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Gamma-ray quasi-periodicities of blazars. A cautious approach

S. Covino,[1★] A. Sandrinelli[1,2] and A. Treves[1,2]

[1] *INAF – Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Brera, Via Emilio Bianchi 46, I-23807 Merate, Italy*
[2] *Università degli Studi dell'Insubria, Via Valleggio 11, I-22100 Como, Italy*

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ABSTRACT

The availability of about a decade of uninterrupted sky monitoring by the *Fermi* satellite has made it possible to study long-term quasi-periodicities for high-energy sources. It is therefore not a surprise that for several blazars in the recent literature claims for such periodicities, with various level of confidence, have been reported. The confirmation of these findings could be of tremendous importance for the physical description of this category of sources and have consequences for the gravitational wave background interpretation. In this work, we carry out a temporal analysis of the *Fermi* light curves for several of the sources mentioned in recent literature by means of a homogeneous procedure and find that, globally, no strong cases for blazar year-long quasi-periodicities can be confirmed. The computed power spectral densities are all essentially consistent with being generated by red-noise only. We further discuss the meaning and the limitations of the present analysis.

Key words: method: statistics – galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual (PKS 0301−243, PKS 0426-380, PKS 0537−441, S5 0716+714, PKS 0805−077, 4C+01.28, PG 1553+113, PKS 2052−474, PKS 2155−304, BL Lac) – galaxies: jets.

1 INTRODUCTION

Blazars are the dominant sources of the extragalactic γ-ray sky. The *Fermi* mission, with its continuous monitoring of the entire sky, produced light curves of the brightest objects for a duration now approaching a decade and, by adopting a week/month binning, the curves are also practically evenly sampled. As in other spectral bands, the light curves indicate large variability basically on any time-scale. A topic of particular interest is about the possibility to identify a periodic behaviour superposed to the usually dominant stochastic variability. Long periods, of the order of months or years, are of particular relevance, since the merger of two supermassive black holes ($M \sim 10^8$ M$_\odot$), possibly the final act of the interaction of two galaxies, could result in year-long orbital periods (e.g. Begelman, Blandford & Rees 1980). As a matter of fact, with year-long periods, the number of full cycles covered by the *Fermi* monitoring is unavoidably small, and this clearly affects the estimates of the significance of any claimed periodicity and increases the probability of spurious detections.

In the recent literature, several claims for year-long periodicities based on analyses of *Fermi* data have been proposed (i.e., Sandrinelli, Covino & Treves 2014; Ackermann et al. 2015; Sandrinelli et al. 2016a; Sandrinelli, Covino & Treves 2016b; Prokhorov & Moraghan 2017; Sandrinelli et al. 2017; Zhang et al. 2017a,b,c; Tavani et al. 2018; Sandrinelli et al. 2018). These analyses rely on different procedures and assumptions, making often a direct comparison arduous. In this paper, we therefore reanalyse the gamma-ray light curves for the objects reported in literature following a homogeneous procedure well suited for relatively high-signal-to-noise (S/N) evenly sampled light curves, and critically evaluate the solidity of these claims. In Section 2, we describe the analysis procedure we have applied, in Section 3, we present the *Fermi* blazar sample we have selected, in Section 4, we describe and discuss our main results and, finally, in Section 5, we summarize our conclusions.

2 DATA AND METHODS

We considered aperture photometry light curves with 30-d time resolution in the 100 MeV to 200 GeV energy range available from the Fermi website.[1] They cover about a decade of uninterrupted observations for all the sources considered in this work. The regular sampling considerable simplifies the timing analysis.

Blazar light curves are characterized by intense variability at any time scale and show evidence of correlated noise (e.g., Press 1978; Abdo et al. 2010; Lindfors et al. 2016; Goyal et al. 2018). Singling out possible quasi-periodicities in these data is a difficult task and requires to model the red noise in order to derive an assessment of

★ E-mail: stefano.covino@brera.inaf.it

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/ap_lcs.php

the significance of any possible periods with respect to the noise model. Red noise can also, if not properly modelled, alter the output of the analysis due to leakage of power from lower to higher frequencies possibly and mimicking unreal quasi-periodicities often of transient nature (Kelly et al. 2014). We mainly followed the procedure described in Vaughan (2010, 2013) and Guidorzi, Dichiara & Amati (2016). Power Density Spectra (PDS) are derived by discrete Fourier transform and are normalized following the considerations reported in Leahy et al. (1983) and Guidorzi (2011). The noise was modelled as a power-law (PL) plus a constant (e.g., Konig & Timmer 1997; Kelly, Bechtold & Siemiginowska 2009; Edelson et al. 2013):

$$S_{\mathrm{PL}} = N f^{-\alpha} + G, \tag{1}$$

where N is a normalization factor, f the frequency, α the PL index, and G is the uncorrelated statistical noise that has a value of 2 for pure Poissonian noise with the adopted normalization (see also Guidorzi et al. 2016). We computed the best-fitting parameters for our PDS in a Bayesian framework. We initially maximized the *Whittle* likelihood function (Barret & Vaughan 2012) by a non-linear optimization algorithm and integrated the posterior probability density of the parameters of our models by a Markov Chain Monte Carlo (MCMC) affine-invariant Hamiltonian algorithm (Foreman-Mackey et al. 2013). We started the chains from small Gaussian balls centred on the best-fit values. The first third of each chain (the 'burn-in phase') was discarded and we checked that a stationary distribution was reached (Sharma 2017). Fit quality was evaluated by Kolmogorov–Smirnov (KS) tests of the residuals against the expected χ^2 distribution with two degrees of freedom and from posterior predictive assessment (Gelman, Meng & Stern 1996) based on the 'summed square error' test statistics (TSSE, Vaughan 2010). Posterior predictive assessment is a Bayesian technique to evaluate any test statistics over the range of parameter values, weighted by the posterior distribution of parameters (see also, e.g., Protassov et al. 2002; Lucy 2018). We assumed a Jeffrey prior for the normalization, strict positivity for the PL index, and a large Gaussian distribution centred on 2 for the uncorrelated noise. In Bayesian analysis, the posterior distribution is a complete summary of our inference about the parameters given the data, model, and any prior information. For each set of simulated parameters, we generated spectral models and use this to generate a periodogram from the posterior predictive distribution. Then, sampling the parameters from the posterior distribution, we drew the $T_{\mathrm{R}} = \max_j R_j$ statistics to evaluate the global significance of any peak in the PDS (see Vaughan 2010; Guidorzi et al. 2016, for more details), where $R = 2P/S$, P is the simulated or observed PDS, and S the best-fit PDS model. This statistic selects the maximum deviation from the continuum spectrum for each simulated PDS. The observed value of T_{R} is then compared with the simulated distribution and the significance is evaluated directly. Given that the same procedure is applied to the simulated as well as to the real data, a correction for the multiple trials carried out is already included in the analysis.

3 THE *Fermi* BLAZAR SAMPLE

Our sample consists of 10 objects: PKS 0301–243, PKS 0426−380, PKS 0537−441, S5 0716+714, PKS 0805−077, 4C +01.28, PG 1553+113, PKS 2052−474, PKS 2155−304, and BL Lac. These sources have been selected since a possible periodicity in their *Fermi* light-curves was proposed in the literature. No attempt to secure a complete sample based on any criterion was tried. With some more detail, for PKS 0301 − 243 a periodicity of about 2.1 years was suggested by Zhang et al. (2017c). An even longer periodicity of about 3.4 years was proposed for PKS 0426−380 by Zhang et al. (2017b). S5 0716+714 was studied in Sandrinelli et al. (2017) and no interesting periodicities were proposed. However, S5 0716+714 (∼346 d), PKS 0805–077 (∼658 d), 4C+ 01.28 (∼445 d), PG 1553+113 (∼798 d, PKS 2052−474 (∼637 d), PKS 2155−304 (∼644 d), and BL Lac (∼698 d) are part of a set of blazars suggested to show periodical behaviour in their high-energy data by Prokhorov & Moraghan (2017). Some of these sources are among the most extensively studied blazars at any wavelength. In particular, for PKS 0537−441, Sandrinelli et al. (2016b) singled out a ∼280 day periodicity analysing the high-energy data during a high-state period. A periodicity at about 2.2 years for PG 1553+113 was initially proposed by Ackermann et al. (2015) and then discussed in several more studies, i.e., Stamerra et al. (2016); Cutini et al. (2016); Sandrinelli et al. (2018); Tavani et al. (2018). For PKS 2155−304, a periodicity of about 642 days was suggested by Sandrinelli et al. (2014, 2016a); Zhang et al. (2017a); and Sandrinelli et al. (2018). Finally, BL Lac was discussed in Sandrinelli et al. (2018) and a periodicity of about 680 days was proposed.

In a few cases, the reported claims only mention hint of periodicities, the significancies are modest, although multiwavelength studies could improve the solidity of these detections (e.g., for PKS 0537−441, PG 1553+113, PKS 2155−304, and BL Lac).

4 RESULTS AND DISCUSSION

Our results can simply be summarized stating that all the analysed PDS (see Fig. 1) are compatible with being due to noise only, i.e., no periodicities can be singled out at a significance level better than 95 per cent. In Table 1, we also report the PDS best-fit parameters. In a fair fraction of cases, the PL index is consistent with ∼1, although there are a few exceptions showing a steeper relation as for PKS 0537−441. Features (maxima in the computed PDS) of some interest can anyway be identified in the periodograms as, e.g., for PKS 2155−304 or PKS 0537−441, and typically they correspond to the features already proposed in the literature for these sources.

The lack of statistically solid quasi-periodicities in the sample can be partly surprising due to the rich literature about this subject. However, in several cases, the authors only mention hints of periodical behaviours, and often based on the coincidence of modest-significance features in PDS computed for light-curves in different bands (e.g., Sandrinelli et al. 2018, and references therein). The present study typically agrees with these past results for what concerns the analysis of the high-energy light curves. In other cases, differences in the adopted analysis techniques, or even the omission of the multi-trial correction, can probably partly justify the different results. It is not expected, in general, that highly significant features can be lost adopting different, well-posed, analysis recipes.

Our analysis is rather standard but it is unavoidable based on several assumption that it is worth reminding here (see also Vaughan 2010, for a more comprehensive discussion). First of all, the *Whittle* likelihood is known to be only an approximation of the true sampling distribution of the periodograms, in particular for light-curves of moderate length. A probably much more important concern is due to the nature of the computed periodograms that, being based on decompositions of the time series on to an ortho-normal basis formed by sinusoidal functions, is clearly more sensitive to oscillations following a sinusoidal pattern (see also van der Klis 1989). This might be particularly important for sources the periodicity of which are inferred by the recurrence of flare-like events more

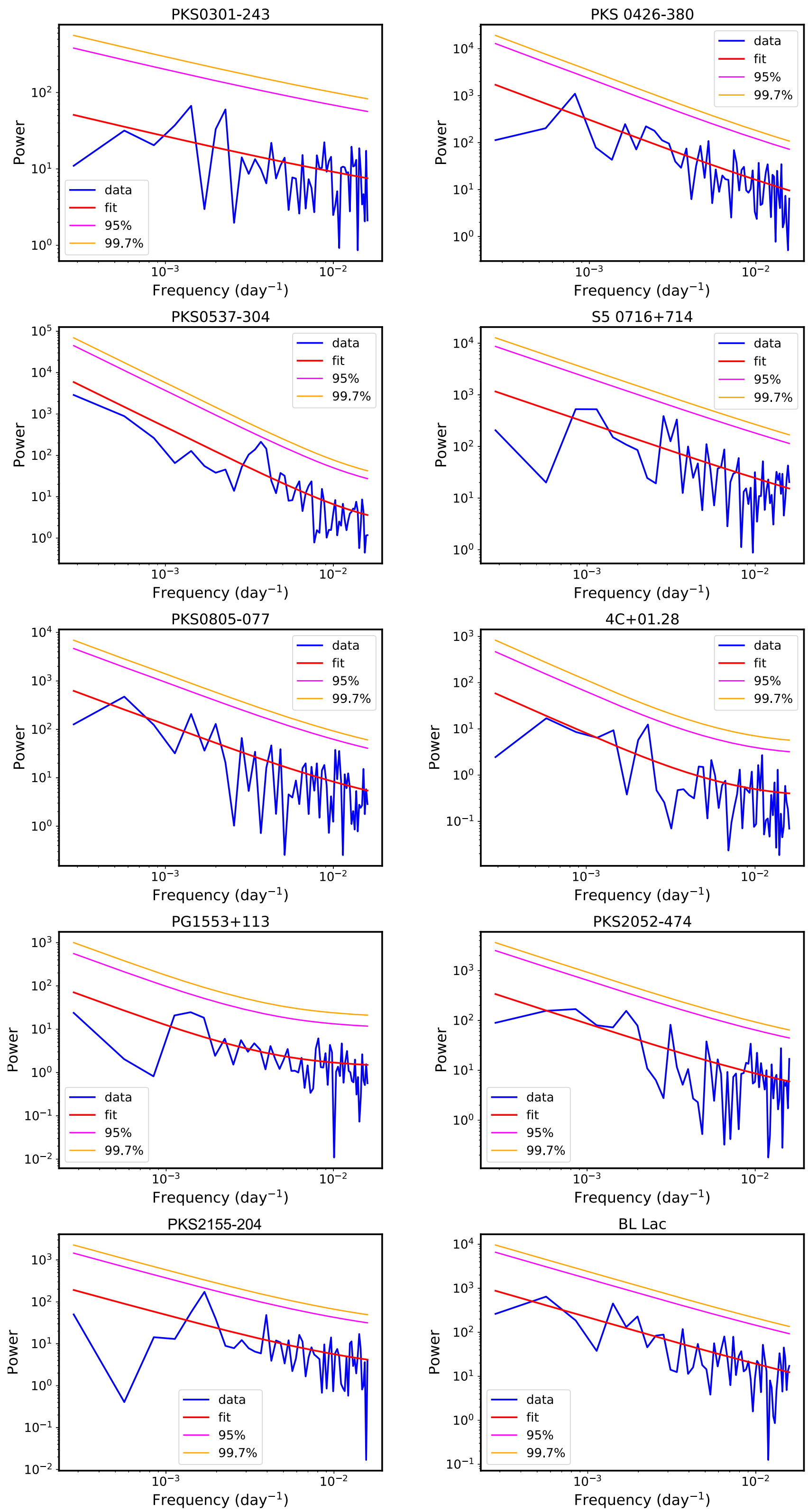

Figure 1. PDS (blue) for the blazars considered in this study. The best-fit noise model (red). The 95 per cent (magenta) and 99.7 per cent (orange) limits are computed evaluating the global significance of any peak in the PDS (see Section sec:search).

than a real long-lasting modulation. It is also worth remembering here that blazar light curves are severely dominated by stochastic variability. Non-parametric analyses (e.g., Huijse et al. 2018; Tavani et al. 2018) can likely alleviate this difficulty. Our analysis is also performed at the Fourier frequency grid that might not be necessarily the most suitable for identifying possible periodicities. In any case, as already mentioned, looking for possible periodicities of at least several months (bin time 30 d), implies that only a few

Table 1. PDS best-fit parameters for the noise model adopted in the present analyses. 1σ credible intervals are also reported. The reported *p*-values are computed by a KS test with respect to the theoretical χ^2 distribution with two degrees of freedom and by posterior predictive assessment (Gelman et al. 1996) based on the TSSE test statistics.

Source	PL index	Poisson noise	*KS* p-value	TSSE p-value
PKS 0301−243	$0.54^{+0.13}_{-0.13}$	$2.03^{+0.40}_{-0.42}$	0.24	0.05
PKS 0426−380	$1.33^{+0.13}_{-0.12}$	$1.96^{+0.40}_{-0.41}$	0.80	0.26
PKS 0537−441	$2.00^{+0.17}_{-0.15}$	$1.68^{+0.39}_{-0.39}$	0.55	0.66
S5 0716+714	$1.11^{+0.13}_{-0.12}$	$2.01^{+0.40}_{-0.40}$	0.95	0.54
PKS 0805−077	$1.29^{+0.13}_{-0.12}$	$2.02^{+0.39}_{-0.39}$	0.82	0.66
4C+01.28	$1.63^{+0.32}_{-0.27}$	$0.32^{+0.13}_{-0.11}$	0.03	0.89
PG 1553+113	$1.44^{+0.31}_{-0.25}$	$1.29^{+0.26}_{-0.26}$	0.47	0.15
PKS 2052−474	$1.11^{+0.14}_{-0.12}$	$2.08^{+0.38}_{-0.39}$	0.99	0.55
PKS 2155−304	$1.11^{+0.17}_{-0.15}$	$1.96^{+0.39}_{-0.38}$	0.97	0.75
BL Lac	$1.10^{+0.12}_{-0.11}$	$2.02^{+0.42}_{-0.40}$	0.78	0.26

cycles could have been effectively covered by the *Fermi* monitoring, making the evaluation of the statistical weight of the possibly identified features intrinsically more difficult. None of the mentioned limitations are actually expected to be able to hiden very significant long periodicities, while they can definitely give negative results in case of modest significant features, although a discussion of the many pros and cons of different recipes for temporal analysis is well beyond the scope of this work.

One more point worth mentioning is not related to the temporal analysis, but to the *Fermi* light-curves adopted in this paper. They are those provided automatically by the *Fermi* team and suffer from a few limitations since they are not background-subtracted and are possibly contaminated by nearby bright sources. While these are important details to consider, the sources selected in this work are all rather bright and, for a periodicity analysis, the reported limitations should not constitute a real issue.

5 CONCLUSIONS

The main result of our study is that there is no solid evidence for year-long periodicities based on the homogeneous procedure applied to the high-energy emission data available at this time for several γ-ray bright blazars. Considering the intrinsic complexity of a temporal analysis, the limited analysed sample, and the role, often underestimated, of the assumptions behind any recipe, there is still room for single events showing moderately significant oscillations. There is little doubt that this phenomenon is anyway not common for the whole population of blazars. In particular, the estimate of $\sim$10 per cent of bright gamma-ray blazars exhibiting year-long periodicities proposed by Sandrinelli et al. (2017, 2018), which was based on the results of Prokhorov & Moraghan (2017) appears now poorly justified.

Nevertheless, identifying a solid periodicity for a blazar could have an important impact. For instance, adopting the most popular interpretative scenario, a year-long periodicity could be due to supermassive black holes forming a binary system (e.g., Lehto & Valtonen 1996; Graham et al. 2015). This scenario has indeed been recently invoked and discussed by several authors (e.g., Sandrinelli et al. 2014; Ackermann et al. 2015; Sandrinelli et al. 2016a; Cavaliere, Tavani & Vittorini 2017; Caproni et al. 2017; Sobacchi, Sormani & Stamerra 2017; Tavani et al. 2018; Yan et al. 2018) for some of the blazars considered in this study. A direct consequence of a relatively large population of binary supermassive black holes could be the emission of gravitational waves producing a background important in the frequency range covered by the pulsar timing array (Hobbs & Dai 2017). As discussed in Sandrinelli et al. (2018) and Holgado et al. (2018), already now the upper limits constrain the possible binary fraction to be much lower than 10 per cent of the whole population, thus indirectly confirming our negative results.

The low fraction of systems showing year-long quasi-periodic oscillations also constrain other scenarios where the oscillations are induced by instabilities in the relativistic jet or in the accretion disk (e.g., Camenzind & Krockenberger 1992; Marscher 2014; Raiteri et al. 2017), although it is difficult to derive strict upper limits on the presence of quasi-periodic oscillations from our sample due to the biased selection.

It is anyway clear that the availability of high-quality and well-sampled light curves in the γ-rays open exciting perspectives for timing analysis both to confirm low-significance yet not negligible periodicity already proposed and to sample time-scales still not accessible due to the (relatively) limited length of the *Fermi* monitoring. We finally mention that interesting perspectives for singling out binary supermassive black holes are also allowed by the future availability of accurate astrometric measurements by the GAIA[2] mission as discussed in D'Orazio & Loeb (2018). This technique could offer a synergistic view to the problem since it does not require to solve the difficult problem to identify possible periodicities in their electromagnetic emission hidden in the always-present stochastic variability.

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