Characterizing Long-term Optical Variability Properties of γ-Ray-bright Blazars

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Abstract
Optical observations of a sample of 12 γ-ray-bright blazars from four optical data archives—American Association of Variable Star Observers, Small and Moderate Aperture Research Telescope System, Catalina, and Steward Observatory—are compiled to create densely sampled light curves spanning more than a decade. As a part of the blazar multiwavelength studies, several methods of analysis, e.g., flux distribution and rms–flux relation, are performed on the observations with the aim to compare the results with the similar ones in the γ-ray band presented in Bhatta & Dhtial. It is found that, similar to the γ-ray band, blazars display significant variability in the optical band that can be characterized with lognormal flux distribution and a power-law dependence of rms on flux. It could be an indication of a possible inherent linear rms–flux relation, yet the scatter in the data does not allow to rule out other possibilities. When comparing variability properties in the two bands, the blazars in the γ-rays are found to exhibit stronger variability with a steeper possible linear rms–flux relation and a flux distribution that is more skewed toward higher fluxes. The cross-correlation study shows that except for source 3C 273, the overall optical and the γ-ray emission in the sources are highly correlated, suggesting a cospatial existence of the particles responsible for both the optical and γ-ray emission. Moreover, sources S5 0716+714, Mrk 421, Mrk 501, PKS 1424-418, and PKS 2155-304 revealed possible evidence of quasi-periodic oscillations in the optical emission with the characteristic timescales, which are comparable to those in the γ-ray band detected in our previous work.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16)

1. Introduction
A small class of active galactic nuclei (AGNs) that possess parsec-scale radio jets pointing toward the Earth are widely known as blazars. The sources represent one of the most luminous objects (L ∼ 10^{47} erg s^{-1}), which derive their power by accretion onto supermassive black holes at the center. The sources shine exclusively in the Doppler-boosted nonthermal emission that can be distinguished by its extreme properties e.g., high luminosity, strong polarization, and rapid flux variability. Blazars, which illuminate the γ-ray sky, could also be sources of cosmic neutrinos (see IceCube Collaboration et al. 2018a, 2018b). The spectral energy distribution of the broadband continuum emission from the sources is usually recognized by the two distinct hump-like energy distribution of the broadband continuum emission from the low-energy regime, whereas inverse Compton scattering of low-energy photons by the energetic particles could result in the higher energy feature. However, various models attempt to furnish the details of the origin of the latter component. Particularly, two widely discussed leptonic models are the synchrotron self-Compton (SSC) model and the external Compton (EC) model. According to SSC (e.g., Maraschi et al. 1992; Mastichiadis & Kirk 2002) the same population of electrons emitting synchrotron photons are responsible for upscattering the low-energy photons to produce high-energy emission; whereas in the EC models the softer seed photons can come from various regions that are external to the jets, e.g., accretion disk (AD; Dermer & Schlickeiser 1993), broad-line region (BLR; Sikora 1994), and dusty torus (DT; Blažejowski et al. 2000).

Blazars are mainly grouped into two flavors: flat-spectrum radio quasars (FSRQs), which are the more powerful sources, show emission lines over the continuum; whereas BL Lacertae (BL Lac) objects, the less powerful ones, show weak or no such lines. The peak of the synchrotron emission from FSRQs lies in the low-frequency regime, that is, radio to optical, and the peak of the IC component can extend up to the GeV regime. In FSRQs, we find evidence of abundant presence of seed photons from the AD, BLR, and DT (Ghisellini et al. 2011) such that EC processes can result in a copious amount of high-energy emission. Consequently, the continuum emission from FSRQs is mostly dominated by γ-rays. On the other hand, in BL Lac objects, in which the synchrotron peak lies in the UV or X-ray regions, the IC component can peak up to TeV energies making the objects an extreme class of sources. The apparent low luminosity of this class of sources could be linked to the absence of strong circumnuclear photon fields and relatively low accretion rates. We also find another classification scheme based on the location of the synchrotron peak frequency (ν_{\gamma}), according to which the sources can be classified as low-synchrotron-peaked blazars (ν_{\gamma} ≤ 10^{10.0} Hz), intermediate-synchrotron-peaked blazars (10^{14} < ν_{\gamma} ≤ 10^{15.3} Hz), and high-synchrotron-peaked blazars (ν_{\gamma} > 10^{15} Hz) (Fan et al. 2016; for previous similar classification see Abdou et al. 2010).

Blazar emission is found to be variable over a wide range of spectral and temporal frequencies, e.g., in the optical (Bhatta et al. 2013, 2016a; Bhatta & Webb 2018), X-rays (Bhatta et al. 2018b), and γ-rays (Bhatta & Dhtial 2020; see also recent works, e.g., Weaver et al. 2020). The studies of the multifrequency variability properties are utilized to explore the physical mechanisms occurring at the innermost regions of the source. The observed multiwavelength (MWL) variability can be linked to a number of processes occurring either in the accretion disk and/or in the jet; e.g., the accretion disk revolving around the supermassive black hole, various magnetohydrodynamic instabilities in the disk and the jets, shocks traveling down the turbulent jets, and relativistic effects due to jet orientation (e.g., Camenzind & Krockenberger 1992; Wagner & Witzel 1995; Bhatta et al. 2013; Marscher 2014, and references therein). However, the exact details of the models are widely discussed and debated. In such context, the study of
optical long-term variability of blazars in relation to the similar variability in the γ-rays, could be important to probe the jet dynamics, particle acceleration, and energy dissipation mechanisms producing γ-ray emission.

Apart from the generic multi-timescale aperiodic flux variability over a wide range of electromagnetic frequency bands, some of the blazars are known to display periodic or quasiperiodic oscillations (QPOs) in their flux (for a recent review on QPOs in blazars see Gupta 2018; Bhatta 2019a). In these cases, the multifrequency long-term light curves exhibit a characteristic timescale of a few years. In particular, in our previous work (Bhatta & Dhital 2020; henceforth BD20), a detailed study of γ-ray emission from blazars, we reported QPOs in the sources Mrk 421, Mrk 501, PKS 1424-418, Mrk 421 located at redshifts of 1.522 and 0.03, respectively. Similarly, the brightest source in the sample is 3C 273, which has a mean magnitude of 12.80, and the faintest source, PKS 1424-418, with a mean magnitude of 17.15, 0.31 magnitudes, was converted to the Cousins–Johnson system given in Table A2 of Bessell et al. (1998). Also, the flux was corrected for interstellar extinction in the V magnitudes for the sources, as listed in the NED.5 In addition, to perform a cross-correlation study between the optical and γ-ray bands (0.1–300 GeV), observations from the Fermi Large Area Telescope (LAT) telescope were utilized. The data acquisition and the processing of the γ-ray observations are discussed in detail in BD20.

The source brightness in the V magnitudes was converted into flux in Jansky units by using the zero points for the V band in the Cousins–Glass–Johnson system given in Table A2 of Bessell et al. (1998). Also, the flux was corrected for interstellar extinction in the V magnitudes for the sources, as listed in the NED.5 In addition, to perform a cross-correlation study between the optical and γ-ray bands (0.1–300 GeV), observations from the Fermi Large Area Telescope (LAT) telescope were utilized. The data acquisition and the processing of the γ-ray observations are discussed in detail in BD20.

The source names, R.A., decl., redshift, source classification, and mean magnitude with standard deviations are presented in columns 1, 2, 3, 4, 5, and 6, respectively, of Table 1. Of the 12 sources, the farthest and the nearest sources are PKS 1424-418 and Mrk 421 located at redshifts of 1.522 and 0.03, respectively. Similarly, the brightest source in the sample is 3C 273, which has a mean magnitude of 12.80, and the faintest source AO 0235+164, with a mean magnitude of 18.19 and standard deviation of 0.87 mag, is highly variable. The second faintest source, PKS 1424-418, with a mean magnitude of 17.15 is also the most variable source, as indicated by its standard deviation of magnitude of 1.01.

Table 1
The Source Sample of the γ-Ray-bright Blazars

| Source Name | R.A. (J2000) | Decl. (J2000) | Redshift | Source Class | Mean mag. ± stdv. | FV (%) |
|-------------|--------------|--------------|----------|--------------|------------------|-------|
| 3C 66A      | 02h22m41.6   | +43d02m35.5  | 0.444    | BL Lac       | 14.69 ± 0.38     | 37.83 ± 0.23 |
| AO 0235+164 | 02h38m38.9   | +16d36m59.0  | 0.94     | BL Lac       | 18.19 ± 0.87     | 115.00 ± 0.24 |
| S5 0716+714 | 07h21m53.4   | +71d20m36.6  | 0.3      | BL Lac       | 13.62 ± 0.59     | 53.74 ± 0.09 |
| Mrk 421     | 11h04m27.3   | +38d12m32.0  | 0.03     | FSRQ         | 12.80 ± 0.16     | 14.44 ± 0.28 |
| 3C 273      | 12h29m61.0   | +02d03m08.59 | 0.158    | FSRQ         | 15.73 ± 0.82     | 80.60 ± 0.10 |
| Mkr 501     | 16h53m52.2   | +39d45m56.09 | 0.0334   | BL Lac       | 13.90 ± 0.07     | 6.00 ± 1.46  |
| PKS 2155-304| 21h58m52.0   | −30d13m32.118| 0.116    | BL Lac       | 13.49 ± 0.45     | 46.01 ± 0.22 |
| BL Lac      | 22h02m43.3   | +42d16m40.0  | 0.068    | FSRQ         | 16.44 ± 0.51     | 46.22 ± 0.07 |
| CTA 102     | 22h53m36.4   | +11d43m51.2  | 1.037    | FSRQ         | 16.34 ± 1.02     | 353.27 ± 0.02 |
| 3C 454.3    | 22h53m57.7   | +16d08m54.2  | 0.859    | FSRQ         | 15.75 ± 0.63     | 78.16 ± 0.11 |

1 http://james.as.arizona.edu/~pmsmith/Fermi/
2 http://nesssi.cacr.caltech.edu/DataRelease/
3 https://www.aavso.org/data-download
4 http://www.astro.yale.edu/smarts/glast/home.php
5 https://ned.ipac.caltech.edu/
3. Analysis

With the aim to study the MWL statistical properties of blazar variability, various methods of variability analysis, e.g., fractional variability, rms–flux relation, and flux distribution, similar to those discussed in BD20, were performed on the optical light curves of the sample sources. In addition, the search for QPOs was carried out using Lomb–Scargle periodogram and comparing the possible QPO feature with the ones from the γ-ray observations of the similar duration. A detailed discussion on the methods and the corresponding results of the analyses are presented below.

3.1. Fractional Variability

The light curves constructed from the multi-instrument optical observation, as shown in Figure 1, clearly show the modulations in the source flux over the period. It is one of the primary goals of the study to constrain the possible mechanisms playing out in the prevailing physical conditions that result in such a dramatic variability. Fractional variability (FV), as presented in the form of Equation (1), provides a quantified measure of the average variability in the light curve. It is expressed as,

\[
F_{\text{var}} = \sqrt{\frac{S^2 - \langle \sigma^2_{\text{err}} \rangle}{\langle F \rangle^2}},
\]

and the uncertainty in the FV can be written as,

\[
\sigma_{F_{\text{var}}} = \sqrt{\frac{F^2_{\text{var}} + \frac{2}{N} \langle \sigma^2_{\text{err}} \rangle^2 + \frac{4}{N} \langle \sigma^2_{\text{err}} \rangle^2 F^2_{\text{var}}}{\langle F \rangle^2}} - F_{\text{var}},
\]

where \( F \) and \( S \) stand for the flux and the variance in the flux, respectively (Vaughan et al. 2003; see also Bhatta & Webb 2018). The FV of the light curves of the sample blazars along with the associated uncertainty are listed in the 7th column of Table 1, which shows that the source light curves display remarkable variability in the optical emission. The mean FV of the sources in the sample is 79% with a standard deviation of 87%—the mean FV of BL Lac objects is 47.82% with standard deviation of 33.47% and that of FSRQs is 124.54% with a standard deviation of 123.20%. Of the sample sources, the most variable source is FSRQ CTA 102 (z = 1.037) with \( F_{\text{var}} \sim 117\% \) and \( \sigma_{F_{\text{var}}} \sim 335\% \), whereas the least variable source turns out to be the BL Lac object Mrk 501 with \( F_{\text{var}} \sim 6\% \).

To compare the variability properties in the two bands, the linear correlation between the FV in the γ-ray and optical bands were estimated. It resulted in a strong correlation, as given by the Pearson linear correlation coefficient value of 0.68 with a p value of 0.01. Furthermore, comparing the FV values in Table 1 in this work with those in BD20, it is found that sources, in general, exhibit larger variability in the γ-ray band with an exception of a few sources, e.g., AO 0235+164, PKS 1424-418, and CTA 102. Also, it is interesting to note that the FV of the source PKS 2155-304 is \( \sim 46\% \) in both of the bands, which shows very similar variability in these bands.

3.2. Rms–Flux Relation

In order to further investigate the variability properties, the variability distribution over the source optical fluxes was studied by employing excess variances as an estimator of the intrinsic source variance and thereby exploring the correlation between excess variances and the mean flux for a particular time bin in a light curve. This kind of relation between these quantities is commonly known as rms–flux relation (see Vaughan et al. 2003). For this purpose, the light curves were divided into \( N \) segments of equal lengths, and to ensure a robust and meaningful statistical results, each segment included at least 20 observations. For a given segment of the light curve, the excess variance was obtained by subtracting the Poisson noise from the sample variance, that is, \( \sigma^2_{\text{ex}} = S^2 - \sigma^2_{\text{err}} \), where \( S^2 \) represents the sample variance, and the mean square of measurement error is given by \( \sigma^2_{\text{err}} = 1/\sum \sigma^2_{\text{err}} \) (see Nandra et al. 1997). The rms–flux plots for the sample blazar sources are shown in Figure 2. To characterize the trend on the rms–flux, the observation were fitted using a linear model both with and without an intercept, as shown by the magenta and blue lines, respectively, in the figure. The resulting slope and intercept parameters of the linear fits are presented in columns 2 and 5, and 3 of Table 2, and also the corresponding reduced \( \chi^2 \) statistics are listed in columns 4 and 6. The negative intercept in the rms axis, equivalently a positive intercept on the flux axis, can be interpreted as a component of constant flux in the linear rms–flux relation. On the other hand, a positive rms intercept implies the presence of an excess rms even when the rms–flux relationship is extrapolated to zero flux, which obviously is nonphysical. However, it is possible that in addition to the linear rms–flux relation, there could be another component that can dominate in the very low flux states (see Gleissner et al. 2004).

From Figure 2 and Table 2, it can be gathered that the source observations exhibit a general positive correlation between rms and the mean flux, possibly a linear rms–flux relation. However, as a standard practice in X-ray astronomy, in order to truly investigate the relation between the long-term mean flux and the short-term fluctuations, the segments of light curve are further divided into several subsegments so that the rms–flux relation is observed over many different frequency ranges (e.g., see Alston et al. 2019). This usually requires a larger number of observations, which may not be possible in the case of the optical observations obtained from ground-based telescopes, e.g., due to the local weather and seasonal conditions. Another important caveat is that generally, in radio-quiet AGNs, the frequency range being sampled has low intrinsic rms (typically \( \lesssim 15\% \) fractional rms), and the method is more suitable to such analysis. However, in the case of blazars, which are most variable in all frequencies (e.g., see column 7 of Table 1), there is a small chance that a spurious linear rms–flux relation may appear in the data (see Uttley et al. 2005, for more details). Nevertheless, the analysis presented here reveals a trend of rms–flux relation inherent in the optical light curves of the sample blazars.

By comparing the slope parameters of the possible linear rms–flux relation observed here and the corresponding results in BD20, it is found that for FSRQs the average slope of the rms–flux linear fit results in 0.58, whereas for BL Lac objects the average value is 0.30—i.e., FSRQs show a steeper slope in the rms–flux pane. The result implies that FSRQs, in general, exhibit relatively enhanced variability during elevated flux states. A similar result was reported in the γ-ray observations in BD20. By comparing the results in the optical and γ-rays, it is found that the slope of the linear fit to the rms–flux relation is steeper in the case of γ-ray analysis, except for the FSRQs PKS 1424-418 and 3C 454.3, as reported in BD20.
Figure 1. Long-term optical observations of a sample of γ-ray-bright blazars as obtained from four optical data archives (see Section 2). The observation from different data archives are presented in different colors, i.e., AAVSO, Catalina, SMARTS, and Steward Observatory in black, green, magenta, and blue, respectively.
3.3. Flux Distribution: Normal and Lognormal

As the flux of the variable sources undulate over time, it passes through various flux states, such as high and low flux states. Therefore, the flux distribution of blazars can offer important insight regarding the origin and nature of the variability. To carry out a statistical analysis of the optical
flux distribution, a lognormal and a normal probability density function (PDF) were fitted to the unbinned histogram of the sources fluxes. A lognormal PDF in its familiar form can be expressed as,

\[
\frac{1}{\sqrt{2\pi} s} \exp\left( -\frac{(\ln x - m)^2}{2s^2} \right)
\]

where \( m \) and \( s \) define the mean flux location and the scale parameters of the PDF, respectively. Similarly, a normal PDF can be written as,

\[
\exp\left( -\frac{(x - \mu)^2}{2\sigma^2} \right)
\]
where \( \mu \) and \( \sigma \) are the mean and the standard deviation of the PDF, respectively.

To implement the statistical analysis, the maximum likelihood estimation (MLE) method was applied on the source flux distribution using the PDF fitting software package \textit{fidistrplus}\(^\text{5}\) (Delignette-Muller & Dutang 2015) publicly available in the MASS library of R. The package attempts to fit the PDFs to the unbinned flux distribution following MLE method. The source histograms fitted with normal and lognormal PDFs are presented in Figure 3. The residuals corresponding to the model fit are shown in the lower panels of the plots. Similarly, the mean of the flux and scale for the lognormal fitting are listed in columns 2 and 3, respectively, of Table 3; and the corresponding fitting statistics, that is, the lognormal PDF, are listed in columns 4, 5, and 6, respectively. The corresponding quantities for the normal PDF are listed in columns 7, 8, 9, 10, and 11. It can be seen that the lognormal PDF fitting results in smaller AIC and BIC compared to the normal PDF.

### 3.4. Cross-correlation between the Optical and the \( \gamma \)-Ray Bands

A study of the correlation among emissions in different energy bands can shed light on the structure of the blazar emission regions, and the dominant radiation mechanisms participated by various distributions of particles. In this work, a cross-correlation study between the long-term optical light curves and the \( \gamma \)-ray light curve from the Fermi/LAT telescope is conducted using the method based on the discrete correlation function (DCF; Edelson & Krolik 1988). The method is particularly known to deal with unevenly spaced time series.

To follow the method, the unbinned DCFs are computed as

\[
\text{UDCF}_{ij} = \frac{(x_i - \bar{x})(y_j - \bar{y})}{\sqrt{(\sigma_x^2 - 
\bar{x}^2)(\sigma_y^2 - \bar{y}^2)}},
\]

where \( \bar{x} \) and \( \bar{y} \) represent the mean fluxes of the two light curves with their corresponding variances, \( \sigma^2 \), and uncertainties in the flux \( \epsilon^2 \). These discrete pairs are subsequently binned in equal-width time bins that are comparable to the sampling of the light curves. Then the average DCF of the bin containing the \( M \) pairs of UDCFs is given as

\[
\text{DCF}(\tau) = \frac{1}{M} \sum_{ij} \text{UDCF}_{ij}.
\]

However, as the sampling distributions of DCF are highly skewed, using sample variance as an estimator of the DCF uncertainty can be inaccurate. To address this issue, the DCFs representing the cross-correlation coefficients, \( r \), are \( z \)-transformed (ZDCFs) according to the following Fisher transformations

\[
z = \frac{1}{2} \ln \left( \frac{1 + r}{1 - r} \right), \quad \rho = \tanh z, \quad \zeta = \frac{1}{2} \ln \left( \frac{1 + \rho}{1 - \rho} \right),
\]

which now approximately follow a normal distribution, and therefore the variance of the distribution provides a more robust estimation of DCF uncertainties. Once the mean and the variance of the \( z \)-transformed distributions are computed, they are inverse-transformed to the original distribution (for details see Alexander 2013). Furthermore, in contrast to the original DCF method in which regularly spaced time bins are used, in ZDCF the unbinned DCFs are averaged from the bins that contain a fixed number of populations, at least 11 pairs of observations.

The cross-correlation between the \( \gamma \)-ray and \( V \) band optical observations of the sample sources was implemented by using publicly available software.\(^7\) The duration of the optical observations was chosen to be similar to that of the \( \gamma \)-ray observations, and the light curves were binned weekly to match the sampling of the weekly binned \( \gamma \)-ray observations, as

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5. https://cran.r-project.org/web/packages/fidistrplus/index.html

7. http://www.weizmann.ac.il/particle/tal/research-activities/software
Figure 3. Histogram of the optical flux of the sample blazars. The blue and the red curves represent the normal and lognormal PDF fits to the observations, respectively. The corresponding residual plots are shown in the lower panels.
presented in BD20. The diagrams for lag against the ZDCF value of the sample blazars are shown in Figure 4. The lag between the emissions was estimated by computing the centroid of the ZDCF peak, i.e., $\tau_c = \sum \tau_i ZDCF/\sum ZDCF$, where $\tau_i$ is calculated using the ZDCFs around the DCF peak that are greater than 0.8 times the ZDCF peak value.

For the normal fit, $\mu$ and $\sigma$ are presented in units of mJy, whereas for the lognormal fit, $m$ is in units of the natural log of flux. The lead/lag of the most significant ZDCF peak and its ZDCF value in a source are listed in columns 2 and 3, respectively. To estimate the significance of the observed peaks against possible peaks that might have originated owing to the underlying red-noise variability in the two emission bands, 1000 artificial light curves were generated using a single power-law model. In the optical and the $\gamma$-ray emission from the sample blazars are summarized in Table 4. The lead/lag of the most significant ZDCF peak and its ZDCF value in a source are listed in columns 2 and 3, respectively. To estimate the significance of the observed peaks against possible peaks that might have originated owing to the underlying red-noise variability in the two emission bands, 1000 artificial light curves were generated using a single power-law model (Timmer & Koenig 1995). The optical emission and $\gamma$-ray emission have different natures of variability, as indicated by the two different spectral indices listed in columns 5 and 6, respectively, of Table 4, and these spectral parameters were taken from Nilsson et al. (2018) and Bhatta & Dhital (2020), respectively. The distribution of ZDCFs between a random set of the simulated light curves and the real optical light curve were utilized to compute the 90% and 99% significance curves that are presented in magenta and red color, respectively, in Figure 4.

In order to estimate the uncertainty in the observed time lag, flux redistribution/random subset selection (FR/RSS), as described in Peterson et al. (1998, 2004) was followed. From 2000 MC simulations of FR/RSS realizations, a distribution of the centroid lags was created, and the 1$\sigma$ of the distribution was taken as a measure of the uncertainty in the time lag. As an illustration, the distribution of lag centroids for blazar S5 0716+714 is presented in Figure 5. In the figure, the vertical line shown in magenta color marks the location of the peak centroid corresponding to the observed time lag.

As the plots in Figure 4 and the corresponding Table 5 show, in most of the cases, the optical and $\gamma$-ray emissions seem to be largely correlated. Moreover, the light curves in both the optical and $\gamma$-rays are presented in the normalized flux units in the Appendix, which shows that in most of the instances the optical variability tracks the $\gamma$-ray variability very closely, or vice versa. The result is mostly consistent with the results of earlier works (see, e.g., Chatterjee et al. 2012; Cohen et al. 2014; Ramakrishnan et al. 2016; Liodakis et al. 2018). In the sources 3C 279, Mrk 421, CTA 102, Mrk 501, PKS 0454-234, PKS 1424-418, and PKS 2155-304, the most significant ZDCFs have lag within the error bars, or lead/lag less than the sampling time bin, i.e., 7 days, meaning no significant average lead/lag between the emissions can be claimed. The BL Lac objects 3C 66A and 3C 454.4 display positive lags of a few days. The most distinct significant lag, which is 66 days, is observed in source S5 0716+714. Although the correlation coefficient is $\sim$0.4, it shows higher significance (98.5%) against correlated noise. Also, it is noted that sources Mrk 421 and 3C 66A reveal a complex pattern of cross-correlation, in the sense that in addition to the prominent zero lag, the sources also reveal another significant peak around 300 days. Of all the sources, FSRQ PKS 1424-418 shows the highest value (0.86) of correlation coefficient with a large significance of 99.90%, followed by BL Lac object AO 0235+164 0.68 with a significance of 99.40% and FSRQ CTA 102 0.62 with 99.70% significance. Also, it is interesting to note that, of all the sample sources, blazar 3C 273 clearly shows no significant correlation between the optical and $\gamma$-ray emission within a few hundred days.

### 3.5. Quasiperiodic Oscillations

The power spectral density (PSD) analysis performed on long-term optical light curves of a large number of blazar sources suggests that the blazar periodograms can be largely represented by a single power-law PSD in the logarithmic frequency–power plane (Nilsson et al. 2018). A similar conclusion was presented during the PSD analysis of 20 blazar $\gamma$-ray light curves in BD20. Nonetheless, evidence of presence of QPOs can be derived from the periodogram, which peaks at some characteristic frequencies corresponding to timescales of a few years, although occasional low-frequency peaks can also arise owing to the red noise–like behavior of blazar variability. In the literature, several AGNs, both radio-loud and radio-quiet, are known to show QPOs in their light curves in different energy bands on a wide range of timescales (see Bhatta et al. 2016b; Gupta 2018; Bhatta 2019b, and reference therein). In probably the first case of MWL QPO, a characteristic timescale of $\sim$2 yr was reported in blazar PG 1153+113 using...
Fermi/LAT, X-ray, optical, and GHz radio observations (see Ackermann et al. 2015). In the optical, blazar OJ 287 is famous for its characteristic double-peak feature in its historical optical light curve that keeps repeating approximately after every $\sim 12$ yr (e.g., Sillanpää et al. 1988; Kidger et al. 1992; Valtonen et al. 2006). Search for QPOs in the optical emission of a

Figure 4. Z-transformed discrete cross-correlation between the long-term $\gamma$-ray and optical observations of the sample sources. A positive lag indicates variability features in optical emission lagging in time behind the similar features in the $\gamma$-ray emission of the sources. The magenta and red curves mark the 90% and 99% significant contours, respectively, estimated using Monte Carlo (MC) simulations. The most significant lag and the associated significance, estimated taking into account the correlated red noise, are presented in Table 5.
Table 4: Cross-correlation between γ-Ray and Optical Light Curves

| Source   | Lag (days) | ZDCF (3) | Significance (%) | αγ | αopt  |
|----------|------------|----------|------------------|----|--------|
| 3C 279   | −1.61 ± 7  | 0.43 ± 0.04 | 99.91 | 1.10 | 1.52  |
| Mrk 421  | −1.22 ± 6  | 0.55 ± 0.04 | 99.96 | 1.00 | 1.38  |
| S5 0716+714 | 66.75 ± 11 | 0.30 ± 0.05 | 99.92 | 1.00 | 1.18  |
| CTA 102  | 1.35 ± 5   | 0.62 ± 0.04 | 99.91 | 1.20 | 1.60  |
| BL Lac   | 23.42 ± 15 | 0.48 ± 0.04 | 99.96 | 1.00 | 1.27  |
| 3C 66A   | 25.15 ± 13 | 0.55 ± 0.04 | 99.97 | 0.90 | 1.40  |
| 3C 273   | −80.35 ± 19 | 0.23 ± 0.06 | 76.71 | 1.20 | 1.50  |
| Mrk 501  | 10.41 ± 8  | 0.42 ± 0.06 | 98.03 | 1.10 | 1.65  |
| AO 0235+164 | 35.66 ± 9  | 0.68 ± 0.04 | 94.42 | 1.40 | 1.55  |
| 3C 454.3 | 10.90 ± 5  | 0.49 ± 0.04 | 99.93 | 1.30 | 1.50  |
| PKS 1424-418 | −4.90 ± 10 | 0.86 ± 0.02 | 99.99 | 1.50 | 1.75  |
| PKS 2155-304 | 2.80 ± 7   | 0.62 ± 0.02 | 99.98 | 0.90 | 1.55  |

Note. Here positive lag implies variability features in optical emission lagging in time behind the similar features in γ-ray emission from the sources.

Table 5: List of the Blazars in the Sample that Show Significant QPO in the γ-Ray Light Curves

| Source   | γ-ray Period (days) | Optical Period (days) | αopt  |
|----------|---------------------|-----------------------|-------|
| S5 0716+714 | 1002 ± 0.71 | 1000 ± 0.50 | 1.18  |
| Mrk 421   | 981 ± 0.46   | 978 ± 0.52   | 1.38  |
| Mrk 501   | 332 ± 0.53   | 333 ± 0.24   | 1.65  |
| PKS 1424-418 | 353 ± 0.68   | 326 ± 0.14   | 1.75  |
| PKS 2155-304 | 610 ± 0.64   | 643 ± 0.38   | 1.55  |

Figure 5. Histogram of the lags corresponding to the centroids of the ZDCF peaks resulting from the optical—γ-ray emission correlation in blazar S5 0716+714, which allows us to estimate the uncertainty in the observed lag. The light-curve data were randomly resampled, and the ZDCFs were computed for 2000 realizations following the method presented in Peterson et al. (1998, 2004). The vertical line in magenta marks the lag corresponding to the centroid of the observed ZDCF peak.

Table 5. Moreover, to present a measure of the significance of the observed LSP features against the variability owing to inherent power-law noise, 10,000 MC simulated light curves were employed. The spectral power-law indexes required for the simulations were taken from Nilsson et al. (2018), which uses a similar length of optical light curves of the sources. The simulated light curves were resampled to match the sampling and gaps of the real observation. In addition, to account for the observed linear r.m.s.—flux relation with the slopes listed in Table 2, the simulated light curves were exponentiated (Uttley et al. 2005; Alston 2019). The 90% and 95% significance contours resulting from the distribution of the simulated LSP are presented in magenta and red curves, respectively. The possible QPOs present in each of the sources are discussed below.

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1. S5 0716+714: The QPO in the optical observations corresponding to the γ-ray QPO at 346 days, as reported in BD20 and marked in Figure 6(a), was not observed. However, a QPO with a period of ~1000 days with more than 99% significance is clearly visible with an appreciable overlapping in timescales in both the optical and γ-ray bands. Such overlapping provides strong evidence for the existence of real and physical QPOs, as opposed to...
mere artifacts owing to inherent red noise. A similar optical QPO of 1223 days in the 20 day binned $R$-band light curve spanning longer duration was detected previously Raiteri et al. (2003). In addition to these, another possible QPO around 100 days was found to be significant above 99%.

2. Mrk 421: An optical LSP peak around $\sim$978 days was detected very close to the 983 day $\gamma$-ray QPO reported...
in BD20. It is interesting to note that both peaks were found be to 90% significant against underlying power-law noise in the corresponding bands. LSPs in the γ-ray and optical bands are shown in black and blue color, respectively, in Figure 6(b). The more significant γ-ray QPO at 285 days in the source (see BD20), however, was not detected in the V-band light curves. Similarly, the 310 day optical QPO seen after removing flares in the optical observations, including AAVSO data, as reported by Benítez et al. (2015), and the QPO with a characteristic timescale of \( \sim 480 \) days in the rest frame, equivalent to observed \( \sim 490 \) days, reported by Nilsson et al. (2018), were not observed in the LSP analysis.

3. Mrk 501: In blazar Mrk 501, an optical LSP peak with 95% significance centered at 333 days was found to clearly coincide with the 332 day γ-ray QPO reported in Bhatta (2019b), as shown in Figure 6(c). The significant temporal coincidence further strengthens the evidence for the multifrequency nature of the observed QPO.

4. PKS 1424-418: A γ-ray QPO with a 353 day characteristic timescale was reported for the first time in BD20. The LSP analysis of the optical observations of the source also revealed a peak at 326 days, which is is coincident with the γ-ray QPO within the range of the associated uncertainty. However, the significance of the possible QPO turns out to be below 90% against the power-law noise of spectral index 1.75. The optical and γ-ray LSPs of blazar PKS 1424-418 are shown in Figure 6(d) in blue and black color, respectively.

5. PKS 2155-304: The LSP of the optical light curves implied the presence of a 643 day QPO in blazar PKS 2155-304, as shown in Figure 6(e). This QPO, 97% significant against red noise in the optical light curve, is closer within the error to the 610 day γ-ray periodic flux oscillations reported in Bhatta & Dhital (2020) and the 620 day QPO reported in Sandrinelli et al. (2018). The 317 day timescale reported by Zhang et al. (2014) in the R-band light curves spanning 35 yr, however, was not detected in the V-band light curve presented here. On the other hand, a 96% significant LSP peak around 259 days, which is very close to the 257 day γ-ray QPO reported in BD20, was observed.

4. Discussion

In this section, possible implications of the results obtained from the analysis of the decade-long optical observations of blazars and the comparison between the variability properties in the optical and γ-ray bands are discussed. The results are interpreted within the context of the standard model for blazars.

1. Optical variability in blazars:

The optical light curves of the blazar sources, as presented in Figure 1, exhibit brightness modulations of various degrees. To conduct variability analysis, the observed variability was quantified by employing FV, which serves as an estimator of the average flux modulations in the light curves over time. The numbers listed in column 7 of Table 1 suggest that blazar sources are distinctly characterized by their remarkable activity in the optical band. Furthermore, it is seen that, on average, FSRQs are more variable than BL Lac objects. This is consistent with the variability in the γ-ray band, as reported in BD20. The origin of the optical emission from blazars can be of both thermal and nonthermal nature. In particular, in FSRQs the signatures of thermal emission in the optical/UV related to the accretion disk and emission lines from the BLR can be observed. In the context of multicolored thin disk approximation, for a black hole with mass \( M_\text{BH} \), expressed in units of \( 1 \times 10^9 \) solar masses, accreting at a rate \( \dot{m} \), expressed in units of the Eddington accretion rate \( \dot{m}_\text{Edd} \), the temperature profile of the accretion disk as a function of distance from the central black hole can be written as

\[
T(r) \sim 1 \times 10^6 \left( \frac{\dot{m}}{\dot{m}_\text{Edd}} \right)^{1/4} \left( \frac{1}{M_\text{BH}} \right)^{1/4} \left( \frac{r}{r_\text{s}} \right)^{-3/4},
\]

(see Peterson 1997) where the gravitational radius is given by \( r_\text{s} = GM_\text{BH}/c^2 \). With the assumption of blackbody radiation, the temperature can be translated into the wavelength range of optical emission. For a typical blazar mass of \( 1 \times 10^9 M_\odot \), the region that emits V-band optical emission, with an effective wavelength of 0.545 μm, lies at a distance of \( \sim 1000 r_\text{s} \), a distance that falls within the inner region of the disk. In such a scenario, the observed long-term variability can originate from changes at the disk, e.g., perturbation in the viscosity, accretion rate, and turbulence, in the corresponding characteristic timescales (see Czerny 2006). However, in blazars the flux variability originating at the disk could easily be modified by the Doppler-boosted emission from jets in the course of their propagation along the jets. Nevertheless, it could be possible that the signatures of the modulations should propagate along the jet through disk–jet coupling mechanisms (see, e.g., Blandford & Payne 1982; Bhatta et al. 2018a).

In the scenario of nonthermal emission from the jets, shock waves propagating the jet can result in a power-law distribution of energetic particles, \( N(\gamma) \propto \gamma^{-p} \). These particles in the ambient magnetic field emit synchrotron emission (optical emission in the present case) with a power-law spectral profile. In the context of leptonic models, if we make a simple and crude approximation that each electron radiates all of its power at the single frequency given by \( \nu \approx \gamma^2 \nu_G \), where \( \nu_G = qB/2\pi m \) represents the gyration frequency of a particle with mass \( m \) and charge \( q \) moving in a magnetic field \( B \), and further assume a typical magnetic field of 1 G, the Lorentz factors of these synchrotron electrons responsible for the nonthermal optical emission can be estimated to be as high as \( \sim 10^4 \). In hadronic models, it is also possible for the protons to contribute to the synchrotron emission. However, in such a scenario, with protons being nearly 1836 times more massive than electrons, the Lorentz factor and/or ambient magnetic field must be proportionally larger. In the jet models, the observed optical variability could be driven by a combination of factors, e.g., modulations in the distribution of particles and ambient magnetic field at the emission region. Moreover, it is also possible that a part of the observed variability could also be merely projection effects, e.g., arising owing to twists and bends along the jets, such that changes in either the velocity and/or the project angle of the emission region can lead to an amplified flux modulation (see, e.g., Raiteri et al. 2017; Bhatta 2018).
In order to be able to utilize the light curves to extract information about the dynamical states of the central engine and thereby achieve a complete characterization of the variability phenomenon, one would require an approach invoking nonlinear differential equations in the framework of relativistic gravito-magneto-hydrodynamics, an extremely daunting task. In the absence of such a treatment, it is often convenient to model the observed variability in blazars as being driven by linear and nonlinear stochastic processes. Nonetheless, more recent studies reveal deterministic content in the light curves with an indication that the dynamical evolution at the center can be tracked in the long-term light curves (see Bhatta et al. 2020, and references therein).

2. Flux distribution and rms–flux relation:

In order to study the distribution of the fluxes from the modulating optical light curves of the sample blazars, normal and lognormal PDFs—two widely employed PDFs—were fitted to the unbinned flux histogram. The resulting AIC and BIC values suggest that the observed flux histogram of blazars could be the realization of the underlying lognormal processes yielding a heavy tail skewed toward higher fluxes. Recently, a lognormal PDF has been applied to characterize the blazar MWL flux distribution in a number of sources (see, e.g., Bhatta & Dhillon 2020; Shah et al. 2018, for γ-ray emission; Chakraborty 2020; Acciari et al. 2021, for Mrk 421 multifrequency). Similarly, the rms–flux relation is widely observed in astrophysical systems, especially ubiquitous among black hole X-ray binaries (see Heil et al. 2012, and references therein). A linear rms–flux relation as well as lognormal flux distribution have been reported in a number of blazar sources in several frequency bands, e.g., in X-rays (Giebels & Degrange 2009), the optical (Edelson et al. 2013), and γ-rays (Bhatta & Dhillon 2020; Kushwaha et al. 2017). Recently, Bhattacharyya et al. (2020) reported the presence of a linear rms–flux relation in the X-ray light curves of blazars Mrk 421, PKS 2155-304, and 3C 273; these sources are among the ones studied in BD20 and this work. The linear rms–flux relation suggests that the variability properties of AGNs are largely correlated during multiple flux states and thereby could be an indication of the underlying nonlinear processes driving the observed variability resulting in the flux distribution that is skewed toward higher flux, such as a lognormal PDF (see Uttley et al. 2005). Moreover, the observed lognormal distribution of the blazar flux might imply the presence of multiplicative processes in operation, e.g., multiplicative coupling of the perturbations occurring at either the disk and/or the jet, as opposed to additive coupling as in shot-noise-like perturbation (Lehto 1989; Arévalo & Uttley 2006). However, such observations could as well be the manifestation of linear processes (for a recent critical review on nonlinearity, the rms–flux relation, and lognormal flux distributions readers are directed to Scargle 2020). Similarly, the lognormal distribution of jet powers, resulting from the multiplicative process in the jets operating in long timescales, could explain the observed ultrahigh energy cosmic rays (see Matthews & Taylor 2021).

Furthermore, in accretion disk models, the lognormal flux distribution and the linear rms–flux relation could be associated to the uncorrelated fluctuations in the α-parameter, governed by viscosity fluctuations that take place at different radii and gradually propagate outwards modulating the mass accretion rates at larger scales (see Lyubarskii 1997). Such disk modulations can propagate through the jet via a strong disk–jet connection in radio-loud AGNs. In the case of blazars, the modulations subsequently are amplified owing to relativistic beaming effects, and thereby could be affected by projection effects. In the relativistic jets models, highly skewed flux distribution could be produced in the jets-in-jets scenario, in which the jets dominated by the Poynting flux can give rise to the condition for the production of isotropically distributed mini-jets (see Giannios et al. 2009). The distribution of the emission produced in such a case has been found to hold the rms–flux relation (see Biteau & Giebels 2012). In hadronic models, such a scenario can be efficient in obtaining a large bulk Lorentz factor required for the synchrotron emission from protons.

3. Optical γ-ray correlation:

Cross-correlation between the optical and the γ-ray emission from the sample blazar sources was studied applying the ZDCF. The method provides an estimator for the average correlation between the variable emission features in the two spectral bands. As we observe from Table 5 and Figure 4, although highly significant, the ZDCF values seem to be relatively moderate. This is most likely due to differences in the overall nature of the statistical variability properties in the two different bands, as characterized by the different PSD slope indexes. The observed strong long-term correlation between the variability features in the optical and the γ-ray emission finds a natural explanation within the framework of leptonic blazar models. In such models, both synchrotron and IC processes, that result in low-energy photons (optical emission in this case) and γ-ray emission, respectively, take place within the jet. As a result, a positive correlation between the low- and high-energy emission can be expected. Moreover, in the SSC flavor of the leptonic models, the same population of high-energy electrons participate in both the synchrotron and IC processes, resulting in even higher correlation. A positive optical lag (in the sense that variable features in the γ-ray light curves precede the ones in the optical), which was found to be pronounced in the case of blazar S5 0716 + 714, can be explained in terms of the opacity distance (e.g., Fuhrmann et al. 2014; Max-Moerbeck et al. 2014) and strongly stratified radiation field in the ambient magnetic field profile (e.g., B ∝ 1/r) such that the high-energy emission, e.g., γ-ray emission, is produced closer to the central engine (see Marscher 2016). The observed lag also suggests a cospatial nature of the particles emitting the radiation, in which case the spatial separation can be associated with the light travel distances.

In hadronic blazar models, γ-ray emission could arise due to proton–proton interactions and/or proton–photon interactions within and/or outside the jets. In such cases, neutral and charged pions are produced, of which neutral pions, being quite unstable, quickly decay to γ-rays. On the other hand, the charged pions decay producing secondary electrons/positrons, which can subsequently emit synchrotron in the ambient magnetic...
field. It is also possible that the observed $\gamma$-ray emission could be the direct result of proton synchrotron emission. Therefore, in the hadronic scenario, the correlation between the $\gamma$-rays and the lower-energy emission, e.g., optical emission, could be much more complex. Nonetheless, due to the lack of a complete understanding of the dominant jet particles and the emission processes they participate in, contribution of hadronic processes to the observed correlation between the optical and the $\gamma$-ray emission cannot be ruled out.

In the case of distinct flaring events, $\gamma$-rays lead over the optical emission and can be linked to the differences in the profiles of the magnetic energy density and the external radiation energy density during a Gaussian-type particle injection in the jet (see Hayashida et al. 2012). However, assuming the cooling of the particles through synchrotron and inverse Compton on an external radiation field, depending upon the profile of those parameters along the jet, both soft or hard lag can occur (see Janiak et al. 2012). In any case, study of the individual flares in multiple emission bands, especially orphan flares (see, e.g., Rajput et al. 2020), could provide further details necessary to identify the dominant process operating in blazar jets (see Liodakis et al. 2019).

It is interesting to note that while the rest of the sources in the sample exhibit a significant correlation between the two emission, blazar 3C 273 does not show such a correlation within the lag of a few hundred days. The apparent lack of correlation between the emission could be owing to the presence of the prominent big blue bump in the source (Shang et al. 2005). Also, the jet in the source has been found to contribute only a small fraction ($\sim$10% and $\sim$40% at the minimum and the maximum, respectively) to the total optical emission (see Li et al. 2020). This clearly results in a weak correlation between the optical emission, which is a mixture of the emission from the jet and the disk, and $\gamma$-ray emission that primarily originates in the jets.

4. Quasiperiodic oscillations:

In this work, search for QPOs in the optical light curves of the sample blazars was mainly focused on the possible QPOs in the sources for which high-significance QPOs in the decade-long Fermi/LAT observations were reported in BD20. Indeed, in some of the sources, e.g., S5 0616+714, Mkr 421, Mrk 501, PKS 2155-304, and PKS 1424, the optical LSP peaks at the timescale close to the $\gamma$-ray QPO timescales were observed, as shown in Figure 6(f). The significance of the possible QPO features against spurious detection due to the red-noise behavior of blazars was estimated employing a large number of simulated light curves with similar statistical properties, e.g., mean, standard deviation, observation length, and sampling rates. However, the significance levels presented here should be interpreted in the light of a few important caveats. The first, and possibly the most important, one is that the assumed single power-law model used in the simulation could be too simplistic, such that for the rigorous PSD estimation more complex models, e.g., model with a break frequency and autoregressive models, should be considered. Similarly, as the current source sample is derived from the $\gamma$-ray sample defined in BD20, there is no direct way to estimate the trial factor to account for the “look-elsewhere effect.” Consequently, this could lead to the overestimation of the confidence levels. Lastly, the simulations of the light curves do not directly consider the uncertainties in the PSD indexes reported in Nilsson et al. (2018). Nevertheless, it is emphasized that the optical and $\gamma$-ray light curves have different sampling rates, duration, and nature of their red noise, e.g., power-law spectral slope indexes in the $\gamma$-ray and optical band are $\sim$1.0 and $\sim$1.5, respectively. In such a context, if a peak in the LSP appears at the same temporal frequency in both bands, this would serve as a strong qualitative indication of the presence of QPOs at that temporal frequency, and therefore it is less likely to have arisen due to correlated noise.

QPOs in blazars can naturally arise in gravitationally bound supermassive binary black hole (SMBBH) systems, especially lying at the milliparsec separation, which is well within the gravitational wave–driven regime (Begelman et al. 1980; Liao et al. 2021). The observed timescales can be interpreted as the Keplerian periods of the secondary black hole around the central black hole. The periodic timescale in such a close SMBBH system can change due to emission of low-frequency (a few tens of nano–Hertz) gravitational waves (GWs); however, the changes in the periods cannot be detectable before a few thousands years (see Peters 1964). The observed QPOs might as well have originated at the innermost regions of the central engine where the effect of the gravitational field is strong. As a result, the rapidly spinning supermassive black hole can warp spacetime and give rise to the precession of the disk owing to the Lense–Thirring precession. In blazars, such disk precession can lead to jet precession, which in turn can appear as QPOs (e.g., Liska et al. 2018). Similarly, jet precession (Graham et al. 2015) and jet precession induced in SMBBH systems can also result in periodic optical outbursts (Caproni et al. 2017; Qian et al. 2018). Moreover, in the case of strong gravitational fields, relativistic orbit models can be employed to explain the QPOs (see Rana & Mangalam 2020).

In the accretion disk–based models, various hydrodynamic instabilities can lead to the formation of bright hotspots, which revolve around the central black hole with a Keplerian period comparable to the periods of observed QPOs. For a typical black hole of mass of $10^9 M_\odot$, the radius of the Keplerian orbit corresponding can be located at a few tens of gravitational radii ($r_g$). Similarly, hydrodynamical instability at the disk could be induced in a binary system (see Kelley et al. 2019). In such a scenario, if the orbital plane of the secondary companion forms an angle with the plane of the accretion disk, it can exert a torque resulting in the precession of the disk. This in turn can cause the disk to precess with a characteristic timescale (see Katz 1997; Romero et al. 2000). Also, thick accretion disks can be globally perturbed and consequently undergo p-mode oscillations with a fundamental frequency similar to the temporal frequencies associated with the QPO periods (see An et al. 2013, and reference therein).
QPOs also arise when an emission region follows a helical path along the magnetized jets (e.g., Camenzind & Krockenberger 1992; Rieger 2004; Mohan & Mangalam 2015). In the case of nonballistic motion with a typical inclination angle $i \sim 1/\Gamma_b$ and bulk Lorentz factor $\Gamma_b \sim 10$, the observed period $P$ can be significantly shortened by the relation $P \simeq \Gamma_b^2/(1 + z)P_{\text{obs}}$. In such a scenario, relativistic effects become dominant, and the periodic changes in the viewing angle translate into the periodic flux modulation.

The presence of similar timescale QPOs in more than one wave bands supports the argument for the MWL nature of these oscillations. Periodic modulations in the optical emission could well be dictated by the processes at the innermost regions of the accretion disk. However, the observed strong correlation in the optical and $\gamma$-ray emission, and the fact that the QPOs were observed at the similar characteristic temporal frequency in both bands, suggest that the processes generating optical QPOs should be cospatial to the regions where $\gamma$-ray emission is produced in blazars.

5. Conclusion

Decade-long observations from four AGN optical data archives AAVSO, SMARTS, Catalina, and Steward Observatory were gathered to construct densely sampled light curves of 12 $\gamma$-ray-bright blazars. The light curves were performed adopting several methods of time series analysis with the goal to study the long-term variability properties of the sample blazars. The results of the analysis were compared with those from the similar analysis in the $\gamma$-ray band performed on the same sources in our previous work (BD20). It was found that, similar to the $\gamma$-ray emission, the optical emission from the sample blazars was found to display pronounced flux modulation characterized by a linear rms–flux relation and lognormal PDF. Therefore, as in the case of $\gamma$-ray variability, the processes driving optical variability could be multiplicative nonlinear processes correlated over diverse timescales and flux states. When comparing the results of the similar analyses performed for the same source in $\gamma$-rays and the optical band, the observed variability properties in $\gamma$-rays were found to be more enhanced, in the sense that, compared to optical emission, $\gamma$-ray emission showed stronger variability, a steeper rms–flux relation, and larger PDF skewness. Furthermore, the results of cross-correlation between the variability features in the two bands resulted in a strong optical–$\gamma$-ray correlation. The observed strong correlation is naturally explained within the framework of leptonic blazar emission models including both SSC and EC. Additionally, to examine the multifrequency nature of the QPOs in the sources, including S5 0716–714, Mrk 421, Mrk 501, PKS 1424–418, and PKS 2155–304, the LSP features in the optical and $\gamma$-ray bands were compared. The analysis of these sources revealed hints of MWL QPOs of similar characteristic timescales.

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Appendix

In this section, contemporaneous optical and $\gamma$-ray light curves of 12 $\gamma$-ray-bright blazars are presented to complement the discrete cross-correlation analysis presented in Section 3.4. The $\gamma$-ray Fermi/LAT observations (0.1–300 GeV) were processed during the work of BD20. For better comparison, the source light curves in the two bands are normalized and presented in the same panel. As the figures show, we find that in general the source flux varies harmoniously in both bands.
Figure 7. Weekly binned optical (red) and $\gamma$-ray light curves from Fermi/LAT (black) of 12 $\gamma$-ray-bright blazars.
Figure 7. (Continued.)
