

# The Relationship Between Spectral Curvature and Gamma-Ray Luminosity in BL Lac Objects: Postprint

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## Abstract

Extragalactic gamma-ray sources are predominantly blazars, and their study is instrumental in revealing the physics of active galactic nuclei jets, the origin of high-energy cosmic rays, and even cosmic evolution. This work investigates why some BL Lacertae objects exhibit strong gamma-ray emission while others do not. We selected 170 BL Lacertae objects with measured Doppler factors and spectral curvatures, and divided them into two categories: those detected by Fermi LAT and those not detected by Fermi LAT. Our analysis reveals that the multi-band spectral energy distributions of these two source populations show significant differences in curvature, with sources detected by Fermi LAT having significantly smaller curvature than undetected sources; this trend persists even after accounting for Doppler factor effects. The BL Lacertae objects PKS 0048-09 and S5 0716+714 exhibit similar synchrotron luminosities but different gamma-ray luminosities. Employing the synchrotron self-Compton model together with a parabolic electron spectrum yields excellent fits to their multi-band spectral energy distributions, revealing that the fitted curvature and emission region size differ but are proportional to each other. PKS 0048-09 may host a more compact jet, resulting in a larger Compton factor. These results indicate that, for a given synchrotron luminosity, spectral curvature and Compton factor are critical for detectability by the Fermi Gamma-ray Space Telescope; the implications for particle statistical acceleration and radiation mechanisms are discussed.

## Full Text

### The Curvature of Spectral Energy Distribution and $\gamma$ -ray Dominance of Fermi BL Lac Objects

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**Abstract:** The extragalactic  $\gamma$ -ray sky is dominated by blazars, and their study plays an important role in understanding jet physics, cosmic evolution history, and the origin of ultra-high-energy cosmic rays. In this work, we investigate why some BL Lac objects exhibit strong  $\gamma$ -ray emission while others do not. We selected 170 BL Lac objects with measured Doppler factors and spectral curvature, dividing them into Fermi-LAT detected (FBLs) and non-detected (NFBLs) sources. We find that the multi-band spectral energy distributions (SEDs) of these two classes show significant differences in curvature: FBLs have systematically smaller curvature than NFBLs. This result remains robust even after correcting for Doppler beaming effects. The BL Lac objects PKS 0048–09 and S5 0716+714 have similar synchrotron luminosities but markedly different  $\gamma$ -ray luminosities. Using a synchrotron self-Compton (SSC) model combined with a log-parabolic electron energy distribution, we can successfully fit their multi-band SEDs, revealing that while the fitted curvature and emission region size differ between the sources, they are proportional to each other. PKS 0048–09 likely possesses a more compact jet, resulting in a larger Compton dominance. Our results indicate that, for a given synchrotron luminosity, both spectral curvature and Compton dominance are crucial factors for detection by the Fermi  $\gamma$ -ray satellite. We discuss the implications of these findings for particle acceleration statistics and radiation mechanisms.

**Keywords:** active galactic nuclei; BL Lac objects; radiation mechanisms; non-thermal radiation

## 1 Introduction

Since the first identification of the extragalactic source 3C 273,  $\gamma$ -ray astronomy has made tremendous progress thanks to the unprecedented detection capabilities of new-generation telescopes. The Large Area Telescope (LAT) onboard the Fermi satellite has detected more than 3,000  $\gamma$ -ray sources in its first four years of operation, approximately half of which are extragalactic. The extragalactic  $\gamma$ -ray sky is dominated by blazars (about 98%), which represent an extreme subclass of active galactic nuclei (AGN) with relativistic jets pointing close to our line of sight. Blazars are classified as BL Lac objects (BL Lacs) or flat-spectrum radio quasars (FSRQs) based on whether the rest-frame equivalent width of their broad emission lines is smaller than (for BL Lacs) or greater than (for FSRQs) 5 Å. Due to their very high luminosity and violent variability, their  $\gamma$ -ray emission is believed to be produced in relativistic jets making a small angle to our line of sight. The intensity is significantly boosted by the Doppler beaming effect through the transformation  $I_\nu = \delta^3 I'_\nu$  with  $\delta = \nu/\nu'$  from the intrinsic to observational frames, where primed quantities refer to values measured in the jet co-moving frame, while  $\delta = 1/[\Gamma(1 - \beta \cos \theta)]$  is the Doppler beaming factor.

The study of  $\gamma$ -ray emission from blazars plays a crucial role in understanding jet physics (including jet launching, energy dissipation, and particle acceleration), cosmic evolution history, and the origin of ultra-high-energy cosmic rays. The  $\gamma$ -rays can be explained as inverse Compton (IC) emission from accelerated electrons in the jet. In BL Lacs, the IC emission arises from internal synchrotron photons and is called synchrotron self-Compton (SSC).

The multi-wavelength catalog of blazars, Roma-BZCAT v5.0, is the most comprehensive catalog in the literature, containing 3,561 confirmed blazars or candidates. Recently, the Fermi Fourth LAT AGN Catalog (4LAC) presented a sample of nearly 3,000 blazars or blazar candidates at high Galactic latitude. Therefore, there may be more than 500 blazars that have not been detected in  $\gamma$ -rays ( $\gamma$ -ray quiet), although they have similar emission properties at lower energy wavelength bands (radio through X-ray) compared to  $\gamma$ -ray detected blazars.

The origin of this discrepancy remains unknown. Many studies have focused on this question and found that  $\gamma$ -ray loud blazars have relatively larger jet opening angles, larger apparent superluminal velocities, and higher brightness temperatures compared to  $\gamma$ -ray quiet blazars. All these properties are attributed to a relativistic geometric effect—the Doppler beaming effect. The smaller viewing angle in  $\gamma$ -ray loud blazars leads to a larger apparent jet opening angle and larger Doppler beaming factor, which give rise to larger apparent superluminal velocity and higher brightness temperature. In addition to this geometric effect, the origin of the discrepancy between  $\gamma$ -ray loud versus  $\gamma$ -ray quiet blazars might be intrinsic, though this remains uncertain.

The spectral energy distribution (SED) of synchrotron emission from blazars is usually curved and presents a significant bump in the  $\nu-\nu f_\nu$  frame, which peaks between infrared and X-ray bands. The curvature of the broadband SED of the synchrotron bump differs among various blazars, meaning that some SED bumps are broad while others are narrow. If the SED (broadband or single band) is fitted by a log-parabolic function,  $-b(\lg \nu - \lg \nu_p)^2$ , the coefficient of the second-order term  $b$  can be considered a “surrogate” to measure the curvature. The curvature is found to be negatively correlated with the SED peak frequency, offering supporting evidence of statistical or stochastic particle acceleration at work in blazar jets, through studying broadband observations or single-band (X-ray) observations. It should be noted that the broadband curvature of a blazar does not change with transformation from observer to AGN frame (cosmological redshift) and jet co-moving frame (Doppler beaming). However, the single-band curvature is affected due to the Doppler effect causing spectral shifts. In this work, we investigate the possible relation between  $\gamma$ -ray emission and the SED curvature for BL Lacs. The curvature in the SED is produced due to an intrinsic curvature in the emitting electron energy distribution (EED) arising from competition between particle acceleration and cooling.

We assume a  $\Lambda$ CDM cosmology with values from the Planck results in our calculations; in particular,  $\Omega_m = 0.32$ ,  $\Omega_\Lambda = 0.68$ , and the Hubble constant

$$H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

## 2 The Sample

Beginning with Mrk 421, Massaro et al. found that curvature is an important feature of BL Lacs in X-rays. Even the Fermi-LAT  $\gamma$ -ray spectra of bright blazars show curvature. The high-energy photon spectra can be fitted by a log-parabolic law,  $F(E) = KE^{-(\alpha+\beta\log(E/E_0))}$ , with spectral index  $\alpha$  at reference energy  $E_0$  and  $\beta$  as the curvature of the bump. The corresponding peak energy of the spectral bump becomes  $E_p = E_0 10^{(2-\alpha)/2\beta}$ .

Ackermann et al. found that the LAT spectra of about 160 blazars show deviation from a power-law  $F(E) = KE^{-p}$  and are better fitted with a log-parabolic law. This suggests that curvature is a common feature of blazar SEDs in any energy band. The Fermi-LAT detected 1,591 blazars at high Galactic latitude in its Third LAT AGN Catalog (3LAC) based on the first four years of operations. Based on 3LAC, Fan et al. collected available spectral data of 1,392 blazars from NED to build broadband SEDs of the synchrotron bump and fitted them with a log-parabolic function. We compile the synchrotron spectral curvature ( $b$ ), synchrotron peak flux ( $F_s = \nu_p f_{\nu_p}$ ), and integrated  $\gamma$ -ray flux  $F_\gamma$  in the 0.1 – 100 GeV band for 620 confirmed BL Lacs in 3LAC. Wu et al. presented the Doppler factors of these BL Lacs. Cross-matching the two catalogs, we compile the spectral parameters and Doppler factors for a total sample of 170 BL Lacs.

## 3 Methods and Results

A curved SED necessarily suggests that the underlying emitting EED may be curved. A log-parabolic EED can arise due to the stochastic nature of acceleration gain. Anjum et al. found that only BL Lacs show signatures of stochastic acceleration, whereas FSRQs do not show any signature of such an acceleration mechanism. The broadband SED in the log-parabolic model can be described as  $\lg \nu f_\nu = \lg \nu_p f_{\nu_p} - b(\lg \nu - \lg \nu_p)^2$ , where  $b$  measures the width (curvature) of the SED bump. The synchrotron bump is particularly important as it reveals the intrinsic curvature of the EED. Since the accretion disk continuum emission in FSRQs is usually presented as a big blue bump at ultraviolet wavelengths, affecting accurate measurement of the curvature parameter, we selected only BL Lacs for our study. The selection of BL Lacs is further motivated by the fact that the high-energy bump in FSRQs arises due to external Compton (EC) emission; therefore, their curvature of the IC bump may be related to the complex seed photon distribution and any absorption. Although the curvature of the high-energy bump in BL Lacs mimics the synchrotron curvature as it arises from internal synchrotron seed photons, it is hard to constrain the intrinsic properties of the EED from the IC bump, since the observed SED curvature of the IC bump may also depend on the IC cooling regime. Paggi et al. found that the IC curvature in the Thomson regime is smaller than in the Klein-Nishina

regime. Therefore, we constrain the intrinsic curvature of the EED  $r$  from the synchrotron spectral curvature  $b$  rather than the  $\gamma$ -ray curvature  $\beta$ . The intrinsic curvature of the EED  $r \simeq 5b$ , and  $\gamma$ -ray emission in BL Lacs is expected to be intrinsically related and can be used to investigate the origin of the discrepancy between Fermi-detected BL Lacs (FBLs) and non-detected ones (NFBLs).

### 3.1 FBLs versus NFBLs

A large amount of multi-wavelength data for objects in the Metsähovi radio observatory BL Lac sample was collected by Nieppola et al., which is supposed to have no selection criteria (other than declination) in addition to those in the original surveys. The Metsähovi radio observatory BL Lac sample includes 381 objects selected from the Veron-Cetty & Veron BL Lac Catalog, and 17 objects from the literature, many of which are from well-known BL Lac samples such as 1Jy, S4, S5, Einstein Medium Sensitivity Survey (EMSS), Einstein Slew Survey, and ROSAT Deep X-ray Radio Blazar Survey (DXRBS). Based on the multi-wavelength data, the SED of each source was constructed in the  $\lg \nu - \lg \nu F_\nu$  representation, and the synchrotron bump was fitted with a log-parabolic function. Using this sample, Wu et al. collected available data at 330 MHz, 360 MHz, 408 MHz, and 1.4 GHz from the Astrophysical Catalogues Support System (CATs) maintained by the Special Astrophysical Observatory, Russia, as well as available VLA or MERLIN core and extended flux, resulting in a sample of 170 BL Lacs. The low-frequency radio power can be a reliable indicator of the intrinsic radio power, while Doppler beaming can affect the observed radio power of the core. Therefore, using the VLA or MERLIN core and the 408 MHz luminosity and assuming a jet speed  $\beta = 5$ , consistent with Metsähovi radio monitoring studies, the Doppler beaming factors have been estimated.

We compiled the Doppler factors and curvature parameters of these 170 BL Lacs. By cross-correlating this sample with 3LAC, 34 out of these 170 BL Lacs are not found to have  $\gamma$ -ray emission (NFBLs). These NFBLs are: NRAO 5, NPM1G +41.0022, 1ES 0145+138, MS 0158.5+0019, MS 0257.9+3429, RXS J0314.0+2445, S5 0454+84, MS 0607.9+7108, B3 0651+428, 4C 22.21, RXS J0916.8+5238, B2 0927+35, RGB J0952+656, 1ES 1044+549, 1ES 1212+078, 1ES 1255+244, 1ES 1320+084N, MC 1400+162, MS 1407.9+5954, RGB J1427+541, MS 1443.5+6349, RXS J1516.7+2918, MS 1534.2+0148, RXS J1602.2+3050, RXS J1644.2+4546, RGB J1652+403, B3 1746+470, RXS J1750.0+4700, RGB J1811+442, PKS 2254+074, Q J2319+161, 1ES 2326+174, MS 2336.5+0517, and MS 2347.4+1924. The remaining 136 BL Lacs are therefore considered FBLs. Although many of these NFBLs might be detected in 4LAC, their  $\gamma$ -ray flux must be lower than that of the FBLs.

The SED of blazars is usually curved even in a single energy band. Doppler factor changes cause the peak  $\nu_p = \nu'_p \delta$  to shift in the SED ( $\nu I_\nu = \delta^4 \nu' I'_\nu$ ), which affects the spectral curvature of blazars in the Fermi-LAT  $\gamma$ -ray band. In addition to these peak shifts, intrinsic differences in curvature may account for the discrepancy between FBLs and NFBLs. We reduce the effect of relativistic

Doppler beaming and directly compare FBLs and NFBLs. We searched the literature for published and archival observations that allow us to obtain both curvature parameters and Doppler beaming factors for our Fermi BL Lacs. We plot the curvature parameter (in  $1/b$ ) against  $\delta$  for FBLs and NFBLs in [Figure 1: see original paper], which shows that both FBLs and NFBLs overlap, but the curvature of FBLs is on average smaller than that of NFBLs. We binned the data in  $\lg(\delta)$  and found the average value of curvature in each bin, represented by large circles in the figure. Due to only one NFBL in the last bin, we consider it as the average curvature value. FBLs, on average, appear to have smaller curvature (higher value of  $1/b$ ) and thus broader SEDs than NFBLs.

To eliminate the effect of Doppler beaming as much as possible, we artificially defined a new parameter,  $b - \lg \delta$ , which roughly measures the curvature given the same beaming factor. [Figure 2: see original paper] shows the distributions of  $b - \lg \delta$  and the cumulative fractions of FBLs and NFBLs. It can be seen that statistically, FBLs have relatively smaller values of  $b - \lg \delta$  than NFBLs, confirming the above finding that smaller curvature of the synchrotron SED bump is attributed to larger  $\gamma$ -ray power. The Kolmogorov-Smirnov (KS) test yields a significance level probability for the null hypothesis that FBLs and NFBLs are drawn from the same distribution of  $P = 5.87 \times 10^{-5}$ , and the maximum separation of the two cumulative fractions is  $D_{KS} = 0.43$ . TeV BL Lacs (TBLs) with synchrotron peak frequency  $\nu_p > 10^{15}$  Hz showed similar behavior. Massaro et al. found the X-ray band curvature of TBLs to be systematically smaller than that of sources not detected at TeV energies. They suggested that X-ray flux can be used as a predictor for TeV  $\gamma$ -ray detection of BL Lacs. However, the TeV spectral curvature may not correspond to X-ray curvature, as TeV emission is significantly attenuated by the extragalactic background light (EBL). Since GeV  $\gamma$ -ray emission is not absorbed, we argue that it can provide better constraints on TeV detection compared to X-rays.

### 3.2 SED Curvature and $\gamma$ -ray Dominance

The fact that the synchrotron SED is significantly curved inevitably implies curvature in the steady electron energy distribution  $N(\gamma)$ . This curvature may result from particle cooling and acceleration operating on different timescales. Based on a scenario of re-acceleration rather than continuous injection, the curvature can be related to the stochastic acceleration term in the Fokker-Planck kinetic equation. A more efficient stochastic acceleration process makes the electron energy distribution relatively broader, manifested by smaller curvature. Higher acceleration efficiency implies less time ( $t = R/c$ ) spent by particles in the acceleration region and a larger number of acceleration steps, which corresponds to a smaller size of the acceleration/emission region. Therefore, the spectral curvature of the EED is expected to be proportional to the size of the blazar region. Since the  $\gamma$ -rays from BL Lacs are believed to be SSC emission from the same non-thermal electron population that produces the low-energy synchrotron emission, a smaller size would enhance the synchrotron seed photon

energy density  $u_s = L_s/(4\pi R^2 c \delta^4)$  in the jet, leading to higher Compton dominance  $CD = u_s/u_B$ , i.e., higher relative  $\gamma$ -ray power. This implies that among BL Lacs with the same synchrotron luminosity  $L_s$ , sources with relatively high  $\gamma$ -ray dominance may have relatively compact emission regions.

Abdo et al. provided broadband simultaneous or quasi-simultaneous spectral data from radio through  $\gamma$ -rays for 48 LAT Bright AGNs within the first three months of Fermi-LAT operation, from 2008 August 4 to October 31. The broadband spectral data were derived from many ground-based and space-based observatories, including Swift (UVOT, XRT, BAT), Effelsberg, OVRO, RATAN, GASP-WEBT, Spitzer-MIPS, and AGILE. We show examples of SEDs for two BL Lacs (PKS 0048–09 and S5 0716+714) in [Figure 3: see original paper]. These sources have similar synchrotron peak frequency and luminosity but different  $\gamma$ -ray power, i.e., different Compton dominance. Their quasi-simultaneous broadband SEDs are compiled from Abdo et al., shown as large and small black squares for PKS 0048–09 and magenta circles for S5 0716+714. S5 0716+714 included three observations at optical and X-ray bands during those three months; we use the average flux values for this BL Lac object.

We use the standard one-zone SSC model to fit their SEDs. The one-zone model is widely used in blazar SED modeling. Since coordinated variability in different wavelength bands is often seen (although not always) in blazars, a one-zone model assumes that the bulk of the non-thermal emission is produced from a “one-zone” region, typically assumed to be a spherical blob with radius  $R$  embedded in a homogeneous but tangled magnetic field  $B$  and filled with an emitting electron population. Since the considered emitting region is always compact, its synchrotron self-absorption frequency is always large; therefore, the model cannot account for radio flux at observed frequencies smaller than a few hundred GHz, which are produced by the superposition of several larger components. The emitting relativistic blob moves at an angle  $\theta$  with respect to the line of sight, yielding a Doppler beaming factor  $\delta$ . To maintain consistency with the log-parabolic shape of the synchrotron SED bump, the emitting particles are assumed to be leptons with an energy distribution following a log-parabolic function,  $N(\gamma) = N_0(\gamma/\gamma_0)10^{-r \log(\gamma/\gamma_0)^2}$ , where  $r$  measures the curvature of the electron energy distribution. As discussed above, the curvature may be proportional to the size of the emission region in the SSC model. Therefore, in our calculations, the curvature parameter  $r$  is assumed to be proportional to the radius of the emission sphere, i.e.,  $r \propto R$ .

The calculated SEDs are also presented in [Figure 3: see original paper]. Both SEDs can be well fitted with the same jet parameters except for the radii of the emission sphere:  $R_{0048} = 2.8 \times 10^{16}$  cm and  $R_{0716} = 5.0 \times 10^{16}$  cm for PKS 0048–09 and S5 0716+714, respectively (and therefore the curvature  $r_{0048} = 0.5$  and  $r_{0716} = (R_{0716}/R_{0048})r_{0048} = 0.89$ ). The other constant jet parameters are: magnetic field strength  $B = 0.15$  G, Doppler factor  $\delta = 24$ , peak electron energy  $\gamma_0 = 8,660$ , and normalized total electron number  $N_0 = 6.8 \times 10^{45}$ . This modeling example illustrates that higher  $\gamma$ -ray luminosity intrinsically accompanies

smaller curvature, which may be related to a smaller emission region size and the processes governing jet microphysics, i.e., particle acceleration and cooling. This is further consistent with the fact that bright  $\gamma$ -ray blazars are more (rapidly) variable than  $\gamma$ -ray weak blazars, possibly due to smaller emission region size and/or larger Doppler beaming factor in bright sources. [Figure 3: see original paper] shows that among BL Lacs with a given synchrotron peak luminosity and frequency, the object with the highest Compton dominance might have smaller curvature (i.e., a harder spectrum). High Compton dominance coupled with lower curvature favors detection of a blazar by Fermi. Therefore, we argue that both Compton dominance and curvature are important parameters for Fermi detection.

## 4 Summary

We investigated why some BL Lacs are detected in  $\gamma$ -rays by Fermi while others are not. We find that the SED curvature and  $\gamma$ -ray dominance of BL Lacs might be intrinsically related. We selected 170 BL Lacs with reported synchrotron SED curvature  $b$  and Doppler factor  $\delta$ , dividing them into FBLs and NFBLs. We find that FBLs have smaller curvature than NFBLs even after correcting for beaming effects. The two Fermi BL Lac objects PKS 0048–09 and S5 0716+714 have similar synchrotron peak frequency and luminosity but different Compton dominance. PKS 0048–09 shows relatively high  $\gamma$ -ray dominance compared to S5 0716+714. Within a one-zone SSC model, we find their quasi-simultaneous SEDs can be well fitted by the same physical jet parameters except for the emission region size and EED curvature (assuming curvature is proportional to size). PKS 0048–09 manifests a relatively smaller source size and smaller curvature compared to S5 0716+714. These results imply that differences in curvature might be related to  $\gamma$ -ray dominance and may account for the intrinsic discrepancy between FBLs and NFBLs. A broader SED with a compact jet size demands efficient stochastic acceleration. As emitting particles have less time to spend in a compact jet, the acceleration gain or number of acceleration steps should be large. Thus, more efficient stochastic acceleration in compact jets of FBLs makes the EED relatively broad, yielding a smaller curvature parameter. A smaller source size, in turn, implies a higher synchrotron photon energy density in the jet, producing powerful  $\gamma$ -ray emission through the SSC process. Therefore, at a given synchrotron luminosity, FBLs may have intrinsically smaller curvature and higher Compton dominance compared to NFBLs.

Future studies of larger samples may be necessary to further investigate the relationship between curvature and  $\gamma$ -ray dominance in blazars.

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