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## GAMMA-RAY AND OPTICAL OSCILLATIONS IN PKS 0537–441

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### ABSTRACT

We have considered the *Fermi*  $\gamma$ -ray light curve of the blazar PKS 0537–441 during a high state extending from 2008 August 10 to 2011 August 27. The periodogram exhibits a peak at  $T \sim 280$  days, with a significance of  $\sim 99.7\%$ . A peak of similar relevance at  $\frac{1}{2}T$  is found in the optical light curves. Considering the entire duration of the *Fermi* light curve 2008–2015, no significant peak is revealed, while the optical one remains meaningful. Comparing with recent observations of PKS 2155–304 and PG 1553+113 it seems that month–year oscillations can characterize some blazars. Month-scale oscillations can also show up only during phases of enhanced or bursting emission, such as in the case of PKS 0537–441.

**Key words:** BL Lacertae objects: general – BL Lacertae objects: individual (PKS 0537–441) – galaxies: jets – gamma rays: galaxies – gamma rays: general

### 1. INTRODUCTION

Blazars are jet-dominated active galactic nuclei with the jet pointing in the observer direction. A characteristic of the class is a large variability on various timescales and in all spectral bands (for a recent review see Falomo et al. 2014). Periodicities have been searched for since the discovery of the first members of the class. No convincing period was found, with the possible exception of the case of OJ 287, where the claim of a 12-year period (e.g., Sillanpää et al. 1988) appears rather robust, but not uncontroversial (e.g., Hudec et al. 2013).

The situation has changed significantly in recent years because it has become clear that blazars are the main constituents of the extragalactic  $\gamma$ -ray sky and the *Fermi* mission, since its launch has monitored the entire celestial sphere every three hours. The consequence is that  $\gamma$ -ray light curves of blazars are easily available. The *Fermi* Large Area Telescope (LAT) observations and light curve extraction procedures are described in detail, e.g., in Abdo et al. (2010). The *Fermi* Collaboration provides daily and weekly flux light curves of monitored sources of interest in automated analysis.<sup>4</sup> The available energy ranges are 1–300 GeV, 300 MeV–1 GeV, and 100 MeV–300 GeV. At the same time, robotic optical telescopes have become rather common, so that the monitoring time dedicated to blazars has substantially increased.

Sandrinelli et al. (2014a) examined the *Fermi* light curves of the prototypical BL Lac object PKS 2155–304 (redshift  $z = 0.116$ ,  $R$  magnitude  $\sim 13$ ) and discovered a significant periodicity of  $T \sim 630$  days, which is twice that obtained by Zhang et al. (2014), from a collection of all the published optical photometry of the source in 35 years. The existence of the optical periodicity was confirmed by our independent Rapid Eye Mounting Telescope (REM, Covino et al. 2004; Zerbi et al. 2004) photometry, which covered the source from 2008 to 2015/03 (Sandrinelli et al. 2014b, 2016). Recent papers (Ackermann et al. 2015; M. L. Ahen et al. 2016, in preparation) considered the *Fermi* light curves of another bright BL Lac object PG 1553+113 ( $z \sim 0.4$ ,  $R \sim 14$ ). A periodicity of 2.18 years is found with interesting significance  $S \gtrsim 99\%$ ,

which also shows up clearly in the  $R$ -monitoring. In Sandrinelli et al. (2016), we examined the  $\gamma$ -ray and optical light curves of PKS 0537–441, OJ 287, 3C 279, PKS 1510–089, PKS 2005–489, and PKS 2155–304. While the power spectra indicated several peaks in all sources, sometimes at related frequencies in  $\gamma$ -ray and optical filters, their significance is not very high, with the exception of PKS 2155–304. Short duration oscillatory patterns have been reported in various light curves of blazars, both in the optical and X-rays, e.g., in PKS 2155–304 (Urry et al. 1993; Lachowicz et al. 2009), OJ 287 (Kinzel et al. 1988), S5 0716+714 (Rani et al. 2010). Year timescale modulations were found in GB6 J1058+5628 (Nesci 2010) and also in radio bands, e.g., J1359+4011 (King et al. 2013), and PKS 1156+295 (Wang et al. 2014) Quasi-periodical outbursts were observed occurring in, e.g., S5 0716+714 Raiteri et al. (2003) and AO 0235+164 (Raiteri et al. 2008 and references therein).

In this paper, we refocus the case of PKS 0537–441, concentrating only on a rather high state.

### 2. PKS 0537–441

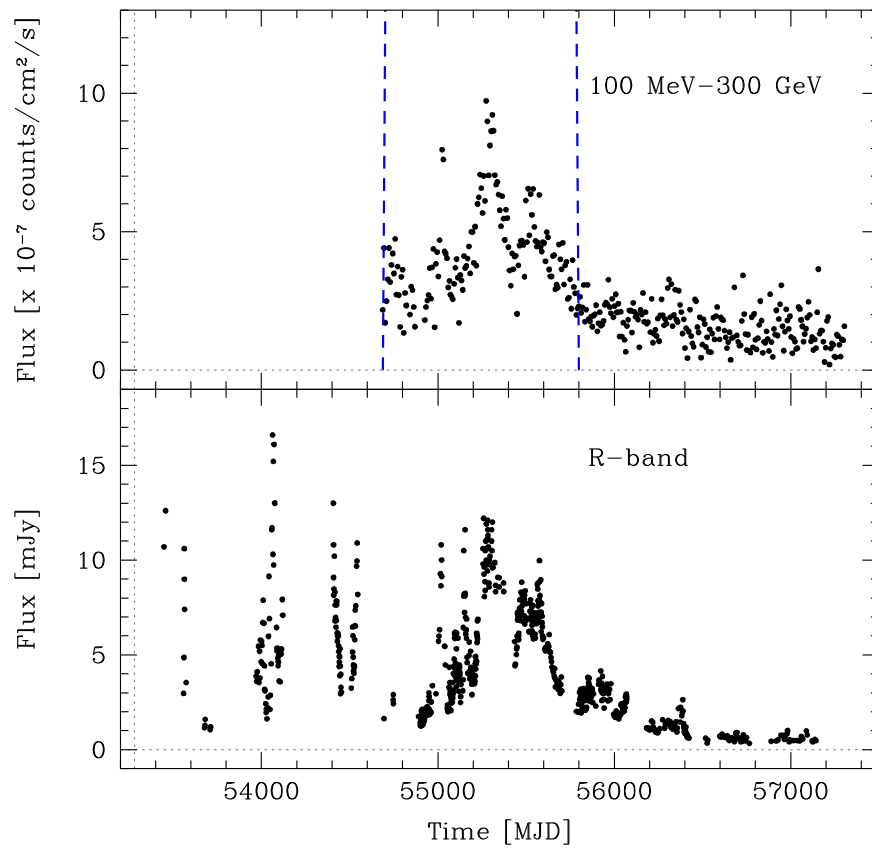
PKS 0537–441 is a very well studied object ( $z = 0.896$ ,  $R \sim 14$ ), with characteristics intermediate between Optically Violently Variable Quasars and BL Lacs. It was observed in all spectral bands from radio to GeV  $\gamma$ -rays. Detailed information on the source can be found in Pian et al. (2007) and D’Ammando et al. (2013). In Figure 1, we report the *Fermi*  $\gamma$ -ray light curve with one-week integration in the 100 MeV–300 GeV energy band, as provided by the *Fermi* LAT team (see above). We also report the  $R$ -band light curve obtained combining REM and Small Moderate Aperture Research Telescope System data (SMARTS<sup>5</sup>, Bonning et al. 2012). Details can be found in Sandrinelli et al. (2016).

### 3. SEARCH FOR PERIODICITIES

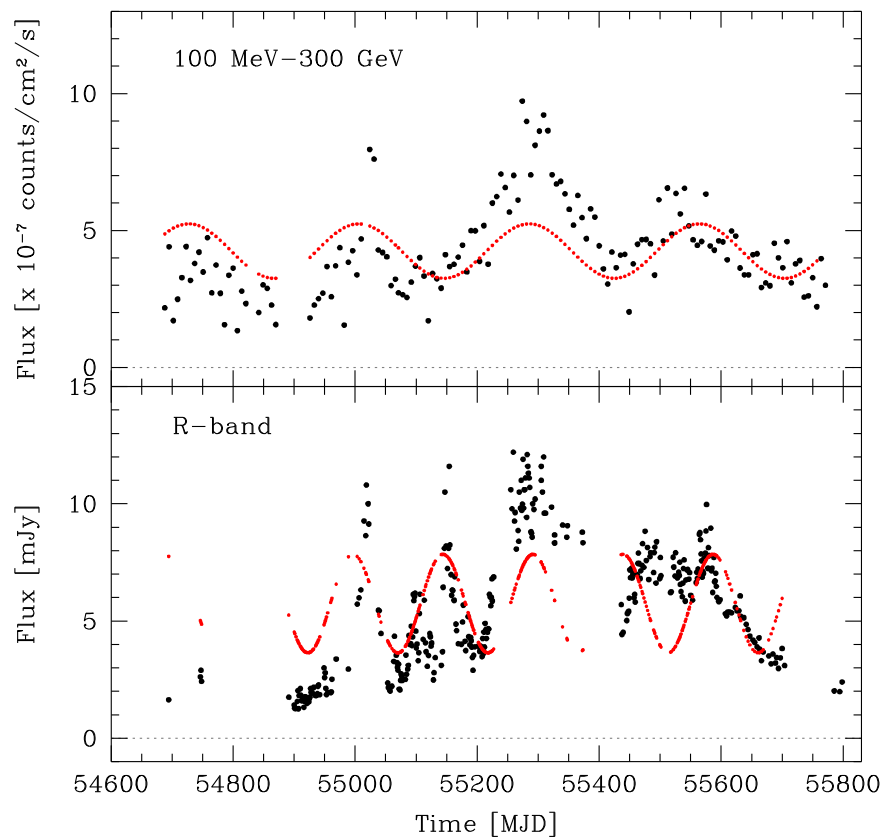
Our procedure for searching for regular oscillations closely follows that of Sandrinelli et al. (2016) and is based on the

<sup>4</sup> [http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl\\_lc/](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/)

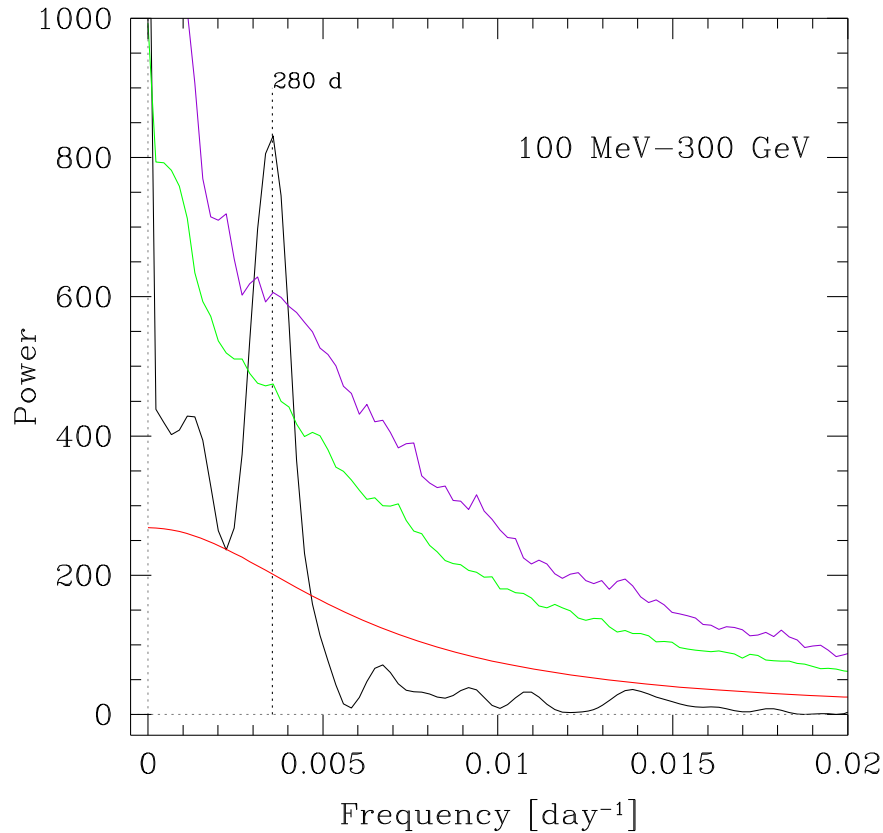
<sup>5</sup> <http://www.astro.yale.edu/smarts/glast/home.php>



**Figure 1.** Weekly averaged Fermi  $\gamma$ -ray light curve of PKS 0537–441 in the 100 MeV–300 GeV energy range (top panel). Nightly averaged REM and SMARTS light curve in  $R$  band is also reported (bottom panel). Vertical lines identify the  $\gamma$ -ray *high state* of the source. Errors are omitted for readability.



**Figure 2.** Enlargement of the high state of the source, see Figure 1. The red lines are the sinusoidal artificial models referring to the  $\gamma$ -ray period  $T_0 = 280$  day and to the optical period  $T_1 = 148$  day. Errors are omitted for readability.



**Figure 3.** Periodogram (black line) of the active phase of PKS 0537–441 (from 2008 August 10 to 2011 August 27) obtained from the *Fermi* 100 MeV–300 GeV data. The curves from the bottom are: red-noise spectrum (red curve), 95% ( $2\sigma$ , green curve) and 99% ( $2.5\sigma$ , purple curve) Monte Carlo significance levels after 1000 simulations. The period in days corresponding to the prominent peak is marked.

scheme proposed by Schulz & Mudelsee (2002): (1) it yields the Lomb and Scargle (Scargle 1982) periodograms also accounting for unevenly spaced photometry, when it is the case, (2) it models the red noise with a first-order autoregressive process as a null hypothesis of stochastic events, (3) it provides the bias-corrected periodograms and significance levels using Monte Carlo simulations.

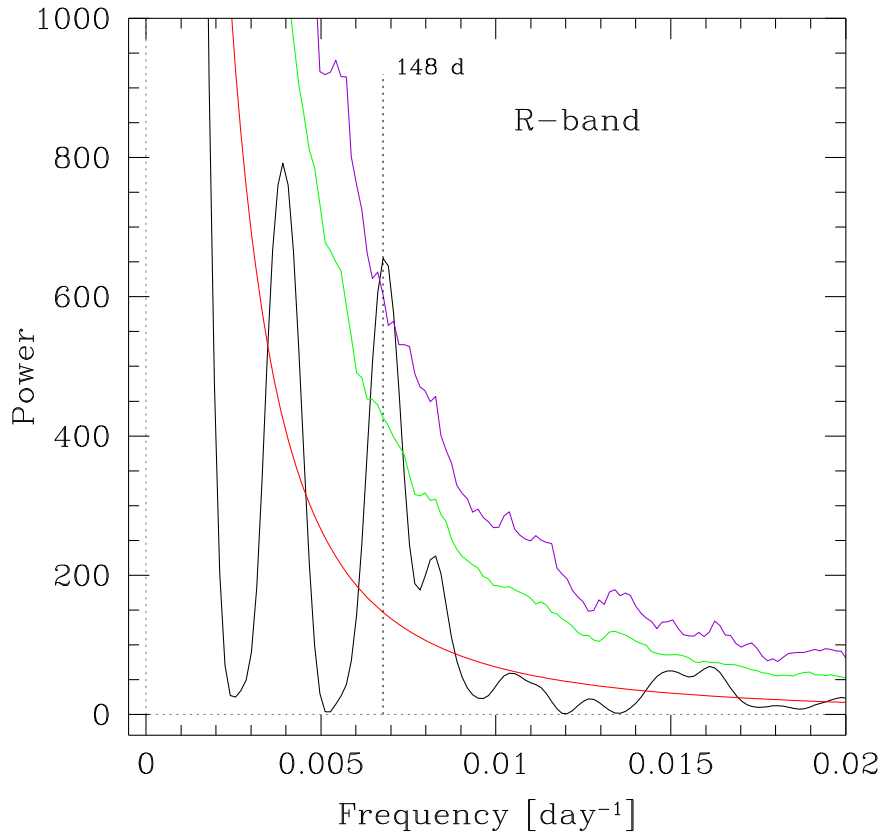
The analysis of the entire  $\gamma$ -ray light curve from 54688 MJD (2008 August 10) to 57304 MJD (2015 October 09) gives a peak of low significance at 351 day ( $S \sim 90\%$ ). Interestingly enough, in the  $R$ ,  $J$ ,  $K$  curves, there are peaks of significance  $\geq 99\%$  at  $\sim 150$  day (see also Figure 8 in Sandrinelli et al. 2016, for both  $\gamma$ -ray and optical power spectra). The absence of significant  $\gamma$ -ray peaks is consistent with the results of D’Ammando et al. (2013), who considered the *Fermi* light curve only up to 55290 MJD (2010 April 04), and to the standard time analysis<sup>6</sup> provided by the *Fermi* collaboration for the 2008–2015 light curve.

An examination of the  $\gamma$ -ray light curve (100 MeV–300 GeV) reported in Figure 1 indicates a rather high  $\gamma$ -ray state of the source from  $\sim 54688$  MJD (2008 August 10) to  $\sim 55800$  MJD (2011 August 27), followed by a lower state. The same is found in the 300 MeV–1 GeV and 1 GeV–300 GeV  $\gamma$ -ray light curves. We note that the state of the source remains low until the last available observations of *Fermi*. Moreover, the high state is only partially contained in the  $\gamma$ -ray light curve reported by D’Ammando et al. (2013). Both high and low  $\gamma$ -ray

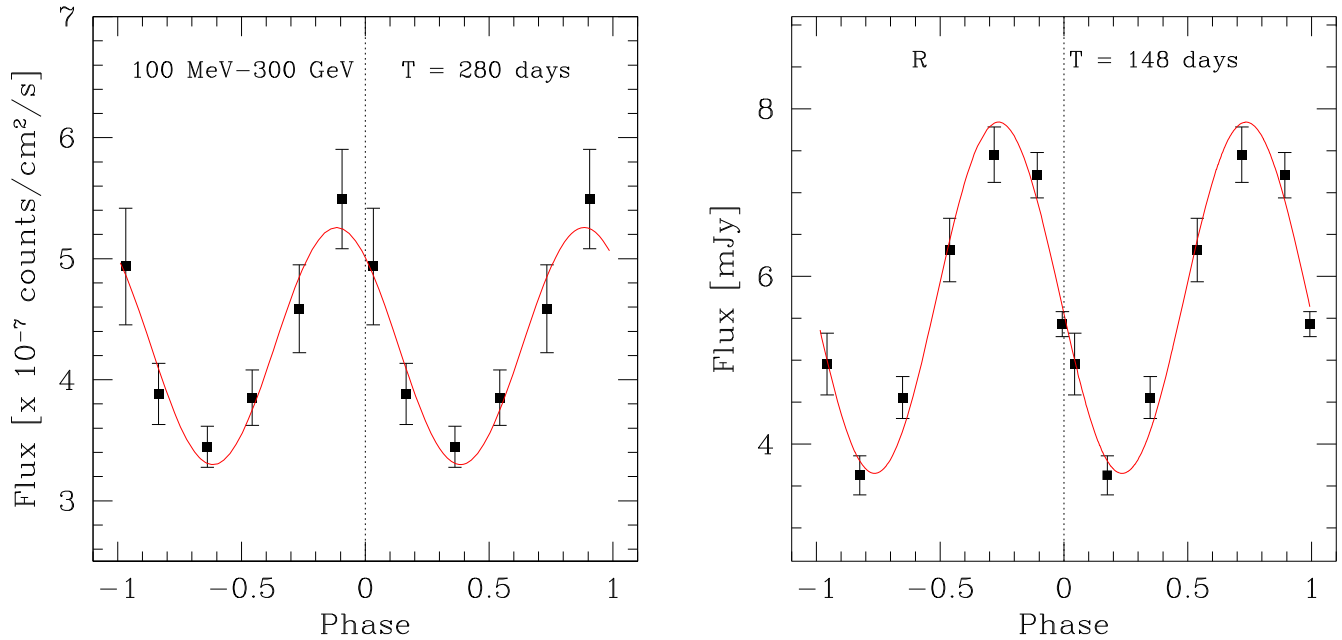
states have clear counterparts in the optical bands (see also Sandrinelli et al. 2016). The historical optical light curves, in fact, show that high states of duration of years are not infrequent (Pian et al. 2007). This kind of pattern is present also in the blazar 3C 454.3 (Abdo et al. 2011, and references therein). Here we concentrate on the high  $\gamma$ -ray state of PKS 0537–441. (Figure 2). The Lomb–Scargle analysis, as specified above, shows a peak at 279 days with 99% significance. We also proceeded in splitting the light curve into two segments, which are overlapping for 50% of their length, adopting the Welch-overlapped-segment-averaging (WOSA, Welch 1967) to enhance enduring quasi-periodicities. The obtained periodogram is given in Figure 3, where the peak at  $T_0 = 280 \pm 39$  day with  $S \sim 3\sigma$  (99.7%) is apparent. The errors are evaluated following Schwarzenberg-Czerny (1991), who applies the Mean Noise Power Level (MNPL) method. The  $1\sigma$  confidence interval on the investigated period  $T$  is the width of the peak at the  $p$ - $n$  level, where  $p$  is the height of the peak and  $n$  is the mean noise power level in the vicinity of  $T$ . We adapted the approach to our data considering the mean local first-order autoregressive red-noise power level (Schulz & Mudelsee 2002).

The periodogram referring to the  $R$  light curve is reported in Figure 4. It is important to note that the peak at  $T_1 = 148 \pm 17$  day has a  $S \sim 99\%$  and it is within the errors at one half of the  $\gamma$ -ray period  $T_0$ . It is also compatible with the peak in the periodogram of the 2008–2014 observations (see the Introduction). The analysis applied to the other optical bands yields comparable results. In Figure 2 we reported sinusoidal

<sup>6</sup> [http://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr\\_catalog/ap\\_lcs.php](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/ap_lcs.php)



**Figure 4.** Periodogram (black line) of the active phase of PKS 0537-441 (from 2008 August 10 to 2011 August 27) obtained from the REM+SMARTS *R*-band photometry. The curves from the bottom are red-noise spectrum (red curve), 95% ( $2\sigma$ , green curve), and 99% ( $2.5\sigma$ , purple curve) Monte Carlo significance levels after 1000 simulations. The period in days corresponding to the prominent peak is marked.



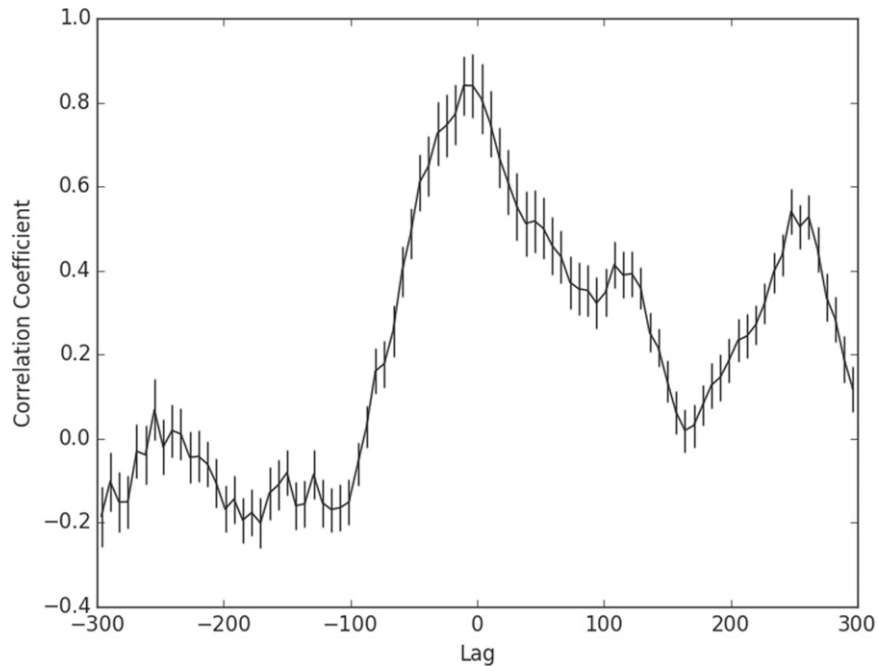
**Figure 5.** Folded light curves for the active phase of PKS 0537-441. Vertical bars are the standard errors of the average.

artificial light curves with periods specified above calculated using the Vstar package.<sup>7</sup> The amplitude of the components are  $A = 1.0 \times 10^{-7}$  photons  $s^{-1} cm^2$  in 100 MeV-300 GeV ( $T_0 = 280$  day), and  $A = 2.1$  mJy in *R* ( $T_1 = 148$  day). Clearly the

sinusoidal pattern is superposed to a strong chaotic variability. Folded light curves for the  $\gamma$ -ray and optical data obtained by the same package are reported in Figure 5.

The  $\gamma$ -ray/optical discrete cross-correlation was obtained following Edelson & Krolik (1988), and it is shown in Figure 6. The main peak is at zero delay with full width half intensity

<sup>7</sup> <http://www.aavso.org/vstar-overview>



**Figure 6.** Discrete cross-correlation function (seven-day bin) between 100 MeV–300 GeV and *R*-band data.

estimated from the left side of  $\sim 70$  day. The ( $-100$  day;  $+100$  day) section is similar to that obtained by D’Ammando et al. (2013). There are also two peaks at  $\sim 125$  days and  $\sim 265$  days, which are possibly related to the mentioned oscillations.

#### 4. SUMMARY AND DISCUSSION

We have concentrated on a high state of PKS 0537–441 of a duration of  $\sim 1000$  days, and have shown that the periodogram of the  $\gamma$ -ray light curve exhibits a peak at  $T_0 \sim 280$  days with a significance of 99.7%. At  $T_1 \sim \frac{1}{2} \times T_0$  there is also a peak in the optical light curve with 99% significance. Because our light curve covers only  $\sim 3$  periods, the indication is at most for a short-lived quasi-periodicity rather than a true period. Interestingly enough, a  $\gamma$ -ray period at twice the optical one was also found in PKS 2155–304 (Sandrinelli et al. 2014a). We note that no explanation for the difference of a factor of two in the timescales of the optical and  $\gamma$ -ray oscillations has been suggested thus far. Also, considering the quasi-periodicity in PG 1553–113 (see the Introduction), it seems to us that even if in each source the significance is not extreme, the indication of month–year oscillations in some blazars should be considered in detail. For possible preliminary interpretative scenarios, we refer to Sandrinelli et al. (2014a, 2016) and Ackermann et al. (2015), where oscillations are interpreted as periodic phenomena, related to a binary system of two supermassive black holes (SMBH) or the precession of the jet-accretion disk system. For the case of the observed short-lived periodicities in PKS 0537–411, which exhibits regular patterns during the  $\gamma$ -ray/optical simultaneous flares, outbursts could be ascribed to periodic tidal-induced disk instabilities and relaxation processes, due, e.g., to a secondary orbiting black hole (e.g., Lehto & Valtonen 1996; Valtonen et al. 2009) or to a binary SMBH torque-warped circumbinary disk (e.g., Graham et al. 2015). Disk-connected jet flow, where optical and  $\gamma$ -ray emissions are generally considered co-spatial (e.g., Ghisellini &

Tavecchio 2009), could mimic these regular oscillations. These perturbations, or different disk instabilities, could also excite dynamical oscillatory responses into the accretion disk, where the presence of a number of restoring forces can be invoked, similarly to the quasi-periodic oscillations in micro quasars (see, e.g., Abramowicz & Fragile 2013, and references therein).

If the oscillations are not related to a real periodicity, they could be due to some global instabilities in the jet connected to its helical pattern or shocks in jets. Several possible explanations are discussed in Marscher (2014), Godfrey et al. (2012), Larionov et al. (2013), Camenzind & Krockenberger (1992), and Marscher & Gear (1985).

A consequence of our results is that the *Fermi* light curves of blazars should be carefully reconsidered. It is possible that quasi-periodicities do not always appear in the long-term  $\gamma$ -ray light curve, but rather, they show up episodically, possibly in correspondence to the higher states.

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<sup>8</sup> [www.astroyale.edu/smarts/glast/home.php](http://www.astroyale.edu/smarts/glast/home.php)

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