STUDY OF OPTICAL AND GAMMA-RAY LONG-TERM VARIABILITY IN BLAZARS*

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Blazars, a subset of powerful active galactic nuclei, feature relativistic jets that shine in a broadband electromagnetic radiation, *e.g.* from radio to TeV emission. Here, I present the results of the studies that explore gamma-ray and optical variability properties of a sample of gamma-ray bright sources. Several methods of time-series analyses are performed on the decade-long optical and *Fermi*-LAT observations. The main results are as follows: The sources are found highly variable in both the bands, and the gamma-ray power spectral density is found to be consistent with the flicker noise suggesting long-memory processes at work. While comparing two emissions, not only the overall optical and the γ-ray emission are highly correlated but also both the observation distributions exhibit heavy-tailed log-normal distribution and linear RMS-flux relation. In addition, in some of the sources, indications of quasi-periodic oscillation were revealed with similar characteristic timescales in both the bands. We discuss the results in light of current blazar models with relativistic shocks propagating down the jet viewed close to the line of sight.

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1. Introduction

Active galactic nuclei (AGN) are one of the most luminous sources in the Universe. The sources are powered by the accretion onto the supermassive black holes at the center of the distant galaxies. The objects can be broadly classified into two main groups: radio-loud AGN and radio-quiet AGN. While a large fraction of AGN does not show prominent radio emission, about 10% of them output a significant amount of radio emission [1]. The emission can be linked to the presence of kpc/Mpc scale radio jets as seen in the VLBI images. The bipolar jets are often found to remain highly collimated over large distances and mostly contain plasma matter traveling at nearly the speed of the light. In a small sub-group of the radio-loud AGN,

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the jet is aligned to the line of sight at $\lesssim 6^\circ$ [2], such that the relativistic beaming effects dominate lending the sources some of their extreme observational properties such as high luminosity, TeV emission, and rapid variability.

The broadband emission from blazars can be characterized by a double-hump feature in the frequency-flux plane. It is widely accepted that the low-frequency feature of the spectrum, that lies between radio and X-ray, arises due to the synchrotron emission by the energetic charged particle moving in the jet magnetic field; whereas the high-frequency feature, that lies between UV and gamma-rays, probably results due to the inverse-Compton scattering of the low-energy photons by high-energy particles. In the synchrotron self-Compton (SSC) leptonic models, the same population of electrons up-scatters the co-spatial synchrotron photons. But in the external Compton (EC) models, the low-energy seed photon could be contributed by the accretion disk, dusty torus, and broad-line regions (BLR). Blazars can be further sub-classified into two groups: the more powerful flat spectrum radio quasars (FSRQ) that show emission line over the continuum emission and the less powerful BL Lacs showing weak or no presence of emission lines. The sample of TeV blazars is mostly dominated by BL Lacs.

Blazars display multi-timescales variability across a broad range of the electromagnetic spectrum (see *e.g.* [3–6]). The basic character of variability appears to be stochastic in nature such that the statistical properties of the variability can be fairly represented by power-law models in the frequency domain. In addition, the sources light curves also show occasional rapid flares and quasi-periodic oscillations [7].

As multi-wavelength (MWL) variability is defining properties of AGN, variability studies are an important tool to probe the energetics of the central engines of AGN. In these proceedings, I discuss the recent results of the studies focused on the time-series analysis of a sample of gamma-ray bright blazars. The decade-long gamma-ray observations from *Fermi*-LAT and the optical observations from four different observatories were analyzed and the results in the two bands were compared.

2. Observations and data

Gamma-ray variability of blazars was investigated using *Fermi*-LAT observations spanning nearly 10 years from 2008 to 2018 in the spectral range of 100 MeV to 300 GeV. The sample source along with their *Fermi*-LAT 4-year Source Catalog (3FGL) name, source classification, and red-shift are listed in Table 1. The data processing was performed using the standard procedure of likelihood analysis of the unbinned analysis and weekly binned source light curves were produced[1] (for details, see [8]).

[1] https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/likelihood_tutorial.html

That optical data for the sources marked in the bold fonts in Table 1 were gathered from four ground-based observatories: SMARTS[2], Steward observatory[3], Catalina[4], and AAVSO[5]. The data were compiled to create dense observations constructing 10 year-long optical light curves (for details, see [9]).

Table 1. Sample sources for study of gamma-ray and optical variability of blazars.

Source name	3FGL name	Source class	Red-shift
3C 66A	J0222.6+4301	BL Lac	0.444
AO 0235+164	J0238.6+1636	BL Lac	0.94
PKS 0454-234	3FGLJ0457.0-2324	BL Lac	1.003
S5 0716+714	J0721.9+7120	BL Lac	0.3
Mrk 421	3FGLJ1104.4+3812	BL Lac	0.03
TON 0599	J1159.5+2914	BL Lac	0.7247
ON +325	J1217.8+3007	BL Lac	0.131
W Comae	J1221.4+2814	BL Lac	0.102
4C +21.35	3FGLJ1224.9+2122	FSRQ	0.432
3C 273	J1229.1+0202	FSRQ	0.158
3C 279	J1256.1-0547	FSRQ	0.536
PKS 1424-418	3FGLJ1427.9-4206	FSRQ	1.522
PKS 1502+106	3FGLJ1504.4+1029	FSRQ	1.84
4C+38.41	J1635.2+3809	FSRQ	1.813
Mrk 501	J1653.9+3945	BL Lac	0.0334
1ES 1959+65	J2000.0+6509	BL Lac	0.048
PKS 2155-304	J2158.8-3013	BL Lac	0.116
BL Lac	J2202.7+4217	BL Lac	0.068
CTA 102	J2232.5+1143	FSRQ	1.037
3C 454.3	J2254.0+1608	FSRQ	0.859

[2] http://www.astro.yale.edu/smarts/glast/home.php
[3] http://james.as.arizona.edu/~psmith/Fermi/
[4] http://nesssi.cacr.caltech.edu/DataRelease/
[5] https://www.aavso.org/

3. Analysis and results

The decade-long optical and gamma-ray observations were analyzed using several methods of the time-series analysis. In particular, the observed variability was quantified by computing the fractional variability of the source light curves [10, 11]. The large fractional variability values are the indications that blazars exhibit remarkable variability on diverse time scales. Moreover, to compare the variability in the optical and the gamma-ray band, the results show that the variability amplitude is larger in the gamma-ray.

The power spectral density analysis of the gamma-ray light curves was performed by computing the discrete Fourier periodogram of the source light curves. The effects of unevenly sample, discrete observations, and finite observation lengths were corrected by the use of a large number of mock light curves that were simulated by the Monte Carlo method described in [12]. It is found that the power spectral density of the gamma-ray observations is consistent with the single power-law model with spectral index ~ 1, often known as a long-memory flicker noise. The result implies a strong disk–jet connection in the sense that the jet modulations are somehow coupled to the disk modulations. The optical PSD is however steeper, closer to the Brownian motion than that of the gamma-ray PSD slope index.

The flux distribution of the gamma-ray and optical flux of the blazar was explored by fitting the flux histograms with normal and log-normal probability distribution functions (PDF). The analysis revealed that flux distribution can be represented by log-normal PDF [8]. Similar results were obtained in a study of optical variability of blazars using decade-long optical observations [9]. In addition, the source light curves in both the bands were divided into several segments, and the relation between the mean and RMS of the segments was analyzed. It was found that the majority of the sample sources displayed a linear dependence between the RMS and the flux, a so-called linear RMS–flux relation.

In addition to the PSD and PDF, the light curves were studied to look for possible quasi-periodic oscillations (QPO) in the light curves. For this purpose, the gamma-ray observations were analyzed using the Lomb–Scargle periodogram [13, 14] and Z-transformed Weighted Wavelet methods [15]. The results showed that the light curves of the sources Mrk 501, Mrk 421, S5 0716+714, PKS 1424-418, ON+325, and PKS 2155-314 revealed year time-scale QPOs which were found to be significant over the red-noise inherent in blazar light curves [7, 8]. Moreover, in the sources Mrk 501, Mrk 421, S5 0716+714, and PKS 2155-314 the observed QPOs were found to have similar characteristic time-scales (see Table 4 in [9]).

Furthermore, a cross-correlation study between the optical and gamma-ray light curves was conducted using the Z-transformed discrete correlation function (ZDCF) [16], a method frequently used in the discretely sampled data sets with gaps. Moreover, the significance of the ZDCF peaks against any spurious correlation arising due to red-noise is computed. The results suggest that both optical and gamma-ray emissions from the sources highly correlate with each other within the time-scales of a few weeks (see Table 5 in [9]).

4. Discussion

A study of long-term variability properties of gamma-ray bright blazar was performed using the gamma-ray observations from the *Fermi*-LAT space telescopes and the optical observation. In the Standard Model of blazars, the observed variability can be mainly ascribed to the processes occurring at the accretion disk and jets of AGN. In the disk scenario, the magnetohydrodynamics instabilities arising from modulations in the accretion rates, viscosity parameter, and the magnetic field can lead to the observed variability. Similarly, in jets-related scenarios, some of the widely discussed models are based on particle acceleration due to shock waves and/or due to turbulence widespread in the jets, and the subsequent cooling of the particles via dissipative processes such as synchrotron and inverse-Compton emission [17–20]. In such scenarios, variable injection rates could also produce the optical variability [3]. Moreover, a strong correlation between the optical and the gamma-ray emission suggests existence of a co-spatial particle that contributes to both the emissions. In the case of magnetized jets, magnetic reconnection could be a dominant particle accelerating mechanism and several mini-jets could form within the main jets such that they could be a source of TeV emission [21]. The observed log-normal PDF of blazar flux could be an indication of such processes [22]. Power-law PSD of slopes of unity in particular describes the long-memory processes at work such that the flux changes in the accretion disk can propagate along the jets and somehow affect the variable processes along the jets. The fact that the source flux distribution is consistent with the log-normal PDF indicates the processes being multiplicatively coupled to result in the total observed variable emission, as opposed to a linear combination of additive processes such as shot noises [23]. Moreover, the linear dependence between the flux and the RMS, which are more relevant to the galactic X-ray binary systems, is often explained in terms of the propagation of viscosity modulations at the disk [24]. The fact that we observe the similar trend in the blazar sample sources, where the disk emission is completely swamped by the jet emission, indicates a strong coupling between the jet and disk.

The peaks in the periodogram that appear in both the bands on similar time-scales imply the plausibility of MWL QPOs with a common origin. Such QPO can arise either from the accretion disk and the jets. Some of the widely discussed blazar QPO models include binary supermassive black holes, the passage of the emission region along helical jets, Lense-Thirring precession, and periodic jet angle modulations (readers are directed to [4, 5, 7] for a detailed discussion on the topic)

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