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Periodic Variability in γ-ray Emitting Blazars with Fermi-LAT

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Blazars display variable emission across the entire electromagnetic spectrum, ranging in time from minutes to years. This variability is generally interpreted as stochastic and unpredictable processes. However, recent studies have inferred the presence of periodic signals coming from blazars. These could be caused by, e.g., a helical jet or a precessing jet due to the presence of a supermassive black hole binary. In this work, we will report on the largest systematic search of periodic emission in the gamma-ray lightcurves of 351 blazars. Using 12 years of Fermi-LAT data, we have built a sample of 24 blazars displaying tentative periodic emissions. These results will be interpreted in the modeling framework of supermassive black hole binaries.

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1. Introduction

The emission of a blazar is highly variable at different time scales, from minutes to years [e.g., 11], and at all wavelengths ranging from radio to γ rays [e.g., 12].

Traditionally, this variability has been associated with stochastic processes [e.g., 16]. However, in some cases, this variability presents a periodic pattern [e.g., 1, 10].

The approach to search for periodicity at γ-ray energies is to study a few blazars by applying two or three analysis methods [e.g., 22]. In [9], we developed a pipeline to perform a systematic search for periodicity in hundreds of blazars. As a result, we discovered 24 blazars with a tentative periodicity (with significance $< 5\sigma$) with periods in the range of [1.2-4.1].

2. Blazar sample

Here, we re-analyze the 24 periodicity candidates that were presented in [9]. In [9], this sample was analyzed using nine years of *Fermi*-Large Area Telescope (LAT) observations [2]. In this new study, we use twelve years of *Fermi*-LAT telescope time, from August 2008 until December 2020. We use 28-day binned γ-ray light curves (LCs) to be consistent with our previous work. Finally, we extend the lower energy bound from > 1 GeV to > 0.1 GeV. The upper-limit data are substituted with the flux value that maximizes the likelihood function for that time bin. In that way, We solve the problems we had with the upper limits in [9].

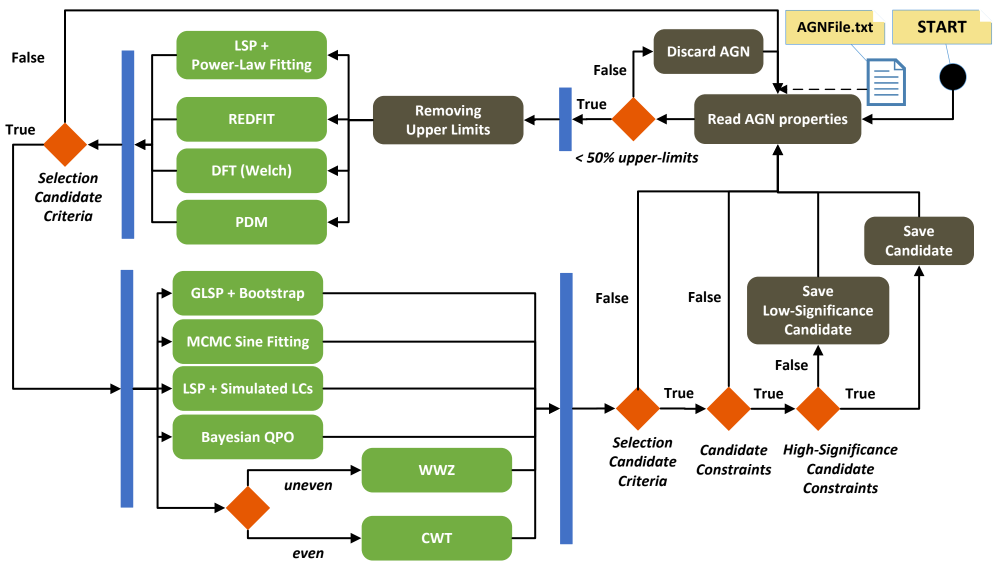

Figure 1: Periodicity search pipeline developed by [9].

3. Methodology

The periodicity search is performed systematically by using a pipeline, which was introduced in [9]. The periodicity-search pipeline consists of more than ten different methods to detect

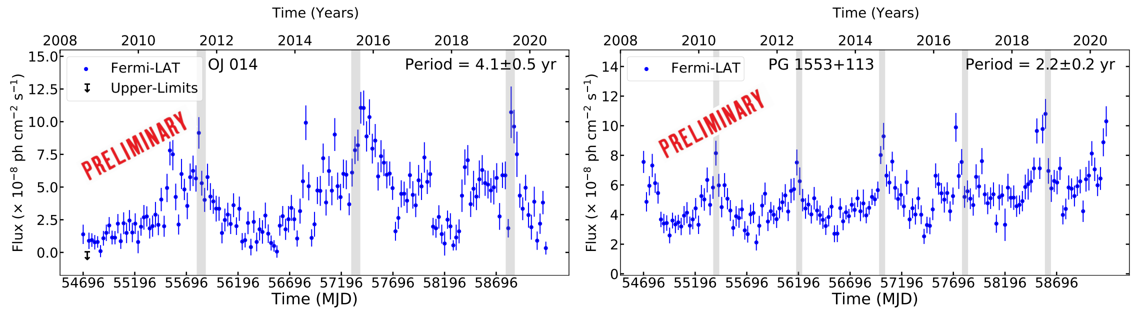

Figure 2: Example of light curves of the 5σ (pre-trial) periodicity candidates. Left: OJ 014. Right: PG 1553+113. The grey vertical lines denote the high-flux emissions.

periodicity and the significance associated with such detection, organized in different stages (that is schematically shown in Figure 1). Examples of these methods are the Generalized Lomb-Scargle periodogram [GLSP, 21], and the phase dispersion minimization [PDM, 17]. The reader is referred to [9] for details about all the methods.

In this new analysis, new methods are included in the pipeline. Specifically, we use the autoregressive models, which are suitable for analyzing astronomical time series since they allow modeling a wide variety of LC properties, e.g., irregular or quasi-periodic, constant mean or variable mean [5]. We employ the autoregressive models ARIMA [4] and ARFIMA [5].

4. Blazars with $\geqslant 5\,\sigma$ Periodicity

The sample comprises a number of the blazars, including OJ 014 and PG 1553+113, which are discussed in detail here (see Table 1). In [9], the significance of the periods were >3.5σ, and >4σ, respectively.

Table 1: List of $\geqslant 5\,\sigma$ periodicity Candidates. The blazars are characterized by their *Fermi*-LAT name, coordinates, AGN type (BL Lac, bll), redshift, association name, and period (in years) obtained in this work.

Name	RAJ2000	DecJ2000	Type	Redshift	Association Name	Period (yr)
J0811.3+0146	122.86418	1.77344	bll	1.148	OJ 014	4.1±0.5 (≈5.0σ)
J1555.7+1111	238.93169	11.18768	bll	0.433	PG 1553+113	2.1±0.2(>5σ)

Regarding OJ 014 and PG 1553+113, we confirm our previous period detection [for PG 1553+113, compatible with 18]. The authors of [20] analyzed most of the blazars included in [9], reporting no evidence of periodicity in the sample candidates, except for PG 1553+113, obtaining a compatible period.

We correct the significance by using the look-elsewhere effect to estimate the "global significance" [7]. The "global significance" is performed by applying the trial factor to the significance provided by each method of the pipeline (local significance). The trial factor is the combination of the number of independent periods N we search for periodicity, 35 (see Figure 3), and the size of our sample of blazars, 351. As a result, for the local significance of 5.5σ and 5.0σ, we obtain the global significance of ≈3.5σ and ≈2.8σ, respectively.

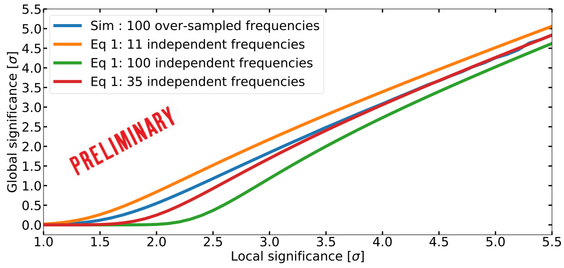

Figure 3: Left: Relation to estimate the number of oversampled frequencies. "Eq1" denotes the results of applying $p_{\text{global}} = 1 - (1 - p_{\text{local}})^N$, where N is the number of frequencies.

4.1 Power-spectral index estimation

The power spectral index is estimated using the algorithm presented by Uttley et al. [13], the Power Spectrum Response Method (PSRESP), according to the expression $\propto \text{f}^{-\beta}$. PSRESP also provides the uncertainty of the estimated slope and the “success fraction” that indicates the goodness of fit by giving the probability of a model being accepted. To implement PSRESP for each candidate, we simulate 1,000 artificial LCs using the technique of Timmer and Koenig [19]. The results for PG 1553+113 and OJ 014 are 1.28±0.2 and 1.17±0.4, respectively.

The power-law indices are consistent with a pink-noise process (spectral index ≈1), which may be caused by disk modulations that materialize as jet modulations. [3].

4.2 Flux emission prediction

We propose to predict the low-high emission states of the periodicity candidates [e.g., 1]. Using the results of the Markov Chain Monte Carlo (MCMCM) sine fitting method [9], we estimate the future oscillations of the blazars in Table 1. Our predictions are presented in Table 2. The prediction for PG 1553+113 (a high-flux emission in the spring of 2021) was confirmed by the MAGIC observatory[1].

Table 2: List of predictions for the flux states of the periodicity candidates. The predictions are implemented, organizing the year in four slices, according to the seasons in the Northern Hemisphere.

Association Name	Peak	Valley	Peak	Valley
OJ 014	–	spring 2021	spring 2024	spring 2026
PG 1553+113	spring 2021	spring 2022	spring 2023	spring 2024

5. Discussion on the origin of periodicities

Various theoretical models are proposed to explain the physical mechanisms that may be responsible for the periodic emission in blazars. These models can be organized according to whether there is a single or a binary supermassive black hole (SMBH) in the blazar. In the case of a single SMBH, there are at least two possible scenarios: (i) the jet variability may be due to

[1] https://www.astronomerstelegram.org/?read=14520

relativistic blobs moving on a helical path along a funnel or cone-shaped magnetic surface anchored to the accretion disk near the black hole [8]; (ii) periodic variations in the energy outflows could be induced by thermal-viscous instabilities in the accretion flow [6].

In the case of a binary SMBH system, there are different scenarios: (i) perturbations caused by the secondary SMBH destabilize the accretion flow of the primary SMBH, modulating the accretion rate and, as a consequence, the luminosity of the blazar [14]; (ii) alternatively, the periodic emission may be due to a precession of the jet, ultimately caused by the orbiting SMBHs [15]. These models are proposed to explain the periodic emissions of PG 1553+113.

6. Summary

We have identified two blazars with periodic γ-ray emissions detected at a global significance of $\geq 3.0\sigma$, using 12 years of *Fermi*-LAT observations. Specifically, these blazars are OJ 014 and PG 1553+113.

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