The Relationship Between the Inverse Compton Peak Frequency and Gamma-Ray Photon Spectral Index in Blazars: Postprint

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Abstract

Using blazars from the 3rd revision of the 4th source catalog (The 4th Fermi Gamma-ray LAT-Data Release 3, 4FGL-DR3) based on 12,yr of Fermi/LAT (Large Area Telescope) observations as the sample, we investigated the relationship between the inverse Compton peak frequency ($\lg \nu_\mathrm{p}$IC) and the γ-ray photon spectral index ({Γ}) for different subclasses of blazars. The results indicate that for all blazar subclass samples, lg IC_p and Γ exhibit a strong negative correlation, i.e., the γ-ray photon spectral index strongly dominates the inverse Compton energy spectrum of blazars, and the inverse Compton peak frequency can be rapidly estimated using their relationship; the energy spectral distribution of the inverse Compton component for different blazar subclass samples should have different spectral structure functions, and therefore, different functions should be employed to fit their energy spectral distributions for different samples.

Full Text

The Relationship between the Inverse Compton Peak Frequency and the Gamma-Ray Photon Spectral Index for Blazars

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Abstract

Using blazars from the 4FGL-DR3 (The 4th Fermi Gamma-ray LAT-Data Release 3) catalog based on 12 years of Fermi/LAT (Large Area Telescope) observations, we investigate the relationship between the inverse Compton peak frequency (lg (cid:23)IC p) and the gamma-ray photon spectral index (Γ) for different subclasses of blazars. The results demonstrate a strong negative correlation between lg (cid:23)IC p and Γ across all blazar subclasses, indicating that the gamma-ray photon spectral index strongly dominates the inverse Compton energy spectrum of blazars and enabling rapid estimation of the inverse Compton peak frequency through this relationship. Furthermore, the energy spectral distribution of the inverse Compton component likely follows different spectral structure functions for different blazar subclasses; consequently, different fitting functions should be employed when modeling their spectral energy distributions.

Keywords: galaxies: active, galaxies: nucleus, quasars: general, BL Lacertae objects: general, gamma rays: galaxies, methods: statistical

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Blazars constitute a subclass of active galactic nuclei (AGN) exhibiting extreme observational properties, including rapid and large-amplitude variability, high polarization, apparent superluminal motion, and high-energy gamma-ray emission. The physical origins of these extreme phenomena, particularly the mechanisms responsible for high-energy gamma-ray radiation, remain not fully understood. Based on their emission line characteristics, blazars are classified into flat-spectrum radio quasars (FSRQ) and BL Lacertae objects (BL Lac) [1–3].

Blazars emit strong electromagnetic radiation from radio to gamma-ray bands, with their broadband spectral energy distributions (SEDs) displaying two distinct peaks—one at low energies and another at high gamma-ray energies [3–8]. Current research suggests that the low-energy peak originates from synchrotron radiation (referred to as the synchrotron peak), while the high-energy peak is primarily produced by inverse Compton radiation (referred to as the inverse Compton peak) [9–12]. The spectral structure and its parameters are crucial for understanding the radiative properties of blazars. The double-peak parameters—including spectral curvature, peak frequency, and peak flux or luminosity—are typically obtained through SED fitting [4, 6–8, 13–20].

In the gamma-ray band, the photon spectral index serves as another important parameter reflecting the properties of the high-energy radiation spectrum. What relationship exists between this spectral index and the peak frequency, and how does it differ among various blazar subclasses? To address this question, we utilize blazars from the 4FGL-DR3 catalog (The 4th Fermi Gamma-ray LAT-Data Release 3) [21] based on 12 years of Fermi/LAT observations to investigate the relationship between the inverse Compton peak frequency and the gamma-ray photon spectral index for different types of blazars. This analysis allows us to discuss the properties of different source types and develop simple methods for estimating the inverse Compton peak frequency. In this work, the relationship between flux density f(cid:23) at frequency (cid:23) and spectral index (cid:11) follows f(cid:23)   (cid:23)(cid:0)(cid:11).

The recently released gamma-ray data table 4FGL-DR3 represents an incremental version of the fourth source catalog, containing 3743 blazars, including 794 FSRQs, 1432 BL Lacs, and 1517 BCUs (Blazar Candidates of Uncertain type) [21]. Yang et al. [18] fitted the high-energy portion of the SED for 4FGL-DR3 blazars using eight energy-band gamma-ray data and a parabolic equation lg((cid:23)f(cid:23)) = P4(lg (cid:23) (cid:0) P5)^2 + P6, obtaining inverse Compton peak parameters for all 3743 blazars: spectral curvature (P4), peak frequency (P5, lg (cid:23)IC p), peak flux (P6, lg((cid:23)IC f(cid:23)IC p)), and peak luminosity (lg LIC p). They classified blazars according to inverse Compton peak frequency, designating sources with lg((cid:23)IC p =Hz) $\leq$ 22.9 as low inverse Compton peak frequency (LCP) blazars and those with lg((cid:23)IC p =Hz) $>$ 22.9 as high inverse Compton peak frequency (HCP) blazars.

Yang et al. [17] also fitted the low-energy portion of the SED for 4FGL-DR3 blazars using radio, optical, and X-ray data from NED (NASA/IPAC Extragalactic Database) with the parabolic equation lg((cid:23)f(cid:23)) = P1(lg (cid:23) (cid:0) P2)^2 + P3, obtaining synchrotron peak parameters for 2709 blazars: spectral curvature (P1), synchrotron peak frequency (P2, lg (cid:23)Syn p), and peak flux (P3, lg((cid:23)Syn f(cid:23)Syn p)). This study additionally provided blazar classifications based on synchrotron peak frequency: high synchrotron peak (HSP), intermediate synchrotron peak (ISP), and low synchrotron peak (LSP) blazars. For BL Lacs specifically, these correspond to high synchrotron peak BL Lacs (HBL), intermediate synchrotron peak BL Lacs (IBL), and low synchrotron peak BL Lacs (LBL).

Our study employs 4FGL-DR3 blazars to investigate the relationship between lg (cid:23)IC p and the gamma-ray photon spectral index (Γ) across different subclasses. The required data include blazar classifications (FSRQ, BL Lac, BCU, HBL, IBL, LBL, HCP, LCP), lg (cid:23)IC p , and Γ. The subclassifications HBL, IBL, LBL, HCP, LCP, and lg (cid:23)IC p were obtained from references [17–18], while classifications FSRQ, BL Lac, BCU, and Γ were taken from 4FGL-DR3 [21].

Figure 1 [Figure 1: see original paper] illustrates the relationship between lg (cid:23)IC p and Γ for different blazar subclasses, using the sample classifications, lg (cid:23)IC p , and Γ from references [17–18] and [21]. Linear regression analysis of these relationships yields detailed correlations presented in Table 1 . The fitted equation takes the form lg (cid:23)IC p = k (cid:1) Γ + b, where k represents the slope and b the intercept. In Table 1, n denotes sample size, r the correlation coefficient, and p the chance probability.

Although we present results for BCU and IBL samples, subsequent discussion excludes them because BCUs are blazars of uncertain type composed of both FSRQs and BL Lacs, exhibiting statistical properties similar to the overall sample [18, 22]. IBLs represent an intermediate state between HBLs and LBLs, with properties falling between the two subclasses [7].

The fitting results for the relationship between lg (cid:23)IC p and Γ (Figure 1, Table 1) reveal strong anti-correlations for all blazar subclasses, with correlation coefficients ranging from (cid:0)0.91 to (cid:0)0.98 and chance probabilities below 10(cid:0)4. Previous studies with smaller samples have examined this relationship: Abdo et al. [4] calculated SEDs for 48 bright blazars, obtaining lg (cid:23)IC p = (cid:0)4.0Γ + 31.6; Lin et al. [23] derived lg (cid:23)IC p = (cid:0)4.59Γ + 32.67 for a sample of 69 TeV BL Lacs; and Arsioli et al. [24] obtained Γ = (cid:0)0.229 lg (cid:23)IC p + 7.34 for an LSP blazar sample. Comparison shows our results are fully consistent with these literature findings.

Since the spectral index is a fundamental parameter, correlations with SED parameters (spectral curvature, peak frequency, peak flux, or luminosity) are expected. Wang et al. [22] discovered a positive correlation between radio spectral index and synchrotron spectral curvature, finding that radio emission influences the synchrotron spectra of LBLs, FSRQs, and HBLs in decreasing order. Our results demonstrate a strong negative correlation between lg (cid:23)IC p and Γ, indicating that the gamma-ray photon spectral index strongly dominates the inverse Compton spectrum of blazars—steeper gamma-ray spectra correspond to lower inverse Compton peak frequencies. While this correlation shows no significant differences across subclasses, Table 1 reveals that samples with higher peak frequencies exhibit larger absolute values of the slope k (e.g., |k|BLLac > |k|FSRQ, |k|HBL > |k|LBL, |k|HCP > |k|LCP), suggesting an anti-correlation between slope magnitude and peak frequency.

Theoretical Relationship between lg (cid:23)IC p and Γ

From the physical meaning of the integrated gamma-ray energy spectrum (lg f(cid:23) (cid:0) lg (cid:23)) and our definition of spectral index, the gamma-ray spectral index (cid:11)(cid:13) = (cid:0) d(lg f(cid:23))/d(lg (cid:23)). Since 4FGL-DR3 adopts the same spectral index definition for the gamma-ray photon spectral index (Γ), we have Γ = (cid:11)(cid:13) + 1, which yields d(lg f(cid:23))/d(lg (cid:23)) = 1 (cid:0) Γ. Reference [18] fitted the inverse Compton portion of the SED using the parabolic equation lg((cid:23)f(cid:23)) = P4(lg (cid:23) (cid:0) P5)^2 + P6, where P4, P5, and P6 represent the spectral curvature, peak frequency, and peak flux of the inverse Compton component, respectively. Combining d(lg f(cid:23))/d(lg (cid:23)) = 1 (cid:0) Γ with lg((cid:23)f(cid:23)) = P4(lg (cid:23) (cid:0) P5)^2 + P6 yields:

lg (cid:23)IC p = lg (cid:23) (cid:0) 1/(2P4) (cid:1) (Γ (cid:0) 1) (1)

Since P4 is always negative, equation (1) demonstrates that the inverse Compton peak frequency (P5; lg (cid:23)IC p) anti-correlates with the gamma-ray photon spectral index (Γ), consistent with our fitting results. Equation (1) further indicates that the theoretical slope (kT) and intercept (bT) of the lg (cid:23)IC p –Γ relationship are:

kT = 1/(2P4) (2)
bT = lg (cid:23) (cid:0) 1/(2P4) (cid:1) (Γ (cid:0) 1) (3)

For a given blazar subclass, substituting the average spectral curvature (P4) and average inverse Compton peak frequency (lg (cid:23)IC p) into equations (2) and (3) yields the theoretical slope (kT) and intercept (bT). Based on our sample, we calculated the average inverse Compton spectral curvature and peak frequency for each subclass (Table 2) and derived the corresponding theoretical values, which are presented in Table 2.

Table 2 shows that the theoretical slopes (kT) and intercepts (bT) for each subclass are essentially consistent with the fitted values. The slope derived from the parabolic equation depends only on spectral curvature (kT = 1/(2P4)). However, actual blazar SEDs are not perfect parabolic spectra, so the slope should not be a function of spectral curvature alone. Nevertheless, spectral curvature appears to be the primary influencing factor. Our earlier analysis revealed that the slope also correlates with peak frequency, indicating that the slope depends on both spectral curvature and peak frequency—likely explaining discrepancies between theoretical and fitted values.

Equation (1) assumes a parabolic SED for the inverse Compton component and relates lg (cid:23)IC p to Γ and P4. Substituting the average peak frequencies of the total, FSRQ, BL Lac, and BCU samples into equation (1) along with Γ and P4 from reference [18] yields the inverse Compton peak frequencies. Figure 2 [Figure 2: see original paper] compares these calculated peak frequencies with those from reference [18] (where lg (cid:23)IC p by Eq. (1) denotes values obtained from equation (1)), and Table 3 presents the linear fitting results in the form y = (a (cid:6) Δa) + (b (cid:6) Δb)x.

Figure 2 and Table 3 demonstrate strong positive correlations between peak frequencies calculated from equation (1) and those from reference [18] for the total, FSRQ, BL Lac, and BCU samples, with correlation coefficients of 0.86–0.94 and chance probabilities below 10(cid:0)4. Notably, for the BL Lac sample, the best-fit line nearly coincides with the equality line (Figure 2c), indicating excellent consistency and validating equation (1) for estimating BL Lac inverse Compton peak frequencies. However, for the total, FSRQ, and BCU samples (Figures 2a, 2b, 2d), the best-fit lines lie above and significantly deviate from the equality line, indicating that equation (1) systematically underestimates the peak frequencies relative to reference [18]. This systematic difference likely arises because inverse Compton SEDs are not strictly parabolic. The varying magnitude of this systematic offset across samples suggests that different subclasses may have different spectral structure functions (lg((cid:23)f(cid:23)) (cid:0) lg (cid:23)), implying that different fitting functions—such as quadratic (parabolic), cubic, power-law, or composite functions—should be used for different samples.

Quick Estimation Method for Inverse Compton Peak Frequency

We estimated inverse Compton peak frequencies for different blazar subclasses using the subclass-specific lg (cid:23)IC p −Γ relationships from Table 1 (Eq (Total), Eq (FSRQ), Eq (BL Lac), Eq (HBL), Eq (IBL), Eq (LBL), Eq (HCP), Eq (LCP)) and compared these estimates with reference [18] results. Figure 3 [Figure 3: see original paper] shows the correlations, Table 4 presents the linear fitting results (y = (a(cid:6)Δa)+(b(cid:6)Δb)x), and Table 5 provides the mean values and Kolmogorov-Smirnov (KS) test results.

Table 5 columns: (1) sample, (2) mean and standard deviation of peak frequencies from reference [18], (3) mean and standard deviation of our estimates, (4) sample size, (5) inverse Compton peak frequency at maximum cumulative probability difference, (6) maximum cumulative probability difference between the two distributions, and (7) probability that the two distributions originate from the same parent distribution.

Figure 3 and Table 4 show strong positive correlations between our estimated inverse Compton peak frequencies and reference [18] values for all subclasses, with correlation coefficients of 0.90–0.98 and chance probabilities below 10(cid:0)4. Table 5 indicates that the mean values and standard deviations of our estimates match those from reference [18]. KS test results show high probabilities that the distributions are drawn from the same parent population for the total (20.56%), FSRQ (28.66%), BL Lac (39.12%), HBL (73.17%), IBL (83.73%), and LBL (90.92%) samples. However, HCP and LCP samples show lower probabilities (3.74% and 0.20%, respectively), likely due to their narrower peak frequency distributions.

Consequently, the gamma-ray photon spectral index can be used with Eq (Total) to rapidly estimate blazar inverse Compton peak frequencies. For subclass samples, Eq (BL Lac) and Eq (FSRQ) provide quick rough estimates for BL Lacs and FSRQs, respectively, while Eq (HBL), Eq (IBL), and Eq (LBL) yield more accurate estimates for HBLs, IBLs, and LBLs. However, Eq (HCP) and Eq (LCP) are not suitable for estimating inverse Compton peak frequencies of HCP and LCP blazars.

Summary

Using 3743 blazars from 4FGL-DR3, we obtained classifications, inverse Compton peak frequencies (lg (cid:23)IC p), and gamma-ray photon spectral indices (Γ) from literature. Blazar classifications include optical types (FSRQ, BL Lac, BCU), BL Lac subclasses based on synchrotron peak frequency (HBL, IBL, LBL), and subclasses based on inverse Compton peak frequency (HCP, LCP). Our investigation of the relationship between inverse Compton peak frequency and gamma-ray photon spectral index yields the following conclusions:

1. All blazar subclasses exhibit strong anti-correlations between lg (cid:23)IC p and Γ, demonstrating that the gamma-ray photon spectral index

strongly dominates the inverse Compton spectrum—steeper gamma-ray spectra correspond to lower inverse Compton peak frequencies.

2. Different blazar subclasses likely have different spectral structure functions for their inverse Compton energy distributions, necessitating the use of different fitting functions for different samples.
3. The inverse Compton peak frequency can be rapidly estimated using lg (cid:23)IC p = (cid:0)4.40Γ + 32.59. For subclass samples, use lg (cid:23)IC p = (cid:0)4.36Γ + 32.56 and lg (cid:23)IC p = (cid:0)4.51Γ + 32.82 for quick rough estimates of FSRQ and BL Lac peak frequencies, respectively, and lg (cid:23)IC p = (cid:0)3.88Γ + 31.35 and lg (cid:23)IC p = (cid:0)3.97Γ + 31.44 for more accurate estimation of HBL and LBL peak frequencies.

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