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Quasi-periodic oscillations in quasars to nano-quasars

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Abstract. TAUVEX brings us a unique opportunity to explore the temporal variability of UV emitting objects in the sky. One of the questions that we intend to resolve with TAUVEX is whether the 'variabilities' detected in active galaxies and quasars and in radiations around massive black holes in general are just random variations of the intensities or these are intrinsic to the disk system, and possibly due to the quasi-periodic oscillations (QPOs) which are well known to be observed in smaller black holes (nano-quasars). In this article, we present a physical mechanism for the QPOs and show that this is a generic mechanism which should be manifested in all types of active compact objects, ranging from quasars to nano-quasars. We propose some tests by which we may be able to tell if these are QPOs, even without waiting for a large number of cycles to test the periodicity. We present a few examples to impress that perhaps we have already seen QPOs in some objects. Multi-wavelength observation capabilities in TAUVEX may be used to pinpoint the nature of the variable sources more accurately.

Keywords : Black hole physics – radiative transfer – shock waves – X-rays: binaries

1. Introduction

It is generally accepted that the massive black holes power the active galaxies and quasars. In these systems, the upper limit of the mass of the black hole could be as high as a few times a billion solar mass as in M87. On the other hand, quasar-like behaviours are common even in stellar mass black holes, such as GRS 1915+105 where the mass may

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be a few times the solar mass. The generic nature of the properties in quasars ($M \sim$ a few $\times 10^9\ M_\odot$) to nano-quasars ($M \sim$ a few $\times M_\odot$) is due to the most basic fact that majority of the black hole physics is only a function of the mass of the black hole, if it is a Schwarzschild black hole and, to some extent, on the angular momentum, if it is a Kerr black hole. In other words, the physics of the formation of accretion disks and jets are roughly the same but the properties scale with some power of the central mass. The unique nature of the black holes is reflected by the fact that all types of accreting matter, independent of their sources, must enter through the horizon with the velocity of light and thus are supersonic. This nature, uniquely picks a single solution out of many which must pass through at least one sonic point. When it passes through two sonic points, whether steadily or in a time-dependent way, an accretion shock forms (Chakrabarti 1990; 1996) in the flow which basically dictates most of the observed properties of the black hole accretion. Even though a black hole does not have a hard surface, this shock, formed due to the competition between the gravitational and centrifugal force behaves like a boundary layer of a star and is called the CENtrifugal barrier supported BOundary Layer or CENBOL.

The first attempt to incorporate the CENBOL, i.e., shocked sub-Keplerian accretion flows (see Chakrabarti 1990; Abramowicz & Chakrabarti 1990) to explain spectral characteristics of quasars was made in Chakrabarti & Wiita (1992). This was extended to include the Keplerian disk itself, first qualitatively in Chakrabarti (1994) for active galaxies and subsequently, in the context of quasars and stellar mass black holes by Chakrabarti & Titarchuk (1995, hereafter CT95) in detail. Here, the soft photons from the Keplerian disk were intercepted by the CENBOL and these intercepted photons were reprocessed through inverse comptonization to produce hard X-rays. Chakrabarti & Titarchuk (1995) also extended the concept of converging flows (Blandford & Payne 1982) in the context of black hole accretion and showed that even in the soft state, when the CENBOL is cooled down due to the excessive soft photon supply from the Keplerian disk, there may be a faint power-law hard tail due to the comptonization by bulk-motion of the flow between the innermost sonic point (which has to be present in any black hole accretion) and the horizon. Mandal & Chakrabarti (2005, hereafter MC05) included stochastic magnetic fields also. Apart from the usual comptonization by the thermal electrons, MC05 also included the shock acceleration of the electrons and the non-thermal electrons so produced, generated power-law synchrotron photons and at the same time, inverse Comptonize soft photons. Subsequently, Chakrabarti & Mandal (2006a, hereafter CM06) included the Keplerian disk also as in CT95, and showed that observations of black hole candidates such as Cyg X-1 in soft and hard states can be easily explained by variation of the Keplerian and sub-Keplerian rates.

Fig. 1 shows the cartoon diagram of the CENBOL and the radiation processes. This background of the flow structure and the mechanism of the emission of radiation are provided for understanding the non-steady behaviour of the radiation. Soft X-rays and hard X-rays emitted in nano-quasars will be replaced by UV (even optical) and soft-Xrays

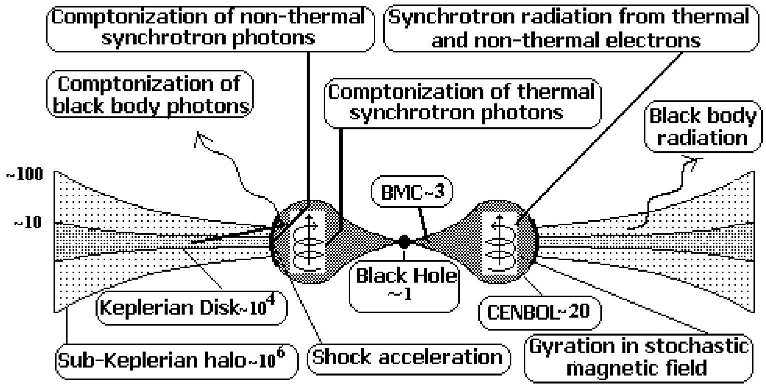

Figure 1. A cartoon diagram of the accretion flow with all the physical and spectral components. The dimension of different regions are in units of r_g, the radius of the black hole. The Keplerian flow is sandwiched by a sub-Keplerian halo which extends till the accretion shock. CENBOL is the post-shock region which is the source of thermal and non-thermal electrons. Soft photons from the Keplerian disk intercepted by the CENBOL and the synchrotron radiations from the thermal and the non-thermal electrons generated within CENBOL are inverse-comptonized to higher energies (adapted from CM06).

(EUV) in the case of quasars as the energy release takes place in lower frequencies in the electromagentic spectrum for the massive objects.

Figs 2(a-d) show various contributions to the total spectrum when the masses are varied (marked). The curve marked '1' indicates the synchrotron radiation from the pre-shock flow, '2' represents black body radiation from the Keplerian disk, '3' represents the comptonization of the intercepted black body photons by the CENBOL,'4' is due to comptonization of the soft photons by the convergent flow, '5' and '6' are the comptonization of the synchrotron soft photons by the thermal electrons and non-thermal electrons respectively. Finally, the curve marked '7' represents the total spectrum (Chakrabarti & Mondal 2006b). Masses of the black holes are marked in each box. The disk and halo accretion rates are, in units of the Eddington rate, 0.01 and 0.01 respectively for a strong shock (compression ratio $R = 4$) located at $r_s = 10$. Different curves have the same meanings as before. These should be the typical spectra of the (a) quasars, (b) milli-quasars, (c) microquasars and (d) nano-quasars respectively. The presence of two accretion rates (without increasing the number of parameters, since the viscosity parameter is absent) increases the types of spectra that one can have. For instance, one can have an 'abnormal' spectrum in which the Keplerian bump itself is missing as in observed in M87. In this case, the whole radiation is produced from the sub-Keplerian components. Due to the shock acceleration process, a fraction of the electrons obey power-law distribution. The comptonization spectrum of the synchrotron soft photons emitted by these non-thermal electrons shows a power-law nature extended up to a very high energy (> 20 MeV).

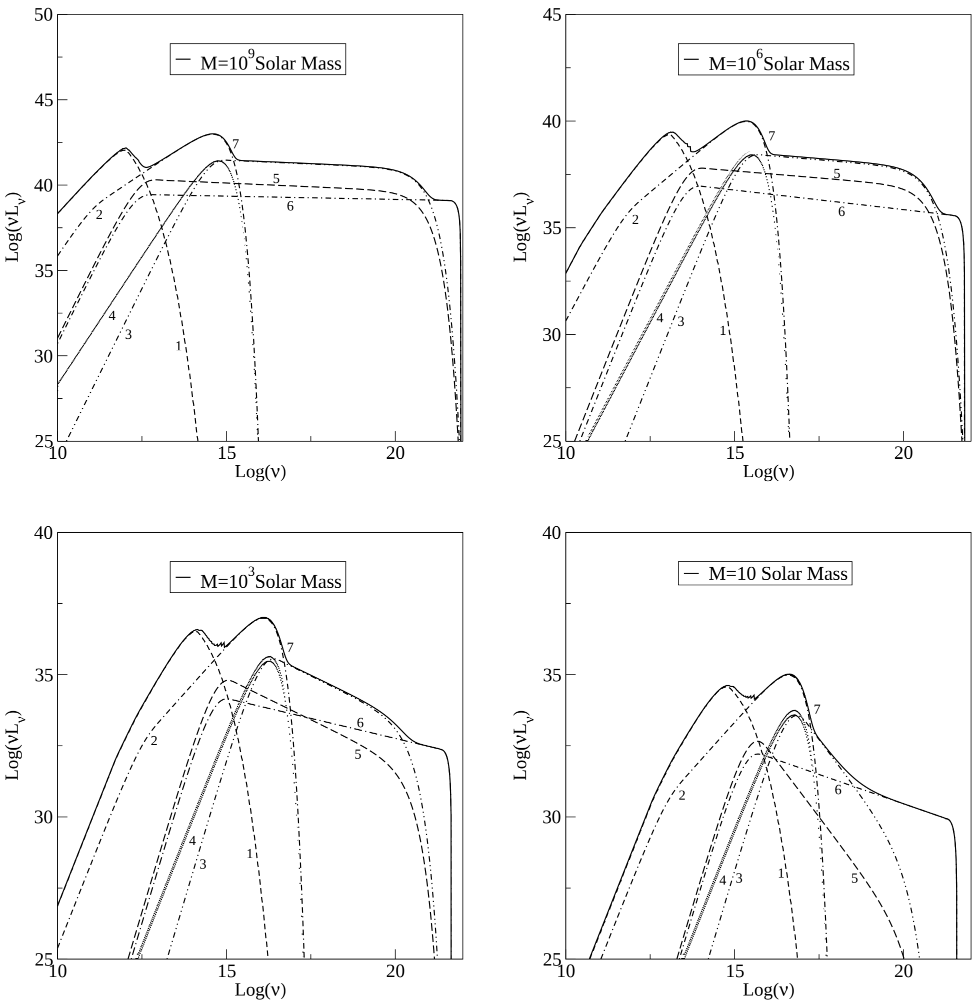

Figure 2. Net spectra and their components emitted by our two component flow from quasars to nano-quasars. (a) $M = 10^9 M_\odot$, (b) $10^6 M_\odot$, (c) $10^3 M_\odot$ and (d) $10 M_\odot$ respectively.

2. Quasi-periodic oscillations in black holes

It is generally believed that the inner stable circular orbit (ISCO) has *always* some thing to do with the quasi-periodic oscillations (QPOs). The reason why this is wrong is that, for a given black hole candidate (i.e., for a given ISCO location, and thus frequency of the Keplerian orbit), there can be a wide variation in QPO frequency, often ranging from a few mHz to a few Hz (see, works of Remillard et al. 1999 and references therein and Chakrabarti & Manickam 2000; Chakrabarti et al. 2006). Sometimes, there are several

QPO frequencies which are detected simultaneously. Second important fact about QPO is that it has a significant power (a few percent of rms value). So it should not be looked upon as a 'vibration' (i.e., disko-seismological effects). Rather, it is an oscillation of a region (causing it to have a 'Q' value of around 5 to 40 or so) as a whole. In a two component advective paradigm (Fig. 1), there are several length scales which may participate in 'natural' oscillations. These are: (a) $r = r_{Kep}$ which is the inner edge of the Keplerian disk which need not be ISCO. r_{Kep} could extend to even a few hundred r_g, the Schwarzschild radius. (b) $r = r_s$ is the mean location of the shock. This can vary from $\sim 5r_g$ to $100r_g$ depending on specific energy and specific angular momentum. For a Kerr black hole the lower limit could be even closer to the black hole. (c) $r = r_{in}$, the location of the inner sonic point. This usually varies between the marginally stable and the marginally bound orbits, i.e., between 2 to 3 Schwarzschild radii for a Schwarzschild black hole. For Kerr black holes, both of these orbits are closer to the black hole and thus the frequency can rise. In reality, it is the inner strong shock $r_{in} \lesssim r_{ws} \lesssim 10$ with a typical location of $r \sim 7$ just behind r_{in} is more important (Samanta, Chakrabarti & Ryu 2007) for the purpose of radiative transfer. (d) $r = r_{sr}$, the size of the sonic radius of the outflow or jet which comes out of the CENBOL. This is usually a few times the shock location (Chakrabarti 1999; Chakrabarti & Nandi 2000). The outflow till r_{sr} being sub-sonic, it is denser and could be cooled by the soft photons from the disk, especially in the pre-shock flow ($r > r_s$). The cold outflow then falls back and is recycled through the accretion disks again.

Note that the four lengths just mentioned directly scales with the mass of the black holes. Since they also correspond to four time scales, they can also produce four types of QPOs which scale as the inverse of the mass. The QPO frequency ν is, as a rule of thumb, given by the inverse of the infall time t_{QPO} from one of the first three types of the oscillating scales r to the horizon, i.e., $t_{QPO} \sim \nu^{-1} \sim Rr^{3/2}\ 2GM/c^3$s, where R is the shock strength ($R = 1$ for $r = r_{Kep}$) which could be ~ 7 for a strong shock and M is the mass of the black hole, be it a quasar or a nano-quasar. For a $M = 10^7 M_\odot$ Schwarzschild black hole, for instance, the QPO frequency will be (a) 1.9 μHz $< \nu_a <$ 1942μHz for $3 < r < 300$, (b) 1.4 μHz $< \nu_b <$ 127.8μHz for $R = 7$, and $5 < r < 100$, (c) $\nu_c \sim 77\mu$Hz for typical values ($R = 7$, $r_{ws} = 7$, $M = 10^7 M_\odot$). The fourth type of oscillation depends on the time in which the volume r_{sr}^3 is filled in till the optical depth $\tau \sim 1$ (Chakrabarti & Manickam 2000). It turns out that this oscillation is of low frequency ($\sim$ MHz) and brings the spectrum from on to off states in quick succession (few minutes) due to local recycling of matter. As Chakrabarti & Manickam (2000) showed, the duration (recycling time t_{rec}) of the QPO, depends on the QPO frequency ν_b (in the off-state) itself through the relation $t_{rec} = \nu_d^{-1} \propto \nu_b^{-2}$. So, ν_d is not totally independent.

Molteni, Sponholz & Chakrabarti (1996), using bremsstrahlung cooling first showed that the oscillations of the post-shock region, namely the CENBOL, can cause considerable periodic oscillation of the luminosity. Furthermore, these oscillations turn out to have a frequency inversely proportional to the cooling time scale in the CENBOL. As such, increase in the accretion rate would then reduce the cooling time scale and increase the frequency. Increased cooling reduces the post-shock pressure and thus the shock moves closer to the black hole and oscillates at a faster rate. Subsequently, Chakrabarti, Acharyya & Molteni (2004) showed using simple cooling laws, that shocks oscillated both vertically and horizontally (Fig. 3). A Fourier analysis of the emitted luminosity variation shows QPO peaks with similar characteristics as in observed radiation. Figs 4 (a-d) and Figs 5 (a-d) showed the variation of intensity with time and the power density spectrum (PDS) of this variation when the accretion rates are varied. We note that the apparent noisy lightcurve of the simulated result produces a PDS which has distinct signatures of QPOs. The mass of the black hole chosen is $10^8 M_\odot$ and ν_{QPO} is in the range mentioned above. Because the time period scales with the mass of the black hole, the QPO observed could have periodicities from a few hours to a few years.

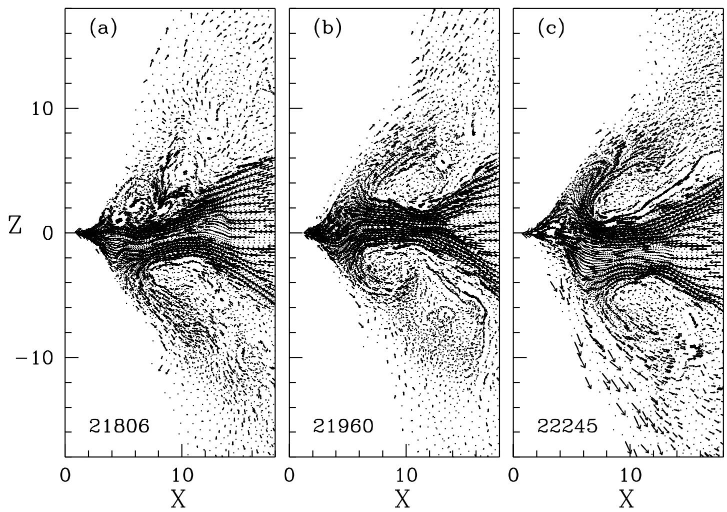

Figure 3. Simulation results showing varying disk configuration in successive half cycles. Both vertical and horizontal oscillations of the shock are observed. Jets are produced from the post-shock region.

In Ryu, Chakrabarti & Molteni (1996), yet another type of shock oscillation was observed. In case the standing shock conditions (Chakrabarti 1989) are not satisfied, but still the flow topology shows the presence of two saddle type sonic points, then such an oscillation could take place. The ν_{QPO} is inversely proportional to the infall time-scale of matter. Since this is not induced by dissipation or cooling effects, the dependence on accretion rate is not very direct. Rather, the oscillation amplitude depends on how fast the matter is lost through winds, and thus on the specific energy and angular momentum of the flow.

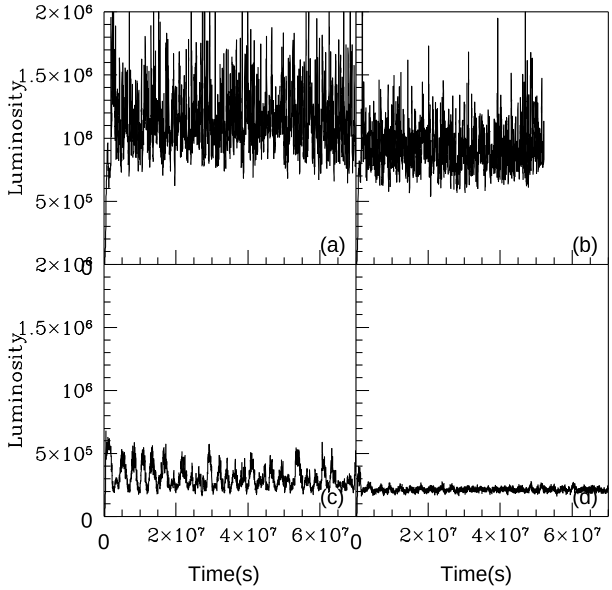

Figure 4. Examples of the time variation of the total bremsstrahlung luminosity of the radiation which is emitted from the accretion flow when the density at the injection in increased (a) $\rho_{inj} = 0.95 \times 10^{-14}$gm s^{-1}, (b) 1.265×10^{-14}gm s^{-1}, (c) 3×10^{-14}gm s^{-1} and (d) 5×10^{-14}gm s^{-1} respectively. These densities correspond to the accretion rates of 0.27, 0.22, 0.37 and 0.39 (in units of the Eddington rate) respectively in the equivalent Compton cooling problem. The mass of the black hole is $10^8 M_\odot$.

3. Observational results of massive and super-massive black holes

We now present examples of some of the variabilities observed in quasars and milliquasars. Figs. 6(a-f) give examples of variable light curves in several active galaxies. Fig. 6(a), shows the mean quasi-cyclic ($P \sim 13$ yr) changes in the blazar PKS 0736+017 with rapid flares super-imposed on it (Smith 1996). While short timescale flares could be due to the propagating shocks in the jets pointing at us, the long timescale variability is due to a variation of the fundamental flow properties. In Fig. 6(b), we show very short timescale, quasi-sinusoidal ($P \sim 4 \times 10^4$s) variation in MCG-6-30-15 (Arevalo et al. 2002; see also, McHardy et al. 2005). Variations in a wide range of timescale have been detected (frequency ranging from 10^{-8}Hz to 10^{-2}Hz) with a spectral break frequency at 7.6×10^{-5}Hz (McHardy et al. 2005). For a typical shock at $100r_g$, this timescale would correspond to a few million solar mass, which is what is found from dispersion relation as well. In this object, while the X-ray intensity changes by a factor of two, UV variation is only a few percent. In Chakrabarti & Manickam (2000) it was shown that the radiation emitted from the pre-shock region, does not participate in the variability while

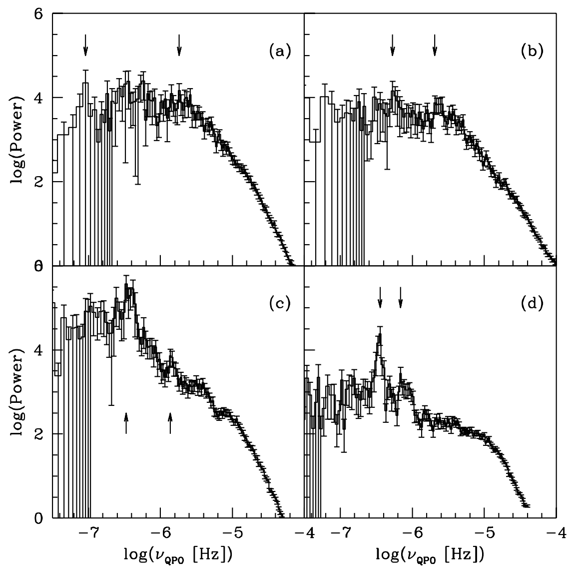

Figure 5. Power density spectra of the four cases presented in Figs 4(a-d). The QPO frequencies are at (a) 1.83μHz and .092μHz; (b) 2.06μHz and 0.534μHz, (c) 1.37μHz and 0.34μHz and (d) 0.69μHz and 0.36μHz. The second frequency is due to shock oscillation and is increasing with accretion rate.

the comptonized radiation of the post-shock region showed more variation. Thus, the behaviour of X-ray/UV variation in MCG-6-30-15 is in line with the CENBOL oscillation model. In Fig. 6(c), we show the light curve of Seyfert I galaxy RX J0437.4-4711 in EUV (Halpern & Marshall 1996). Here, the periodicity is about 0.9d. In Fig. 6(d), the optical and X-ray variation in the narrow line Seyfert I galaxy NGC 4051 are presented (Peterson et al. 2000). Here too, we find that the fractional change in softer radiation is much smaller (factor of a few percent) than the X-rays (factor of a few). The variations are in time scales of $\sim$ hundred days. If the black hole is only a few million solar mass, such a large time scale is unusual, unless it is of type (d) given in section 2 above, where the cooling rate of the outflow may play a role in deciding the time variation. In Fig. 6(e), we show variations of Ark 564 (Shemmer et al. 2001). Here, the Optical, UV and X-ray correlations are presented. Clearly, as the wavelength increases, the amplitude of variation is also lower. This is in line with our present understanding of QPOs in small black holes. In Fig. 6(f), we present the results of the peculiar Blazar OJ 287, which is thought to have a pair of black holes, one of which interacts with the disk of the other causing double peaked flares every 12 years (e.g. Valtonen et al. 2006). However, multiwavelength campaigns have seen variation in spectral states (Ciprini 2006) also. The cyclic outburst could very well be due to the interaction of the outflow with disk photons (see, type (d) QPO in Section 2) and need not be due to any binary system. The double peaked nature of the flare is common in stellar mass black hole such as GRS 1915+105.

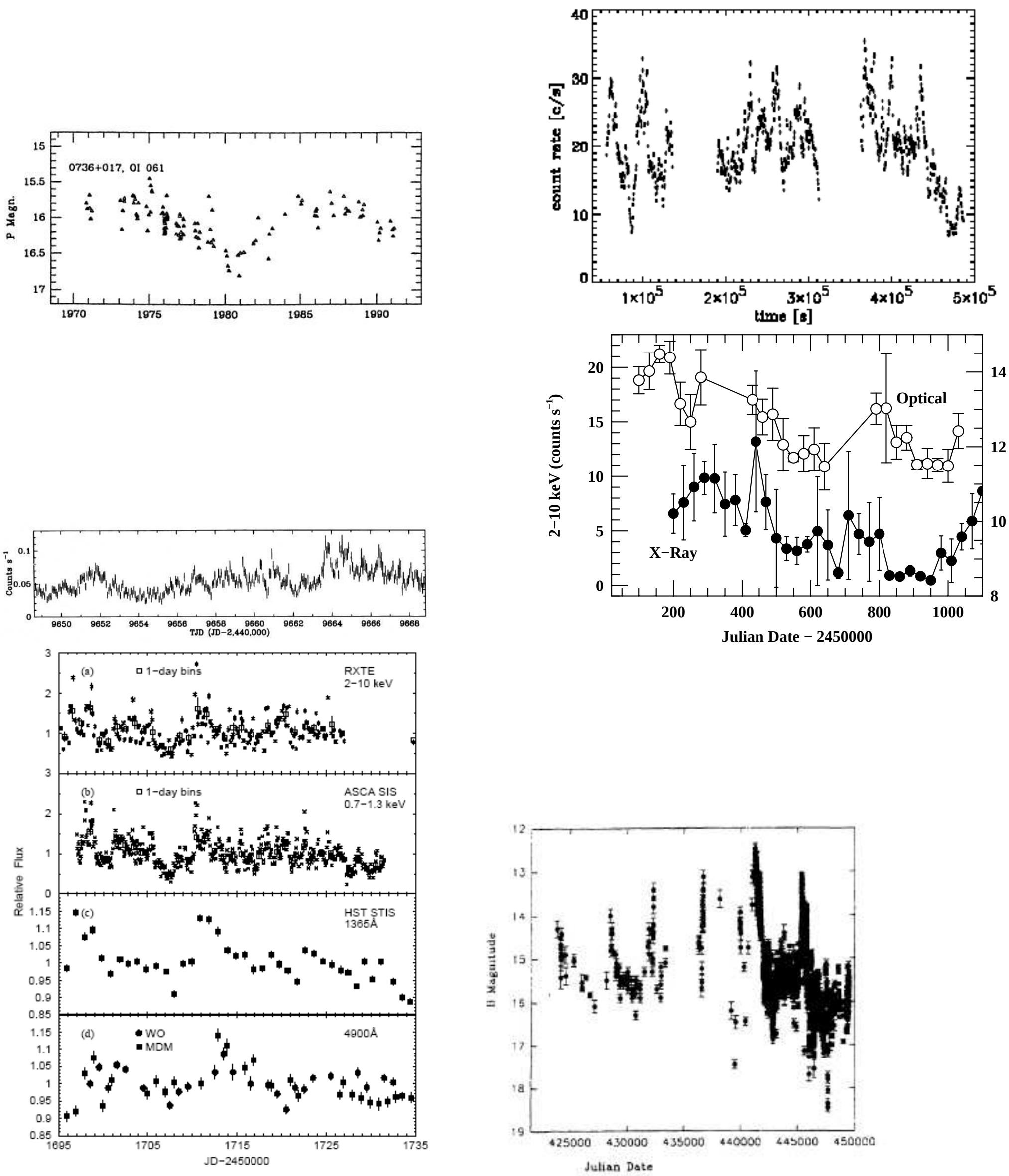

Figure 6. Observed variabilities of a few active galaxies (a) PKS 0736+017 (top left) in optical , (b) MCG-6-30-15 (top right), (c) RX J0437.4-4711 (middle/left), (d) NGC 4051 (middle/right), (e) ARK 564 (bottom/left) and (f) OJ 287 (bottom/right).

4. Concluding remarks

In the paper, we presented a generic view of the quasi-periodic variations of intensity of radiation emitted from accretion disks and jets. We showed that the generic oscillation of the centrifugal pressure supported boundary layer of an accretion flow around a black hole can satisfactorily explain the QPOs and the energy dependence of the amplitude of variation. As shown in Chakrabarti & Manickam (2000), the amplitude does go down at lower energy, simply because the pre-shock flows do not participate in the oscillations, only Comptonized radiation from the CENBOL do. If we extrapolate this understanding to Quasars (few $\times 10^9 M_\odot$), milli-quasars (few $\times 10^6 M_\odot$) and micro-quasars (few $\times 10^3 M_\odot$), we simply have to scale the radiation energy as appropriate for the respective masses. The time scale of variation scales with the mass linearly. We expect that TAUVEX can be used to detect these variations and especially, its multi-wavelength capabilities can be used to discern whether the variabilities are indeed QPO equivalents observed in nano-quasars (few $\times M_\odot$).

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References

Abramowicz, M. A., & Chakrabarti, S. K., 1990, ApJ, 350, 281
Arevalo, P., Papadakis, I., Kuhlbrodt, B., & Brinkman, W., 2002, A&A, 430, 435
Blandford, R. D., & Payne, D., 1981, MNRAS, 194, 1033
Chakrabarti, S.K., 1989, ApJ, 347, 365
Chakrabarti, S. K., 1990, Theory of Transonic Astrophysical Flows, World Scientific: Singapore
Chakrabarti, S. K., 1994, Proc. 17th Texas Symposium, ed. H. Böhringer et al., Academy of Sciences, New York, 546
Chakrabarti, S.K., 1996, Phys. Rep., 266, 229
Chakrabarti, S. K., 1999, A&A, 351, 185
Chakrabarti, S. K., Acharyya, K., & Molteni, D., 2004, A&A, 421, 1
Chakrabarti, S. K., & Mandal, S., 2006a, ApJ, 642, L49
Chakrabarti, S. K., & Mandal, S., 2006b, Proc. Science, VI Microquasars Workshop: Microquasars and Beyond, ed. T. Belloni, SISSA: Trieste, 38
Chakrabarti, S. K., & Manickam, S. G., 2000, ApJ, 531, L41
Chakrabarti, S. K., & Nandi, A., 2000, Ind. J. Phys., 75B, 1
Chakrabarti, S.K., Nandi, A., Dennath, D., Sarkar, R., & Dutta, B.G., 2006, Proc. Science, VI Microquasar Workshop: Microquasars and Beyond, ed. T. Belloni, SISSA: Trieste, 103
Chakrabarti, S. K., & Titarchuk, L. G., 1995, ApJ, 455, 623 (CT95)
Chakrabarti, S. K., & Wiita, P. J., 1992, ApJ, 387, L21
Ciprini, S., 2006, Proc. 8th ENIGMA Meeting, eds T. Hovatta et al. 1
Halpern, J.P., & Marshall, H.L., 1996, ApJ, 464, 760
Hudec, R., Hudec, L., Sillanp, A., Takalo, L., & Kroll, P., 2001, Exploring the Gamma-Ray Universe, ed. B. Battrick, 295
Mandal, S., & Chakrabarti, S. K., 2005, A&A, 434, 839

Molteni, D., Sponholz, H., & Chakrabarti, S.K., 1996, ApJ, 457, 805
Peterson, B. et al., 2000, ApJ, 542, 161
Remillard, R.E., Morgan, E.H., McClintock, J.E., Bailyn, C.D., & Orosz, J. A., 1999, ApJ, 522, 397
Ryu, D., Chakrabarti, S.K., & Molteni, D., 1997, ApJ, 474, 378
Samanta, M.M., Chakrabati, S.K., & Ryu, D., 2007 (submitted)
Shemmer, O. et al. 2001, ApJ, 561, 162
Smith, A.G., 1996, in Blazer Continuum Variability, ASP conference Ser., 110, 110
Valtonen, M. J., Nilsson, K., Sillanpää, A., Takalo, L. O., Lehto, H. J., Keel, W. C., Haque, S., Cornwall, D., & Mattingly, A., 2006, ApJ, 643, 9