Postprint of the W-K Relation in Black Hole Binary Systems Observed by Insight-HXMT

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Abstract

Decades of observational studies have revealed some characteristics of black hole X-ray binaries (XRBs). However, the structure of the accretion disk remains uncertain. The correlation between the cutoff frequency of the power density spectrum of black hole XRBs and quasi-periodic oscillations (QPO), known as the W-K relation, can constrain the accretion disk structure. Using data from five black hole XRBs observed by Insight-HXMT (Hard X-ray Modulation Telescope), we studied the W-K relation for black hole XRBs. The results show that the W-K relation holds in the three detector energy bands observed by Insight-HXMT. Additionally, in MAXI J1535-571, there exists a correlation between the cutoff frequency and the inner radius of the accretion disk, which is consistent with a truncated accretion disk structure. If the observed power density spectrum originates from the propagation of mass accretion rate fluctuations, it can be inferred that the inner radius of the accretion disk is close to the innermost stable circular orbit (ISCO), suggesting that this black hole may be a high-spin system.

Full Text

Preamble

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The W-K Relation in Black Hole X-ray Binaries from Insight-HXMT Observations

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Abstract

Through decades of observational studies, the characteristics of black hole X-ray binaries (XRBs) have been gradually revealed. However, the structure of their accretion disks remains uncertain. The correlation between the break frequency in the power density spectrum of black hole XRBs and their quasi-periodic oscillations (QPOs)—known as the W-K relation—can constrain accretion disk models. Using data from five black hole XRBs observed by Insight-HXMT (Hard X-ray Modulation Telescope), we have investigated this W-K relation. Our results demonstrate that the W-K relation holds across all three detector energy bands of Insight-HXMT. Moreover, for MAXI J1535-571, we find a correlation between the break frequency and the inner radius of the accretion disk, consistent with a truncated disk geometry. If the observed power density spectra originate from propagating mass accretion rate fluctuations, we can infer that the accretion disk inner radius approaches the innermost stable circular orbit, suggesting this black hole may be rapidly spinning.

Key words X-rays: binaries; relativistic processes; accretion disks; radiation mechanisms: general

1 Introduction

X-ray binary (XRB) systems typically consist of a compact object and a companion star. Based on the companion' s mass, they are classified as low-mass X-ray binaries (LMXBs) or high-mass X-ray binaries (HMXBs). According to the nature of the compact object, XRBs can be further divided into black hole X-ray binaries (BHBs), neutron star X-ray binaries, and others. As material from the companion star is accreted by the central compact object, its gravitational potential energy is converted into radiation through physical interactions, with the primary emission occurring in the X-ray band. Roche lobe overflow accretion forms an accretion disk around the central compact object [1]. Most black hole LMXBs are transient sources that remain in quiescence for extended periods (total luminosity $L_X < 10^{31}$ erg s^{-1}), occasionally producing bright outbursts due to thermal instability in the accretion flow.

The evolution of black hole transient outbursts exhibits different spectral states as the luminosity varies [2]. Although the spectral components are complex, the energy spectrum is typically divided into two parts: a thermal component from the accretion disk and a non-thermal component from the hot inner flow (corona). During the initial outburst phase, sources are usually in the low hard state (LHS), dominated by non-thermal emission with a power-law index $\Gamma \sim$ 1–1.7 and a spectral cutoff at 100–200 keV. As the mass accretion rate increases, the thermal component gradually strengthens and the source evolves into the intermediate state (IMS). Based on spectral and timing properties, the IMS can be further subdivided into the hard intermediate state (HIMS) and soft intermediate state (SIMS) [3]. With further luminosity increase, when the thermal component dominates the radiation, the source enters the high soft state (HSS), where Γ generally exceeds 2 and the accretion disk inner radius is believed to be at the innermost stable circular orbit (ISCO) [4]. At outburst decay, the source returns to the LHS or quiescence through the intermediate states [5]. A complete outburst cycle of a black hole LMXB can also be represented on a hardness-intensity diagram (HID), where hardness is defined as the ratio of high-energy to low-energy photon count rates. For typical black hole LMXB outbursts, the evolutionary track on the HID forms a counterclockwise q-shaped pattern. Based on the source' s position on the HID, the outburst can be classified into the four spectral states mentioned above: LHS, HIMS, SIMS, and HSS. This also demonstrates spectral state evolution during outbursts, which theoretical studies suggest results from the inward movement of the disk truncation radius and increasing accretion rate [2].

Black hole X-ray binaries exhibit extensive long-term spectral variability and short-term timing phenomena. Timing studies of black hole transients have revealed that low-frequency quasi-periodic oscillations (LFQPOs) are ubiquitous in black hole LMXBs. QPOs appear as narrow peaks in power density spectra (PDS), with the remaining components referred to as broadband noise. QPOs are classified as low-frequency or high-frequency, with low-frequency QPOs further categorized into types A, B, and C based on their shape in the PDS, root mean square (RMS) amplitude, quality factor, and time lags [6–9]. Type C QPOs are associated with a flat-topped low-frequency noise component (called band-limited noise) and appear in the hard and hard intermediate states. By comparing QPO phenomena in black hole and neutron star LMXBs, researchers believe they may share similar physical origins [6, 10–12]. For other types of QPOs not detailed in this paper, readers may refer to the works of Motta et al. [9], Wijnands et al. [6], Psaltis et al. [10], and Belloni et al. [11].

Extensive studies of LFQPOs in X-ray binaries have led to several models explaining their origin [13–14]. These models generally fall into geometric and physical categories of accretion, with growing observational evidence supporting the relativistic Lense-Thirring (L-T) precession model for type C QPOs [13, 15–16]. The L-T precession model was initially proposed by Stella et al. [17] to explain QPOs in neutron star LMXBs and later applied to black hole XRBs by Ingram et al. [13, 15-16]. In this model, the hot inner flow within the truncated disk undergoes relativistic precession due to the black hole's strong gravitational field and spin, producing the observed low-frequency QPOs.

Timing studies have revealed that the QPO centroid frequency correlates linearly with the broadband noise break frequency in logarithmic coordinates for both black hole and neutron star LMXBs, following the same relationship. This was discovered by Wijnands and van der Klis [6] and is known as the W-K relation. The W-K relation suggests that in all these different types of sources, the band-limited noise is related to instabilities in the inner accretion flow rather than the mass or magnetic field of the compact object. This indicates that accretion flows near black holes and neutron stars may follow similar physical laws, providing a pathway to study the dynamics of accretion onto compact objects.

Since its launch in 2017, the Insight-HXMT (Hard X-ray Modulation Telescope) satellite has successfully conducted extensive observations of black hole transients. This paper utilizes data from five typical black hole transients observed by Insight-HXMT between 2017-2020 to study their timing properties. Insight-HXMT' s broad energy band (1-250 keV) enables investigation of the spectral and timing properties of black hole transients across a wider energy range. Our study extends the W-K relation to energy bands up to 120 keV and places constraints on truncated disk models.

2 Data Processing

Insight-HXMT, China' s first X-ray astronomy telescope launched on June 15, 2017 [18], consists of three collimated telescopes: the High Energy X-ray Telescope (HE) [19], Medium Energy X-ray Telescope (ME) [20], and Low Energy X-ray Telescope (LE) [21]. These instruments feature broad energy coverage, large effective area, and high time resolution, making them well-suited for studying the timing and spectral properties of black holes. The basic parameters of Insight-HXMT are listed in Table 1 .

To investigate the timing properties of black hole binaries, we used observational data from five black hole binaries (MAXI J1535-571, GX 339-4, MAXI J1348-630, MAXI J1631-479, and GRS 1915+105) observed by Insight-HXMT. Based on previous works [22-26] that analyzed these sources and classified their spectral states, we selected only observations from the LHS and HIMS that exhibited clear type C QPOs (Tables 2-4). From left to right, the tables list: Observation ID (ObsID), time (MJD), low-frequency break frequency (ν_b), high-frequency break frequency (ν_h), and QPO frequency (ν_{QPO}). Some observations lack data in certain energy bands. We analyzed all data in Tables 2-4 using the Insight-HXMT Data Analysis Software (HXMTDAS v2.04) with default parameters: (1) pointing offset angle $< 0.04°$; (2) Earth elevation of FOV center position (ELV) $> 10°$; (3) geomagnetic cutoff rigidity (COR) > 8 GV.

For timing analysis of high-energy astrophysical radiation, Fourier analysis methods are typically employed to calculate frequency-domain characteristics such as power density, time lags, and coherence from light curves [11, 27]. Here we used the `powspec` tool to compute power density spectra, generating PDS from 128 s intervals with a time bin of 1/128 s, corresponding to a Nyquist frequency of 64 Hz. We averaged the PDS from all intervals for each observation, subtracted Poisson noise, and applied Miyamoto normalization [28]. Dead time effects are negligible for LE and HE; ME dead time correction follows the method of Huang et al. [22]. To improve the signal-to-noise ratio of the PDS, observations shorter than 640 s were excluded. Additionally, observations with similar QPO frequencies (centroid frequency difference less than the QPO' s full width at half maximum) and close temporal proximity were combined for PDS calculation. Among our selected Insight-HXMT observations, MAXI J1535-571, GX 339-4, MAXI J1348-630, MAXI J1631-479, and GRS 1915+105 yielded 10, 2, 8, 3, and 3 valid observation IDs, respectively (Tables 2–4).

As described in the introduction, the PDS in the LHS and HIMS consists of broadband noise plus QPOs. Following the approach of Wijnands et al. [6], we used XSPEC v12.12.1 [29] to fit the PDS: Lorentzian models for QPOs and their harmonic components, and `bknpow` or `bkn2pow` models for the noise components, thereby obtaining QPO frequencies and broadband noise break frequencies. The fitting range was 0.01–64 Hz. Figure 1 [Figure 1: see original paper] shows two typical examples: the upper panel displays the ME PDS for ObsID P0114535005, where a clear break in the broadband noise is fitted with `bknpow` to obtain ν_b; the lower panel shows the ME PDS for ObsID P0114535005 fitted with `bkn2pow`, yielding two break frequencies ν_b and ν_h. XSPEC' s `error` command provides parameter uncertainties at 90% confidence level, as listed for the break and QPO frequencies in Tables 2–4. For our processed observations, ν_b in the LHS typically ranges from 0.04–0.4 Hz, reaching \$ \$1–2 Hz in the HIMS. The Lorentzian model' s centroid frequency gives the QPO frequency $\nu_{\rm QPO}$. XSPEC also provides the reduced χ^2 value (reflecting fit quality, with values closer to 1 indicating better fits); our fits yield reduced $\chi^2 < 1.5$ (with 186 degrees of freedom), mostly around 1.2, demonstrating good fit quality. We used XSPEC' s `flux` command to estimate the RMS amplitude of the low-frequency noise component in different energy bands from 2–120 keV.

3 Results

Based on the data processing described above, we computed PDS for each source in the three detector energy bands; the fitting results are presented in Tables 2–4. Figure 2 [Figure 2: see original paper] combines the break frequency versus QPO frequency relation (ν_b vs. $\nu_{\rm QPO}$) for all five sources (MAXI J1535-571, GX 339-4, MAXI J1348-630, MAXI J1631-479, and GRS 1915+105) across different energy bands. For comparison, Figure 2 also includes black hole data from Wijnands et al. [6]. The Insight-HXMT data points from all three energy bands are distributed around the fitted line, validating the W-K relation, though with increased scatter. Notably, HE data points show a downward deviation from the Wijnands et al. [6] data.

The W-K relation reveals a power-law correlation between ν_b and $\nu_{\rm QPO}$. For our observational data, we fitted the W-K relation in different energy bands using $\nu_{\rm QPO} = n\nu_b^k$ (where n and k are parameters). Accounting for uncertainties in both break and QPO frequencies, the fitted parameters are: LE: $n = 3.72 \pm 0.19$, $k = 0.69 \pm 0.07$; ME: $n = 5.61 \pm 0.50$, $k = 0.95 \pm 0.15$; HE: $n = 6.08 \pm 0.60$, $k = 0.94 \pm 0.12$; and for historical data from Wijnands et al. [6]: $n = 5.33 \pm 0.17$, $k = 0.88 \pm 0.07$.

These fits are also shown in Figure 2 [Figure 2: see original paper]. Qualitatively, the Insight-HXMT observations are consistent with the original W-K relation. Quantitatively, the increased scatter and differences in fitted parameters may relate to the signal-to-noise ratio of the observational data—for example, due to shorter exposure times for Insight-HXMT' s three detectors and smaller effective areas at low and medium energies compared to detectors used by Wijnands et al. [6] (such as RXTE, Rossi X-ray Timing Explorer). Another possibility is that different components cannot be clearly distinguished in Insight-HXMT PDS; for instance, the noise components in MAXI J1820+070 during the LHS require multiple components for adequate modeling [30–31]. Additionally, the relation between QPO frequency and break frequency may exhibit intrinsic scatter, as seen in the increased dispersion for atoll sources and complete deviation for Z sources in the W-K relation [6, 32–33]. Therefore, more sources and higher-quality observational data are needed to verify the universality of the W-K relation.

To illustrate the energy dependence of break frequencies, Figure 3 [Figure 3: see original paper] shows how the high-frequency break (ν_h) and low-frequency break (ν_b) of the broadband noise in MAXI J1535-571 vary with energy. The results indicate that ν_b shows no significant energy dependence, which differs somewhat from findings in MAXI J1820+070 and may be related to the signal-to-noise ratio of the observations. In contrast, ν_h shows an increasing trend with energy above 20 keV. It should be noted that the energy ranges of Insight-HXMT' s detectors overlap. In these overlapping bands, different detectors yield results with varying signal-to-noise ratios due to differences in effective area and background levels; in our analysis here and below, we retain only the high signal-to-noise ratio results.

To demonstrate how rapid variability amplitude changes with energy, Figure 4 [Figure 4: see original paper] presents the RMS spectrum of the low-frequency noise component below ν_b for the typical source MAXI J1535-571. The broadband noise RMS remains nearly constant at low energies but shows a decreasing trend at high energies, consistent with typical black hole LMXBs [34].

4 Discussion

This paper utilizes Insight-HXMT observations of five black hole transients to study their timing properties and the constraints they place on physical models of the accretion process.

4.1 The W-K Relation and Its Energy Dependence

Overall, the five black hole sources in our study follow the traditional W-K relation, albeit with slightly increased scatter. The W-K relation shows minor variations across different energy bands, primarily due to shifts in break frequencies, which warrant further investigation with new observational data.

During the RXTE era, researchers found that different types of X-ray binary transients, despite having different X-ray energy spectra, exhibited similar PDS shapes, with broadband noise break frequencies and QPO frequencies following similar patterns. However, RXTE could only study rapid timing properties in a narrow energy band (3-30 keV). Recent studies have shown that different components in the PDS are energy-dependent. Kawamura et al. [30] used NICER (Neutron Star Interior Composition Explorer) to study the energy dependence of noise in MAXI J1820+070, finding that break frequencies increase with energy in the 0.5-10 keV range. Yang et al. [31] used Insight-HXMT' s broad energy coverage to study the PDS of MAXI J1820+070, also finding that break frequencies are photon-energy dependent and increase with energy. Our study of five black hole sources indicates that although the scatter is large and break frequencies show some increase with energy in each detector, the linear relationship remains approximately constant across energy bands and consistent with Wijnands et al. [6]. This suggests that, at our observational signal-to-noise level and detector precision, the energy dependence of break frequencies does not significantly alter the W-K relation.

The consistency of different types of compact object XRBs with the same W-K relation indicates that these systems have similar accretion disk components and that their non-periodic rapid variability may share a common physical mechanism. Studies of broadband noise and QPO amplitudes have found RMS values up to 50% in the LHS, suggesting the noise cannot originate from a standard thin accretion disk [35], with time lag properties also supporting this conclusion [33]. These rapid variability phenomena likely arise in the non-thermal emitting inner accretion flow (corona). Various models have been developed for noise generation mechanisms [36], with the currently dominant model being the propagating mass accretion rate fluctuations model. In this model, mass accretion rate variations are transmitted by viscous changes, with perturbations far from the black hole modulating the more stable accretion rate near the black hole. The superposition of perturbations at different radii in the inner flow thus forms the observed PDS. In this framework, the two break frequencies correspond to different characteristic radii in the accretion flow: the low-frequency break ν_b relates to the outer radius of the hot inner flow $r_{\rm out}$ (i.e., the inner radius of the accretion disk), while the high-frequency break ν_h corresponds to the inner radius of the corona $r_{\rm in}$, with noise components above ν_h dropping rapidly in amplitude (as shown in Figure 1).

Both breaks may correspond to the same viscous frequency formula in the corona [37-38]. Our studies of different XRBs show that the coronal distribution varies, with the corona' s outer radius decreasing as the spectral fitting temperature increases, consistent with the understanding that plasma corona temperature decreases with radius. Our results also indicate that the corona' s inner radius $r_{\rm in}$ remains stable during evolution, suggesting $r_{\rm in}$ may be close to the innermost stable circular orbit ($R_{\rm ISCO}$) [39].

In this model, as the black hole accretion rate increases, the hot inner flow cools and contracts, causing ν_b to increase along with $\nu_{\rm QPO}$, producing the observed W-K relation. The mechanisms by which ν_b and $\nu_{\rm QPO}$ vary with $r_{\rm out}$ can both be expressed analytically, as discussed below.

4.2 Accretion Disk Geometry

In the propagating perturbation model, short-timescale variability originates from the hot inner flow (corona) within the disk, while the accretion disk itself has a relatively larger accretion radius. During transient outburst evolution, as the accretion rate and flux increase, the disk inner radius decreases; in the HSS, the accretion disk reaches $R_{\rm ISCO}$. However, spectral analysis results [40-42] suggest that in the LHS, the accretion disk may be non-truncated—already at $R_{\rm ISCO}$—inconsistent with the standard truncated disk model. This implies there may be two classes of black hole transients with different disk structures, or that current telescope observations lack the precision to distinguish between theoretical models, leading to degeneracies between different spectral models and consequently different inferred disk structures [41]. Combining X-ray timing and spectral properties has become a pathway for further investigating disk structure [30, 43–44]. To this end, we selected the data-rich black hole transient MAXI J1535-571 to study its disk structure and evolution through both timing and spectral analysis.

Kong et al. [26] and Huang et al. [22] have already performed spectral analysis of this source; we directly adopt their spectral parameters to calculate the accretion disk inner radius. Assuming stable connection between the accretion disk and hot inner flow, then in the accretion rate perturbation model, ν_b should be inversely correlated with the hot inner flow' s outer radius $r_{\rm out}$, which is also the disk inner radius. Figure 5 [Figure 5: see original paper] shows the correlation between $r_{\rm out}$ and ν_b for MAXI J1535-571 [35]. Statistically, the figure indeed shows an inverse correlation between truncation radius and break frequency (with different colors representing ν_b from different detectors), supporting the truncated disk evolution model for black hole transients—i.e., the physical picture where the disk inner radius shrinks as the black hole accretion rate increases. We also note that different ν_b values can correspond to very similar $r_{\rm out}$ values, suggesting that spectral analysis may not sensitively reflect evolution of the disk inner radius, though the overall evolutionary trend remains clear.

4.3 Calculation of Inner Radius and the L-T Precession Model

The hot inner flow moves toward the black hole on the viscous timescale under the influence of viscosity. The viscous frequency associated with this timescale is expressed as [37–38]:

$$\nu_{\rm visc} = \alpha \frac{h}{r} \nu_k(r)$$

where $\nu_{\rm visc}$ is the viscous frequency at any radius in the hot inner flow, α is the viscosity parameter, h is the semi-thickness (scale height) of the hot inner flow, r is the radius, and ν_k is the Keplerian frequency. The low-frequency break ν_b represents the viscous frequency at the truncation radius, i.e., $r_{\rm out}$. Since both

$(h/r)^2$ and ν_k are power-law functions of radius, when calculating the correlation between viscous frequency and radius at different locations within the flow at the same time, Equation (1) can be simplified to $r = B\nu_{\rm visc}^{\beta}$, where B and β are parameters of this power-law relation. Simulations of magnetorotational instability in accretion flows show [35] that both α and h in the hot inner flow are functions of $r_{\rm out}$. We assume that viscosity-related parameters of the inner flow remain approximately constant over short periods when $r_{\rm out}$ is similar—i.e., they follow the same Equation (1). We grouped exposure IDs with similar $r_{\rm out}$ and QPO frequencies that were temporally continuous, then fitted the data in Figure 5 using Equation (1). Since ν_b variations across different energy bands in MAXI J1535-571 are relatively small compared to other black holes, and because our truncation radii are derived from full-band spectral fitting with Insight-HXMT, we jointly fitted data from all three detectors to improve signal-to-noise ratio, excluding the three rightmost observation IDs where the truncated disk may have reached the ISCO and no high-frequency break was detected. Fitting the data points in Figure 5 with uncertainties in both X and Y axes yields parameters $B = 289 \pm 88$ and $\beta = 1.07 \pm 0.32$. Using this fitted relation and the high-frequency break ν_h from the three detectors, we can calculate the corona's inner characteristic radius $r_{\rm in}$, as shown in Figure 6 [Figure 6: see original paper].

As the results show, the inner radius of the inner accretion flow varies little (Figure 6). We therefore averaged the inner radius values calculated from the three detectors, obtaining $r_{\rm in} = 26.7$ km. Adopting a black hole mass of 10 solar masses ($M_\odot$) from previous work, this gives $r_{\rm in} \approx 0.89 R_g$, where R_g is the gravitational radius. In standard accretion disk theory, the inner accretion flow cannot stably exist inside $R_{\rm ISCO}$ and plunges into the black hole; the high-frequency break is also believed to originate near the ISCO. For an extreme Kerr black hole, $R_{\rm ISCO} \approx R_g$. Our result of $r_{\rm in} \approx R_{\rm ISCO} \approx R_g$ is consistent with the hot inner flow model and a black hole spin of $a = 0.993$, indicating that our derived $r_{\rm in}$ is physically reasonable.

Using the simplified formula above, we can infer that the inner radius of the inner flow remains nearly constant. Based on the calculated $r_{\rm in}$ and other black hole physical parameters, we can compute both break frequencies and QPO frequencies. In the L-T precession model [35], the QPO frequency is given by:

$$\nu_{\rm QPO} = \frac{5-2\xi}{2\pi(1+2\xi)} a \left[1 - \left(\frac{r_{\rm in}}{r_{\rm out}}\right)^{1/2+\xi}\right] \left[1 - \left(\frac{r_{\rm in}}{r_{\rm out}}\right)^{5/2-\xi}\right]^{-1} \frac{c^3}{GM}$$

where a is the black hole spin parameter, the surface density distribution of the hot inner flow follows a power law with index ξ, and $r_{\rm in}$ and $r_{\rm out}$ are the inner and outer radii of the hot inner flow, respectively. Following Ingram et al. [35], we assume a constant surface density for the black hole' s hot inner flow ($\xi = 0$). With the hot inner flow' s inner radius $r_{\rm in}$ fixed at 26.7 km, the QPO frequency $\nu_{\rm QPO}$ can be calculated as a function of $r_{\rm out}$, as can the break frequency, allowing us to plot the theoretical W-K relation. The result is shown in Figure 7 [Figure 7: see original paper], where the line represents theoretical values and data points show actual observations. The points in the upper right were not included in the Figure 5 fit, so the theoretical curve deviates from them. Differences between other data points and theoretical values, aside from the coarse nature of our observational analysis, also stem from the oversimplified parameter assumptions in the formula [35]. However, the trend suggests that the truncated disk evolution model can qualitatively explain QPO generation and the W-K relation.

5 Conclusion

This paper utilizes Insight-HXMT observations of five black hole candidates to study the W-K relation and its energy dependence in the 2–120 keV energy band. Within the three detector energy bands of Insight-HXMT, the low-frequency break ν_b shows no significant energy dependence, consistent with Insight-HXMT and NICER observations of MAXI J1820+070. The W-K relation derived from Insight-HXMT data agrees with the results of Wijnands et al. [6] in the 3-20 keV band. To investigate accretion disk structure, we applied the W-K relation to the transient MAXI J1535-571 using results from spectral analysis, finding that this system is consistent with a truncated accretion disk model. We examined the relationship between QPOs and disk structure, finding that QPO frequencies are consistent with the relativistic precession model of the hot inner flow. Further exploration of X-ray binary accretion disk structure requires larger observational samples.

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