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# Quasi-periodic oscillations in the $\gamma$-ray light curves of bright active galactic nuclei

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The detection of quasi-periodic oscillations (QPOs) in the emission of active galactic nuclei (AGNs) can provide insights into the physics of the super-massive black-holes (SMBHs) powering these systems, and could represent a signature of the existence of SMBH binaries. The identification of long term QPOs, characterized by periods on the order of several months to years, is particularly challenging and can only be achieved via all-sky monitoring instruments like the Fermi-LAT satellite. We aim to identify QPOs in the $\gamma$-ray light-curves of the thirty-five brightest AGNs within the Fermi-LAT catalog, including data from the beginning of the Fermi mission (August 2008) to April 2021, and energies from 100 MeV to 300 GeV. Two time binnings are investigated, 7 and 30 days. The search for quasi-periodic features is then performed using the continuous wavelet transform. The significance of the result is tested via Monte Carlo simulations of artificial light curves with the same power spectral density and probability distribution function as the original light curves. We identify twenty-four quasars with candidate QPOs. Several of our candidates coincide with previous claims in the literature: PKS 0537-441, S5 0716+714, Mrk 421, B2 1520+31, and PKS 2247-131. All our candidates are transient. The most significant multi-year QPO, with a period of about 1100 days, is observed in the quasar S5 1044+71, and is reported here for the first time.

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## 1. Introduction

Searches for $\gamma$-ray periodicities in the light curves of blazars, one of the brightest sources in the Universe, have been an active research topic since the beginning of the *Fermi*-LAT mission [1]. The first claim of a year-long periodicity was presented by [2] who found the first evidence (at about $3\sigma$) for a periodic 2-years modulation in the light curve of the blazar PG 1553+113, coincident in period with a quasi-periodic oscillation (QPO) seen at longer wavelengths. All $\gamma$-ray QPO candidates in blazars shown a period of the order of years. A notable exception is represented by the highly-significant ($5.2\sigma$) QPO seen in PKS 2247-131 which has a period of about a month and, most importantly, seems to be a transient phenomenon [3].

Several models have been developed to explain these quasi-periodicities. They can be associated to the movement of plasmoids in the jet along helical paths [4], or related to precession of the jet itself. This precession could be driven by the gravitational perturbation of another SMBH [5, 6], meaning that QPOs will provide key constraints on SMBH binaries in the Universe.

Fourteen years after the launch of *Fermi*-LAT we have now access to continuous light curves on hundreds of AGNs. The goal of this work is to systematically study the light curves of bright *Fermi*-LAT AGNs to identify QPO candidates. In order to get access to transient QPOs, and QPOs with varying periods that could be hidden in a time-integrated power spectral density, we make use of the continuous wavelet transform (CWT). In this conference contribution we summarize the main findings of our analysis. For the complete results, see the associated refereed publication in [7].

## 2. Sources selection and *Fermi*-LATdata

The sources we wanted to study must be bright enough to have continuous *Fermi*-LAT light curves with time bins of seven days or one month. This was our only selection criterion. It is important to avoid large gaps in the light curve since the CWT works with evenly spaced time series. Thus, we limited the analysis to the 34 brightest AGNs in the 4LAC catalogue. However, an additional source was added manually: PKS 2247-131, due to the high significance QPO detected by [3]. This manual addition brings the total of our sample to 35 AGNs, including 19 FSRQs, 15 BL Lacs, and 1 radio galaxy.

The $\gamma$-ray data which spans from August 8, 2008 to April 4, 2021 (from MJD 54686 to MJD 59308) were downloaded and analyzed using the standard analysis procedure provided by the *Fermi*-LAT collaboration. We produced the light curves binned into weekly and monthly intervals by applying unbinned likelihood analysis in the 0.1 – 300 GeV energy range.

## 3. Method

### 3.1 Continuous Wavelet Transform

The search for quasi-periodic features is performed using the PyCWT code as provided by [8]. This algorithm is based on the CWT technique, which is the convolution of a time series with a dilated and translated wavelet function, to analyse time-frequency properties of any time series,

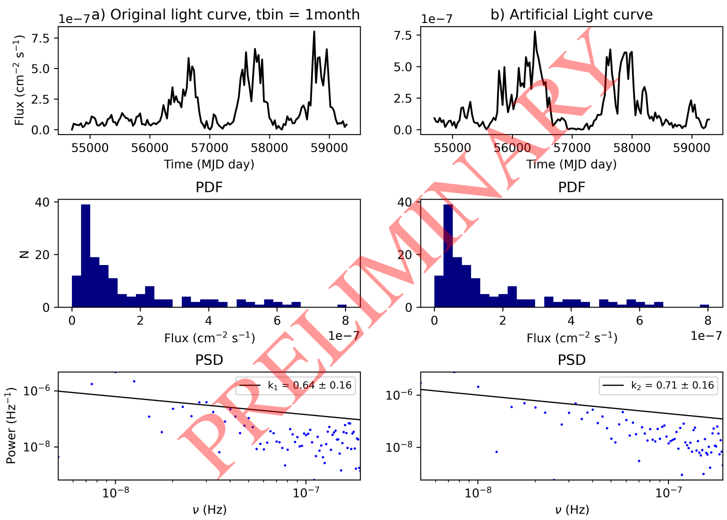


**Figure 1:** Comparison of the PDF and the PSD of the original light curve of the source S5 1044+71 and the light curve simulated by [9], in time bin of 30 days. The solid line in the PSD is a simple power-law fit for a visual check.

e.g., light curves. The CWT technique not only gives access to the frequencies of potential QPOs, but also when the periodicities appear and end, and how they evolve in time.

We used the Morlet wavelet as the mother wavelet. The *wavelet power spectrum* is defined as the square of the amplitude of the wavelet coefficient. The *global wavelet spectrum* can then be computed as the time-average of the wavelet power spectrum. The cone of influence (COI) is defined as the region of the wavelet power spectrum in which edge effects become important due to the finite length of the time series, and is calculated as suggested by [8].

### 3.2 Significance Estimation

To determine the significance and confidence levels of the analysis, we simulated artificial light curves following the work by [10], using the Python version provided by [9]. This algorithm generates artificial light curves having the same power spectral density (PSD) and probability distribution function (PDF) as the original light curve.

For each *Fermi*-LAT light curve, we produced 10000 artificial light curves. We show in Fig. 1 a comparison of the PDF and PSD of one of the simulated light curve to the original one.

The global wavelet spectrum is computed for each simulated light curve, such that a histogram of the power spectrum can be produced at every period. We then fit the histogram with a $\chi^2$ distribution with $k$ degrees of freedom

$$\chi(x,k)^2 = \frac{1}{2^{k/2}\Gamma(k/2)} x^{k/2-1} \exp(-x/2). \tag{1}$$

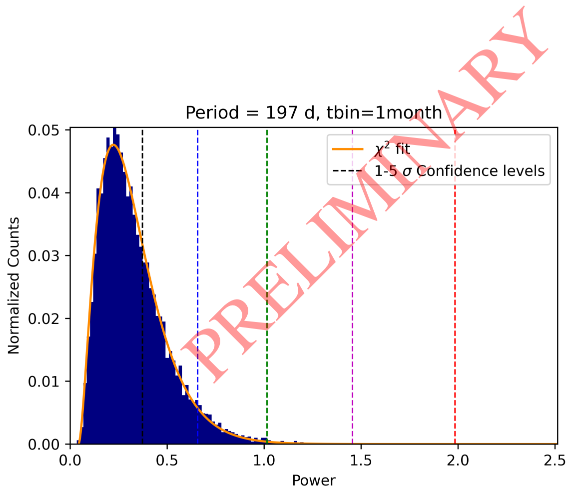


**Figure 2:** Global power spectrum histogram fitted with a $\chi^2$ function, for S5 1044+71. Pre-trial confidence Levels are shown in dashed lines.

| Source | Period(d) 30 d LC | Significance ($\sigma$) | Period(d) 7 d LC | Significance ($\sigma$) |
|---|---|---|---|---|
| B2 1520+31 | 176±48 | >5 | 179±42 | >5 |
| | | | 71±15 | >5 |
| | | | 39±11 | >5 |
| S5 1044+71 | 1133±229 | 4.9 | 1127±226 | 4.6 |
| | 116±33 | >5 | 117±38 | >5 |
| PKS 2247-131 | 217±38 | >5 | 214±43 | >5 |
| | | | 34±13 | >5 |

**Table 1:** QPOs candidates identified by the CWT of the *Fermi*-LAT light curves in time bins of 30 days and 7 days.

The confidence levels are obtained by using the percentiles of the power for each scale, which define the global significance of the results. An example of the $\chi^2$ fitting to the histogram and the resulting confidence levels for the AGN S5 1044+71 are shown in Fig. 2. Post-trial confidence levels are estimated following [11].

## 4. Results and discussions

Here we show the result for three sources showing the most significant QPOs, S5 1044+71, PKS 2247-131 and B2 1520+31, with post-trial significances, in Tab. 1 and Fig. 3.

B2 1520+31: Three possible month-long QPOs are identified. The CWT maps of this source are a good example of the inherent difficulty of this analysis technique when dealing with blazar light curves: rapid flares result in vertical structures in the map that overlap with the horizontal

bands we are interested into, and require visual inspection of all peaks that appear in the global wavelet spectrum.
The first QPO candidate is found in both light curves at around 176±48 d (179±42 d) for the monthly (weekly) binned light curve with a significance above $5\sigma$ in both cases. This QPO candidate is of particular interest because its period seems to increase with time. The second and third candidate QPOs can be better identified in the CWT map of the weekly binned light curve, with periods of 71 ± 15 d and 39 ± 11 d, both exceeding $5\sigma$ significance. The 71 ± 15 d period is compatible with the one reported by [12] with a period of ~71 d. The source has also been studied by [13]: although some signal can be seen in their analysis at around ~70 d, it remains below the $3\sigma$ interval they computed in their study.

S5 1044+71: We identify, for the first time, two highly significant QPO candidates in S5 1044+71, a moderately distant FSRQ. A very evident long term oscillation of period 1133±229 d (1127 ± 226 d) at a conficence level ~$4.9\sigma$ (~$4.6\sigma$) for the monthly (weekly) binned light curve appears in the wavelet map, emerging around MJD 56000 (March 2012). Secondly, a short month-long QPO emerged during the last flaring state of the source, between MJD 58650 and MJD 59000 (June 2019 and September 2020), with a period estimated to be 116 ± 33 d (117 ± 38 d) for the monthly (weekly) binned light curve at a significance more than $5\sigma$.
Three complete cycles of the year-long QPO can be observed. The absence of a clear fourth peak at around MJD 55500 might indicate additional modulation. Regarding the short period QPO, four cycles can be seen, which are the three narrower flares in the last flaring state and a fourth more suppressed one after MJD 59000. Dimmer features also appear during the two previous flaring states, centered at a similar period but at much lower significance and shorter duration. These two signals surely contribute to the global wavelet spectrum, however the short duration and the relatively vertical shape of the second feature centered at around MJD 57500, makes them likely to be compatible with noise.
During the preparation of this work, an analysis of S5 1044+71 has been presented by [14], claiming a 3 years modulation (~3.06 ± 0.43 yr) at a significance level of ~$3.6\sigma$. This result is in total agreement with ours.

PKS 2247-131: The wavelet analysis of this BL Lac object shows two QPO candidates. The first of the QPO candidates is found to be at around 217 ± 38 d (214 ± 43 d), at above $5\sigma$ confidence level in the CWT of monthly (weekly) binned light curves. This QPO candidate seems to span at least from MJD 57600 to MJD 58500 approximately (July 2016 to January 2019) in the CWT map. One can notice the tentative periodic oscillations of this source, presenting 6 peaks.
More interestingly, we identify a QPO candidate in the time interval around MJD 57600 to MJD 57900 approximately (July 2016 to May 2017) with much shorter period, centered at around 34 ± 13 d, with a significance larger than $5\sigma$, and only noticeable in the weekly binned light curve. Tentative oscillations can also be seen, with at least 7 full cycles. The first claim of a month-scale QPO in the $\gamma$-emission of PKS 2247-131 was presented by [3]. Our result is in total agreement with their ~ 34.5 ± 1.5 d period, which can be indicative of the presence of an SMBH binary in the center of this blazar.

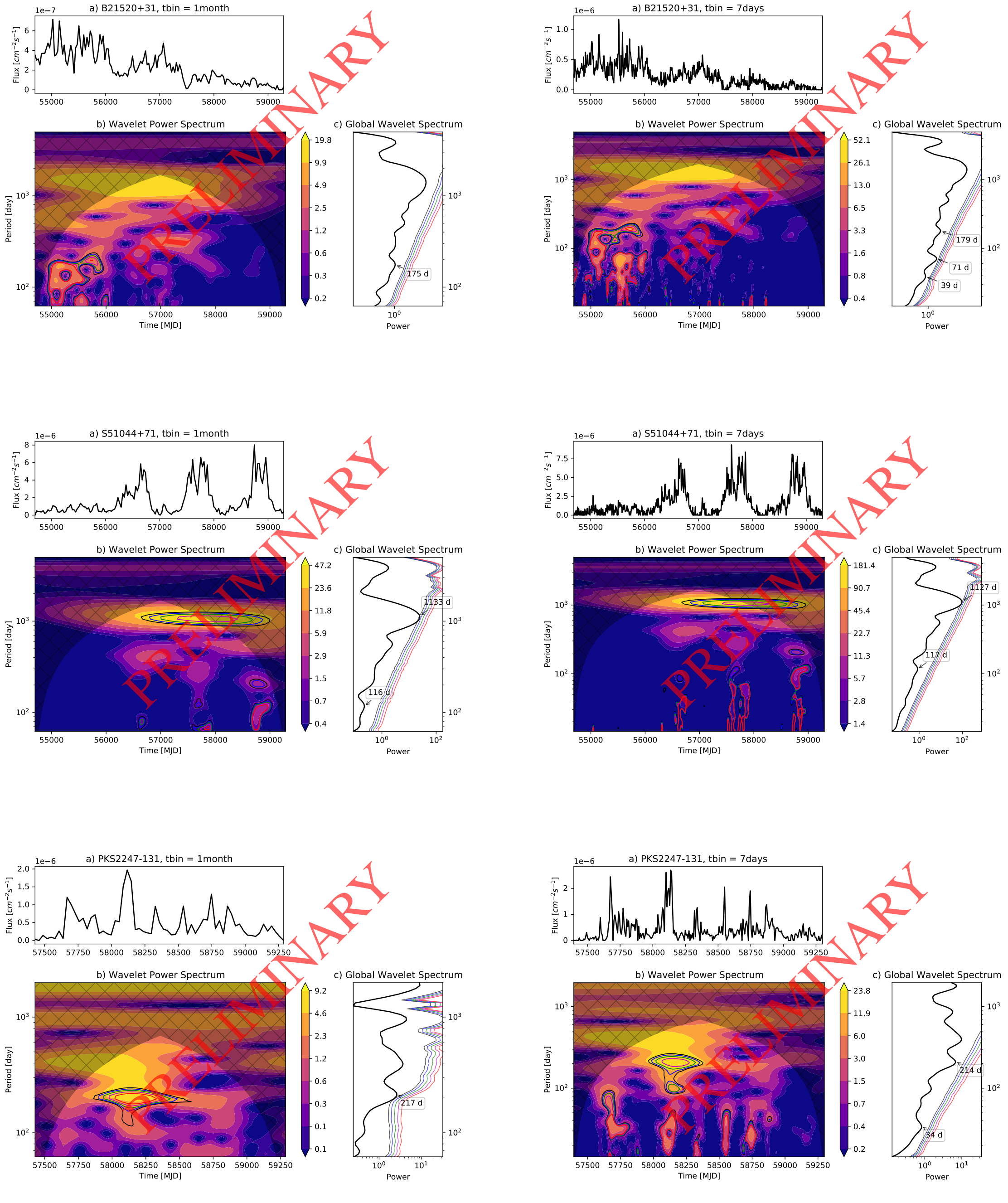


**Figure 3:** CWT map for monthly binned light curve (left) and weekly binned light curve (right) for B2 1520+31, S5 1044+71 and PKS 2247-131. In each subplot, the panels represent a) Fermi-LAT light curve, b) wavelet power spectrum and c) global wavelet power spectrum. The solid coloured contours in b) and the dashed coloured lines in c) are the confidence levels (1 to 5 in black, blue, green, violet, and red).

## 5. Conclusions

36 QPO candidates in 24 sources are identified in our work (at various significance levels) with periods ranging from one month to several years. Our most significant, multi-year QPO candidate is in the blazar S5 1044+71, with a period of about 1100 d. We confirm some previously claimed $\gamma$-ray candidate QPOs in the sources PKS 0537-441, B2 1520+31, PKS 2247-131, S5 0716+714, Mrk 421, Mrk 501 and PKS 2155-304, while new possible QPO candidates are detected in several other sources. [For a complete list, please see 7].

The CWT technique is a very powerful tool identifying QPOs in light curves and highly sensitive to transient and/or period-shifting QPOs. However, it is influenced notably by flares and border effects which leads to the requirement of a visual inspection to avoid misleading results. On the other hand, trial effects are not negligible due to the bins in the time-frequency map and the number of light curves considered.

A natural perspective for a future study would be a multiwavelength analysis of QPOs from the selected interesting sources to boost the significance of the detection or to identify false positives.

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