{ob}) and estimated optical Doppler factors by comparing these with intrinsic efficiencies (_{in} = 0.05). Our sample includes these 23 BL Lacs from Xie et al. (hereafter Xie93). Figure 5 [Figure 5: see original paper] compares our Doppler factors with those from Xie93. The Xie93 Doppler factors range from *δ{Xie93} = 1 to 3.56 with* δ{Xie} = 1.78 ± 0.77. Our spherical jet ($q_1 = 3 + \alpha$) Doppler factors range from $\delta\{TW\} = 0.64\ to\ 2.57\ with\ \ \delta\{\text{TW}\}\ = 1.23 \pm 0.53$, while our continuous jet ($q_2 = 2 + \alpha$) factors range from $\delta\{TW\} = 0.55\ to\ 3.49\ with$ $\delta\{\text{TW}\}\ = 1.35 \pm 0.78$. The correlation coefficient between our spherical jet estimates and Xie93 is r = 0.939 with $p \leq 10^{-11}$; for continuous jets, r = 0.941 with $p \leq 10^{-11}$. The Doppler factor distributions and linear fits demonstrate that our method correlates well with Xie93' s optical variability-based estimates. As shown in Figure 5, the continuous jet linear fit closely follows the y = x line, indicating our $q_2 = 2 + \alpha$ estimates are very similar to Xie93' s optical Doppler factors, confirming the reliability of our method for describing BL Lac optical radiation and jet characteristics.

Liodakis et al. proposed a method to estimate Doppler factors from radio variability under equipartition assumptions (hereafter Liodakis18). Using 8-10 year radio flux variations for 1029 AGN from the OVRO 40 m telescope, they estimated radio Doppler factors by comparing observed and intrinsic brightness temperatures through Bayesian classification. Matching our sample with Liodakis18 yielded 32 common BL Lacs. Figure 6 [Figure 6: see original paper] compares the Doppler factors. Liodakis18 radio Doppler factors reach values as high as 45, generally an order of magnitude larger than optical Doppler factors, indicating that BL Lac radio emission is strongly jet-dominated. A trend exists where larger radio Doppler factors correspond to larger optical Doppler factors. Linear fitting yields r = 0.362, p = 0.057 for spherical jets ($q_1 = 3 + \alpha$) and r = 0.356, p = 0.062 for continuous jets ($q_2 = 2 + \alpha$). These results suggest weak correlation between radio and optical beaming effects, possibly because BL Lac optical emission is influenced not only by nuclear jet effects but also by host galaxies or accretion disks. For example, Hyvönen et al. studied R, H, and V-band data for 18 low-redshift BL Lac host galaxies, including three sources from our sample: 1ES 0229+200 ($\delta = 0.85$), I Zw 187 ($\delta = 0.77$), and 1H 0706+591 ($\delta = 0.62$). They found host galaxy V-band emission 1-2 magnitudes brighter than the nucleus, suggesting that host galaxy thermal emission may dilute the correlation between optical and radio Doppler factors.

5. Conclusion

The Doppler factor is crucial for studying jet effects in blazars. Accurate measurement requires knowledge of the jet viewing angle and velocity, which are difficult to obtain observationally, necessitating approximate estimation methods. Based on the unified model for BL Lacs and FRI/FRII (G) galaxies, we propose that the Hubble diagram relation for FRI/FRII (G) should match the intrinsic Hubble diagram for BL Lacs. Combined with the fact that BL Lac observed magnitudes are boosted by beaming, we derive a formula to estimate BL Lac optical Doppler factors.

The FRI/FRII (G) Hubble diagram slope of 4.99 agrees with the theoretical value of 5, supporting the notion that these radio galaxies have similar absolute magnitudes and can serve as standard candles. Our estimated spherical jet Doppler factors show similar distributions to Xie93' s optical Doppler factors, and the continuous jet linear fit closely follows the y = x line, demonstrating that our $q_2 = 2 + \alpha$ estimates are very similar to Xie93' s results, confirming the reliability of our method for characterizing BL Lac optical radiation and jet properties. Larger samples will reduce bias, and future expansion of the dataset will yield more accurate optical Doppler factors, enhancing our understanding of blazar jet radiation characteristics and intrinsic properties.

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Note: Figure translations are in progress. See original paper for figures.