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# Quasi-Periodic Oscillations in the X-ray Light Curves of Blazars

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**Abstract.** Any quasi-periodic variations discovered in blazar light curves would contain important information on the location and nature of the processes within the emission regions. In non-blazar active galactic nuclei, particularly Seyfert galaxies, any such fluctuations are very likely to be associated with the accretion disks, but in blazars they would almost certainly have to emanate from jets. This brief review summarizes recent claims for the presence of quasi-periodic variability in the X-ray emission of several AGN, focusing on blazars. Although no individual claim of the presence of a QPO in AGN X-ray light curves is absolutely convincing, there are some good cases for the presence of QPOs, including the Narrow Line Seyfert 1 galaxy, RE J1034+396, the quasar, 3C 273 and the BL Lac, PKS 2155−304.

*Key words.* Galaxies: active—BL Lacertae objects: general—galaxies: jets—quasars: general.

## 1. Introduction

The question of the presence of periodic or quasi-periodic components within the tremendous amount of temporal variability seen in blazars is an extremely important one. After decades of observations in assorted bands of the electromagnetic spectrum it is abundantly clear that such signals are quite rare, if present at all. So far there have been no observational results and associated statistical analyses that have provided absolutely convincing evidence for such quasi-periodic oscillations (QPOs) in active galactic nuclei (AGN), though there are now a couple of excellent claims for non-blazar AGN. This is very different from the situation in X-ray binaries (XRBs), where quite a number of binary systems containing neutron stars or black holes have shown clear evidence for QPOs (e.g., Remillard & McClintock 2006). Obviously, the much lower received fluxes and longer periods associated with the $10^6$–$10^{10} M_{\odot}$ supermassive black holes (SMBHs) in distant AGN compared to those associated with neutron stars and BHs of around 1–$10 M_{\odot}$ in stellar XRBs in our galaxy (or a few nearby galaxies) makes clear detection of QPOs far more difficult for AGN.

Nonetheless, continued searches for such variations remain worthwhile, for their discovery and characterization could reveal much about the emitting regions of blazars and AGN in general. The relatively lengthy continuous monitoring that has been available through X-ray satellites, particularly XMM–Newton, over the past decade or so makes the X-ray band attractive for these studies, despite the fact that much more data is available in the optical band. To a large extent this is because nearly all of the optical monitoring is restricted to continuous observations spanning less than 7 hours while quite a few X-ray observations last 10 hours or more. In section 2 of this short review, I briefly discuss several of the mechanisms that could provide QPOs in various bands in blazars. Section 3 summarizes some of the strongest claims for QPOs in the X-ray band for AGN, including some results from the ARIES group in India with which I am associated. Conclusions are given in section 4.

## 2. What could QPOs tell us?

For non-blazar AGN, there is a high probability that variations that have a quasi-periodic component would be related to processes occurring in or in the vicinity of the accretion disk around SMBH. In the optical/UV bands these variations could arise from the disk itself, whereas in the X-ray band they would likely arise from a hot corona sandwiching the disk. As magnetic field fluctuations could tie those disk fluctuations to the corona, even X-ray variability could be tied to the disk's rotation or internal modes. The simplest way in which such variations could arise would be from hot-spots or spiral shocks in accretion disks (e.g., Zhang & Bao 1991; Chakrabarti & Wiita 1993; Mangalam & Wiita 1993; Fukumura & Kazanas 2008). Such rotationally produced variations could indicate the mass, and conceivably even the spin, of the SMBH.

Some nearly periodic variability on time scales of years or decades might arise AGN containing close binary black hole systems. The most plausible case for this type of variation is OJ 287, where flares have been observed over the course of the past century at intervals of $\sim$12 years and where the last two outbursts were predicted. These luminosity changes can be most naturally explained by a less massive SMBH crashing through a large accretion disk surrounding the more massive SMBH (e.g., Sillanpää *et al.* 1996). Assuming this model is correct, quite a few details about the SMBHs can be determined, including some significant general relativistic effects (Valtonen *et al.* 2008).

As the bulk of a blazar's observed emission clearly arises from the relativistic jet pointing close to our line of sight, the variations in brightness that we observe must also emerge from those jets. Only at times when the blazar is observed at an absolutely minimum flux level is there a chance that we could directly see disk-based fluctuations. Nonetheless, it is important to note that non-axisymmetric variations arising in the disk could propagate into a jet and thus instigate the types of variations to be discussed next (e.g., Wiita 2006; Gupta *et al.* 2009).

Non-axisymmetric structures, related most likely to the magnetic field structure in the jet, will produce regions of increased emission towards one side or the other of the jet as a shock propagates outward along it. Because the Doppler boosting factor depends so sensitively on the viewing angle, even minor variations in the direction from which we observe the most strongly boosted emission can easily yield substantial changes in observed flux (e.g., Camenzind & Krockenberger 1991; Gopal-Krishna & Wiita 1992; Roland *et al.* 2009). When the shock propagates through an essentially helical structure in the jet, as has been convincingly argued to be present in some cases (e.g., Marscher *et al.* 2008), the effect is similar to that of a jet whose direction changes. Instabilities in jets can possibly excite helical modes capable of producing such structures (e.g., Romero 1995). The recurring boosts in flux will produce a periodic signal if the jet is cylindrical and the shock velocity is constant. However, in the more likely case that the jet has a finite opening angle or the shock speed changes between one wind of the helix and the next, then only a quasi-periodic signal can be expected. If this is the dominant mechanism producing a QPO then we might expect the fluctuation to last as long as the shock passes through the helical structure. In addition, if this is the fundamental mechanism behind QPOs in blazars, then if a QPO were seen to recur in a particular source we would expect it to have a nearly identical period during the later incarnation. If such a long-lived or repetitious signal were to be observed, changes in the interval and strength of the quasi-periodic component could provide a powerful tool for diagnosing the jet's structure.

Another situation which is likely to occur and which would produce rapid fluctuations emerging from a relativistic jet is when there is strongly turbulent flow behind a propagating shock (Marscher *et al.* 1992) or a standing (reconfinement) shock in the jet (e.g., Marscher *et al.* 2008). If a dominant turbulent cell is present, then we would observe enhanced Doppler boosting, and thus a quasi-periodic component to the variability, at the turn-over period of that cell (e.g., Rani *et al.* 2009). The stochastic nature of turbulence implies that we would not expect this type of QPO to last for very many cycles. If it recurs, the QPO would be likely to have a different dominant time-scale since the size and/or velocity of the biggest cell will normally be changed. Therefore, under most circumstances, merely a spectrum of variations at different temporal frequencies would be observed from turbulent flows, qualitatively consistent with the red-noise seen in most power spectra of AGN variability; QPOs would emerge from such flows only under rare circumstances. Unfortunately, the theory of relativistic turbulence (e.g., Narayan & Kumar 2009; Fouxon & Oz 2010) is not yet well enough developed to allow for reasonable predictions of the duty cycles at which QPOs that arise from this mechanism might be detectable. We are currently considering how models of relativistic turbulence can be extended so as to address this key question.

## 3. Observational evidence for X-ray QPOs

### 3.1 *RE J1034+396*

The strongest evidence for the presence of an X-ray QPO in any AGN is for the Narrow Line Seyfert 1 galaxy, RE J1034+393, where a 91 ks observation with XMM–Newton yielded a signal with period $\sim$1 hr, at least over the last 70% of that stare (Gierliński *et al.* 2008). A light curve folded at 3733 s provided a *prima facie* indication of the presence of a sinusoidal component containing $\sim$6.7% of the signal. A statistical analysis of the periodogram for that observation yields a peak at $\sim 2.7 \times 10^{-4}$ Hz that has a nominal significance of $\sim 5.6\sigma$ when analyzed using the Monte Carlo technique proposed by Vaughan (2005).

Now this source is not a blazar, and therefore this QPO presumably arises from some processes in or above the accretion disk and not from a jet (though the presence of a very weak relativistic jet cannot be ruled out). Assuming a disk related origin, Gierliński *et al.* (2008) suggest analogies with XRB QPOs: if it were a 'low frequency' QPO it would scale to a surprisingly low SMBH mass of $\sim 4 \times 10^5 M_\odot$; whereas if it were a 'high frequency' QPO it would scale to a much more reasonable $\sim 1 \times 10^7 M_\odot$. A recent reconsideration of this data by Czerny *et al.* (2010) used a wavelet analysis to argue that there is a drift in the QPO's central frequency and their approach suggests that there is a linear dependence between the QPO period and the flux. If this interpretation of the data is correct, variations produced by orbiting hot-spots close to the SMBH are disfavoured.

### 3.2 *3C 273*

Another strong case for a QPO was reported by Espaillat *et al.* (2008) for 3C 273, the first source to be recognized as a quasar (Schmidt 1963). They employed a wavelet technique, carefully modelled to take into account both white- and red-noise, to claim that a ∼3.3 ks quasi-period was present throughout the high quality portion, lasting 56 ks, of one XMM–Newton observation at a significance level exceeding 99%. For a best-fit red-noise model the significance is claimed to be 99.979%. This was the only highly significant detection among 19 observations of 10 different AGNs, although another one of the other four observations of 3C 273 provided a suggestion of a QPO around 5.0 ks; however, this was less than 99% of the red-noise confidence level. Espaillat *et al.* (2008) also employed structure functions to try to characterize the noise processes.

Although 3C 273 is a radio loud quasar, its jets are not closely aligned with our viewing direction and so it is also likely in this case that the variability arises from a process associated with the accretion disk and not from the jet. The simplest assumption that the variations arise from orbital motion close to the inner edge of the accretion disk around the SMBH leads to estimates for its mass of $7.3 \times 10^6 M_\odot$ and $8.1 \times 10^7 M_\odot$ for non-rotating and maximally rotating SMBHs, respectively (Espaillat *et al.* 2008). However, there have been several other, and certainly more reliable, mass estimates for the SMBH in 3C 273 using reverberation mapping and correlations between UV luminosity and the radius of the broad line region, all of which yielding masses of at least $2.4 \times 10^8 M_\odot$ (e.g., Kaspi *et al.* 2000). Therefore, the idea that orbital motion around the SMBH yields the QPO is also disfavoured for 3C 273. Instead, Espaillat *et al.* (2008) prefer an interpretation based on a $g$-mode oscillation (with $m \geq 3$) trapped within the accretion disk (e.g., Perez *et al.* 1997) for the physical origin of this apparent QPO.

### 3.3 *AO 0235+164 and 1ES 2321+419*

The Rossi X-ray Timing Explorer satellite (RXTE) contained an All Sky Monitor (ASM) instrument that has provided unique long-term coverage of bright X-ray sources. While a great majority of such sources are XRBs, there were 24 blazars that had sufficient flux to allow for an analysis of their light curves over temporal periods exceeding 12 years between 1996 and 2008 and we have recently analysed those X-ray light curves (Rani *et al.* 2009). As the ASM is not terribly sensitive, the typical S/N is rather poor for each data point, though when binned over several days when the source is weak, or binned over shorter periods during a source's high states, the ASM data is adequate to allow a search for stronger variability signals.

We performed preliminary analyses based on multiple dips in structure functions and followed them up with discrete correlation function and Lomb-Scargle periodogram (LSP) techniques. We found strong hints of nominally periodic signals in a surprising 20 of the 24 blazars (Rani *et al.* 2009). However, 15 of these 20 nominal quasi-periods were within $2\sigma$ of one year and one more was within $3\sigma$ of an annual variation. We rejected these 16 nominal periods because an earlier study had shown that many XRBs observed with RXTE/ASM showed oribital (96 min), daily, satellite precession period (53 day), and annual periods that were clearly artifacts of the instrument (Wen *et al.* 2006).

The remaining four blazars with periods incompatible with a year (or a half-year harmonic) as indicated by both structure functions and LSPs were AO 0235+138, BL Lac, OQ 530 and 2321+419. We then applied discrete correlation function analyses to try to confirm those nominal quasi-periodicities; only the signals for AO 0235+164 at ~17 days, and that of 2321+419 at ~425 days, survived. Therefore, only these two blazars are serious candidates to have exhibited X-ray QPOs. The nominal false-alarm-probability as obtained from their LSPs of the blazar 0235+138 is <0.03 while that of 2321+419 is <0.006. Light curves folded at those periods certainly appear to exhibit sinusoidal components. Thanks to the weak signals for these sources it was not possible to perform an appropriate Monte Carlo simulation and therefore it is extremely difficult to properly assess the significance of these putative QPOs. Regardless, they can be considered intriguing, but certainly not conclusive evidence for quasi-periods on time scales of tens to hundreds of days.

Since both of these sources are certainly blazars, if we assume that these signals do indeed have a physical origin, they are clearly associated with Doppler boosted jets. Rani *et al.* (2009) argue that to explain such relatively lengthy QPOs the most logical model involves shocks intersecting helical structures along probably conical relativistic jets, as described earlier in section 2.

### 3.4 *PKS 2155−304*

The observations of blazars by XMM–Newton that have entered the archive can be profitably searched for QPOs. In many cases the reason these observations were made was to determine the AGN's X-ray spectrum, but if the raw data is gathered into only one or two X-ray bands there is enough flux available to derive temporal variability on time scales of 100 s or less. By demanding that all observations were at least 7 hours in length, one might have a reasonable chance of finding QPOs with periods of ~1 hour, as were coincidentally seen for RE J1034+396 and 3C 273. This criterion left us with 24 X-ray light curves of length between 7.7 and 19 hours with adequate S/N made from measurements of just 4 blazars: PKS 0548−322 (1 observation of 45.5 ks); ON 231 (1 observation of 27.6 ks); 1ES 1426+428 (7 observations totaling 333.7 ks); and PKS 2155−304 (15 observations totaling 633.7 ks) (Gaur *et al.* 2010). For 13 of these 24 light curves, any time scale present exceeds the length of the observation. Structure function analyses provide a possible ~10.4 ks time scale for ON 231 and possible time scales of 15.7, 16.0, 16.6, 24.2 and 41.2 ks during 5 of the 15 stares at PKS 2155−304. However, such analyses based on structure functions have been recently shown to be fraught with difficulties (Emmanoulopoulos *et al.* 2010 and the paper by Emmanoulopoulos in these proceedings) and any time scales supported solely by single plateaus or dips in structure functions cannot be relied upon.

We have found that one of those XMM–Newton measurements of the 0.3–10 keV X-ray fluxes of PKS 2155−304 is particularly interesting (Lachowicz *et al.* 2009). This observation totaled 18 hours on 1 May 2006 and provides quite a strong evidence for the presence of a QPO with a 4.64 hr period. The 0.6–10 keV spectral analysis of this observation was reported in Zhang (2008). The raw light curve clearly indicates a series of four, nearly equally spaced peaks, and a multi-harmonic analysis of variance periodogram shows a strong peak at 4.64 hr that contains 5% of the power. When the light curve is folded at that period, an excellent agreement with a sinusoidal modulation is seen, and the structure function exhibits multiple dips separated by that interval. A wavelet analysis also shows that the period is present throughout the observation; however, much of that signal is in the 'cone of influence', in that the observed period is too close to the total length of the observation, so that one's confidence in the reality of this signal cannot be as high as it would seem at first. A periodogram in which both red-noise and white-noise are modelled via Monte Carlo simulations provides a significance for the QPO of $>0.999$; even if two power-laws are considered the significance is $\sim 3\sigma$.

Given that only $\sim 4$ cycles of this apparent period are covered by the data, even the high statistical support for this QPO cannot be taken at face value and this strong case for its presence in PKS 2155−304 is not an overwhelming one. It is perhaps worth noting that IUE observations of this bright blazar provided a hint of a 0.7-day periodicity during part of a multi-day observation long ago, but once again it was not present for a sufficient number of cycles to be convincing (Urry *et al.* 1993).

If we allow the reality of the 4.6-hr QPO, then the picture of a disturbance propagating through a helical structure in the jet, perhaps one engendered by instabilities, is most plausible. Still, for time scales of this length, the presence of turbulence behind a shock is also capable of providing a sensible physical explanation.

## 4. Conclusions

There are three distinct reasonable explanations for the reported X-ray QPOs in blazars that have been summarized in sections 3.3 and 3.4. The first possibility is that we have not yet seen a true QPO and that all of the measurements to date are actually very rare fluctuations in an overall red-noise power spectrum. The second is that some helical structure is being lit up by a passing shock. In that case the resulting variable Doppler factors are indeed providing us with important information on the jet's structure, although teasing out that information in fashion that can tightly constrain jet parameters will not be a trivial task. Finally, we may be witnessing the temporarily dominant fluctuations associated with the largest cells in a turbulent relativistic flow. If this is the mechanism responsible for these organized variations, rapid changes in the dominant frequency should occur, and it will be even more difficult to learn anything specific about the jet. The best hope here is to gather high quality data taken for the same source at different epochs that indicate different quasi-periods;

this type of information could reveal, in principle at least, much about the nature of relativistic turbulence in jets.

Given the difficulties in obtaining enough X-ray photons from most blazars for temporal analyses and the even greater difficulties in persuading time allocation committees to devote extremely long times to stare at individual blazars, obtaining iron-clad evidence for the presence of QPOs in blazars remains a daunting task.

The focus and required brevity of this invited review precluded my addressing the fairly large number of papers suggesting the presence of QPOs in blazars in the optical band as well as few such papers over the past couple of decades that provide indications of such variations in the UV or radio bands. Still, it is worth noting that probably the best of the recent optical measurements were obtained by the ARIES and PRL groups using an electron multiplying CCD camera that enables very fast (10 s cadence) measurements of bright blazars to be taken with a modest (1.2 m) telescope (Rani *et al.* 2010). A short (3 hour) observation of the BL Lac S5 0716+714 provided an indication of the presence of $\sim$7 cycles of an optical QPO of only $\sim$15 minutes. This signal appears clear in a folded light curve and is strongly indicated by LSP and structure function analyses. In order to quantify the significance of the signal in the presence of both red- and white-noise a Monte Carlo analysis was performed; it indicates that this QPO is significant at $\sim 3\sigma$ (Rani *et al.* 2010).

Nonetheless, all of these works suffer from difficulties similar to those afflicting the claims for X-ray QPOs. In no case have there been observations of more than 7 or 8 cycles that extend throughout an entire observing run and thus indicate that the actual observations are merely part of a substantially longer-lived phenomenon. While statistical tests may provide support at the 2.5–5.6$\sigma$ level, the latter high value has only been claimed for a Narrow Line Seyfert 1 galaxy, and not a blazar. In no case have the claims based on statistics carefully crafted to deal with the combination of red- and white-noise that we know to be present, managed to exceed roughly a $3\sigma$ level of significance.

Therefore, despite the growing amount of evidence in favor of the presence of some short-lived quasi-periodic variability in a number of sources, skeptics have the right to reserve judgement on this important phenomenon until such overwhelming data can be obtained. Unfortunately, if the variability does arise from processes such as turbulence in relativistic jets, there will hardly ever be a large number of cycles present and it is distinctly possible that such high thresholds of significance may not be crossed, even when substantially better data is collected in the future.

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