Postprint: Study of Outburst Evolution in Black Hole X-ray Binaries with the Insight-HXMT Satellite

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Abstract

Thanks to the wide energy band (1–250 keV) and large effective area of the Insight Hard X-ray Modulation Telescope (Insight-HXMT) satellite, it has achieved a series of important scientific results during its on-orbit operation. Insight-HXMT has monitored the outburst evolution of a sample of black hole X-ray binaries, providing important observational data for studying the accretion properties during outbursts of black hole X-ray binaries. The outbursts of these black hole transient sources include not only typical complete outbursts that have experienced the hard state, intermediate state, and soft state, but also "failed state transition outbursts" that have only evolved to the hard state or intermediate state. The wide-band data of Insight-HXMT not only provides an important opportunity for in-depth understanding of the properties of accretion disks, coronae, and jets in black hole X-ray binaries, but also provides important observational evidence for studying the outburst mechanisms of sources and the physics of accretion radiation. Using Insight-HXMT data, this paper presents with emphasis the evolution and properties of black hole X-ray binary outbursts.

Full Text

Preamble

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Study of Outburst Evolution in Black Hole X-ray Binaries with Insight-HXMT*

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Abstract

Thanks to its broadband coverage (1–250 keV) and large effective area, the Insight-HXMT (Insight Hard X-ray Modulation Telescope) satellite has achieved a series of important scientific results during its on-orbit operation. Insight-HXMT has monitored the outburst evolution of a sample of black hole X-ray binaries, providing crucial observational data for studying their accretion properties during outbursts. These outbursts from black hole transients include not only typical full outbursts that evolve through hard, intermediate, and soft states, but also "failed state transition outbursts" that only reach the hard or intermediate states. The broadband data from Insight-HXMT not only offer an important opportunity to deepen our understanding of the accretion disc, corona, and jet properties in black hole X-ray binaries, but also provide key observational evidence for investigating outburst mechanisms and accretion radiation physics. Using Insight-HXMT data, this review focuses on the evolution and properties of black hole X-ray binary outbursts.

Keywords accretion, accretion disks, X-rays, binaries, stars: black holes

1 Introduction

Black hole X-ray binaries consist of a black hole and a companion star. When material from the companion is accreted by the black hole, a large amount of gravitational potential energy is released, producing strong X-ray radiation, sometimes accompanied by disc winds and relativistic jets. This enables us to directly study the complex accretion radiation physics processes in regions close to the black hole, including the dynamics of black hole accretion discs and jet formation mechanisms. However, due to current observational limitations, direct imaging of black hole X-ray binaries is not possible, and we must rely primarily on spectral and timing characteristics to understand the geometry and properties of the accretion flow.

Spectral analysis shows that X-ray radiation is mainly composed of emission from the accretion disc [**?**], a high-energy corona formed through Comptonization by hot electrons (with radiation extending up to 100 keV [**?**]), and a reflection component (including the iron line at 6.4–7 keV and the Compton hump at 20–30 keV) [**?**]. In terms of timing properties, variations on different timescales are observed, with one important phenomenon being quasi-periodic oscillations (QPOs) [**?**, **?**].

The Insight-HXMT satellite is China's first space X-ray astronomy satellite, and its successful launch and operation mark an important milestone for China in the field of space astronomy [?]. With an energy range of 1–250 keV, HXMT offers advantages of broadband coverage, a large field of view, and a large effective area, and it does not suffer from pile-up effects when observing bright sources. These features give it unique capabilities for studying short-timescale variability and broadband spectral properties of high-energy objects such as black holes and neutron stars. During its nearly seven years of on-orbit operation, HXMT has achieved a series of important scientific results [?, ?, ?]. Its high-cadence observations and broadband coverage from 1–250 keV provide unique advantages for detecting and studying transient outbursts, such as those from black hole X-ray binaries, offering valuable data support for revealing the radiation mechanisms of black hole X-ray binary systems and providing crucial experimental evidence for the establishment and verification of theoretical models.

This review systematically examines the properties of outburst evolution in black hole X-ray binaries and summarizes the important scientific results from the HXMT satellite in this area.

2 Outburst Evolution Process of Black Hole X-ray Binaries

Most black hole X-ray binaries are transients, meaning that after remaining in quiescence for months or even decades, their accretion rate suddenly increases, producing X-ray outbursts that last for weeks to months. Based on their X-ray properties, these "typical outbursts" from black hole transients can be divided into different spectral states, with their outburst tracks showing a counterclockwise "q" -shape in the hardness-intensity diagram (HID) [?, ?, ?].

At the beginning of an outburst, the source enters the (low) hard state ((L)HS) from quiescence, with the spectrum dominated by a non-thermal component having a power-law index typically between 1.5–2.1 [?, ?]. In the hard state, the accretion disc is generally considered to be truncated, with a truncation radius of tens to hundreds of gravitational radii [?, ?, ?]. However, some studies have shown that broad iron lines detected in the hard state [?] imply that the accretion disc remains at or near the innermost stable circular orbit [?]. The power density spectrum shows prominent QPOs, typically type-C QPOs and strong broadband noise features [?]. A persistent, compact jet is also generally present in the hard state [?]. As the source brightness increases, the inner radius of the accretion disc decreases [?] and the disc temperature increases, with thermal disc emission becoming comparable to non-thermal coronal emission [?], indicating that the source has entered the intermediate state (IMS) [?, ?].

The intermediate state can be further divided into the hard intermediate state (HIMS) and soft intermediate state (SIMS), with the SIMS having a softer spectrum than the HIMS. The strong broadband noise and type-C QPOs characteristic of the hard state and HIMS are replaced by relatively weaker broadband noise and type-B QPOs [?]. In the intermediate state, the compact jet is typically suppressed, while highly relativistic intermittent jets appear [?]. When the source enters the (high) soft state ((H)SS), the spectrum is dominated by thermal emission from the accretion disc, with the non-thermal component' s power-law index increasing to typically greater than 2.1 [?]. Sometimes weak type-A QPOs and power-law noise are observed in the soft state [?]. In this state, jets are generally undetectable, and the accretion disc inner radius is believed to reach the innermost stable circular orbit. As the outburst evolves, the source' s radiation flux decreases, and it returns from the intermediate state to the hard state and eventually to quiescence, completing a full typical outburst.

Studying these typical outbursts from black hole transients helps us understand the accretion processes and underlying physics of black hole X-ray binaries. However, some outbursts from black hole transients never reach the soft state, with their spectra remaining dominated by a power-law component. These are called "failed state transition outbursts" [?, ?, ?, ?]. Figure 1 [Figure 1: see original paper] shows the HID tracks for different types of outbursts. Failed state transition outbursts are not rare, accounting for about 38% of all outbursts [?]. The cause of failed state transition outbursts may be that the accretion rate is too low, below 0.1 times the Eddington luminosity, preventing the accretion disc inner radius from reaching the innermost stable circular orbit and the corona from cooling and collapsing [?, ?]. Another type of "failed outburst" may lack a clear initial hard state, or the initial hard state may be too weak or too brief to be detected above the sensitivity threshold of current satellites. This latter "failed outburst" phenomenon is quite rare, having been observed in only a handful of sources to date. Therefore, this review will not discuss this type of "failed outburst" in depth; interested readers can consult references [?, ?, ?] for more details. Thanks to HXMT' s broadband coverage and high-cadence monitoring capabilities, its data play an important role in studying the outburst processes of black hole X-ray binaries, including both "classic outbursts" and different types of "failed outbursts," not only expanding the outburst sample of black hole X-ray binaries but also providing important references for understanding the evolution of accretion geometry and radiation mechanisms in black hole transients.

3 Observational Cases of Outburst Evolution in Black Hole X-ray Binaries with Insight-HXMT

Since its launch in 2017, the Insight-HXMT satellite has accumulated a wealth of valuable observational data during its seven years of stable operation, leveraging its advantages of broadband coverage (1–250 keV) and large effective area. The total observation time for black hole X-ray binaries (such as MAXI J1820+070, MAXI J1348-630, and Swift J1727.8-1613) has exceeded 24 Ms. These data provide crucial support for spectral and timing analysis, particularly opening new research opportunities for understanding the properties of accretion discs, coronae, and jets in black hole X-ray binaries, while offering important evidence for investigating outburst mechanisms and accretion radiation physics.

This section presents several typical cases, especially bright sources with complete outburst observations, to systematically describe the important scientific results achieved by Insight-HXMT in studying the outburst evolution of black hole X-ray binaries.

3.1 The 2018 Outburst of MAXI J1820+070

MAXI J1820+070 is a new black hole X-ray binary discovered by MAXI (Monitor of All-sky X-ray Image) in March 2018. HXMT conducted continuous broadband (1–250 keV) monitoring throughout its entire outburst, yielding a series of important scientific results. For example, You et al. [?] performed spectral analysis using HXMT data to study the dynamic evolution of the corona and accretion disc during the hard state. The authors proposed that as the corona contracts toward the black hole, its outflow velocity also increases. The dynamic evolution of the disc-corona geometry is shown in Figure 2 [Figure 2: see original paper]. This result is significant for understanding the physical properties of coronae and jet formation mechanisms in black hole X-ray binaries. Additionally, Ma et al. [?] detected QPOs up to 200 keV throughout the outburst, providing key observational evidence for jet physics.

Furthermore, Peng et al. [?] conducted a detailed analysis of MAXI J1820+070 based on HXMT data, revealing the time lag phenomenon between soft and hard X-ray photons during three phases of the outburst. The results show that during the first two phases, low-energy (below 140 keV) photons lag behind high-energy (140–170 keV) photons, while during the decay phase, the opposite occurs, with high-energy photons lagging behind low-energy photons. These lag timescales are on the order of several days. After accounting for the time differences between photons of different energies, the typical "q" -shape in the hardness-intensity diagram can be corrected to a linear relationship. Based on timing analysis results, the authors further discussed the possible evolution of the corona: from a radial corona covering the accretion disc at the beginning of the outburst, gradually evolving into a vertically contracted, jet-like corona, and during the decay phase, the corona first expands vertically before eventually covering the accretion disc again. This work provides new insights into understanding the evolution of disc-corona structures in black hole X-ray binary systems.

You et al. [?] also investigated the formation mechanism of magnetically arrested disks (MADs) in X-ray binary outbursts by combining HXMT X-ray data with optical observations from AAVSO (American Association of Variable Star Observers) and radio data from AMI-LA (Arcminute Microkelvin Imager-Large Arrays). The results show that radio and optical fluxes lag behind X-ray flux by approximately 8 days and 17 days, respectively. The authors suggest that this delay may be due to magnetic field amplification in the accretion disc by an extended corona during the X-ray outburst, leading to the formation of a magnetically arrested disk. Additionally, they propose that thermal-viscous instabilities in the outer disc may be the key factor causing the optical band delay.

This study not only reveals the connection between accretion disc magnetic field evolution and multi-wavelength radiation but also provides important observational evidence for understanding the formation and dynamics of large-scale magnetic fields in black hole accretion discs.

3.2 The 2019 Outburst of MAXI J1348-630

Zhang et al. [?] conducted an in-depth analysis of the spectral properties of the black hole X-ray binary MAXI J1348-630 during its 2019 outburst, based on data from HXMT and the X-ray Telescope (XRT) onboard Swift. The source evolved from the hard state through intermediate and soft states and back to intermediate and hard states, completing a full outburst that followed the classic outburst track of black hole transients, showing a "q" -shape in the HID. Throughout the outburst, the source' s spectrum could be well fitted with a multi-temperature disc and a power-law model. In the soft intermediate state and soft state, the disc luminosity and color temperature followed the standard relationship, indicating that the inner disc radius was stable (reaching the innermost stable circular orbit). However, during other phases of the outburst, MAXI J1348-630 exhibited unusual behavior inconsistent with typical black hole transient evolution: in the initial hard state, the accretion disc' s inner radius was smaller and its color temperature higher than during the soft state (the evolution of disc-corona parameters is shown in Figure 3 [Figure 3: see original paper]). This peculiar behavior of the accretion disc can be partially explained by self-consistent Comptonization models, such as the model. This model considers inverse Compton scattering of photons from the accretion disc by a high-energy corona. However, even after accounting for coronal scattering effects, this unusual behavior persists. To explain the anomalous trend of increasing inner radius and decreasing color temperature, the authors propose that the hardening factor in the early outburst is greater than the typical value (approximately 1.7). Further analysis shows that this evolutionary trend between disc inner radius and temperature indeed requires variation of the hardening factor, evolving from approximately 3.5 in the hard state to approximately 1.7 in the hard intermediate state. The authors suggest that the evolution of the hardening factor reveals a real and possibly rare accretion disc evolution process: at the beginning of the outburst, the inner disc is in a process of condensation from an optically thin medium and has not yet reached a sufficiently high optical depth, so its spectrum cannot be modeled with a standard optically thick disc. As the outburst evolves and the source transitions from the hard state to the hard intermediate state, the accretion disc density continues to increase and reaches equilibrium. These findings are important for understanding the outburst evolution and accretion disc dynamics in black hole X-ray binaries.

Weng et al. [?] revealed through detailed timing analysis of the 2019 outburst of MAXI J1348-630 that radiation time lags between the accretion disc and corona produce hysteresis effects and X-ray delays. The authors presented a physical picture of the entire outburst process, where hard X-ray bursts from the corona almost immediately cause optical brightening of the outer disc, after which accretion enhancement and inward propagation in the outer disc lead to delayed soft X-ray bursts on viscous timescales (approximately 8-12 days). This disc-corona model is crucial for understanding energy transfer and interaction mechanisms between the accretion disc and corona. By correcting for this time delay, the authors reinterpreted the hardness-intensity diagram, showing a linear correlation between thermal disc flux and non-thermal power-law flux, in stark contrast to the previous non-linear "q"-shaped track. Furthermore, the authors discussed how this time delay mechanism may be universally applicable to other black hole X-ray binary systems. These results not only challenge previous views that accretion flow and radiation properties are uniquely determined by mass accretion rate but also provide new perspectives for future observations and theoretical models.

3.3 The 2021 Outburst of 4U 1543-47

After 21 years in quiescence, the black hole X-ray binary 4U 1543-47 underwent a new outburst in 2021, reaching a peak flux of 8 Crab. Thanks to HXMT's immunity to detector pile-up effects at high fluxes, the outburst was observed with high cadence. Zhao et al. [?] conducted a comprehensive study of the accretion dynamics and geometric structure during this outburst using data from HXMT, NuSTAR (Nuclear Spectroscopic Telescope Array), and Swift. The best-fit and residual analysis for HXMT low-energy (black) and medium-energy (red) data are shown in Figure 5 [Figure 5: see original paper]. Through spectral analysis, the authors found significant reflection components when the source was in the soft state, as shown by the purple line in Figure 5. They proposed that this reflection may arise from photons in the inner disc region being bent by strong gravitational fields and re-illuminating the disc surface, producing a self-irradiation effect. Notably, the best-fit parameters indicate that this reflection component contributes more than 50% of the total flux. The authors further employed general relativistic ray-tracing simulations and found that when the accretion rate approaches or exceeds the Eddington limit, the accretion disc develops a geometrically thick, funnel-like structure that successfully reproduces the observed results. For 4U 1543-47, particularly when the disc surface inclination exceeds 45° relative to the equatorial plane, the observed self-irradiation intensity can be reasonably explained. This study not only reveals the geometric structure evolution of accretion discs at high accretion rates but also provides new observational evidence and theoretical insights for understanding radiation processes in strong gravitational field environments.

3.4 The 2023 Outburst of Swift J1727.8-1613

Swift J1727.8-1613 is a new X-ray transient first detected by the Swift satellite in August 2023, with subsequent multi-wavelength observations confirming it as a black hole X-ray binary. During this outburst, the source reached a peak brightness of 7 Crab, and HXMT conducted high-cadence monitoring. Liu et al. [?]

and Peng et al. [?] performed detailed analyses of the source' s X-ray spectral properties using quasi-simultaneous observations from HXMT, NuSTAR, and NICER (Neutron star Interior Composition Explorer). Spectral fitting results show that, unlike typical black hole X-ray binary spectra, this source exhibits a significant additional hard component. Based on this finding, Peng et al. [?] estimated the source' s spin parameter and measured the accretion disc inclination to be approximately 40° after accounting for this component. Peng et al. [?] proposed that this additional hard component may be related to relativistic jets or the jet base/corona beneath slower jets, offering new perspectives for understanding the high-energy radiation mechanism of this source.

3.5 The 2018 Failed Transition Outburst of H 1743-322

In addition to complete outbursts from black hole X-ray binaries, there are failed transition outbursts that only evolve to the hard or intermediate state. Wang et al. [?] studied the 2018 failed transition outburst of the black hole transient H 1743-322 using observations from HXMT, NICER, and NuSTAR, covering a broad X-ray band from 1 to 120 keV. Through analysis of the source's spectral and timing properties throughout the outburst, the authors found that although the source showed slight spectral softening at peak flux, it remained in the hard state throughout the entire outburst, meaning H 1743-322' s 2018 outburst was a failed transition outburst that did not enter the soft state, as shown in the HID in Figure 6 [Figure 6: see original paper]. The authors also focused on the evolution of type-C QPO properties, finding that the QPO centroid frequency increased from approximately 0.1 Hz to about 0.4 Hz during the outburst rise and decreased during the decay. Additionally, they found a positive correlation between X-ray flux, photon index, QPO frequency, and QPO rms amplitude. The QPO amplitude in the soft X-ray band (12%-16%) was slightly higher than in the hard X-ray band (8%-10%). Through comparative analysis of spectral and timing properties between failed transition outbursts and successful outbursts, the authors found that although this failed transition outburst did not reach the accretion rate threshold for transitioning to the soft state, both types of outbursts follow the same initial evolutionary track. This work enriches the outburst sample of black hole transients and is important for further understanding their outburst mechanisms.

4 Summary and Outlook

Black hole X-ray binary systems are important research objects in high-energy astrophysics, and their complex outburst evolution processes have long been a focus of astronomers. By studying the outburst evolution of these transient systems, we can gain deep insights into the accretion geometry, its evolution, and the physical laws of accretion radiation. The operation of the Insight-HXMT satellite has provided valuable observational data for this field, particularly through its broadband X-ray monitoring capabilities and high-cadence observations, enabling more in-depth studies of short-timescale variability and spectral properties of black hole X-ray binaries. From typical full outbursts to "failed transition outbursts," HXMT data have played an important role in studying outburst mechanisms, constructing accretion radiation models, and constraining fundamental source properties. Furthermore, with the upcoming launch of China' s next-generation space science mission—the enhanced X-ray Timing and Polarimetry mission (eXTP)—we anticipate revealing more secrets about black hole X-ray binary systems and advancing the field of high-energy astrophysics.

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References

2001, 132: 377 Homan J, Belloni T. Ap&SS, 2005, 300: 107 Remillard R A, McClintock J E. 2006, ARA&A, 44: 49 McClintock J E, Haswell C A, Garcia M R, et al. ApJ, 2001, 555: 477 Done C, Gierliński M, Kubota A. A&ARv, 2007, 15: 1 Done C, Diaz Trigo M. MNRAS, 2010, 407: 2287 Miller J M, Homan J, Steeghs D, et al. ApJ, 2006, 653:

Esin A A, McClintock J E, Narayan R. ApJ, 1997, 489:

Remillard R A, Sobczak G J, Muno M P, et al. ApJ, 2002, 564: 962 Fender R P. MNRAS, 2001, 322: 31 Gierliński M, Done C, Page K. MNRAS, 2008, 388: 753 Cúneo V A, Alabarta K, Zhang L, et al. MNRAS, 2020, 496: 1001 Casella P, Belloni T, Stella L. ApJ, 2005, 629: 403 Fender R P, Belloni T M, Gallo E. MNRAS, 2004, 355:

Motta S E. AN, 2016, 337: 398 Brocksopp C, Bandyopadhyay R M, Fender R P.

NewA, 2004, 9: 249 Tetarenko B E, Sivakoff G R, Heinke C O, et al. ApJS, 2016, 222: 15 Capitanio F, Belloni T, Del Santo M, et al. MNRAS, 2009, 398: 1194 Alabarta K, Altamirano D, Méndez M, et al. MNRAS, 2021, 507: 5507 Ma R C, Soria R, Tao L, et al. MNRAS, 2022, 514:

McClintock J E, Remillard R A. Black Hole Binaries// lar X-ray Sources, Cambridge: Cambridge University Press, 2006, 157-213 Sunyaev R A, Titarchuk L G. A&A, 1980, 86: 121 Gilfanov M. LNP, 2010, 794: 17 van der Klis M, Jansen F, van Paradijs J, et al. Nature, 1985, 316: 225 van der Klis M. ARA&A, 1989, 27: 517 Zhang S N, Li T, Lu F, et al. SCPMA, 2020, 63: 249502 Li C K, Lin L, Xiong S L, et al. NatAs, 2021, 5: 378 Ma X, Tao L, Zhang S N, et al. NatAs, 2021, 5: 94 Soria R, Ma R, Tao L, et al. MNRAS, 2022, 515: 3105 Peng J Q, Zhang S, Wang P J, et al. ApJ, 2023, 955: 96 Peng J Q, Zhang S, Chen Y P, et al. MNRAS, 2023, 518: 2521 You B, Cao X, Yan Z, et al. Science, 2023, 381:

961 Zhang W, Tao L, Soria R, et al. ApJ, 2022, 927: 210 Weng S S, Cai Z Y, Zhang S N, et al. ApJ, 2021, 915:

Zhao S J, Tao L, Li P P, et al. A&A, 2024, 685: A42 Liu H X, Xu Y J, Zhang S N, et al., arXiv: 2406.03834 Peng J Q, Zhang S, Shui Q C, et al. ApJ, 2024, 960:

You B, Tuo Y, Li C, et al. NatCo, 2021, 12: 1025 Méndez M, van der Klis M. ApJ, 1997, 479: 926 Wang P J, Kong L D, Chen Y P, et al. MNRAS, 2022, Homan J, Wijnands R, van der Klis M, et al. ApJS, 512: 4541

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