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QUASI-PERIODIC OSCILLATIONS IN THE X-RAY FLUX FROM THE BLACK HOLE CANDIDATES

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Abstract. Quasi-periodic oscillations (QPOs) in the X-ray flux from the black hole candidates (BHCs) are reviewed. It is found that BHCs take basically two states: one in which the optically thick accretion disk extends close to the black hole, and the other in which the hot corona develops around the black hole to produce hard emission via the Compton up scattering. QPOs tend to become prominent near the transition between these two states.

1. Introduction

X-ray binary sources including black holes are important target in X-ray astronomy. Mass accretion onto a black hole is believed to be the energy source of various high energy phenomena in the universe. However, little is known about how the gravitational potential energy of the accreting matter is converted to X-ray and γ-ray radiation. One of the key characteristics to understand is that the emission mechanism varies with time. Rapid X-ray variabilities ($\leq$1 sec) are considered to originate in the vicinity of the black hole, and convey useful information, yet difficult to obtain. In fact, X-ray emission from the black holes is notably variable. Its fractional root mean square (rms) amplitude often reaches 30–40 %. Among the time variations, quasi-periodic oscillations (QPOs), unlike the $1/f$-noise universal to natural phenomena, may afford quite important clues to understanding the emission mechanism of the black hole, because QPOs may be intrinsic to mass accretion.

The term quasi-periodic oscillations is used to indicate a well-defined and resolved peak in the power spectrum (van der Klis, 1989). They are different from coherent oscillations in the sense that they emerge as a broad

peak in the power spectra. Relative width of the peak is a measure of the coherence. And a Q-value, defined by the ratio of the centroid frequency to the width, is used to indicate the coherence of the oscillation. Even if the power spectrum has a local maximum, it may be called as band-limited noise (BLN), if the Q-value is small (e.g. ≤ 1).

In this paper, we review the observational results of the QPOs from the black hole candidates (BHCs), *i.e.*, close binary system suspected to contain a black hole (for a review, see Tanaka & Lewin 1995). In §2, we explain the classification of the BHCs and spectral states. Characteristics of the QPOs are summarized for each class of BHCs in §3–5. Section 6 is dedicated to discussion on the nature of the QPOs from the BHCs.

2. Classification of the BHCs and the Spectral States

BHCs may be classified into several classes based on their X-ray characteristics (Tanaka & Lewin, 1995). This classification is important because the time variations, including the QPOs, seem to be different among these classes. Other than the conventional persistent and transient sources, we introduce here another class of BHCs, jet sources. As explained later, jet sources are also transient, but are unique in various aspects and deserve an independent class. In each class of BHCs, the X-ray source moves between several different spectral states, which is defined by the correlated spectral and timing behaviors of the source. The spectral states are analogous to the branches of the Z/atoll sources (van der Klis, 1989). It is also important to distinguish spectral states when we discuss the nature of the QPOs.

Persistent sources are, as indicated by the name, persistently bright BHCs. Only three sources are known to date as persistent BHCs, Cyg X-1, LMC X-1 and LMC X-3. All these sources are massive binaries, *i.e.*, the mass donating star is an early-type star (typically, O–B). Cyg X-1 is considered to be a prototype of the BHCs (Liang & Nolan, 1984). Its characteristics, such as high/low transition, ultra-soft spectrum, flickering, etc., are considered to be diagnostics of BHCs. Two spectral states, soft and hard states, are known in the persistent sources[1] . These two states have been referred to as high and low states in the literature according to the soft X-ray ($\leq$10 keV) flux. However, wide-band observations covering from soft X-ray through γ-ray reveal that the bolometric luminosity does not change very much between these two states (Zhang *et al.*, 1997). Thus, the term of soft and hard states is more appropriate. The hard state, in which Cyg X-1 is mostly found, is characterized by a hard, power-law energy spectrum ($\Gamma \sim 1.7$) with rapid and large time variations, refereed to as flickering. The

[1]Some of the soft state in Cyg X-1 might be an intermediate state (Belloni *et al.*, 1997).

power spectrum is dominated by the band-limited noise (BLN), which is flat below ~0.1 Hz and $1/f^{\alpha}$ ($\alpha \sim 1-2$) in higher frequencies. The soft state is characterized by the dominant soft X-ray emission from the optically thick accretion disk and a steep power law component ($\Gamma \sim 2.5$). Time variation is rather small, and the power spectrum shows a power-law shape. LMC X-1 and LMC X-3 are always found in the soft state.

BHCs in transient are sometimes called X-ray novae (Tanaka & Shibazaki, 1996). They are low-mass systems, *i.e.*, the mass donating star is mostly K or M dwarf star. Typically, they show an outburst once per several decades (some has shorter recurrence period) with a duration of a few months. Besides the hard and soft states, transient BHCs show a very high state (Miyamoto *et al.*, 1991). The very high state is characterized by a large luminosity close to the Eddington limit, simultaneous presence of the soft disk emission and a steep power law component in the energy spectrum, and large and rapid time variabilities. However, it is not clear whether or not the large luminosity is intrinsic to the very high state. GS2023+33 showed a hard, single power law spectrum characteristic to the hard state, even at the peak of the outburst (Tanaka, 1992). If the source luminosity is important to determine the spectral state, we may need to introduce an intermediate state (Méndez & van der Klis, 1997), in which the spectral and timing properties are similar to the very high state, but the source luminosity is lower by more than an order of magnitude. Transient sources spend most of the time in the quiescent state ($L_X \leq 10^{32}$ erg/sec; Tanaka & Shibazaki 1996). Characteristics of the quiescent state are not known due to the limited observational data.

Jet sources include two BHCs, GRS 1915+105 (Nova Aql 1992; Mirabel & Rodriguez 1994) and GRO J1655-40 (Nova Sco 1994; Tingay *et al.* 1995; Hjellming & Rupen 1995). Both sources show radio jets revealing the superluminal motion, which indicate the presence of the relativistic jets close to the speed of light. These sources are also transient sources, but their recurrence period seems to be significantly shorter than the X-ray novae. No consensus has been achieved on the spectral states of the jet sources.

3. Persistent Sources

Typical power spectra of Cyg X-1 in hard and soft states obtained with the ASCA GIS are shown in figure 1. The hard state power spectrum is characterized by the flat-top BLN (brake frequency, ~0.1 Hz, is variable; Belloni & Hasinger 1990), whereas soft state power spectrum shows a power law shape. As shown later, these are two fundamental shapes of the power spectra in BHCs. QPOs with centroid frequency of 4–12 Hz have been observed from Cyg X-1 during the transition between the hard and the

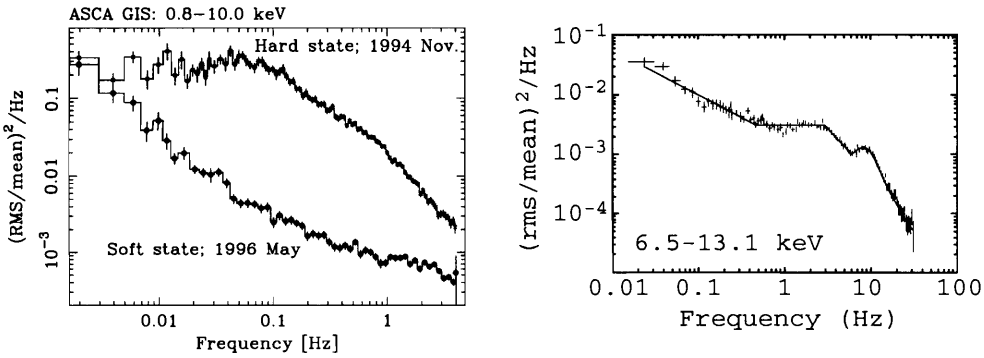

Figure 1. (Left) Representative power spectra of Cyg X-1 in hard and soft states obtained with the ASCA GIS. Power due to the Poisson fluctuation is subtracted. (Right) Example of the power spectra by RXTE PCA showing the QPO at 8 Hz and the accompanied BLN. Adapted from Cui *et al.* (1997).

soft states (Cui *et al.*, 1997). The power spectrum of the QPO obtained by RXTE PCA is also shown in figure 1. As seen in the figure, the QPO accompanies a BLN dominant around a few Hz. The break frequency of the noise and the QPO centroid frequency show a clear positive correlation. Thus the QPO and the BLN may have common origin. The QPO may be connected to the power law component in the energy spectrum, because it becomes more prominent at higher energies.

Low-frequency QPOs have been sometimes observed from persistent sources. QPO in 1–3 Hz was detected from Cyg X-1 in the hard state with Ginga when the spectrum was relatively soft (Rutledge *et al.*, 1998). Fractional rms amplitude of the QPO was about 10 %. Also QPO in ~0.04–0.07 Hz was observed from Cyg X-1 by the SIGMA telescope in 40–150 keV in the hard state (Vikhlinin *et al.*, 1994). The QPO had a broad peak ($Q \sim 1$) with a rms fractional variation of 10–15 %. QPO of similar frequency (0.075 Hz) was detected from LMC X-1 with Ginga (Ebisawa *et al.*, 1989). The peak was relatively sharp ($Q \sim 8$) and had a significant second harmonic; no BLN was accompanied.

4. Transient Sources

Very prominent QPOs have been observed from the two transient BHCs, GS1124–68 and GX339–4[2] , in the very high state (Dotani, 1989; Miyamoto

[2]GX339–4 might be a jet source as indicated by the presence of a jet-like morphology in the radio band (Fender *et al.*, 1997) and a short recurrence time (Rubin *et al.*, 1998).

TABLE 1. Two types of QPOs in the very high state of the transient BHCs

	BLN associated QPO		PL associated QPO	
	GS1124–68	GX339–4	GS1124–68	GX339–4
Centroid Frequency[1]	3.0–7.6 Hz	6.3–7.6 Hz	4.7–6.6 Hz	5.4–6.1 Hz
Fractional rms Amplitude[1]	~2–4 %	~2–4 %	~1–2 %	~4–5 %
Presence of Harmonics	Sub and 2nd harmonics		2nd harmonics	
Intensity Dependence	$\propto \log(I)$	–[2]	$\propto I^{0.27}$	$(\propto I^{1.5})$[3]
Fractional rms Amp. of BLN	5–12 %	9–13 %	$\leq$1 %	$\leq$2 %

[1]Parameters for the fundamental oscillation in 1–14 keV.
[2]Intensity variation is not large enough to distinguish various models.
[3]Linear model can also fit the data.

et al., 1991; Takizawa *et al.*, 1997). Fractional rms amplitude of the QPO reached 10 % at high energies (>10 keV). The spectral and time variabilities, including the QPOs, were very similar between GS1124–68 and GX339–4. Two patterns of correlated spectral and timing behaviors were identified in both sources. These two branches may be common and unique to BHCs in the very high state, like the spectral branches in the Z-sources.

Characteristics of the two types of QPO observed from GS1124–68 and GX339–4 are summarized in table 1. Figure 2 shows the power spectra calculated from the Ginga data of GS1124–68 (Takizawa *et al.*, 1997). A clear contrast is seen between these two types of QPOs, especially in the amplitude of the BLN, intensity dependence, and the presence of sub-harmonics. We refer these two types of QPOs, respectively, as BLN associated QPO and PL (power law) associated QPO. In spite of these differences, energy dependence of the QPO amplitude and time lags are rather similar between the BLN and PL associated QPOs (Dotani, 1992). Especially, co-existence of soft and hard lag behind the ~3 keV photons is unique to the QPOs in the very high state.

It was found that the transition between these two branches can be very short (<1 sec) and frequent (a few times per minute). Thus the transition is called flip-flop transition. Flip-flop transition was observed in both GS1124–68 (Takizawa *et al.*, 1997) and GX339–4 (Miyamoto *et al.*, 1991). An example of the light curve and the dynamic power spectrum of the flip-flop transition is shown in figure 2. Correlation between the count rate and the power spectrum (QPO and BLN) is clearly seen in the figure. However, change of the energy spectrum with this flip-flop transition is rather small; a slight softening is seen in the lower intensity level.

Several low-frequency QPOs were also observed from GX339–4. A QPO

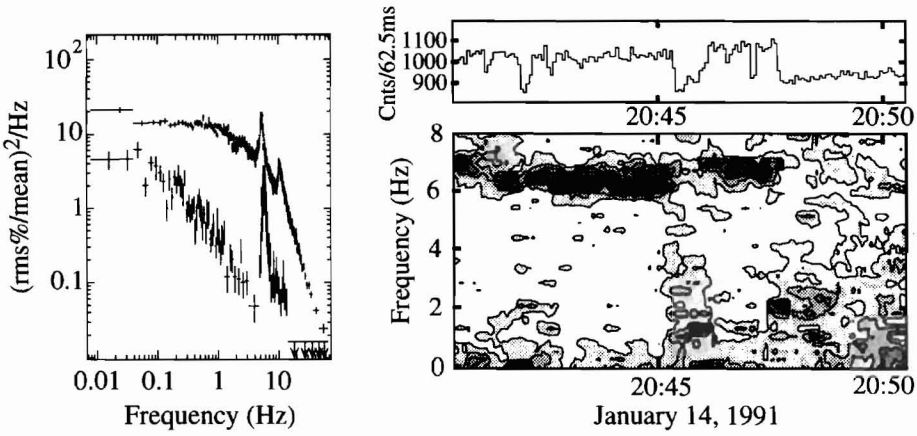

Figure 2. (Left) Two typical types of the power spectra of GS1124–68 in the very high state; both show clear QPOs. (Right) Dynamic power spectrum of GS1124–68 during the flip-flop transitions. Clear contrast of the QPO and BLN is seen in the power spectrum between high and low count rate levels.

of 0.8 Hz was detected by GRANAT when the source was in the hard state (low state) (Grebenev *et al.*, 1991). The QPO had a fractional rms amplitude of 7 %, and accompanied a prominent BLN. Although the observational data are limited, this QPO may be similar to the 1–3 Hz QPO from Cyg X-1 detected by Ginga. Optical QPOs of time scales between 7–190 sec have also been detected from GX339–4 (Motch *et al.*, 1983; Motch *et al.*, 1985; Imamura *et al.*, 1990; Steiman-Cameron *et al.*, 1990).

5. Jet sources

Violent time variations have been detected from GRS 1915+105 on various time scales during the outburst (Greiner *et al.*, 1996). QPO phenomena were also found to be rich in varieties. Chen *et al.* (1997) investigated the correlation between the hardness-intensity diagram and the power spectra, and identified two spectral branches, hard and soft branches, in GRS 1915+105. In the hard branch, the spectral hardness was anti-correlated with the X-ray intensity, and the power spectra showed QPOs of 0.5–6 Hz accompanied by the BLN (Morgan *et al.*, 1997); second harmonics of the QPO were also prominent. Centroid frequency of the QPOs increased with X-ray intensity, but saturated around ~6 Hz. QPOs observed by the Indian X-ray Astronomy Experiment at 0.62–0.82 Hz may also be the same type (Paul *et al.*, 1997; Paul *et al.*, 1998b). On the other hand, in the soft branch the spectral hardness was positively correlated with the X-ray in-

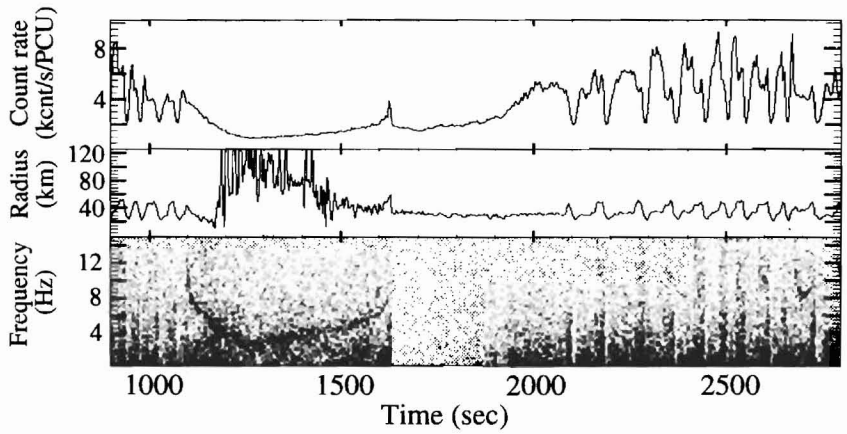

Figure 3. An example of the dynamic power spectrum of GRS 1915+106 during the "sputters". Note the changes of the BLN, QPOs and the disk radius between the high and low flux levels. Adapted from Swank *et al.* (1998).

tensity. The power spectra took approximately a power law shape, but a broad feature was sometimes seen around 1–6 Hz.

GRS 1915+105 stayed in between these two branches when the source showed repeating dip-like variations, called "sputters" (Greiner *et al.*, 1996). Spectroscopic analysis showed that the optically thick inner accretion disk disappeared and a power law spectral component became prominent during the low flux level of "sputters," while the optically thick disk extended inward during the high flux level (Belloni *et al.*, 1997; Taam *et al.*, 1997; Paul *et al.*, 1998a; Swank *et al.*, 1998). Time-resolved energy and power spectra analysis indicate that, when the inner disk disappears and the power law component become dominant, large hardness, intensity-dependent QPOs are observed in 2–14 Hz accompanied by the BLN (Swank *et al.*, 1998). On the other hand, when the optically thick disk extends inward and the power law component becomes weak and steep, corresponding to small hardness, neither the QPO nor the BLN is detected. An example of the dynamic power spectrum is shown in figure 3. These characteristics are in accordance with those of the hard and soft branches. Therefore, sputters are in fact rapid and repeated transitions between the hard and the soft branches.

Diverse and complex QPOs between 1 mHz and 10 Hz with various coherence ($1 < Q < 50$) have been observed in the bright state (Morgan *et al.*, 1997). This bright state, according to their classification, is considered to be in fact the soft branch by Chen *et al.* (1997). Continuum of the power spectra showed moderate strength of the BLN. Waveform of the

QPO was investigated in the light curve for those with a high Q-value (0.067 Hz QPO), and the mean "QPO-folded" profile was calculated. The profile contains a dip-like feature, whose repetition produced the QPO. The dip depth, ~20–40 %, increases with the energy, thus the energy spectrum becomes soft at the bottom of the dip. A narrow QPO ($Q \sim 20$) centered at 67 Hz was also detected in several occasions in the bright state (Morgan *et al.*, 1997). The centroid frequency was very stable; its variation was only 1 Hz. The fractional rms amplitude increased with energy from 1.5 % (<5 keV) to 6 % (>13 keV).

Rapid time variabilities of GRO J1655–40 have been investigated by Méndez *et al.* (1998). Around the peak of the outburst, the energy spectrum was hard, and the power spectrum took a power law shape with relatively small variabilities. During the decay of the outburst, the power spectrum changed to show prominent BLN with a break at <1 Hz, and a QPO feature moving from ~6.5 Hz to ~0.8 Hz appeared. The energy spectrum in this period was soft. These changes of the spectral and timing behaviors are interpreted as the transition from the soft state to the hard state.

A high frequency QPO centered at 298 Hz was detected from GRO J1655–40 (Remillard *et al.*, 1997). The QPO feature was broad (width of 120 Hz) and had an amplitude of 0.8 %.

6. Discussion

6.1. CORONA AND DISK STATES

When we compare the correlation patterns of the timing (including the QPOs) and spectral behaviors of all the three classes of BHCs, we notice the presence of two basic states. In one state, power spectrum is dominated by the BLN with intensity dependent QPOs, and the energy spectrum has a relatively large contribution from the power law component resulting from the Compton up-scattering of soft photons by the hot corona. In the other state, the power spectrum has a power law shape with QPOs whose intensity dependence is small, and the energy spectrum is dominated by the emission from the optically thick accretion disk. From the analogy of GRS 1915+105 results (Belloni *et al.*, 1997; Swank *et al.*, 1998), we call the former a corona state and the latter a disk state. The key parameter which defines the corona/disk state seems to be the presence of the optically thick inner disk.

We reorganize the various spectral states and branches under the light of the corona/disk states in figure 4. The very high state (and the intermediate state) of the transient sources is considered to fall in between the corona and the disk states (Rutledge *et al.*, 1998). Flip-flop transitions in GS1124-68 and GX339–4, "sputters" and the low-frequency QPO (~0.1 Hz) in GRS

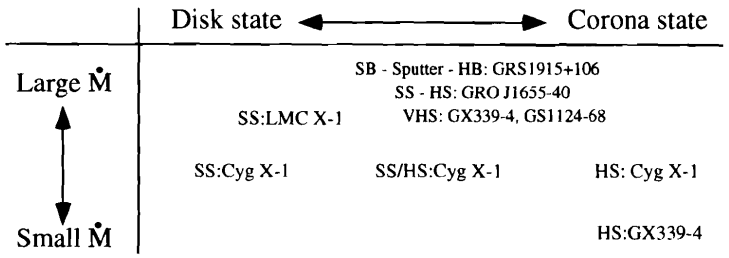

Figure 4. Spectral states of BHCs which showed QPOs are indicated in the scatter diagram between the corona/disk states and the mass accretion rate. Abbreviation in the figures are HS (hard state), SS (soft state), VHS (very high state), HB (hard branch) and SB (soft branch).

1915+105 may in fact be rapid and repeated transitions between the two states. As indicated in the figure, corona/disk states can not be determined only by the mass accretion rate. Some other parameters, such as abundance of the accreting matter, angular momentum of the black hole, etc. may affect the determination of the state. QPOs seem to be most prominent in between the corona and the disk states (Rutledge *et al.*, 1998). This means that QPOs are more easily excited when the inner disk and/or the hot corona becomes unstable ready for the transition.

6.2. COMPARISON WITH Z-SOURCES

There may be similarities between the rapid time variabilities of the BHCs and the Z-sources, bright neutron star binaries with low magnetic field (van der Klis, 1995). From the resemblance of BLN and QPO properties, it is suspected that the corona state of BHCs would correspond to the horizontal branch of Z-sources, and the disk state to the normal and flaring branches, respectively. However, the change in the energy spectrum of Z-sources along the branches is very subtle (Asai *et al.*, 1994; Hasinger *et al.*, 1990), and the drastic change like the one associated to the hard/soft transition of Cyg X-1 has never been observed. Copious X-ray photons from the neutron star surface may work to suppress instabilities of the accretion disk and the development of the hot corona, which may lead to the small change in the energy spectrum. This may also explain relatively small-time variabilities of Z-sources compared to those of the BHCs.

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