Comprehensive Study of the Blazars from Fermi-LAT LCR: The Log-Normal Flux Distribution and Linear rms–Flux Relation postprint

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Abstract

Fermi-LAT LCR provides continuous and regularly sampled gamma-ray light curves, spanning about 14 yr, for a large sample of blazars. The log-normal flux distribution and linear rms–flux relation of the light curves for a few Fermi blazars have been examined in previous studies. However, the probability that blazars exhibit the log-normal flux distribution and linear rms–flux relation in their gamma-ray light curves has not been systematically explored. In this study, we comprehensively research the distribution of γ-ray flux and the statistical characteristics on a large sample of 1414 variable blazars from the Fermi-LAT LCR catalog, including 572 FSRQs, 477 BL Lacs, and 365 BCUs, and statistically compare their flux distributions with normal and log-normal distributions. The results indicate that the probability of not rejecting log-normal is 42.05% for the large sample, and there is still a 2.05% probability of not rejecting normality, based on the joint of Kolmogorov–Smirnov, Shapiro–Wilk, and Normality tests. We further find that the probability that BL Lacs conform to the log-normal distribution is higher than that of FSRQs. Besides, after removing sources with less than 200 data points from this large sample, a sample of 549 blazars, which is still a large sample compared to the previous studies, was obtained. Based on dividing the light curves into segments every 20 points (or 40 points, or one year), we fitted the linear rms–flux relation of these three different sets and found that the Pearson correlation coefficients are all close to 1 for most blazars. This result indicates a strong linear correlation between the rms and the flux of these 549 blazars. The log-normal distribution and linear rms–flux relation indicate that the variability of the γ-ray flux for most blazars is a non-linear and multiplicative process.

Full Text

Preamble

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Comprehensive Study of the Blazars from Fermi-LAT LCR: The Log-Normal Flux Distribution and Linear rms–Flux Relation

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Abstract

The Fermi-LAT Light Curve Repository (LCR) provides continuous and regularly sampled gamma-ray light curves spanning approximately 14 years for a large sample of blazars. While previous studies have examined the log-normal flux distribution and linear rms–flux relation for a few individual Fermi blazars, the probability that blazars exhibit these properties in their gamma-ray light curves has not been systematically explored.

In this study, we comprehensively investigate the distribution of γ-ray flux and its statistical characteristics for a large sample of 1414 variable blazars from the Fermi-LAT LCR catalog, including 572 flat-spectrum radio quasars (FSRQs), 477 BL Lacertae objects (BL Lacs), and 365 blazar candidates of uncertain type (BCUs). We statistically compare their flux distributions with both normal and log-normal distributions. The results indicate that, based on a joint analysis using the Kolmogorov–Smirnov, Shapiro–Wilk, and normality tests, the probability of not rejecting the log-normal hypothesis is 42.05% for the full sample, while there remains a 2.05% probability of not rejecting normality. We further find that BL Lacs show a higher probability of conforming to a log-normal distribution than FSRQs. Additionally, after removing sources with fewer than 200 data points from this large sample, we obtain a subsample of 549 blazars—still substantial compared to previous studies. By dividing the light curves into segments of 20 points, 40 points, or one year, we fit the linear rms–flux relation for these three different binning schemes and find that the Pearson correlation coefficients are all close to 1 for most blazars, indicating a strong linear correlation between the rms and flux for these 549 sources. The log-normal distribution and linear rms–flux relation suggest that the variability of γ-ray flux in most blazars is a non-linear, multiplicative process.

Key words: (galaxies:) quasars: general – (galaxies:) BL Lacertae objects: general – galaxies: jets – galaxies: active

1. Introduction

Blazars, a special subclass of Active Galactic Nuclei (AGNs), exhibit unique properties characterized by their highly relativistic jets oriented along the line of sight to observers (Urry & Padovani 1995; Jovanović et al. 2023). These objects display extreme observational properties including high luminosity, strong polarization, and rapid variability. Blazars are divided into two main subclasses: BL Lac objects (BL Lacs) and flat-spectrum radio quasars (FSRQs). The spectra of BL Lacs show only weak emission lines or none at all, whereas FSRQs exhibit strong emission lines (Urry & Padovani 1995; Abdo et al. 2010). Over the past three decades, advances in gamma-ray astronomy have enabled detailed studies of the temporal and spectral behavior of blazars. The Fermi telescope provides a platform for exploring high-energy γ-ray sources beyond our Galaxy (Atwood et al. 2009; Razzano et al. 2009). The latest catalog update includes over 5000 γ-ray sources above 4σ significance, 60% of which are blazars (Abdollahi et al. 2020).

The flux distribution of blazars has been extensively studied to understand the nature of their emission processes (Urry & Padovani 1995; Biteau & Giebels 2012a; Bhatta & Dhital 2020; Khatoon et al. 2020). Numerous blazars observed by Fermi-LAT show log-normal distributions in their long-term γ-ray light curves (Scarpa & Falomo 1997; Uttley et al. 2005; Ackermann et al. 2015; Romoli et al. 2018; Shah et al. 2018; Bhatta & Dhital 2020; Zhang et al. 2022, 2023). In recent years, progress in astronomical observations has provided important opportunities for analyzing long-term flux distributions. Multiple investigations have revealed log-normal distributions of X-ray flux in AGNs and X-ray binaries (Lyubarskii 1997; Uttley & McHardy 2001; Quilligan et al. 2002; McHardy 2010). Subsequently, a log-normal flux distribution was discerned in the γ-ray light curves of PKS 1510-089 and PKS 2155-304, with a linear correlation linking the root mean square (rms) and the average flux (Kushwaha et al. 2016; H.E.S.S. Collaboration et al. 2017).

Lyutyj & Oknyanskij (1987) found that a linear correlation between X-ray flux and its corresponding variation implies a log-normal distribution in Seyfert galaxies. In the X-ray band, many AGNs exhibit both log-normal distributions and linear rms–flux connections (McHardy et al. 2004; Kushwaha et al. 2017). This proportional linear correlation indicates that the absolute amplitude of rms is linked to the mean flux, thereby inferring that sources with greater luminosity show greater degrees of rms fluctuation. Furthermore, this linear relationship may be more intrinsic and fundamental than the power spectral density (PSD)

(McClintock et al. 2003; Gleissner et al. 2004; Pottschmidt et al. 2004). The origin of flux variability in blazars—whether from the jet itself or from the disk that could modulate the jet emission—has long been controversial. The linear rms–flux connection can facilitate studies of potential physical process changes in blazars and is therefore of great significance for time variability analysis, helping us understand the origin of blazar variability.

In the γ-ray band, the rms–flux relation and log-normal distribution have been researched for some individual sources, such as Mrk 421, Mrk 501, and 1ES 1011+496 (Tluczykont et al. 2010; Chakraborty et al. 2015; Sinha et al. 2017). Small samples of log-normal distributions have also been investigated (Kushwaha et al. 2017; Shah et al. 2018; Bhatta & Dhital 2020). However, systematic research on the flux distribution and rms–flux relation of γ-ray emission from blazars is still lacking. To address this gap, we perform a comprehensive study of the γ-ray flux of Fermi-LAT blazars based on a large sample. From the 1525 variable sources (variable index > 21.67) in the Fermi-LAT LCR catalog (Abdollahi et al. 2023), we obtained a large sample of 1414 variable blazars. These sources have been continuously monitored with a cadence of three days, making them well-suited for time series analysis. The data samples are described in Section 2. The flux distributions are fitted with both normal and log-normal functions in Section 3. In Section 4, we analyze and fit the rms–flux relation on the light curves using three different binnings and compare results statistically between the three subtypes: FSRQs, BL Lacs, and blazar candidates of uncertain type (BCUs). The results and possible implications are discussed in Section 5.

2. Data Samples

The Fermi Gamma-ray Space Telescope was launched in 2008 with the Large Area Telescope (LAT) as its principal scientific instrument. It typically operates in survey mode, covering the entire sky for γ-ray photon events in the energy range from 20 MeV to >300 GeV every approximately 3 hours with a field of view of ~2.4 steradians. The telescope provides continuous and nearly uniform observations of persistent and transient γ-ray sources, yielding the longest and most uniformly sampled γ-ray data available (Abdo et al. 2009). Light curves with time intervals of 30 days (monthly), 7 days (weekly), and 3 days are available for 1414 variable blazar sources (variable index > 21.67) in the Fermi-LAT LCR (Abdollahi et al. 2023). Here, we select the light curves with a cadence of 3 days and minimum detection significance TS > 4 (2σ) from 2008 to the present, providing more data points for studying the rms–flux relation and flux distribution. We further investigated and removed any outliers (photon flux $> 5 \times 10^{-5}$) before using the data for detailed analysis. These blazars can be classified into FSRQs, BL Lacs, and BCUs, accounting for 40.453%, 33.734%, and 25.813% of the sample, respectively. We use the light curves of these three types to study the flux distribution. After removing sources with fewer than 200 data points (to reduce the influence of small-number statistics on the rms–

flux relation), we obtain a subsample including 41 BCUs, 236 BL Lacs, and 272 FSRQs for fitting the rms–flux relation.

3. Flux Distribution Analysis

Histograms are a valuable tool for characterizing the flux distribution of blazars. The flux histograms of 365 BCUs, 477 BL Lacs, and 572 FSRQs are shown in Figure 1 [Figure 1: see original paper]. We find that most histograms have a prominent peak and a high-flux tail. To further understand these distributions, we fit them with normal and log-normal functions and compare the results using reduced ^{2}. The fit parameters together with the reduced ^{2} for both distributions are shown in Table 1 . We also compare the results using three statistical tests: the Kolmogorov–Smirnov (K-S), Shapiro–Wilk (S-W), and normality tests, as presented in Table 1.

We conducted statistical analysis on the results of these three tests and the reduced ^{2} values for BCUs, BL Lacs, and FSRQs. We counted the proportion of each subtype that did not reject the null hypothesis under the three tests (i.e., the proportion with p-values > 0.05). As shown in Table 2 , we computed statistical results for the 572 FSRQs to verify the normality or log-normality of the probability density function (PDF) from these histograms. Across the three tests, the percentages that do not reject the normal distribution are 20.98%, 1.92%, and 2.45%, respectively ($p > 0.05$). Conversely, the percentages of FSRQs that do not reject the log-normal distribution are 77.45%, 37.41%, and 37.41%, respectively. Among the 477 selected BL Lacs, we performed a similar analysis. The percentages of BL Lacs that do not reject the normal distribution are 21.59%, 0.84%, and 1.89%, while 95.18%, 52.41%, and 52.83% do not reject the log-normal distribution, respectively. In addition to FSRQs and BL Lacs, there are 365 BCUs that lack reliable classification. To study the flux distribution characteristics of these sources, we analyzed them as described above, with results shown in Table 2. We find differences among the three test results, with the K-S test results being significantly different from the S-W and normality test results, while the latter two are essentially consistent. To unify the results, we define the flux distribution of blazars that do not reject the null hypothesis under all three tests as conforming to that distribution. Under this criterion, out of 1414 variable blazars, the flux distributions of 199 FSRQs, 230 BL Lacs, and 179 BCUs conform to the log-normal distribution, while the flux distributions of 9 FSRQs, 4 BL Lacs, and 16 BCUs conform to the normal distribution.

Furthermore, based on the K-S, S-W, and normality test results, we obtained the distribution of p-values. As shown in Figure 2 [Figure 2: see original paper], the p-value distributions for FSRQs, BL Lacs, and BCUs are similar. These distributions reveal that the p-values of the K-S (log-normal), S-W (log-normal), and normality (log-normal) tests are predominantly concentrated in the range where $p > 0.05$. Conversely, p-values of the three tests (normal) are mainly concentrated where $p < 0.05$. Generally, the better the flux distribution of blazars fits the log-normal distribution, the less it fits the normal distribution.

These consistent results indicate that the flux distributions of all three blazar subtypes prefer log-normal over normal distribution.

The results in Table 2 and Figure 2 from the three tests demonstrate that most blazars prefer log-normal distribution. According to the comparison of flux distribution results, the probability that BL Lacs conform to the log-normal distribution is higher than that of FSRQs, while the probability that BCUs conform to the log-normal distribution is similar to that of BL Lacs. The histograms and fits are shown in Figure 1.

In the multiplicative model, flux naturally generates a log-normal distribution. If we let f be the product of flux A in a large number of isotropic regions, then log f is the sum of log A. According to the Central Limit Theorem (CLT), the logarithmic value of f follows a normal distribution, or equivalently, f adheres to a log-normal distribution (Biteau & Giebels 2012b). Assuming in the context of a log-normal distribution that observed flux f can be expressed as a function of an underlying variable x, i.e., f = f(x), where f follows an exponential pattern while x conforms to a normal distribution. Fluctuations in x in the form of a slight deviation from a given value, δx, result in corresponding deviations in f around f(x_0), δf (Biteau & Giebels 2012a). It is noteworthy that the flux variance is inevitably dependent on that of the variable x. When the flux deviation is proportional to f(x_0), the relation can be equivalent to one of the definitions of the exponential function. The flux is proportional to its rms only when the flux is an exponent of the underlying variable. Therefore, the rms–flux relation can be interpreted as a consequence of a log-normal flux distribution (Uttley et al. 2005; Biteau & Giebels 2012a, 2012b).

4. Rms–Flux Relation

The rms–flux relation has been most convincingly demonstrated on relatively short timescales in the X-ray band. To study the rms–flux relations of blazars in the γ-ray band, we selected 1414 blazars from the Fermi-LAT LCR. To avoid statistical insignificance from too few bins that would affect the fitting results, we chose blazars with more than 200 data points as a subsample. After removing sources with fewer than 200 data points, we obtained a sample of 549 blazars, including 272 FSRQs, 236 BL Lacs, and 41 BCUs. We separately fit and estimate the rms–flux relation for three different binnings of the light curves: 20 data points per bin, 40 data points per bin, and one year (365 days) per bin, and calculate their Pearson correlation coefficients. These three binnings are based on time series. The first two involve dividing the data into bins of fixed point numbers, with each bin consisting of 20 or 40 data points, respectively. To further investigate whether the binnings impact the rms–flux relation, the third scheme involves grouping data based on fixed time intervals, with all points within a 365-day interval forming a bin. We calculate the rms and average flux for each bin and perform linear regression analysis, obtaining the Pearson correlation coefficient for the rms–flux relation. The interdependence between rms and flux is noteworthy, with a substantial and coherent correlation between the two. Linear fitted plots of the rms–flux relation are shown in Figure 3 [Figure 3: see original paper].

Statistical results for the three different binnings are presented in Figure 4 [Figure 4: see original paper] and Table 3 . As shown in Table 4 , when using 20 data points per bin, the mean slopes of the rms–flux relation for FSRQs, BL Lacs, and BCUs are 1.860, 1.996, and 1.985, respectively. The mean Pearson correlation coefficients for the rms–flux relation for all three types are 0.977, 0.961, and 0.979, respectively, indicating a strong correlation between rms and flux. For the other two binnings, the Pearson correlation coefficients for the rms–flux relation are ~1, demonstrating a strong linear rms–flux relation for all 549 sources, as shown in Table 4.

Based on the fitting of the rms–flux relation for BL Lacs, FSRQs, and BCUs using different grouping schemes, the slopes for these three source types are all greater than zero. BL Lacs exhibit a steeper slope than FSRQs. However, the differences in slopes among the three source types are too small to be used as a criterion for distinguishing between them.

5. Discussion and Conclusion

In this work, we investigate the variability properties of γ-ray emission by analyzing the flux distribution and linear rms–flux relation of a large blazar sample from the Fermi-LAT LCR, including 572 FSRQs, 477 BL Lacs, and 365 BCUs. We fitted the flux distribution histograms to determine whether they conform to normal or log-normal functions. Of the 572 FSRQs, 199 show log-normal distributions while only 9 follow a normal distribution. Of the 477 BL Lacs, 230 show log-normal distributions while only 4 follow a normal distribution. Of the 365 BCUs, 179 show log-normal distributions while only 5 follow a normal distribution. The probability that the flux distribution of BL Lacs is log-normal is greater than that of FSRQs. Interestingly, we find that the flux of a few sources is normally distributed, though the flux distribution is also consistent with log-normal.

Further analysis is required for those blazars whose distribution does not conform to either log-normal or normal distributions. In particular, Peñil et al. (2022) fitted both normal and log-normal PDFs to the γ-ray flux distribution of S5 0716+714 and found that the normal PDF best fit the light curves (using 28-day binning). However, for the same source, our fit to the flux distribution follows a log-normal distribution (using 3-day binning). This indicates that binning choices for light curves affect the fitting results. As shown in Figure 5 [Figure 5: see original paper], we also found some histograms showing bimodal patterns, though the statistics for these distributions are not significant enough, so these results should be considered only indicative.

In addition to using Fermi data with $TS > 4$, we attempted to use Fermi data with $TS > 9$ to study flux distributions and summarize the results under the K-S, S-W, and normality tests. For the K-S test, 86.21% of blazar flux distributions show a log-normal distribution, while 57.99% show a normal distribution. In the S-W test, 61.60% show log-normal distributions, while 24.47% show normal distributions. For the normality test, 60.82% show log-normal distributions, while 28.08% show normal distributions. The flux distribution generally tends to be log-normal. However, the number of data points with TS > 9 per bin is too small, which affects the statistical significance of fitting results, so we did not analyze the rms–flux relationship for TS > 9.

Many studies have explained why log-normal distributions appear in many sources across different bands (Kirk et al. 1998; Giebels & Degrange 2009; Kushwaha et al. 2017; Shah et al. 2018, 2020; Khatoon et al. 2020; Scargle 2020). Blazar variability may result from a combination of intrinsic source events, such as instabilities in both the disk and jet, and extrinsic influences on the source geometry and projection. Three main explanatory models for the log-normal distribution have been proposed: (1) In the X-ray band, the propagating fluctuations model from accretion disks, where flux variations from different radii accumulate multiplicatively, was initially believed to explain this behavior (Lyubarskii 1997; Meyer 2019; Khatoon et al. 2020); (2) Inherent particle acceleration in the acceleration region on acceleration timescales leads to linear normal perturbations, resulting in log-normal flux distributions (Giannios et al. 2009; Narayan & Piran 2012; Sinha et al. 2018); (3) The log-normal distribution of blazars has also been interpreted as the sum of emission from small-scale jets (Biteau & Giebels 2012a, 2012b). The “minijets in a jet” model was developed based on the second explanatory approach. In this statistical model, emission from identical, independent but randomly oriented minijets follows a Pareto distribution, which produces both normal and log-normal distributions while preserving a linear rms–flux relationship in all cases (Biteau & Giebels 2012b). This model is favored by our statistical results: in addition to many sources exhibiting log-normal distributions, some sources also exhibit normal distributions.

In general, the log-normal distribution of flux implies a linear rms–flux relation (Biteau & Giebels 2012b). Furthermore, the linear rms–flux relation implies that the variability process and associated perturbations are multiplicative in nature (Lyubarskii 1997; Arévalo & Uttley 2006). Mathematically, additive processes produce normal distributions, while multiplicative processes produce log-normal distributions. In the X-ray band, the log-normal flux distribution and linear rms–flux relation can be explained by accretion disk models where inward-propagating fluctuations from different radii accumulate multiplicatively (Arévalo & Uttley 2006). In the γ-ray band, blazar variability is primarily associated with non-thermal radiation from the jet. If this radiation is relativistically beamed, all possible contributing factors—such as variable magnetic fields, high-energy particle density, seed-photon density, particle acceleration, and diffusion processes—could be coupled in a complex manner, resulting in log-normal flux distributions in blazars (Bhatta & Dhital 2020).

Both normal and log-normal distributions can be interpreted as special cases of a more general class of skewed distributions, such as Pareto distributions, with variable degrees of skewness. In the Pareto distribution scenario, the resulting flux distribution maintains the rms–flux relation (Biteau & Giebels 2012a). We selected blazars with more than 200 data points for rms–flux fitting across different types and binnings. The fitting results show that the rms and flux of all three blazar subtypes have a strong linear relationship in all three binning schemes, with average Pearson coefficients above 0.95. About 75% of the blazars have an intercept less than 0. Additionally, the slope of BL Lacs is generally greater than that of FSRQs. The strong correlation of the linear rms–flux relation appears to be an intrinsic property of blazars.

Among the 549 blazars with linear rms–flux relations, the flux distributions of 415, 183, and 187 blazars show log-normality based on the K-S, S-W, and normality tests, respectively. There are 172 sources common to both the 595-source sample and the 549-source sample. Sources whose flux distribution conforms to the log-normal distribution have a strong linear rms–flux relation. However, the reverse is not true, as a log-normal flux distribution is not a necessary consequence of a linear rms–flux relation. The "minijets in a jet" model indicates that the sample rms is proportional to the sample flux if and only if the flux is the exponential of an underlying variable, as is the case for a log-normally distributed flux. This rms–flux relationship is a necessary but insufficient condition for the log-normal distribution.

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