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Flare Duty Cycle and Energy Fraction of Gamma-Ray Blazars and Implications for High-Energy Neutrinos

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According to the three-sigma high-energy neutrino source association of IC-170922A with a gamma-ray flare of a blazar TXS 0506+056, it is expected that gamma-ray flares of blazars would be ideal periods for high-energy neutrino emission. In this work, we present our findings from analyzing 145 gamma-ray bright blazars observed by Fermi-LAT to determine the contribution of gamma-ray blazar flares to high-energy neutrino emission. We derived the flare duty cycle and energy fraction from the weekly binned light curves of these blazars, identifying a significant difference in flare duty cycles between FSRQs and BL Lacs at a significance level of 5 %. We also estimated the neutrino energy flux of each gamma-ray flare using a general scaling relation for the neutrino and gamma-ray luminosities, $L_\nu \propto (L_\gamma)^\gamma$ with $\gamma = 1.0 - 2.0$, normalized to the quiescent gamma-ray and X-ray flux of each blazar. Lastly we present the upper-limit contribution of gamma-ray blazars to the isotropic diffuse neutrino flux.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1475

1. Introduction

The IceCube Collaboration discovered high-energy astrophysical neutrinos that exhibit an evenly distributed arrival pattern in the 100 TeV – PeV range [1]. The detected diffuse neutrino flux can be interpreted as a uniform background of neutrinos generated by numerous extragalactic sources (e.g., [2]). The IceCube Collaboration et al. (2018) [3] explored a muon neutrino event known as IceCube-170922A, which had energy below the PeV scale. This event was observed to occur simultaneously in both directions and times with a gamma-ray flare emitted by the blazar TXS 0506+056. They determined that the correlation between the neutrino event and the gamma-ray flare had a statistical significance of 3 σ. Furthermore, before the flaring event in 2017, the IceCube Collaboration (2018) independently conducted a thorough search of past IceCube data and provided evidence, at a significance level of 3.5 σ, for neutrino events originating from the direction of TXS 0506+056 [4].

Blazars represent the most exceptional category of active galactic nuclei (AGNs), distinguished by their radiant central region, exceedingly swift fluctuations, elevated polarization, superluminal motion, and extensive non-thermal spectra. According to current understanding, it is postulated that their relativistic jets, emanating from the central supermassive black hole, align closely with the observer's line of sight [5]. Blazars stand as primary contenders for the sources of ultrahigh-energy cosmic rays and high-energy neutrinos (e.g., [6] and references therein). Blazars are recognized as sources that undergo flare events, characterized by significant fluctuations in flux across the electromagnetic spectrum spanning various timescales. Although the precise cause of blazar flares remains elusive, it is anticipated that the production of neutrinos becomes more pronounced during these periods of heightened flux ([2] and references therein).

In this work, we present our results about flare duty cycle and flare energy fraction of 145 gamma-ray bright blazars. We also discuss the implications of our results on the high-energy neutrino emission from flaring blazars.

2. Gamma-ray data and analysis

2.1 Gamma-ray data

We picked out 145 blazars with high gamma-ray emissions from the Fermi Large Area Telescope (LAT) Monitored Source List[1] including TXS 0506+056. The group is made up of 106 Flat Spectrum Radio Quasars (FSRQs), 31 BL Lacs, and 8 blazar candidates of uncertain type (BCUs), which are identified as blazars with the Fourth Catalog of AGN detected by the LAT (4LAC-DR2, hereafter 4LAC) [7].

The gamma-ray light curve of each source was acquired through a comprehensive analysis, employing identical processing procedures as the spectral analysis, within each temporal interval using the `Fermi Science Tools` version 11-05-03[2] and `Fermipy` version 0.17.3 [8]. The period spanning from MJD 54682 to MJD 58739 was partitioned into ~570 bins, each corresponding to a duration of 7 days. The spectral model utilized for the target source was sourced from 4FGL [9], wherein all parameters were allowed to vary freely during the spectral fitting process. Subsequently,

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/
[2] http://fermi.gsfc.nasa.gov/ssc/data/analysis/software

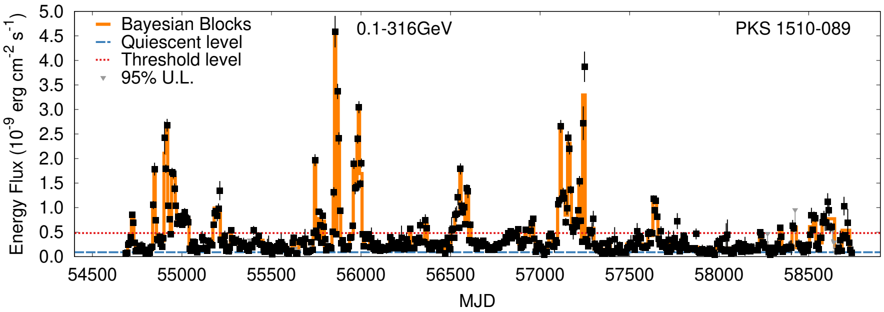

Figure 1: An example of gamma-ray light curves in the 0.1 – 316 GeV with black points, including 95 % upper limits depicted by grey triangles. Overlaid on this representation is the Bayesian Blocks, represented by a solid orange line.The quiescent and flare thresholds at 6σ are indicated by dashed cyan and red lines, respectively.

the determined best-fit parameters were utilized to compute the gamma-ray energy flux within the energy range of 0.1 to 316 GeV for each time bin of the light curve. Figure 1 presents an illustrative representation of the gamma-ray light curves. The energy flux data points are depicted along with their corresponding 1σ uncertainties, represented by black symbols. This representation is applicable when the source is detected with a test statistic (TS) exceeding 9 and the energy flux value within a given bin surpasses its associated uncertainty. Conversely, when these conditions are not met, the flux upper limits are exhibited, established at a 95% confidence level. As an illustrative instance, Figure 1 exhibits the gamma-ray light curve of PKS 1510-089. Additionally, the Bayesian Blocks [10–12] representation is presented through a solid orange line. Furthermore, the quiescent flux level, computed from the Bayesian Blocks light curve, is indicated by a dashed cyan line.

Here, we define a gamma-ray flare flux as the energy flux of the weekly-binned light curves that surpasses a specific threshold, denoted as $F_\gamma^{\rm th}$, which is determined by the equation: $F_\gamma^{\rm th} = F_\gamma^q + s\langle F_\gamma^{\rm err}\rangle$, where F_γ^q refers to the gamma-ray quiescent level, $\langle F_\gamma^{err}\rangle$ is the mean of the gamma-ray flux errors, and s represents the significance above the quiescent level in units of the standard deviation σ. Unless otherwise specified, we use $s = 6$ in this study. Figure 1 illustrates the flaring threshold level of the gamma-ray light curve, with a dashed red line denoting the threshold.

2.2 Flare Duty Cycle and Flare Energy Fraction

The fraction of time spent in the flaring state, the flare duty cycle, is given by

$$f_{\rm fl} = \frac{1}{T_{\rm tot}} \int_{F_\gamma^{\rm th}} dF_\gamma \frac{dT}{dF_\gamma} \tag{1}$$

where F_γ is the gamma-ray energy flux and $T_{\rm tot}$ is the total observation time. The fraction of energy emitted in the flaring state, the gamma-ray flare energy fraction, is given by

$$b_{\rm fl}^\gamma = \frac{1}{F_\gamma^{\rm ave} T_{\rm tot}} \int_{F_\gamma^{\rm th}} dF_\gamma F_\gamma \frac{dT}{dF_\gamma} \tag{2}$$

where $F_\gamma^{\rm ave}$ represents the average gamma-ray energy flux during the entire observation period. Figure 2 presents the cumulative distributions of the flare duty cycles ($f_{\rm fl}$) and flare energy fractions

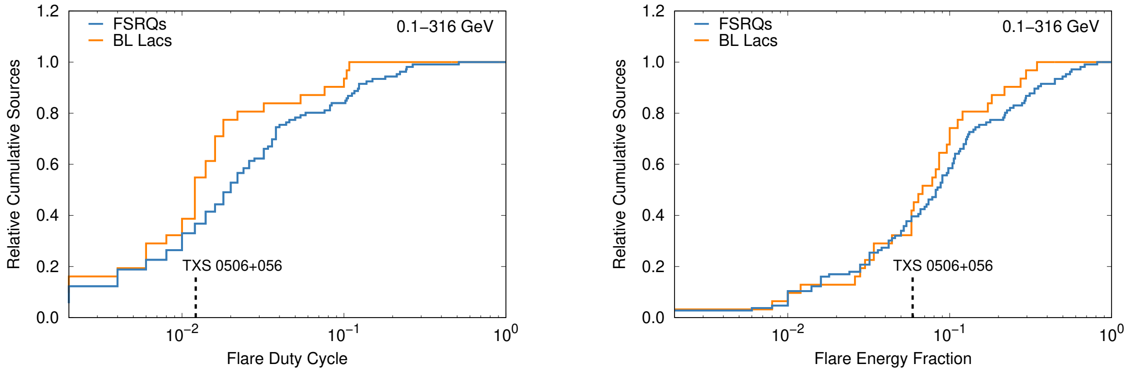

Figure 2: Cumulative histograms of the gamma-ray flare duty cycles and flare energy fractions for 106 FSRQs (blue solid) and 31 BL Lacs (orange solid) in the energy range of $0.1 - 316$ GeV. The left panel shows the duty cycles, while the right panel displays the energy fractions. The vertical dashed line in both panels marks the values of TXS 0506+056.

($b^{\gamma}_{\rm fl}$) for the 0.1 – 316 GeV gamma-ray light curves of 106 FSRQs and 31 BL Lacs. The vertical dashed lines indicate the $f_{\rm fl}$ and $b^{\gamma}_{\rm fl}$ values of TXS 0506+056. A two-sample Kolmogorov-Smirnov test is performed to determine whether the cumulative distributions of either $f_{\rm fl}$ or $b^{\gamma}_{\rm fl}$ are the same for FSRQs and BL Lacs. Under the null hypothesis that the FSRQs and BL Lacs distributions are derived from the same parent distribution, the probabilities are $p = 0.039$ for the flare duty cycles distributions with the K-S statistic $D = 0.279$, and $p = 0.521$ for the gamma-ray flare energy fraction distributions with $D = 0.159$, respectively. Thus, we can reject the null hypothesis that the distributions of flare duty cycles for FSRQs and BL Lacs are drawn from the same parent population at a significance level of 5 %. While we cannot exclude the null hypothesis for the flare energy fractions of FSRQs and BL Lacs at a significance level of 10 %.

3. Implication for high-energy neutrino emission

3.1 Estimation of Muon Neutrino Flux

According to the standard leptonic models of the blazar gamma-ray emission, it is suggested that flares have the potential to dominate the neutrino output of a blazar [e.g., 2]. Typically, in the leptonic models, the neutrino flux is linked to the gamma-ray luminosity through the equation:

$$L^{\rm fl}_{\nu} = L^{q}_{\nu} \left(\frac{L^{\rm fl}_{\gamma}}{L^{q}_{\gamma}} \right)^{\gamma} , \tag{3}$$

where $L^{\rm fl}_{\nu}$ is the flare neutrino luminosity, L^{q}_{ν} is the quiescent neutrino luminosity, $L^{\rm fl}_{\gamma}$ is the gamma-ray luminosity in the flaring state, L^{q}_{γ} is the quiescent gamma-ray luminosity, and γ is the index within the range of approximately 1.0 to 2.0 ([2], and references therein).

3.1.1 Scenario 1: the quiescent gamma-ray flux

Firstly, the quiescent neutrino flux can be estimated through the quiescent gamma-ray flux, denoted by $E_{\gamma} F^{q}_{E_{\gamma}}$, at the pivot energies. These energies correspond to the de-correlation energy that minimizes the correlation of the fitted spectral parameters for each weekly bin. Subsequently, the muon neutrino flare flux can be represented by

$$E_{\nu_\mu} F^{\mathrm{fl}}_{E_{\nu_\mu}} = E_{\nu_\mu} F^{q}_{E_{\nu_\mu}} \left(\frac{F^{\mathrm{fl}}_\gamma}{F^{q}_\gamma} \right)^{\gamma} = A_\gamma \frac{E_\gamma F^{q}_{E_\gamma}}{3} \left(\frac{F^{\mathrm{fl}}_\gamma}{F^{q}_\gamma} \right)^{\gamma}, \tag{4}$$

where A_γ is a normalization parameter, and the factor of 3 comes from neutrino flavour mixing in vacuum.

3.1.2 Scenario 2: the quiescent X-ray flux

Motivated by the results obtained after the observation of TXS 0506+056, it can be inferred that the X-ray quiescent flux level in the energy range of 0.3-10 keV provides an upper limit to the muon neutrino quiescent flux in the range of 100 TeV - PeV (for further details, please refer to [13, and references therein]). To obtain the X-ray data, we have utilized the Open Universe for Blazars, which offers blazar X-ray light curves based on 14 years of Swift-XRT data [14]. The computation of the X-ray quiescent flux level has been carried out using the same methodology as the gamma-ray quiescent flux level (see section 2.1). The estimation of the muon neutrino flare flux, $E_{\nu_\mu} F^{\mathrm{fl}}_{\nu_\mu}$, is subsequently achieved as

$$E_{\nu_\mu} F^{\mathrm{fl}}_{\nu_\mu} = E_{\nu_\mu} F^{q}_{E_{\nu_\mu}} \left(\frac{F^{\mathrm{fl}}_\gamma}{F^{q}_\gamma} \right)^{\gamma} = A_X \frac{E_X F^{q}_{E_X}}{3} \left(\frac{F^{\mathrm{fl}}_\gamma}{F^{q}_\gamma} \right)^{\gamma}, \tag{5}$$

where $E_X F^{q}_{E_X}$ is the X-ray quiescent level and A_X is a normalization parameter. The neutrino flare fluxes for 129 blazars (97 FSRQs, 26 BL Lacs, 6 BCUs) are derived by utilizing equation (5), ignoring 16 sources of non-flaring state with the 6 σ threshold or the unavailable quiescent state with the Swift X-ray data. As seen in Figure 3, the muon neutrino flare fluxes from scenario 2 with $A_X = 1.0$ and $\gamma = 1.5$ are estimated with respect to the sinδ (δ: declination). The red dotted line represents the weekly IceCube 90 % sensitivity calculated with an E^{-2} neutrino spectrum taken from Vandenbroucke *et al.* (2019) [15]. Some blazars such as 3C 273, CTA 102, and 3C 454.3 surpass the IceCube 90 % sensitivity in the neutrino flare flux.

3.2 Contribution of Blazar Flares to the Isotropic Diffuse Neutrino Flux

We utilized flux stacking analyses of blazar flares to estimate the upper limits on the diffuse isotropic neutrino flux in this work. Our sample consists of 145 bright gamma-ray blazars in the 4LAC catalog. However, there are also fainter blazars in the same catalog, and there are likely numerous undetected blazars in the vast expanse of the universe.

In order to determine the upper limits on the all-sky neutrino flux, we divide the estimated neutrino fluxes from the flaring blazars in our sample by 4π and then apply two correction factors for completeness. The first factor involves obtaining the correction factor of all 4LAC blazars and the blazars of our sub-sample by calculating the fraction of the total gamma-ray energy fluxes in the 0.1 – 316 GeV range (raised to the power of γ) of 4LAC blazars to the sample blazars. To account for blazars that are either too far away or have too low gamma-ray luminosity to detect, a second correction factor of the whole blazars from 4LAC blazars is calculated using completeness correction factors with γ, as shown in Figure 1 of Yuan *et al.* (2020) [16]. However, since the

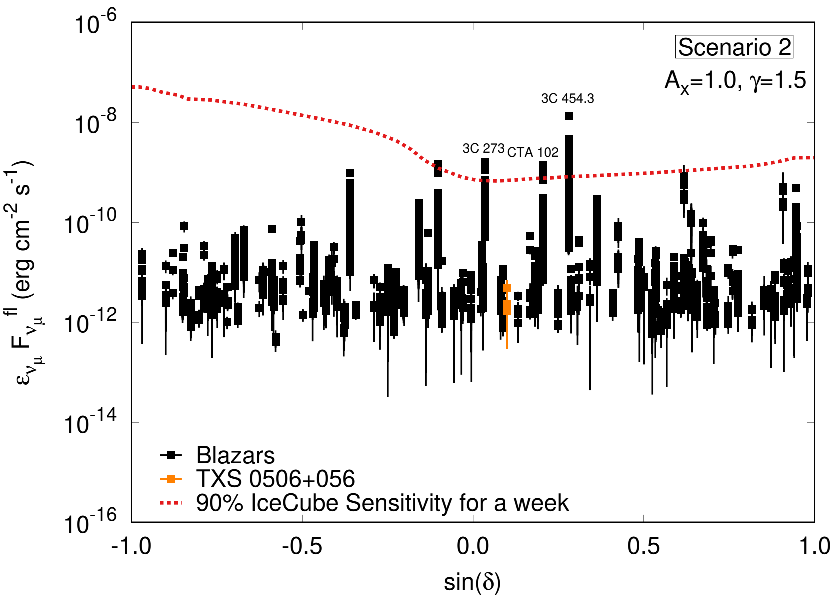

Figure 3: Estimated muon neutrino flare fluxes of scenario 2 with $A_X = 1.0$ and $\gamma = 1.5$ as a function of $\sin\delta$. The red dotted line shows the IceCube 90 % sensitivity.

analysis of Yuan *et al.* (2020) [16] is based on the 3LAC catalog, our results may be slightly conservative when applied to the 4LAC catalog. The correction factors of all the 4LAC FSRQs (BL Lacs) are 1.76 (4.24). 1.22 (2.21), and 1.06 (1.60) for γ of 1.0, 1,5 and 2.0, respectively. The correction factor of the whole population of blazars are 3.87, 1.09, and 1.01 for γ of 1.0, 1,5 and 2.0, respectively.

Figure 4 illustrates the estimated muon neutrino fluxes, obtained from our bright gamma-ray FSRQs and BL Lacs, adjusted by applying correction factors to account for the contribution of the 4LAC blazars and the unresolved blazars that emit gamma rays too faint to be included in the 4LAC catalog. The muon neutrino fluxes for scenarios 1 and 2 of both FSRQs and BL Lacs are plotted against the γ parameter. These fluxes are compared to a reference flux representing the isotropic diffuse muon neutrino flux [17]. Three upper limits derived by Hooper *et al.* (2019) [18] are also included in the comparison, with their values reduced to $1/3$ for muon neutrinos.

4. Summary

We analyzed 145 bright gamma-ray blazars within the 4LAC blazar set. Our findings indicate a significant distinction between blazar sub-classes for the flare duty cycles at a 5 % significant level. M. Ackermann *et al.* (2011) [19] utilized monthly-binned light curves from the 2FGL catalog to demonstrate that bright FSRQs and BL Lacs have flare duty cycles of around 0.05 – 0.10. Our flare duty cycles from the weekly-binned light curves display much wider distributions for both blazar sub-classes, which range from 0.0 to 0.6. As per Table 2 in Abdollahi *et al.* (2017)[20], the flare duty cycles in the FAVA analysis seem to be less suppressed than ∼0.2, while our flare duty cycles range up to ∼0.6. We have calculated the fluxes of muon neutrino flares by utilizing a scaling law

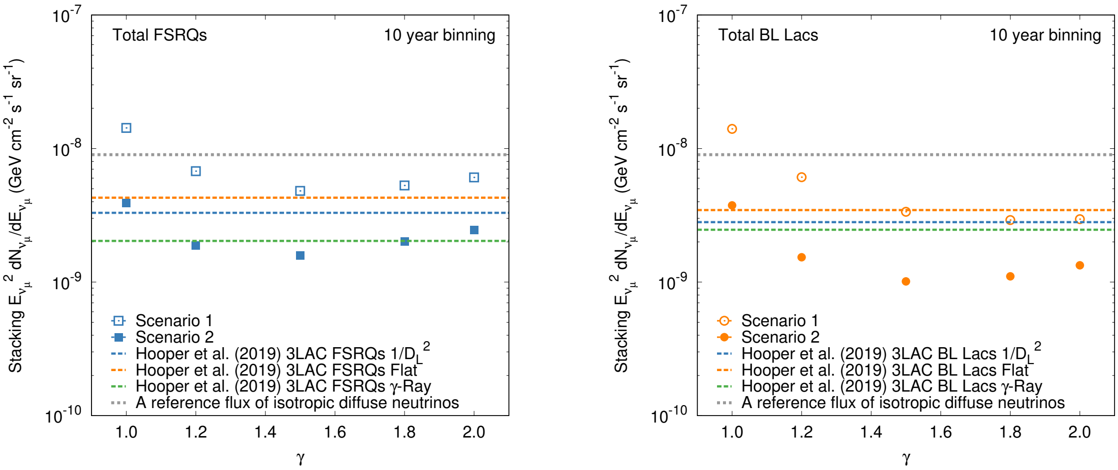

Figure 4: The total muon neutrino fluxes of gamma-ray flaring FSRQs and BL Lacs as a function of γ. The muon neutrino fluxes are estimated from the sample, multiplied by correction factors that account for the 4LAC blazars and the contribution of not-yet-detected blazars. The results of scenarios 1 and 2 are represented by open squares/circles and solid squares/circles, respectively, compared to a reference flux of all-sky muon neutrinos illustrated by a gray dashed line [17]. The figure also features three upper limits by Hooper *et al.* (2019) [18] for different assumptions about the source evolution ($1/D_L^2$, Flat, γ-Ray) reduced to $1/3$ for muon neutrinos.

of $L_\nu^{\rm fl} = L_\nu^q \left(L_\gamma^{\rm fl}/L_\gamma^q\right)^\gamma$. The benchmark of the quiescent neutrino flux was done with two proxies - the quiescent γ-ray flux and the quiescent X-ray flux, with the normalization parameters of A_γ and A_X, whose upper limits are 1.0. After comparing the estimated muon neutrino flare fluxes with the IceCube 90% sensitivities, we have restricted A_γ and A_X to values lower than or equal to 1.0. The inquiry into the source of all-sky neutrinos detected in IceCube is one of the most significant enigmas in high-energy neutrino astrophysics. Our discoveries indicate that scenarios 1 and 2 propose that the all-sky neutrino flux may only originate from gamma-ray flares of FSRQs and BL Lacs up to approximately 50 and 14 %, respectively. For further information on this study, please refer to Yoshida *et al.* (2023) [21].

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