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Introduction to quasi periodic oscillations (QPO) in the X-ray emission from neutron stars and black hole candidates

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Abstract. We review the present status of the nature of Quasi Periodic Oscillations (QPO) observed in X-rays from black holes and neutron star candidates. We also present model existing in the literature for these QPOs.

Keywords : Black holes, neutron stars, X-ray sources

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1. Introduction

The sources which produce X-ray radiation are Active Galactic Nuclei, Supernova remnants, Binary systems, Cluster, Stellar corona, and some unidentified objects. Among these, sources which accrete matter, namely Active Galactic Nuclei and binary systems, show QPO behaviour in their X-ray emission. The detection of these X-ray radiation is made mostly using satellites, as earth's atmosphere is not transparent to X-rays. The study of QPO acts as probe for the dynamics of matter in the accretion disk as direct imaging is not possible with the current instruments. The energy dependence of QPO timing behaviour also gives indirect information of the accretion disk structure.

2. Physical mechanisms for X-ray generation

There are basically three physical mechanisms for producing X-rays, namely thermal emission from a hot gas, synchrotron radiation from relativistic electrons in the presence of a magnetic field, and blackbody radiation [1].

2.1. *Thermal emission from a hot gas*

The electrons which are in thermal equilibrium have a Maxwellian distribution of velocities. The average energy of all electrons in thermal equilibrium is the same and is dictated by the temperature T. The electrons passing close to a positive ion experiences an acceleration and hence produces radiation via thermal bremsstrahlung. The expression for the energy spectrum is, $I(E,T) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$, where $G(E,T)$ is the Gaunt factor, Z is the atomic number of the ion, n_e, n_i are the number density of electrons and ions respectively, and k is the Boltzmann constant. In addition to this continuum spectrum there can also be line emission.

2.2. *Synchrotron radiation from the relativistic electrons*

The electrons gyrating in a magnetic field at relativistic velocities produce synchrotron radiation via magnetic bremsstrahlung. The radiation-energy spectrum is given as, $I(E) = AE^{-\alpha}$ for an assumed power-law of energy distribution. The magnetic field is somewhat aligned but the particle velocities are expected to be isotropic, and hence the observed spectrum depends only on the magnetic field B and the energy spectrum of electrons.

2.3. *Blackbody radiation*

The expression for blackbody radiation is given as, $I(E,T) = \frac{2E^3}{h^2c^2(e^{E/kT}-1)}$. More energetic photons are produced when the temperature is higher. The spectrum retains the overall shape, although it is strongly modified by the stellar atmosphere. The surface temperature of a newly formed neutron star is around one million degrees and will emit in the X-ray range.

3. Quasi Periodic Oscillations(QPO)

There are two types of objects which show quasi periodic oscillations, namely, Low Mass X-ray Binaries (LMXB) and Active Galactic Nuclei (AGN) [2]. In LMXB, the compact accreting object could be either a neutron star or a black hole candidate. In LMXB the mass of the companion is less than $1M_\odot$. They are part of older galactic population of age greater than 10^9 years. They have X-ray bursts and soft X-ray spectra but lack X-ray pulsations and eclipses. The optical light is dominated by the disk. The magnetic field strength is much less than 10^{12}-10^{13} gauss. In contrast, the massive X-ray binaries (MXB) with companion mass greater than $10M_\odot$ have age less than 10^7 years. X-ray bursts are absent but X-ray pulsations and eclipses are seen often in MXB, and the magnetic field strength is around 10^{12}-10^{13} gauss. Brightest LMXB are in galactic bulge and are less likely to show X-ray bursts than fainter ones.

4. QPOs from neutron stars

The timing analysis and spectral analysis could give information about the decay of the magnetic field, disk-magnetosphere interaction, inner radiation pressure dominated accretion disk near Eddington limit, and the evolutionary connection between LMXB and millisecond radio pulsars. The X-ray radiation is detected in different energy channels as function of time. When the QPOs of a source are plotted in Hardness-Intensity Diagram (HID) or in Colour-Colour Diagram (CCD) i.e. hard colour vs. soft colour they trace out distinctive patterns and hence creating a possibility for their classification.

4.1. *Z sources*

They trace out a Z pattern in HID and CCD. The parameter which is varying along Z is most likely the accretion rate. There are no 'jumps' when the source traces out the Z pattern. The three branches of the Z are named as Horizontal Branch (HB), Normal Branch (NB), and Flaring Branch (FB). The HB has Very Low Frequency Noise (VLFN), Low Frequency Noise (LFN), and High Frequency Noise (HFN) components. The frequency of QPO (ν_{QPO}) is high, and it is strongly correlated with position (hence the intensity I_X). The QPO frequency is in the range 15-55 Hz and the sharpness of the QPO, defined as $\frac{\Delta\nu}{\nu_{QPO}}$, is in the range 0.12-0.4. The X-ray spectrum of LFN in HB QPO is harder than time averaged flux. The HB QPO has hard lags and there are soft lags in LFN. In the NB, the QPO frequency is anti-correlated to the intensity, and the change in ν_{QPO} is small. The range QPO frequency is 5-7 Hz. In the FB, the QPO frequency increases as the intensity increases. The width of the QPO, $\Delta\nu$ increases and finally becomes HFN.

There is a discontinuous jump in the QPO frequency at the HB-NB transition. The HB QPO may persist along with NB QPO in the NB. These indicate that there are different physical phenomena for HB QPO and NB QPO. FB QPO is probably the same as NB QPO. A possible understanding of the Z sources should explain the process which drives the source along Z and what happens at the branch transitions. The HB QPO and LFN can possibly be explained by beat frequency model [3].

4.2. *Atoll sources*

The *Atoll* sources are fainter than Z sources, but some of them are reliable X-ray bursters. They are further classified as Island and Banana sources as the pattern traced in the CCD is like an island and banana. The island sources are less active in CCD. Their X-ray intensity is low and HFN dominates. Bananas have strongest VLFN which is approximately the $1/f$ noise. Bananas recur at roughly the same place. One transition from island to left end of banana state is observed, but there is no clear fixed position of island with respect to banana.

If the accretion rate is the only difference between Z and *Atoll* sources, then the transition from Z to *Atoll* or vice versa is possible in LMXB with large range of accretion rate. It is possible that the *Atoll* sources have low magnetic field strength, so that the beat frequency model does not work.

5. QPOs from Black hole candidates

The strong ($> 20\%$ rms) and rapid (> 1 Hz) variations are no longer good argument for Black Hole Candidates (BHCs). Many pulsars are now known to be strongly and rapidly variable. The following are the examples of some black hole candidates and their main characteristics.

1. *LMC X-3*: This a strong BHC based on the companion star's orbital velocity curve, but does not show strong, rapid variability.
2. *Cyg X-1*: This is a good BHC which shows rapid variability but has noise power spectrum similar to the pulsars.
3. *LMC X-3*: This a strong BHC based on the companion star's orbital velocity curve, but does not show strong, rapid variability.
4. *LMC X-1*: A tentative BHC based on the low quality optical radial curve and the ultra-soft X-ray spectrum. It has a slow QPO of frequency 0.075 Hz.
5. *GX 339-4*: This is a BHC based on the ultra soft spectrum and the bimodal spectral behaviour.
6. *GRS 1915+105*: This is a BHC with X-ray transients. Very chaotic hard X-ray profile.

The BHC have three source states, low, high, and very high. The accretion rate is the dominant parameter which decides the state. The Power Density Spectrum(PDS) of very hard state has 3-10 Hz QPOs.

6. Cyg X-1

The data of 1100 days obtained using BATSE (Burst And Transient Source Experiment) on CGRO (Compton Gamma Ray Observatory) is reported in Crary et al. [4]. The presence of hard component indicates that the source is in low state. There is a strong correlation between power law index α and fractional rms amplitude f, and also between α and the flux F, determined by a basic system parameter, the accretion rate($\dot{M}$). The fast time variability can be explained in terms of shot-noise models [5-7]. where the decay time of shots implies the break frequency in the PDS. Mineshige et al. [8-9] propose that the disk is in self-organized critical state. Qualitative arguments lead to the conclusion that f increases as α decreases.

Chakrabarti & Titarchuk [10] predicts a shock at several tens of Schwarzschil radius. In the low state the post shock region is quite hot and the emergent spectrum is very hard (energy spectral index $\alpha \sim 0.5$). The photon index α increases with accretion rate in the low state. Molteni et al. [11] finds oscillation of shock location when a "resonance" condition is satisfied. The centroid frequency of oscillations increases as $\dot{M}$ increases. The α-f correlation can be accounted for by [10-11]. At super Eddington accretion rate, [10] predicts that the flow inside the shock is cooled by Comptonization of low energy photons from the disk, and post-shock flow is predominantly radial and converging. Comptonization in this region can still occur due to bulk motions producing hard tail, $\alpha \approx 1.5$. The photon index increases weakly with the accretion rate.

7. GRS 1915+105

The source was observed over a long period (see, [12] for recent results). The regular bursts can be due to periodic infall of matter in black hole from an oscillating shock front [10-11]. The peculiarities of this source are regularity over a time-scale of several days, presence of secondary peaks, and spectrum is hardest near the end of the burst. As the burst progresses, the temperature of the infalling matter increases which implies spectral hardening. Irregular and long bursts can be produced when accreting matter has large angular momentum, so that momentary disk is formed before advection. Details of some of the RXTE observations are in Manickam and Chakrabarti [13].

8. GX 339-4

This source was discovered in 1973 [14]. The companion of BHC is a low mass, spectral class F2 star. The maximum magnitude in blue region of 21 during the *OFF* state implies that luminosity of the star less than 1-2 $L_\odot$. It has an orbital period of 14.8 hrs and its distance is 4 kpc. The *ON* and *OFF* states are distinct, each last for a time of the order of months. It has three X-ray states, namely *OFF*, low(hard), and high(soft). There is an anti-correlation between X-ray and visible region luminosity in low and high states. The time duration for state transition is of the order of less than a day. Intensity changes by a factor greater than 60 in time-scale of months. The photon index is 2.4-2.7 in the high state and 1.6 in the low state. The period of observed QPOs are 1.2s, 10s, 20s in low state. In very bright state it shows 6 Hz QPO along with LFN and VLFN. Rapid variability is seen only in hard and *OFF* state.

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