
**Multiwavelength Evidence for Quasi-periodic Modulation in the Gamma-Ray Blazar PG 1553+113**

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ABSTRACT

We report for the first time a $\gamma$-ray and mult iwavelength nearly periodic oscillation in an active galactic nucleus. Using the Fermi Large Area Telescope we have discovered an apparent quasi-periodicity in the $\gamma$-ray flux ($E > 100$ MeV) from the GeV/TeV BL Lac object PG 1553+113. The marginal significance of the 2.18 ± 0.08 year period $\gamma$-ray cycle is strengthened by correlated oscillations observed in radio and optical fluxes, through data collected in the Owens Valley Radio Observatory, Tuorla, Katzman Automatic Imaging Telescope, and Catalina Sky Survey monitoring programs and Swift-UVOT. The optical cycle appearing in ~10 years of data has a similar period, while the 15 GHz oscillation is less regular than seen in the other bands. Further long-term multiwavelength monitoring of this blazar may discriminate among the possible explanations for this quasi-periodicity.

Key words: accretion, accretion disks – BL Lacertae objects: general – BL Lacertae objects: individual (PG 1553+113) – galaxies: jets – gamma rays: galaxies – gamma rays: general

1. INTRODUCTION

Among active galactic nuclei (AGNs), blazars are distinguished by erratic variability at all energies on a wide range of timescales. They are generally thought to be powered by supermassive black holes (SMBHs; $10^8$–$10^9 M_\odot$). PG 1553+113 (1ES 1553+113, $z \sim 0.49$; Danforth et al. 2010; Abramowski et al. 2015; Aliu et al. 2015) is an optically/X-ray selected BL Lac object (Falomo & Treves 1990) emitting variable GeV/TeV $\gamma$ radiation (Abramowski et al. 2015; Aleksić et al. 2015). As is typical in very high energy (VHE) BL Lacs, the energetic non-thermal emission of PG 1553+113 originates in a relativistic jet and has a spectral energy distribution (SED) with two humps, overwhelming any other component from either the nucleus or the host galaxy.

The Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope is providing continuous monitoring of the high-energy $\gamma$-ray sky. The apparent modulation noted in the $\gamma$-ray flux of PG 1553+113 initiated the multifrequency and long-term variability study described in this paper.

In Section 2 we describe the Fermi-LAT data analysis and the sources of multiwavelength data; Section 3 details the multiple approaches used for light curves and the cross-correlation analysis; Section 4 outlines preliminary scenarios to interpret these results.

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performed as part of the Tuorla blazar monitoring program
(Takalo et al. 2008). The data are reduced using a semi-
automatic pipeline (K. Nilsson et al. 2015, in preparation).
Public data from the Katzman Automatic Imaging Telescope
(KAIT) and the Catalina Sky Survey (CSS) programs are also
added. V-band magnitudes are scaled to the R-band values.

As part of an ongoing blazar monitoring program supporting
Fermi (Richards et al. 2011), the Owens Valley Radio
Observatory (OVRO) 40 m radio telescope has been observing
PG 1553+113 continually (about every 1–23 days) since 2008
August. Figure 2 reports published 15 GHz light curves for the
period from 2008 August 19 to 2014 May 18 (MJD 54697-
56795). OVRO instrumentation, data calibration, and reduction
are described in Richards et al. (2011).

Swift observed PG 1553+113 110 times between 2005 April
20 and 2015 July 18 (unabsorbed 0.3–2 keV flux light curve
in Figure 2). X-Ray Telescope (XRT) data were first calibrated
and cleaned (xrtipeline, XRTDAS v.3.0.0) and then
energy spectra were extracted from a region of 20 pixel (∼47")
radius, with a nearby 20 pixel radius region as a background.
Individual XRT spectra are well fitted with a log-parabolic
model, with column density fixed to the Galactic value of
3.6 × 10^{20} cm⁻² (Kalberla et al. 2005). Aperture photometry
(5") radius) for the UVOT V-band filter was performed.

3. TEMPORAL VARIABILITY ANALYSIS AND
CROSS-CORRELATION ANALYSIS

We performed continuous wavelet transform (CWT) and
Lomb–Scargle Periodogram (LSP) analyses on the light curves.
Figure 3 shows clear peaks at ∼2 years for γ-ray and optical
power spectra. We also made an epoch folding (pulse shape)
analysis to extract the period, shape, amplitude, and phase with
uncertainties (Larsson 1996). The χ² for the folded pulse as a
function of the trial periods was fitted with a model containing
four Fourier components, giving a period of 798 ± 30 days
(2.18 ± 0.08 years), consistent with the CWT and LSP
findings (Figure 3). The value of the signal power peak does not change
using regular 20 day and 45 day bins or an adaptive-bin
technique (Lott et al. 2012) for construction of the LAT light
curve.

A direct power density spectrum (PDS) constructed from a
LAT count rate light curve using exposure-weighted aperture
photometry (Corbet et al. 2007; Kerr 2011) above 100 MeV for
a region with 3° radius with 600 s time bins (Figure 4)
confirms previous results with a peak at 2.16 ± 0.08 years, at 82×
the mean power level. The low-frequency modulation prevents an
easy fit subtraction to the PDS continuum. The peak is ∼5
times the mean level using a 4th order polynomial fit.

The significance of any apparent periodic variation depends on
what assumption is made about spurious stochastic
variability mimicking a periodic variation. The significance of
the ∼2 year γ-ray periodicity is difficult to assess given the
limited length of the γ-ray light curve. Red noise, i.e., random
and relatively enhanced low-frequency fluctuations over

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intervals comparable to the sample length, hinders the evaluation of the periodicity significance (e.g., Hsieh et al. 2005; Lasky et al. 2015). We have approached the problem with two procedures.

1. The red noise is assumed to be produced by similar amplitude flares (as seen in PG 1553+113 and some other LAT blazars), and the probability for these to line up in a regular pattern is estimated. The coherence of the periodic modulation was investigated by studying phase variations along the light curve. The local phase at each minimum and maximum was estimated by correlating a one-period-long data segment with the Fourier template of the full light curve. The rms variations relative to a perfectly coherent modulation were 27.4 days. The chance probabilities for three, four, and five random events to be distributed with at least this coherence, as estimated by Monte Carlo simulations, are 0.0535, 0.0105, and 0.0027, respectively, implying a chance probability of a few percent for the 3.5 peak γ-ray light curve of PG 1553+113.

2. We modeled the red noise using Monte Carlo simulations with a first-order autoregressive process as the null hypothesis to assess whether the signal is consistent with a stochastic origin. The nonlinear influence on the PDS is minimal thanks to the evenly spaced γ-ray light curve. The power peak in Figure 3 is above the 99% confidence contour level, i.e., has <1% chance of being a statistical fluctuation. The optical power peak has <5% chance of being a statistical fluctuation.

Although the γ-ray periodicity signal alone is not compelling, the 9.9 years of optical data support the finding of a periodic oscillation in PG 1553+113. The optical data, although affected by seasonal gaps, were analyzed using the same techniques as for the γ-ray data. This analysis gives a period of 754 ± 20 days (2.06 ± 0.05 years), consistent within uncertainties with the γ-ray results (Figure 3).

The less coherent 15 GHz light curve (5.7 years OVRO data) shows a signal power peak at 1.9 ± 0.1 year, with an additional power component at a 1.2 year timescale. Swift-XRT data show a factor of 5 variation linearly correlated with the γ-ray flux, while the synchrotron peak frequency shows a factor of ∼6 increase during high X-ray states, as suggested by Reimer et al. (2008).

The long-term X-ray count rate light curve from the RXTE ASM instrument (1996 February 20 to 2010 September 11) and the Swift-BAT (from 2005 May 29) were also analyzed but do not show any signal above the low-frequency noise because of insufficient statistics.

An important diagnostic for multifrequency periodicity analysis is the discrete cross-correlation function (DCCF) used with two independent and complementary approaches.

In the first procedure, flux variations are modeled assuming a simple power law $\propto 1/f^\alpha$ (with $f = 1/t$) in the PDS as measured directly from the light curve data, allowing us to estimate the cross-correlation significance, and avoiding the
assumption of equal variability in all sources at the cost of a model assumption (Max-Moerbeck et al. 2014). For the γ-ray light curve with 20 day binning we obtain a best fit $\alpha = 0.8$, but the error is unconstrained, indicating that the length of the data set is too short (i.e., below five cycles) relative to the suspected periodic modulation to enable a reliable data characterization. The 45 day bin light curve yields a best fit $\alpha = 0.1$ with unconstrained error. The optical PSD is constrained: the best fit value is $\alpha = 1.85$, with 1σ limits at $[1.75, 2.00]$.

The 15 GHz flux light curve has a slope of $\alpha = 1.4$, with unconstrained limits on the $\alpha$ values as for the γ-ray data. The DCCF between the unbinned radio light curve and the 20 day bin γ-ray light curve results in a most probable time lag for the radio flux lagging the γ-ray flux by $50 \pm 20$ days, with 98.14% significance for the best PSD fit with a range of $[89.56\%–99.99\%]$ when fit errors are taken into account (Figure 5) using the fitting procedure of Max-Moerbeck et al. (2014). The DCCF between the unbinned optical light curve and the 20 day bin γ-ray light curve results in a most probable time lag for the γ-ray flux lagging the optical flux by $130 \pm 14$ days, with 99.14% significance for the best PSD fit and $[96.09\%–99.97\%]$ when fit errors are taken into account (Figure 5). The DCCF peak is broad, however, and consistent with no lag. This is also seen when the optical data are rebinned into 20 day intervals, as shown in the bottom panel, where the most probable lag is $10 \pm 51$ days.

In the second procedure, the significance of the γ-ray–radio correlation was estimated to be 95% using a mixed source correlation procedure (Fuhrmann et al. 2014), cross-correlating the PG 1553+113 light curve with those of 132 comparison sources in that work, and evaluating the average DCCF level for time lags of $-100$ to $+100$ days. The γ-ray–optical correlation is significant at the 99% level, even though it is partly limited by the number of comparison sources and optical light curves.
light curve and bins each bin. the signiﬁcance of this is hard to determine. With the mixed in principle a 99% level of signiﬁcance contours in this case is due to the number of samples in each bin. 

Figure 5. Discrete cross-correlation plots from the approach with the PDS model measured from the light curve data (Max-Moerbeck et al. 2014). In each plot the black dots are the DCCF estimates and the red, orange, and green lines are the 1σ, 2σ, and 3σ signiﬁcance levels, respectively. Top panel: DCCF between the radio 15 GHz and γ-ray (20 day time bins) light curve. Central panel: DCCF between the unbinned optical light curve and γ-ray (20 day time bins) light curve. Bottom panel: DCCF between the 20 day rebinned optical light curve and γ-ray (20 day time bins) light curve. The oscillating shape of the significance contours in this case is due to the number of samples in each bin.

light curve gaps. With only 132 comparison light curves we can measure a minimum probability value of 0.0075, therefore in principle a 99% level of signiﬁcance, but in this approach the error in that estimate is hard to determine. With the mixed source methods there are two limitations: (1) the assumption that all sources can be described with the same model for the variability, and (2) the sample variance due to the limited number of light curves must be assessed. The optical ﬂux is found to lead the γ-ray variations by 75 ± 27 days and the radio by 158 ± 10 days (γ-ray variations lead the 15 GHz ﬂux variations by 83 ± 27 days). The possible reverse γ-ray–optical time lag decreases to 28 ± 27 days when the optical light curve is binned.

The possible optical–γ-ray lag was already pointed out by Cohen et al. (2014) using KAIT unbinned optical light curves and LAT data. The high degree of γ-ray–radio correlation in PG 1553+113 is not typically found in other individual blazars/AGNs (see Max-Moerbeck et al. 2014). Signiﬁcant cross-correlations are, nevertheless, found when stacking blazar samples (radio lagging γ-rays; Fuhrmann et al. 2014).

4. DISCUSSION AND CONCLUSIONS

Factors that led to the indication of a possible ∼2 year periodic modulation in PG 1553+113 are the continuous all-sky survey of Fermi, the increased capability of the new Fermi-LAT Pass 8 data, and the long-term radio/optical monitoring of γ-ray blazars. Although the statistical signiﬁcance of periodicity is marginal in each band, the consistent positive cross-correlation between bands strengthens the case, making PG 1553+113 the ﬁrst possible quasi-periodic GeV γ-ray blazar and a prime candidate for further studies. Hints of possible γ-ray periodicities are rare in the literature (for example Sandrinelli et al. 2014). The similarity of the low- and high-energy modulation in PG 1553+113 is also a novel behavior for AGNs (Rieger 2004, 2007). Any periodic driving scenario should be related to the relativistic jet itself or to the process feeding the jet for this VHE BL Lac object. We outline, as examples, four possibilities.

1. Pulsational accretion ﬂow instabilities. Approximating periodic behavior, are able to explain modulations in the energy outﬂow efﬁciency. Magnetically arrested and magnetically dominated accretion ﬂows (MDAFs) would be suitable regimes for radiatively inefﬁcient BL Lacs (Fragile & Meier 2009), characterized by advection-dominated accretion ﬂows and subluminal, turbulent, and peculiar radio kinematics (Kharb et al. 2008; Karouzos et al. 2012; Piner & Edwards 2014). Such kinematics are sometimes explained as a precessing or helical jet (Conway & Murphy 1993). MDAFs in an inner disk portion are able to efﬁciently impart energy to particles in the jets of VHE BL Lacs (Tchekhovskoy et al. 2011). Periodic instabilities are believed to have short periods, ∼10^5 s (M_{SMBH}/10^8 M_{Sun}) (Honna et al. 1992), but MHD simulations of magnetically choked accretion ﬂows are seen to produce longer periods for slow-spinning SMBHs (McKinney et al. 2012).

2. Jet precession (e.g., Romero et al. 2000; Sühring et al. 2003; Caproni et al. 2013), rotation (Camenzind & Krockenberger 1992; Vlahakis & Tsinganos 1998; Hardee & Rosen 1999), or helical structure (e.g., Conway & Murphy 1993; Roland et al. 1994; Villata & Raiteri 1999; Nakamura & Meier 2004; Ostorero et al. 2004; Mohan & Mangalam 2015), i.e., geometrical models (Rieger 2004), in the presence of a jet wrapped by a sufﬁciently strong magnetic ﬁeld, could have a net apparent periodicity from the change of the viewing angle. Correspondingly, the resulting Doppler magniﬁcation factor changes periodically without the need for intrinsic variation in outﬂows and efﬁciency. Non-ballistic hydrodynamical jet precession may explain variations with periods >1 year (Rieger 2004). A differential Doppler factor ∆D(t)=Γ^{-1}(1−β(t)cos θ(t))^{-1} ≤ 40% variation (precession angle ∼1°) might be sufﬁcient to support the ∼2.8 amplitude ﬂux modulation seen in γ rays. A homogeneous curved helical jet scenario for PG 1553+113 was proposed in Raiteri et al. (2015).
3. A mechanism analogous to low-frequency QPO from Galactic high-mass binaries/microquasars could produce an accretion–outflow coupling mechanism as the basis of the periodicity (Fender & Belloni 2004). King et al. (2013) ascribed the radio QPO in the FSRQ CGRαS J1359+4011 to this mechanism. However BL Lac objects like PG 1553+113 are thought to possess a lower accretion rate. The microquasar QPO mechanism of Lense–Thirring precession (Wilkins 1972) requires that the inner accretion flow forms a geometrically thick torus rather than a standard thin disk as the latter warps (Bardeen–Petterson effect, Bardeen & Petterson 1975) rather than precesses (Ingram et al. 2009). A low mass accretion rate means that the accretion process probably forms an advection-dominated accretion flow (ADAF) so it can precess (Fragile & Meier 2009). The X-ray emission in PG 1553+113 is probably from the jet rather than from the flow, making it unlikely that the changing inclination of the hot flow causes the QPO. However, Lense–Thirring precession of the flow could affect the jet direction, giving the QPO as in (2) above.

4. The presence of a gravitationally bound binary SMBH system (Begelman et al. 1980; Barnes & Hernquist 1992) with a total mass of $\sim 10^9 M_\odot$ and a milliparsec separation in the early inspiral gravitational-wave driven regime might be another hypothesis. Keplerian binary orbital motion would induce periodic accretion perturbations (Valtonen et al. 2008; Pihajoki et al. 2013; Liu et al. 2015) or jet nutation expected from the misalignment of the rotating SMBH spins or the gravitational torque on the disk exerted by the companion (Katz 1997; Romero et al. 2000; Caproni et al. 2013; Graham et al. 2015). Significant acceleration of the disk evolution and accretion onto a binary SMBH system is depicted by modeling (Nixon et al. 2013; Doğan et al. 2015).

Binary SMBH induced periodicities have timescales ranging from $\sim 1$ to $\sim 25$ years (Komossa 2006; Rieger 2007). The SMBH total mass in PG 1553+113, estimated utilizing the putative link between inflow/ outflow (disk luminosity) and outflow/jet (jet power) in blazars (Ghisellini et al. 2014), is $\approx 1.6 \times 10^8 M_\odot$ using a 0.1 $M_{\text{Edd}}$ rate and Doppler factor $D = 30$, in agreement with estimates for VHE BL Lacs (Woo et al. 2005).

The observed 2.18 year period is equivalent to an intrinsic orbital time $T_{\text{Kepler}} \leq T_{\text{obs}}/(1 + z) \approx 1.5$ years, and the binary system size would be 0.005 pc ($\sim 100$ Schwarzschild radii). The probability of observing such a milliparsec system, estimated from the binary mass ratios $\sim 0.1-0.01$ and the GW-driven regime lifetime (Peters 1964), $t_{\text{GW}} \approx 10^5-10^6$ years, might be too small.

Periodicities claimed for AGNs are often controversial; however, PG 1553+113 may potentially represent a key $\gamma$-ray/multimessenger laboratory in the hypothesis of low-frequency gravitational-wave emission and may have associated PeV neutrino emission (Padovani & Resconi 2014). Very long baseline interferometry structure observations (Kharb et al. 2008), radio/optical polarization data, and a prolonged multi-frequency monitoring campaign will shed light on the situation. If the periodic modulation is real and coherent, as would be expected for a binary scenario, then subsequent maxima would be expected in 2017 and 2019, well within the possible lifetime of the Fermi mission.

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Facilities: Fermi Gamma-ray Space Telescope, Swift, OVRO:40m, KAIT.

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