Detection of a quasi-periodic oscillation in $\gamma$-ray light curve of the high redshift blazar B2 1520+31

Alok C. Gupta$^{1,2,*}$, Ashutosh Tripathi$^3$†, Paul J. Wiita$^4$‡, Pankaj Kushwaha$^5$, Zhongli Zhang$^1$, Cosimo Bambi$^{3,6}$

$^1$Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
$^2$Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital – 263 001, India
$^3$Center for Field Theory and Particle Physics and Department of Physics, Fu Jen University, 220 Handan Road, Shanghai 200433, China
$^4$Department of Physics, The College of New Jersey, P.O. Box 7718, Ewing, NJ 08628-0718, USA
$^5$Department of Astronomy (IAG-USP), University of Sao Paulo, Sao Paulo 05508-090, Brazil
$^6$Theoretical Astrophysics, Eberhard-Karls-Universität Tübingen, D-72076 Tübingen, Germany

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ABSTRACT

We detected a possible quasi-periodic oscillation (QPO) of $\sim 71$ days in the $0.1 - 300$ GeV $\gamma$-ray Fermi-LAT light curve of the high redshift flat spectrum radio quasar B2 1520+31. We identify and confirm that quasi-period by Lomb Scargle periodogram (LSP), and weighted wavelet z-transform (WWZ) analyses. Using this QPO period, and assuming it originates from accretion-disc fluctuations at the innermost stable circular orbit, we estimate the central supermassive black hole mass to range between $\sim 5.4 \times 10^9 M_\odot$ for a non-rotating black hole and $\sim 6.0 \times 10^{10} M_\odot$ for a maximally rotating black hole. We briefly discuss other possible radio-loud active galactic nuclei emission models capable of producing a $\gamma$-ray QPO of such a period in a blazar.

Key words: galaxies: quasars : general – quasars: individual: B2 1520+31

1 INTRODUCTION

Active galactic nuclei (AGN) powered by accreting black holes (BHs) with masses of $10^6 - 10^{10} M_\odot$ have several similarities to scaled-up galactic X-ray emitting BH binaries. In both BH and neutron star binaries in our and nearby galaxies, the presence of quasi-periodic oscillations (QPOs) in the time series data, or light curves, is fairly common (e.g. Remillard & McClintock 2006). But it is quite rare to detect QPOs in the time series data of AGN. Blazars are a subclass of radio-loud AGN with their relativistic jets aligned along the observer’s line of sight. They have been empirically classified further into BL Lac objects (BLLs) and flat spectrum radio quasars (FSRQs) based on the strength of optical emission lines, where the former show no or very weak ones while the latter have prominent broad lines. All blazars exhibit highly variable fluxes across the entire accessible electromagnetic (EM) spectrum from radio to GeV and even TeV $\gamma$-rays and on all temporal scales from minutes to decades. This temporal variability is essentially stochastic (e.g. Kushwaha et al. 2017b) but there have been occasional claims of QPOs in time series data of blazars in different EM bands. Similar to the temporal variability time scales, these QPOs apparently have been seen on diverse timescales ranging from a few tens of minutes to hours to days and even years, although many of these claims are marginal.

Some of the early claims of QPO detections were in the bright blazar OJ 287, where a 15.7 minute periodicity in 37 GHz radio observations taken in April 1981 (Várlaogh et al. 1985) and a 23 minute periodicity in optical band observations taken in March 1983 (Carrasco, Dultzin-Hacyan, & Cruz-Gonzalez 1985), were argued for. A quite convincing $\sim 11.7$ yr QPO was seen using a century long optical data (Sillanpää et al. 1996) and subsequent flares were predicted in terms of a binary BH model (Valtonen et al. 2008). The blazar S5 0716+714 once seemed to show a QPO period of $\sim 1$ day followed by a weaker period of $\sim 7$ days; these fluctuations were present in both optical and radio bands during a coordinated optical and radio monitoring campaign (Quirrenbach et al. 1991). On another occasion, optical observations of S5 0716+714 also indicated a QPO period of $\sim 4$ days (Heidt & Wagner 1996). On longer timescales, five optical outbursts during 1995 to 2007 were suggested to have a quasi-period of $\sim 3.0 \pm 0.3$ years (e.g. Raiteri et al. 2003; Foschini et al. 2006; Gupta et al. 2008). For the blazar PKS 2155–304 a possible QPO of $\sim 0.7$ day was seen with UV and optical monitoring using IUE (International Ultraviolet Explorer) over five days (Urry et al. 1993). A peculiar blazar, AO 0235+164, may have shown a QPO of $\sim 5.7$ years in long term radio band data (Raiteri et al. 2001).

* acgupta30@gmail.com
† ashutosh31tripathi@gmail.com
‡ wiitap@tcnj.edu
Over the last decade there have been more claims of detections of QPOs in several other blazars (e.g. Espaillat et al. 2008; Gupta, Srivastava, & Wita 2009; Lachowicz et al. 2009; King et al. 2013; Sandrinelli, Covino, & Treves 2014, 2016b; Sandrinelli et al. 2016a, 2018; Graham et al. 2015; Ackermann et al. 2015; Bhatta et al. 2016; Bhatta 2017, 2018; Li et al. 2017; Xiong et al. 2017; Zhang et al. 2017a, Zhang et al. 2017b, 2018; Gupta et al. 2018, and references therein). QPOs in blazars apparently are occasionally present on diverse timescales in γ-ray, X-ray, optical, and radio bands, where the monitoring data has come from a broad range of space and ground based telescopes. Many hundreds of light curves with different time resolutions in different EM bands have been analyzed by a variety of groups around the globe and QPOs have been only firmly detected in a few light curves of AGN of different sub-classes. We are unaware of a claimed detection of a QPO in the same AGN with a nearly similar central period in the same EM band. Hence it is a logical conclusion that QPOs in AGNs are both rare and transient in nature.

B2 1520+31 (α2000.0 = 15h22m09.99s, δ2000.0 = +31°44′14.4″) is a high redshift FSRQ located at z = 1.49 (Shaw et al. 2012; Paris et al. 2017). This blazar was detected in the first 3 months of Fermi-LAT observations and marked as a variable source (Abdo et al. 2009, 2010c). It has shown daily activity with γ-ray flux in the LAT band ≥10−6 ph cm−2 s−1 (Cutini & Hays 2009; Sanchez 2010). The broadband spectral energy distribution (SED) is a typical of FSRQs, with more than an order of magnitude more emission at γ-ray energies than in the optical, so the higher energy bump of the entire spectrum dominates the overall emission (Abdo et al. 2010a). The simultaneous broadband SED of B2 1520+31 has been investigated (Cao & Wang 2013; Pacciani et al. 2014) and can be explained with a one zone emission model. Considering temporal properties Kushwaha et al. (2017b) analysed the γ-ray Fermi-LAT light curve of this blazar in the energy range 0.1–300 GeV, binned in 3-day intervals. They found that the flux distribution is log normal, with a linear relation between flux and intrinsic variability. They suggested that the variability is of a non-linear, multiplicative nature and are consistent with the statistical properties of magnetic reconnection powered minijets-in-a-jet model (Biteau & Giebels 2012; Clausen-Brown & Lyutikov 2012).

Here we report the first probably QPO detection in the blazar B2 1520+31 with a period of ∼71 days in 0.1–300 GeV γ-ray energies. This is also the first QPO detection in the blazar B2 1520+31 in any EM band at any timescale.

In Section 2 of the manuscript, we briefly describe the γ-ray Fermi LAT data and our analysis procedure. In Section 3 we present the QPO search methods we employed and the results of those analyses. A discussion and our conclusions are given in Section 4.

2 DATA AND REDUCTION

We downloaded γ-ray data for B2 1520+31 for the period between October 5, 2008 to October 5, 2015 (MJD: 54683 – 57300) from the Large Area Telescope (LAT) on board the space-based Fermi observatory that was processed through the PASS8 (P8R2) instrument response function. We analyzed the data with the Fermi Science Tool (v10r0p5) software for photon energies between 100 MeV to 300 GeV. For a given time interval, we first selected the "SOURCE" class registered events between these energies from a 15° circular region of interest (ROI) centered on the source location (RA: 230.541632, DEC: 31.737328). At the same time, a maximum zenith angle restriction of 90° was applied to avoid the contamination of γ-rays from the Earth’s limb. The corresponding good time intervals (GTIs) were generated using the flag "(DATA_QUAL>0)&(LAT_CONFIG==1)" which characterizes the spacecraft operation in Scientific mode.

Finally, the effect of selections, cuts, point spread function and presence of point sources were accounted for in the exposure map, generated on a ROI+10° radius. The input model spectrum XML file of sources within this region was generated using the LAT 3rd catalog (3FGL;Lpulsar_v16.fit; Acero et al. 2015) which also includes the contribution of Galactic diffuse and isotropic extra-galactic emission through the respective emission templates “gll_ebl_v06.fits” and “isoP8R2_SOURCE_V6_v06.txt”, as provided by the LAT Science Team. Finally, the selected events were optimized against the input model spectrum file and exposure to extract the best fit model parameters using the python implementation of the "unbinned likelihood analysis" method (GTLIKE) provided with the software.

We extracted the light curve of the source over every 3-day interval by following the above procedures. The optimization over input source model spectrum file was performed iteratively by removing insignificant sources, measured by Test Statistics (TS) < 0 and freezing the parameters of low TS sources until convergence is reached (e.g. Kushwaha, Singh, & Sahayananthan 2014). All the sources in the model file had the default spectrum from the 3FGL catalog assumed. Finally, only fluxes ≥3σ defined by a TS of ≥9 were considered, resulting in a ∼97% coverage of the source over the lengthy duration of these observations (e.g. Kushwaha et al. 2017b).
3 LIGHT CURVE ANALYSIS AND RESULTS

The 0.1 – 300 GeV Fermi LAT \(\gamma\)-ray light curve of the blazar B2 1520+31, binned in 3 day intervals, for observations taken from August 5, 2008 to October 5, 2015 is plotted in Fig. 1(a). A visual inspection indicated a possible a QPO in the observations made during the first portion of this interval (August 5, 2008 to June 22, 2012) which are replotted in Fig. 1(b). To examine and quantify the possibility of a QPO, we analyzed the nearly four-year long light curve data of Fig. 1(b) employing the extensively used Lomb-Scargle periodogram (LSP) and weighted-wavelet z-transform (WWZ) techniques. In the following subsections we briefly explain these techniques and the QPO periods detected by them.

3.1 Lomb-Scargle periodogram

The LSP method is widely used to determine if periodicities are present in the data (Lomb 1976; Scargle 1982) and can be applied to unequally sampled data. The method basically involves fitting the sine function throughout the data by using \(\chi^2\) statistics. It reduces the effect of the noise on the signal and also provides a measure of the significance of any periodicity it indicates (Hong, Xiong, & Bai 2018; Zhang et al. 2017a; Xiong et al. 2017; Bhatta et al. 2016). For more details of our implementation of the LSP please see Gupta et al. (2018, and references therein).

In Fig. 2, the normalized power of the LSP is plotted against the time period. The horizontal line represent the false alarm probability of 0.0001 which corresponds to a nominal 99.999% confidence level. One signal, at the period of 70.8\(^{+3.7}_{-2.8}\) days, reached that significance level. This raises the possibility of there being a true QPO of this period which we found to be supported by other methods.

The light curves of AGNs in a range of electromagnetic bands from optical through X-rays and \(\gamma\)-rays are usually dominated by red noise, which arises from stochastic processes in the accretion disks, or in the case of blazars, more likely from jets (e.g., Fan et al. 2014; Xiong et al. 2017; Zhang et al. 2017a,c; Bhatta 2017; Hong, Xiong, & Bai 2018, and references therein). Hence we also employed the REDFIT method to fit the data with a first order auto-regressive (AR1) process (Schulz & Mudelsee 2002; Fan et al. 2014; Xiong et al. 2017; Hong, Xiong, & Bai 2018; Gupta et al. 2018). In auto-regressive models the data at a given time are related with previous values through a regressive relation, and these can involve different numbers of previous values. In the simplest AR1 model the data point at any instance is taken to be related to just the previous one. This code first computes the time series based on AR1 and generates a theoretical AR1 spectrum. It then calculates significance levels based on the \(\chi^2\) distribution. In Fig. 3, the bias corrected power spectrum and a modeled AR1 spectrum are plotted against the temporal frequency. We find two peaks which are above the displayed 95\% significance level. One peak corresponds to the period 70.8\(^{+1.83}_{-0.74}\) days and the other is at 39.33\(^{+0.54}_{-0.36}\) days. The second peak could be a harmonic of the first peak, which is more significant.

3.2 Wavelet analysis

Wavelet analyses allow for the determination and estimate of the significance of a period by decomposing the data into time and frequency domains simultaneously (Torrence & Compo 1998). For more details on this approach, see Gupta et al. (2018, and references therein). We used the WWZ1 software to calculate the weighted wavelet z-transform (WWZ) power for a given time and frequency (e.g. King et al. 2013; Bhatta et al. 2016; Bhatta 2017, 2018; Zhang et al. 2017a,b, 2018, and references therein). To estimate the significance of the signal, we also calculate the time averaged WWZ power, which gives the strength of the signal at each frequency.

Figure 4 shows the results of our WWZ analysis. The left panel of the figure plots the WWZ determined power. It illustrates strong concentrations of power around two periods: 71.43\(^{+0.51}_{-0.41}\)

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1 https://www.aavso.org/software-directory
days and 178.57$^{+6.25}_{-3.13}$, The feature around 71 days is strong and persistent throughout most of the observation. The feature a period of around 179 days is of more moderate strength and is persistent throughout the observation; however, it is very close to 0.5 years and thus has a significant chance of being an observational artifact. The time averaged WWZ powers in the right panel of Fig. 4 is plotted shows that these periods exceed $3\sigma$ (99.73%) significance.

4 DISCUSSION AND CONCLUSION

We examined the long term 0.1 - 300 GeV energies $\gamma$-ray light curves of four AGNs (the FR I radio galaxy NGC 1275, the BL Lac Mrk 421, and the FSRQ, PKS 1510-089) as well as B2 1520+31, as presented in (Kushwaha et al. 2017b) to see if they showed any indications of quasi-periodicity. We analyzed these light curves using two techniques, LSP (including REDFIT) and WWZ, which are commonly used for searching for QPOs in AGN time series data (Gupta et al. 2018, and references therein). We found a probable QPO with a period of ~ 71 days in an extended segment of the light curve of the FRSQ B2 1520+31, but did not find a QPO in any of the other three AGN.

In general, blazar emission across the complete EM spectrum is dominated by non-thermal jet emission. This is primarily because in blazars, the jet is seen at very small angle ($< 10^\circ$) the the line of sight to the observer (Urry & Padovani 1995). Jet emission will be strongly amplified due to the relativistic beaming effect, often overwhelming all the thermal contributions from the AGN and the host galaxies stars. But in the FSRQ class of blazars, relatively efficient accretion disk emission and broad line region (BLR) emission lines are present (D’Ammando et al. 2011). Since B2 1520+31 is a FSRQ, the total emission from this blazar will be expected to have contributions from the accretion disk and the BLR as well as the jet emission. Many FSRQs show a quasi-thermal excess blue/UV bump above the synchrotron emission in their broad band SEDs (e.g. Pian et al. 1999; Grandi & Palumbo 2004; Raiteri et al. 2007, 2008; D’Ammando et al. 2009; Vercellone et al. 2010; Abdou et al. 2010b; D’Ammando et al. 2011, and references therein). This portion of the emission from FSRQs is due to both the accretion disk (the so-called “big blue bump”), (e.g. Laor 1990) and the BLR (the so-called “little blue bump”), (e.g. Wills, Netzer, & Wills 1985). The contribution of these thermal features will have important consequences in the low-energy part of the SED, in which this emission could be directly observed. Meanwhile, the photons produced by the accretion disk, either directly or through reprocessing in the BLR or the dusty torus, are the source of seed photons for the external Compton (EC) mechanism that is often apparently responsible for the $\gamma$-ray emission of FSRQs, which comprises the high energy hump of the SED and the $\gamma$-ray fluxes considered here (e.g. Gaur, Gupta, & Wiita 2012; Kushwaha et al. 2017a; Gupta et al. 2017, and references therein).

The mass of the central supermassive black hole (SMBH) in an AGN is, along with the accretion rate and efficiency of mass to energy conversion, one of the most important quantities to characterize. The most accurate, or primary, black hole mass estimation methods include stellar and gas kinematics and reverberation mapping (e.g. Vestergaard 2004). All these methods require high spatial resolution spectroscopy data from the host galaxy and/or higher-ionization emission lines and are not applicable to most blazars. The BLL class of blazars have essentially featureless spectra, so, primary methods can not be used. But in the case of FSRQs, prominent emission lines are present, so we can use the method (Vestergaard & Peterson 2006).

An alternative way to estimate the SMBH mass of an AGN comes from using the period of a detected QPO if we assume the QPO is related to the orbital timescale of a hot spot, spiral shocks, or other non-axisymmetric phenomena in the innermost portion of the rotating accretion disk (e.g. Zhang & Bao 1991; Mangalam & Wiita 1993; Chakrabarti & Wiita 1993; McKinney et al. 2012). Using this assumption for the origin of a QPO, one has an expression for the SMBH mass, $M$ (Gupta, Srivastava, & Wiita 2009)

$$M = \frac{3.23 \times 10^4 P}{(r^3/2 + a)(1 + z)}.$$  

in terms of the QPO period $P$ in seconds and the radius of this source zone, $r$ (in units of $GM/c^2$), and SMBH spin parameter $a$. The range of nominal masses of the SMBH with such a QPO source can be evaluated in this fashion for perturbations at the innermost stable circular orbit for a Schwarzschild BH (with $r = 6.0$ and $a = 0$), and for a maximal Kerr BH (with $r = 1.2$ and $a = 0.9982$) (Gupta, Srivastava, & Wiita 2009).

In the case of FSRQ B2 1520+31, using equation (1) for the period of 71 days, we get an SMBH mass estimate of $5.41 \times 10^9 \ M_\odot$ for the Schwarzschild limit and $6.02 \times 10^{10} \ M_\odot$ for the maximal Kerr limit. Even the former estimate is very large while the latter exceeds essentially all other SMBH mass estimates (e.g. Dietrich & Hamann 2004; Valtonen, Ciprini, & Lehto 2012; Wu et al. 2015; Zuo et al. 2015; Ghisellini et al. 2015), so attributing this apparently detected QPO to emission directly reflecting a transient non-axisymmetric accretion structure is rather unlikely, particularly for the high energy emission that would not directly emerge from the disk. If the portion of the disk taken to be responsible for a QPO is further out than the innermost portions assumed above, then the estimated mass decreases, perhaps to more reasonable values.

Nonetheless, it is also a prior more likely that the detected QPO in any blazar is related to the jet emission and not directly to that of the accretion disk. If the jet precesses or has an internal helical structure, which is certainly plausible in blazars (e.g. Camenzind & Krockenberger 1992; Villata & Raiteri 1999; Rieger 2004; Mohan & Mangalam 2015), then as shocks advance along the helical structure of the jet or as the jet precesses or twists, quasi-periodic flux variations would arise from variations in the Doppler boosting factor as seen by the observer. Ackermann et al. (2015), in describing a possible roughly 2 year QPO in the $\gamma$-ray (and other band as well) emission from the blazar PG 1553+113, nicely summarize several possibilities along these lines. For instance, Lense-Thirring precession of the disk (e.g. Wilkins 1972) could modulate the direction of the jet (e.g. Fragile & Meier 2009).

Another clear way to induce jet precession is for the AGN to be part of a binary SMBH system (e.g., Begelman et al. 1980; Valtonen et al. 2008; Graham et al. 2015), but these orbits are most likely to produce physical periods in the jets exceeding 1 year (e.g. Rieger 2007) and several candidate $\gamma$-ray QPOs with periods longer than that have recently been discussed in this framework (e.g. Ackermann et al. 2015; Sandrinelli et al. 2016a; Sandrinelli, Covino, & Treves 2016b; Zhang et al. 2017a,b,c) However, as noted by (Rieger 2004), the observed periods could be substantially shorter for sufficiently well aligned jets and large enough Lorentz factors. This scenario was shown to be quite reasonable for an apparent QPO in the BLL PKS...
$\gamma$-ray QPO in the blazar B2 1520+31

Figure 4. Weighted wavelet z-transform of the light curve presented in Fig. 1(b). The left panel shows the distribution of color-scaled WWZ power (with red most intense and black lowest) in the time-period plane; the right panel shows the time-averaged WWZ power (solid blue curve) as a function of period and the 99.73% global significance (dashed black curve).

2247–131 of an even shorter observed oscillation at around $\sim$ 34 days (Zhou et al. 2018).

Unfortunately, B2 1520+31 was not the subject of frequent VLBI measurements, nor was there good optical monitoring of this blazar between 2008 and 2012. Without a good measurement of the jet Lorentz factor and the angle to our line of sight of the center of the jet of B2 1520+31 it is not possible to reasonably constrain the parameters of any of these jet based models to produce the variations in Doppler factors that would be required to yield the high amplitude apparent $\sim$ 71d QPO we have found.

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