

Multi-wavelength Emission Relations of Fermi Blazars (Postprint)

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Abstract

Multi-band radiation flux densities were collected for a sample of blazars from the Fermi Large Area Telescope Fourth Source Catalog Data Release 3 (4FGL-DR3). The collected data cover radio at 1.4 and 143 GHz, near-infrared (J, H, and K), optical (u, g, r, i, and z), ultraviolet (far ultraviolet and near ultraviolet), X-ray, and γ -ray in six energy bands between 0.1–100 GeV (0.1–0.3, 0.3–1, 1–3, 3–10, 10–30, and 30–100 GeV). Correlations were analyzed between high-energy γ -ray bands and between γ -ray bands and multi-band radiation from radio to X-ray for the blazar and subclass samples. Linear regression fitting results between fluxes in various bands show: among γ -ray energy bands, the proportion with correlation coefficient greater than 0.7 is 70%, and the proportion with confidence level higher than 95% is 95%; between γ -ray and synchrotron radiation, the proportion with correlation coefficient greater than 0.4 is 42%, and the proportion with confidence level greater than 95% is 94.4%, indicating a certain degree of correlation; for Blazar of Unknown Types (BCU), the correlation between high-energy γ -ray and synchrotron radiation is very weak, with all correlation coefficients less than 0.4. Analysis indicates: the fitted slope of the BCU sample lies between that of the BL Lac Object (BLL) sample and the Flat-Spectrum Radio Quasar (FSRQ) sample, which should be caused by the BCU sample being a mixture of BLL and FSRQ. The correlation between synchrotron radiation and γ -ray radiation indicates that the high-energy γ -ray of BLL is mainly dominated by the Synchrotron Self-Compton (SSC) mechanism, while X-ray may be a mixture of synchrotron radiation and Inverse Compton (IC) radiation.

Full Text

A Study of Multi-band Radiation Correlations in Fermi Blazars

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Abstract

We collected multi-band radiation flux density data for a blazar sample from the Fermi Large Area Telescope Fourth Source Catalog Data Release 3 (4FGL-DR3). The dataset covers radio bands at 1.4 and 143 GHz, near-infrared (J, H, and K bands), optical (u, g, r, i, and z bands), ultraviolet (far ultraviolet and near ultraviolet), X-ray, and gamma-ray bands across six energy segments (0.1–0.3, 0.3–1, 1–3, 3–10, 10–30, and 30–100 GeV) within the 0.1–100 GeV range. We analyzed correlations among different gamma-ray energy bands and between gamma-ray bands and multi-band radiation from radio to X-ray for both the total blazar sample and its subclasses. Linear regression fitting results reveal that: among gamma-ray bands, 70% of the correlation coefficients exceed 0.7, with 95% of the results showing confidence levels above 95%; between gamma-ray and synchrotron radiation, 42% of the correlation coefficients exceed 0.4, with 94.4% showing confidence levels above 95%, indicating a moderate correlation; the correlation between high-energy gamma-ray and synchrotron radiation in Blazars of Unknown Types (BCU) is very weak, with all correlation coefficients below 0.4. Further analysis shows that the fitted slopes for the BCU sample fall between those of the BL Lac Object (BLL) and Flat-Spectrum Radio Quasar (FSRQ) samples, suggesting that the BCU sample is likely a mixture of BLL and FSRQ. The correlation between synchrotron and gamma-ray radiation suggests that high-energy gamma-ray emission in BLL is predominantly produced by the Synchrotron Self-Compton (SSC) mechanism, while X-ray emission may represent a mixture of synchrotron radiation and Inverse Compton (IC) radiation.

Keywords: galaxies: nuclei, gamma rays: galaxies, methods: data analysis, radiation mechanisms: non-thermal

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1 Introduction

Blazars constitute a special subclass of radio-loud active galactic nuclei, characterized observationally by dramatic multi-band variability and high polarization in optical and radio bands. Based on the presence of prominent emission lines in their spectroscopic spectra, blazars are classified into Flat-Spectrum Radio Quasars (FSRQs), with equivalent width (EW) $> 5 \text{ \AA}$, and BL Lac Objects (BLLs), with EW $< 5 \text{ \AA}$. FSRQs exhibit higher luminosities and lower

synchrotron peak frequencies compared to BLLs, while BLLs show extremely high radiation intensity from hard X-ray to TeV energies. Blazars that cannot be definitively classified as either FSRQ or BLL are designated as Blazars of Unknown Types (BCU). The observed variability of blazars is attributed to relativistic jets beaming toward the observer, with relativistic beaming effects greatly enhancing jet radiation that dominates the overall emission. The low-energy radiation component (from radio to soft X-ray) is widely believed to be produced by synchrotron radiation, while the high-energy component (hard X-ray and gamma-ray) originates from Inverse Compton (IC) scattering. However, the origin of gamma-ray emission in blazars remains to be further investigated, with major controversies concerning the seed photons and high-energy charged particles involved in the IC process. The External Compton (EC) mechanism proposes that seed photons primarily come from the dusty torus, broad-line region, or accretion disk, whereas the Synchrotron Self-Compton (SSC) mechanism suggests that seed photons are dominated by synchrotron radiation produced by high-energy charged particles themselves.

Numerous studies have discussed the relationship between synchrotron and gamma-ray radiation in blazars. Abdo et al. analyzed strong correlations between optical and gamma-ray bands in the blazar PKS 1510–089. Rajput et al. found different flux variation relationships between optical and GeV bands for four FSRQs. Tuo et al. examined the relationship between gamma-ray multi-band radiation and radio emission in Fermi blazars. Yang et al. and Fossati et al. discussed the relationship between synchrotron peak frequency and gamma-ray emission. Zhang et al. discovered varying relationships between optical and gamma-ray bands across blazars. This study analyzes correlations between gamma-ray and synchrotron radiation fluxes across various bands using multi-band radiation flux data, including gamma-ray, from the Fermi Large Area Telescope Fourth Source Catalog Data Release 3 (4FGL-DR3) blazar sample, to investigate the dominant radiation mechanisms and differences between different types of blazars (BLL and FSRQ) in the Fermi 4-year source catalog.

2.1 Sample Selection

This study utilizes blazars from the 4FGL-DR3 catalog as the analysis sample. The Fermi survey telescope, launched in 2008, is dedicated to detecting high-energy gamma-rays in the universe, with its Large Area Telescope providing a wide field of view. Blazars constitute a significant fraction of gamma-ray sources detected by Fermi, collectively known as Fermi blazars. The high-energy gamma-ray (0.1–100 GeV) flux data used in this study were obtained from Abdollahi et al., who calculated 12-year average fluxes for blazars in the 4FGL-DR3 catalog across eight energy bands (bands 1–8 corresponding to 0.05–0.1, 0.1–0.3, 0.3–1, 1–3, 3–10, 10–30, 30–100, and 100–1000 GeV) and provided Test Statistic (TS) values. Considering data reliability, we adopted data with $TS > 4$ (corresponding to standard deviation $\sigma > 2$) for our analysis. We excluded data from bands 1 and 8 due to their generally low TS values (mean values of

2.3 and 2.7, respectively, with some TS values being 0). Additionally, Abdollahi et al. cross-matched their analyzed sources with the 4FGL catalog; we selected blazars with 4FGL-associated sources, yielding a total of 3,437 sources after filtering. We converted flux data from each band to flux density at the band's central frequency, with units of $\text{W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$. The data are presented in Table 1 (due to the large volume of data, only partial sources are listed; complete data are available in Appendix B1).

2.2 Radio, Optical, and X-ray Band Data

Abdollahi et al. used Bayesian probability to estimate the most likely counterparts for blazars in their sample. We retrieved average flux density data for these counterparts from the NASA/IPAC Extragalactic Database (NED) at radio 1.4 GHz, near-infrared (NIR) J, H, and K bands, optical u, g, r, i, and z bands, and ultraviolet (UV) far UV (FUV) and near UV (NUV) bands. Optical data were obtained from the Sloan Digital Sky Survey Data Release 6 (SDSS DR6), which from DR2 onward no longer includes extinction corrections, requiring compensation. NED calculated extinction magnitudes in each direction based on the work of Schlafly et al., and we applied these extinction corrections to the optical data. Radio 143 GHz data were taken from Massaro et al. X-ray (0.1–2.4 keV) data were obtained from Ackermann et al. Flux density data for multi-band radiation from radio to X-ray are presented in Table 2 (due to the large volume of data, only partial entries are shown for reference; complete data are available in Appendix B2).

3.1 Correlations among Gamma-ray Energy Bands

Some studies analyzing relationships between gamma-ray bands typically calculate gamma-ray flux using total radiation in the 0.1–100 GeV range, which may mask detailed characteristics of gamma-ray emission. To minimize this effect, we directly used multi-band data from Fermi/LAT observations to examine their interrelationships. We calculated flux densities at the central energies of each band based on the fluxes provided by Abdollahi et al., with results shown in Table 1. For convenience, we followed the convention of Abdollahi et al. by designating the six bands from low to high energy as numbers 2–7: “2” represents the 0.1–0.3 GeV band, with correlation analysis performed using flux density at 0.2 GeV; “3” represents the 0.3–1 GeV band, using flux density at 0.65 GeV, and so forth. Linear regression fitting results for flux densities between gamma-ray bands 2–7 for the total blazar sample and its subclasses are presented in Table 3.

3.2 Correlations between Gamma-ray Energy Bands and Radio-to-UV Bands

Blazar observed radiation is dominated by non-thermal emission, though thermal radiation may become apparent during low states. Since thermal radiation does not significantly affect our analysis, we treated data from 1.4 GHz to UV

bands obtained from NED and literature as synchrotron radiation data, and analyzed their flux correlations with gamma-ray bands to discuss the applicability of the SSC mechanism. In our correlation analysis, linear regression fitting results between flux densities in the three NIR bands (J, H, and K) and different gamma-ray energy bands showed minimal differences, and historical literature indicates that light curves at these three frequencies vary synchronously with near-zero time delays. Therefore, we used the sum of flux densities at these three frequencies as the NIR fitting data. The same approach applied to optical bands, where linear regression fitting results also showed minimal differences. However, correlations between flux densities in the two UV bands (NUV and FUV) and different gamma-ray energy bands showed substantial differences, warranting separate discussion. Additionally, due to the large wavelength separation between the two radio bands, they were also discussed separately. Correlation analysis results between synchrotron radiation and gamma-ray bands indicate significant differences among different blazar subclasses. Overall, the gamma-ray synchrotron correlation is most significant in the BLL sample, moderate in the FSRQ sample, and weakest in the BCU sample. Balancing data quantity and representativeness, we present fitting results for gamma-ray band 3 (0.3–1 GeV) and band 6 (10–30 GeV) in Table 4 ; complete results are available in Appendix A.

3.3 Correlations between X-ray and Radio, Optical, and Gamma-ray Bands

In the double-peaked spectral energy distribution of blazars, X-ray emission appears at the intersection between synchrotron and IC radiation components. Therefore, analyzing correlations between different X-ray bands and various other bands contributes to a more comprehensive understanding of interactions between high-energy charged particles and synchrotron radiation, though such data are rarely reported. We therefore collected X-ray data in the 0.1–2.4 keV band to explore relevant radiation mechanisms through correlation analysis of flux densities. Correlation analysis between X-ray flux density and synchrotron radiation bands as well as gamma-ray energy bands reveals significant differences among different blazar subclasses. Overall, the FSRQ sample shows the strongest correlations between X-ray and synchrotron/gamma-ray bands (though weaker than BLL in the UV band), followed by the BLL sample. The BCU sample has insufficient data, but shows extremely weak correlation between X-ray and gamma-ray. Linear regression fitting results are presented in Table 5 .

4.1 Relationships among Gamma-ray Energy Band Flux Densities

We refer to the direction near 0.1 GeV in the 0.1–100 GeV gamma-ray range as the “low-energy end” and that near 100 GeV as the “high-energy end.” Correlation analysis results indicate clear differences between high-energy and low-

energy ends in 4FGL blazars, with different samples showing distinct variation patterns. Using the lower-energy band as the X-axis and the adjacent higher-energy band as the Y-axis, we examined differences among samples through the strength of correlations and variations in linear regression slopes for adjacent bands 2–3, 3–4, 4–5, 5–6, and 6–7 (Table 3). All these adjacent band pairs show strong correlations ($r > 0.7$), allowing reliable discussion of slope differences. The regression slopes for the BLL sample are 0.341, 0.324, 0.312, 0.331, and 0.311, respectively. For the FSRQ sample, the slopes are 0.251, 0.216, 0.166, 0.128, and 0.080. The BCU sample, with very few data points, shows slopes of 0.328, 0.233, 0.181, 0.177, and 0.200. The total sample slopes are 0.328, 0.233, 0.181, 0.177, and 0.200. Figure 1 [Figure 1: see original paper] illustrates the slope differences among different blazar samples. In Figure 1, represents the BLL sample, the FSRQ sample, the BCU sample, and the total sample. The curve of fitted slope variation with gamma-ray energy band changes according to the proportion of different blazar subclasses in the sample. Figure 1 shows the BCU sample's slope variation curve transitioning from near the FSRQ curve to near the BLL curve, which roughly corresponds to the changing BLL/FSRQ number ratio in the total sample (Table 3): 161/372, 667/595, 1006/506, 1004/273, and 637/78. This precisely demonstrates that the BCU sample is composed of a mixture of BLL and FSRQ.

4.2 Correlations between Gamma-ray and Radio/Optical Band Flux Densities

Considerable debate exists regarding SSC and EC models for blazars. Individual case studies illustrate this controversy: PKS 0537–441, classified as a BLL, was fitted with a single-zone SSC model by Pian et al., while Ammando et al. argued that the SSC model is insufficient to explain its spectrum and employed an EC model instead. For the FSRQ 3C 273, Sokolov et al. used the SSC model to explain its time delays. Furthermore, Arsioli et al. studied the gamma-ray emission region in low-synchrotron-peaked blazars (with a sample of 104 sources containing comparable numbers of BLL and FSRQ), finding that an EC mechanism dominated by infrared radiation fields better explains their sample's spectral energy distributions. In Ghisellini et al.'s study of blazar unification (also with a mixed BLL and FSRQ sample), they found it difficult to distinguish which model was more appropriate from basic spectral fitting. This study investigates blazar gamma-ray production mechanisms based solely on correlations between observed flux densities across various bands. Using band 3 as representative of the low-energy end and band 6 as representative of the high-energy end, we present correlation variations between gamma-ray and synchrotron radiation in Figures 2 [Figure 2: see original paper] through 4 [Figure 4: see original paper]. Figure 2 shows correlations between gamma-ray band 3 and various synchrotron radiation bands; Figure 3 [Figure 3: see original paper] shows correlations between gamma-ray band 6 and synchrotron radiation bands; Figure 4 displays correlation variations between gamma-ray and synchrotron radiation bands for the BLL sample. Hollow data points indi-

cate linear regression fit P-values less than 0.05, while dashed lines cross bands lacking data. Generally, correlation coefficients greater than 0.7 or less than -0.7 are considered strong, 0.4 to 0.7 or -0.7 to -0.4 moderate, and 0.2 to 0.4 or -0.4 to -0.2 weak. These intervals are marked with dot-dashed lines in Figures 2–5. Complete correlation analysis results are available in Tables 1–6 of Appendix A. Overall, BLL shows moderate correlation between synchrotron and gamma-ray radiation; FSRQ shows weak correlation; BCU shows almost no correlation. These results support the view that the SSC mechanism dominates in BLL. The different trends of the two curves in Figure 4 indicate that high-energy gamma-ray in BLL is more strongly associated with high-energy synchrotron radiation (optical and UV bands), while low-energy gamma-ray is more associated with low-energy synchrotron radiation (radio bands). In Figure 2, FSRQ shows moderate correlation between radio bands and low-energy gamma-ray, suggesting the SSC mechanism is important for its low-energy gamma-ray emission. The significant negative correlation between FSRQ and NIR bands with low-energy gamma-ray in Figure 2 may be due to the influence of the dusty torus on NIR bands, though the extremely limited data prevent further speculation.

4.3 Correlations between X-ray and Radio, Optical, and Gamma-ray Band Flux Densities

To investigate the X-ray radiation mechanism, we analyzed correlation variations between X-ray flux density and radio bands, optical bands, and multiple gamma-ray energy bands. In the BLL sample, X-ray shows the strongest correlation with the far UV band, with a correlation coefficient of 0.495 (Table 5), and the rising trend of the curve in Figure 5 [Figure 5: see original paper] suggests even stronger correlations at higher frequencies. The FSRQ sample shows the strongest correlation between X-ray and optical bands, with a correlation coefficient of 0.700 (Table 5). Examining the curve variations in the synchrotron radiation region in Figure 5 reveals similarities to Figures 2 and 3 (for BLL, the similarity lies in the inflection point of the curve; for FSRQ, ignoring the data-deficient NIR band, the similarity lies in the overall curve shape). Combined with the correlation results, we conclude that the SSC mechanism contributes significantly to X-ray emission in both FSRQ and BLL, and is particularly important for FSRQ X-rays. Fan et al. proposed that X-ray originates from synchrotron radiation or a mixture of synchrotron and IC mechanisms, which we believe better explains the complex relationship between X-ray and gamma-ray shown in Figure 5. The two curves on the right side of Figure 5 show an upward trend from band 5 onward, possibly because high-energy charged particles producing high-energy gamma-ray also produce part of the X-ray through synchrotron radiation. Tavecchio calculated that electrons radiating X-rays (1–10 keV) via synchrotron radiation in low magnetic fields (not exceeding 0.1 G) have Lorentz factors on the order of Γ_1 . According to Rybicki et al., these electrons would produce gamma-ray at observed frequencies of ν_2 Hz through inverse Compton scattering of near-infrared photons (ν_3 Hz), precisely the range from band 5 onward. In the gamma-ray region of the FSRQ

sample, the curve shows a downward trend from band 2 to band 5 (for the BLL sample, reliable correlations do not exist in this region, but the trend appears from band 2 to band 3), possibly because although seed photons for both low-energy gamma-ray and part of X-ray in the IC process come from the same radiation field, and combined with the discussion in Section 4.2 this IC process should be dominated by the SSC mechanism, the high-energy charged particles producing the two types of radiation are far apart in their energy distribution. If we hypothesize that blazar X-ray is a mixture of synchrotron radiation from particles producing high-energy gamma-ray and SSC radiation from particles producing low-energy gamma-ray, the contributions of the two particle populations to the two X-ray components vary inversely as their separation in the energy distribution increases. The boundary point between these two particle populations in the energy distribution corresponds to the turning point of the gamma-ray region curve in Figure 5, located at bands 3–4 for BLL and band 5 for FSRQ.

5 Conclusions

This study investigates relationships among flux densities of various gamma-ray energy bands and correlations between gamma-ray bands and radio, optical, and X-ray bands for the 4FGL-DR3 blazar sample. The main conclusions are as follows: (1) The regression fitted slopes for the BCU sample fall between those of the BLL and FSRQ samples, and the variation curve of these slopes is consistent with the changing BLL/FSRQ number ratio, confirming that BCU is a mixture of BLL and FSRQ. (2) Correlations between synchrotron and gamma-ray radiation indicate that the gamma-ray emission mechanism in BLL is dominated by SSC, while FSRQ low-energy gamma-ray contains a significant SSC component and high-energy gamma-ray is dominated by EC. (3) Both BLL and FSRQ samples show significant correlations between X-ray and synchrotron radiation, similar to their gamma-ray synchrotron correlation results, suggesting the importance of the SSC mechanism in the X-ray band. Combined with analysis of the complex relationship between X-ray and gamma-ray, X-ray emission in both blazar types is primarily a mixture of synchrotron radiation and IC radiation dominated by SSC.

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References

- Li F-T, Zhang X, Xiong D-R, et al. *Astronomical Research & Technology*, 2020, 17: 405
- Xu X-L, Zhang H-J, Yi T-F, et al. *Astronomical Research & Technology*, 2019, 16: 131

- Ding N. *Physical Characteristics of Blazar Jets and Variability*. Kunming: Yunnan Normal University, 2017: 22
- Urry C M, Padovani P. *PASP*, 1995, 107: 803
- Massaro E, Maselli A, Leto C, et al. *Ap&SS*, 2015, 357:
- Wang G G, Xiao H B, Fan J H, et al. *ApJS*, 2024, 270:
- Ackermann M, Ajello M, Atwood W B, et al. *ApJ*, 2015, 810: 14
- Peterson B M. *An Introduction to Active Galactic Nuclei*. Cambridge: Cambridge University Press, 1997:
- Perlman E. *PoS*, 2009, 2008: 009
- Sambruna R M, Tavecchio F, Ghisellini G, et al. *ApJ*, 2007, 669: 884
- Longair M S. *High Energy Astrophysics*. Cambridge: Cambridge University Press, 2011: 606
- Yang J H, Fan J H, Liu Y, et al. *ApJS*, 2022, 262: 18
- Mingaliev M G, Sotnikova Y V, Mufakharov T V, et al. *AstBu*, 2015, 70: 264
- Böttcher M. *Galax*, 2019, 7: 20
- Gupta A C, Kushwaha P, Carrasco L, et al. *ApJS*, 2022, 260: 39
- Sobacchi E, Lyubarsky Y E. *MNRAS*, 2020, 491: 3900
- Manzoor A, Sahayanathan S, Shah Z, et al. *MNRAS*, 2023, 525: 3533
- Guise E, Hönig S F, Almeyda T, et al. *MNRAS*, 2022, 510: 3145
- Celotti A, Fabian A C. *MNRAS*, 1993, 264: 228
- Safna P Z, Stalin C S, Rakshit S, et al. *MNRAS*, 2020, 498: 3578
- Błażejowski M, Sikora M, Moderski R, et al. *ApJ*, 2000, 545: 107
- Sarkar A, Chitnis V R, Gupta A C, et al. *ApJ*, 2019, 887: 185
- Lindfors E J, Valtaoja E, Türler M. *A&A*, 2005, 440: 845
- Abdollahi S, Acero F, Ackermann M, et al. *ApJS*, 2020, 247: 33
- Abdo A A, Ackermann M, Agudo I, et al. *ApJ*, 2010, 721: 1425
- Rajput B, Stalin C S, Sahayanathan S. *MNRAS*, 2020, 498: 5128
- Tuo M X, Dong J J, Yang J H, et al. *ChA&A*, 2020, 44: 428
- Pian E, Romano P, Treves A, et al. *ApJ*, 2007, 664: 106
- Ammando F D, Antolini E, Tosti G, et al. *MNRAS*, 2013, 431: 2481
- Sokolov A, Marscher A P, McHardy I M. *ApJ*, 2004, 613: 725
- Yang J H, Fan J H, Liu Y, et al. *Ap&SS*, 2017, 362:
- Arsioli B, Chang Y L. *A&A*, 2018, 616: 63
- Ghisellini G, Celotti A, Fossati G, et al. *MNRAS*, 1998, 301: 451
- Fossati G, Maraschi L, Celotti A, et al. *MNRAS*, 1998, 299: 433
- Zhang S, Yi T-F, Lu H, et al. *Astronomical Research & Technology*, 2023, 20: 510
- Tavecchio F. *Galax*, 2021, 9: 37
- Abdollahi S, Acero F, Baldini L, et al. *ApJS*, 2022, 260:
- Rybicki G B, Lightman A P. *Radiative Processes in Astrophysics*. New York: A Wiley-Interscience Publication, 1979: 197
- Schlaflly F, Finkbeiner D P. *ApJ*, 2011, 737: 103

Appendices

Appendix A contains complete correlation analysis results referenced in Sections 3.2, 4.2, and 4.3.

Appendix B1 contains the complete gamma-ray flux density data for all 3,437 sources.

Appendix B2 contains the complete multi-band flux density data from radio to X-ray.

Due to the large volume of data, Appendix B is made publicly available on figshare for readers to access:

Appendix B2: <https://figshare.com/s/a93999a6c299acda9b72>

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

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