Magnetic Field Transport and Jets in Black Hole X-ray Binaries: Postprint

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Date: 2025-08-19T00:00:00+00:00

Abstract

Black hole X-ray binary (BHXRB) is a binary system composed of a central compact black hole and its companion star. During its outburst phase, it is always accompanied by multi-wavelength radiation. With the development of multi-wavelength astronomy, a general picture of the physical processes behind its multi-wavelength radiation and spectral energy distribution (SED) has emerged: the accretion disk and corona around the black hole dominate the X-ray radiation; black hole X-ray binaries are always accompanied by jets, which constitute the main source of radio-band radiation; the physical processes dominating optical/near-infrared band radiation are relatively complex, generally considered to involve three processes: X-ray re-radiation, viscous thermal radiation from the outer accretion disk, and jet emission. Studies have found that there often exists a power-law correlation between the luminosities of various wavebands. This implies that there are connections among the physical processes behind the radiation in different wavebands. However, the specific physical processes connecting the jet and the accretion disk remain unclear. Studies have shown that weak external magnetic fields in BHXRBs can be advected inward through the accretion disk, forming strong magnetic fields within the accretion disk. This process significantly enhances the magnetic field inside the accretion disk, providing a prerequisite for the BZ (Blandford-Znajek) and BP (Blandford-Payne) models that theoretically explain jet production and acceleration. Meanwhile, strong magnetic fields can also alter the structure of the inner accretion flow, potentially forming a magnetically arrested accretion disk (MAD) in the region near the black hole. With the broad-band X-ray observations from the Insight Hard X-ray Modulation Telescope (Insight-HXMT), it becomes possible to glimpse the high-energy radiation processes in such compact regions. Considering the magnetic field transport process in black hole binaries can partially explain the accretion disk-jet coupling relationship. This review summarizes recent research on magnetic field transport and jets in BHXRB accretion, and introduces the latest advances in black hole accretion and magnetic

field transport.

Full Text

Preamble

Vol. 66 No. 4

July 2025

Acta Astronomica Sinica Vol. 66 No. 4 Jul., 2025 doi: 10.15940/j.cnki.0001-5245.2025.04.006

Magnetic Field Transport and Jets in Black Hole X-Ray Binaries

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Abstract

Black hole X-ray binaries (BHXRBs) are binary systems consisting of a central compact black hole and its companion star. Their outburst phases are always accompanied by multi-wavelength radiation. With the development of multi-wavelength astronomy, a general picture has emerged of the physical processes behind this multi-wavelength emission and the spectral energy distribution (SED): the accretion disk and corona around the black hole dominate X-ray emission; BHXRBs are invariably accompanied by jets, which constitute the primary source of radio emission; the physical processes dominating optical/near-infrared emission are more complex, generally believed to involve three mechanisms: X-ray reprocessing, viscous thermal radiation from the outer accretion disk, and jet emission. Studies have revealed power-law correlations between radiation luminosities across different wavebands, suggesting connections among the underlying physical processes. However, the specific physical processes linking jets and accretion disks remain unclear. Research indicates that weak external magnetic fields in BHXRBs can be dragged inward through the accretion disk to form strong magnetic fields near the black hole. This process significantly amplifies the magnetic field within the accretion flow, providing a prerequisite for theoretical models of jet launching and acceleration such as the BZ (Blandford-Znajek) and BP (Blandford-Payne) models. Meanwhile, strong magnetic fields can also alter the structure of the inner accretion flow, potentially forming magnetically arrested accretion disks (MADs) in regions near the black hole. With broadband X-ray observations from the Insight-HXMT (Insight Hard X-ray Modulation Telescope), we can probe the high-energy radiation processes in such compact regions. Considering magnetic field transport in black hole binaries may partially explain the accretion disk-jet coupling relationship. We review recent research on magnetic field transport and jets in

BHXRB accretion, and introduce the latest advances in black hole accretion and magnetic field transport.

Keywords stars: black holes, X-rays: binaries, radiation mechanisms: general, accretion disk, relativistic processes

1 Introduction

Black hole X-ray binaries (BHXRBs) are binary systems composed of a central compact black hole and its companion star. The black hole accretes matter from the companion, forming an accretion disk structure in its vicinity, where gravitational energy of the accretion flow is released through viscous dissipation [?]. A hotter plasma gas cloud (the corona) also exists around the black hole, though its structure and location remain uncertain. Current interpretations place it near the black hole, at the base of the jet, or above the accretion disk, with its geometry still unclear [?, ?, ?].

Decades of research have shown that black hole accretion is often accompanied by jet emission [?, ?]. These physical processes produce multi-wavelength radiation (from radio to X-ray bands), which we detect to study the underlying physical mechanisms and behavioral patterns of BHXRBs. In 2017, China launched its first X-ray space telescope, the Insight Hard X-ray Modulation Telescope (Insight-HXMT). Insight-HXMT has played an important role in BHXRB research; its broadband observing capability of 1–250 keV enables systematic detection of thermal radiation from black hole accretion disks, high-energy Comptonization components, and non-thermal radiation features associated with jets. Additionally, Insight-HXMT' s excellent time resolution allows study of rapid variability in different radiation components, helping to reveal physical processes in the extreme gravitational environment near black holes.

Most BHXRBs remain in quiescence for extended periods, with very low levels of X-ray and radio emission, before undergoing one or several outburst cycles lasting months to years. During an outburst, X-ray luminosity rises by 2–3 orders of magnitude within days, persists at high levels for weeks to months, then gradually decays back to pre-outburst quiescent levels [?].

We use "low/hard state" to describe the initial outburst phase when BHXRBs are faint in X-rays with a power-law photon index of approximately 1.5 and a hard X-ray spectrum. Radio emission in this state shows characteristics of steady jet synchrotron radiation. During the early rising phase (the "hard intermediate state"), both X-ray and radio luminosities increase while the X-ray spectrum remains hard, dominated by a power-law spectrum believed to result from inverse Compton scattering in a corona of hot electrons near the black hole [?, ?]. The weaker thermal component is generally attributed to a truncated, geometrically thick, optically thin accretion disk [?]. As the outburst progresses, thermal radiation from the accretion disk strengthens until it dominates the X-ray emission, causing the X-ray spectrum to soften rapidly. This disk-dominated state is called the "high/soft state," characterized by a geometrically thin, optically thick accretion disk with an effective temperature $kT_{\rm bb} \sim 1$ keV, where k is the Boltzmann constant and $T_{\rm bb}$ is the blackbody effective temperature. The disk' s inner radius is considered to be the innermost stable circular orbit (ISCO). Between the low/hard and high/soft states exist two intermediate states—the hard-intermediate and soft-intermediate states—not all BHXRBs experience both during outburst. Some remain in the low/hard state until returning to quiescence [?, ?].

During the transition from low/hard to high/soft state, radio flares have been observed in some BHXRBs [?, ?]. Regardless of whether such flares are observed (possibly due to lack of radio coverage during transition), radio emission is suppressed when entering the high/soft state [?]. As thermal disk radiation weakens in the soft state, the non-thermal component gradually recovers, and the system transitions back to the low/hard state at lower luminosity than during the hard-to-soft transition, with radio emission reappearing. When the BHXRB returns to quiescence, luminosity continues to decrease, marking the end of the outburst.

BHXRBs always exhibit multi-wavelength radiation during outburst. The current picture describes: an accretion disk emitting blackbody radiation that contributes soft X-rays; a corona structure near the black hole where UV and soft X-ray photons from the disk undergo inverse Compton scattering, producing hard X-ray power-law spectra. These two processes dominate X-ray emission. Additionally, BHXRBs feature intermittent relativistic outflows (jets) detected primarily in radio, constituting the main radio emission source. In the optical/near-infrared (OIR) band, the radiation origin and associated physical processes are less clear compared to other bands. Optical observations of BHXRBs are often comprehensive, and extensive studies have been conducted on OIR emission during both outburst and quiescence. OIR spectra and variability are complex and diverse, indicating multiple contributing physical processes [?]. Each process depends independently on specific physical parameters, requiring many parameters to describe the spectral and temporal characteristics, which explains their complexity. In high-mass X-ray binaries (HMXBs), OIR emission is largely dominated by the massive companion star [?, ?], with minor contributions from processes like X-ray reprocessing. In low-mass black hole X-ray binaries, spectral and timing analyses of many sources suggest OIR emission results from X-ray reprocessing in the outer accretion disk [?, ?], though this is not universal—observational analyses of some BHXRBs indicate other processes can produce (or even dominate) OIR emission [?].

Studies show that viscous heating in the outer accretion disk produces thermal radiation extending from optical through UV to X-ray bands [?, ?]. The OIR characteristics of BHXRBs indicate this process plays an important role in some systems [?, ?, ?]. Meanwhile, in quiescent low-mass X-ray binaries, thermal emission from companion stars has been observed [?, ?, ?]. Jet research over the years reveals that jets' optically thick flat spectra extend from radio to optical bands [?, ?, ?, ?]. These three processes—X-ray reprocessing from the outer disk, viscous thermal radiation from the accretion disk, and jet emission—have been most commonly used to explain optical emission for decades. Spectral and timing behaviors inconsistent with these processes have been attributed to other mechanisms such as magnetic reconnection in the outer disk [?], radiation from magnetically dominated coronae [?], or advection-dominated regions [?].

When studying relationships between multi-wavelength radiation, clear power-law correlations are often observed between luminosities in two bands: $L_A/L_B \propto L_B^{\alpha}$, where L_A and L_B represent radiation luminosities in the respective bands and α is the power-law index. Investigating these correlations across different bands and outburst phases is an important research topic, as they help study binary radiation mechanisms, estimate mass accretion rates, constrain physical parameters, and limit jet power [?].

The power-law correlation between OIR and X-ray bands can be derived from radiation processes. In 1995, van Paradijs and McClintock [?] proposed that if OIR emission originates from X-ray reprocessing in the accretion disk, then $L_{\mathrm{OIR}} \propto T^2/L_{0.5X}$, where the subscript denotes the corresponding band, a is the orbital separation, and T is temperature. This correlation was indeed observed in a series of low-mass X-ray binaries. If OIR emission originates from viscous thermal radiation, a similar correlation can be derived. Additionally, if OIR radiation comes from jets, an OIR/X-ray correlation is also predicted. Steady compact jet models indicate a relationship between radio luminosity and total jet power [?, ?, ?, ?]. Migliari et al.' s research shows that in the hard state of BHXRBs, jet power is proportional to the accretion disk mass accretion rate [?]. For processes with high radiative efficiency, X-ray luminosity satisfies $L_X \propto \dot{m}$, while for low-efficiency objects, $L_X \propto \dot{m}^2$. BHXRBs in the hard state have low radiative efficiency, with most gravitational potential energy dissipated via viscosity rather than converted to radiation. Therefore, for hard-state BHXRBs:

$$L_{\mathrm{radio}} \propto L_{\mathrm{jet}} \propto \dot{m} \propto L_X^{0.5} \tag{1}$$

Corbel et al. observed this correlation in the BHXRB source GX 339-4 in 2003 [?]. Based on this, if the optically thick jet spectrum is indeed flat from radio to optical bands, then:

$$L_{\mathrm{OIR}} \propto L_{\mathrm{radio}} \propto L_X^{0.7} \tag{2}$$

Homan et al. observed a near-infrared–X-ray correlation $F_{\mathrm{NIR}} \propto F_X^{0.53\pm0.02}$ in GX 339-4 in 2005 [?], where F_{NIR} and F_X represent near-infrared and X-ray fluxes, respectively.

The radio–X-ray correlation in BHXRBs was first discovered in the source GX 339-4. [Figure 1: see original paper] shows the radio–X-ray power-law correlation obtained by Corbel et al. in 2003 from 1997-2000 observations of GX 339-4. Their simultaneous correlation analysis of radio and X-ray luminosities in the low/hard state revealed that this relationship extends over three orders of magnitude down to quiescence. Subsequently, this radio–X-ray correlation was found in other black hole binaries and even in active galactic nuclei. The correlation takes the form $L_{\text{radio}} \propto L_X^{0.7}$. The strong correlation observed across multiple sources indicates a tight connection between the physical processes dominating radio emission (the jet) and X-ray emission (the accretion flow including disk and corona) in the hard state [?, ?, ?]. Fender et al. conducted detailed studies of this correlation in the binary system GRS 1915+105 and proposed a unified disk–jet coupling model based on existing observational data. A primary goal of studying the coupling between inflow (accretion flow) and outflow (jet) in BHXRBs is to link the evolution of radio emission (originating from the jet) with that of X-ray emission (originating from the inner accretion flow or jet base) [?]. This model was further refined with higher-frequency, higher-resolution radio observations.

2 Accretion Disk and Large-Scale Magnetic Field

For low-mass black hole X-ray binaries, the truncated disk model can well explain the spectral and timing properties during state transitions, such as in the transient source V404 Cyg [?, ?]. In this model, a standard thin disk extends from the outer radius R_{out} inward to a truncation radius R_{in}, where it transitions to an advection-dominated accretion flow (ADAF) in the inner region. Observations using this model show that the truncation radius obtained from spectral fitting agrees well with that derived from quasi-periodic oscillations (QPOs). BHXRBs undergo state transitions during outburst evolution, which the truncated disk model can explain well [?]. In the hard state, BHXRB X-ray spectra often show reflection components [?], which some studies suggest can be explained by the truncated disk model.

Magnetic fields are ubiquitous in astrophysical objects. In BHXRB systems, magnetic fields also exist around the central black hole, likely formed by the inward dragging of weak magnetic fields from the outer disk region through the accretion disk [?, ?, ?, ?]. In binary systems, the weak external magnetic field is generally considered to be provided by the companion star [?, ?, ?, ?]. The widely accepted view is that large-scale magnetic fields around black holes play a crucial role in accelerating and collimating jets or outflows [?, ?, ?]. Theoretical studies of jet launching and acceleration, such as the BZ (Blandford-Znajek [?]) and BP (Blandford-Payne [?]) models, both require large-scale magnetic fields with open configurations. This section introduces large-scale magnetic fields in standard thin disks and ADAFs.

2.1 Standard Thin Disk and Large-Scale Magnetic Field

Research suggests that large-scale poloidal magnetic fields in the outer disk are dragged inward by accreting plasma while simultaneously diffusing outward. When inward advection balances outward diffusion, the magnetic field in the accretion disk forms a stable configuration [?]. This implies that the magnetic field structure is primarily determined by the disk' s radial velocity and magnetic diffusivity. Since the disk' s radial velocity is roughly proportional to the kinematic viscosity, the magnetic configuration is very sensitive to the magnetic Prandtl number $P_m = \eta/\nu$, where η is magnetic diffusivity and ν is kinematic viscosity. The disk' s radial velocity is approximately proportional to ν. Parker argued that in isotropic turbulence, $P_m \sim 1$ [**?**], and many numerical simulations have since indicated that the magnetic Prandtl number should be around 1 [**?**, **?**, **?**]. An appropriate magnetic field configuration is crucial for jet launching from accretion disks. Specifically, launching jets from a Keplerian cold disk requires the angle between magnetic field lines and the disk plane to be less than 60°. For black holes with high spin, this critical angle may exceed 60° [**?**, **?**]. In 1994, Lubow et al. investigated the final stable magnetic field configuration resulting from the balance between large-scale magnetic field advection and diffusion, finding that significant magnetic dragging only occurs when $P_m \leq H/R$ (where H is the disk height at radius R) [**?**]. This indicates that for geometrically thin standard disks, the efficiency of external magnetic field advection is always low, with small radial velocities in the accretion flow.

Several models have been proposed to address the inefficient magnetic field advection in standard thin disks [**?**, **?**, **?**, **?**, **?**]. Some studies suggest that a hot corona above the standard thin disk, moving inward relatively quickly, can effectively transport magnetic flux inward through the disk' s outer region [**?**]. The hot gas above the standard thin disk can accrete inward faster than gas inside the disk, partially solving the problem of low magnetic flux transport efficiency. However, if the magnetic field required for jet launching is provided by the corona, the maximum jet power would be less than 0.05 times the Eddington luminosity, inconsistent with strong jets observed in some binary systems [**?**]. Cao and Spruit argued that most angular momentum in standard thin disks can be removed by magnetically driven outflows [**?**], making the radial velocity significantly higher than in classical standard thin disks, with gas rapidly accreting onto the black hole. Their calculations showed that even moderate-strength magnetic fields can cause sufficient angular momentum loss through magnetically driven outflows, accelerating inward magnetic field advection to balance outward magnetic diffusion. In 2019, Li and Cao performed numerical simulations considering the global structure of thin accretion disks driven by magnetic outflows [**?**]. [Figure 2: see original paper] shows their main results. Panels (A)-(C) display the magnetic field configuration of the thin disk with outflows, showing that the magnetic field is transported inward, forming an open configuration penetrating the disk with field lines clearly inclined toward the disk—necessary for outflow launching. Panels (D)-(E) show the radial distribution of magnetic field strength formed by inward transport of external fields for different external magnetic field strengths. The magnetic field strength is significantly enhanced in the inner region of the standard thin disk. Without considering magnetically driven outflows, magnetic field advection efficiency is extremely low, and the resulting magnetic field is not significantly enhanced in the disk's inner region. The enhancement amplitude in the inner disk is sensitive to the external field strength—a strong external field produces strong outflows, which remove more angular momentum from the standard thin disk, causing rapid inward accretion and efficient magnetic field transport. The stronger the external field, the stronger the final magnetic field in the disk' s inner region.

Panels (F)-(G) show that outflows appear to have radial stratification, meaning they have velocity gradients along the radial direction of the disk surface where they are launched. Long-term studies of the active galactic nucleus PG 1211+143 found multiple blueshifted absorption lines in its X-ray spectrum, corresponding to outflow velocities of $0.06c$, $0.13c$, and $0.18c$, indicating that outflows do not move outward at a single velocity but likely have a multi-velocity radial stratification [**?**, **?**, **?**]. In Li and Cao' s work [**?**], gas flowing out from the disk interior reaches velocities of $0.1c$–$0.3c$, decreasing with radius, while gas from the outer standard thin disk has velocities of $0.01c$–$0.02c$, consistent with observations of some high-luminosity quasars.

2.2 Advection-Dominated Accretion Flow (ADAF) and Large-Scale Magnetic Field

ADAF, as a low-accretion-rate accretion flow model, primarily considers advective cooling in energy dissipation. ADAFs are geometrically thick and optically thin, resulting in low density, low accretion rate, low radiative efficiency, and relatively large radial velocity. As mentioned above, when $P_m \leq H/R$, significant magnetic field advection occurs. For geometrically thick ADAFs with large radial velocities, the efficiency of external field advection is significantly higher than in standard thin disks. Cao [**?**] studied the advection/diffusion problem of large-scale magnetic fields in ADAFs, with [Figure 3: see original paper] showing the main numerical simulation results. Panels (A)-(B) display the large-scale poloidal magnetic field configuration in ADAFs, demonstrating clear inward magnetic field transport. As shown in panels (C)-(E), the ADAF structure also changes due to magnetic fields. Notably, the radial velocity of the accretion flow near the black hole is reduced by magnetic fields, indicating that if the magnetic field strength provided by the external field is sufficiently large, the accretion flow will be trapped by magnetic fields, forming a magnetically arrested accretion disk (MAD), confirming the main assumptions of qualitative MAD analysis [**?**]. In this case, plasma in the region near the black hole horizon may accrete in the form of magnetically confined gas blobs along field lines. Numerical simulations show that the magnetic field strength near the black hole horizon in ADAFs is primarily determined by the external field strength and the ADAF' s outer radius. Figure 3: see original paper shows the radial distribution of large-scale magnetic field strength in ADAFs for different P_m values and outer radii. It is found that if gas begins accreting from a larger ADAF outer radius, the final magnetic field at the ADAF' s inner edge will be stronger.

Due to magnetic pressure acting perpendicular to the disk plane, ADAFs experience significantly increased gas pressure near the black hole' s inner region, with noticeably reduced vertical scale. Compared to ADAF models without magnetic fields, the estimated magnetic field strength near the black hole' s inner region is much higher.

3 Jet Observations and Theory

Relativistic outflows, or jets, are extremely important and observationally prominent phenomena associated with accreting relativistic objects including X-ray binaries. Jets were initially considered phenomena associated with active galactic nuclei (AGN), first described in images as elongated structures connected to AGN at one end. Soon they were identified as powerful energy and matter flows ejected from near black holes into intergalactic space, leading to the conclusion that jets are common features of accretion onto relativistic objects [**?**]. Subsequently, the connection between jets and accretion onto stellar-mass black holes was systematically studied.

Although it is now generally accepted that jet electromagnetic radiation can extend from radio to X-ray bands, historically the key observational band for jets has been radio. Since the discovery of bright X-ray binary sources in the 1960s–70s, strong radio sources have been associated with these high-energy objects. However, the field of X-ray binary jet research only truly opened after high-resolution observations of the strong radio source associated with the binary SS 433 [**?**, **?**]. Outbursts of "soft X-ray transients" are often associated with intermittent strong radio emission. In the 1990s, apparent superluminal motion was observed in the X-ray transient GRS 1915+105 [**?**, **?**, **?**], marking a new stage in X-ray binary jet research. For the first time, it was realized that jets from X-ray binaries could exhibit the clear relativistic velocities (Lorentz factors $\Gamma \sim 2$) observed in AGN jets. Since then, jets from X-ray binaries have been studied in detail in radio and shorter wavelength bands (such as optical), providing clearer understanding of jet behavior and offering unique insights into the coupling between inflow and outflow in BHXRBs. However, as research has deepened, jet behavior has proven increasingly complex, representing a rapidly developing field.

[Figure 4: see original paper] shows radio images of the jet in the BHXRB MAXI J1820+070 on arcsecond scales.

3.1 Physical Properties of Jets

Observational evidence for jets in X-ray binaries—including their "non-thermal" spectra, high radio brightness temperatures, and in some cases high linear polarization—indicates that they are synchrotron radiation mechanisms. [Figure 5: see original paper] shows an observed radio flare event, generally believed to result from short-duration energy and particle injection into an expanding plasma cloud, observationally manifested as a jet [**?**]. Such radio flare events are characterized by optically thin spectra associated with X-ray transients or persistent flaring sources. The rise and decay phases of radio flares can be clearly defined. For the rising phase, van der Laan and Hjellming proposed the "synchrotron bubble" model to explain its behavior [?, ?, ?]. Radio flares from X-ray transients show monotonic decay after a few days, seemingly caused primarily by adiabatic expansion losses, characterized by consistent decay rates across all frequencies. This can also be explained by significant energy loss through synchrotron radiation or inverse Compton scattering, characterized by faster decay rates at higher frequencies that steepen the spectrum.

Mirabel and Rodriguez first observed apparent superluminal motion in GRS 1915+105 [?, ?, ?]. After accounting for Doppler shift effects, jet velocities can be estimated. There are essentially no direct measurements of velocities for the steady jets inferred to exist in the low/hard state of BHXRBs. Nevertheless, some clues suggest these jets may be mildly rather than highly relativistic. For intermittent jets in BHXRBs with low inferred relativistic speeds, such as the apparent superluminal motion observed in GRS 1915+105, the jets are generally described as relativistic with Lorentz factors $\Gamma \sim 2$—clearly relativistic but much less extreme than the most extreme AGN jets. However, Fender et al. suggest the range of Lorentz factors may be much broader [?]. With relatively precise distance estimates, jet Lorentz factors cannot be constrained by measuring radio component motions. Nonetheless, Fender and Kuulkers argue that the average Lorentz factor for BHXRB transients is likely $\Gamma \leq 5$, as higher values would probably disrupt the observed correlation between radio and X-ray peak fluxes [?].

Do jet velocities need to remain constant? In SS 433, they apparently do not—Eikenberry et al. showed jet velocity variations may exceed 10% [?]. In Corbel et al.'s study of XTE J1550-564, clear jet deceleration was observed [?], likely resulting from interaction with the interstellar medium (ISM), a phenomenon that probably occurs to varying degrees in all X-ray binaries. In summary, steady jets in the low/hard state of BHXRBs appear to be only mildly relativistic, while intermittent jets associated with X-ray transients almost certainly have much higher Lorentz factors that decrease over time through interaction with the ISM.

3.2 Steady Jets in the Low/Hard State

Low/hard state jets are characterized by "flat" spectra extending from radio to shorter wavelengths (spectral index $\alpha \sim 0$), linear polarization levels of 1%-3%, and power-law correlations between radio flux evolution and X-ray radiation. These observational features, distinct from intermittent jets, are found in nearly every BHXRB in the low/hard state [?]. By analogy with AGN, dense self-absorbed jets have been proposed to explain these properties [?, ?, ?, ?]. In 2001, milliarcsecond imaging of the low/hard state jet in Cyg X-1 by Stirling et al. confirmed this interpretation [?]. The radio spectrum of low/hard state sources appears "flat" or "inverted," extending to millimeter bands in Cyg X-1 and XTE J1118+480 [?, ?]. In most low/hard state sources, optical emission appears to lie on the "flat" extension of the radio spectrum [?, ?]. Jain et al. observed a secondary flare in the near-infrared light curve of XTE J1550-564, temporally coinciding with the source' s transition to the low/hard state, which they attributed to self-absorbed synchrotron radiation from the jet [?]. Rapid optical variability in XTE J1118+480 during the low/hard state can also be explained by self-absorbed synchrotron radiation. If the "flat" or "inverted" radio spectrum results from self-absorbed synchrotron radiation in a conical jet, the spectrum should break at some frequency to an optically thin spectrum with spectral index $\alpha \sim -0.5$ to -0.7. Corbel et al. found such a break in the near-infrared band for GX 339-4 in the low/hard state based on systematic observations [?].

After establishing that radio emission originates from steady self-absorbed synchrotron jets, the key is to determine jet power. Estimates are made through: (1) careful measurement of the synchrotron spectrum' s extent; and (2) introduction of radiative efficiency to estimate total jet power. The jet power can be estimated as:

$$P_J = \frac{L_J}{\eta} F(\Gamma, i) \tag{3}$$

where L_J is the total radiative luminosity of the jet (integrated from radio to the highest observed frequency), η is the radiative efficiency, and $F(\Gamma, i)$ is a correction factor for bulk relativistic motion with Lorentz factor Γ and Doppler factor, where i is the inclination angle [?].

A reasonable assumption is that all radiation observed in radio bands originates from synchrotron radiation [?], allowing investigation of how far the radio synchrotron spectrum extends into other bands to obtain total synchrotron luminosity. For the transient XTE J1118+480, its low/hard state spectrum is basically consistent with the theoretically predicted broadband spectral picture. It shows clear excess components in near-infrared and possibly optical bands, while the radio spectrum connects smoothly with 850 μm observations [?]. Fender et al. argued that in this case, the synchrotron luminosity exceeds the observed X-ray luminosity by more than 10% [?]. The key to estimating jet power then lies in estimating radiative efficiency. Fender and Pooley estimated $\eta \sim 0.15$ for radio "oscillations" in GRS 1915+105 [?]; in Blandford and Konigl' s original model, η was likely < 0.1 [?]; in Markoff et al.' s model, $\eta \sim 0.15$ [?]; Celotti and Ghisellini estimated $\eta \sim 0.02$ for AGN samples [?]. Theoretical studies of synchrotron processes in jets suggest $\eta > 0.2$ is unlikely and lacks observational support. Therefore, for XTE J1118+480, jet power may exceed X-ray luminosity by more than 10%. Nearly all low/hard state BHXRBs show similar broadband spectral pictures. [Figure 6: see original paper] shows broadband jet model fitting results for GX 339-4 in the low/hard state. It can be concluded that almost all BHXRBs produce powerful steady jets in the low/hard state.

3.3 Jet Disappearance in the Soft State

The discovery that BHXRBs lack radio compact jets in the X-ray soft state dates back to Tananbaum et al.' s 1972 work [?], which found that radio flares in Cyg X-1 were associated with its transition back to the hard state from the soft state. Although it was speculated that radio variations were related to changes in X-ray properties, the specific pattern was unclear. In 1998, observations showing GX 339-4 persisting in the high/soft state for a year changed this situation. Before 1998, radio monitoring of GX 339-4 in the low/hard state had identified weak radio emission, but throughout the entire subsequent soft state, despite multiple observations, no radio emission was detected. The source then returned to the low/hard state, and weak radio emission reappeared [?]. This result provided strong evidence that in the soft state of BHXRBs, when the accretion disk dominates X-ray emission, radio emission is either absent or very weak. High-cadence radio and X-ray observations of Cyg X-1 showed that once the source transitions to the high/soft state, radio emission is rapidly suppressed to a few percent of Eddington luminosity [?]. No counterexamples have been observed, leading to the conclusion that strong steady radio jets do not exist in the soft state of BHXRBs. Klein-Wolt et al.' s long-term study of GRS 1915+105 also confirmed this conclusion, finding that its soft state was never associated with bright radio emission [?].

4 Studies on MAXI J1820+070

You et al. [?] conducted a detailed study in 2021 of the 2018 outburst of the BHXRB MAXI J1820+070, revealing possible corona configurations and behavior patterns in the hard state and providing new insights into accretion disk, corona, and jet behavior and disk-jet coupling. [Figure 7: see original paper] shows the light curve and hardness-intensity diagram (HID) of MAXI J1820+070 during its 2018 outburst. The first outburst lasted from MJD 58200 to MJD 58286, with the source remaining in the hard state. This outburst was divided into rising and decaying phases based on X-ray luminosity. Spectral fitting of X-ray spectra during the outburst revealed that the reflection fraction rose sharply to about 0.5 during the rising phase, then slowly decreased to about 0.1 during the decaying phase. The reflection fraction is defined as the ratio of coronal intensity illuminating the accretion disk to that directly reaching the observer, meaning the proportion of photons from the corona that illuminate the disk increased during the rising phase and decreased during the decaying phase.

Previous studies suggested that if the corona' s geometric structure above the black hole is a point-like "lighthouse" structure at a certain height, then given other model parameters, the corona' s height above the black hole uniquely determines the reflection fraction [?]. The relationship is: as the corona accelerates away from the black hole, beaming effects reduce the flux illuminating the disk, decreasing the reflection fraction. Generally, the corona structure is believed to be located at the jet base [?], more complex than a lighthouse structure and characterized by two parameters—position and bulk velocity. You et al. [?] studied the relationship between coronal parameters and reflection fraction, concluding that the reflection fraction increases as coronal height decreases, while given a fixed height, increasing bulk velocity decreases the reflection fraction. For the decaying phase of MAXI J1820+070, X-ray timing analysis indicated the corona contracted as its height decreased [?], which should increase the reflection fraction. However, spectral fitting showed the reflection fraction decreased over time. To resolve this contradiction, You et al. [?] proposed that as the corona contracted toward the black hole, the outflow velocity of coronal material increased significantly. In this scenario, the effect of coronal outflow on the reflection fraction outweighs that of contraction toward the black hole, consistent with observations. [Figure 8: see original paper] shows a schematic of their proposed coronal evolution over time.

You et al. [?] revisited the 2018 outburst of MAXI J1820+070 in 2023, focusing on the transition from soft to hard state at the outburst' s end and investigating multi-wavelength behavior and correlations from radio to X-ray bands. This study provided the first observational evidence for MAD formation around black holes. Specifically, during the decaying hard state, MAXI J1820+070 transitioned from soft to hard state after MJD 58380. Multi-wavelength light curve analysis revealed that radio emission lagged X-ray emission by 8 days, and optical emission lagged X-ray by 17 days. Such day-scale time delays between wavebands had never before been observed in BHXRBs. You et al. [?] argued that this reflects the formation process of a MAD.

Numerous observations support a basic structure where the accretion flow around black holes consists of coexisting inner hot corona and outer cold thin disk. Interaction between corona and thin disk creates a truncated disk structure. In low-mass BHXRBs, matter from the companion first enters the thin disk. In the disk' s inner region, gas evaporates from the disk plane into the corona. In ADAF-structured coronae, when the accretion rate exceeds the critical rate where ion-electron equilibrium timescale equals accretion timescale, the corona condenses into a disk [?]. When the companion' s mass supply is insufficient to replenish evaporated gas, the accretion disk exhibits a truncated structure; otherwise, it is non-truncated [?]. Generally, for low-mass X-ray binaries, the accretion disk structure in the soft state is non-truncated, with an optically thick disk extending inward to the ISCO. This is also true for MAXI J1820+070. We can consider that at the moment the source left the soft state and entered the intermediate state (MJD 58381), its thin disk extended to the ISCO. However, after entering the intermediate state, we clearly observed enhanced hard X-ray radiation, indicating enhanced inverse Compton scattering, generally believed to originate from the jet base or ADAF. More interestingly, You et al. [?] found that radio emission during this period lagged hard X-ray emission by about 8 days, much larger than predicted by light travel time.

To explain the day-scale delay between radio and X-ray emission, You et al. [?]

proposed that MAXI J1820+070' s accretion disk behavior during this period could be explained by the truncated disk model [?]. As described earlier, this model' s basic structure consists of a standard thin disk truncated at radius $R_{\rm tr}$, with ADAF inside extending to the ISCO. For MAXI J1820+070, the 8-day radio lag behind X-rays ruled out the possibility that hard X-ray emission originated from a corona at the jet base, suggesting it likely came from ADAF, with the inner ADAF region being the main source of hard X-ray emission. After MAXI J1820+070 left the soft state, spectral fitting results showed the truncation radius continued to increase while the accretion rate decreased. In this case, the total gravitational dissipation power of the entire ADAF increased with $R_{\rm tr}$, while the radiative power of the ADAF' s innermost region decreased with accretion rate. These two mechanisms compete: initially, the $R_{\rm tr}$ effect dominates, causing hard X-ray flux to rise; when their effects become comparable, hard X-ray flux peaks around t_1 = MJD 58389; subsequently, the accretion rate effect dominates, and hard X-ray flux declines. How does this accretion disk structural evolution lead to the observed day-scale radio delay? This requires consideration of magnetic fields' role in the process. As discussed earlier, due to ADAF's high radial velocity, even a weak external magnetic field can be dragged inward and amplified by ADAF. Larger ADAFs are expected to drag and amplify external magnetic fields more efficiently. Although hard X-ray flux peaked at t_1 = MJD 58389, magnetic field dragging by ADAF continued to strengthen. The magnetic field at the ISCO did not saturate and begin to decline until t = MJD 58397. Jet power increases with magnetic field strength near the black hole, so radio emission also increases until peaking at t_2 = MJD 58397. This explains the observed 8-day radio lag behind hard X-rays.

Assuming substantial magnetic flux near the black hole, the gravitational pressure from continuously accreted matter prevents magnetic field escape. Thus, magnetic fields accumulate within the magnetospheric radius R_m, where accumulated magnetic flux interferes with the original accretion flow. Noting that R_m is larger than the horizon radius indicates a region exists where the inner accretion flow is clearly affected by magnetic fields. When $r \geq R_m$, the accretion flow behaves like a standard ADAF. When $r < R_m$, the large-scale accretion flow breaks into small gas blobs or streams. Gas must penetrate layers of magnetic fields to ultimately fall into the black hole, so the radial velocity of accretion flow in this region is much smaller than in the external accretion flow. This accretion flow region is called a MAD [?]. Observationally, MAD contributions to the spectrum are not clearly distinguishable from standard and normal evolution (SANE) accretion flows [?]. Therefore, although MAD formation in BHXRBs had been predicted, it had never before been observed in black hole sources. This study [?] provides the first observational evidence for MAD formation around black holes. Based on the above accretion flow evolution model, during MAXI J1820+070's transition from soft to hard state, the magnetic field in the ADAF' s inner region continuously strengthened, and this increasingly strong magnetic field in turn affected the ADAF' s own structure because magnetic pressure opposes gravitational pressure. Calculations show that after the hard X-ray peak, the continued expanding ADAF' s innermost magnetic field continued to be amplified, further dominating at the inner edge, and finally reaching the magnetic field strength required for MAD formation near the black hole when radio emission peaked (MJD 58397), forming a magnetically arrested accretion disk in the ADAF' s innermost region. [Figure 9: see original paper] shows the overall schematic of this process.

5 Summary and Outlook

Throughout their entire outburst cycle, black hole X-ray binaries experience several different accretion modes, from low/hard to high/soft states. The behavior of accretion disks and jets and their internal magnetic fields differ greatly among these modes. Multi-wavelength observations from radio through X-ray to gamma-ray bands are crucial for studying accretion processes, jet mechanisms, and ultimately understanding black holes [?, ?].

Previous studies widely used SED fitting and correlation analysis to investigate the origins of multi-wavelength radiation and related physical processes in BHXRBs [?, ?, ?]. In recent years, increasing research has combined timing and spectral analysis to further explore multi-wavelength variability of accretion disks and jets on different timescales [?, ?, ?]. These studies have confirmed correlations between X-ray, optical, and radio emissions in BHXRBs, while discovering minute-scale time delays between optical, X-ray, and radio bands. These results can well constrain jet composition and geometry [?]. You et al. [?] discovered day-scale radio delays in the BHXRB MAXI J1820+070, far exceeding previous theoretical predictions. When considering magnetic field variations around black holes combined with disk-jet coupling and truncated disk models, this observational result can be quantitatively explained. Thus, building on previous research, magnetic field variations in BHXRBs have gained further attention, and we have for the first time observed the formation process of a MAD around a black hole.

Coordinated multi-wavelength observations are crucial for BHXRB research. Over the past 20 years, the number of space X-ray telescopes has continuously increased, including RXTE (Rossi X-ray Timing Explorer), MAXI (Monitor of All-sky X-ray Image), and NuSTAR (Nuclear Spectroscopic Telescope Array). In 2017, China launched and operated its first X-ray space telescope, Insight-HXMT. In the X-ray band, its unique capability for broadband X-ray observations, particularly its large effective area in the hard X-ray band, enables systematic study of various radiation processes from accretion disks to jets in BHXRBs, making it one of the few satellites worldwide capable of continuous observations across such a wide energy band. On January 9, 2024, China' s first wide-field X-ray survey satellite, the "Einstein Probe" (EP), was successfully launched and has been operating smoothly. EP offers significant advantages in real-time survey capability and detection sensitivity, completing a half-sky survey in half a day with sensitivity more than an order of magnitude higher than similar space detectors. With increasing observational resources, joint observations among multiple detectors are becoming more frequent, greatly compensating for previous shortages of simultaneous observational data. We can obtain larger observational samples to more comprehensively and systematically study physical processes such as accretion flow dynamical evolution and jet formation. Improved observational capabilities also enable studies of BHXRB accretion in the very early and late stages of outbursts. It is foreseeable that our understanding of physical processes in binary systems will be greatly expanded in the future.

References

Shakura N I, Sunyaev R A. A&A, 1973, 24: 337
Laor A. ApJ, 1991, 376: 90
Martocchia A, Karas V, Matt G. MNRAS, 2000, 312: L13
Haardt F, Maraschi L, Ghisellini G. ApJ, 1994, 432: L95
Spencer R E. Nature, 1979, 282: 483
Hjellming R M, Johnston K J. Nature, 1981, 290: 100
McClintock J E, Remillard R A. Black Hole Binaries // Lewin W H G, van der Klis M. Compact Stellar X-ray Sources. Cambridge: Cambridge University Press, 2006: 157
Corbel S, Fender R P, Tzioumis A K, et al. A&A, 2000, 359: 251
Corbel S, Nowak M A, Fender R P, et al. A&A, 2003, 400: 1007
Lasota J P, Narayan R, Yi I. A&A, 1996, 314: 813
Brocksopp C, Bandyopadhyay R M, Fender R P. NewA, 2004, 9: 249
Capitanio F, Belloni T M, Del Santo M, et al. MNRAS, 2009, 398: 1194
Fender R P, Belloni T M, Gallo E. MNRAS, 2004, 355: 1105
Fender R P, Homan J, Belloni T M. MNRAS, 2009, 396: 1370
Fender R, Corbel S, Tzioumis T. ApJ, 1999, 519: L165
van Paradijs J, McClintock J E. Optical and Ultraviolet Observations of X-ray Binaries // Lewin W H G, van Paradijs J, van der Heuvel E P J. X-ray Binaries. Cambridge: Cambridge University Press, 1995: 58
van den Heuvel E P J, Heise J. NPhS, 1972, 239: 67
Treves A. ApJ, 1980, 242: 1114
Cunningham C. ApJ, 1976, 208: 534
Vrtilek S D, Raymond J C, Garcia M R, et al. A&A, 1990, 235: 162
Homan J, Belloni T M. Ap&SS, 2005, 300: 107
Frank J, King A, Raine D J. Accretion Power in Astrophysics. 3rd ed. Cambridge: Cambridge University Press, 2002: 80
Kuulkers E. NewA, 1998, 42: 1
Soria R, Wu K, Johnston H M. MNRAS, 1999, 310: 71
Bailyn C D. ApJ, 1992, 391: 298
Greene J, Bailyn C D, Orosz J A. ApJ, 2001, 554: 1290
Mikolajewska J, Rutkowski A, Goncalves D R, et al. MNRAS, 2005, 362: L13
Lovelace R V E, Rothstein D M, Bisnovatyi-Kogan G S. ApJ, 2009, 701: 885
Fender R P. MNRAS, 2001, 322: 31
Corbel S, Fender R P. ApJ, 2002, 573: L35

Markoff S, Nowak M, Corbel S. A&A, 2003, 397: 645
Zurita C, Casares J, Shahbaz T. ApJ, 2003, 582: 369
Merloni A, DiMatteo T, Fabian A C. MNRAS, 2000, 318: L15
Shahbaz T, Dhillon V S, Marsh T R, et al. MNRAS, 2003, 346: 1116
Guilet J, Ogilvie G I. MNRAS, 2012, 424: 2097
Guilet J, Ogilvie G I. MNRAS, 2013, 430: 822
Cao X W, Spruit H C. ApJ, 2013, 765: 149
Beckwith K, Hawley J F, Krolik J H. ApJ, 2009, 707: 428
Cao X W. MNRAS, 2018, 473: 4268
Li J W, Cao X W. ApJ, 2019, 872: 149
Pounds K A, Reeves J N, King A R, et al. MNRAS, 2003, 345: 705
Russell D M, Fender R P, Hynes R I, et al. MNRAS, 2006, 371: 1334
Pounds K, Lobban A, Reeves J, et al. MNRAS, 2016, 457: 2951
Blandford R D, Konigl A. ApJ, 1979, 232: 34
Falcke H, Biermann P L. A&A, 1996, 308: 321
Pounds K A, Lobban A, Reeves J N, et al. MNRAS, 2016, 459: 4389
Heinz S, Sunyaev R A. MNRAS, 2003, 343: L59
Migliari S, Fender R P. MNRAS, 2006, 366: 79
Cao X. ApJ, 2011, 737: 94
Narayan R, Igumenshchev I V, Abramowicz M A. PASJ, 2003, 55: L69
Narayan R. ApJ, 1996, 462: 136
Fender R. Jets from X-ray Binaries // Lewin W H G, van der Klis M. Compact Stellar X-ray Sources, 2006, 39: 381
Esin A A, McClintock J E, Narayan R. ApJ, 1997, 489: 865
Zdziarski A A, Lubinski P, Gilfanov M, et al. MNRAS, 2003, 342: 355
Bisnovatyi-Kogan G S, Ruzmaikin A A. Ap&SS, 1974, 28: 45
Mirabel I F, Rodriguez L F. Nature, 1994, 371: 46
Mirabel I F, Rodriguez L F. ARA&A, 1999, 37: 409
Rodriguez L F, Mirabel I F. ApJ, 1999, 511: 398
Bright J S, Fender R P, Motta S E. et al. NatAs, 2020, 4: 697
Bisnovatyi-Kogan G S, Ruzmaikin A A. Ap&SS, 1976, 42: 401
Longair M S. High Energy Astrophysics. Stars, the Galaxy and the Interstellar Medium. Cambridge: Cambridge University Press, 1994, 2: 331
Spruit H C, Uzdensky D A. ApJ, 2005, 629: 960
Konigl A, Pudritz R E. Disk Winds and the Accretion-Outflow Connection // Mannings V, Boss A P, Russell S S. Protostars and Planets IV. Tucson: University of Arizona Press, 2000: 759
Pudritz R E, Ouyed R, Fendt C, et al. Disk Winds, Jets, and Outflows: Theoretical and Computational Foundations // Reipurth B, Jewitt D, Keil K. Protostars and Planets V. Tucson: University of Arizona Press, 2007: 277
Spruit H C. Theory of Magnetically Powered Jets // Wolf B, Jurgen E, Klaus H. Lecture Notes in Physics. Berlin: Springer Verlag, 2010: 233
Blandford R D, Znajek R L. MNRAS, 1977, 179: 433
Blandford R D, Payne D G. MNRAS, 1982, 199: 883
Parker E N. Cosmical Magnetic Fields: Their Origin and Their Activity. Oxford: Clarendon Press, 1979: 80

Fender R P, Kuulkers E. MNRAS, 2001, 324: 923
Eikenberry S S, Matthews K, Muno M, et al. ApJ, 2002, 523: L33
Falcke H, Biermann P L. A&A, 1999, 342: 49
Stirling A M, Spencer R E, de la Force C J, et al. MNRAS, 2001, 327: 1273
Fender R P, Pooley G G. MNRAS, 2000, 318: L1
Brocksopp C, Jonker P G, Fender R P, et al. MNRAS, 2001, 323: 517
Corbel S. ApJ, 2001, 554: 43
Jain R K, Bailyn C D, Orosz J A, et al. ApJ, 2001, 554: L181
Hynes R I, Mauche C W, Haswell C A, et al. ApJ, 2000, 539: L37
Yousef T A, Brandenburg A, Rudiger G. A&A, 2003, 411: 321
Fromang S, Stone J M. A&A, 2009, 507: 19
Celotti A, Ghisellini G. MNRAS, 2008, 385: 283
Tananbaum H, Gursky H, Kellogg E, et al. ApJ, 1972, 177: L5
Guan X, Gammie C F. ApJ, 2009, 697: 1901
Cao X W, Spruit H C. A&A, 1994, 287: 80
Gallo E, Fender R P, Pooley G G. MNRAS, 2003, 344: 60
Klein-Wolt M, Fender R P, Pooley G G, et al. MNRAS, 2002, 331: 745
Yuan F, Narayan R. ARA&A, 2014, 52: 529
Xie F G, Zdziarski A A. ApJ, 2019, 887: 167
Homan J, Buxton M, Markoff S, et al. ApJ, 2005, 624: 295
You B, Tuo Y, Li C, et al. NatCo, 2021, 12: 1025
Dauser T, Garcia J, Walton D J, et al. A&A, 2016, 590: A76
Marino A, Barnier S, Petrucci P O, et al. A&A, 2021, 656: A63
Henri G, Pelletier G. ApJ, 1991, 383: L7
Coriat M, Corbel S, Prat L, et al. MNRAS, 2011, 414: 677
Kara E, Steiner J F, Fabian A C, et al. Nature, 2019, 565: 198
Tetarenko A J, Casella P, Miller-Jones J C A, et al. MNRAS, 2019, 484: 2987
You B, Cao X W, Yan Z, et al. Science, 2023, 381: 961
Cao X W, You B, Yan Z. A&A, 2021, 654: A81
Tetarenko A J, Casella P, Miller-Jones J C A, et al. MNRAS, 2021, 504: 3862

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