Correlation between 3:2 QPO pairs and Jets in Black Hole X-ray Binaries

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ABSTRACT

We argue, following our earlier works (the 'CEBZMC model'), that the phenomenon of twin peak high frequency quasi-periodic oscillations (QPOs) observed in black hole X-ray binaries is caused by magnetic coupling (MC) between accretion disk and black hole (BH). Due to MC, two bright spots occur at two separate radial locations r_{in} and r_{out} at the disk surface, energized by a kind of the Blandford-Znajek mechanism (BZ). We assume, following the Kluzniak-Abramowicz QPO resonance model, that Keplerian frequencies at these two locations are in the 3:2 ratio. With this assumption, we estimate the BH spins in several sources, including GRO J1655-40, GRS 1915+105, XTE J1550-564, H1743-322 and Sgr A*. We give an interpretation of the 'jet line' in the hardness-intensity plane discussing the parameter space consisting of the BH spin and the power-law index for the variation of the large-scale magnetic field in the disk. Furthermore, we propose a new scenario for the spectral state transitions in BH X-ray binaries based on fluctuation in densities of accreting plasma from a companion star.

Subject headings: accretion, accretion disks - black hole physics - magnetic fields - instabilities - stars: individual (GRO J1655-40, GRS 1915+105, XTE J1550-564, H1743-322, XTE J1859+226) - stars: oscillations - X-rays: stars

1. INTRODUCTION

Data collected by the NASA satellite Rossi X-Ray Timing Explorer (RXTE; Bradt, Rothschild & Swank 1993) added a new impetus to studies of QPOs, observed in X-ray binaries and other sources. The QPO observations are described in several recent reviews, e.g. by Remillard (2005) or Remillard & McClintock 2006 (hereafter RM06). The QPO observations present several puzzles, including why is the occurrence of high frequency QPOs correlated with the occurrence of relativistic jets. The jets in microquasars were first observed by Mirabel & Rodrigues (1998, 1999). For references to more recent works see McClintock & Remillard (2006, hereafter MR06) and Kalemci et al. (2006). It is widely agreed (Mirabel & Rodrigues 1999; Blandford 2002) that in both active galactic nuclei (AGNs) and microquasars, relativistic jets must be powered by a process similar to the celebrated Blandford-Znajek (1977, hereafter BZ) mechanism. A particular variant of BZ, in the form of magnetic couplings (MC) between a rotating BH and its surrounding disk, has been recently investigated by several authors, including Blandford (1999), Li (2000, 2002), and Wang et al. 2002, hereafter W02). Our 'CEBZMC' model (Wang et al. 2003a, 2004, hereafter W04) also belongs to the BZ plus MC class.

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In this paper we consider a particular realization of the CEBZMC model, in which MC between BH and accretion disk energizes 'hot spots' on the accretion disk surface. As discussed by Wang et al. 2005 (hereafter W05), a pair of hot spots produce a pair of QPOs, with frequencies ν_{in} and ν_{out} that correspond to Keplerian frequencies at the locations of the two spots, r_{in} and r_{out}. We *assume* that the two locations agree with the Kluzniak-Abramowicz resonance condition, $\nu_{in}/\nu_{out} = 3/2$. Abramowicz and Kluzniak (2001, hereafter AK01) realized that frequencies of the QPO pairs in BH sources are in the exact 3:2 ratio. They also recognized and stressed the fundamental importance of this fact[1]. They first noticed the 3:2 ratio in the QPO pair with frequencies 450 Hz and 300 Hz in GRO J1655-40, observed by Strohmayer, (2001a, b). This important discovery was strengthened by numerous authors, who found the 3:2 ratio in different BH sources: in GRS 1915+105 MR06, in XTE J1550-564 Miller (2001) and Remillard et al (2002), and in H1743-322 Homan et al. (2005) and Remillard et al. (2006). There is less certain evidence that the same 3:2 ratio occurs for QPOs observed in low-mass active galactic nuclei - in e.g. Sgr A* (Török 2005a, b; Ashenbach 2005) and in a few nearby Seyferts (Lachowicz et al., 2006). The 3:2 ratio of frequencies is the basic feature of the Kluzniak-Abramowicz QPO resonance model (see a collection of reviews in Abramowicz 2005 for references). In other QPOs models, the 3:2 ratio of observed frequencies is either incidental or impossible as for example, in the Lamb and Miller (2004) model that considered the QPO pairs to be a beat frequency between neutron star spin and disk rotation, or in the Wagoner et al., (2001) model, in which they are fundamental g-mode and c-mode in thin disk oscillations, or in the Stella and Vietri (1999) model where they emerge as a combination of Keplerian and radial epicyclic frequencies. In our CEBZMC model, in its present state of development, the 3:2 ratio does not directly follow from the model basic assumption (MC, BZ). However, as we will see later, the 3:2 ratio occurs in an interesting region of the parameter space of the CEBZMC model. We therefore *assumed* that the ratio is equal 3:2, and examined consequences of this assumption. This phenomenological approach has at least three virtues. Firstly, it allows us to estimate the spin of BHs in the BH sources that display the QPOs with the 3:2 ratio, using a method first applied by AK01 and more recently Török et al. (2005). Secondly, it is directly related to the correlation between the occurrence of the QPO 3:2 pairs and the jets. Thirdly, we may offer an interpretation of the 'jet line' in the hardness-intensity diagram (HID), by which the hard state and the soft state of the BH X-ray binaries (BHXBs) are separated (Fender et al. 2004, hereafter FBG04; Belloni 2006, hereafter B06, Remillard 2005).

This paper is organized as follows. In § 2 we give a brief description of our model and explain the correlation between the 3:2 QPO pairs and the jets in BHXBs. In § 3 we compare the BH spins measured by different methods. It turns out that the BH spin of GRO J1655-40 estimated by CEBZMC is consistent with those estimated by X-ray continuum fittings. By fitting the 3:2 QPO pairs, we estimate the spin of the galactic massive BH, Sgr A*, for a given range of the BH mass, and also estimate the spin and mass of the BH candidate H1743-322. In addition, the spin of the BH X-ray binary XTE J1859+226 is estimated by fitting its single–component high frequency QPO. In § 4 we propose a new scenario for the state transitions in BHXBs based on the variation of the power-law index n, which arises from the fluctuation of the number densities of the accreting plasma from a companion star. Finally, in § 5, we summarize the main results, and discuss the issues related to this model. Throughout this

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[1] Abramowicz et al. (2003) also argued that there is a statistical evidence for the same 3:2 ratio for QPOs in neutron star sources. This was later confirmed by Belloni et al. (2005). More recently, Abramowicz et al. (2005) found an additional, independent, and direct proof for the 3:2 ratio in the QPO neutron star data. They proved that although in neutron star sources the *observed* frequencies vary in a wide range, the variations uniquely point to the 3:2 ratio of the *eigenfrequencies*.

paper the geometric units $G = c = 1$ are used.

2. CORRELATION BETWEEN 3:2 QPO PAIRS AND JETS

In order to discuss the correlation of the 3:2 QPO pairs with the jets in the BHXBs we give a brief review of our previous works. In W05 we approached the 3:2 QPO pairs by virtue of the MC of a Kerr BH with its surrounding disk as shown in Figure 1, in which the large-scale magnetic field at the BH horizon consists of the open and closed field lines with an angular boundary at θ_S. The open field lines transfer the energy and angular momentum from the BH to the remote astrophysical loads in the BZ process, while the closed field lines transfer those between the BH and the surrounding accretion disk in the MC process. The angular boundary θ_S is determined by a criterion of the screw instability of the magnetic field given in W04.

The upper and lower frequencies of the 3:2 QPO pairs correspond respectively to the inner and outer hotspots rotating with the Keplerian angular velocities of the disk, which are produced by the MC with the non-axisymmetric magnetic field at the BH horizon (Wang et al. 2003b). As argued in W05, the positions of the inner and outer hotspots are determined by the maximum radiation flux from the disk and the screw instability of the non-axisymmetric magnetic field, respectively.

It turns out that the 3:2 QPO pairs fitted in our model depend mainly on two parameters, i.e., the BH spin a_* and the power-law index n. The parameter $a_* \equiv J/M^2$ is defined in terms of the BH mass M and angular momentum J, and the parameter n is defined in terms of the variation of the poloidal magnetic field B_D^P with the disk radius, $B_D^P \propto r^{-n}$.

It has been argued in W04 that the state of CEBZMC always accompanies the screw instability, provided that the BH spin a_* and the power-law index n are greater than some critical values. Based on the criterion of the screw instability derived in W04 we have a contour of the angular boundary $\theta_S\left(a_*, n\right) = 0$ in the $a_* - n$ parameter space as shown in Figure 2.

Inspecting Figure 2, we have the following results:

(1) The shaded region indicated “BZMC with Jet” represents the value ranges of the parameters a_* and n for CEBZMC, in which the jet driven by the BZ process exists.

(2) The inner hotspot arises from energy transferred from a fast-rotating BH into the disk by non-symmetric MC.

(3) The outer hotspot is produced by the screw instability, which always accompanies the state of CEBZMC.

Recently, the 3:2 QPO pair has been observed in near infrared flares of the massive BH Sgr A* in the Galactic Center (1.445, 0.886mHz; Aschenbach 2004a, 2004b; Török 2005). In addition, Bower et al. (2004) state that their radio measurements of Sgr A* are consistent with jet models. Based on the model of CEBZMC given in W04 and W05 we have the fitting results of the 3:2 QPO pairs for the three BHXBs and Sgr A* as shown in Table 1. It should be noticed that the BH spins given in Table 1 are a little less than those given in W05 (see Table 1), because some errors in calculations have been corrected and the ranges of the BH masses have been updated.

As argued in W05, the upper and lower frequencies of the 3:2 QPO pairs are equal to the Keplerian frequencies of the inner and outer hotspots, respectively, being expressed by

$$\nu_i = \nu_0 (\xi_i^{3/2} \chi_{ms}^3 + a_*)^{-1}, \tag{1}$$

where $\nu_0 \equiv (m_{BH})^{-1} \times 3.23 \times 10^4 Hz$ with $m_{BH} \equiv M/M_\odot$. The parameter $\xi_i \equiv r_i/r_{ms}$ is the disk radius expressed in terms of r_{ms}, the radius of the innermost stable circular orbit (ISCO). The frequency ν_i represents ν_{upper} and ν_{lower} for ξ_i equal to ξ_{upper} and ξ_{lower}, respectively. As argued in W05 both ξ_{upper} and ξ_{lower} depend on the parameter a_* and n, i.e.,

$$\begin{cases} \xi_{upper} = \xi_{upper}\left(a_*, n\right), \\ \xi_{lower} = \xi_{lower}\left(a_*, n\right). \end{cases} \tag{2}$$

It is obvious that the 3:2 QPO pair can be completely determined by combining equation (2) with equation (1), provided that the BH mass m_{BH}, ν_{upper} and ν_{lower} are given. This implies that the 3:2 QPO pair with the given BH mass corresponds to one ‘representative point’ in the $a_* - n$ parameter space. Thus we have a characteristic line of the 3:2 QPO pair for a continuous distribution of m_{BH} within its upper and lower limits as shown by the thick solid line in Figure 3.

On the other hand, $\nu_{upper} = const$ corresponds to a contour with the given BH mass in the $a_* - n$ parameter space based on equations (1) and (2), and we have two contours of $\nu_{upper} = const$ corresponding to the lower and upper BH masses in the parameter space as shown in Figure 3.

It is found from Figure 3 that the characteristic lines of the 3:2 QPO pairs for the four BH systems are all located in the shaded region indicated “BZMC with Jet”. These results provide a natural explanation for the correlation between the 3:2 QPO pairs and the jets driven by the BZ process, being consistent with the fact that jets are found in the above BH systems (Mirabel & Rodrigues 1998, 1999; Aschenbach 2004b; Bower et al. 2004; Török 2005; MR06).

3. ESTIMATING BH SPINS BY VIRTUE OF HIGH FREQUENCY QPOS

A Kerr BH is described completely by its mass M and spin a_*. The masses of twenty BHs in the Galaxy have already been measured or constrained, and the next goal is to measure spin. As pointed out by RM06, there are four avenues for measuring BH spin, which include (1) X-ray polarimetry, (2) X-ray continuum fitting, (3) the Fe K line profile and (4) high frequency QPOs. Among these approaches high frequency QPOs are likely to offer the most reliable measurement of spin once the correct model is known. Unfortunately, there are significant differences in the BH spins measured by different models, and a reasonable model for measuring BH spins has not been accepted by astrophysical community. In this paper we compare the values of the BH spins of the three BHXBs and Sgr A*, which are measured by X-ray continuum and 3:2 QPO pairs as listed in Table 2.

The method of X-ray continuum fitting is used to measure the BH spins of the binaries based on a fully relativistic model of a thin accretion disk around a Kerr BH. In order to estimate the BH spin by fitting the broadband X-ray spectrum, one must know the BH mass, the inclination$i$ of the accretion disk, and the distance to the binary.

The approach to the BH spin based on the 3:2 QPO pair consists of two basic methods. One method is based on the epicyclic resonance model (ERM), in which the resonance between orbital and epicyclic motions of accreting matter is invoked (Abramowicz & Kluznick 2004 and references therein), and another method is based on CEBZMC, in which the inner and outer hotspots are produced by a non-axisymmetric MC and the screw instability of the magnetic field, respectively. The BH spin measured by ERM and CEBZMC depends on the BH masses.

From Table 2 we find that the spin of GRO J1655-40 measured by CEBZMC is in a good agreement with those measured by X-ray continuum fittings given in G01, S06 and M06. However, an intersection of the BH spins has not been found for XTE J1550-564 and GRS 1915+105 based on the above two methods.

It is found that the spin of Sgr A* measured by CEBZMC is generally not overlapped with those measured by ERM except those given in Br05. Up to date, the BH spin of Sgr A* has been estimated only by using ERM and CEBZMC, depending sensitively on the BH mass. For example, based on CEBZMC the spin is estimated as 0.811–0.951 and 0.800–0.841 for $m_{BH} = (2.6-4.4)\times 10^6$ and $(2.53-2.84)\times 10^6$, respectively. Based on ERM the spin is constrained to be 0.9865–0.9965 and 0.99616 for $m_{BH} = (2.53-2.84)\times 10^6$ and 3.3×10^6 in A04a and A06, respectively.

A common feature in the above measurements lies in the fact that the BH spins are constrained more tightly for the narrower ranges of the BH masses. Although the BH mass of H1743-322 has not been constrained, it is identified as a BH candidate by the X-ray light curve and variability characteristics during its 2003 outburst, and its behavior resembles the BHXBs XTE J1550-564 and GRO J1655-40 in many ways (Remillard et al. 2002, 2006). It is interesting to note that both the 3:2 QPO pair and the jet have been observed in H1743-322 also (Homan et al. 2005; Remillard et al. 2006; Kalemci et al. 2006). Thus we can constrain the BH mass and spin also by the 3:2 QPO pair (240, 160Hz) based on the model of CEBZMC.

As shown in Figure 3, a characteristic line in the $a_* - n$ parameter space represents the 3:2 QPO pair, which is located between two contours of $\nu_{upper} = const$ for the lower and upper BH masses. In the case of H1743-322 the BH mass and spin can be also constrained by the characteristic line above the contour $\theta_S(a_*, n) = 0$ in the $a_* - n$ parameter space as shown in Figure 4.

Inspecting Figure 4, we find that the characteristic line is located in the shaded region indicated by "BZMC with Jet", and it spans a very wide range of the BH spin. Required by the 3:2 QPO pair (240, 160Hz) and the upper limit ($a_* \le 0.998$) to the BH spin given by Thorne (1974) we have the leftmost and rightmost points of the characteristic line as follows:

$$(a_*, n, \xi_{\max}) = \begin{cases} (0.371,\ 5.670,\ 2.271), \\ (0.998,\ 4.105,\ 1.187), \end{cases} \tag{3}$$

where the upper and lower lines correspond to the leftmost and rightmost points of the characteristic line in Figure 4, respectively. Combining $\nu_{upper} = 240Hz$ with equations (1)–(3) for the leftmost and rightmost points of the characteristic line, we can estimate the value range of the BH mass: $3.76 < m_{BH} < 48.23$. Although the BH mass and spin of H1743-322 are only constrained loosely by the 3:2 QPO pair, they can be further constrained by other observations. For example, the BH mass and spin can be limited to a smaller range by fitting the observed jet power in terms of the BZ power based on the model of CEBZMC.

It is well known that single–component high frequency QPOs have been observed in some confirmed and candidate BHXBs (MR06), such as XTE J1859+226 (190 Hz), 4U1630–47 (184 Hz) and XTE J1650–500 (250 Hz). According to the model of CEBZMC the single–component high frequency QPO can be fitted by ONE rotating hotspot arising from the maximum radiation flux due to the non-axisymmetric MC.

Since neither jets nor 3:2 QPO pairs are observed in XTE J1859+226, its state should be confined in the shaded region below the contour of $\theta_S\left(a_*, n\right) = 0$ as shown in Figure 5. As argued by Li (2002) the minimum spin for transferring energy from the BH to the disk in the MC process is $a_* = 0.3594$, and it is regarded as the left boundary of the shaded region in Figure 5. Thus the BH spin of XTE J1859+226 can be estimated as $0.3594 < a_* < 0.5890$ by combining $\nu_{QPO} = 190Hz$ with the BH mass, $7.6 < m_{BH} < 12.0$, which is taken from RM06.

4. A SCENARIO FOR STATE TRANSITIONS IN BHXBS

The prominent feature of the model of CEBZMC lies in the correlation of the high frequency QPO pairs with the jets from the BHXBs. As is well known, state transitions in BHXBs involve a number of unresolved issues in astrophysics, displaying complex variations not only in the luminosities and energy spectra, but also in presence/absence of jets and QPOs. How to analyze and classify states in BHXBs from observations in multi-wavelength band is of foremost importance.

Recently, FBG04 proposed a unified semi-quantitative model for the disk-jet coupling in BHXBs, in which the states of BHXBs are described in an X-ray hardness-intensity diagram (HID), and the states with jet and those with no jet are divided by a 'jet line' in HID. Later, B06 classified the states of BHXBs into four types: (1) Low/Hard State (LS), (2) Hard Intermediate State (HIMS), (3) Soft Intermediate State (SIMS) and (4) High/Soft State (HS), which display different luminosity and hardness associated with different behavior of QPOs and radio loudness. It is pointed out in B06 that these states might be reduced to only two basic states, i.e., a hard state and a soft one. The states LS and HIMS are included in the hard state, and the states SIMS and HS in the soft state. The jets can be observed in hard states, but can not in soft states.

Very recently, MR06 used four parameters to define X-ray states based on the very extensive RXTE data archive for BHXBs, in which three states are included: (1) thermal state (high/soft state), (2) hard state (low/hard state) and (3) steep power law (SPL) state. In the thermal state, the flux is dominated by the heat radiation from the inner accretion disk, and QPOs are absent or very weak. The hard state is characterized by a hard power-law component at 2–20 keV, being associated with the presence of a quasi-steady radio jet. The SPL state is a strong power-law component with $\Gamma \sim 2.5$, which is associated with high-frequency QPOs. In MR06 luminosity is abandoned as a criterion for defining the X-ray states.

However, a consistent interpretation for the state transitions in BHXBs remains controversial, and this becomes a great challenge to the present theoretical models. Some authors (e.g. Belloni et al. 1997a,b; 2000) interpreted the transition between State C and States A/B as being caused by the disappearance and reappearance of the inner accretion disk due to a disk instability mechanism. Livio et al. (2003) pointed out that the inner disk remains present rather than absent in the state transitions, and it switches between two states in two different ways of converting accretion energy. In one state, the accretion energy is dissipated locally to produce the observed disk luminosity. In another state the energy liberated in the accretion is converted efficiently into magnetic energy in the form of a magnetically dominated outflow or jet. However, a detailed argument for producing jets in BHXBs has not been given by these authors.

Motivated by the above discussion we suggest a new scenario for the state transition in BHXBs based on the model of CEBZMC. Inspecting Figures 2–4, we find that the two basic states suggested by B06 can be naturally divided by the contour of $\theta_S\left(a_*, n\right) = 0$ in $a_* - n$ parameter space: a hard state with jet is represented by a point in the shaded region above the contour of $\theta_S\left(a_*, n\right) = 0$, while a soft state without jet by a point in the region below this contour. The state transition in BHXBs can be interpreted in terms of the variation of the power-law index$n$. As shown in Figure 6, a hard state will transit to a soft state with the decreasing n, while a soft state will change to a hard state with the increasing n. The contour of $\theta_S\left(a_*, n\right) = 0$ corresponds exactly to the 'jet line' in HID.

One of the main problems of this scenario is in knowing what mechanism gives rise to the variation of the power-law index n. This issue might be related to the fluctuation in the number density of the accreting plasma from the companion star, and a rough explanation is given as follows.

In our model the power-law index n is used to describe the variation of the poloidal magnetic field with the disk radius, i.e.,

$$B_D^p = \left(B_D^p\right)_{ms} \left(r/r_{ms}\right)^{-n} = \left(B_D^p\right)_{ms} \xi^{-n}, \tag{4}$$

where $\left(B_D^p\right)_{ms}$ is the poloidal magnetic field at ISCO. Based on Ampere's law we have the toroidal current density j_φ at the disk as follows,

$$j_\varphi = \frac{1}{4\pi} \frac{dB_D^p}{dr} = \frac{1}{4\pi r_{ms}} \frac{dB_D^p}{d\xi} = -\frac{n\left(B_D^p\right)_{ms}}{4\pi M \chi_{ms}^2} \xi^{-(n+1)}. \tag{5}$$

From equations (4) and (5) we find that the profile of the magnetic field at the disk is related directly to the toroidal current at the same place, and the power-law index of the latter becomes $n+1$. Thus the variation of the magnetic field can be explained by the variation of the toroidal current, and the latter might be produced due to the fluctuation of the accreting plasma coming from the companion star.

As a simple analysis, we assume that the accreting plasma consists of electrons and protons, of which the number densities are n_e and n_p, respectively. Generally, the two number densities are not equal exactly, and they are related by $n_p = n_e + n_\delta$. Thus a toroidal current density could be generated due to the charged particles' Keplerian rotation and it reads

$$j_\varphi = e n_\delta v_\varphi = e n_\delta \xi \chi_{ms}^2 \big/ \left(\chi_{ms}^3 + a_*\right). \tag{6}$$

where $e = 4.8 \times 10^{-10} e.s.u.$ is the electron charge. Incorporating equations (5) and (6), we have

$$n_\delta = -\frac{n\left(B_D^p\right)_{ms}}{4\pi e \xi M} \left(\frac{\chi_{ms}^3 + a_*}{\chi_{ms}^4}\right) \xi^{-(n+1)}. \tag{7}$$

As argued in W05, $B_4 \approx 10^5$ is the strength of the magnetic field required by the hotspots for emitting X-ray. Taking $\left(B_D^p\right)_{ms} = B_4 \times 10^5 gauss$, $M = m_{BH} M_\odot$ and $\xi = 1$, we have

$$| n_\delta |= 4.5 \times 10^8 \times \left(B_4 m_{BH}^{-1}\right) \left(\chi_{ms}^{-1} + a_* \chi_{ms}^{-4}\right) cm^{-3}. \tag{8}$$

By taking the disk mass as $M_{disk} = \alpha_m m_{BH} M_\odot$, the average disk height as $H = \beta r$ and the outer boundary radius $r_{out} = 1000 r_{ms}$, the average number density of protons can be estimated as

$$\bar{n}_p = \frac{M_{disk}}{m_p \int_{r_{ms}}^{r_{out}} 2\pi r H dr} = \left(\alpha_m \beta^{-1} m_{BH}^{-2} \chi_{ms}^{-6}\right) \times 1.77 \times 10^{32} cm^{-3}, \tag{9}$$

where $m_p = 1.67 \times 10^{-24} g$ is a proton's mass. Incorporating equations (8) and (9) with the given values of the concerned parameter, such as $\alpha_m \approx 10^{-3}$, $\beta = 0.1$, $m_{BH} = 10$, $B_4 \approx 10^5$, and $0.3594 < a_* < 0.9980$, we have

$$7.3 \times 10^{-16} <| n_\delta | / \bar{n}_p < 1.28 \times 10^{-14}. \tag{10}$$

It seems reasonable that the fluctuation in the number densities of the accreting plasma can be realized in the realistic astrophysical context for the small value of $n_\delta / \bar{n}_p$ given in equation (10).

Another issue related to the state transition in BHXBs is how to estimate the timescale of the fluctuation in density of the accreting plasma. If the toroidal current arises from the fluctuation of the number density of the accreting plasma, we think that the variation of the power-law index n might occur due to this fluctuation, and it gives rise to the state transition in BHXBs. Not long ago, Brown et al. (2000) discussed the MC effect on the accretion flow, and they estimated the viscous inflow time for the fluctuations as

$$\tau \sim r/\upsilon_r \sim (r/H)^2 \alpha_{vis}^{-1} \Omega_D^{-1}, \tag{11}$$

where υ_r is radial velocity of the accreting plasma and H is the height of the disk at radius r. We take the coefficient of kinematic viscosity $\alpha_{vis} = 0.1$ in calculations. Since the variation occurs within the outer boundary of the MC, we calculate the timescale corresponding to $r_{out} = \xi_{lower} r_{ms}$ by using equation (11) as listed in Table 3.

It is obvious, from equation (11) and Table 3, that the ratio r/H is dominative in determining the timescales of state transitions, which are insensitive to the parameters, m_{BH}, a_* and ξ_{lower}. Inspecting Table 3, we find that the timescales of state transitions in BHXBs from less than one second to more than one hour can be fitted by the fluctuation in density of the accreting plasma. We expect that the timescales of the state transitions in the above sources can be fitted by adjusting the ratio r/H based on this simplified model.

Since the fluctuation in densities of the accreting plasma is stochastic, this results in a stochastic variation of the power-law index n, and it is consistent with the observation of the state transitions in BHXBs: a hard state can transit to a soft one and then back to the hard one again, passing across the jet line several times as shown in Figure 7 of FBG04.

5. DISCUSSION

In this paper, we assume that Keplerian frequencies at two locations are in the 3:2 ratio based on the CEBZMC model. Compared with the Kluzniak-Abramowicz QPO resonance model, the 3:2 QPO pairs arising from the two hotspots are produced by the MC between a rotating BH and its surrounding disk. The BH spins of several BH sources measured by different methods are compared. It turns out that the BH spin of GRO J1655-40 measured by the CEBZMC model is in a good agreement with the recent results based on X-ray continuum fitting. In addition, the correlation of the 3:2 QPO pairs with the jet from the BH systems including Sgr A* is discussed in the parameter space. It is shown that the 'jet line' in HID can be interpreted naturally by the CEBZMC model. Finally, we suggest that the state transition in BHXBs could be realized by virtue of the variation of the power-law index n, which could be related to the fluctuation of the number densities of the accreting plasma from the companion star.

In our model the 3:2 QPO pairs are determined by the BH spin a_* and the power-law index n for the given BH mass. The parameter n is introduced to describe the basic feature of the large-scale magnetic field anchored at the disk, indicating the degree of its concentration at the inner region. It turns out that the parameter n plays a very important role not only in fitting the 3:2 QPO pairs but also in interpreting the state transitions of BHXBs.

It is easy to find from the parameter spaces in Figures 2—6 that the state transition from a hard state to a soft state can be realized by decreasing the BH spin, and the inverse transition occurs with the increasing spin. However, our calculations show that the timescale for the variation of the spin is too long to fit the observations. In addition, the evolution of the BH spin is generally one-direction, i.e., it decreases from a high spin to the equilibrium spin or increases from a low spin to the equilibrium spin as argued in W02. Thus, this account of the BH spin is not consistent with the observations: the states of BHXBs can switch from time to time between a hard state and a soft state. Compared with the BH spin the variation of the parameter n involves the timescale of the fluctuation of the number density, which is consistent with the state transition of BHXBs both in the timescale and in the repeating switches between the hard and soft states.

Very recently, Ma et al. (2006) introduced corona into the model of CEBZMC, which might be helpful to understand the association of the SPL state with the high frequency QPOs in BHXBs as argued in MR06. We shall discuss this issue in our future work.

Acknowledgements: This work is supported by the National Natural Science Foundation of China under grants 10373006, 10573006 and 10121503. We are very grateful to the anonymous referee for his (her) instructive comments on the role of MC in the 3:2 frequency ratio and the related issues.

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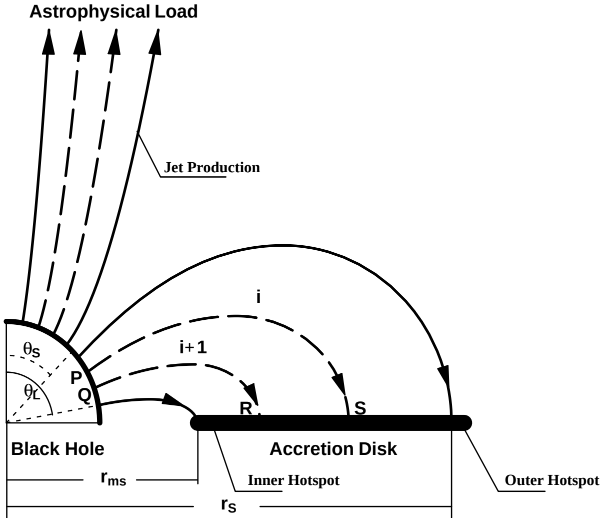

Fig. 1.— Poloidal magnetic field connecting a rotating BH with a remote astrophysical load and the surrounding disk. The inner and outer hotspots are located at different places of the disk.

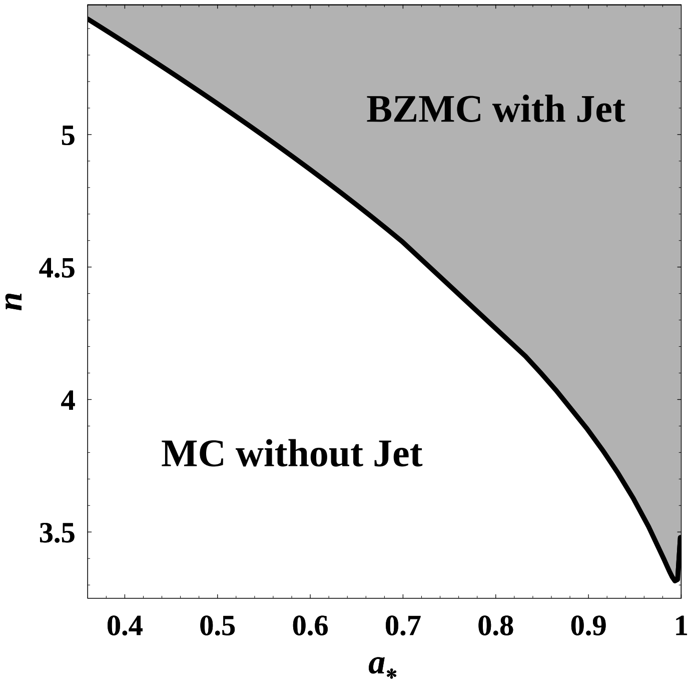

Fig. 2.— The contour of angular boundary $\theta_S(a_*, n) = 0$ in $a_* - n$ parameter space.

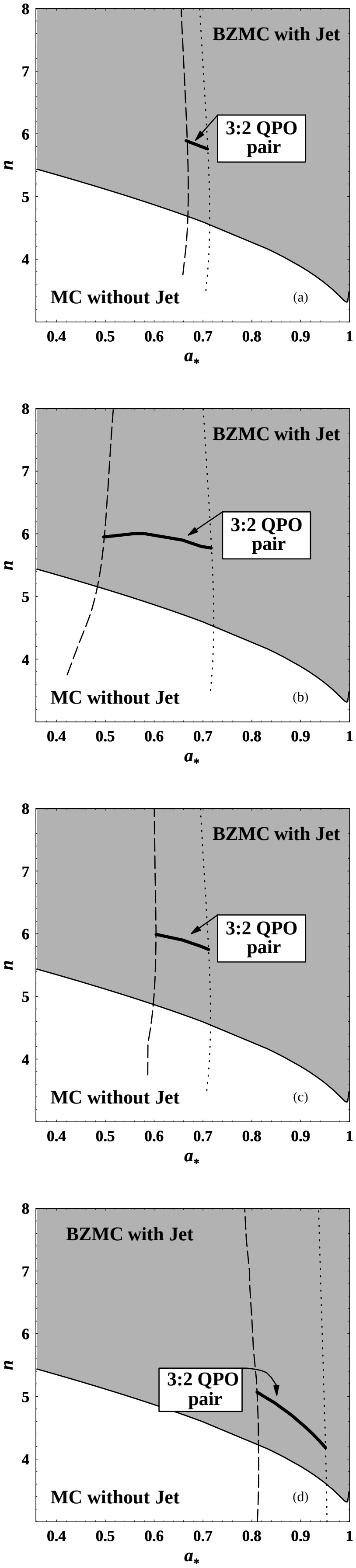

Fig. 3.— Two contours of $\nu_{upper} = const$ corresponding to the lower and upper BH masses are shown

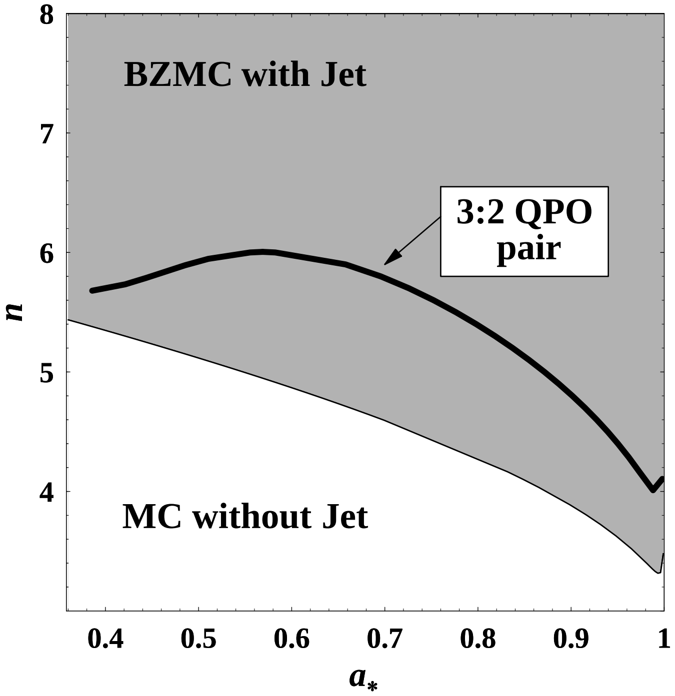

Fig. 4.— The characteristic line of the 3:2 QPO pair (240, 160Hz) for H1743-322 in $a_* - n$ parameter space.

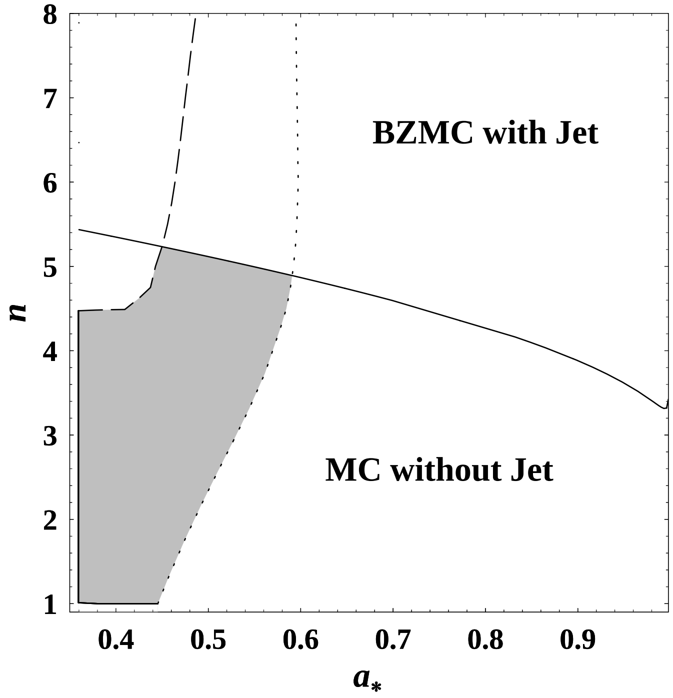

Fig. 5.— Two contours of $\nu_{QPO} = 190Hz$ corresponding to the lower and upper BH masses of XTE J1859+226 are shown in dashed and dotted lines, respectively.

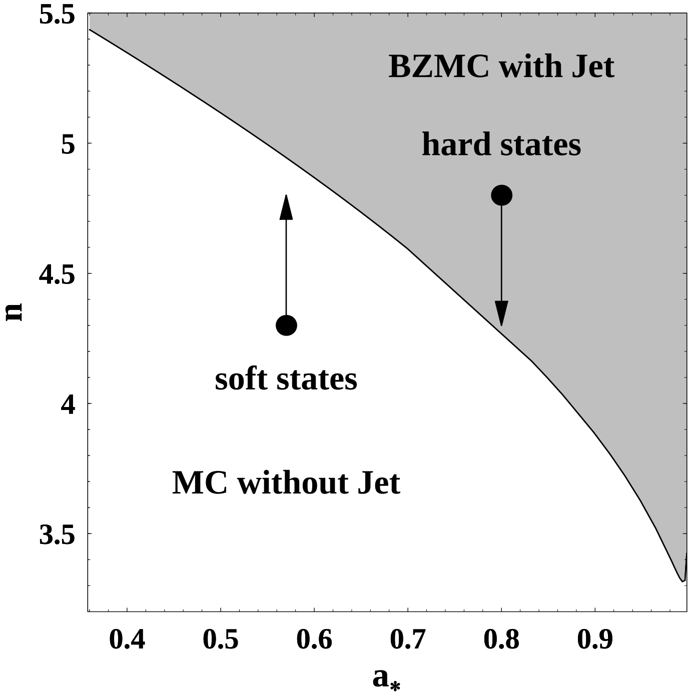

Fig. 6.— A schematic drawing for interpreting the state transitions of BHXBs in $a_* - n$ parameter space.

Table 1. The fitting results for the 3:2 QPOs pairs in GRO J1655-40, XTE J1550-564, GRS 1915+105 and Sgr A*.

Source	m_{BH}	a_*	n	Jet	Inner Hotspot		Outer Hotspot	
					ξ_{upper}	$\nu_{upper}(Hz)$	ξ_{lower}	$\nu_{lower}(Hz)$
GRO J1655-40	6.0	0.667	5.887	Yes	1.421	450	1.887	300
	6.6	0.709	5.763		1.400		1.863	
XTE J1550-564	8.4	0.603	5.996	Yes	1.473	276	1.949	184
	10.8	0.710	5.771		1.397		1.860	
GRS 1915+105	10.0	0.496	5.955	Yes	1.660	168	2.174	113
	18.0	0.716	5.785		1.395		1.845	
Sgr A*	$2.6\text{x}10^6$	0.811	5.069	Yes	1.378	$1.445\ \text{x}10^{-3}$	1.961	$0.886\ \text{x}10^{-3}$
	$4.4\text{x}10^6$	0.951	4.181		1.334		1.957	

Note. — The value ranges of the BH mass corresponding to GRO J1655-40, GRS 1915+105 and XTE J1550-564 are adopted from RM06, and the BH mass of Sgr A* is taken from Török (2005).

Table 2. The BH spins measured by X-ray continuum and 3:2 QPO pairs

Sources	Methods		
	X-ray continuum	3:2 QPO pairs	
		ERM	CEBZMC
GRO J1655-40	0.633-0.651 (D06), 0.65-0.80 (M06) 0.65-0.75 (S06), 0.7-0.95 (Z97), 0.68-0.88 (G01)	0.2-0.67 (AK01), 0.96 (AK04), 0.996 (A04b), 0.31-0.42 (KF06), 0.64-0.76 (Br05)	0.667-0.709
XTE J1550-564	0.71-0.87 (D06)	0.94 (AK04), 0.99616 (A04b) 0.11-0.42 (KF06), 0.1-0.6 (RM02), 0.41-0.77 (Br05)	0.603-0.710
GRS 1915+105	>0.98 (M06), 0.7 (MD06)	0.84(AK04), 0.996 (A04b), negative-0.44(KF06), -0.09-0.78(Br05)	0.496-0.716
Sgr A*		0.99616 (A06), 0.9865-0.9965 (A04a)	0.811-0.951

Note. — **The abbreviations for the references in Table 2 are given as follows:** AK01—Abramowicz & Kluzniak (2001); AK04—Abramowicz & Kluzniak (2004); A04a—Aschenbach, et al., (2004); A04b—Aschenbach, (2004); A06—Aschenbach, (2006); Br05—Bursa, (2005); D06—Davis et al. (2006); G01—Gierlinski et al.(2001); KF06—Kato & Fukue (2006); M06 —McClintock et al.(2006); MD06 — Middleton et al. (2006); RM02— Remillard et al. (2002); S06—Shafee et al.(2006); Z97—Zhang et al. (1997).

Table 3. The timescale of state transition in BHXBs fitted by the fluctuations in accreting plasma.

Sources	m_{BH}	a_*	ξ_{lower}	τ(sec)		
				$r/H = 10$	$r/H = 100$	$r/H = 1000$
GRO J1655-40	6.0	0.667	1.887	0.5305	53.05	5305
	6.6	0.709	1.863			
XTE J1550-564	8.4	0.603	1.949	0.8650	86.50	8650
	10.8	0.710	1.860			
GRS 1915+105	10.0	0.496	2.174	1.408	140.8	14080
	18.0	0.716	1.845			
Sgr A*	$2.6\text{x}10^6$	0.811	1.961	1.796×10^5	1.796×10^7	1.796×10^9
	$4.4\text{x}10^6$	0.951	1.957			

Correlation between 3:2 QPO pairs and Jets in Black Hole X-ray Binaries

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ABSTRACT

We argue, following our earlier works (the 'CEBZMC model'), that the phenomenon of twin peak high frequency quasi-periodic oscillations (QPOs) observed in black hole X-ray binaries is caused by magnetic coupling (MC) between accretion disk and black hole (BH). Due to MC, two bright spots occur at two separate radial locations r_{in} and r_{out} at the disk surface, energized by a kind of the Blandford-Znajek mechanism (BZ). We assume, following the Kluzniak-Abramowicz QPO resonance model, that Keplerian frequencies at these two locations are in the 3:2 ratio. With this assumption, we estimate the BH spins in several sources, including GRO J1655-40, GRS 1915+105, XTE J1550-564, H1743-322 and Sgr A*. We give an interpretation of the 'jet line' in the hardness-intensity plane discussing the parameter space consisting of the BH spin and the power-law index for the variation of the large-scale magnetic field in the disk. Furthermore, we propose a new scenario for the spectral state transitions in BH X-ray binaries based on fluctuation in densities of accreting plasma from a companion star.

Subject headings: accretion, accretion disks - black hole physics - magnetic fields - instabilities - stars: individual (GRO J1655-40, GRS 1915+105, XTE J1550-564, H1743-322, XTE J1859+226) - stars: oscillations - X-rays: stars

1. INTRODUCTION

Data collected by the NASA satellite Rossi X-Ray Timing Explorer (RXTE; Bradt, Rothschild & Swank 1993) added a new impetus to studies of QPOs, observed in X-ray binaries and other sources. The QPO observations are described in several recent reviews, e.g. by Remillard (2005) or Remillard & McClintock 2006 (hereafter RM06). The QPO observations present several puzzles, including why is the occurrence of high frequency QPOs correlated with the occurrence of relativistic jets. The jets in microquasars were first observed by Mirabel & Rodrigues (1998, 1999). For references to more recent works see McClintock & Remillard (2006, hereafter MR06) and Kalemci et al. (2006). It is widely agreed (Mirabel & Rodrigues 1999; Blandford 2002) that in both active galactic nuclei (AGNs) and microquasars, relativistic jets must be powered by a process similar to the celebrated Blandford-Znajek (1977, hereafter BZ) mechanism. A particular variant of BZ, in the form of magnetic couplings (MC) between a rotating BH and its surrounding disk, has been recently investigated by several authors, including Blandford (1999), Li (2000, 2002), and Wang et al. 2002, hereafter W02). Our 'CEBZMC' model (Wang et al. 2003a, 2004, hereafter W04) also belongs to the BZ plus MC class.

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In this paper we consider a particular realization of the CEBZMC model, in which MC between BH and accretion disk energizes ‘hot spots’ on the accretion disk surface. As discussed by Wang et al. 2005 (hereafter W05), a pair of hot spots produce a pair of QPOs, with frequencies ν_{in} and ν_{out} that correspond to Keplerian frequencies at the locations of the two spots, r_{in} and r_{out}. We *assume* that the two locations agree with the Kluzniak-Abramowicz resonance condition, $\nu_{in}/\nu_{out} = 3/2$. Abramowicz and Kluzniak (2001, hereafter AK01) realized that frequencies of the QPO pairs in BH sources are in the exact 3:2 ratio. They also recognized and stressed the fundamental importance of this fact[1]. They first noticed the 3:2 ratio in the QPO pair with frequencies 450 Hz and 300 Hz in GRO J1655-40, observed by Strohmayer, (2001a, b). This important discovery was strengthened by numerous authors, who found the 3:2 ratio in different BH sources: in GRS 1915+105 MR06, in XTE J1550-564 Miller (2001) and Remillard et al (2002), and in H1743-322 Homan et al. (2005) and Remillard et al. (2006). There is less certain evidence that the same 3:2 ratio occurs for QPOs observed in low-mass active galactic nuclei - in e.g. Sgr A* (Török 2005a, b; Ashenbach 2005) and in a few nearby Seyferts (Lachowicz et al., 2006). The 3:2 ratio of frequencies is the basic feature of the Kluzniak-Abramowicz QPO resonance model (see a collection of reviews in Abramowicz 2005 for references). In other QPOs models, the 3:2 ratio of observed frequencies is either incidental or impossible as for example, in the Lamb and Miller (2004) model that considered the QPO pairs to be a beat frequency between neutron star spin and disk rotation, or in the Wagoner et al., (2001) model, in which they are fundamental g-mode and c-mode in thin disk oscillations, or in the Stella and Vietri (1999) model where they emerge as a combination of Keplerian and radial epicyclic frequencies. In our CEBZMC model, in its present state of development, the 3:2 ratio does not directly follow from the model basic assumption (MC, BZ). However, as we will see later, the 3:2 ratio occurs in an interesting region of the parameter space of the CEBZMC model. We therefore *assumed* that the ratio is equal 3:2, and examined consequences of this assumption. This phenomenological approach has at least three virtues. Firstly, it allows us to estimate the spin of BHs in the BH sources that display the QPOs with the 3:2 ratio, using a method first applied by AK01 and more recently Török et al. (2005). Secondly, it is directly related to the correlation between the occurrence of the QPO 3:2 pairs and the jets. Thirdly, we may offer an interpretation of the ’jet line’ in the hardness-intensity diagram (HID), by which the hard state and the soft state of the BH X-ray binaries (BHXBs) are separated (Fender et al. 2004, hereafter FBG04; Belloni 2005, hereafter B05, Remillard 2005).

This paper is organized as follows. In § 2 we give a brief description of our model and explain the correlation between the 3:2 QPO pairs and the jets in BHXBs. In § 3 we compare the BH spins measured by different methods. It turns out that the BH spin of GRO J1655-40 estimated by CEBZMC is consistent with those estimated by X-ray continuum fittings. By fitting the 3:2 QPO pairs, we estimate the spin of the galactic massive BH, Sgr A*, for a given range of the BH mass, and also estimate the spin and mass of the BH candidate H1743-322. In addition, the spin of the BH X-ray binary XTE J1859+226 is estimated by fitting its single–component high frequency QPO. In § 4 we propose a new scenario for the state transitions in BHXBs based on the variation of the power-law index n, which arises from the fluctuation of the number densities of the accreting plasma from a companion star. Finally, in § 5, we summarize the main results, and discuss the issues related to this model. Throughout this

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[1] Abramowicz et al. (2003) also argued that there is a statistical evidence for the same 3:2 ratio for QPOs in neutron star sources. This was later confirmed by Belloni et al. (2005). More recently, Abramowicz et al. (2005) found an additional, independent, and direct proof for the 3:2 ratio in the QPO neutron star data. They proved that although in neutron star sources the *observed* frequencies vary in a wide range, the variations uniquely point to the 3:2 ratio of the *eigenfrequencies*.

paper the geometric units $G = c = 1$ are used.

2. CORRELATION BETWEEN 3:2 QPO PAIRS AND JETS

In order to discuss the correlation of the 3:2 QPO pairs with the jets in the BHXBs we give a brief review of our previous works. In W05 we approached the 3:2 QPO pairs by virtue of the MC of a Kerr BH with its surrounding disk as shown in Figure 1, in which the large-scale magnetic field at the BH horizon consists of the open and closed field lines with an angular boundary at θ_S. The open field lines transfer the energy and angular momentum from the BH to the remote astrophysical loads in the BZ process, while the closed field lines transfer those between the BH and the surrounding accretion disk in the MC process. The angular boundary θ_S is determined by a criterion of the screw instability of the magnetic field given in W04.

The upper and lower frequencies of the 3:2 QPO pairs correspond respectively to the inner and outer hotspots rotating with the Keplerian angular velocities of the disk, which are produced by the MC with the non-axisymmetric magnetic field at the BH horizon (Wang et al. 2003b). As argued in W05, the positions of the inner and outer hotspots are determined by the maximum radiation flux from the disk and the screw instability of the non-axisymmetric magnetic field, respectively.

It turns out that the 3:2 QPO pairs fitted in our model depend mainly on two parameters, i.e., the BH spin a_* and the power-law index n. The parameter $a_* \equiv J/M^2$ is defined in terms of the BH mass M and angular momentum J, and the parameter n is defined in terms of the variation of the poloidal magnetic field B_D^P with the disk radius, $B_D^P \propto r^{-n}$.

It has been argued in W04 that the state of CEBZMC always accompanies the screw instability, provided that the BH spin a_* and the power-law index n are greater than some critical values. Based on the criterion of the screw instability derived in W04 we have a contour of the angular boundary $\theta_S\left(a_*, n\right) = 0$ in the $a_* - n$ parameter space as shown in Figure 2.

Inspecting Figure 2, we have the following results:

(1) The shaded region indicated “BZMC with Jet” represents the value ranges of the parameters a_* and n for CEBZMC, in which the jet driven by the BZ process exists.

(2) The inner hotspot arises from energy transferred from a fast-rotating BH into the disk by non-symmetric MC.

(3) The outer hotspot is produced by the screw instability, which always accompanies the state of CEBZMC.

Recently, the 3:2 QPO pair has been observed in near infrared flares of the massive BH Sgr A* in the Galactic Center (1.445, 0.886mHz; Aschenbach 2004a, 2004b; Török 2005). In addition, Bower et al. (2004) state that their radio measurements of Sgr A* are consistent with jet models. Based on the model of CEBZMC given in W04 and W05 we have the fitting results of the 3:2 QPO pairs for the three BHXBs and Sgr A* as shown in Table 1.

It is noticed that the BH spins given in Table 1 are a little less than those given in W05 (see Table 1), because some errors in calculations have been corrected and the ranges of the BH masses have been updated.

As argued in W05, the upper and lower frequencies of the 3:2 QPO pairs are equal to the Keplerian frequencies of the inner and outer hotspots, respectively, being expressed by

$$\nu_i = \nu_0 (\xi_i^{3/2} \chi_{ms}^3 + a_*)^{-1}, \tag{1}$$

where $\nu_0 \equiv (m_{BH})^{-1} \times 3.23 \times 10^4 Hz$ with $m_{BH} \equiv M/M_\odot$. The parameter $\xi_i \equiv r_i/r_{ms}$ is the disk radius expressed in terms of r_{ms}, the radius of the innermost stable circular orbit (ISCO). The frequency ν_i represents ν_{upper} and ν_{lower} for ξ_i equal to ξ_{upper} and ξ_{lower}, respectively. As argued in W05 both ξ_{upper} and ξ_{lower} depend on the parameter a_* and n, i.e.,

$$\begin{cases} \xi_{upper} = \xi_{upper}(a_*, n), \\ \xi_{lower} = \xi_{lower}(a_*, n). \end{cases} \tag{2}$$

It is obvious that the 3:2 QPO pair can be completely determined by combining equation (2) with equation (1), provided that the BH mass m_{BH}, ν_{upper} and ν_{lower} are given. This implies that the 3:2 QPO pair with the given BH mass corresponds to one 'representative point' in the $a_* - n$ parameter space. Thus we have a characteristic line of the 3:2 QPO pair for a continuous distribution of m_{BH} within its upper and lower limits as shown by the thick solid line in Figure 3.

On the other hand, $\nu_{upper} = const$ corresponds to a contour with the given BH mass in the $a_* - n$ parameter space based on equations (1) and (2), and we have two contours of $\nu_{upper} = const$ corresponding to the lower and upper BH masses in the parameter space as shown in Figure 3.

It is found from Figure 3 that the characteristic lines of the 3:2 QPO pairs for the four BH systems are all located in the shaded region indicated "BZMC with Jet". These results provide a natural explanation for the correlation between the 3:2 QPO pairs and the jets driven by the BZ process, being consistent with the fact that jets are found in the above BH systems (Mirabel & Rodrigues 1998, 1999; Aschenbach 2004; Bower et al. 2004; Török 2005; MR06).

3. ESTIMATING BH SPINS BY VIRTUE OF HIGH FREQUENCY QPOS

A Kerr BH is described completely by its mass$M$ and spin a_*. The masses of twenty BHs in the Galaxy have already been measured or constrained, and the next goal is to measure spin. As pointed out by RM06, there are four avenues for measuring BH spin, which include (1) X-ray polarimetry, (2) X-ray continuum fitting, (3) the Fe K line profile and (4) high frequency QPOs. Among these approaches high frequency QPOs are likely to offer the most reliable measurement of spin once the correct model is known. Unfortunately, there are significant differences in the BH spins measured by different models, and a reasonable model for measuring BH spins has not been accepted by astrophysical community.

In this paper we compare the values of the BH spins of the three BHXBs and Sgr A*, which are measured by X-ray continuum and 3:2 QPO pairs as listed in Table 2.

The method of X-ray continuum fitting is used to measure the BH spins of the binaries based on a fully relativistic model of a thin accretion disk around a Kerr BH. In order to estimate the BH spin by fitting the broadband X-ray spectrum, one must know the BH mass, the inclination$i$ of the accretion disk, and the distance to the binary.

The approach to the BH spin based on the 3:2 QPO pair consists of two basic methods. One method is based on the epicyclic resonance model (ERM), in which the resonance between orbital and epicyclic motions of accreting matter is invoked (Abramowicz & Kluznick 2004 and references therein), and another method is based on CEBZMC, in which the inner and outer hotspots are produced by a non-axisymmetric MC and the screw instability of the magnetic field, respectively. The BH spin measured by ERM and CEBZMC depend on the BH masses.

From Table 2 we find that the spin of GRO J1655-40 measured by CEBZMC is in a good agreement with those measured by X-ray continuum fittings given in G01, S06 and M06. However, an intersection of the BH spins has not been found for XTE J1550-564 and GRS 1915+105 based on the above two methods.

It is found that the spin of Sgr A* measured by CEBZMC is generally not overlapped with those measured by ERM except those given in Br05. Up to date, the BH spin of Sgr A* has been estimated only by using ERM and CEBZMC, depending sensitively on the BH mass. For example, based on CEBZMC the spin is estimated as 0.811–0.951 and 0.800–0.841 for $m_{BH} = (2.6 - 4.4) \times 10^6$ and $(2.53 - 2.84) \times 10^6$, respectively. Based on ERM the spin is constrained to be 0.9865–0.9965 and 0.99616 for $m_{BH} = (2.53 - 2.84) \times 10^6$ and 3.3×10^6 in A04a and A06, respectively.

A common feature in the above measurements lies in the fact that the BH spins are constrained more tightly for the narrower ranges of the BH masses. Although the BH mass of H1743-322 has not been constrained, it is identified as a BH candidate by the X-ray light curve and variability characteristics during its 2003 outburst, and its behavior resembles the BHXBs XTE J1550-564 and GRO J1655-40 in many ways (Remillard et al. 2002, 2006). It is interesting to note that both the 3:2 QPO pair and the jet have been observed in H1743-322 also (Homan et al. 2005; Remillard et al. 2006; Kalemci et al. 2006). Thus we can constrain the BH mass and spin also by the 3:2 QPO pair (240, 160Hz) based on the model of CEBZMC.

As shown in Figure 3, a characteristic line in the $a_* - n$ parameter space represents the 3:2 QPO pair, which is located between two contours of $\nu_{upper} = const$ for the lower and upper BH masses. In the case of H1743-322 the BH mass and spin can be also constrained by the characteristic line above the contour $\theta_S\left(a_*, n\right) = 0$ in the $a_* - n$ parameter space as shown in Figure 4.

Inspecting Figure 4, we find that the characteristic line is located in the shaded region indicated by "BZMC with Jet", and it spans a very wide range of the BH spin. Required by the 3:2 QPO pair (240, 160Hz) and the upper limit ($a_* \le 0.998$) to the BH spin given by Thorne (1974) we have the leftmost and rightmost points of the characteristic line as follows:

$$(a_*, n, \xi_{\max}) = \begin{cases} (0.371,\ 5.670,\ 2.271), \\ (0.998,\ 4.105,\ 1.187), \end{cases} \tag{3}$$

where the upper and lower lines correspond to the leftmost and rightmost points of the characteristic line in Figure 4, respectively. Combining $\nu_{upper} = 240Hz$ with equations (1)–(3) for the leftmost and rightmost points of the characteristic line, we can estimate the value range of the BH mass: $3.76 < m_{BH} < 48.23$. Although the BH mass and spin of H1743-322 are only constrained loosely by the 3:2 QPO pair, they can be further constrained by other observations. For example, the BH mass and spin can be limited to a smaller range by fitting the observed jet power in terms of the BZ power based on the model of CEBZMC.

It is well known that single–component high frequency QPOs have been observed in some confirmed and candidate BHXBs (MR06), such as XTE J1859+226 (190 Hz), 4U1630–47 (184 Hz) and XTE J1650–500 (250 Hz). According to the model of CEBZMC the single–component high frequency QPO can be fitted by ONE rotating hotspot arising from the maximum radiation flux due to the non-axisymmetric MC.

Since neither jets nor 3:2 QPO pairs are observed in XTE J1859+226, its state should be confined in the shaded region below the contour of $\theta_S\left(a_*, n\right) = 0$ as shown in Figure 5.

As argued by Li (2002) the minimum spin for transferring energy from the BH to the disk in the MC process is $a_* = 0.3594$, and it is regarded as the left boundary of the shaded region in Figure 5. Thus the BH spin of XTE J1859+226 can be estimated as $0.3594 < a_* < 0.5890$ by combining $\nu_{QPO} = 190Hz$ with the BH mass, $7.6 < m_{BH} < 12.0$, which is taken from RM06.

4. A SCENARIO FOR STATE TRANSITIONS IN BHXBS

The prominent feature of the model of CEBZMC lies in the correlation of the high frequency QPO pairs with the jets from the BHXBs. As is well known, state transitions in BHXBs involve a number of unresolved issues in astrophysics, displaying complex variations not only in the luminosities and energy spectra, but also in presence/absence of jets and QPOs. How to analyze and classify states in BHXBs from observations in multi-wavelength band is of foremost importance.

Recently, FBG04 proposed a unified semi-quantitative model for the disk-jet coupling in BHXBs, in which the states of BHXBs are described in an X-ray hardness-intensity diagram (HID), and the states with jet and those with no jet are divided by a 'jet line' in HID. Later, B05 classified the states of BHXBs into four types: (1) Low/Hard State (LS), (2) Hard Intermediate State (HIMS), (3) Soft Intermediate State (SIMS) and (4) High/Soft State (HS), which display different luminosity and hardness associated with different behavior of QPOs and radio loudness. It is pointed out in B05 that these states might be reduced to only two basic states, i.e., a hard state and a soft one. The states LS and HIMS are included in the hard state, and the states SIMS and HS in the soft state. The jets can be observed in hard states, but can not in soft states.

Very recently, MR06 used four parameters to define X-ray states based on the very extensive RXTE data archive for BHXBs, in which three states are included: (1) thermal state (high/soft state), (2) hard state (low/hard state) and (3) steep power law (SPL) state. In the thermal state, the flux is dominated by the heat radiation from the inner accretion disk, and QPOs are absent or very weak. The hard state is characterized by a hard power-law component at 2–20 keV, being associated with the presence of a quasi-steady radio jet. The SPL state is a strong power-law component with $\Gamma \sim 2.5$, which is associated with high-frequency QPOs. In MR06 luminosity is abandoned as a criterion for defining the X-ray states.

However, a consistent interpretation for the state transitions in BHXBs remains controversial, and this becomes a great challenge to the present theoretical models. Some authors (e.g. Belloni et al. 1997a,b; 2000) interpreted the transition between State C and States A/B as being caused by the disappearance and reappearance of the inner accretion disk due to a disk instability mechanism. Livio et al. (2003) pointed out that the inner disk remains present rather than absent in the state transitions, and it switches between two states in two different ways of converting accretion energy. In one state, the accretion energy is dissipated locally to produce the observed disk luminosity. In another state the energy liberated in the accretion is converted efficiently into magnetic energy in the form of a magnetically dominated outflow or jet. However, a detailed argument for producing jets in BHXBs has not been given by these authors.

Motivated by the above discussion we suggest a new scenario for the state transition in BHXBs based on the model of CEBZMC. Inspecting Figures 2–4, we find that the two basic states suggested by B05 can be naturally divided by the contour of $\theta_S(a_*, n) = 0$ in $a_* - n$ parameter space: a hard state with jet is represented by a point in the shaded region above the contour of $\theta_S(a_*, n) = 0$, while a soft state without jet by a point in the region below this contour. The state transition in BHXBs can be interpreted in terms of the variation of the power-law index$n$. As shown in Figure 6, a hard state will transit to a soft state with the decreasing n, while a soft state will change to a hard state with the increasing n. The contour of $\theta_S(a_*, n) = 0$ corresponds exactly to the 'jet line' in HID.

One of the main problems of this scenario is what mechanism gives rise to the variation of the power-law index n. This issue might be related to the fluctuation in the number density of the accreting plasma from the companion star, and a rough explanation is given as follows.

In our model the power-law index n is used to describe the variation of the poloidal magnetic field with the disk radius, i.e.,

$$B_D^p = \left(B_D^p\right)_{ms} \left(r/r_{ms}\right)^{-n} = \left(B_D^p\right)_{ms} \xi^{-n}, \tag{4}$$

where $\left(B_D^p\right)_{ms}$ is the poloidal magnetic field at ISCO. Based on Ampere's law we have the toroidal current density j_φ at the disk as follows,

$$j_\varphi = \frac{1}{4\pi}\frac{dB_D^p}{dr} = \frac{1}{4\pi r_{ms}}\frac{dB_D^p}{d\xi} = -\frac{n\left(B_D^p\right)_{ms}}{4\pi M \chi_{ms}^2}\xi^{-(n+1)}. \tag{5}$$

From equations (4) and (5) we find that the profile of the magnetic field at the disk is related directly to the toroidal current at the same place, and the power-law index of the latter becomes $n+1$. Thus the variation of the magnetic field can be explained by the variation of the toroidal current, and the latter might be produced due to the fluctuation of the accreting plasma coming from the companion star.

As a simple analysis, we assume that the accreting plasma consists of electrons and protons, of which the number densities are n_e and n_p, respectively. Generally, the two number densities are not equal exactly, and they are related by $n_p = n_e + n_\delta$. Thus a toroidal current density could be generated due to the charged particles' Keplerian rotation and it reads

$$j_\varphi = e n_\delta v_\varphi = e n_\delta \xi \chi_{ms}^2 / \left(\chi_{ms}^3 + a_*\right). \tag{6}$$

where $e = 4.8 \times 10^{-10} e.s.u.$ is the electron charge. Incorporating equations (5) and (6), we have

$$n_\delta = -\frac{n\left(B_D^p\right)_{ms}}{4\pi e \xi M}\left(\frac{\chi_{ms}^3 + a_*}{\chi_{ms}^4}\right)\xi^{-(n+1)}. \tag{7}$$

As argued in W05, $B_4 \approx 10^5$ is the strength of the magnetic field required by the hotspots for emitting X-ray. Taking $(B_D^p)_{ms} = B_4 \times 10^5 gauss$, $M = m_{BH} M_\odot$ and $\xi = 1$, we have

$$| n_\delta |= 4.5 \times 10^8 \times \left(B_4 m_{BH}^{-1}\right) \left(\chi_{ms}^{-1} + a_* \chi_{ms}^{-4}\right) cm^{-3}. \tag{8}$$

By taking the disk mass as $M_{disk} = \alpha_m m_{BH} M_\odot$, the average disk height as $H = \beta r$ and the outer boundary radius $r_{out} = 1000 r_{ms}$, the average number density of protons can be estimated as

$$\bar{n}_p = \frac{M_{disk}}{m_p \int_{r_{ms}}^{r_{out}} 2\pi r H dr} = \left(\alpha_m \beta^{-1} m_{BH}^{-2} \chi_{ms}^{-6}\right) \times 1.77 \times 10^{32} cm^{-3}, \tag{9}$$

where $m_p = 1.67 \times 10^{-24} g$ is a proton's mass. Incorporating equations (8) and (9) with the given values of the concerned parameter, such as $\alpha_m \approx 10^{-3}$, $\beta = 0.1$, $m_{BH} = 10$, $B_4 \approx 10^5$, and $0.3594 < a_* < 0.9980$, we have

$$7.3 \times 10^{-16} <| n_\delta | / \bar{n}_p < 1.28 \times 10^{-14}. \tag{10}$$

It seems reasonable that the fluctuation in the number densities of the accreting plasma can be realized in the realistic astrophysical context for the small value of $n_\delta / \bar{n}_p$ given in equation (10).

Another issue related to the state transition in BHXBs is how to estimate the timescale of the fluctuation in density of the accreting plasma. If the toroidal current arises from the fluctuation of the number density of the accreting plasma, we think that the variation of the power-law index n might occur due to this fluctuation, and it gives rise to the state transition in BHXBs. Not long ago, Brown et al. (2000) discussed the MC effect on the accretion flow, and they estimated the viscous inflow time for the fluctuations as

$$\tau \sim r/\upsilon_r \sim (r/H)^2 \alpha_{vis}^{-1} \Omega_D^{-1}, \tag{11}$$

where υ_r is radial velocity of the accreting plasma and H is the height of the disk at radius r. We take the coefficient of kinematic viscosity $\alpha_{vis} = 0.1$ in calculations. Since the variation occurs within the outer boundary of the MC, we calculate the timescale corresponding to $r_{out} = \xi_{lower} r_{ms}$ by using equation (11) as listed in Table 3.

It is obvious, from equation (11) and Table 3, that the ratio r/H is dominative in determining the timescales of state transitions, which are insensitive to the parameters, m_{BH}, a_* and ξ_{lower}. Inspecting Table 3, we find that the timescales of state transitions in BHXBs from less than one second to more than one hour can be fitted by the fluctuation in density of the accreting plasma. We expect that the timescales of the state transitions in the above sources can be fitted by adjusting the ratio r/H based on this simplified model.

Since the fluctuation in densities of the accreting plasma is stochastic, this results in a stochastic variation of the power-law index n, and it is consistent with the observation of the state transitions in BHXBs: a hard state can transit to a soft one and then back to the hard one again, passing across the jet line several times as shown in Figure 7 of FBG04.

5. DISCUSSION

In this paper, we assume that Keplerian frequencies at two locations are in the 3:2 ratio based on the CEBZMC model. Compared with the Kluzniak-Abramowicz QPO resonance model, the 3:2 QPO pairs arising from the two hotspots are produced by the MC between a rotating BH and its surrounding disk. The BH spins of several BH sources measured by different methods are compared. It turns out that the BH spin of GRO J1655-40 measured by the CEBZMC model is in a good agreement with the recent results based on X-ray continuum fitting. In addition, the correlation of the 3:2 QPO pairs with the jet from the BH systems including Sgr A* is discussed in the parameter space. It is shown that the 'jet line' in HID can be interpreted naturally by the CEBZMC model. Finally, we suggest that the state transition in BHXBs could be realized by virtue of the variation of the power-law index n, which could be related to the fluctuation of the number densities of the accreting plasma from the companion star.

In our model the 3:2 QPO pairs are determined by the BH spin a_* and the power-law index n for the given BH mass. The parameter n is introduced to describe the basic feature of the large-scale magnetic field anchored at the disk, indicating the degree of its concentration at the inner region. It turns out that the parameter n plays a very important role not only in fitting the 3:2 QPO pairs but also in interpreting the state transitions of BHXBs.

It is easy to find from the parameter spaces in Figures 2—6 that the state transition from a hard state to a soft state can be realized by decreasing the BH spin, and the inverse transition occurs with the increasing spin. However, our calculations show that the timescale for the variation of the spin is too long to fit the observations. In addition, the evolution of the BH spin is generally one-direction, i.e., it decreases from a high spin to the equilibrium spin or increases from a low spin to the equilibrium spin as argued in W02. Thus the regime of the BH spin is not consistent with the observations: the states of BHXBs can switch time and time between a hard state and a soft state. Compared with the BH spin the variation of the parameter n involves the timescale of the fluctuation of the number density, which is consistent with the state transition of BHXBs both in the timescale and in the repeating switches between the hard and soft states.

Very recently, Ma et al. (2006) introduced corona into the model of CEBZMC, which might be helpful to understand the association of the SPL state with the high frequency QPOs in BHXBs as argued in MR06. We shall discuss this issue in our future work.

Acknowledgements: This work is supported by the National Natural Science Foundation of China under grants 10373006, 10573006 and 10121503. We are very grateful to the anonymous referee for his (her) instructive comments on the role of MC in the 3:2 frequency ratio and the related issues.

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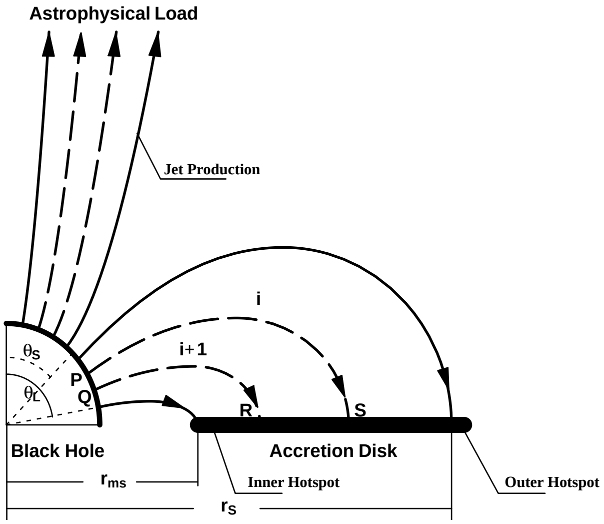

Fig. 1.— Poloidal magnetic field connecting a rotating BH with a remote astrophysical load and the surrounding disk. The inner and outer hotspots are located at different places of the disk.

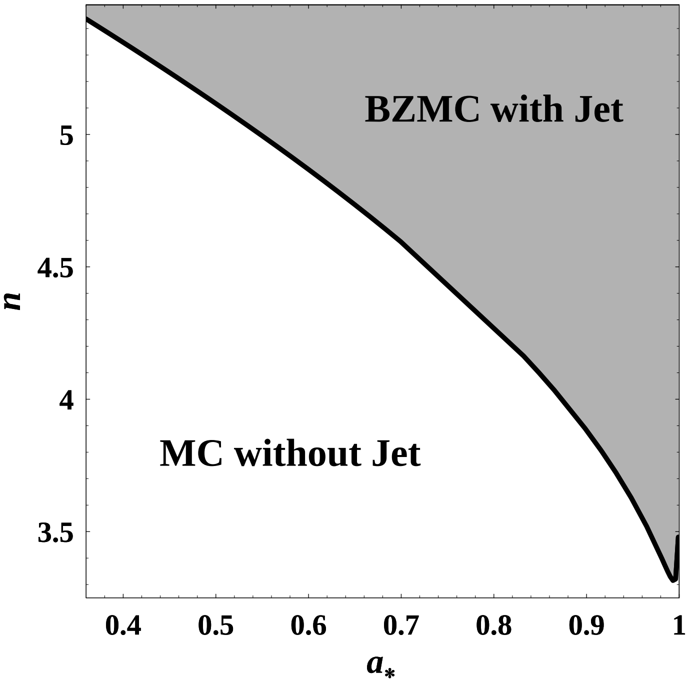

Fig. 2.— The contour of angular boundary $\theta_S(a_*, n) = 0$ in $a_* - n$ parameter space.

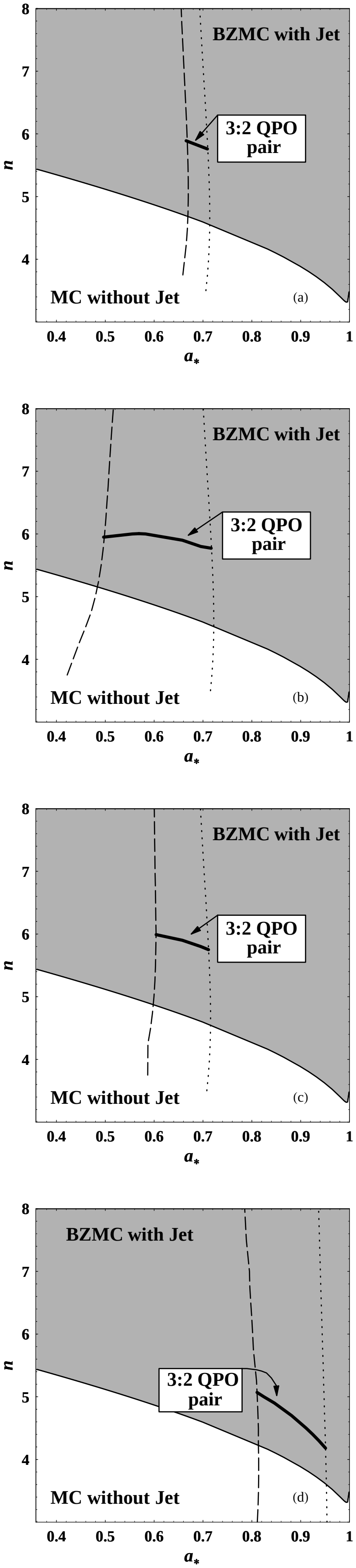

Fig. 3.— Two contours of $\nu_{upper} = const$ corresponding to the lower and upper BH masses are shown

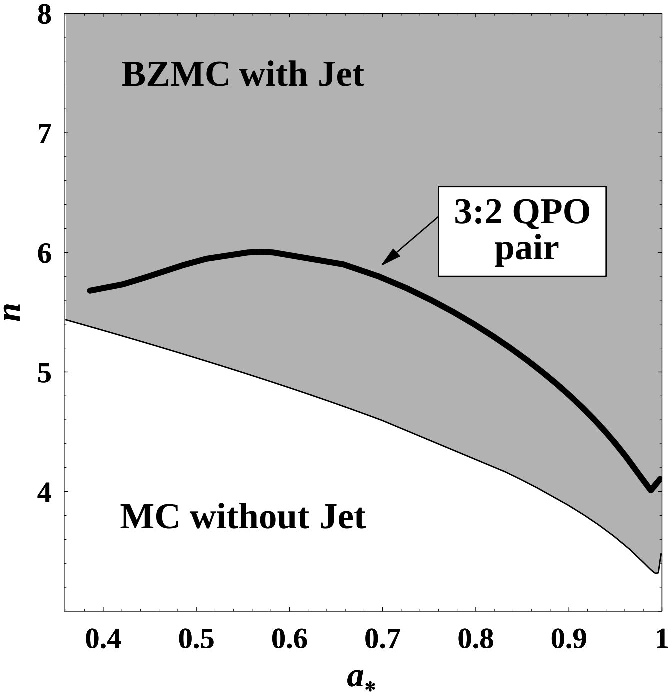

Fig. 4.— The characteristic line of the 3:2 QPO pair (240, 160Hz) for H1743-322 in $a_* - n$ parameter space.

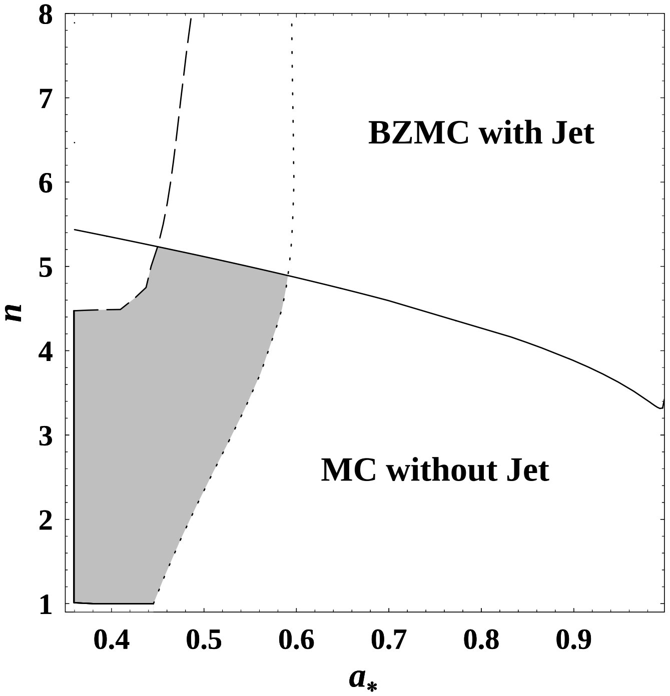

Fig. 5.— Two contours of $\nu_{QPO} = 190Hz$ corresponding to the lower and upper BH masses of XTE J1859+226 are shown in dashed and dotted lines, respectively.

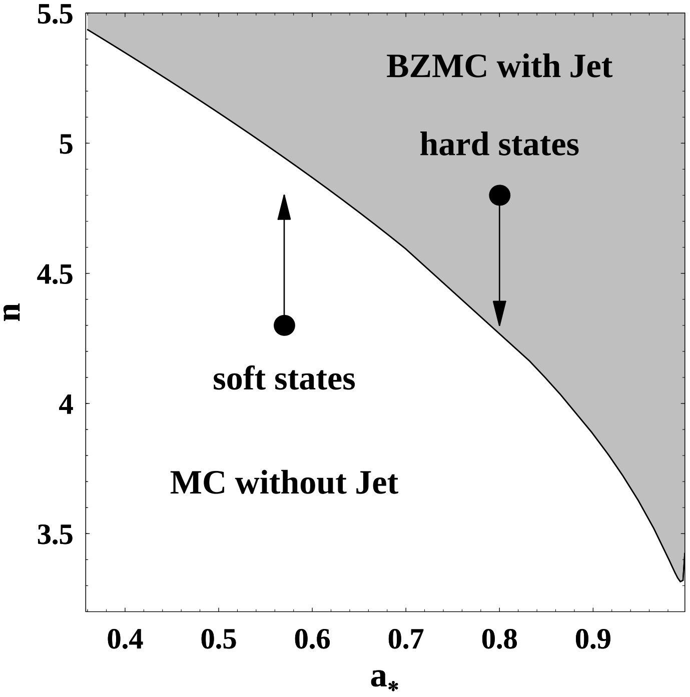

Fig. 6.— A schematic drawing for interpreting the state transitions of BHXBs in $a_* - n$ parameter space.

Table 1. The fitting results for the 3:2 QPOs pairs in GRO J1655-40, XTE J1550-564, GRS 1915+105 and Sgr A*.

Source	m_{BH}	a_*	n	Jet	Inner Hotspot		Outer Hotspot	
					ξ_{upper}	$\nu_{upper}(Hz)$	ξ_{lower}	$\nu_{lower}(Hz)$
GRO J1655-40	6.0	0.667	5.887	Yes	1.421	450	1.887	300
	6.6	0.709	5.763		1.400		1.863	
XTE J1550-564	8.4	0.603	5.996	Yes	1.473	276	1.949	184
	10.8	0.710	5.771		1.397		1.860	
GRS 1915+105	10.0	0.496	5.955	Yes	1.660	168	2.174	113
	18.0	0.716	5.785		1.395		1.845	
Sgr A*	$2.6 \text{x} 10^6$	0.811	5.069	Yes	1.378	$1.445 \text{ x} 10^{-3}$	1.961	$0.886 \text{ x} 10^{-3}$
	$4.4 \text{x} 10^6$	0.951	4.181		1.334		1.957	

Note. — The value ranges of the BH mass corresponding to GRO J1655-40, GRS 1915+105 and XTE J1550-564 are adopted from RM06, and the BH mass of Sgr A* is taken from Török (2005).

Table 2. The BH spins measured by X-ray continuum and 3:2 QPO pairs

Sources	Methods		
	X-ray continuum	3:2 QPO pairs	
		ERM	CEBZMC
GRO J1655-40	0.633-0.651 (D06), 0.65-0.80 (M06) 0.65-0.75 (S06), 0.7-0.95 (Z97), 0.68-0.88 (G01)	0.2-0.67 (AK01), 0.96 (AK04), 0.996 (A04b), 0.31-0.42 (KF06), 0.64-0.76 (Br05)	0.667-0.709
XTE J1550-564	0.71-0.87 (D06)	0.94 (AK04), 0.99616 (A04b) 0.11-0.42 (KF06), 0.1-0.6 (RM02), 0.41-0.77 (Br05)	0.603-0.710
GRS 1915+105	>0.98 (M06), 0.7 (MD06)	0.84(AK04), 0.996 (A04b), negative-0.44(KF06), -0.09-0.78(Br05)	0.496-0.716
Sgr A*		0.99616 (A06), 0.9865-0.9965 (A04a)	0.811-0.951

Note. — **The abbreviations for the references in Table 2 are given as follows:** AK01—Abramowicz & Kluzniak (2001); AK04—Abramowicz & Kluzniak (2004); A04a—Aschenbach, et al., (2004); A04b—Aschenbach, (2004); A06—Aschenbach, (2006); Br05—Bursa, (2005); D06—Davis et al. (2006); G01—Gierlinski et al.(2001); KF06—Kato & Fukue (2006); M06 —McClintock et al.(2006); MD06 — Middleton et al. (2006); RM02— Remillard et al. (2002); S06—Shafee et al.(2006); Z97—Zhang et al. (1997).

Table 3. The timescale of state transition in BHXBs fitted by the fluctuations in accreting plasma.

Sources	m_{BH}	a_*	ξ_{lower}	τ(sec)		
				$r/H = 10$	$r/H = 100$	$r/H = 1000$
GRO J1655-40	6.0	0.667	1.887	0.5305	53.05	5305
	6.6	0.709	1.863			
XTE J1550-564	8.4	0.603	1.949	0.8650	86.50	8650
	10.8	0.710	1.860			
GRS 1915+105	10.0	0.496	2.174	1.408	140.8	14080
	18.0	0.716	1.845			
Sgr A*	$2.6 \text{x} 10^6$	0.811	1.961	1.796×10^5	1.796×10^7	1.796×10^9
	$4.4 \text{x} 10^6$	0.951	1.957			