BLAZAR MRK 501 SHOWS RHYTHMIC OSCILLATIONS IN ITS $\gamma$-RAY EMISSION

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ABSTRACT

In this letter, we report the detection of transient rhythmic oscillations in the $\sim$10-year long Fermi/LAT observations of the famous blazar Mrk 501. Using two widely accepted methods, Lomb-Scargle periodogram and weighted wavelet z-transform, we found a strong signal of quasi-periodic oscillation (QPO) with a periodicity centered around 332 days. In addition, we noted that the $\gamma$-ray flux modulations gradually decayed in strength during the recent years. A large number of Monte Carlo simulations were performed to properly account for the red-noise inherent in the light curve and thereby estimate both the local and global significances of the signal to be above 99%. In the context where not many $\gamma$-ray QPOs are reported to show more than 5 cycles, this might be one of the few instances where we witness a relatively high frequency, having a period of less than a year, $\gamma$-ray QPO persisting nearly 7 cycles before it weakens. Mrk 501 being one of the best studied sources, the detection, complemented with what has been already known about the source, can lead us to the understanding of extreme conditions prevailing around the supermassive black holes that potentially lead to the launch of the relativistic jets. In addition, the detection might contribute to the broader program of searching for characteristic timescales in the blazar light curves. Furthermore, the core of the distant sources being unresolved by our current telescopes, such timescales provide us with important clues about the processes taking place at the heart of active galactic nuclei. Several possible scenarios that possibly give rise to such a transient $\gamma$-ray QPO are discussed.

Subject headings: galaxies: active — BL Lac objects: individual (Mrk 501) — galaxies: jets — radiation mechanisms: non-thermal— methods: statistical

1. INTRODUCTION

Blazars, the most powerful sources in the universe, are a small sub-class of active galactic nuclei (AGN). They are believed to harbor monstrously giant black holes, billions times massive than the sun, squeezed within a volume as small as the solar system. The surrounding accretion disk constantly feeds the black hole with tremendous amount of matter which makes the nuclei extremely bright and consequently outshine the whole galaxy. The central engine spews out matter nearly at the speed of the light in the form of the relativistic jets directed towards the earth. Blazars further can be classified into two kinds of sources: flat-spectrum radio quasars (FSRQ), the ones which show emission lines and have the synchrotron peak in the lower electromagnetic frequency; and BL Lacertae (BL Lac) objects, the others which show weak or no emission lines and have synchrotron peak in the higher frequency. Although less powerful than FSRQs, BL Lacs are considered an extreme class of sources with highest synchrotron and inverse-Compton energies. More recently, blazar TXS 0506+056 was associated with the first non-stellar neutrino emission detected by the IceCube experiment (Padovani et al. 2018).

Blazars being the most luminous sources are visible across the universe; and therefore they can be used to probe the large scale geometry of the universe. Furthermore, understanding of blazars are crucial to the modern (astro)physics because the sources provide natural laboratory for both the highest energy particles (quantum physics regime) and the strongest gravity environment (General Relativity domain). Moreover, blazars could form an ideal sample of sources to study some of the challenging issues related to AGN, e.g., the interaction between the accretion disk and the jets, and the conditions leading to the launch of the jet around the supermassive black holes. Although the distant blazar cores are not resolved by any current instruments, the presence of the relativistic jets in blazars “highly exaggerates” the variability amplitudes and the timescales through relativistic beaming effects (see Urry & Padovani [1995]) such that the information about the central engine can be carried along to us. For the reason, variability studies can be one of the powerful methods – if not the only method – that guide us to the innermost regions of AGN, otherwise completely hidden from our view.

Although, the flux variability shown by AGN, in general, appears to be aperiodic, the statistical nature of the observed variability can often be characterized as red-noise, meaning the source flux changes by larger amount over the longer period of time. However, past few years presence of quasi-periodic oscillations (QPO) in the multi-frequency light curves on diverse characteristic timescales have been reported (see Bhatta 2017). Particularly, the detection of QPOs in the $\gamma$-ray light curves of a small number of blazars are intriguing. Of them, the famous case of 2.18-year periodicity in the TeV blazar PG 1553+113 was reported in Ackermann et al. [2015] and more recently in Tavani et al. [2018]. Sandrinelli et al. [2014] and later Zhang2017c claimed $\sim$1.73-year QPO in the $\gamma$-ray light curve of the blazar PKS 2155-304. Similarly, Zhang et al. [2017a] reported 3.35-year periodicity in the blazar PKS 0426-380 in 8-year long period period.
Zhang et al. (2017b) claimed 2.1-year QPO in the 9 year observations of the source PKS 0301-243. In 8-years long γ-ray observations, Sandrinelli et al. (2017) studied QPO in three blazars 0716+714, MRK 421, BL Lac and concluded that the first two ones do not show any periodicity while BL Lac exhibited \( \sim \)1.86-year QPO, similar to the one found in optical observations the source. It is important to note here that in all of these cases the claimed periodic timescale is near two years and above, and number of periodic cycles were less than 5.

Also Sandrinelli et al. (2016b) studied a number of blazars in the γ-ray band, including PKS 2155-304, OJ 287, and 3C 279 PKS 1510-089 and claimed the presence of year-like QPOs with modest significance. Similarly, Prokhorov & Moraghan (2017) in their search for the γ-ray sources showing periodicities confirmed previously reported quasi-periodicities in the three blazars, PG 1553+113, PKS 2155-304 and BL Lacertae, and further observed evidence for quasi-periodic behaviors of four blazars: S5 0716+716 and three of the high redshift blazars MRK 421, BL Lac and PKS 2155-304. In 8-years long γ-ray observations of the source PKS 0301-243. In 8-years long γ-ray light curve of the blazar Mrk 501 (or 3FGL J1653.9+3945) from the epoch 2008-08-04 – 2018-06-01 (equivalently, 54682 – 58270 MJD) and in the energy range 20 MeV – 300 GeV were considered. Fermi/LAT observations of the source Mrk 501 were processed following the standard procedures of the unbinned likelihood analysis. In particular, only the events within a circular region of interest (ROI) of 10° radius centered around the source were considered; and to minimize the contamination of γ-rays from the Earth limb the zenith angle was limited to less than 90°. The python application make3FGLxml.py was used to create source models for all the sources from the Fermi/LAT catalog within the ROI. Then the diffuse source response was calculated using the Galactic and extragalactic models of the diffuse γ-ray emission such as gl_\text{iso} v06.fit and iso_P8R2 SOURCE V6 v06.txt. Finally, to estimate the significance of the γ-ray events, likelihood ratio test (Mattox et al. 1996) was performed using the task gtlike; the likelihood ratio test statistic given by \( TS = 2(\log L_1 - \log L_0) \), where \( L_1 \) and \( L_0 \) denote the likelihood of the optimized parameters with and without the source at the location, respectively. Then the significance of a source detection is expressed by \( \sim \sqrt{TS} \sigma \) (Abdo et al. 2010). (details on the Fermi/LAT data processing are also discussed in Bhatta 2017). To construct the light curve, a graph that shows observations plotted against the time, we binned the observations in a 7-day bin. For the robust analysis, only the observations with TS value > 10 (or above 3σ significance) were included for the analysis, of which 80% observations were above 5σ significance level.

### 3. Analysis and Results

Figure 1 shows the long-term Fermi/LAT light curve of the blazar Mrk 501. In the figure, it can be seen that γ-ray emission displays considerable variability during the total observational period. As a quantitative measurement of the variability, fractional variability (Vaughan et al. 1997) was used."

**Figure 1.** The Fermi/LAT (0.1–300 GeV) observations of the blazar Mrk 501 are shown by symbols.
where the power spectral density of AGN (e.g., Edelson et al. 2003; Bhatta & Webb 2018) of the source is estimated to be $33 \pm 4\%$. The search for the presence of QPOs in the Fermi/LAT light curve was conducted using Lomb-Scargle periodogram (LSP), (Lomb 1976; Scargle 1982), one of the methods that approaches the periodicity analysis from multiple directions e.g. Fourier analysis, least-squares method, Bayesian probability theory, and bin-based phase-folding techniques (see VanderPlas 2018).

The Lomb-Scargle periodogram of the ~10 years long X-ray light curve of the source is presented in Figure 2 which shows a distinct peak around the timescale of $332 \pm 17$ days suggesting presence of a strong periodic signal at the timescale. The uncertainties in the period are represented by the half-width at the half-maximum (HWHM) of the peaks. Now, it is important to point out that, in general, the statistical properties of blazar light curves can be characterized as red-noise processes such that the light curves dominated by such noise can occasionally mimic a periodic behavior for a few-cycles, especially in the low-frequency (i.e. longer timescale) regime (see Vaughan et al. 2016; Press et al. 1978, for the discussion). Therefore while estimating the significance of any periodic feature observed in a periodogram, the red-noise behavior should be properly accounted along with the other effects due to the discrete sampling, finite observation length and uneven sampling of the light curve. For the reason, we first modeled the discrete Fourier transform of the light curve with a power-law power spectrum density (PSD) of the form $P(\nu) \propto \nu^{-\beta} + C$; where $\nu$, $\beta$, and $C$ represent temporal frequency, spectral slope and Poisson noise level, respectively. Subsequently, MC simulations of the light curves were performed by the method described in (Timmer & Koenig 1995) to obtain a distribution the LS periodograms which subsequently were used to compute the significance of the observed periodic signal.

We followed the power response method (PSRESP; Uttley et al. 2002), a widely used method to characterize the power spectral density of AGN (e.g., Edelson et al. 2003; Bhatta & Webb 2018), of the source is estimated to be $33 \pm 4\%$. The search for the presence of QPOs in the Fermi/LAT light curve was conducted using Lomb-Scargle periodogram (LSP), (Lomb 1976; Scargle 1982), one of the methods that approaches the periodicity analysis from multiple directions e.g. Fourier analysis, least-squares method, Bayesian probability theory, and bin-based phase-folding techniques (see VanderPlas 2018).

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ing the WWZ software\footnote{https://www.aavso.org/software-directory} 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 4 which reveals significant WWZ power centered around the period 332 days, further confirming the detection of the QPO by LSP method. The figure also shows that the QPO starts to decay from the time 3000 days and gradually disappears towards the end of the observation period. Such a behavior is also visible in the light curve in Figure 1 which clearly shows the amplitude of modulations grow weaker after the year 2016. The right panel of Figure 4 shows the time-averaged WWZ power at a given period. Once again, in the panel, we can see a distinct peak centered around the periods of 332±17 days. As in the LSP, HWHMs about the central peaks provide a measure for the uncertainties in the observed period.

We took a similar approach to evaluate the significance of the WWZ detected quasi-periodic feature at the timescale of ~332 days. We first simulated 10000 light curves from the best-fitting PSD model and re-sampled them according to the source light curve. Subsequently, wavelet analysis was performed to calculate time averaged WWZ power for the given periods. In particular, the time ($\tau$) averaged WWZ power of the source was compared against the 90% and the 99% local significance contours derived from the distribution of the time averaged WWZ power of the simulated light curves. In the right panel of Figure 4 the 90% and 99% local significance contours are shown by the magenta and the red curves, respectively. The local and global significances of the QPO were estimated to be 99.7% and 99.2%, receptively. We note that a slightly larger local significance, in comparison to the one in the LSP method, is consistent with the fact that wavelet analysis looks for periodic behavior locally.

4. SUMMARY AND CONCLUSION

We analyzed ~10 year long Fermi/LAT observations of the famous blazar Mrk 501, and using Lomb-Scargle Periodogram and z-transformed weighted wavelet detected a significant transient quasi-periodic oscillations of the period centered around 332 days. The period in the source rest frame ($P$) is estimated as $P = P_{\text{obs}}/(1 + z) = 321$ days, where $P_{\text{obs}}$ and $z$ are the observed period and the red-shift, respectively. To robustly estimate the local and global significances of the observed period, we properly took account a number of effects that potentially could produce spurious peaks e.g. red-noise, discrete data, finite observation length, and uneven data sampling. We simulated a large number of light curves from the best-fit power-law spectral model and subsequently assigned the sampling of the real observation. The significance (both local and global) of the detection in both of the methods was found to be above 99%.

It should be pointed out that most of the $\gamma$-ray QPOs mentioned in the introduction are reported to have lasted only a few cycles (typically less 5 cycles). Against such a backdrop, what we have observed might be the first interesting event where we witness a transient $\gamma$-ray periodic modulations in the high energy emission of the blazar that persist up to 7 cycles before they gradually fade away. It could be also possible that the flux modulations started long before the Fermi launch year (i.e. 2008). In that case, the modulations might have spanned more than 7 cycles. In any case, the detection adds Mrk 501 to the list of a few reported cases for QPOs in the $\gamma$-ray band.
Study of quasi-periodic oscillations sheds light into various aspects of AGN research such as strong gravity environment and disk-jet connection. In principle, (quasi-) periodic oscillations in AGNs can be linked to a host of possible scenarios: for example, supermassive binary black holes (SMBBH) (e.g., Lehto & Valtonen 1996, Valtonen et al. 2008), SMBH induced jet precession (Caproni et al. 2017, Sobacchi et al. 2017), and globally perturbed torus (e.g., Rezzolla et al. 2003, Zanotti et al. 2003). High frequency QPOs are frequently interpreted in the context of the Lense-Thirring precession of the accretion disks (see Stella & Vietri 1998 [Motta et al. 2011], γ-ray flux modulations are most likely to originate from the relativistic jets, but we may still need a periodic perturbation close to the central engine which would propagate along the jet. We find that SMBBH systems provide the most natural model for such recurring perturbation which can be placed behind a host of other scenarios e.g. jet precession (Begelman et al. 1980), misalignment in the jet position angle (Conway & Wrobel 1995), periodic impact as in OJ 287 (Sillanpää et al. 1988), and accretion disk precessing under gravitational torque (Katz 1997).

In case of the blazar Mrk 501, due to transient nature of the observed 332-day QPO, SMBBH interpretation might not be directly relevant, although the 23-day periodic behavior previously reported was based on this model Rieger & Mannheim (2000). Interestingly, 332-day period is nearly 10 times the 23-day period and in both the cases the maxima are nearly 8 times the minima of the modulations. The transient 332-day period, however, could be linked to instabilities in the highly magnetized jets and rotating magnetic field (e.g. Meisenheimer & Roeser 1984). Particularly, 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 set up transient periodic oscillations at the interface of the disk and the magnetosphere as a result of sudden change in the density and the magnetic flux (Li & Narayan 2004, Fu & Lai 2012). Depending upon the black hole spin parameter the timescale for these QPOs can range from a few days to several months. In fact, similar QPOs are observed in the recent magneto-hydrodynamical (MHD) simulations of the large scale jets McKinney et al. (2012). However, without further analysis and collective discussion on the topic, it would be difficult to single out a particular scenario behind such a transient rhythmic flux modulations.

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