Radio and γ-Ray Variability in the BL Lac PKS 0219–164: Detection of Quasi-periodic Oscillations in the Radio Light Curve

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Abstract
In this work, we explore the long-term variability properties of the blazar PKS 0219–164 in the radio and the γ-ray regime, utilizing the OVRO 15 GHz and the Fermi/LAT observations from the period 2008–2017. We found that γ-ray emission is more variable than the radio emission implying that γ-ray emission possibly originated in more compact regions while the radio emission represented continuum emission from the large-scale jets. Also, in the γ-ray, the source exhibited spectral variability, characterized by the softer-when-brighter trend, a less frequently observed feature in the high-energy emission by BL Lac. In radio, using Lomb–Scargle periodogram and weighted wavelet z-transform, we detected a strong signal of quasi-periodic oscillation (QPO) with a periodicity of 270 ± 26 days with possible harmonics of 550 ± 42 and 1150 ± 157 day periods. At a time when detections of QPOs in blazars are still under debate, the observed QPO with high statistical significance (~97%–99% global significance over underlying red-noise processes) and persistent over nearly 10 oscillations could make one of the strongest cases for the detection of QPOs in blazar light curves. We discuss various blazar models that might lead to the γ-ray and radio variability, QPO, and the achronomeric behavior seen in the high-energy emission from the source.

Key words: accretion, accretion disks – galaxies: active – radiation mechanisms: non-thermal

1. Introduction
Active galactic nuclei (AGNs) are the brightest sources in the universe, widely accepted to be powered by accretion onto supermassive black holes. Based on their radio continuum, they can be broadly classified as radio-loud and radio-quiet objects: the sources with the ratio of nuclear radio emission at 5 GHz to the optical emission at (4400 Å) greater and less than 10, respectively (Kellermann et al. 1989). Most of the radio-loud AGNs display relativistic jets originating close to the central region and extending up to Mpc scales (Fanaroff & Riley 1974). Blazars are the subclass of radio-loud AGNs with their jets aligned close to the line of sight such that the relativistic effects become pronounced leading to the Doppler boosted emission that is highly variable over the entire electromagnetic spectrum (Urry & Padovani 1995). The broadband spectral energy distribution (SED) of blazars can often be recognized by the double-peak featured in the ν−νFν representation. The lower peak, usually found between the radio and the X-ray, is attributed to the synchrotron emission by the energetic particles —electrons in leptonic models, e.g., Maraschi et al. (1992) and Bloom & Marscher (1996), and protons in hadronic models, e.g., Mannheim & Biermann (1992), Aharonian (2000), and Mücke et al. (2003)—encircling the jet magnetic field; the other peak mostly lying between UV to γ-ray resulted due to the inverse-Compton scattering of the soft seed photons by the energetic particles accelerated by various mechanisms. In such a case, the seed photons might originate at the various components of an AGN, e.g., the accretion disk (Dermer & Schlickeiser 1993), the broad-line region (BLR; Sikora 1994), and the dusty torus (Bläzquezowski et al. 2000). Some of the widely discussed particle acceleration scenarios producing highly energetic particles include impulsive electron injections near the base of a jet (e.g., Dermer et al. 1997), internal shocks propagating along the jets (e.g., Marscher & Gear 1985; Kirk et al. 1998; Sokolov et al. 2004), stochastic particle acceleration in the shear boundary layer of the relativistic jets (see Ostrowski & Bednarz 2002) and particle acceleration due to the turbulence in the relativistic jets (see Marscher 2014, and the references therein).

Blazars further consist of two kinds of sources: flat-spectrum radio quasars (FSRQ) and BL Lac (BL Lac) objects. FSRQs are more powerful, show emission lines over the continuum, and have the synchrotron peak in the lower part of the spectrum; whereas BL Lac objects are less powerful, show weak or no emission lines, and have synchrotron peak in the higher part of the spectrum. BL Lacs represent an extreme class of sources with maximum synchrotron and inverse-Compton energies (hard X-rays to TeV emission); however, in comparison to the more luminous FSRQs, they accrete at relatively low rates, and do not possess strong circumnuclear photon fields.

Blazar continuum emission is characterized by broadband emission, which is variable, both flux and polarization, on diverse timescales. The variability timescales can be broadly classified as long-term, short-term, and intraday/night variability. Long-term variability, typically in the timescale of a few years, might arise due to variable accretion rates; short-term variability, which are usually identified with flaring episodes lasting a few weeks to a few months, could be the result of the passage of the shock waves propagating down the blazar jets; and the intraday variability might result due to the turbulence in the innermost region of the jets (e.g., Marscher & Travis 1996; Hughes et al. 1998; Lister & Homan 2005; Cawthorne 2006).

In general, the variability shown by AGNs appears to be predominantly aperiodic in nature. However, in recent times, reports of QPOs in the multi-frequency light curves of AGNs have begun to accumulate. Generally, signatures of (quasi-)periodic oscillations can be revealed as the large peaks in the periodograms of the source light curves. QPOs have been
claimed to have been found in various frequencies, on diverse characteristic timescales, and in various classes of AGNs; some of them are listed below.

1. QPOs in the radio light curves of AGNs were reported to show periodicities in the timescales of a few years, (e.g., Raiteri et al. 2001; Liu et al. 2006; Hovatta et al. 2008; Xie et al. 2008; An et al. 2013; Wang et al. 2014).

2. QPOs were detected in the optical light curves of blazars with periodicities in the timescales of a few years (e.g., Bhatta et al. 2016b; Sandrinelli et al. 2016).

3. QPOs in X-ray light curves of AGNs were reported with periodicities in the timescales a few hours (e.g., Gierliński et al. 2008; Lachowicz et al. 2009).

4. QPOs were found in the γ-ray light curves of blazars with periodicities in the timescales a few years (e.g., Sandrinelli et al. 2014; Ackermann et al. 2015; Zhang et al. 2017).

5. QPOs were reported in the light curves of radio-quiet quasars (e.g., King et al. 2013; Graham et al. 2015a, 2015b; Zheng et al. 2016).

6. QPO was detected in a high-redshift (z = 2) radio-loud quasar (Liu et al. 2015).

From above, it is clear that QPOs do not seem to prefer any particular system or timescale; rather they could be found in a wide range of AGN classes.

PKS 0219−164 (R.A. = 02h22m00s, decl. = −16°15′17″, and z = 0.7) is a BL Lac reported to have been observed over a broad range of the electromagnetic spectrum: e.g., optical (Ballard et al. 1990), infrared (Impey & Neugebauer 1988), infrared, and optical polarization (Mead et al. 1990) and radio 5 GHz observations (Kharb & Shastri 2004). Condon et al. (1977) first estimated the accurate position of the source at radio frequency (2700 MHz) along with the position of its optical counterpart, and later the source was classified as a quasi-stellar object by Hewitt & Burbidge (1993). In their observations, Meisenheimer & Roesser (1984) found the optical emission to be strongly polarized, up to as high as ~19%, and highly variable. Similarly, the flux was also displaying a dramatic variability, changing its brightness by ~3 mag within a period of a week. An upper limit of 0.23% circular polarization was estimated during a 5 GHz survey of the parsec-scale polarization properties of 40 AGNs made with the Very Long Baseline Array (Homan et al. 2001). An upper limit of the TeV range flux, 1.8 × 10^{-12} photons cm^{-2} s^{-1}, was measured by High-energy-gamma-ray Astronomy Cherenkov telescopes (Aharonian et al. 2004). In the cross-correlation of the Fermi 11-month survey (1FGL) catalog with the 20 GHz Australia Telescope Compact Array (AT20G) radio survey catalog, the radio and γ-core of the source, separated by 4.09 arcmin, were found to be highly correlated with a probability of 0.95 (Ghirlanda et al. 2010). Also included in a very sensitive 21 cm survey (Lockman et al. 2002), the source is being monitored regularly by the 15 GHz 40 m telescope at the Owens Valley Radio Observatory (OVRO; Richards et al. 2011). The source is listed as “3FGL J0222.1−1616” in the Fermi/LAT 3rd catalog (Ackermann et al. 2015).

In this paper, we present our analysis and results of the radio and γ-ray variability study of the BL Lac source PKS 0219−164 using the observations from OVRO and Fermi/LAT spanning ~9 years (Section 2). In particular, we analyzed the long-term OVRO light curve using the Lomb-Scargle periodogram (LSP) and the weighted wavelet z-transform (WWZ) methods. We report the detection of statistically significant quasi-periodic oscillations in the flux with a characteristic timescale of 270 ± 26 days along with possible low-frequency harmonics at the periods of 550 ± 42 and 1150 ± 157 days. Using Monte Carlo (MC) simulations, the global significance of the detection over underlying red-noise processes was found to be 97.5%–99.6%. In addition, we observed an interesting spectral behavior in the Fermi/LAT observations, which displayed a softer-when-brighter trend (Section 3). Finally, we present our discussion and conclusions in Section 4.

2. Observations and Data Reduction

2.1. Radio Observations

The 15 GHz radio observations of the source PKS 0219−164 were obtained from the AGN monitoring program at the Owens Valley Radio Observatory using the 40 m telescope. The radio light curve from the observation epoch 54633–57700 MJD is presented in Figure 1.

2.2. Fermi/LAT Observations

The Large Area Telescope (LAT) of the Fermi Gamma-ray Space Telescope (Fermi/LAT) is an all-sky monitoring instrument operating between the 20 MeV and 300 GeV energy range (Atwood et al. 2009). With its large effective area (>8000 cm^{-2}), wide field of view (>2 sr), and high-energy resolution (<3.5% around 100 MeV and <0.15 above 10 GeV), the telescope is one of the most useful instruments in the study of the universe in high energy. Fermi/LAT observations of the source PKS 0219−164 (or 3FGL J0222.1−1616) were processed using the Fermi Science Tools along with the Fermi/LAT catalog, Galactic diffuse emission model, and isotropic model for point sources; and the standard procedures of the unbinned likelihood analysis were followed. The observations from the period 2008 August 04–2017 January 23 (equivalently 54682–57776 MJD) were considered for the analysis. First, selections of the events were made, using the Fermi tool gselect, selecting only the events in a circular region of interest (ROI) of 10° radius centered around the source, and then limiting the zenith angle <90° to minimize the contamination of γ-rays from the Earth limb. Subsequently, the tool gmktime was used to select the good time intervals to ensure that the satellite was operating in the standard science mode resulting in the good quality of the observations. After making an exposure map using gtexpmap and gtlf cube, a source model file containing model parameters and the source positions for all the sources within the ROI was created using the Python application make3FGLxml.py. Then the diffuse source response was calculated using the Galactic and extragalactic models of the diffuse γ-ray emission such as gll iem v06.fit and iso_P8R2 SOURCE V6 v06.txt. Finally, a likelihood ratio test (Mattox et al. 1996) was performed (using gtlike) to estimate the significance of the γ-ray events from the source. With the set of the parameters given in the input source models, the task attempts to maximize the probability density of the data (given the current model) by fitting all the sources within the ROI. The maximum probability density of the data under two different models is then compared in the

https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/
likelihood ratio test statistic given by \( TS = -2(\log L_1 - \log L_0) \), where \( L_1 \) and \( L_0 \) represent the likelihood of the optimized parameters given the data, under the null and alternative model, respectively. Then the significance of a source detection is expressed by \( \sim \sqrt{TS} \sigma \) (Abdo et al. 2010).

We first analyzed the entire data to estimate the average flux and spectrum using a power-law model for the input source model. The resulting TS value and average photon index were 296.8 and \( 2.59 \pm 0.06 \), respectively, and the average photon flux was found to be \( 1.5819 \pm 0.08 \times 1.5453 \pm 0.09 \text{ photons cm}^{-2} \text{s}^{-1} \). These values are in close agreement with the values from the 3FGL catalog. The likelihood analysis resulted in the count distribution for all the sources in the ROI which, along with the total model (blue dashed curve) and the source model (orange dashed curve), is shown by the red symbols in Figure 2.

We then generated light curves using three different kinds of time bins, i.e., 10, 15, and 30 day bins. But the 10 day bin resulted in the maximum number (although only 31 for the total observation period) of observations with TS value > 10. Although, for a robust conclusion, only the observations with TS value > 10 are considered; for a tentative trend, the observations with \( 4 < TS < 10 \) will also be considered in the following analyses.

3. Analysis and Results

3.1. Radio and \( \gamma \)-Ray Variability

Figure 1 shows the long-term Fermi/LAT and OVRO light curves of the blazar PKS 0219−164. The red symbols in the \( \gamma \)-ray light curve represent the Fermi/LAT detections with TS > 10, and therefore the results from the analysis of such
observations will be considered more robust. However, as there is a considerably lower number of observations with TS > 10, the observations with 4 < TS < 10 are also presented. From the figure, it can be seen that both radio and γ-ray emission display considerable variability during the observation period. As a quantitative measurement of the variability, fractional variability (Vaughan et al. 2003; Aleksić et al. 2015) for the radio and the γ-ray light curves are estimated to be 0.14 ± 0.01 0.51 ± 0.05, respectively. The observed more rapid variability and the higher fractional variability in γ-ray emission suggests that the source is more variable in γ-ray than in the radio emission. The observation is consistent with the fact that the SEDs of BL Lacs peak in the higher part of the spectrum (e.g., in the X-ray and TeV range).

3.2. Spectral Variability: Softer-when-brighter Trend

Study of the correlation between simultaneous variability in flux and spectrum offers an important insight into the blazar physics, in particular, the particle acceleration and the energy dissipation mechanisms. In this context, we find some observational properties that characterize the correlation between the flux and the spectral slope of AGNs. In the optical, the anti-correlation between them has been observed in the form of the bluer-when-brighter trend in some BL Lacs (see Raiteri et al. 2001; Villata et al. 2002, 2004; Wu et al. 2007; Sasada et al. 2008; Ikejiri et al. 2011; Wierzbowska et al. 2015); whereas, in some FSRQs, a correlation between the flux and the spectral index has been reported in the form of the redder-when-brighter trend (e.g., Villata et al. 2006; Raiteri et al. 2008; Bonning et al. 2012). Similarly, in the hard X-ray, harder-when-brighter was observed in Tev blazars (Pandey et al. 2017).

To explore a similar correlation in the source, γ-ray photon indexes were plotted against the corresponding simultaneous fluxes as shown in Figure 3. A large value of Spearman’s correlation coefficient (≈0.90) implies a strong correlation between the spectral index and the source intensity suggesting a presence of the softer-when-brighter trend. In the figure, the trend is also traced by the less significant observations (with 4 < TS < 10) as shown by the cyan symbols. In γ-ray, we find more reports of harder-when-brighter cases (Brown &

Figure 3. Fermi/LAT photon indexes are plotted against the simultaneous fluxes of the source PKS 0219–164. The red symbols represent the observations with test statistics (TS) > 10 and the cyan ones with 4 < TS < 10.

3.3. Periodicity Search: LSP and WWZ

The search for the presence of QPOs in the OVRO light curve was conducted using LSP (Lomb 1976; Scargle 1982) and WWZ, which are frequently used methods in the astronomical time series analysis. The LSP method, although a form of the traditional discrete Fourier transform (DFT), has the advantages over DFT that it reduces the effect of irregular sampling by the least-square fitting of the sinusoidal waves to the data. Consequently, such fitting increases the significance of the observed power spectral features (or peaks), which can potentially represent QPO signals present in the light curves. The LSP powers of the OVRO light curve of the source for the observation period considered are presented in Figure 4. The figure shows three distinct peaks around the periods 270 ± 26, 550 ± 42, and 1150 ± 157 days. The uncertainties in the period are represented by the half-width at the half-maximum (HWHM) of the peaks.

Although the LSP method is suitable for the periodicity analysis of the light curves with irregular sampling, the method tries to fit the waves throughout the entire data set. In other words, it does not consider the fact that in the real astronomical systems the periodic oscillations may evolve over time; i.e., frequency and amplitude of the oscillations may change over time. In such situations, the wavelet transform method becomes a more suitable tool to investigate the presence of the QPOs, which develop and decay with time. The method, like the LSP, also attempts to fit sinusoidal waves to the data; however, the waves can be localized in both time and frequency domains to account for the transient nature of QPOs (Torrence & Compo 1998; Bravo et al. 2014). The method has been widely used in the time series analysis of blazar light curves (e.g., Hovatta et al. 2008; Bhatta et al. 2013; Mohan & Mangalam 2015; Bhatta et al. 2016b). To look for the possible QPOs in the radio
light curve of the blazar PKS 0219−164, we employed WWZ, a method described in Foster (1996). Using the WWZ software, we estimated the WWZ power of the light curve as a function of time and period. The color-scaled WWZ powers of the source light curve in the time-period plane are presented in Figure 5, which reveals large WWZ power centered around the periods of 270, 550, and 1150 days, implying the presence of the possible QPOs with the corresponding periods. The QPO with the period of 270 days appears to gradually develop from the start of the observation epoch and grows stronger toward the end of the observations; the QPO corresponding to the period of 550 days, most likely the first harmonics gradually decays before the end of observations. On the other hand, the signal corresponding to the period of 1150 days seems to be persistent throughout the observational period. The right panel of Figure 5 shows the time-averaged WWZ power at a given period. Once again, in the panel, we can see three distinct peaks centered at the periods of 270 ± 21, 550 ± 52, and 1150 ± 182 days. As in the LSP, HWHMs about the central peaks provide a measure of the uncertainties in the observed periods.

3.4. Significance Estimation: MC Simulations

Due to the noisy nature of the periodogram, large spurious peaks can be mistaken as the periodic signals. Therefore, it is important that we carefully analyze the effect of the uneven sampling on the noisy behavior of the periodogram. In addition, blazar variability, in general, exhibits red-noise-like behavior such that the periodograms can be well represented by a power spectral density (PSD) of the form $P(\nu) \propto \nu^{-\beta}$; where $\nu$ and $\beta$ represent temporal frequency and spectral slope (see Max-Moerbeck et al. 2014). This means that the light curves showing such power-law-like PSD oscillate with large amplitudes on longer timescales, and hence there is always a chance that these oscillations can also be mistaken as QPO features (see Press 1978; Vaughan et al. 2016). Therefore, for a rigorous estimation of the significance of the QPO features revealed by the LSP and WWZ methods, both of these issues should be taken into consideration. In this work, these issues are addressed by studying the periodograms and WWZ powers of a large number of simulated light curves that have the same sampling as that of the source light curve. For this purpose, the Monte Carlo (MC) simulations of the light curves were performed by randomizing the amplitude as well as the phase of the Fourier components (for details, see Timmer & Koenig 1995).

Now, to estimate the power spectral shape of the underlying colored noise in the light curve of the source, we followed the power response method (PSRESP; Uttley et al. 2002)—one of the widely used methods to characterize AGN PSD (e.g., Chatterjee et al. 2008; Edelson et al. 2014; Bhatta et al. 2016a, 2016b). To evaluate the best-fit PSD model, the method calculates the probability that the source periodogram best represents a given model PSD. Various model PSDs with varying parameters (e.g., spectral slope in our case) are fitted to the binned source periodogram to obtain the highest probability. The resulting best-fit model PSD is then used to simulate the light curves for further analysis. Using the best-fit PSD model, 10,000 light curves were simulated and subsequently resampled according to the sampling of the source light curve. The spectral distribution of the simulated light curves was analyzed to evaluate the local significance of the QPO features seen in the observed LSP. In particular, the local 99.5% significance (99.5 percentile) contour, shown by the red
curve in Figure 4, were determined (for further details, see Bhatta et al. 2016a, 2016b). As seen from the figure, the local significance of the observed QPO feature at the period of 270 days turns out to be greater than 99.5%.

The above method of estimating the significance of an LSP peak provides local estimates as it represents the significance only at a particular period. Since we do not have a priori knowledge of where the significant peak might occur, a more robust measure of the significance can be global significance which is associated with the fraction of the simulated LSP powers at any period below the observed power at the period of our interest (see Bell et al. 2011). We evaluated the global significance of the LSP peak at the period 270 to be 99.6%. These large values of both local and global significances indicate that the spectral peak at 270 days represents a real and physical periodic signal as opposed to the oscillations due to the underlying red-noise processes. However, for the spectral features at the periods of 550 and 1110 days, the significances look much smaller.

We took a similar approach to evaluate the significance of the observed WWZ features at 270 day, 550 day, and 1110 day periods. We first simulated 10,000 light curves from the best-fitting PSD model and resampled them according to the source light curve. Subsequently, wavelet analysis was performed to calculate time-averaged WWZ power for a given period. In particular, the time $(\tau)$ averaged WWZ power of the source was compared against the 99% local significance and 97% global significance contours derived from the distribution of the time-averaged WWZ power of the simulated light curves. In the right panel of Figure 5, the 99% local significance and 97% global significance contours are shown by the red curve and the magenta line, respectively. As before, with the estimated global significance of 97.5%, the 270 day QPO feature turns out to be highly significant. However, as in LSP, the significances for the possible harmonics at 550 day and 1110 day periods are observed to be much lower.

## 4. Discussion and Conclusion

### 4.1. Radio and $\gamma$-Ray Variability

Multi-frequency variability in blazars over various time-scales could be the result of a combination of modulations in the emission originating at various geometric components, including accretion disk, jets, dusty torus, BLR etc. In particular, the origin of long-term radio variability in blazars could primarily be associated with the synchrotron emission from the large-scale jets. In blazars, the large-scale radio jets are clearly resolved in the radio images; some of the radio knots appear to be moving with superluminal motion with apparent velocity up to $\sim 37c$ (Jorstad et al. 2001). This indicates that the variability in the radio continuum most likely arises due to the modulations in the radio emission from the jets.

As for the origin of the $\gamma$-ray emission, there appears to be an uncertainty about its exact location relative to the central engine. Given the high-energy activity and rapid variability in the timescales of a few minutes (e.g., Ackermann et al. 2016 for 3C 279 and Aharonian et al. 2007 for PKS 2155−304), $\gamma$-ray emission could originate at compact regions close to the central black hole. However, in such a scenario, the bulk Doppler factor has to be very large (typically $\delta > 60$) to limit the $\gamma\gamma$ opacity in the rest frame below the threshold value above which the pair production takes over depleting $\gamma$-ray photons drastically. On the other hand, the emission could also originate near the millimeter-wave core, a few kiloparsecs from the central region (in case of blazar OJ 287, see Agudo et al. 2011). But there seems to be an apparent lack of intense photon field required for the inverse-Compton process to boost the soft photons up to the $\gamma$-ray regime (for further discussion, see Dermer 2015).

The modulation in the flux of blazars could arise due to the propagation of the relativistic shocks along the blazar jets viewed at small angles (e.g., Marscher & Gear 1985; Spada et al. 2001; Joshi & Böttcher 2011). In addition, the non-thermal emission variability can arise due to various instabilities in the jet, e.g., turbulence behind the shocks (e.g., Bhatta et al. 2013; Marscher 2014). Similarly, sometimes the disk-based hotspots or instabilities (e.g., Chakrabarti & Wiita 1993; Urry & Padovani 1995; Wagner & Wittel 1995) can propagate into the jet to modulate the physical parameters of the jet such as its velocity, density, and magnetic field, which in turn can also result in flux variability (e.g., Wiita 2006).

Alternatively, such variations can be of extrinsic origin, e.g., geometrical effects involving swing in the emission region about the line of sight. For instance, even a slight change in viewing angle and/or bulk Lorentz factor leading to variation in the Doppler factor can produce large variations in observed Doppler boosted flux by the relations $F_i = \delta^{3+\alpha}F_o$, and $\delta = 1/\Gamma (1 - \beta \cos \theta)$, where the bulk Lorentz factor, velocity, spectral index, and the viewing angle are represented by $\Gamma$, $\beta$, $\alpha$, and $\theta$, respectively; and the primed quantities in the relation represent the quantities in the co-moving frame (Blandford & Rees 1978; Gopal-Krishna et al. 2003). To illustrate the argument, a slight swing ($\theta = 0.6^\circ$) in the viewing angle made by an emission region of moderate $\Gamma = 10$ with a spectral index of 1.6 (spectral index for PKS 0219−164 equivalent to the Fermi/LAT photon index of 2.6) can produce a change of $\sim 50\%$ in flux, which is the order of the variability we see in the source in the $\gamma$-ray band (for a detailed discussion, refer to Ghisellini et al. 1997).

### 4.2. Achromatic Behavior

Any correlation between flux and spectral variability in a source implies a close connection between the observed flux enhancement and renewed particle injection in situ (e.g., Kirk et al. 1998; Mastichiadis & Kirk 2002). However, in blazars, the nature of the correlation between the flux and the spectral index is somewhat uncertain so far. In the optical band, generally, BL Lacs have been found to exhibit bluer-when-brighter tendencies, whereas FSRQs often show redder-when-brighter trends. However, several sources have been reported to exhibit both kinds of spectral behaviors depending on their flux state (for a recent study, see Acosta-Pulido et al. 2017). In the $\gamma$-ray regime, blazars were also found to behave in a similar fashion i.e., in some cases, the spectrum hardens with the source intensity and in other cases the spectrum softens with the flux enhancements. In addition, some sources show both correlation and anti-correlation between the spectral index and the flux state (see Nandikotkur et al. 2007). In the particle acceleration scenario, where the distribution of the injected particle is of the single-power-law form, such multi-frequency achromatic behavior is difficult to explain considering only purely geometrical or beaming effects of the emission regions. But, on the other hand, the correlation between spectral index and flux (i.e., softer-when-brighter similar to redder-when...
brighter in optical) observed in the source PKS 0219–164 could be explained assuming an underlying steady electron energy spectrum of a curved (particularly convex) shape. In such cases, if the dominant population of energetic particles participating in the inverse-Compton process are near the lower energy of the spectrum, the resulting $\gamma$-emission can exhibit a softer-when-brighter trend. Alternatively, local enhancements of the magnetic field in the jets could lead to synchrotron emission with an excess of hard photons, which could be further up-scattered by lower energy electrons to the $\gamma$-ray regime where they exhibit the softer-when-brighter trend. However, for a robust and clear picture of the achronomic behavior to emerge out, further systematic study involving simultaneous multi-wavelength observations of blazar will be required.

4.3. Quasi-periodic Variability

The study of quasi-periodic oscillations sheds light on various aspects of AGN research such as the strong gravity environment and the disk–jet connection. In principle, (quasi-) periodic oscillations in AGNs can originate in various scenarios. The simplest among them is the emission region moving in the Keplerian orbits around the central black hole. Other possible cases might include periodicity of a binary black hole system (e.g., Lehto & Valtonen 1996; Graham et al. 2015a), jet precession due to a nearby massive object or warped accretion disks (Graham et al. 2015b; Sandrinelli et al. 2016). Similarly, jet modulation by various instabilities evolving near the innermost regions of accretion disks also could result in quasi-periodic modulation of the observed jet emission (see Liu et al. 2006; Wang et al. 2014). In addition, globally perturbed torus or a thick disk of finite radial extent could also give rise to QPOs (e.g., Rezzolla et al. 2003; Panottti et al. 2003).

In the particular case of the blazar PKS 0219–164, the detected QPO with a periodicity of ~270 days—along with the accompanying ~510 day and ~1150 day harmonics—could be explained in the context of highly magnetized jets and rotating magnetic field as suggested by Meisenheimer & Roers (1984). In such a case, relativistic motion of the emission regions along the helical path of the magnetized jets could make a more plausible explanation (e.g., Camenzind & Krockenberger 1992; Mohan & Mangalam 2015). Similarly, in the magnetic flux paradigm for the jet launching in AGNs (see Sikora & Begelman 2013), the magnetic flux accumulation can lead to the formation of so-called magnetically choked accretion flow. In that case, the Rayleigh–Taylor and Kelvin–Helmholtz instabilities can cause QPO oscillations at the interface of the disk and the magnetosphere due to a sudden change in the density and the magnetic flux (Li & Narayan 2004; Fu & Lai 2012). The periodicities for these QPOs could range from a few days to a few months depending upon the black hole spin parameter. Furthermore, QPOs are also found to develop in recent magneto-hydrodynamical simulations of the large-scale jets (McKinney et al. 2012) considering magnetically arrested disks perturbing the jets. We also note that the QPOs observed in the source appear to be accompanied by lower frequency harmonics, similar to the low-frequency “C-type” QPOs found in Galactic X-ray binaries. These QPOs are frequently interpreted in the context of the Lense–Thirring precession of the accretion disks (see Stella & Vietri 1998; Motta et al. 2011). However, in our case, the harmonics show lower significance over the red-noise processes. Besides, as there are not many studies focused particularly on this source, there are no robust estimates of its mass and the jet angle. Hence, it is difficult to attribute the observed QPO conclusively to a singular scenario.

In the case of the detected QPO in the blazar PKS 0219–164, the ratio of the total observation period to the observed primary period is (3053 days/270 days), more than 10. This implies that there are nearly 10 cycles of the quasi-periodic oscillations present in the source light curve. In addition, the significance estimated taking account of the fact the oscillations might be due to red-noise processes rather than the true periodicity is fairly large—global 99.6% significance from the LSP and 97.5% significance from the WWZ. The observed difference in the significances could be accounted for by the fact that the WWZ method considers the transient nature of the QPO, whereas the LSP method expects periodic oscillations to persist throughout the entire observation period. Moreover, during the course of the significance estimation in the WWZ method, the comparison is made between the source and the simulated variability powers, which are averaged over the time; hence we lose some information. Therefore, it might present one of the strongest cases of the detection of QPOs in blazars. Finally, the analyses of the $\gamma$-ray observations were motivated to perform similar QPO analyses in the high energy, and thereby to further investigate the location and nature of the QPO in the blazar. However, due to the smaller number of observations with TS > 10, this could not be achieved.

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References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJS, 188, 405
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14
Ackermann, M., Anantua, R., Asano, K., et al. 2016, ApJL, 824, L20
Acosta-Pulido, J., Castro Segura, N., Carnerero, M., & Raiteri, C. 2017, Galax, 5, 1
Agudo, I., Jorstad, S. G., Marscher, A. P., et al. 2011, ApJL, 726, L13
Aharonian, F., Akhperjanian, A., Beilicke, M., et al. 2004, A&A, 421, 529
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2007, ApJL, 664, L71
Aharonian, F. A. 2000, NewA, 5, 377
Aleksic, J., Ansoldi, S., Antonelli, L. A., et al. 2015, A&A, 576, A126
An, T., Baan, W. A., Wang, J.-Y., Wang, Y., & Hong, X.-Y. 2013, MNRAS, 434, 3487
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Ballard, K. R., Mead, A. R. G., Brand, P. W. J. L., & Hough, J. H. 1990, MNRAS, 243, 640
Bell, M. E., Tzioumis, T., Uttley, P., et al. 2011, MNRAS, 411, 402
Bhatta, G., Stawarz, L., Ostrowski, M., et al. 2016a, ApJ, 831, 92
Bhatta, G., Webb, J. R., Hollingsworth, H., et al. 2013, A&A, 558, 92
