The Multimessenger Chakra of Blazar Jets
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Gamma-ray flux distribution analysis on 145 gamma-ray bright blazars

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Abstract. We present the results of the gamma-ray flux distribution analysis on 145 gamma-ray bright blazars observed by Fermi-LAT. For the gamma-ray flux distribution, we applied a log-normal distribution to discuss the nature of the high-energy emission processes of blazars and a power-law distribution convolved with a Poisson distribution to investigate the implications of gamma-ray bright blazars for neutrino emission. Both distributions can represent the observed flux distributions as well. The leptonic models, which give the physical relationship between neutrinos and gamma rays, indicate that the flaring contribution to the neutrino emission can be dominant for the power-law index less than ~ 2.5. From the power-law distribution analysis, we found that the power-law index < 2.5 accounts for the 82 % blazars. This result suggests that the flaring contribution of blazars is dominant for high-energy neutrino emission.

Keywords. galaxies: active, galaxies: jets, gamma rays: observations, methods: data analysis

1. Introduction

The flux distributions of blazars have been used to study the temporal variation to provide valuable clues to the origin and nature of their variability. One distribution of light curves which is commonly found in blazars is the log-normal distribution (e.g., Shah *et al.* 2018; Bhatta *et al.* 2020). The log-normal distribution can interpret as multiplicative processes with the analog of the normal distribution as additive processes (Uttley *et al.* 2005, and references therein). That is, a process produced by the multiplication of many independent ones may have a log-normal distribution. On the other hand, Scargle (2020) discusses that a distribution resembling a log-normal one can be reproduced by additive processes with a power-law distribution.

As another approach, Murase *et al.* (2018) applied a power-law distribution convolved with a Poisson distribution for six blazar light curves using the public Fermi All-sky Variability Analysis (FAVA) data by *Fermi* LAT (Abdollahi *et al.* 2017). As described in Murase *et al.* (2018), the gamma-ray flux distribution analysis provides us how dominant the flaring contribution is to the neutrino emission, according to the various leptonic models, which give the physical relationship between neutrinos and gamma rays.

In this paper, we present a statistical study of the gamma-ray flux distribution analysis to investigate the implications of blazars for high-energy neutrino emission.

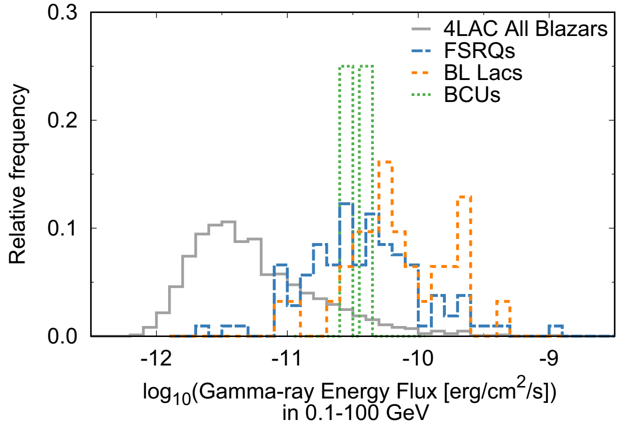

Figure 1. Relative frequencies of the $0.1-100$ GeV gamma-ray energy fluxes of 4LAC all 1701 blazars (dark gray line), 106 FSRQs (blue line), 31 BL Lacs (orange line), and eight BCUs (green line).

2. Data analysis

Our samples are 145 gamma-ray bright blazars observed by Fermi-LAT. The blazar subclasses are 106 FSRQs, 31 BL Lacs, and eight blazar candidates of uncertain type (BCUs). Figure 1 shows relative frequencies of the gamma-ray energy fluxes in $0.1-100$ GeV of our samples with 4LAC all 1701 blazars (Ajello *et al.* 2020). As shown in Fig. 1, our sample blazars are bright gamma-ray blazars in 4LAC blazars.

Using the $0.1-316$ GeV gamma-ray light curves with a one-week time bin through 2008-2019 in Yoshida *et al.* (2023), we derived the distribution of the number of time bins with gamma-ray flux: dN/dF_γ. We applied two model distributions for the gamma-ray flux distributions: log-normal and power-law ones. A log-normal distribution is given by

$$\frac{dN}{dF_\gamma} = \frac{N}{\sqrt{2\pi}F_\gamma\sigma}\exp\left(-\frac{(\ln F_\gamma - \mu)^2}{2\sigma^2}\right), \tag{1}$$

where N is the total number of time bins, μ and σ are the mean and standard deviation in units of the log of gamma-ray flux F_γ. A power-law distribution convolved with a Poisson distribution is given by

$$\frac{dN}{dk} = \sum_{n=n_0}^{\infty} An^{-\alpha}P(n+n_B, k+n_B), \tag{2}$$

where A is a normalization factor, k is the number of detected photons with a time bin, n and n_B are the numbers of source and background photons, $P(n+n_B, k+n_B)$ is a Poisson distribution, and n_0 is a minimum number of photons per bin that corresponds to a "quiescent" flux. Figure 2 gives two examples of the gamma-ray flux distributions fitted with a log-normal distribution and a power-law distribution convolved with a Poisson distribution for PKS 0250-225 and Mkn 501.

The Kolmogorov-Smirnov goodness-of-fit test gives the p-values under the null hypothesis that the observed flux distribution follows a model flux distribution. The blazars with a p-value > 0.05 account for 83% for the log-normal distribution and 86% for the power-law distribution. Hence the power-law distribution is applicable in equal or more blazars than the log-normal distribution. Figure 3 presents scatter plots between the log-normal mean μ and the power-law quiescent flux F_0, and the log-normal standard deviation σ

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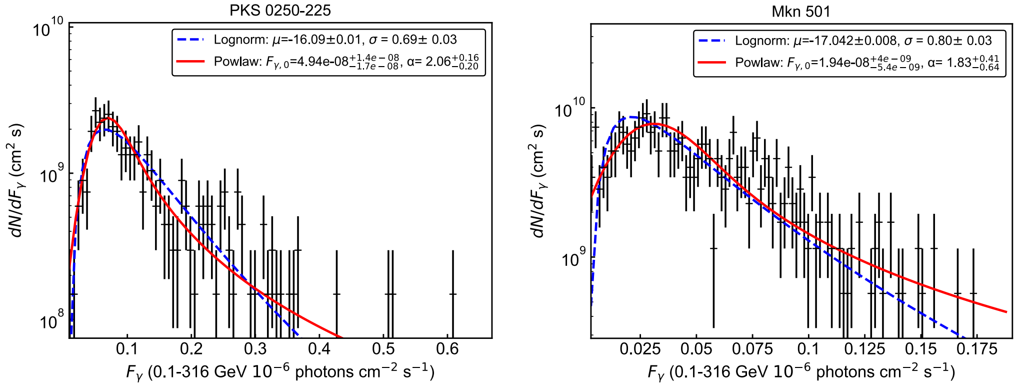

Figure 2. The gamma-ray flux distributions of PKS 0250-225 (left) and Mkn 501 (right) in $0.1-316$ GeV fitted with a log-normal distribution (blue line) and a power-law distribution convolved with a Poisson distribution (red line).

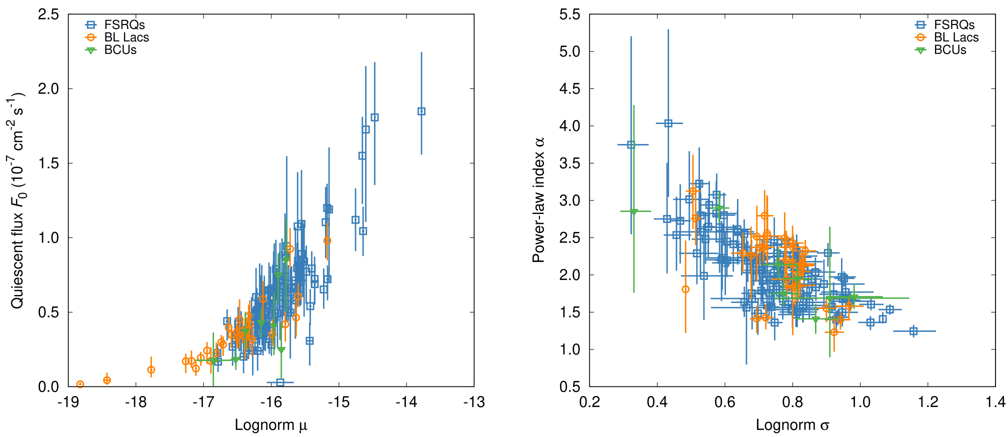

Figure 3. Scatter plots between the log-normal mean μ and power-law quiescent flux F_0 (left), and the log-normal standard deviation σ and power-law index α (right). The blue squares, orange circles, and green triangles show FSRQs, BL Lacs, and BCUs, respectively.

and the power-law index α. As we might expect, there are clear correlations between μ and F_0, and between σ and α as shown in Fig. 3.

As for μ and F_0, the Brunner-Munzel test (Brunner & Munzel 2000) suggests significant differences between FSRQs and BL Lacs with p-values of 5.3×10^{-5} % for μ and 1.9×10^{-2} % for F_0 for the null hypothesis that FSRQs and BL Lacs are equal. On the other hand, the Brunner-Munzel test suggests no significant differences between FSRQs and BL Lacs with p-values of 32 % for the log-normal standard deviation σ and 39 % for the power-law index α.

3. Discussion and Conclusions

The high-energy neutrinos from blazar jets are expected to be produced by photohadronic interactions of high-energy protons with target photons. Under different assumptions of the target photons, the leptonic models give a relation between the neutrino luminosity and gamma-ray luminosity of $L_\nu \propto L_\gamma^\gamma$ with $\gamma \simeq 1.0-2.0$ (Murase & Waxman 2016; Murase *et al.* 2018). Taking the power-law flux distribution

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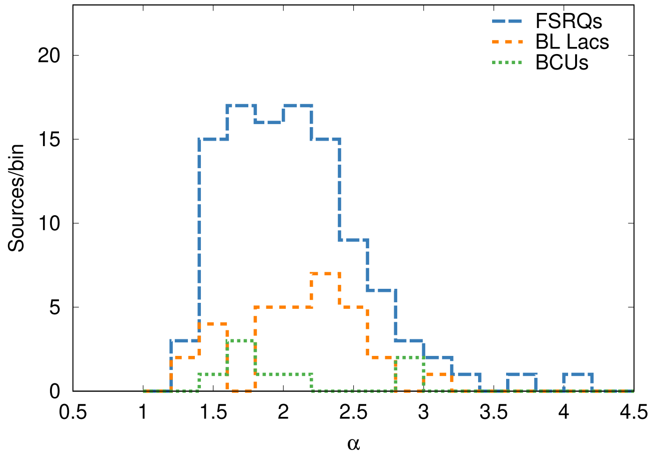

Figure 4. Distributions of power-law index α for FSRQs (blue line), BL Lacs (orange line), and BCUs (green line). The power-law index α less than 2.5 accounts for the 82% (119/145) blazars.

of $dN/dL_\gamma \propto L_\gamma{}^{-\alpha}$, we obtain

$$L_\nu{}^2 \frac{dN}{dL_\nu} \propto L_\nu{}^{\frac{\gamma+1-\alpha}{\gamma}}. \tag{3}$$

This relation implies that gamma-ray flares can dominate the neutrino production of a blazar for $\alpha < \gamma + 1$. Using $dN/dL_\gamma \propto dN/dF_\gamma$ and $dN/dL_\nu \propto dN/dF_\nu$, we can estimate the power-law index α from the gamma-ray flux distributions with a power-law distribution convolved with a Poisson distribution. Figure 4 presents frequency distributions of power-law index α for FSRQs, BL Lacs, and BCUs. Corresponding to $\alpha < \gamma + 1$, the power-law indices α less than 2.0 with $\gamma = 1.0$, 2.5 with $\gamma = 1.5$, and 3.0 with $\gamma = 2.0$ account for the 46 % (67/145), 82 % (119/145), and 96 % (139/145) blazars, respectively. Hence, our results suggest that the flaring contribution of gamma-ray bright blazars is dominant for high-energy neutrino emission. The power-law index $\alpha = 2.1 \pm 0.3$ of TXS 0506+056 might be the case for the multi-messenger flare associated with IceCube-170922A (IceCube-Collaboration *et al.* 2018).

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