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Evidence for a bursty gamma-ray QPO in the TeV blazar PKS 1424-418 using Fast Template Periodograms and Machine Learning

by A. A. Maldonado, et al. (including A. Domínguez, A. Dinesh)

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Plaza de las Ciencias, 1 28040 Madrid, Spain

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Abstract

Context: Standard frequency-domain periodicity searches in active galactic nuclei (AGN) typically assume sinusoidal modulations. However, gamma-ray blazar emission often features asymmetric flares and localized bursts. This structural mismatch can cause severe spectral leakage, reducing the sensitivity of standard methods to non-sinusoidal periodic signals.

Aims: We aim to investigate the intra-cycle light-curve profiles of blazar quasi-periodic oscillation (QPO) candidates, specifically targeting burst-dominated periodicities to assess whether morphology-aware templates can recover signals hidden from standard harmonic searches, and to structurally validate these candidates against stochastic red noise.

Methods: We evaluated a blind sample of 100 high-cadence (7-day binned) Fermi-LAT blazar light curves. Following a robust baseline detrending via Singular Spectrum Analysis, we analyzed the data using the Fast Template Periodogram (FTP). We compared the results obtained with three template families: a standard sinusoid, a Gaussian burst, and an empirical asymmetric template derived via epoch-folding the historical light curve of PG 1553+113. Finally, we deployed a Random Forest machine learning classifier, trained on 5×10^4 simulated light curves, to rigorously validate the topological structure of the resulting candidates.

Results: We identify 9 $>3\sigma$ candidates, including those accounting for false-alarm probability. Three highly persistent periodicities (including PG 1553+113) are consistently recovered across all template models. However, the remaining 6 periodicities are strongly degraded by spectral leakage under a standard sinusoidal assumption. Non-sinusoidal templates successfully recover this hidden variance. Nevertheless, subsequent machine learning evaluation reveals that 5 of these 6 signals lack stable phase coherence. The dual-pillar pipeline definitively validated a 4.8-year periodicity in PKS 1424-418. While an extended observational baseline is inherently required to resolve this long timescale, we demonstrate that morphology-aware templates are necessary to elevate this structurally stable, burst-dominated QPO above traditional discovery thresholds.

Conclusions: While standard harmonic searches effectively capture overwhelmingly powerful, persistent QPOs, morphology-aware periodograms are required to uncover hidden burst-dominated variance. Furthermore, structural machine learning validation helps separate genuine periodic phase-structures from the high-variance colored noise that can mimic these bursts. The case of PKS 1424-418 highlights how high-cadence analysis may aid in the detection of discrete periodic phenomena driven by localized plasma mechanisms.

