Title of your IAU Symposium
Proceedings IAU Symposium No. 342, 2018
A.C. Editor, B.D. Editor & C.E. Editor, eds.

DOI: 00.0000/X000000000000000X

Search for QPOs in Perseus with *Fermi* LAT

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Abstract. We report an analysis of the gamma-ray variability of NGC 1275–the radio galaxy at the center of the Perseus cluster. NGC 1275 has been observed continuously with the *Fermi* Large Area Telescope over the last nine years. We applied different time-domain analysis methods including Fourier, wavelets and Bayesian methods, in order to search for quasi-periodic oscillations (QPO) in the gamma-ray emission. We found no evidence for any periodicity of astrophysical origin.

Keywords. Keyword1, keyword2, keyword3, etc.

1. Introduction

NGC 1275 is the brightest central galaxy in the nearby Perseus galaxy cluster. It is a radio galaxy producing collimated, relativistic jets of particles outflowing from its center at velocities $0.3 - 0.5c$ Walker, Romney & Benson (1994). These jets are strongly interacting with the intracluster medium, heating it up, offsetting radiative cooling and creating X-ray bright cavities where star formation is quenched (e.g. contributions by Churazov, Zuravleva in these proceedings).

Importantly, the center of NGC 1275 is the *brightest gamma-ray emitter* (e.g. Abdo *et al.* (2009)) among nearby AGN. The availability of a high-quality, high-cadence light curve (LC) observed with Fermi LAT for NGC 1275 over the last 9 years with uniform sampling make this galaxy not only a remarkable laboratory for high-energy astrophysical processes around black holes in the nearby universe but also an ideal place for mining for interesting time-domain signals due to e.g. potential massive binary black holes.

In this contribution, we will not address the gamma-ray emission due to the galaxy cluster itself; instead, our focus is on the AGN activity. Galaxy clusters are not detected in gamma-rays, an observation that challenges the simplest hadronic models and implies a low energy density in cosmic rays Ackermann *et al.* (2014).

2. NGC 1275 gamma-ray flares

The broadband emission of NGC 1275 has been varying dramatically over the last forty years in radio Dutson *et al.* (2014). More recently, NGC 1275 has been showing increased activity and flaring in the gamma-ray band Tanada *et al.* (2018), with a broad correspondence between the high-frequency radio data and gamma-rays. NGC 1275 is also detected at TeV energies during periods of γ-ray flaring Aleksic *et al.* (2012).

Recently, Tanada *et al.* (2018) presented an analysis of eight years of Fermi-LAT (0.1-300 GeV) γ-ray observations for NGC 1275 (cf. Figure 1 in Tanada et al.). Besides finding that the gamma-flux has been steadily increasing and is highly variable on short

timescales (days to weeks–cf. also contribution of Sahakyan who reports variability on timescales of hours; Baghmanyan *et al.* (2017)), Tanada et al. also found essentially two distinct periods of flaring activity:

Period A From $\approx$ 2009 to 2011, strong variability in spectral index, quiescent flux

Period B From $\approx$ 2013 to 2016, spectral index does not change much, strong variation in flux

Based on these observations, Tanada *et al.* (2018) argues that in each of these periods the source is in two different states. During *period A*, NGC 1275 would be in a state where there is a fresh production of nonthermal electrons (e.g. internal shocks or magnetic reconnection). This period could be associated with the C3 hotspot observed in radio (cf. contributions by Hodgson, Savolainen in these proceedings). *Period B* can be explained by variations in Doppler factor of the emitting plasma, possibly associated with a small change in the line-of-sight.

3. Radio galaxies and QPOs

Quasi-periodic oscillations (QPOs) correspond to strong, narrow peaks in the Fourier power spectrum of a time series indicative of the presence of deterministic processes with a characteristic period. For this reason, QPOs are very useful as indirect probes for separating stochastic versus deterministic processes operating in the central engines of accreting black holes in stellar mass black holes and active galactic nuclei Remillard & McClintock (2006), Gierlinski *et al.* (2008).

In the case of a radio galaxy such as NGC 1275, there are different processes associated with the central black hole(s) that could introduce a characteristic period in the jet gamma-ray light curve:

- *Jet-disk instabilities* due to the unstable magnetospheric interface between the accretion flow and the jet McKinney, Blandford & Tchekhovskoy (2012) (QPO period $\tau_{\rm inst}$).
- Jet precession due to the Lense-Thirring precession caused by a accretion flow misaligned with the black hole spin vector Liska *et al.* (2018) (period $\tau_{\rm prec}$).
- Supermassive binary black hole system where the main period corresponds to the binary orbital period, with possible harmonics (e.g. Roedig *et al.* (2012), Gold *et al.* (2014)) (period $\tau_{\rm BBH}$).

We should expect that roughly $\tau_{\rm inst} < \tau_{\rm prec} \lesssim \tau_{\rm BBH}$. All of these processes can introduce characteristic QPOs in the NGC 1275 gamma LC, thus motivating a detailed study of this time series.

4. Search for gamma-ray QPOs in NGC 1275

We used three methods to search for the presence of QPOs in the gamma LC of NGC 1275: Fourier transform, continuous wavelet transform and a Bayesian QPO search framework. In our experience, the most robust method for QPO search was the Bayesian method as we will describe below. As pointed out before (Vaughan *et al.* (2016) and references therein), one must be very careful to properly model the time series power spectrum (e.g. red noise, power-law) when searching for QPOs.

Figure 1 shows NGC 1275's LC extracted with standard analysis parameters in the energy range 0.1-300 GeV from a circular region of radius 15° (Pass 8). The spectral index was free to vary. We used the Fermi Science Tools version v10r0p5. Whereas the upper panel clearly demonstrates the progressive increase in the gamma flux over time, an inspection of the lower panel indicates the potential presence of oscillatory behavior.

Figure 2 shows the LC power spectrumm compared with the red noise fit (cf. Torrence

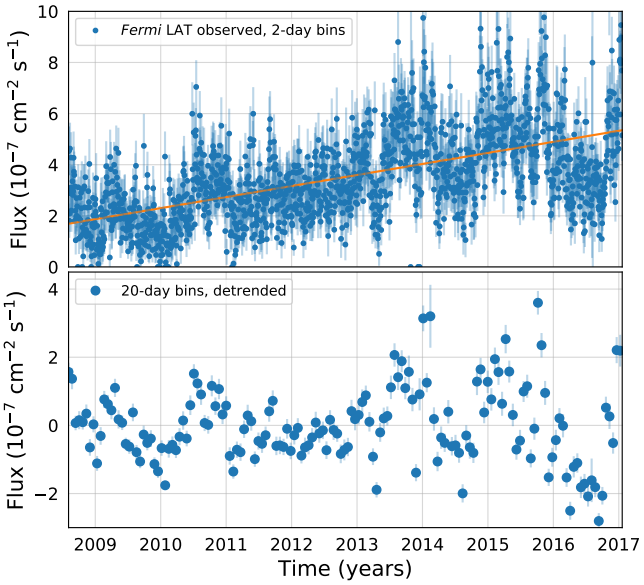

Figure 1. NGC 1275 γ-ray light curve observed with Fermi LAT. Upper panel: LC with bins of 2 days. Lower panel: LC with bins of 20 days after a linear detrending.

& Compo (1998) for details on the red noise model). No QPOs are clearly evident in this figure.

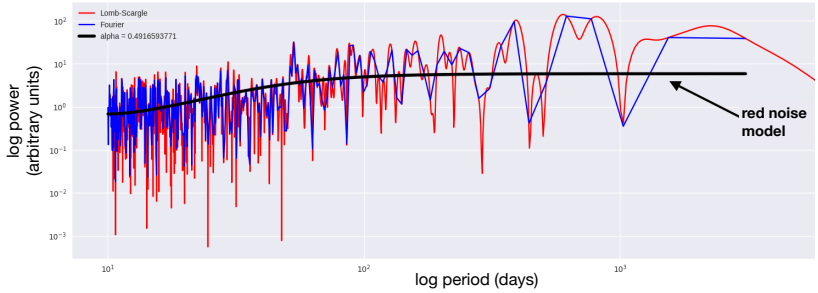

Figure 2. Power spectrum for the light curve computed with the Fourier (blue line) and Lomb-Scargle methods (red line). The black line shows a red noise fit to the LC.

To settle the issue, we used the Bayesian QPO search procedure outlined in Huppenkothen *et al.* (2013). This method consists of comparing the broadband noise model to a more complex model combining both the broadband noise model and a Lorentzian to account for possible QPOs. The noise model is assumed to be either a power-law or broken power-law models, similarly to the noise models assumed in time-domain analysis of X-ray binaries and Seyfert 1 X-ray data. The results from this analysis are shown in Figure 3 demonstrating that the signal is broadly consistent with noise. There is one

significant QPO which is indicated with an arrow; however, this feature is compatible with the rocking period of the *Fermi* satellite.

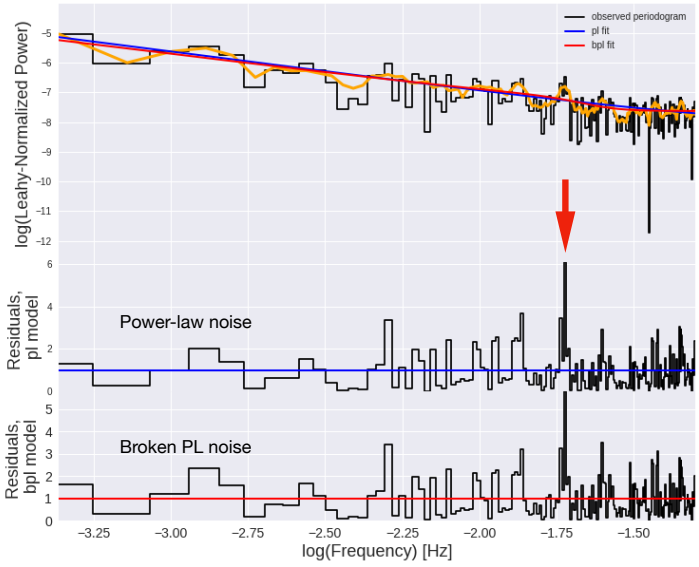

Figure 3. Results of Bayesian QPO search applied to NGC 1275's light curve. The arrow indicates one potential QPO, which is consistent with the rocking period of the *Fermi* satellite.

5. Summary

NGC 1275 is a rich lab for investigating high-energy phenomena and black hole physics, particularly in the time domain. It has been brightening in radio and gamma-rays and displayed gamma-ray flares over the last nine years. Motivated by the prospect that different processes could introduce QPOs in the light curves of radio galaxies with periods ranging from months to years–such as precession and the presence of accreting binary black holes–we searched for the presence of QPOs in its Fermi-LAT light curve using a range of methods including a powerful Bayesian QPO search framework. We found no evidence for periodicities of astrophysical origin. The Bayesian QPO search method employed in this work should be a powerful tool for future searches of QPOs in AGNs and blazars.

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