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Letter to the Editor

A ~4.6 h quasi-periodic oscillation in the BL Lacertae PKS 2155−304?

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ABSTRACT

We report a possible detection of an ~4.6-h quasi-periodic oscillation (QPO) in the 0.3–10 keV emission of the high-energy peaked blazar PKS 2155−304 from a 64 ks observation by the *XMM-Newton* EPIC/pn detector. We identify a total modulation of ~5% in the light curve and confirm that nominal period by periodogram, structure function, and wavelet analyses. The limited light curve duration allows the capture of only 3.8 cycles of this oscillation and thus precludes a very strong claim for this QPO, despite a nominally high ($\gtrsim 3\sigma$) statistical significance. We briefly discuss models capable of producing an X-ray QPO of such a period in a blazar.

Key words. galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual: PKS 2155−304 – X-rays: galaxies

1. Introduction

Active galactic nuclei (AGN) presumably possess accreting black holes (BHs) with masses of 10^6–10^{10} $M_\odot$ and have many similarities to scaled-up galactic X-ray emitting BH binaries. The presence of quasi-periodic oscillations (QPOs) is fairly common in both BH and neutron star binaries in our and nearby galaxies (e.g., Remillard & McClintock 2006). Despite several earlier claims, until recently there have been no convincing cases of QPOs in AGN. A clear detection of a QPO of ~1 h been made for the narrow-line Seyfert 1 galaxy (NLS1), RE J1034+396 (Gierliński et al. 2008), and a very strong case for one (also about 1 h) in a flat spectrum radio quasar, 3C 273, has been reported (Espaillat et al. 2008). Both use data from the *XMM-Newton* satellite.

The BL Lacertae object PKS 2155−304 (z = 0.116) is one of the brightest BL Lac objects from UV to TeV energies in the southern hemisphere. Therefore it is well studied and known to be rapidly and strongly variable throughout the electromagnetic spectrum on diverse timescales (e.g., Carini & Miller 1992; Urry et al. 1993; Brinkmann et al. 1994; Marshall et al. 2001; Ahronian et al. 2005; Dominici et al. 2006; Dolcini et al. 2007; Piner et al. 2008; Zhang 2008; Sakamoto et al. 2008, and references therein). A giant TeV flare from this source was observed in July 2006 (e.g., Ahronian et al. 2007; Foschini et al. 2007; Sakamoto et al. 2008). Its extreme TeV variability seems to demand an ultra-relativistic flow (bulk Lorentz factor ~50) in at least portions of the jet that is believed to dominate the emission from this and other BL Lacs and blazars (Ghisellini & Tavecchio 2008). This BL Lac has been the target of several simultaneous multi-wavelength monitoring campaigns (e.g., Urry et al. 1993; Brinkmann et al. 1994; Edelson et al. 1995; Courvoisier et al. 1995; Urry et al. 1997; Pian et al. 1997; Pesce et al. 1997; Foschini et al. 2007, 2008). PKS 2155−304 is among the few blazars for which claims of an apparent QPO have been made, with UV and optical monitoring (from *IUE*) over five days possibly having a ~0.7 d periodicity (Urry et al. 1993). Simultaneous X-ray observations tracked those UV variations fairly well (Brinkmann et al. 1994).

2. Data and reduction

We reanalyzed archival *XMM-Newton* EPIC observations of PKS 2155−304 taken on 2006 May 1 (orbit 1171, ObsID 0158961401). The 0.6–10 keV spectral analysis of this observation has been reported in Zhang (2008). We used pipeline products and applied the *XMM-Newton* Science Analysis System (SAS) version 8.0.0 for the light curve (LC) extraction. We confined our analysis to EPIC/pn data because only they were free of soft-proton flaring events and pile-up effects. In contrast to the data reduction conducted by Zhang (2008), we read out source photons recorded in the entire 0.3–10 keV energy band, using a circle of 45 arc-sec radius centered on the source. Background photons were read out from the same sized area located about 180 arc-sec off the source on the same chipset. We finally obtained a source LC (corrected for background flux) of the total duration, $T = n\Delta t = 64.1$ ks, of the observation evenly sampled every $\Delta t = 100$ s. The mean count rate and rms variability equal 21.9 cts s^{-1} and 3.1%, respectively.

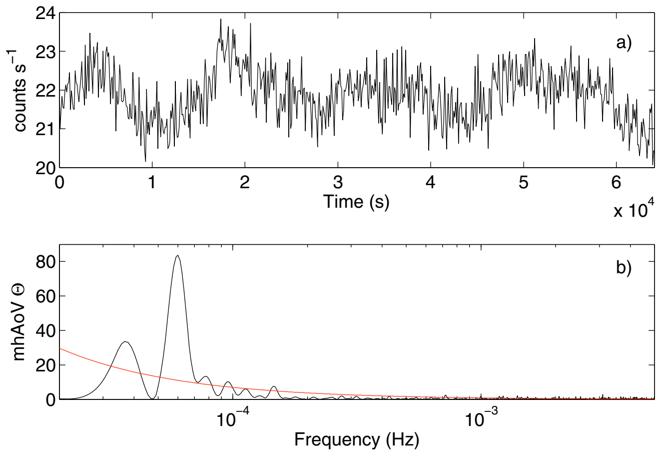

Fig. 1. a) The 0.3–10 keV LC of PKS 2155−304 as observed by *XMM-Newton* EPIC/pn (orbit 1171) showing a noticeable periodic flux modulation in the signal. **b)** Corresponding mhAoV periodogram revealing a dominant periodicity at 4.64 ± 0.21 h. The solid red line denotes the mean fitted red-noise model of a power-law form.

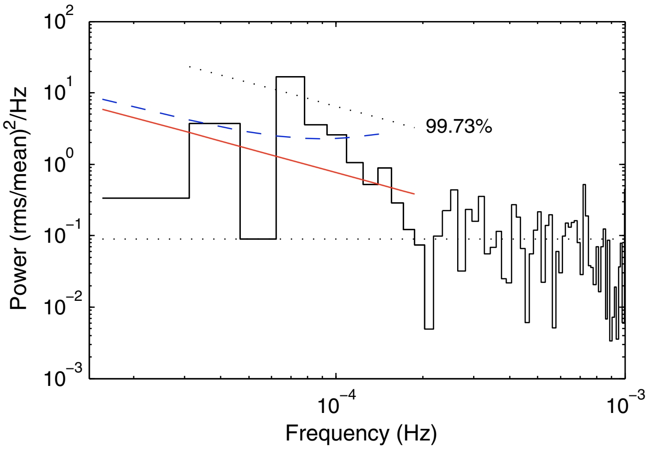

Fig. 2. Fourier power spectrum of PKS 2155−304 (histogram) and estimated 99.73% (3σ) level of confidance (dotted curve). The solid red line denotes the best-fit power-law model of the underlying red noise with an index of $\alpha = -1.10 \pm 0.48$, while the dashed blue line marks the upper uncertainty in this model. The horizontal dotted line denotes the expected Poisson noise level.

3. Light curve analysis

A visual inspection of the LC (Fig. 1a) suggests that the X-ray emission of PKS 2155−304 is modulated by a periodic component. We conducted periodogram, structure function, and wavelet analyses to explore this possibility and to provide a more complete picture of the observed variability.

3.1. Periodogram analyses

We first used the multi-harmonic AoV periodogram (mhAoV) of Schwarzenberg-Czerny (1996) to analyze the LC. An extensive description of mhAoV with its statistical advantages over the classical Lomb-Scargle method, and examples of applications to X-ray time-series analyses can be found in Lachowicz et al. (2006). In the periodogram calculations for the signal x, we employed Szegö orthogonal trigonometric polynomials as model functions, $x_{\parallel}$. A series of $n_{\parallel} = 2N + 1$ polynomials correspond to the orthogonal combinations of the N lowest Fourier harmonics, where $n_{\parallel}$ denotes the number of a model's free parameters. The consistency of the data with the model is measured by a statistic, $\Theta \equiv \Theta(f)$, which is a function of frequency. In the mhAoV periodogram, Θ is defined by the Fisher AoV statistic, namely $\Theta_{\rm AoV} = (n - n_{\parallel})||x_{\parallel}||^2/(n_{\parallel}||x - x_{\parallel}||^2)$, and follows the Fisher-Snedecor probability distribution, F. Since different periodograms use different models and statistics, therby facilitating their comparison, we convert $\Theta_{\rm AoV}$ into the false alarm probability, P_1. It can be directly calculated as $P_1 = 1 - F(n_{\parallel}, n_{\perp}/n_{\rm corr}; \Theta_{\rm AoV}/n_{\rm corr})$ where $n_{\perp} = n - n_{\parallel}$ and $n_{\rm corr}$ defines a number of consecutive observations being correlated (see Sect. 3.1.4 of Lachowicz et al. 2006). A direct derivation of P_1 returns the significance of the periodogram peak (centered at the frequency f_0) only under the assumption that any modulation detected has a period, $P_0 = 1/f_0$, which is known in advance. In practice, when a set of $N_{\rm eff}$ frequencies in a band, Δf, is scanned for significant periodicities, a selected peak's significance level should be corrected for multiple trials, so $P_{N_{\rm eff}} = 1 - (1 - P_1)^{N_{\rm eff}}$. Since there is no analytical method that determines $N_{\rm eff}$, we follow Lachowicz et al. (2006) and assume a simple estimate, $N_{\rm eff} = \min(\Delta f/\delta f, N_{\rm calc}, n)$, where δf defines the peak's FWHM and $N_{\rm calc}$ is the number of frequencies at which the periodogram is calculated.

For this PKS 2155−304 LC, we employed the mhAoV assuming a simple model of $x_{\parallel}$ with $N = 1$ (a sinusoid). This periodogram analysis revealed a dominant peak around the frequency of $f \simeq 6 \times 10^{-5}$ Hz (Fig. 1b). Since the standard frequency resolution (defined by $1/T$) for frequencies below $f < 10^{-4}$ Hz is poor, we oversampled our periodogram in frequency by a factor of 5. This allowed us to determine the period more precisely and to estimate its 1σ error (Schwarzenberg-Czerny 1991). We find $P = 16\,707 \pm 747$ s (4.64 ± 0.21 h). In the error calculation we took into account a correction to the peak's power from the fitted mean red noise background (assuming a power-law model) around the suspected QPO frequency (Fig. 1b; red line), which reduces $\Theta_{\rm AoV}$ by a factor of about 1.2. We computed the peak significance and find it to be $P_{N_{\rm eff}} < 10^{-10}$ ($\gtrsim 7\sigma$) using the determined values $\Theta_{\rm AoV} = 70.4$, $n_{\rm corr} = 1.33$ and $N_{\rm eff} = n$. Therefore, in terms of the mhAoV method, the underlying 4.6 h periodicity stands as statistically significant even though we capture only 3.8 cycles during the total LC duration. We find the suspected QPO has a quality factor, $Q = f/\Delta f \simeq 12$, and a fractional rms of 1.6%.

The underlying continuum that includes red noise can easily give rise to nominally apparent, but not actually significant, periodicities, particularly when the dataset only spans a few of the putative periods (Press 1978). To more conservatively estimate the significance of this possible QPO in PKS 2155−304, we also employed the approach of Vaughan (2005), which was used by Gierliński et al. (2008) in their analysis of RE J1034+396. This analysis basically involves first measuring the Fourier periodogram, then estimating the slope of that red noise continuum contribution through a least-squares fit to the log of the periodogram, and finally estimating the significance of any peaks above that power spectrum (Vaughan 2005). Although only strictly valid when the spectrum of the underlying noise is exactly a power-law in frequency, it is a very good approximation as long as the signal is in the portion of the power spectrum that is close to a power-law. The results of this analysis are given in Fig. 2, where the peak is just slightly above the 99.73% confidence level. This result of $\gtrsim 3\sigma$ would normally be strong enough to claim a significant QPO detection. As a comparison, the result using this approach for the QPO found in the NLS1 galaxy discussed by Gierliński et al. (2008) is $\sim 5.6\sigma$ for the

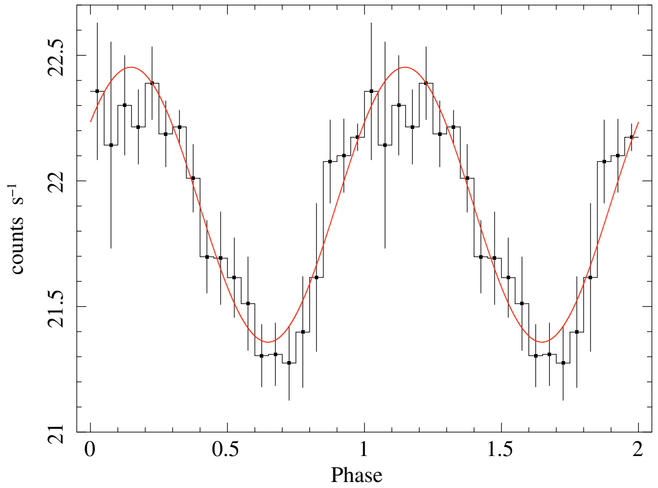

Fig. 3. Folded 0.3–10 keV LC with period P = 16 707 s and best-fit sinusoid describing flux modulation. Two cycles are displayed for clarity.

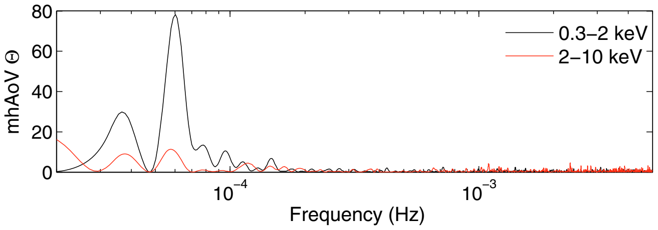

Fig. 4. Periodograms calculated using mhAoV for PKS 2155−304 LCs corresponding to 0.3–2 keV and 2–10 keV emission.

better "Segment 2" of their LC and ~3.4σ when their entire LC is considered. Using Monte Carlo simulations we also estimated a chance probablity of finding a spurious QPO of the >3σ significance seen in Fig. 2 from that underlying power-law power spectrum to be 4×10^{-4}.

In Fig. 3 we present a folded LC with a period of 4.64 h re-binned into 20 flux bins per one cycle of the modulation. The best χ^2 fit of a sinusoidal model to the data is overplotted and returns a reduced-χ^2 of 0.63 for 17 degrees of freedom. We calculated the relative modulation depth, defined by $\phi_{\rm mod} = (y_{\max} - y_{\min})/y_{\max}$ where $y_{\min}$ and $y_{\max}$ denote the minimum and maximum count rates of the fitted model and find $\phi_{\rm mod} = 4.9 \pm 0.3\%$. This is about 40% of the periodic modulation at P = 3733 s found by Gierliński et al. (2008) in the 0.3–10 keV flux of RE J1034+396.

We also checked how much this detection of ~4.6 h periodicity depends on the energy band. In Fig. 4 we compare the mhAoV periodograms computed for two energy intervals, the "soft" 0.3–2 keV and "hard" 2–10 keV bands. Surprisingly, while the periodicity is easily detected in the soft band and is still at a high estimated significance level ($P_{N_{\rm eff}} < 10^{-10}$; mhAoV), it is visible but not significant in the source's hard X-ray emission.

3.2. Structure function analysis

The structure function (SF) is an alternative technique that provides information on the time structure of a data train, and it is able to discern the range of the characteristic time scales that contribute to the fluctuations. It is less affected by any gaps in the light curves and is free of any constant offset in the time series (e.g., Rutman 1978). Introduced by Kolomogorov (1941), the SF has frequently been applied in astronomy (e.g.,

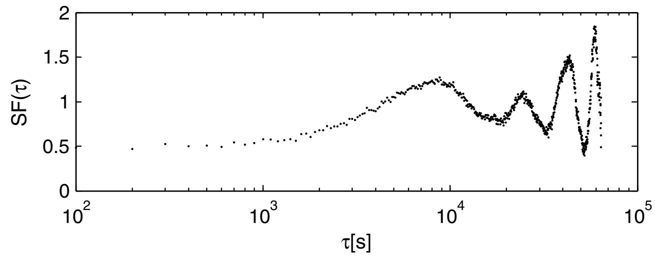

Fig. 5. Structure Function for the 0.3–10 keV LC of PKS 2155−304.

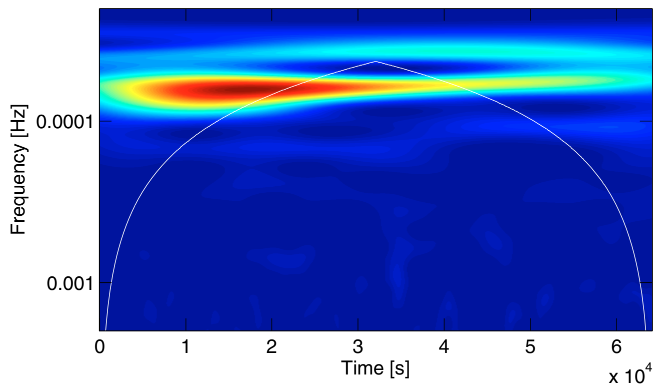

Fig. 6. Wavelet analysis for the 0.3–10 keV blazar LC, with redder colors corresponding to stronger signals. The cone-of-influence is marked by the solid white line.

Simonetti et al. 1985; Paltani et al. 1997), and has been recently used by Rani et al. (2009) for spotting nearly periodic fluctuations in the long-term X-ray LCs of blazars.

The first-order SF is a time domain technique, defined as $\mathrm{SF}(\tau) = \langle [x(t+\tau) - x(t)]^2 \rangle$ where $x(t) \equiv x$ is the LC. For strictly sinusoidal flux variability with period P, the SF has minima for τ equal to P and its subharmonics (e.g., Lachowicz et al. 2006). Thus, an SF allows for quick confirmation of the findings provided by the periodogram techniques. Figure 5 displays the SF computed for our X-ray LC of PKS 2155−304. The first and subsequent dips clearly indicate a periodic component at $\tau \simeq 17\,000$ s, which is in good agreement with the periodograms.

3.3. Wavelet analysis

We employed the standard wavelet Matlab® codes of Torrence & Compo (1998) to scan a time-frequency plane of the blazar's 0.3–10 keV LC. In the wavelet analysis we used the Morlet mother function as a basis function. This is a reasonable choice for capturing periodic flux modulations and providing an idea of their lifetimes and frequency evolution along the signal.

Figure 6 presents the calculated squared modulus of the continuous wavelet transform. Two strips of high wavelet power are immediately noticeable for frequencies $f < 1 \times 10^{-4}$ Hz. The frequency of the most prominent one agrees very well with our periodogram and structure function indications, i.e., at the frequency $f \simeq 6 \times 10^{-5}$ Hz of the possible 4.6 h QPO.

It is worth noting that the wavelet map suggests the highest coherence of that periodicity within the first ~35 ks of the LC, which also agrees with a time-domain based signal analysis. For $t > 35$ ks, the 4.6 h modulation weakens and its period may stretch out. Within that time interval, the wavelet map reveals a second flux modulation (i.e. of lower frequency), also seen in the mhAoV results (Fig. 1). However, much of these wavelet signals are in the "cone-of-influence" where putative modulations are either too close to the sampling interval or (as in this case) too close to the total signal length. It is worth noting that this restriction did not apply to the wavelet analyses employed to support recent claims for X-ray (Espaillat et al. 2008) and optical (Gupta et al. 2009) QPOs in other blazars.

4. Discussion and conclusions

Several models for the QPOs in Galactic X-ray binaries have been proposed, and while none seem to be able to explain all of the details of the observations, they are all based on fluctuations in, or oscillations of, accretion disks (e.g., Remillard & McClintock 2006). The simplest of these models for BHs would attribute the quasi-periods to particularly strong orbiting hotspots on the disks at, or close to, the innermost stable circular orbit allowed by general relativity (e.g., Abramowicz et al. 1991; Mangalam & Wiita 1993). If such simple models apply in this case, and the QPO is indeed real, then we would estimate the BH mass for PKS 2155−304 to be 3.29×10^7 $M_\odot$ for a non-rotating BH and 2.09×10^8 $M_\odot$ for a maximally rotating BH (e.g., Gupta et al. 2009; Rani et al. 2009). Other possible mechanisms for QPOs in AGNs that could provide timescales of a few hours can also have a disk origin or can arise from relativistic jets. The former class also includes small epicyclic deviations in both vertical and radial directions from exact planar motions within a thin accretion disk (e.g., Abramowicz 2005), oscillations of standing shocks in transonic flows (e.g., Chakrabarti et al. 2004), and trapped pulsational modes within a disk (e.g., Perez et al. 1997; Espaillat et al. 2008).

In the case of PKS 2144−304, a disk flux variation is unlikely to directly produce any detectable QPO because the disk emission is almost certainly dominated by synchrotron emission at low-energy bands and by inverse Compton emission at higher energy bands. Both of these are expected to arise from from relativistic jets (e.g., Blandford & Königl 1979; Böttcher 2007; Marscher et al. 2008) and their fluxes usually would swamp any disk fluxes. Nonetheless, a disk oscillation could trigger a quasi-periodic injection of plasma into the jets, which could then produce the observed QPO (e.g., Liu et al. 2006). Some recent work has argued that the nuclear emission in low-luminosity radio-loud AGNs indicates that the accretion disk is radiatively inefficient (e.g., Balmaverde et al. 2006; Balmaverde & Capetti 2006). Then the emission in even the low-luminosity radio-loud AGNs that are likely the parent population of BL Lacs is dominated by non-thermal emission from the base of the jet. The observed timescale, $P_{\rm obs}$, of any fluctuation is likely to be reduced with respect to the rest-frame time-scale, $P_{\rm em}$, by the Doppler factor, δ, and is increased by a factor of $(1+z)$. The Doppler factor depends upon the velocity of the shock propagating down the jet, V, and the angle between the jet and the observer's line-of-sight, θ, as $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$, where $\beta = V/c$ and $\Gamma = (1-\beta^2)^{-1/2}$. The value of δ for PKS 2155−304 is probably large, ~30–50 (Urry et al. 1997; Ghisellini & Tavecchio 2008). A shock propagating down a jet which contains quasi-helical structures, whether in electron density or magnetic field, can produce a QPO, with successive peaks seen each time the shock meets another twist of the helix at the angle that provides the maximum boosting for the observer (e.g., Camenzind & Krockenberger 1992; Gopal-Krishna & Wiita 1992). Instabilities in jets just might be able to excite such helical modes capable of yielding fluctuations that are observed to occur on the time-scale seen in PKS 2155−304 (e.g., Romero 1995). Or they could arise as the jet plasma is launched in the vicinity of SMBH and thus actually originate in the accretion flow but become amplified in the jet. Another very plausible origin for a short-lived QPO would be turbulence behind the shock in the relativistic jet (e.g. Marscher et al. 1992), as again intrinsically modest fluctuations could be Doppler boosted.

While this result for the presence of a QPO in a BL Lac is nominally of reasonably high statistical significance, the presence of <4 cycles of the putative period in this dataset means that it can only be considered to be a tantalizing hint, and not a confirmed case. Detailed discussion of physical mechanisms, along with results of searches for QPOs in 24 light curves of four other high energy peaked blazars, will be given in a separate paper (Gaur et al., in preparation).

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