Postprint on the Explanation of the Correlation Between Type-B QPO Frequency and Power-law Flux in Black Hole Binaries

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Abstract

Observations indicate a positive correlation between the frequency of type-B quasi-periodic oscillations (Quasi-Periodic Oscillation, QPO) in black-hole binaries and the power-law flux. This correlation is quantitatively explained based on an Alfvén wave oscillation model. Alfvén wave oscillations at the location of maximum radiation flux in a standard thin accretion disk generate QPOs. The power-law flux is produced via inverse Compton scattering of soft photons from the standard thin disk with hot electron media in the corona or at the base of the jet. Through continuous variation of the accretion rate, analytical and numerical solutions for the relationship between QPO frequency and power-law flux are obtained. The simulated correlation matches observational values within reasonable parameter ranges. The positive correlation between QPO frequency and power-law flux can be understood as follows: stronger magnetic fields lead to higher Alfvén wave frequencies and higher electron temperatures, thereby producing higher power-law flux. The results suggest that type-B QPOs may be associated with activities of the toroidal magnetic field in the accretion disk or jet.

Full Text

Preamble

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An Explanation for the Correlation between Type-B QPO Frequency and the Power-law Flux in Black-hole Binaries

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ABSTRACT

A positive correlation between the frequency of type-B quasi-periodic oscillations (QPOs) and the associated hard power-law flux has been discovered in a few black hole binaries. The correlation is explained quantitatively based on the Alfvén wave oscillation model. The QPO is assumed to be generated by Alfvén wave oscillations in the standard thin Shakura-Sunyaev disk (SSD) at the radius where the radiation flux reaches its maximum. The power-law flux is calculated based on inverse Compton scattering of soft photons from the SSD by a medium of hot electrons in the corona or the base of the jet. Both explicit solutions and numerical results of the correlation between the QPO frequency and the power-law flux with changing accretion rate are obtained. The modeled correlation fits well into the observed one within reasonable parameter range. The positive correlation could be interpreted by the hypothesis that a stronger magnetic field leads to a higher Alfvén wave frequency and a higher electron temperature, and therefore a stronger power-law flux. The results suggest that type-B QPOs may be related to toroidal magnetic activities in the accretion disk or the jet.

Key words: accretion, accretion disks, magnetic fields, black hole physics, stars: black holes, X-rays: binaries
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Introduction

Complex spectral and timing properties have been observed in Black Hole Binaries (BHBs). During an outburst, three stages are classified: the hard state, the soft state, and the steep power-law state [1], or alternatively the intermediate state [2–3]. In the hard state, the spectrum is dominated by a non-thermal power-law component with a typical photon index of 1.7 [1]. In the soft state, the spectrum is commonly described as 1 keV thermal emission and can be well interpreted by the standard thin Shakura-Sunyaev Disk (SSD) model [4]. The spectrum of the intermediate state consists of both strong thermal and non-thermal components with a typical photon index of 2.5, and the luminosity is high. The intermediate state is further divided into the Hard Intermediate State (HIMS) and the Soft Intermediate State (SIMS) by Belloni et al. [3]. The HIMS is spectrally dominated by a hard component and exhibits band-limited noise in the Power Density Spectrum (PDS), while the SIMS is spectrally dominated by a soft component and shows power-law noise in the PDS [3, 5]. These spectral states appear in counterclockwise order in the q-shaped Hardness-Intensity Diagram (HID) following the sequence "hard state → HIMS → SIMS → soft state → SIMS → HIMS → hard state" [1, 3, 5–6].

Strong variabilities and quasi-periodic oscillations (QPOs) are usually observed in the hard and intermediate states. A narrow peak in the PDS is called a QPO if the quality factor Q $>$ 2 (where Q is defined as the ratio of the centroid frequency to the full width at half-maximum of the peak) [7]. Low-frequency QPOs (LFQPOs, 0.1–30 Hz) are common in the hard and intermediate states, while high-frequency QPOs (HFQPOs, >30 Hz) generally appear in the steep power-law state [1, 8] and SIMS [5]. LFQPOs are classified into types A, B, and C according to the characteristics of the PDS and phase lags [9–11]. Type-C QPOs are the most common type of LFQPOs, with Q 8 and centroid frequencies of 0.01–30 Hz, observed in the hard state and HIMS [11–13]. Type-B QPOs are observed in the SIMS with Q 6 and typical centroid frequencies of 6 Hz or 1–3 Hz [8, 14]. Type-A QPOs are characterized by a weak and broad (Q 3) peak with centroid frequencies of 6–8 Hz, which usually appear in the soft state and SIMS just after the transition from the HIMS [13, 15].

The physical mechanisms of QPOs are not well understood, although a variety of models have been proposed. It is believed that HFQPOs are possibly related to the inner region of the accretion disk since their period is comparable to the dynamical timescale of the inner disk [1, 7]. Possible mechanisms for LFQPOs, especially type-C QPOs, include relativistic precession [16], accretion-ejection instability [17], global disk oscillations [18], oscillation of shocks in accretion flows [19], oscillations of the transition layer between the disk and corona [20], and magnetohydrodynamic (MHD) Alfvén wave oscillations in the accretion disk [21], among others. Ingram et al. [22] improved the relativistic precession model for type-C QPOs by considering the Lense-Thirring precession of a radially extended region of the hot inner flow based on the truncated disk model, which successfully explained the frequency range and spectral behavior of type-C QPOs [22–23]. The precession of a small-scale jet is also a possible candidate for the production of LFQPOs, which can naturally explain the high energy, soft lags, and energy dependence for frequency and rms (root mean square) of LFQPOs in MAXI J1820+070 [24].

Type-B and type-A QPOs are poorly understood. Type-B QPOs are usually observed during the transition from the hard to soft state, and their appearance indicates the start of the SIMS [5, 15]. They typically appear when BHBs reach their maximum luminosities [14] and occur almost simultaneously with the “jet line” [6]. Therefore, the interpretation of type-B QPOs is important for understanding the states and state transitions of BHBs. Type-B QPOs have completely different properties from type-C QPOs in many aspects [14, 25–26], and there is growing evidence for a jet origin of type-B QPOs [25–27]. Motta et al. [25] analyzed the LFQPO data of 14 BHBs and found that type-B QPOs are stronger when the accretion disk is closer to face-on, which supports the hypothesis that type-B QPOs are related to the jet. Russell et al. [28] discovered a compact jet in the SIMS contemporaneous with a type-B QPO in the 2002 outburst of 4U 1543-47. Homan et al. [29] found that a discrete jet ejection launched within 2–2.5 hours after the appearance of a type-B QPO in MAXI J1820+070. Kylafis et al. [30] successfully explained the periodic variation of photon index Γ with the type-B QPO frequency in GX 339-4 based on a precessing jet model. The association of type-B QPOs with jets is also evident for H 1743-322 and MAXI J1348-630 [31–33].

A strong correlation between the type-B QPO frequency and the power-law flux (hereafter "the QPO-PL relation") has been discovered for a few BHBs [14, 34], which suggests that type-B QPOs may be related to inverse Compton scattering either from the base of the jet or the corona [14, 25, 34–35]. However, there is a lack of quantitative calculations to interpret this correlation.

In this paper, we attempt to explain the QPO-PL relation quantitatively based on the MHD Alfvén wave oscillation model [21, 36–39], in which the QPO is produced by toroidal Alfvén wave oscillations due to radial perturbations of the accreting matter in the inner region of the accretion disk, and the "soft" photons from the disk are inverse Compton scattered by a medium of hot electrons to generate the power-law flux.

The paper is organized as follows. The description of the model is given in Section 2. The QPO-PL relation is calculated and compared to the observed one in Section 3. Finally, the conclusion is given in Section 4.

2.1 The Power-law Flux

In the relativistic standard thin disk model, the radiation flux per unit disk face area is given by [40], where $r \equiv R/R_g$ ($R_g \equiv GM/c^2$ is the gravitational radius, where c is the speed of light) and BH spin a_* are as defined in Ref. [40]. The flux F is assumed to be radiated as a blackbody with temperature

$$T(r) = \left(\frac{F}{2\sigma}\right)^{1/4}$$

where σ is the Stefan-Boltzmann constant. The radiation intensity is

$$I_{\nu_i} = \frac{2h\nu_i^3}{c^2}\left[\exp\left(\frac{h\nu_i}{kT(r)}\right) - 1\right]^{-1}$$

where h is the Planck constant, k is the Boltzmann constant, and ν_i is the frequency of the emitted disk photons.

We assume the soft photons emitted from the surface of the accretion disk are inverse Compton scattered by hot thermal electrons with temperature T_e in a medium above the disk such as a corona or the base of the jet. If the hot electrons are non-relativistic and the soft photons from the disk satisfy $h\nu_i \lesssim h\nu_s \ll kT_e$ (where ν_s is the maximum frequency of the soft photons), the Comptonized spectrum has a power-law form [41–42]:

$$I_\nu = I_{\nu_s}\left(\frac{\nu}{\nu_s}\right)^{-\Gamma}$$

The typical value of the spectral index in the SIMS associated with type-B QPOs is $\Gamma \sim 1.5$ (corresponding to a photon index of ~ 2.5) [1, 5, 34]. We adopt this value in our calculations.

We take ν_s as the frequency corresponding to the maximum radiation intensity at the hottest part of the disk. By Wien's displacement law, we have

$$h\nu_s \approx 3kT_{\max} = 3k\left(\frac{3GM\dot{M}}{8\pi\sigma R_{\max}^3} f_{\max}(a_*)\right)^{1/4}$$

where G is the gravitational constant, M is the black hole mass, $\dot{M}$ is the disk accretion rate, and f is a function of dimensionless disk radius. That is,

$$\nu_s = 6.55 \times 10^{18} m^{-1/4} \dot{m}^{1/4} f_{\max}^{1/4}(a_*)\ \mathrm{Hz}$$

where $m \equiv M/M_\odot$ ($M_\odot$ is the solar mass), $\dot{m} \equiv \dot{M}/\dot{M}_{\mathrm{Edd}}$ ($\dot{M}_{\mathrm{Edd}} \approx 1.4 \times 10^{18} m$ $\mathrm{g \cdot s^{-1}}$ is the Eddington accretion rate), $T_{\max}$ is the maximum temperature of the disk, and $f_{\max}(a_*)$ is the maximum value of f, which is a function of a_*.

The observed power-law flux is

$$F_{\mathrm{PL}} = \int I_\nu d\nu d\Omega$$

The density ρ can be obtained by solving the relativistic accretion disk equations (5.6.14) and (5.8.1) in Ref. [45] and Eq. (9). Explicit solutions for special cases and typical values of μ are listed below.

(1) **Radiation pressure dominated region** ($P_{\mathrm{tot}} \approx P_{\mathrm{rad}}$, the Rosseland mean opacity $\bar{\kappa} = \bar{\kappa}_{\mathrm{es}} = 0.4\ \mathrm{cm^2 \cdot g^{-1}}$, where $\bar{\kappa}_{\mathrm{es}}$ is the opacity due to scattering from free electrons).

For $\mu = 0$, we have

$$T_c = (5.0 \times 10^7\ \mathrm{K}) \alpha^{-1/4} m^{-1/4} r^{-3/8} A^{-1/2} B^{1/2} E^{1/4}$$

$$\rho = (1.7 \times 10^{-7}\ \mathrm{g \cdot cm^{-3}}) \alpha^{-1} m^{-1} \dot{m}^{-2} r^{3/2} A^{-4} B^6 D E^2 L^{-2}$$

$$B = (6.2 \times 10^8\ \mathrm{Gs}) m^{-1/2} r^{-3/4} A^{-1} B E^{1/2}$$

$$\nu_{\mathrm{QPO}} = (2.9 \times 10^6\ \mathrm{Hz}) \alpha^{1/2} m^{-1} \dot{m} r^{-5/2} A B^{-2} D^{-1/2} E^{-1/2} L$$

where T_c is the central temperature of the disk, and A, B, D, E, and L are relativistic correction factors given in Ref. [45], which are functions of r and a_*.

For $\mu = 0.5$, we have

$$T_c = (3.1 \times 10^8 \text{ K})\alpha^{-2/9}m^{-2/9}\dot{m}^{2/9}r^{-2/3}A^{-2/9}D^{-1/9}E^{1/9}L^{2/9}$$

$$\rho = (2.5 \times 10^{-4} \text{ g} \cdot \text{cm}^{-3})\alpha^{-8/9}m^{-8/9}\dot{m}^{-10/9}r^{1/3}A^{-26/9}B^4D^{5/9}E^{13/9}L^{-10/9}$$

$$B = (6.2 \times 10^8 \text{ Gs})m^{-1/2}r^{-3/4}A^{-1}BE^{1/2}$$

$$\nu_{\text{QPO}} = (7.5 \times 10^4 \text{ Hz})\alpha^{4/9}m^{-19/18}\dot{m}^{5/9}r^{-23/12}A^{4/9}B^{-1}D^{-5/18}E^{-2/9}L^{5/9}$$

For $\mu = 1$, we have

$$T_c = (1.3 \times 10^9 \text{ K})\alpha^{-1/5}m^{-1/5}\dot{m}^{2/5}r^{-9/10}B^{-2/5}D^{-1/5}L^{2/5}$$

$$\rho = (0.09 \text{ g} \cdot \text{cm}^{-3})\alpha^{-4/5}m^{-4/5}\dot{m}^{-2/5}r^{-3/5}A^{-2}B^{12/5}D^{1/5}EL^{-2/5}$$

$$B = (6.2 \times 10^8 \text{ Gs})m^{-1/2}r^{-3/4}A^{-1}BE^{1/2}$$

$$\nu_{\text{QPO}} = (4039 \text{ Hz})\alpha^{2/5}m^{-11/10}\dot{m}^{1/5}r^{-29/20}B^{-1/5}D^{-1/10}L^{1/5}$$

where α is the viscous parameter, $P_{\text{tot}} = P_{\text{gas}} + P_{\text{rad}}$ is the sum of gas pressure P_{gas} and radiation pressure P_{rad}, and $0 \leq \mu \leq 1$ is a free parameter. The magnetic field B and mass density ρ are anti-correlated with μ. The slope of the ν_{QPO}–$\dot{m}$ relation is steeper with smaller μ.

(2) **Gas pressure dominated region** ($P_{\text{tot}} \approx P_{\text{gas}}$, $\bar{\kappa} = \bar{\kappa}_{\text{es}} = 0.4 \text{ cm}^2 \cdot \text{g}^{-1}$). We have (independent of μ)

$$T_c = (1.3 \times 10^9 \text{ K})\alpha^{-1/5}m^{-1/5}\dot{m}^{2/5}r^{-9/10}B^{-2/5}D^{-1/5}L^{2/5}$$

$$\rho = (61 \text{ g} \cdot \text{cm}^{-3})\alpha^{-7/10}m^{-7/10}\dot{m}^{2/5}r^{-33/20}A^{-1}B^{3/5}D^{-1/5}E^{1/2}L^{2/5}$$

$$B = (1.6 \times 10^{10} \text{ Gs})\alpha^{1/20}m^{-9/20}\dot{m}^{2/5}r^{-51/40}A^{-1/2}B^{1/10}D^{-1/5}E^{1/4}L^{2/5}$$

$$\nu_{\rm QPO} = (4039\ {\rm Hz})\alpha^{2/5}m^{-11/10}\dot{m}^{1/5}r^{-29/20}B^{-1/5}D^{-1/10}L^{1/5}$$

We assume that the QPO is produced at the radius $r_{\rm max}$ where the radiation flux reaches its maximum value. We fit the relationship between $r_{\rm max}$ and a_* based on Eq. (1) and obtain $r_{\rm max} \approx 1.59r_{\rm ISCO} - 0.3a_*$. For $a_* = 0.5$, substituting $r_{\rm max}$ into Eqs. (10)–(12), we have

$$\nu_{\rm QPO} = (2373\ {\rm Hz})\alpha^{1/2}m^{-1}\dot{m} \quad (\text{for } \mu = 0)$$

$$\nu_{\rm QPO} = (536\ {\rm Hz})\alpha^{4/9}m^{-19/18}\dot{m}^{5/9} \quad (\text{for } \mu = 0.5)$$

$$\nu_{\rm QPO} = (163\ {\rm Hz})\alpha^{2/5}m^{-11/10}\dot{m}^{1/5} \quad (\text{for } \mu = 1)$$

The numerical results for B, ρ, and $\nu_{\rm QPO}$ at $r_{\rm max}$ as functions of $\dot{m}$ with different parameters (m, a_*, α, and μ) are shown in Fig. 1 [Figure 1: see original paper]. We see that B and $\nu_{\rm QPO}$ are positively correlated with $\dot{m}$, while ρ changes nonmonotonically with $\dot{m}$, first increasing with $\dot{m}$ and then decreasing after reaching a maximum where radiation pressure begins to dominate over gas pressure. B, ρ, and $\nu_{\rm QPO}$ are all anti-correlated with m and positively correlated with a_*. B is insensitive to α and μ. ρ is anti-correlated with α and positively correlated with μ. $\nu_{\rm QPO}$ is positively correlated with α and anti-correlated with μ.

3 The QPO-PL Relation

In order to compare our results to the observed QPO-PL relation in Ref. [34], we adopt the same energy range (3–200 keV) for the power-law flux. Substituting $\nu_1 = 3$ keV$/h$, $\nu_2 = 200$ keV$/h$, $\Gamma = 1.5$, and ν_s from Eq. (6) into Eq. (7), we obtain

$$F_{\rm PL} = 3.13 \times 10^{39} m^{7/8}\dot{m}^{9/8}\frac{\cos i}{d^2}f_{\rm max}^{9/8}(a_*)\int_{r_{\rm ISCO}}^{1000}\left[\exp\left(\frac{h\nu}{kT(r)}\right) - 1\right]^{-1} 2\pi r dr$$

Combining Eqs. (14)–(15), we have the $F_{\rm PL}$–$\nu_{\rm QPO}$ relation for different values of $\dot{m}$ and μ as follows (assuming $a_* = 0.5$, $i = 50^\circ$, and $d = 5$ kpc).

(1) $\dot{m} \gtrsim 0.1$, $\mu = 0$:

$$F_{\rm PL} = 6.5 \times 10^{-12}\alpha^{-9/16}m^2\nu_{\rm QPO}^{9/8}\ {\rm erg \cdot cm^{-2} \cdot s^{-1}}$$

(2) $\dot{m} \gtrsim 0.1$, $\mu = 0.5$:

$$F_{\rm PL} = 1.2 \times 10^{-13} \alpha^{-9/10} m^{241/80} \nu_{\rm QPO}^{81/40} \ {\rm erg \cdot cm^{-2} \cdot s^{-1}}$$

(3) $\dot{m} \gtrsim 0.1$, $\mu = 1$ or $10^{-5} \lesssim \dot{m} \lesssim 0.1$:

$$F_{\rm PL} = 1.5 \times 10^{-20} \alpha^{-9/4} m^{113/16} \nu_{\rm QPO}^{45/8} \ {\rm erg \cdot cm^{-2} \cdot s^{-1}}$$

We can see that the slope of the QPO-PL relation becomes steeper with decreasing accretion rate. Our model predicts $F_{\rm PL} \propto \nu_{\rm QPO}^{45/8}$ at moderate accretion rates.

Numerical results of the modeled QPO-PL relation for different values of m, a_*, α, and μ are shown in Fig. 2 [Figure 2: see original paper]. We find that the influence of a_* and α on the relation is similar. Both larger values of a_* and α cause the curve to move to the right of the graph, while a larger m value causes the curve to move up and left. A larger μ value leads to a steeper correlation when the accretion rate is high. Three curves with different values of μ coincide when the accretion rate is low because $\nu_{\rm QPO}$ is independent of μ when gas pressure dominates, as shown by Eqs. (13)–(14).

In Fig. 3 [Figure 3: see original paper], we compare the modeled correlation with the observed one (Fig. 8 [Figure 8: see original paper] in Ref. [34]). We adjust the values of α and μ to fit the observed relation with fixed $m = 10$, $a_* = 0.5$, $i = 50^\circ$, and $d = 5$ kpc. The modeled QPO-PL relations fit well into the observed three subgroups with $\alpha \sim 0.1$–0.3 and $\mu \sim 0.2$–0.4. A smaller α value and a larger μ value correspond to the upper subgroup.

As shown in Fig. 8 of Ref. [34], the observed QPO frequencies and power-law fluxes for three individual sources—GX 339–4, H1743–322, and XTE J1859+226—are well correlated. We fitted the data of these three sources separately as shown in Fig. 4 [Figure 4: see original paper], adopting the source parameters (BH mass, inclination, and distance) listed in Table 1 of Ref. [34]. For H1743–322, we assume $m = 10$ since its BH mass is unknown and take $a_* = 0.2$ [46]. For GX 339–4, we adopt $i = 50^\circ$ following Ref. [47] and $a_* = 0.94$ [48]. For XTE J1859+226, we take $a_* = 0.5$ since its BH spin is unknown. Approximately the same value $\mu \sim 0.5$ is needed to fit well into the observed correlation of these three sources, as shown in Fig. 4.

The type-B QPO data used in this paper were observed in the rising phase of outbursts as given in Ref. [34]; data from the decay phase are not included. In order to test whether our model is applicable to type-B QPOs in the decay phase, we also compared our modeled QPO-PL relation with the observed one from Ref. [14] that includes data from both the rising and decay phases of GX 339–4. However, the modeled relation does not agree with that observed in the decay phase. In the decay phase, both the observed power-law flux and QPO frequency are low, and the slope of the correlation is gentle and does not become steep at low accretion rates as in our model (Figs. 2 and 3). In the decay phase, the accretion flow may be different, i.e., with different radiative efficiency, or the corona becomes weak.

The association of type-B QPOs with jets is supported by increasingly strong observational evidence [25–33]. We note that toroidal Alfvén wave oscillations could also occur in the jet since the toroidal magnetic field will grow with the rotation of the BH (Blandford-Znajek process [51]) or the disk (Blandford-Payne process [52]). The electrons in the jet may be heated by magnetic energy to produce the power-law flux. Therefore, our model is also applicable to the jet origin of LFQPOs. Further investigations are expected in future work.

4 Conclusion

We explain the QPO-PL relation quantitatively based on the MHD Alfvén wave oscillation model. The type-B QPO is produced by Alfvén wave oscillations in the inner accretion disk. The power-law flux is calculated based on inverse Compton scattering of soft photons from the SSD by a medium of hot electrons. We find that the modeled correlation fits well into the observed one within reasonable parameter range. The results suggest that magnetic fields in the inner region of the accretion disk play a key role in understanding type-B QPOs and the associated power-law flux. The hot electrons could be heated by magnetic reconnection of tangled small-scale magnetic fields in the inner disk [49–50]. More energy is released in magnetic reconnection with a stronger magnetic field, leading to higher electron temperature and stronger power-law flux, which explains the positive correlation between QPO frequency and power-law flux.

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REFERENCES

[1] Remillard R A, McClintock L. ARA&A, 2006, 44: 49
[2] Mendez M, van der Klis M. ApJ, 1997, 479: 926
[3] Belloni T M, Homan J, Casella P, et al. A&A, 2005, 440: 207
[4] Shakura N I, Sunyaev R A. A&A, 1973, 24: 337
[5] Belloni T M. States and Transitions in Black-Hole Binaries//Belloni T M. The Jet Paradigm: from Microquasars to Quasars. Berlin Heidelberg: Springer, 2010: 53–84
[6] Fender R P, Belloni T, Gallo E. MNRAS, 2004, 355: 1105
[7] van der Klis M. ARA&A, 2000, 38: 717
[8] Motta S E. AN, 2016, 337: 398
[9] Wijnands R, Homan J, van der Klis M. ApJ, 1999, 526: L33
[10] Remillard R A, Sobczak G J, Muno M P, et al. ApJ, 2002, 564: 962
[11] Casella P, Belloni T, Stella L. ApJ, 2005, 629: 403

[12] Belloni T M, Stella L. SSRv, 2014, 183: 43
[13] Ingram A R, Motta S E. NewAR, 2019, 85: 101524
[14] Motta S, Muñoz-Darias T, Casella P, et al. MNRAS, 2011, 418: 2292
[15] Belloni T M, Motta S E. Transient Black Hole Binaries//Bambi C. Astrophysics of Black Holes. Berlin Heidelberg: Springer, 2016: 61–97
[16] Stella L, Vietri M. PhRvL, 1999, 82: 17
[17] Tagger R, Donahue J, Darrell T, et al. A&A, 1999, 349: 1003
[18] Titarchuk L, Osherovich V. ApJ, 2000, 542: L114
[19] Chakrabarti S K, Manickam S G. ApJ, 2000, 531, L41
[20] Nobili J, Turolla R, Zampieri L, et al. ApJ, 2000, 548: L25
[21] Wang Z Y, Huang C Y, Wang D X, et al. RAA, 2012, 12: 1
[22] Ingram A, Done C, Fragile P C. MNRAS, 2009, 397: L101
[23] Ingram A, Done C. MNRAS, 2011, 415: 2323
[24] Ma X, Tao L, Zhang S N, et al. NatAs, 2021, 5: 94
[25] Motta S E, Casella P, Henze M, et al. MNRAS, 2015, 447: 2059
[26] Stevens A L, Uttley P. MNRAS, 2016, 460: 2796
[27] Fender R P, Homan J, Belloni T M. MNRAS, 2009, 396: 1370
[28] Russell D M, Casella P, Kalemci E, et al. MNRAS, 2020, 495: 182
[29] Homan J, Bright J, Motta S E, et al. ApJ, 2020, 891: L29
[30] Kylafis N D, Reig P, Papadakis I. A&A, 2020, 640: L16
[31] Harikrishna S, Sriram K. 2022, arXiv: 2209.01643
[32] Zhang L, Altamirano D, Uttley P, et al. MNRAS, 2021, 505: 3823
[33] Liu H X, Huang Y, Bu Q C, et al. ApJ, 2022, 938: 108
[34] Gao H Q, Zhang L, Chen Y, et al. MNRAS, 2017, 466: 2128
[35] Gao H Q, Qu J L, Zhang Z, et al. MNRAS, 2014, 438: 1305
[36] Zhang C. A&A, 2004, 423: 401
[37] Li X D, Zhang C M. ApJ, 2005, 635: L57
[38] Shi C S, Li X D. MNRAS, 2009, 392: 264
[39] Shi C S, Li X D. ApJ, 2010, 714: 1227
[40] Page D N, Thorne K S. ApJ, 1974, 191: 499
[41] Rybicki G B, Lightman A P. AstQ, 1979, 3: 199
[42] Pozdnyakov G B, Sobol I M, Syunyaev R A. ASPRv, 1983, 2: 189
[43] Szuszkiewicz E. MNRAS, 1990, 244: 377
[44] Watarai K Y, Mineshige S. PASJ, 2001, 53: 915
[45] Novikov I D, Thorne K S. Astrophysics of Black Holes//DeWitt C, DeWitt B. Black Holes. New York: Gordon & Breach, 1973: 343–449
[46] Steiner J F, McClintock J E, Reid M J. ApJ, 2012, 745: L7
[47] Tamura M, Kubota A, Yamada S, et al. ApJ, 2012, 753: L32
[48] Miller J M, Reynolds C S, Fabian A C, et al. ApJ, 2009, 697: 900
[49] Di Matteo T. MNRAS, 1998, 299: L15
[50] Liu B F, Mineshige S, Shibata K. ApJ, 2002, 572: L173
[51] Blandford R D, Znajek R L. MNRAS, 1977, 179: 433
[52] Blandford R D, Payne D G. MNRAS, 1982, 199: 883

Note: Figure translations are in progress. See original paper for figures.