The Detection of Possible Transient Quasiperiodic Oscillations in the $\gamma$-Ray Light Curve of PKS 0244-470 and 4C +38.41

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Abstract

The continuous monitoring capability of Fermi-LAT has enabled the exploration of quasiperiodic oscillations (QPOs) in the $\gamma$-ray light curve of blazars that has given a new perspective to probe these sources over a wide range of timescales. We report the presence of transient QPOs in the long-term $\gamma$-ray light curve of blazars PKS 0244-470 and 4C +38.41. We first identified different flux states using the Bayesian block algorithm and then explored the possible transient QPOs in the segments of each flux phase where the flux level changes over fairly regular intervals. Combining this with the source’s intrinsic variance, we identified two flux phases for PKS 0244-470: one activity (AP-1) and one quiescent phase (QP-1). For 4C +38.41, we similarly identified four activity (AP-1, AP-2, AP-3, and AP-4) and two quiescent (QP-1 and QP-2) phases. The AP-1 phase of PKS 0244-470 shows QPO of $\sim$225 days persisting for eight cycles ($\sim$4.1$\sigma$). In 4C +38.41, AP-1 and AP-2 phases show QPO-like behavior of $\sim$110 days and $\sim$60 days, respectively, persisting for five cycles. In AP-3, we identified three subphases, and all show a $\sim$7 day scale possible recurrent rise with five complete cycles, while in QP-1, we could identify two subphases (Q1 and Q2). The Q1 phase shows a period of $\sim$104 days with six complete cycles. The Q2 phase also shows QPO but with only $\sim$3.7 cycles. We discuss the possible origin and argue that the current-driven kink instability and curved jet model seem to be the most likely causes for shorter and longer QPOs.

Unified Astronomy Thesaurus concepts: Active galaxies (17); Gamma-rays (637); Blazars (164)

1. Introduction

Blazars, a subclass of active galactic nuclei (AGNs), are among the most luminous and rapidly variable extragalactic sources in the universe and have been observed in the entire accessible electromagnetic (EM) region (from radio to $\gamma$-ray/very high-energy $\gamma$-ray). The entire emission is primarily from the relativistic jet and exhibits a characteristic broad, double-humped spectral energy distribution (Fossati et al. 1998) with one peak in between near-infrared and X-ray energies (low-energy hump) and the other at MeV–GeV energies (high-energy hump). The low-energy hump is widely accepted as the synchrotron emission from relativistic electrons within the jet, while the high-energy hump origin is still debated and argued to be either due to emission from relativistic leptons and/or hadrons. In the leptonic case, it is due to inverse Compton scattering, while in the hadronic scenario, plausible mechanisms are proton synchrotron and/or cascade initiated as a result of interaction with photons or particles. Traditionally, depending on the strength of optical emission lines, blazars have been categorized into two subclasses: BL Lacertae (BL Lac) objects and flat spectrum radio quasars (FSRQs).

Blazar flux variation is primarily stochastic—random and erratic (e.g., Sobolewska et al. 2014), with statistical behavior similar to the other accretion-powered sources over the long term (e.g., Kushwaha et al. 2016, 2017; Shah et al. 2018). However, several light curves of blazars ($\gamma$-ray and other EM bands) show either transient or persistent (relative) quasiperiodic behavior. Since 2008, the detection or reporting of such QPOs in blazars and in other subclasses of AGNs has been increased—mainly due to much better data sampling as a result of coordinated MW follow-ups under the Fermi AGN Monitoring Program. Many strong QPOs have been reported across the complete EM bands in many sources on different timescales ranging from minutes to hours to days and to years (e.g., Gierliński et al. 2008; Gupta et al. 2009; Lachowicz et al. 2009; King et al. 2013; Alston et al. 2014; Gupta et al. 2014; Ackermann et al. 2015; Alston et al. 2015; Pan et al. 2016; Gupta et al. 2018; Gupta 2018; Zhou et al. 2018; Gupta et al. 2019; Agarwal et al. 2021; Tripathi et al. 2021 and references therein).

The entire blazar emission, especially $\gamma$-rays, are produced in the highly collimated relativistic jet, and as stated, the variability is primarily stochastic in nature (Abdo et al. 2010a; Sobolewska et al. 2014). So, the QPOs reported in $\gamma$-rays are very interesting, indicating processes/mechanisms driving systematic changes than the usual flux variability and thus are crucial in understanding not only jet physics but in indirectly providing clues about acceleration mechanisms as well. The first QPO in a $\gamma$-ray was reported in blazar PG 1553 + 113 by Ackermann et al. (2015), which was later confirmed by Tavani et al. (2018). The QPO period was reported as 2.18 yr, and three cycles were observed. Since then many QPOs in $\gamma$-rays have been reported in other blazars, such as PKS 2155-304 by Sandrinelli et al. (2014), where they detected a QPO of 1.73 yr, which was later confirmed by Zhang et al. (2017a). The $\gamma$-ray QPOs of 3.35 yr and 2.1 yr were reported in blazar PKS 0426-380 and PKS 0301-243, respectively, in long-period light curves (Zhang et al. 2017b, 2017c). A systematic search for $\gamma$-ray QPOs on the Third Fermi Large Area Telescope Source Catalog source was done by Zhang et al. (2020), and they detected a new source PKS 0601-70 with a
possible QPO of 450 days. Apart from the strong detection of QPOs in many blazars, the study done by Covino et al. (2018) claims that the previously reported QPOs at different levels in many blazars using the X-ray light curve is basically not significant, and the red noise highly dominates the power spectral density. The QPOs in the X-ray light curve are also checked for a few BL Lac sources by Sandrinelli et al. (2018), and they argue that if a supermassive binary black hole system is the origin of QPOs in these sources, then there will be tension with the upper limits on the gravitational wave background measured by the future pulsar timing array. Recently, many more QPOs were reported in X-rays in bright AGNs (e.g., Ren et al. 2023 and references therein) and particularly in blazars (e.g., Sarkar et al. 2020, 2021; Gong et al. 2022, and references therein).

PKS 0244-47 is an FSRQ-type blazar with coordinates R.A. = 02°1h46′.1m00′.00, decl. = −46°1′.5m18′.4 (J2000) located at redshift z = 1.385 (Abdo et al. 2010b). It is identified as flaring X-ray blazar in 2010 (Escande & Gasparrini 2010) and was very active until 2013 (see the X-ray light curve on the Fermi repository). Since 2013, the source is in a very low state, and few studies have been done. This is the first time we are presenting a QPO study on this source.

The blazar 4C +38.41 (α2000.0 = 16h 35m 15.4929s, δ2000.0 = +38°08′.04′.5) is also an FSRQ, located at redshift z = 1.814 (Hewett & Wild 2010; Pâris et al. 2018). Ciprini (2009) first reported high state activity of this source with X-ray flux (Fermi-LAT, Large Area Telescope) of (1.38 ± 0.32) × 10^{−6} photons cm^{−2} s^{−1}. It is also observed in different wave bands, from radio to hard X-rays, with the different ground- and space-based telescopes. E.g., Effelsberg 100 m radio telescope, Guillermo Haro Observatory, and Swift X-ray telescope/ultraviolet optical telescope (Raiteri & Villalla 2011; Myserlis et al. 2012; Ghisellini et al. 2015). The blazar 4C +38.41 has been studied on a longer timescale considering the decade-long X-ray data in Bhatta & Dhillon (2020), but they did not observe any QPOs in this source. Recently, Ren et al. (2023) studied 35 brightest sources and explored the QPO nature in the long-term X-ray light curves (~12 yr). They also did not notice any QPOs in 4C +38.41 in light curves extracted using 7 days and 30 days binning of data.

Here, we present the variability study of the X-ray light curves of two blazars (PKS 0244-470 and 4C+38.41) and the detection of transient QPOs on various timescales. In Section 2, we discuss the X-ray light-curve analysis procedure, and in Section 3, we discuss the methods used for QPO detection. In Section 4, we present the method to measure the significance of the detected QPOs, followed by results and discussion on plausible physical scenarios for transients QPOs in Section 5 and Section 6, respectively.

2. Fermi-LAT Data Analysis

Fermi-LAT is a pair conversion and wide-field-of-view (FOV), spaced-based X-ray telescope, working in an energy range between 20 MeV to > 300 GeV (Atwood et al. 2009). Detailed characteristics of the LAT are given in the Fermi webpage. It has an orbital period of ~96 minutes and it alternately observes the northern and southern skies, thereby covering the entire sky in approximately 3 hr.

We have analyzed the ~13 yr (December 2008—December 2021) LAT data of two sources: PKS 0244-470 and 4C+38.41 (catalog name—4FGL J0245.9-4650 and 4FGL J1635.2+3808; Abdollahi et al. 2020; Ballet et al. 2020) between 100 MeV and 300 GeV using the Fermi science tool software package FermiTool (version: 1.0.10). The standard selection criteria were chosen with evtype=3 and the evclass=128 to incorporate all types of photon-like events such as front, back, and front+back. The light curve is extracted using a region of interest (ROI) of 10° around the source and a zenith angle cut of 90°. The latter is chosen to reduce the contamination from the Earth's limbs. We have used the PASS8 data set reprocessed with the instrument response function P8R3_SOURCE_V6. The source of interest is modeled using the likelihood analysis implemented in the Fermi (pyLikelihood) and a model.xml file created from the fourth Fermi source catalog (4FGL). The file also has sources beyond 10° ROI, but their parameters have been frozen to the catalog value during the analysis. The power-law spectral model has been used for these two sources in the analysis. To account for the X-ray background, we have used the latest background models provided by the Fermi team, i.e., iso_P8R3_SOURCE_V6_v06 for isotropic background and gll_iem_v07 to account for the galactic diffuse emission.

The strength of the X-ray signal associated with the source position is characterized by the maximum likelihood analysis and by measuring the test statistics, TS = 2Δlog(L), where L is the likelihood function for the models with and without a point source at the position of the source of interest. Further, to produce the light curve, we have fixed the parameters of all other sources within the ROI except our source of interest and generated the light curve for different bin sizes. We have also checked the outcome by freeing the spectral parameters of other variable sources within the ROI and found that it has no effect on the outcome. In further analysis, we have used only data points with high detection significance (TS > 9). Figure 1 shows the ~13 yr long X-ray photon flux history of the sources. All the reported X-ray fluxes reported here are in units of 10^{−6} ph cm^{−2} s^{−1}.

3. QPO Detection Methods

3.1. Lomb–Scargle Periodogram

The Lomb–Scargle periodogram (LSP) is one of the most well-known methods to search for periodicity in the unevenly spaced light curve. This method fits the sinusoidal wave to the time series data, a form of the least square method. The power of LSP is given by VanderPlas (2018):

\[
P = \frac{1}{2} \left[ \frac{\sum_{i=1}^{N} x_i \sin \Omega (t_i - \tau)^2}{\sum_{i=1}^{N} \sin^2 \Omega (t_i - \tau)} + \frac{\sum_{i=1}^{N} x_i \cos \Omega (t_i - \tau)^2}{\sum_{i=1}^{N} \cos^2 \Omega (t_i - \tau)} \right].
\]

Here \( \tau \) is

\[
\tau = \tan^{-1} \left( \frac{\sum_{i=1}^{N} \sin \Omega (t_i - \tau)}{2 \Omega \sum_{i=1}^{N} \cos \Omega (t_i - \tau)} \right).
\]

References:

5 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/source.html?source_name=4FGL_J0245.9-4650
6 https://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/1633_382.html
7 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/LAT_overview.html
8 https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
9 https://fermipy.readthedocs.io/en/latest/install.html
and $\Omega$ is the angular frequency ($\Omega = 2\pi f$).

In our work, we have chosen minimum ($f_{\text{min}}$) and maximum ($f_{\text{max}}$) values of the temporal frequency as $1/T$ and $1/(2\Delta T)$, respectively. $T$ is the total observation period for different sources. $\Delta T$ is the time duration used for extraction of one data point (e.g., 1, 2, and 10 days). We take the total frequency interval as $N = n_0 f_{\text{max}}$, where $n_0 = 5$.

It is noted that several works have also used the generalized LSP (GLSP)\footnote{https://pyastronomy.readthedocs.io/en/latest/pyTimingDoc/pyPeriodDoc/gls.html} for periodicity search, which takes into account the effect of measurement errors in the analysis. We have also analyzed the light curves with the GLSP method and found similar periods as the LSP method.

### 3.2. Weighted Wavelet Z-transform

Weighted wavelet Z-transform (WWZ) is the most robust method to search for transient periodicity in unevenly spaced time series data, which is relevant for most astronomical observations. This method decomposes the data into time and frequency domains (known as the “WWZ Map”). With this procedure, we can detect periodicities in irregularly spaced light curves in a more sophisticated way than the well-known discrete wavelet transform (DFT). DFT can give nontrivial statistical behavior even with regularly spaced data. For an extended discussion on this and the WWZ technique, we refer to Foster (1996a).

The WWZ method is based on the weighted projection of the data vector onto the subspace, spanned by three trial functions,\footnote{https://pyastronomy.readthedocs.io/en/latest/pyTimingDoc/pyPeriodDoc/gls.html}

$$
\begin{align*}
\phi_1(t) &= 1(t) \\
\phi_2(t) &= \cos(\omega(t - \tau)) \\
\phi_3(t) &= \sin(\omega(t - \tau))
\end{align*}
$$

(3)

where each trial function is an $n$-dimensional (length of the time series) vector:

$$
\phi_i(t) = [\phi_i(t_1), \phi_i(t_2), \ldots, \phi_i(t_n)], \quad i = 1, 2, 3
$$

(4)

with statistical weight given by

$$
\omega_n = e^{-c(\alpha - \tau)^2}, \quad \alpha = 1, 2, \ldots, n.
$$

(5)

Here, $\omega$ and $\tau$ are the scale factor and time shift parameters, respectively. $c$ is known as the tuning parameter. In our study,
we have chosen this value as 0.007. The projection coefficients ($y_i$) of the above three trial functions ($\phi_i$ in Equation 3) have been computed for which the model function ($y(t) = \sum_{i=1}^{N} y_i \phi_i(t)$) best fits to the data vector. The best-fit coefficients are given by

$$y_i = \sum_j S^{-1}_{ij}(\phi_j|x),$$

where $S_{ij}$ is the inverse of S-matrix, defined by $S_{ij} = \langle \phi_i|\phi_j \rangle$, and $x$ is the time series data vector, $x = [x(t_1), x(t_2), ..., x(t_n)]$.

We define the power or universal power statistic by the following formula (Foster 1996b):

$$P = \frac{NV_y}{(r-1)s^2},$$

where $V_y = \langle y|^2 - \langle y \rangle^2 = \sum_{i=1}^{N} N_i y_i^2(t_{a}) - \left[ \sum_{i=1}^{N} N_i y_i(t_{a}) \right]^2 / \sum_{i=1}^{N} N_i$ is the weighted variation of the model function and can be calculated using Equation (6) (i.e., $y(t) = \sum_{i=1}^{N} N_i y_i(t)$) and Equation (5). $r$ and $N$ are the numbers of the trial functions used for the projection and data points in the given time series, respectively. $S^2 = (NV_y/N-1)$ is the estimated variance of the data with

$$V_x = \langle x | x \rangle - \langle x \rangle^2 = \sum_{i=1}^{N} N_i x_i^2(t_{a}) - \left[ \sum_{i=1}^{N} N_i x_i(t_{a}) \right]^2 / \sum_{i=1}^{N} N_i \text{, weighted variation of the data vector. When we treat wavelet transform as weighted projection, we use the effective number of data points (i.e., $N_{\text{eff}} = \sum_{i=1}^{N} N_i N_i$) instead of $N$ (refer to Section 4.3 of Foster 1996b) to compute the power. So, using $r = 3$ and $N = N_{\text{eff}}$ in Equation (7), we get the weighted wavelet transform (WWT):

$$\text{WWT} = \frac{(N_{\text{eff}} - 1)V_y}{2V_x}. \tag{8}$$

However, this quantity is highly sensitive to the $N_{\text{eff}}$ and causes a false peak at low frequency. So instead of WWT, we use the Z-statistic for projection (Foster 1996b), named the weighted wavelet Z-transform (WWZ):

$$\text{WWZ} = \frac{(N_{\text{eff}} - 3)V_y}{2(V_x - V_y)}. \tag{9}$$

which follows the $F$-distribution with degrees of freedom $N_{\text{eff}} - 3$ and 2.

4. Significance Estimation

Though LSP and WWZ methods show recognizable peaks in the power plots, the statistical properties of the blazar light curve exhibit a red-noise process (power-law type). Due to the presence of this noise (it can be shown from the observed periodogram and auto-correlation function of the time series), the light curve can show periodic behavior of few cycles in the low-frequency regime (Press 1978; Vaughan 2005). Therefore, red-noise behavior should be appropriately considered when estimating the significance of the peak observed in the periodogram.

To estimate the significance of the periodicity detection, we have used the Power Spectrum Response Method (PSRESP; Uttley et al. 2002), which has been used extensively to model the periodogram (e.g., Chatterjee et al. 2008; Edelson et al. 2014; Bhatta et al. 2016; Benkhali et al. 2020).

We first modeled the observed periodogram with the power-law model

$$P(\nu) \propto \nu^{-\beta} + C, \tag{10}$$

where $\beta$ is the spectral index of the model. $C$ represents the Poissonian noise level, which is given by Bhatta (2019):

$$C = \frac{2T(F^2_{\text{err}})}{N^2\mu^2}. \tag{11}$$

Here $N$ is the number of data points during the time span of observation $T$. $\mu$ and $(F^2_{\text{err}})$ describe the average flux and mean square of the flux errors, respectively. We are interested in finding the best-fit spectral index ($\beta$) of the given power spectral density (PSD) model. To find this, we simulate 1000 light curves by the Timmer & Koenig (1995) algorithm for each value of $\beta$ between 0.1 to 2.0 with step size 0.1. After that, we calculate the observed and resampled simulated periodograms to compute the following $\chi^2$-like quantities:

$$\chi^2_{\text{obs}} = \sum_{i=1}^{\nu_{\text{max}}} \frac{[P_{\text{sim}}(\nu_i) - P_{\text{obs}}(\nu_i)]^2}{(\Delta P(\nu_{\text{sim}}))^2}, \tag{12}$$

$$\chi^2_{\text{sim},i} = \sum_{i=1}^{\nu_{\text{min}}} \frac{[P_{\text{sim}}(\nu_i) - P_{\text{i}}(\nu_i)]^2}{(\Delta P(\nu_{\text{sim}}))^2}, \quad (i = 1, 2, \ldots, 1000), \tag{13}$$

where $\nu_{\text{min}}$ and $\nu_{\text{max}}$ are the minimum ($\frac{1}{T}$) and maximum ($\frac{N}{2\pi}$) temporal frequencies of the periodograms. $(P_{\text{sim}}(\nu_i))$ and $(\Delta P(\nu_{\text{sim}}))$ are the mean and standard deviation of the simulated periodograms at a given frequency. Powers in the periodogram are not Gaussian variables, hence the above quantities (Equation (12) and Equation (13)) are not the same as the usual $\chi^2$ distribution (Uttley et al. 2002). To quantify the goodness of fit, we have computed the success fraction for each spectral index ($\beta$). \footnote{https://github.com/avikdas4/avikdas4} This is defined by the ratio of the number of $\frac{\chi^2_{\text{sim}}}{\nu_{\text{min}}} > 1$ to the total number of $\chi^2_{\text{obs}}$ value for a given spectral index. The $\beta$ value for which the success fraction is maximum best represents the observed periodogram. We have fitted the results of the success fraction versus $\beta$ with a Gaussian function to estimate the best-fit spectral index.

After modeling the source periodogram using Equation (10), we simulated 10,000 light curves for the best-fit value of $\beta$ (corresponds to the peak of the Gaussian function) and performed the LSP method for each simulated light curve to estimate the significance level of the detection. We have also computed the significance level of WWZ peaks by a similar method.

5. Results

5.1. Identifying Different Time Segments

We have used Bayesian block (BB) representation (Scargle et al. 2013) to identify different flux states of activity. An activity phase (AP) is a sequence of consecutive recurring enhancement states, in which the BB flux level (represented by the black solid line in Figure 1) of every enhancement state crosses above the $5\sigma$ standard deviation of the average flux value. In a few cases, the first or last cycle of the AP phase (e.g., for PKS 0244-470: the last cycle of AP-1 phase) has a low BB flux level
(<μ + 5σ, μ = average flux of the whole light curve) but follows a similar quasiperiodic variability pattern as the identified phase. In these cases, that time duration/cycle has been considered as part of the phase for the periodicity analysis.

Through the above-mentioned procedure, we identified a ∼4 yr prolonged AP, AP-1 (see upper panel of Figure 1) followed by a similar prolong quiescent phase (QP-1) in PKS 0244-470 with apparently quite regular flux changes during the AP phase. Similarly, we identified four high-activity or AP phases (AP-1, AP-2, AP-3, and AP-4; see lower panel of Figure 1) and two quiescent phases (QP-1 and QP-2) in 4C+38.41 with an indication of regular flux changes in both phases.

5.2. QPO Search Results

We exploited two of the most extensively used time series methodologies: LSP and WWZ, based on two different underlying governing principles. We applied the significance estimation method, “PSRESP” (refer to Section 4) on each phase of light curves with different binning (1 day, 2 days, 5 days, and 10 days) criteria. Depending on the uncertainty in photon counts and the detailed structure of the light curve, we use different binning criteria for different phases to explore further. For example, the AP-1 phase of 4C+38.41 shows significant QPO (> 99.99% in both LSP and WWZ methods) at ∼110 days in light curves extracted using 1 day binning, but due to a large error and many low TS data points (many data points have \( F_i \leq e_i \) or TS \( \leq 9 \) or both), we instead used 2 day binning for the AP-1 phase. For similar reasons, we have shown the result of the AP-1 phase of PKS 0244-470 and QP-1 phase (later, we again divide this phase into two different subphases: Q1 and Q2 phases) of 4C+38.41 in the 10 day time bin.

Our study of high-AP AP-1 (MJD 54,685–56,475; see Figure 2) of PKS 0244-470 results in a possible QPO of 225 ± 24 days with a significance of 99.996% and 99.986% in LSP and WWZ methods (see Table 1) persisting for eight cycles. The uncertainty on the periods reported here is estimated using half-width at half-maximum (HWHM) of the LSP result following VanderPlas (2018). We caution that such a measure is not meant for broad QPOs. This phase is very prominent until the seventh cycle and weakens in the eighth cycle, followed by its disappearance afterward. This is also the most significant QPO signal reported in this work. The LSP and WWZ plots are shown in Figure 3. The 99.73% local significance contours are also shown by the dashed cyan curve in the LSP and time-averaged (τ - avg.) WWZ plots.

Similarly, we have also searched for transient QPO-like variations in all the phases (AP-1, AP-2, AP-3, AP-4, QP-1, and QP-2) of 4C+38.41 as marked by dashed-dotted green lines in the lower panel of Figure 1. The light curves of each phase with exact peak positions of oscillation (dashed-dotted red lines) and their corresponding uncertainties (red shaded regions) on the periods have been shown in Figure 4.

In 4C+38.41, AP-1 has a total time span of 463 days (MJD 54,907–55,370). It shows a periodicity of 110 ± 21 days (2 day bin) with four complete cycles with the significance of 99.82% and 99.77% in the LSP and WWZ methods, respectively (see Figure 5). AP-2, on the other hand, has a duration of 319 days (MJD 55,552–55,871) and shows a QPO-like variation of 60 ± 9 days with five complete cycles. The detected significance of the peak is 99.90% in LSP and 99.85% in the WWZ method.

The AP-3 phase lasted for 598 days (MJD 56,150–56,748) with an average flux of 0.37 ± 0.01 unit. We found hints of phases within it. We reapplied our phase-identifying criteria as mentioned before to identify different subphases: AP-3A (MJD 56,178–56,274), AP-3B (MJD 56,274–56,400), AP-3C (MJD 56,400–56,591), and AP-3D (MJD 56,591–56,274) and then explored for recurrent signals in each. AP-3A and AP-3B show a periodicity of 19 ± 2 days and 12 ± 1.5 days, both with five complete cycles and a significance of 99.98% and 99.76% in LSP method (see Table 1). AP-3C, too, shows a periodic flux variation from MJD 56,406 to MJD 56,591 with a periodicity of 35 ± 4 days, but the result is at 99.60% significance only in the LSP method.

The quiescent phase (QP-1) of 4C+38.41, too, has a few active episodes. The total time span of these phases is 1738 days (MJD 56,598–58,135) and 1070 days (MJD 58,495–59,565) for QP-1 and QP-2, respectively. QP-1 shows quasiperiodic-like behavior in two different time ranges. We used the same method to divide these time ranges as in the case of the AP-3 phase. We have defined this time range as Q1 and Q2 phases. The Q1 phase (MJD 56,685–57,315) shows a periodicity of 104 ± 7 days in 10 day binned light curves with greater than 99.93% significance level in both methods, Q2 phase (MJD 57,305–58,135) also shows QPO-like behavior (99.98% in LSP and ∼99.96% in WWZ method with a period

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Figure 2. Fermi-LAT light curve of AP-1 phase (MJD 54,682–56,475) of the blazar PKS 0244-470 in 10 day time bins. The vertical dashed-dotted red lines and red shaded regions indicate the peak positions of the periodic oscillation and uncertainty on the peaks, respectively.
### Table 1

Results of LSP and WWZ Methods for Different Activity Phases

| Activity Phases | PSD-Slope (β) | Detection Methods | Observed Period (days) | No. of cycles | Detection Significance (local) |
|-----------------|---------------|-------------------|------------------------|---------------|-------------------------------|
| AP-1            | 0.67 ± 0.21   | LSP, WWZ          | PKS 0244-470           |               |                               |
|                 |               |                   | ~225                   | 8.0           | 99.996%                       |
|                 |               |                   | ~222                   | 8.0           | 99.986%                       |
|                 |               |                   | 4C+38.41               |               |                               |
| AP-1            | 0.97 ± 0.29   | LSP, WWZ          | ~110                   | 4.2           | 99.82%                        |
|                 |               |                   | ~111                   | 4.2           | 99.77%                        |
| AP-2            | 0.83 ± 0.12   | LSP, WWZ          | ~60                    | 5.4           | 99.90%                        |
|                 |               |                   | ~60                    | 5.3           | 99.85%                        |
| AP-3A           | 0.60 ± 0.29   | LSP, WWZ          | ~19                    | 5.1           | 99.98%                        |
|                 |               |                   | ~19                    | 5.1           | 99.94%                        |
| AP-3B           | 0.80 ± 0.31   | LSP, WWZ          | ~12                    | 5.4           | 99.76%                        |
|                 |               |                   | ~12                    | 5.4           | 99.61%                        |
| AP-3C           | 0.88 ± 0.19   | LSP, WWZ          | ~35                    | 5.3           | 99.60%                        |
|                 |               |                   | ~34                    | 5.4           | 99.54%                        |
| Q1              | 0.73 ± 0.40   | LSP, WWZ          | ~104                   | 6.0           | 99.96%                        |
|                 |               |                   | ~104                   | 6.0           | 99.93%                        |
| Q2              | 0.60 ± 0.26   | LSP, WWZ          | ~227                   | 3.7           | 99.98%                        |
|                 |               |                   | ~223                   | 3.7           | 99.96%                        |

**Note.** Uncertainty on the PSD slopes result from the HWHM (half-width at half-maximum) of the Gaussian fit.

of ~227 days and ~223 days, respectively) but with nearly 3.7 cycles only. The QPO detection results (LSP and WWZ maps) of all the phases of 4C+38.41 (except the AP-1 phase) are shown in Figure 6.

AP-4 (MJD 58,101–58,497) shows QPO-like variation with a periodicity of 166 days. However, this result is relatively less significant (local significance level is 98.76%), and the periodic nature lasts only for ~two cycles and thus, is not reliable from the stochastic-nature point of view of time series. Due to this reason, we have not shown here the result of AP-4. On the other hand, given the source behavior during active episodes revealed by our study, this, too, could be a probable signal. The detailed outcomes of our study for all phases have also been given in Table 1.

We have also searched for QPOs in the entire 10 day binned light curve of 4C+38.41 and noticed three QPO-like features (957 ± 117 days, 647 ± 44 days, and 295 ± 12 days), but none of them are significant (local significance level: ~96.43%, ~99.07%, ~86.64%), which is similar to the results presented by Bhatta & Dhital (2020) and Ren et al. (2023).

### 6. Discussion

We have explored temporal flux variability in ~13 yr of Fermi-LAT data of the FSRQs PKS 0244-470 and 4C+38.41 in 10 days of binning (from MJD 54,685–59,565; see Figure 1). These are both FSRQ-type blazars with γ-ray emission originating due to the inverse Compton scattering of optical-UV photons in the leptonic scenario. The total γ-ray emission can be the sum of the Comptonization of photon fields external to the jet including the accretion disk. If the accretion-disk photon field contribution is significant (relative), then the observed signal could be associated with it.

The QPO study in blazars is one of the tools to know more about the central source, its surroundings, and the physical mechanisms responsible for the multiwavelength emission. However, it requires well-sampled, good-quality data across the entire EM spectrum to help us clearly understand QPOs or their periodic nature. For instance, if the optical light curve also exhibits QPO-like variability correlated with the γ-ray emission, it suggests that the same relativistic electrons are responsible for both types of emissions. On the observational side, we do not see any QPO features in the optical band light curve taken from the Steward Observatory, (Smith et al. 2009), nor do we see any hint of QPO in the Steward polarimetric data, which is expected in kink-instability powered flares (Dong et al. 2020). However, neither data are well sampled and could be one of the reasons for the lack of QPOs in optical. Radio observations also play a crucial role in understanding the cause of significant QPOs or QPO-like variations in the jet. For PKS 0244-470, no radio data during the AP-1 phase are available, and Algaba et al. (2018) reported that 4C+38.41 is not resolvable in 129 GHz KVN (Korean VLBI Network) iMOGABA (Interferometric Monitoring of Gamma-ray Bright AGN) images due to its high-redshift location. However, VLBA BU images (Jorstad et al. 2017) at 43 GHz (with a resolution of 0.2 mas) are available for this source (4C+38.41), and by using this data (from MJD 5,6000–57,250), Algaba et al. (2018) found that in only two cases, the γ-ray flux enhancement occurred with the ejection of new radio components, which supports the shock-in-jet scenario (Marscher & Gear 1985). In other cases, no signature of the new radio component ejection was found during γ-ray flares, suggesting a different origin of the flaring activity, e.g., variation of viewing angle and/or related to plasma instabilities (Raiteri et al. 2012). So far, there is no clear evidence yet about the exact origin of the γ-ray variability for this source and consequently, the observed transient QPO-like features.

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Therefore, further high-resolution VLBI observations, e.g., Event Horizon Telescope (Event Horizon Telescope Collaboration et al. 2019), are needed in the future for a decisive interpretation.

In our study, we have found transient QPOs or QPO-like variations in both sources with significance ranging from the 99.60% to 99.996% levels. It is important to note that the significance levels calculated here are strictly local, where we are interested in estimating the significance level for a particular frequency. However, without prior knowledge of the location of the peaks, it is more robust to check for a “global significance.” In the “global significance,” we include the effect of observing our peak of interest anywhere in the tested range (Bell et al. 2011; Zhou et al. 2018). This effect is popularly known as the “look-elsewhere effect” or “multiple comparison problem” in statistics. We checked this for all the phases and found a reduction in the computed significance level. For example, the significance level of the AP-1 phase (PKS 0244-470) and Q1 phase (4C +38.41) are reduced to 98.164% (99.996% local significance) and 96.37% (99.96% local significance), respectively. These results are consistent with other recent works, e.g., Covino et al. (2019) and Benkhali et al. (2020). However, in this regard, the QPO in PKS 0244-470 during AP-1 is different. If we neglect the last cycle (limiting to seven cycles, from MJD 54,685–56,305) where it has weakened considerably, we get a very significant QPO with a local significance of 99.9997% and a global significance of $\geq 99.73\%$ (from simulating $3 \times 10^5$ light curves) in the LSP method. The above discussions suggest that the claiming of the transient QPOs should be treated with caution. At the same time, it should be noted that very strict significance measures could fail to notice many exceptional/interesting features in the AGN (see “Result and Discussion” section in Bhatta & Dhital 2020), particularly in the low-frequency regime, and we may also miss exciting physics.

6.1. Physical Interpretations

QPOs in blazars can originate entirely within the jet or can be due to jet precession (Rieger 2004) or a binary SMBH scenario.
However, binary SMBH and precession are expected to give long-term QPOs and thus are unable to provide satisfactory explanations as observed in our case. Below, we provide a few possible scenarios that can explain the short-term periodicity (days to month) in the light curves.

One of the well-known origins of the transient QPOs is the presence of a relativistic blob moving on a helical trajectory inside the jet. This blob can emit $\gamma$-ray radiation via external Compton and synchrotron self-Compton processes (one-zone leptonic scenario). In this case, the time-dependent viewing angle ($\theta$) in the observer frame is given by Zhou et al. (2018):

$$\cos \theta(t) = \cos \phi \cos \psi + \sin \phi \sin \psi \cos(2\pi t/P),$$

(14)

where $\phi$ and $\psi$ are the pitch angle (between the blob’s velocity direction and jet axis) and inclination angle (between the jet axis and observer’s line of sight), respectively. We have set $\phi = 2^\circ$ and $\psi = 5^\circ$ as in the case in Zhou et al. (2018). Using the typical value of Lorentz factor $\Gamma = 20$ for FSRQs, we have computed the periodicity in the comoving frame ($P'$), distance traversed in one cycle of the helical motion ($D'$), and total projected distance ($S'$) for different phases of activity (Table 2). The main drawback of this model is that it can explain only the periodicity with constant amplitude. Several authors used a curved jet model to describe the varying amplitude scenario (Camenzind & Krokenberger 1992; Sarkar et al. 2021), where inclination angle $\psi$ is time dependent. However, the curved jet model finds it difficult to explain the short-term periodicity (e.g., AP-3A and AP-3B). We need high curvature for that, which is generally unusual for highly collimated, Mpc-scale FSRQ jets.

Another explanation of the QPO signature is given by Dong et al. (2020). They have identified the blazar emission region inside the jet as the region of strongest kink instability. Due to these instabilities, there is a quasiperiodic conversion of magnetic energy to thermal energy. The observed period, in this case, can be given by

$$P = \frac{R_{K1}}{\nu_0 \delta},$$

(15)

where $R_{K1}$ and $\nu_0$ are the size of the emission region and transverse velocity respectively, $\delta$ is the Doppler factor of the jet. For typical blazar parameter value, they have found periodicities from the week to month scale. They have also found in simulation that the polarization degree (PD) is anticorrelated with the variability of the light curve. However, for our sources, we cannot test this scenario due to the lack of good-quality PD data.
QPO could also arise because of strong turbulent flow behind a propagating shock (Marscher et al. 1992). The dominant turbulent cell exhibits enhanced Doppler boosting and can contribute the QPO component to the observed light curve at the turnover period of the cell. However, due to the stochastic nature of the cell, it is highly likely that these QPOs last only for a few cycles (Wiita 2011). In our case, for AP-3A and AP-3B, this turnover period is calculated as ~68 days and ~43 days, respectively, in the jet frame with the assumed Doppler factor, $\delta=10.0$ (Savolainen et al. 2010; Raiteri et al. 2012). This would require relatively reasonable-sized eddies to explain the observed QPOs (Rani et al. 2009).

Another plausible scenario is a bright hotspot revolving around the SMBH leading to enhanced production of $\gamma$-ray emission via the EC mechanism inside the jet. Due to Doppler boosting of the emission region, this model can explain the observed periodicity with a timescale of approximately a few days (Roy et al. 2022). However, in blazars, the motion of this hotspot is symmetric around the jet axis, and thus it fails to explain the fast variability observed in the $\gamma$-ray light curve.

Though we cannot identify the exact cause behind QPO-like variability as many processes seem consistent, kink instability seems the most probable candidate among all. Another indirect indication in favor of this is that almost all the strong APs have this QPO-like feature, indicating a similar underlying process. In the kink scenario, magnetic topology can give emission regions of varied sizes, and the corresponding magnetic energy can be channeled in different proportions into bulk motion, particle injection, and/or acceleration, giving rise to different observed variability timescales. Even the relatively long-term (approximately a few years) QPOs seen during several phases could result from this as current-driven kink instability is expected in magnetic-dominated regions, i.e., near the black hole (BH) where the magnetic field is expected to be strong and weakened as one moves further from the BH. The occurrence of transient QPO-like variations, with timescales ranging from a few months to years, seems to be common in $\gamma$-ray bright blazars. For instance, a recent study by Ren et al. (2023) claims that 24 out of 35 sources show such a trend. However, there is no study that examines short timescales (days to months) for this phenomenon. In contrast to other works, the occurrence of transient QPO-like variations in 4C +38.41 whenever the source enters a high state (except during AP-4) makes it an interesting source to study. This finding may imply that the kink instability keeps occurring in the jet with different sizes and/or velocities. However, it should be noted that these processes are highly complex and capable of producing a wide range of observational manifestations, and thus, more detailed and better data at the optical and radio band are required. For a longer period, a helical bend or helical jet model is also a possible explanation. However, this requires continuous particle acceleration/injection as the radiative cooling time in FSRQs is dominated by $\gamma$-rays and is of the order of a few minutes (e.g., Kushwaha et al. 2014).

7. Summary and Conclusions

We explored the timing features in the ~13 yr long $\gamma$-ray light curve of FSRQs 4C+38.41 and PKS 0244-470. We first identified the variability episodes and then employed the most widely used methods: LSP and WWZ to explore quasiperiodic features, followed by estimating their significance via the Monte Carlo approach using inputs from the observed light curve. The outcomes from our study are as follows:

1. Fermi-LAT analysis of the sources PKS 0244-470 and 4C +38.41 have been done with ~thirteen yr (MJD 54,800–59,565) of archival data. Using Bayesian block with source intrinsic variability, we identified one activity and one quiescent phase in PKS 0244-470 and four activity and two quiescent phases in 4C+38.41, with most phases showing recurring features.

2. The AP-1 phase of PKS 0244-470 shows QPO-like behavior with a period of ~225 days and persists for nearly eight cycles. This is the first time we have reported this significant result: 99.996% and 99.986% local significance level in the LSP and WWZ methods, respectively. This feature remains significant globally too.

3. All except one (AP-4) of the APs of 4C+38.41 show QPO-like behavior in their light curve with four to five complete cycles. The duration range is from ~10 to 110 days. One of the phases shows three subphases, each showing a QPO-like feature, ranging from ~10 to 40 days.

4. The quiescent phases of 4C+38.41 also show QPO-like behavior on two different times scales: ~104 days (six cycles) and ~223 days (nearly 3.7 cycles) with local significance level $\geq$99.93%.

5. Kink instability seems the most probable explanation for both short- and long-term observed QPOs. However, the curved jet model can also explain the relatively longer-period QPOs.

The global significance of these transient QPO-likes features is within the range reported by researchers in other blazars.

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Figure 6. Results of LSP and WWZ methods for different phases (AP-2, AP-3A, AP-3B, AP-3C, Q1, and Q2 phases of 4C+38.41). WWZ maps are shown below each phase of LSP plots (same as Figure 5). The cyan curve represents the 99.73% local significance contours in both methods.
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Software: Fermi tools (https://fermi.gsfc.nasa.gov/ssc/data/analysis/), Fermi-LAT Light Curve Respiratory (https://fermi.gsfc.nasa.gov/lat/LightCurveRepository), WWZ method (https://github.com/eaydin/WWZ).

Data Availability

This work has made use of publicly available Fermi-LAT data obtained from FSSC’s website data server and provided by NASA Goddard Space Flight Center. Photon index data is taken from Fermi-LAT Light Curve Repository webpage (Fermi Large Area Telescope Collaboration 2021).

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