J. Astrophys. Astr. (2014) **35,** 307–314

Quasi Periodic Oscillations in Blazars

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Abstract. Here we report our recent discoveries of Quasi-Periodic Oscillations (QPOs) in blazars time series data in X-ray and optical electromagnetic bands. Any such detection can give important clues of the location and nature of the processes of emission mechanism. In the case of radio-quiet AGN, the detected QPOs are very likely to be associated with the accretion disk. But in the case of blazars, it may be associated with jets in the high and outburst states, and in the low-state, it is probably associated with the accretion disk. In this brief review, I summarize the recent QPO detections in blazars. There is one strong evidence of QPO detection in XMM–Newton time series data of narrow line Seyfert 1 galaxy RE J1034 + 396 about which we will also discuss briefly.

Key words. Galaxies: active—galaxies: quasars: blazars: blazar: individual: 3C 273, S5 0716 + 714, PKS 2155−304, ON 231, AO 0235 + 164, 1ES 2321 + 419.

1. Introduction

The presence of periodic or Quasi-Periodic Oscillations (QPOs) in the time series data of different electromagnetic (EM) bands of Active Galactic Nuclei (AGN) are very important to understand AGN emission models. The centre of the AGNs have accreting super massive Black Holes (BHs) with masses in the range 10^6–$10^9 M_\odot$ and have many similarities with the scaled up galactic X-ray BH binaries. The presence of QPOs in X-ray time series data of galactic X-ray BH and neutron star binaries in our galaxy and nearby galaxies (e.g., Remillard & McClintock 2006) are fairly common but very rare in AGN, if present at all. So, search for QPOs in the various subclasses of AGNs in different EM bands are very important.

It has long been known that there are two major classes of luminous AGNs (i.e., quasars). Roughly 85–90% of these have very little radio emissions ($F_{5\,\mathrm{GHz}}/F_\mathrm{B} \leq 10$, here $F_{5\,\mathrm{GHz}}$ = flux at radio 5 GHz and F_B = flux at optical B band 4400 Å) and are therefore called radio-quiet quasars (RQQSOs). The remaining 10–15% of quasars are radio-loud quasars (RLQSOs). A small subset of RLQSOs shows rapid flux variability at almost all wavelengths of the electromagnetic (EM) spectrum and also have strongly polarized emission. Such Flat Spectrum Radio Quasars (FSRQs) and highly variable BL Lacertae (BL Lac) objects are collectively known as blazars. BL Lac objects show featureless optical continuum while FSRQs show prominent emission lines in their optical spectra. Blazars have Spectral Energy Distributions (SED) that show two peaks and this leads to two subclasses of blazars: LBL (red or low energy or radio selected) and HBL (blue or high energy or X-ray selected). The lower frequency SED component peaks at IR/optical in LBLs and at UV/X-ray in HBLs. The second component extends up to γ-rays, usually peaking at GeV in LBLs and at TeV in HBLs. The blazar radiation at all wavelengths is predominantly non-thermal. The EM emission is dominated by a synchrotron component at low and high energies probably by an inverse Compton component. The blazar emission is a Doppler-boosted jet emission, and blazars (and other radio loud active galaxies) eject relativistic jets in the opposite directions (perpendicular to the accretion disk and/or aligned with the BH spin axis).

There is considerable uncertainty about the nature of the variable emission from RQQSOs. While many astrophysicists attribute it to thermal emission from the vicinity of the inner accretion disk, several others have proposed that even RQQSOs eject relativistic charged particle jets (like blazars); however, these jets are somehow quenched or disrupted before emerging from the nuclear region, and thus these objects are unable to produce the extended radio structures (e.g., Antonucci *et al*. 1990; Miller *et al*. 1993; Kellermann *et al*. 1994).

In general, blazar variability timescale is divided into three classes. Significant flux variations may occur over the course of less than a day, often called micro-variabilities, intra-night variabilities or Intra-Day Variabilities (IDV) (Wagner & Witzel 1995). The Short Term Variability (STV) can have timescale from days to few months and Long Term Variability (LTV) can range from months to several years (Gupta *et al.* 2004).

This paper is structured as follows. In section 2, we discuss what could cause QPOs in AGNs. In section 3, we describe QPO detection in AGN before 2008. In section 4, we summarize QPOs in AGN results since 2008, and finally in section 5, we give the conclusion.

2. What could cause QPOs in AGN?

In case of blazars, QPOs on year-long timescales might be due to blazar containing binary black hole system. A very well established case is for the blazar OJ 287. By analysing its about century-long optical light curve data, Sillanpää *et al.* (1988) suggested that QPOs detected in the light curve of the period ∼12 years is due to binary black-hole system in the blazar. They predicted its next outburst in 1995–1996 which was observed by Sillanpää *et al.* (1996). If we assume this model to be correct for LTV QPOs in other blazars too, we may determine a few details about SMBHs, including some significant general relativistic effects (Valtonen *et al.* 2008). When a blazar is observed at an absolutely low-flux level and QPO is detected on IDV timescales, then there is a chance that we could directly see disk-based fluctuations (e.g., Wiita 2006, 2011; Gupta *et al*. 2009). But accretion disk based models are ruled out for QPOs detected on STV and LTV timescales in blazars, because the BH mass of the blazar exceeded to $10^9 M_\odot$ (Rani *et al.* 2009). As the blazars observed emission clearly arise from the relativistic jet pointing close to our line-of-sight (Urry & Padovani 1995), the variations in brightness that we observe must also emerge from those jets. So, QPOs detected in IDV and STV timescales are favoured by jet based models (e.g., Lachowicz *et al*. 2009; Rani *et al*. 2009, 2010; Gaur *et al*. 2010 and references therein).

In case of non-blazar AGNs (mainly radio-quiet AGNs), there is a high probability that QPO component would arise by the processes occurring in or in the vicinity of the accretion disk. In X-ray bands, QPOs are due to the hot corona sandwiching the disk and in the optical/UV bands QPOs could arise from the hot-spots or spiral shocks in the accretion disks (e.g., Zhang & Bao 1991; Abramowicz *et al*. 1991; Chakrabarti & Wiita 1993; Mangalam & Wiita 1993; Fukumura & Kazanas 2008).

3. QPOs in AGN detected before year 2008

On IDV timescales, in the blazar OJ 287, the periodic variation of 15.7 min in radio 37 GHz was reported by Valtaoja *et al.* (1985), and 23 min optical periodicity was claimed by Carrasco *et al.* (1985). In the blazar PKS 2155–304, UV and optical QPOs were detected 0.7 day timescale (Urry *et al.* 1993). On STV timescales, in the blazar S5 0716 + 714, simultaneous optical and radio QPO were detected on $\sim$1 day timescale (Quirrenbach *et al.* 1991), and on another occasion, optical QPO on $\sim$4 days were present (Heidt & Wagner 1996). There were also claims of QPOs detection in X-ray data of other AGN classes on IDV and STV timescales (e.g., Fiore *et al*. 1989; Papadakis & Lawrence 1993; Iwasawa *et al*. 1998). On LTV timescales, in the blazar S5 0716 + 714, 5 optical outbursts were seen on $\sim 3.0 \pm 0.3$ year timescale (Raiteri *et al.* 2003; Gupta *et al.* 2008). Using almost a century long optical data of the blazar OJ 287, QPOs of $\sim$12 years were detected (Sillanpää *et al.* 1996), and a binary black-hole model explained such long term outbursts (Sillanpää *et al*. 1988; Valtonen *et al*. 2008).

4. QPOs in AGN detected since year 2008: Individual AGN

4.1 *Narrow line Seyfert 1 galaxy: RE J1034 + 396*

Till date, the strongest claim for the presence of QPO in any AGN or in any EM band is for the narrow line Seyfert 1 galaxy, RE J1034 + 393. Using 91 ks continuous XMM−Newton time series observations, QPO with a period of $\sim$1 hr was detected (Gierliński *et al.* 2008). To confirm the detected QPO, the light curve was folded at 3733 s which showed the presence of a sinusoidal component. The PSD analysis for that light curve gives a peak at $\sim 2.7 \times 10^{-4}$ Hz with a significance of $\sim 5.6\,\sigma$ using Monto–Carlo simulation proposed by Vaughan (2005).

Since this source is a radio-quiet AGN, QPO may not arise from the jet but arises from some processes in or above the accretion disk. Gierliński *et al.* (2008) used analogies with XRB QPOs and quoted surprisingly low mass for the super massive BH of AGN $\sim 4 \times 10^5 M_\odot$ if it was a low-frequency QPO, and for high-frequency QPO, the mass of BH of AGN is $\sim 1 \times 10^7 M_\odot$ which is reasonable. Using the same data and wavelet analysis technique, Czerny *et al*. (2010) found that the central frequency shifted. They also found a linear dependence in AGN flux and QPO period and ruled out QPO due to orbiting hot spot model.

4.2 *Radio loud quasar: 3C 273*

Using 19 XMM–Newton observations of 10 different classes of AGNs in which the data length exceeded 30 ks, Espaillat *et al.* (2008) found QPO with a period of 3.3 ks in the Flat Spectrum Radio Quasar (FSRQ) 3C 273. The data were analysed by wavelet analysis tool and the detected QPO lasted for 56 ks above 99.979% significance using best-fit red noise model. The simplest way to explain QPO is that the variation arises due to orbital timescale originating near a last stable orbit of $3R_s$, which implies a central black hole mass of $7.3 \times 10^6 M_\odot$ for non-rotating black holes, and for a maximal rotating black hole with a last stable orbit of $0.6R_s$, a central black hole mass of $8.1 \times 10^7 M_\odot$ (Espaillat *et al.* 2008). The estimated BH mass in this way was substantially lower than the estimation by the most reliable reverberation mapping method which gives a mass of about $2.4 \times 10^8 M_\odot$ (Kaspi *et al.* 2000). Due to the substantial difference in BH mass by reverberation mapping and orbital motion models, Espaillat *et al.* (2008) interpreted that the physical origin of QPO is based on a *g*-mode oscillation (with $m \geq 3$) trapped within the accretion disk (Perez *et al.* 1997).

4.3 *Blazar: BL Lac S5 0716 + 714*

The blazar S5 0716 + 714 is one of the most extensively searched blazar for optical IDV studies and the large amount of optical IDV time series data are available on the public archive. One of the most extensive optical IDV study of the blazar was done by Montagni *et al.* (2006). In this paper, the authors have published 102 night optical IDV data of the blazar observed during 1996 to 2003. We put several strict data selection criterion (Gupta *et al.* 2009) which was only qualified by 20 light curves. We used wavelet plus randomization technique, which had certain advantages over the commonly used periodogram and Fourier power spectra approaches in searching for statistically significant real periodicities in the IDV light curves. For detailed data analysis and randomlet technique, see O'Shea *et al.* (2001) and Gupta *et al.* (2009). We found significant QPO with significance level ≥99% on 5 of the light curves. The detected QPO periods were in the range of 25 to 73 min (Gupta *et al.* 2009). This was the first evidence of optical QPO detection in optical IDV data of blazar. We explained the detected QPOs by the accretion disk fluctuations or oscillations. The QPO period gave the nominal BH masses of the blazars ranging from 2.47–$7.35 \times 10^6 M_\odot$ by assuming that the period arises from Schwarzschild BH, while for a rapidly rotating Kerr BH the mass ranges between 1.57–$4.67 \times 10^7 M_\odot$.

In another project based on the blazar S5 0716 + 714 to search for optical QPOs on IDV timescale, we have made new optical observations using CCD detector and BVRI optical filter mounted on a 1.2-m optical/IR telescope at Mount Abu, India. In about 3 hours on 2008 December 27, we obtained optical (R band) observations of the blazar S5 0716 + 714 at a very fast cadence of 10 s. We used 4 different methods: SF, data folding, LSP and PSD to detect QPO in the time series optical data. The details about observations and data analysis are given in Rani *et al.* (2010). We found QPO with the period of 15 min in the first-6 ks data. It is the fastest QPO ever detected in any AGN or in any EM band till date (Rani *et al.* 2010). In the simplest way to explain such fast and short-lived QPO by the accretion disk model, i.e. flux arising from hot spots or some other non-axisymmetric phenomenon related to the orbital motions that are close to the innermost stable circular orbit around a super massive

BH, which gives the SMBH mass of $1.5 \times 10^6 M_\odot$ for a non-rotating BH and $9.6 \times 10^6 M_\odot$ for a maximal rotating BH (Gupta *et al.* 2009). Another explanation of the short-lived QPO could be due to jet-based model of radio loud AGNs (e.g., Urry & Padovani 1995), since blazar jets were pointing very close to our line-of-sight, and the emerging flux was dominated by emission from jets. Turbulence behind a shock propagating down a jet (e.g., Marscher *et al*. 1992) or relativistic shock propagating down a jet that possesses a helical structure are very plausible ways to produce short-lived, quasi-periodic fluctuations in emission at different wavelengths.

In a simultaneous multi-wavelength IDV and STV search campaign project of the blazar S5 0716 + 714, we made new optical observations using CCD detectors and BVRI optical filters mounted on about 20 telescopes around the globe. We used 4 different methods: PSD, wavelet, mhAoV and LSP to detect QPO in the time series optical data. The details about observations and data analysis are given in Gupta *et al.* (2012). We found a hint of QPO with the period of 0.9–1.1 days which lasted only for 2.2 cycles.

4.4 *Blazars: BL Lac AO 0235 + 164 and BL Lac 1ES 2321 + 419*

To search for X-ray QPOs in blazars on STV and LTV timescales, we selected X-ray data from ASM (All Sky Monitor) on board RXTE (Rossi X-ray Timing Explorer) X-ray mission. The data was of about 12 years long (January 1, 1996 to September 1, 2008) of 24 LBLs. We extracted 1 day average X-ray fluxes of these 24 LBLs in the energy range 1.5–12 KeV and generated the light curves of the blazars. To search for QPOs in the light curves of these blazars, we used 4 different analysis methods: SF (structure function), DCF (descrete correlation function), data folding and LSP (Lomb Seargle Periodogram). We claimed any result as genuine QPO detection only when the results were verified by all these four different methods. The details about the data selection and analysis methods are given in Rani *et al.* (2009). Out of 24 blazars, 20 of them showed QPOs on year timescale and these periods were clearly related to yearly variations arising from the instrument. But 4 of the blazars showed period different than year timescale using our first method SF to search for QPOs. But when we tried to confirm the periods of the 4 blazars by other methods, i.e. LSP and DCF, two of the results of the 2 blazars did not survive (Rani *et al.* 2009). Finally, we found genuine ∼17 days period in AO 0235 + 164 and ∼420 days period in 1ES 2321 + 419. By discussing several possible explanations for QPOs on STV (in AO 0235 + 164) and LTV (in 1ES 2321 + 419) timescales, we ruled out the possibility of QPO which arise from hot spots, spiral shocks or other non-axisymmetric phenomena related to orbital motions very close to the innermost stable circular orbit around an SMBH. Assuming this orbital signature, we found that the BH masses of these blazars are too high. We finally concluded that the most likely explanation for the detected QPOs period could most likely arise from the intersections of a shock propagating down a relativistic jet that possesses a helical structure (Rani *et al.* 2009).

4.5 *Blazars: BL Lac PKS 2155−304 and BL Lac ON 231*

We searched X-ray QPOs on IDV timescales of 24 light curves of 4 HBLs. These light curve data were taken from EPIC/pn of the XMM–Newton X-ray satellite.

These light curves were extracted in 0.3–10 KeV energy range using the standard method of data analysis using XMM–Newton Science Analysis System (SAS) version 8.0.0. Out of these 24 light curves, we got QPO detection in one light curve of one HBL PKS 2155−304 and the result was confirmed by 5 different analysis methods: SF (structure function), data folding, wavelet analysis, mhAoV periodogram and PSD (power spectrum density). The details about these 5 analysis methods are given in Lachowicz *et al.* (2009). In the rest 23 light curves, we also searched for QPOs on IDV timescales and found hint in 2 HBLs in 1 light curve of each PKS 2155−304 and ON 231. The data analysis was done by 2 different analysis methods: SF and PSD (Gaur *et al.* 2010).

We reanalysed archival XMM–Newton EPIC/pn observations of PKS 2155−304 taken on 2006 May 1 (orbit 1171, ObsID 0158961401). In a visual inspection, we suspected that the time series data may show QPO. To confirm it, we first did SF analysis of the data and QPO with a period of ∼4.6 hours and 3.8 cycles was detected. To verify our result, we analysed the same data by data folding, wavelet analysis, mhAoV periodogram and PSD (power spectrum density), and the results were confirmed by all these methods (Lachowicz *et al.* 2009). We explained the detected QPO by the strong orbiting hotspots on the disks at, or close to, the innermost stable circular orbit allowed by general relativity (e.g., Mangalam & Wiita 1993). Using this model, we estimated the BH mass for PKS 2155−304 to be $3.29 \times 10^7 M_\odot$ for a non-rotating BH and $2.09 \times 10^8 M_\odot$ for a maximal rotating BH (e.g., Gupta *et al.* 2009). An alternative explanation of the detected QPO can be in a different way of jet based model: helical structure in a jet in which change in electron density or magnetic field can produce QPO, turbulence behind shock can also produce short-lived QPO, etc. (Lachowicz *et al.* 2009).

The rest 23 XMM–Newton IDV light curve data of 4 HBLs were analysed to search for IDV timescales and QPOs. First, we used SF to find out IDV timescale and QPO if present. By doing SF analysis, we found 2 light curves, one each of PKS 2155−304 and ON 231 showing possible QPOs. To confirm the result, we did PSD analysis on both the light curves but none showed any QPO frequency $\geq 3\sigma$. So, we can only say that those were only possible weak QPOs detection (Gaur *et al.* 2010). By using the simplest accretion disk based model for QPOs detection, we found that the BH masses of these 2 BL Lacs exceeded $1.2 \times 10^7 M_\odot$. Since, most of the blazar emission is expected to arise from jets which are launched from the immediate vicinity of the SMBH (e.g., Marscher *et al*. 2008), the observed timescale, $P_{\rm obs}$, of any fluctuation is likely to be reduced with respect to the rest-frame timescale, $P_{\rm em}$, by the Doppler factor, δ, as well as increased by a factor of $(1 + z)$. Using the jet model and QPO period ∼5.9 ks and $\delta = 3.2$ of blazar ON 231, we found the BH mass to be $3.8 \times 10^7 M_\odot$ for non-rotating BH, and $2.4 \times 10^8 M_\odot$ for rapidly spinning BH. Similarly, in the case of PKS 2155−304 for the QPO period ∼5.5±1.3 ks and $\delta = 30$, we found that the BH mass would be between $3.6 \times 10^8 M_\odot$ to $2.2 \times 10^9 M_\odot$ (Gaur *et al.* 2010).

5. Conclusion

- QPOs in AGNs are detected on all possible timescales (e.g., IDV, STV and LTV).

- QPOs in AGNs are a rare event and still not well-established. Only a few evidences are known.
- Theoretically there is no AGN model which can explain the detected QPOs clearly.

So, QPO in AGN is a new field of AGN research which needs a focussed effort to establish it. Also there is a need to develop a more general standard model of AGN emission mechanism which can explain AGN variability and QPOs.

References

Abramowicz, M. A. *et al.* 1991, *A&A*, **245**, 454.
Antonucci, R., Barvainis, R., Alloin, D. 1990, *ApJ*, **353**, 416.
Carrasco, L., Dultzin-Hacyan, D., Cruz-Gonzalez, I. 1985, *Nature*, **314**, 146.
Chakrabarti, S. K., Wiita, P. J. 1993, *ApJ*, **411**, 602.
Czerny, B. *et al.* 2010, *A&A*, **524**, 26.
Espaillat, C., Bregman, J., Hughes, P., Lloyd-Davies, E. 2008, *ApJ*, **679**, 182.
Fiore, F., Massaro, E., Perola, G. C., Piro, L. 1989, *ApJ*, **347**, 171.
Fukumura, K., Kazanas, D. 2008, *ApJ*, **679**, 1413.
Gaur, H., Gupta, A. C., Lachowicz, P., Wiita, P. J. 2010, *ApJ*, **718**, 279.
Gierliński, M., Middleton, M., Ward, M., Done, C. 2008, *Nature*, **455**, 369.
Gupta, A. C., Banerjee, D. P. K., Ashok, N. M., Joshi, U. C. 2004, *A&A*, **422**, 505.
Gupta, A. C., Fan, J. H., Bai, J. M., Wagner, S. J. 2008, *AJ*, **135**, 1384.
Gupta, A. C., Srivastava, A. K., Wiita, P. J. 2009, *ApJ*, **690**, 216.
Gupta, A. C. *et al.* 2012, *MNRAS*, **425**, 1357.
Heidt, J., Wagner, S. J. 1996, *A&A*, **305**, 42.
Iwasawa, K. *et al.* 1998, *MNRAS*, **295**, L20.
Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., Giveon, U. 2000, *ApJ*, **533**, 631.
Kellermann, K. I. *et al.* 1994, *AJ*, **108**, 1163.
Lachowicz, P., Gupta, A. C., Gaur, H., Wiita, P. J. 2009, *A&A*, **506**, L17.
Mangalam, A. V., Wiita, P. J. 1993, *ApJ*, **406**, 420.
Marscher, A. P., Gear, W. K., Travis, J. P. 1992, In: *Variability of Blazars* (eds) Valtaoja, E., Valtonen, M. (Cambridge: Cambridge University Press), p. 85.
Marscher, A. P. *et al.* 2008, *Nature*, **452**, 966.
Miller, P., Rawlings, S., Saunders, R. 1993, *MNRAS*, **263**, 425.
Montagni, F., Maselli, A., Massaro, E., Nesci, R., Sclavi, S., Maesano, M. 2006, *A&A*, **451**, 435.
O'Shea, E., Banerjee, D., Doyle, J. G., Fleck, B., Murtagh, F. 2001, *A&A*, **368**, 1095.
Papadakis, I. E., Lawrence, A. 1993, *Nature*, **361**, 233.
Perez, C. A. *et al.* 1997, *ApJ*, **476**, 589.
Quirrenbach, A. *et al.* 1991, *ApJ*, **372**, L71.
Raiteri, C. M. *et al.* 2003, *A&A*, **402**, 151.
Rani, B., Gupta, A. C., Wiita, P. J. 2009, *ApJ*, **696**, 2170.
Rani, B., Gupta, A. C., Joshi, U. C., Ganesh, S., Wiita, P. J. 2010, *ApJ*, **719**, L153.
Remillard, R. A., McClintock, J. E. 2006, *ARA&A*, **44**, 49.
Sillanpää, A., Haarala, S., Valtonen, M. J., Sundelius, B., Byrd, G. G. 1988, *ApJ*, **325**, 628.
Sillanpää, A. *et al.* 1996, *A&A*, **305**, L17.
Urry, C. M. *et al.* 1993, *ApJ*, **411**, 614.
Urry, C. M., Padovani, P 1995, *PASP*, **107**, 803.
Valtaoja, E. *et al.* 1985, *Nature*, **314**, 148.
Valtonen, M. J. *et al.* 2008, *Nature*, **452**, 851.

Vaughan, S. 2005, *A&A*, **431**, 391.
Wagner, S. J., Witzel, A. 1995, *ARA&A*, **33**, 163.
Wiita, P. J. 2006, In: *Blazar Variability Workshop II, ASP Conf. Ser.* (eds) Miller, H. R., Marshall, K., Webb, J., Aller, M. F. (San Francisco: ASP) vol. 350, p. 183.
Wiita, P. J. 2011, *JAA*, **32**, 147.
Zhang, X.-H., Bao, G. 1991, *A&A*, **246**, 21.