Overview of Research on Measuring Black Hole Fundamental Parameters with the Insight-HXMT Scientific Satellite (Postprint)

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Abstract

We systematically review the primary measurement methods for the fundamental parameters of black holes—mass and spin—and briefly introduce distance measurement techniques for black hole binary systems. Through case studies, we demonstrate the importance of precise distance measurements for calibrating black hole fundamental parameters. From three perspectives—dynamical measurement, spectral fitting, and Quasi-Periodic Oscillation (QPO)—we discuss three common methods for black hole mass measurement, and elucidate their specific applications and limitations by combining actual observational results. Regarding spin measurement, focusing on research results from the Insight-HXMT satellite, we provide an in-depth analysis of two methods: thermal continuum spectral fitting and reflection component fitting, emphasizing the critical role of Insight-HXMT in black hole spin research. We thoroughly examine the theoretical foundations, model assumptions, and applicable ranges of these two methods, briefly present their measurement processes through examples, provide the commonly used models in practical applications, and simultaneously demonstrate the role and advantages of Insight-HXMT in employing these methods for spin measurement.

Full Text

Preamble

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An Overview of the Insight-HXMT Scientific Satellite Measuring Fundamental Parameters of Black Holes*

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Abstract

This paper systematically reviews the primary methods for measuring the fundamental parameters of black holes—mass and spin—and briefly introduces techniques for determining the distances to black hole binary systems. Through case studies, it highlights the importance of precise distance measurements in refining black hole fundamental parameters. We explore three common approaches to black hole mass measurement from three perspectives: dynamical measurement, spectral fitting, and Quasi-Periodic Oscillation (QPO), clarifying their practical applications and inherent limitations based on actual observational results. For spin measurement, we focus on the research achievements of the Insight-HXMT satellite, providing an in-depth analysis of two methods: thermal continuum fitting and reflection component fitting. We emphasize the crucial role of Insight-HXMT in black hole spin research, meticulously dissecting the theoretical foundations, model assumptions, and applicable ranges of these two methods. Through examples, we briefly present their measurement processes and commonly used models, while demonstrating the satellite’ s role and advantages in applying these methods to spin measurement.

Keywords black hole physics, X-rays: binaries, accretion disk, radiation mechanism

1 Introduction

Black holes serve as unique laboratories for physics and astronomy, offering us opportunities to glimpse the mysteries of the universe and opening doors to observe a series of fundamental astrophysical phenomena. These include critically important and complex processes such as accretion, relativistic jets, and gamma-ray burst generation, all occurring in the vicinity of black holes and representing major focal points in astrophysical research. From binary systems to ultraluminous X-ray sources, galaxies, and quasars across various scales, black hole research constitutes a vital component. Stellar-mass black holes are considered the most ideal subjects for study because they provide unique and relatively reliable samples that facilitate in-depth exploration and understanding of these astrophysical phenomena. In astrophysics, black holes are characterized by only two parameters: mass and spin. This makes profound understanding of black hole mass and spin essential for analyzing spacetime structure in strong gravitational fields. These parameters not only determine the properties of spacetime around black holes but also play crucial roles in how various gravitational phenomena manifest. Therefore, precise knowledge of these two key parameters enables us to more comprehensively understand black hole behavior in the universe and significantly enhances our understanding of stellar evolution.

Accurate black hole mass measurement is vital for validating models of massive protostars, Type Ibc supernova explosions, and binary evolution [?]. Among the notable issues is the mass gap problem: a significant deficit has been found between the maximum neutron star mass and the lower end of the black hole mass distribution [?], though the existence of this mass gap remains controversial. Kreidberg et al. [?] argue that an important systematic error source was overlooked in previous analyses, suggesting the mass gap likely results from underestimation of inclination angles. By correcting black hole mass estimates based on inclination angle biases in GRO J0422+32, they found this black hole might fall within the mass gap. However, they also note that previous conclusions remain valid if this source is excluded from analysis. Conversely, Belczynski et al. [?] contend the mass gap may be real and could reveal new theories about supernova explosion models. Kochanek [?] proposed an alternative explanation based on the absence of red supergiants in the 16–25 $M_\odot$ range as progenitors of Type IIp supernovae: due to their weak hydrogen envelopes, these massive stars eject their outer layers, leaving behind black holes with masses equivalent to the star' s helium core (5–8 $M_\odot$). This could explain both the missing supernova progenitors in the 16–25 $M_\odot$ range and the existence of the mass gap. Precise black hole mass measurement is key to resolving this issue.

Spin is also a crucial parameter for tracking black hole formation and evolution. The stellar-mass black holes discovered today in Galactic X-ray binary systems formed through core collapse of massive stars. In this context, black hole spin information reflects the physical processes occurring during stellar core collapse. Black hole evolution, particularly its spin, begins with gravitational collapse of the star, imparting non-zero spin to the black hole. The initial spin state depends on the progenitor star' s angular momentum and the magnetohydrodynamics of rotating stellar core collapse. Black hole spin can also change through mergers. Additionally, spin can grow by accreting nearby matter such as plasma and gas. Gammie et al. [?] calculated black hole spin ranges of approximately 0.7–0.9 based on relativistic collapse calculations, also presenting results from relativistic magnetohydrodynamic models describing accretion onto rotating black holes. These results show that accretion does not necessarily lead to near-extreme spin, and even thin-disk accretion may fail to produce spins approaching unity. By comparison, all current spin measurement methods (except those involving gravitational waves, which represent future possibilities) utilize accretion disks to infer black hole spin. The two most commonly used methods include reflection component fitting and continuum fitting. Both methods assume geometrically thin disks with high radiative efficiency, and the fitted radiation essentially terminates within the inner stable circular orbit. Yan et al. [?] compiled current black hole spin measurement results, finding a clear bimodal distribution (peaks at spins of 0.17 and 0.8). They suggest low-spin black holes

($a < 0.3$) resemble low-mass X-ray binaries with neutron stars, where compact objects increase spin through low-level accretion, while high-spin black holes ($a > 0.5$) experienced a brief supercritical accretion state that rapidly increased black hole spin. Both scenarios produce the observed bimodal distribution. Precise and more extensive spin measurements will enable better understanding of black hole formation and evolution processes.

The Insight-HXMT satellite was successfully launched on June 15, 2017, from the Jiuquan Satellite Launch Center in northwestern China, becoming China' s first X-ray astronomy satellite. Its Chinese name honors Academician He Zehui, while its English name is Insight Hard X-ray Modulation Telescope, abbreviated as Insight-HXMT. It operates in a low Earth orbit at an altitude of 550 km with an inclination of 43°. The satellite' s primary scientific objectives include: searching for new transient sources in the Galactic plane and monitoring known variable sources; observing X-ray binaries to study motion and radiation mechanisms in strong gravitational or magnetic fields; and monitoring gamma-ray bursts and electromagnetic counterparts of gravitational wave events. To meet scientific observation requirements, the satellite features three attitude control modes. The first is all-sky survey mode: the sunshade is perpendicular to the solar direction, and the satellite rotates slowly around the solar direction to keep Earth outside the telescope' s field of view, enabling coverage of the entire sky within six months. The second is pointed observation mode: the satellite operates in three-axis stabilization mode with the telescope' s optical axis pointing at the target for a sustained period. The third is small-area scanning mode: the telescope' s optical axis changes slowly along a planned trajectory to cover specific sky regions. Insight-HXMT carries three telescopes: the Low Energy Telescope with a total detection area of 384 cm^2, covering 1–12 keV with 1 ms time resolution; the Medium Energy Telescope with a total detection area of 952 cm^2, covering 8–35 keV with 255 μs time resolution; and the High Energy Telescope with a total detection area of 5100 cm^2, covering 20–350 keV with 4 μs time resolution [**?**].

The main advantages of Insight-HXMT observations include broad energy coverage, large effective area in the high-energy X-ray band, high time resolution, minimal detection dead time, and absence of photon pile-up effects for bright sources. Since its stable operation in orbit, Insight-HXMT has achieved fruitful results in multiple fields, particularly making significant progress in X-ray binary research, including constructing and refining evolutionary images of black hole binary outbursts, studying quasi-periodic oscillations (QPOs) and timing variability in black hole outbursts [**?**], and investigating fundamental black hole properties and accretion disk corona structures [**?**]. This paper primarily introduces measurement methods for black hole fundamental parameters—mass and spin—based on Insight-HXMT research results. Black hole mass measurement mainly employs three methods: dynamical methods, spectral fitting, and quasi-periodic oscillations, while spin measurement primarily uses thermal continuum fitting and reflection component fitting.

2 Distance Measurement

Distance determination is crucial for measuring black hole fundamental parameters, such as mass and luminosity calculations, as well as black hole spin measurement through the thermal continuum method. Therefore, before discussing black hole mass and spin measurements, we briefly overview distance measurement methods and introduce distance measurement results for several sources mentioned later. Distances to black hole X-ray binary systems are typically estimated by studying optical/infrared spectra of the companion star [**?**]. Additionally, jet proper motion can provide upper limits on distance [**?**], while lower limits can be estimated through interstellar extinction measurements [**?**] or HI absorption lines [**?**]. X-ray dust scattering halos have also been used to constrain distances to some black hole X-ray binary systems [**?**]. However, these methods are model-dependent and involve certain assumptions.

The only model-independent distance measurement method is high-precision trigonometric parallax. However, since typical distances to these systems are several kiloparsecs, high-precision observations are only possible with Very-long-baseline interferometry (VLBI) or instruments like the Gaia (Global Astrometric Interferometer for Astrophysics) satellite [**?**]. Gaia’ s high-precision measurements of black hole X-ray binary systems in the Galactic plane may be limited by high extinction and low optical brightness outside outburst periods. Additionally, Gaia’ s parallax measurements suffer from a global zero-point bias [**?**], whose exact magnitude remains controversial. Therefore, targeted VLBI astrometric observations of black hole X-ray binary systems during outbursts remain essential. Among currently observed black hole X-ray binary system candidates, only systems such as V404 Cyg [**?**], Cygnus X-1 [**?**], Cygnus X-3, and GRS 1915+105 [**?**] have relatively accurate parallax measurements.

Atri et al. [**?**] used the Very Long Baseline Array (VLBA) and the European VLBI Network (EVN) to precisely measure the parallax of the black hole X-ray binary system MAXI J1820+070, providing a model-independent distance estimate. The measured parallax was (0.348 ± 0.033) mas, corresponding to a distance of (2.96 ± 0.33) kpc. This distance indicates that the source reached 15% of the Eddington luminosity at its outburst peak. Furthermore, using this distance to revise previous estimates of jet inclination, jet velocity, and black hole mass yielded results of $63^\circ \pm 3^\circ$, $(0.89 \pm 0.09)c$, and $(9.2 \pm 1.3)M_\odot$, respectively. Chauhan et al. [**?**] used the Australian Square Kilometre Array Pathfinder (ASKAP) and MeerKAT (Karoo Array Telescope, KAT) to observe neutral hydrogen absorption spectra of the black hole X-ray binary MAXI J1348-630, obtaining results indicating a most probable distance of $2.2^{+0.5}_{-0.6}$ kpc for MAXI J1348-630, with a strong upper limit of 5.3 ± 0.1 kpc. Further distance estimates show that MAXI J1348-630 reached 17% of the Eddington luminosity at its outburst peak, and the luminosity during the soft-to-hard state transition was $2.5\% \pm 1.5\%$ of the Eddington limit.

3 Black Hole Mass Measurement

3.1 Dynamical Methods

Black hole mass measurement is a complex and critical problem in astronomy. For stellar-mass black holes, the most easily observable systems are those forming binaries with ordinary stars. The most common mass measurement method utilizes the motion characteristics of the visible star to determine the primary star’ s (black hole’ s) mass, typically requiring optical observations to determine the companion’ s motion. In such systems, the companion star’ s radial velocity exhibits periodic variations as it orbits the black hole, allowing us to derive the primary star’ s mass using Kepler’ s laws. The mass function is given by:

$$f(M) = \frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \frac{P_{\rm orb} K_2^3}{2\pi G} \tag{1}$$

where M_1 and M_2 are the masses of the primary and companion stars, i is the binary system’ s inclination, $P_{\rm orb}$ is the companion’ s orbital period, K_2 is the velocity semi-amplitude, and G is the gravitational constant. For companion stars with multi-wavelength observational data, we can use spectral energy distribution fitting to obtain the companion’ s parameters and derive relatively accurate black hole mass estimates. However, in most cases, insufficient observational data necessitate numerous assumptions. Assuming accretion occurs through Roche lobe overflow, we can calculate the companion star’ s mass and radius.

Using MAXI J1820+070 as an example, we briefly introduce the estimation process [?]. [Figure 1: see original paper] shows the observed periodic radial velocity curve of the companion star, from which we can fit to obtain information such as a period of (0.68549 ± 0.00001) d and a velocity semi-amplitude of (417.7 ± 3.9) km $\rm s^{-1}$, yielding a mass function of $(5.18 \pm 0.15) M_\odot$. Spectral analysis reveals the companion’ s spectral type as K3-K5. According to stellar accretion theory [?], when the companion fills its Roche lobe, the orbital period and stellar mean density relate as:

$$\bar{\rho} = 3M/(4\pi R^3) = 35/(8G) P_{\rm orb}^{-2} \approx 110 \text{ g cm}^{-3} P_{\rm orb}^{-2}(\text{h}) \tag{2}$$

where R is the stellar radius. K3-type dwarfs typically have a mean density of 2.7 g $\rm cm^{-3}$ [?], giving a period of about 6.4 h. Given MAXI J1820+070’ s orbital period of (0.68549 ± 0.00001) d, the companion must clearly be an evolved star to fill its Roche lobe. Evolved companions are not uncommon in accreting binaries. Patterson et al. [?] photometric results show a period of (0.703 ± 0.003) d; the difference between photometric and orbital periods is due to the long superhump period caused by precession of the binary’ s accretion disk. Using the relationship between these periods [?], we obtain a mass ratio of 0.12. While Torres et al. [?] discussed many scenarios in their estimation, we provide a simpler calculation here. Based on Frank et al. [?], the relationship between companion mass and period gives a companion mass of approximately $1.72M_\odot$. Assuming an inclination of 77° and substituting into the mass function yields a compact object mass of about $8.27M_\odot$, consistent with Torres et al. [?]' s value of 7-8 $M_\odot$.

The above example using MAXI J1820+070 briefly introduces one method for estimating black hole X-ray binary masses, which primarily relies on optical observations of the visible companion star to obtain required parameters. In another scenario, if periodic dips appear in X-ray light curves, this period can be considered the orbital period, and similar estimation methods can be applied, though with more assumptions and greater uncertainties. For example, when estimating MAXI J1803-298' s mass using this method, the X-ray light curve shows 7 h periodic variations, with velocities derived from optical observations. Using this information yields a mass range of 3-10 $M_\odot$; specific details can be found in Sánchez et al. [?].

Dynamical methods can yield relatively precise black hole mass measurements because they directly utilize motion characteristics of the companion star in binary systems. By measuring periodic variations in radial velocity, we can determine the primary star' s (black hole' s) mass. This process is based on Kepler's laws using parameters like the mass function. However, despite theoretical validity, practical observations present difficulties that limit its application. A major limitation is that many X-ray binary systems lack high-quality observational data for their optical counterparts. In many cases, strong accretion disk radiation or obscuration effects make accurate detection of the companion star' s optical features difficult. This prevents obtaining sufficient information through traditional optical observations, affecting accurate measurement of the companion' s motion. While dynamical methods are theoretically robust, practical applications must overcome optical observational challenges. To compensate for these limitations, researchers must seek alternative methods to estimate black hole mass, such as using periodic features in X-ray light curves. However, these methods' applicability and accuracy depend on various factors, including accretion disk properties and system geometry, resulting in greater uncertainties and lower reliability in mass estimates. In summary, although dynamical methods provide an effective approach to black hole mass measurement, limitations in observing optical counterparts of many X-ray binary systems significantly restrict this method' s application, prompting continuous exploration of alternative observational techniques.

3.2 Spectral Fitting

In the previous section, we discussed black hole mass calculation through radial velocity measurements. Additionally, X-ray telescopes alone can provide approximate black hole mass ranges. In X-ray astronomy, primary obtainable information includes X-ray variability and energy spectra. Spectral fitting to derive various parameters is a common and widely applied method, particularly for black hole binaries lacking dynamical studies. Using simple models can yield black hole mass, though often with large errors. For example, using the nthcomp and kerrbb model combination for MAXI J1803-298 [?] gave a mass range of $7.9^{+1.6}_{-1.2} M_\odot$, significantly larger than the $8.5 - 16 M_\odot$ value from Sánchez et al. [?], mainly due to uncertainties in distance and different assumed inclination ranges during model fitting.

When studying MAXI J1535-571, Shang et al. [?] adopted the Two-Component Advective Flow (TCAF) model for spectral fitting. The TCAF model originates from solutions of radiation hydrodynamics equations, where the "hot" Compton cloud in previous models is replaced by a region formed by the accumulation of low-viscosity (subcritical), low angular momentum, and optically thin matter behind a centrifugal barrier. This region is called CENBOL (CENtrifugal pressure-supported BOundary Layer), and this material is termed the sub-Keplerian or halo accretion component. The other component of the accretion flow is high-viscosity, high angular momentum, geometrically thin, and optically thick Keplerian disk material immersed within the halo component. In this model, the Keplerian disk is naturally truncated at the shock location, which is also the outer boundary of CENBOL. Low-energy (soft) thermal photons from the Keplerian disk interact with CENBOL (composed of hot electrons), emitting high-energy (hard) photons through repeated inverse Compton scattering processes that cool CENBOL. Some emitted hard photons are reflected by the Keplerian disk, and this iterative process self-consistently produces a so-called reflection component. This model can provide relatively accurate accretion parameters in many black hole X-ray binary sources and has therefore been used to study MAXI J1535-571' s properties.

For a black hole binary system, if sufficient dynamical studies have determined the mass, this parameter serves as an input in the model. However, MAXI J1535-571 lacks relevant dynamical studies, making mass an unknown quantity treated as a free parameter during model fitting. [Figure 2: see original paper] shows the evolution of relevant parameters throughout the outburst, with black hole mass as a free parameter but with fitted results roughly between 8.44 and 9.72 $M_\odot$, averaging $8.9 \pm 1.0 M_\odot$ across the outburst.

Another well-studied source is MAXI J1348-630. Jana et al. [?] also used the TCAF model to fit X-ray observational data throughout this source' s outburst, similarly treating mass as a free parameter to obtain a best-fit value, with results shown in [Figure 3: see original paper]. The mass fitting results remained relatively stable throughout the outburst, staying between 8.44 and 9.72 $M_\odot$, with an average black hole mass of $9.1^{+1.6}_{-1.2} M_\odot$. For this source, Tominaga et al. [?] used the simpler kerrbb model for fitting. Since many parameters in this model are coupled, mass cannot be accurately determined. With distance fixed at 4 kpc, masses obtained under given sets of spin and inclination were $7 M_\odot$ ($a = 0$, $i = 0^\circ$), $14 M_\odot$ ($a = 0$, $i = 60^\circ$), $18 M_\odot$ ($a = 0.998$, $i = 0^\circ$), and $76 M_\odot$ ($a = 0.998$, $i = 60^\circ$). Soria et al. [?] used optical and X-ray observational data of MAXI J0637-430 to well constrain black hole parameters, combining radiation characteristics of inner and outer disks with optical He II \$ \$4686 features to constrain the black hole mass range to 4-7 $M_\odot$.

3.3 Quasi-Periodic Oscillations

Quasi-periodic oscillations are commonly observed in black hole X-ray binaries. They appear as narrow peaks in Fourier power density spectra calculated from rapidly varying light curves, indicating quasi-periodic variability in the light curves. Studying this phenomenon helps us understand black hole accretion processes, construct physical images of geometric structures around black holes, and measure fundamental black hole parameters. Numerous methods have been developed for QPO research. Chen et al. [**?**, **?**] developed wavelet analysis methods for QPO analysis based on Insight-HXMT observations of MAXI J1535-571, finding positive correlations between QPO signal frequencies and mean photon count rates above 10 keV, implying QPO signals are related to coronal activity. Jin et al. [**?**] used Insight-HXMT data to conduct detailed studies of QPO phenomena during GX 339-4' s outburst. Zhu et al. [**?**] performed timing analysis of MAXI J1803-298 based on Insight-HXMT observations, investigating relationships between QPO phenomena and energy. Numerous additional studies have used QPOs to investigate black hole surrounding geometry and disk-corona evolution. This paper focuses on detailing the basic process of using QPOs to measure black hole mass.

Black hole mass estimates from spectral fitting are largely correlated with the accuracy of other parameters. Titarchuk et al. [**?**] developed a scaling technique for determining black hole mass, building on Shaposhnikov et al. [**?**]. GRO J1655-40 is a Galactic black hole binary source whose mass, distance, and orbital inclination have been precisely determined through dynamical methods. Fitting the outburst spectrum using the BMC (bulk-motion Comptonization) model [**?**] to describe the Comptonized component, this model depicts Compton scattering of soft photons by relativistically moving matter. Model parameters include the characteristic blackbody temperature of the soft photon source, spectral (energy) index, and irradiation parameter characterizing the illumination of the moving matter flow by the thermal photon source. It must be emphasized that this model is not a simple superposition of power-law and thermal components but represents a self-consistent convolution. Bulk-motion upscattering and Compton recoil combine to produce a hard spectral tail, which combined with the thermal component yields the classic high/soft state spectrum of black hole accretion. The scaling technique primarily requires spectral index and model normalization parameters. Many QPO phenomena were discovered during this source' s outburst, and fitting QPO frequencies revealed strong correlations with spectral index and normalization parameters.

Shaposhnikov et al. [**?**] found similar correlations in black hole binary sources including Cygnus X-1, GX 339-4, 4U 1543-47, XTE J1550-564, XTE J1650-500, H 1743-322, and XTE J1859-226, with results shown in [Figure 4: see original paper]. The plots with frequency on the horizontal axis present data for mass determination using the scaling method, while those with BMC normalization on the horizontal axis present data for distance determination using the scaling method.

The core idea of the scaling method is based on using a source with determined mass and clear evolutionary process as a reference, comparing it with new data to obtain masses of new sources. As mentioned, GRO J1655-40’ s parameters have been precisely determined through dynamical methods, making it the reference source, with other sources as targets. We briefly introduce the specific methodology. First, define a scaling factor:

$$s_\nu = \frac{\nu_r}{\nu_t} = \frac{M_t}{M_r} \tag{3}$$

where ν represents QPO frequency, M is mass, and subscripts r and t denote reference and target sources, respectively. This definition is based on the inverse relationship between low-frequency QPO frequencies and central black hole mass [**?**]. The results in [Figure 4: see original paper] all show similar functional relationships: monotonic increase before reaching a specific frequency (cutoff frequency ν_{tr}), then smoothly transitioning to a horizontal line near this frequency. Based on this characteristic, we select the following function for fitting:

$$f(\nu) = A - D\ln[\exp((\nu_{\mathrm{tr}} - \nu)/B) + 1] \tag{4}$$

where A and B are slopes. On the other hand, for $\nu \ll \nu_{\mathrm{tr}}$, $f(\nu) \approx A$, and for $\nu \gg \nu_{\mathrm{tr}}$, $f(\nu) \approx A - D$. From this asymptotic behavior, parameters A, B, and D can be interpreted. A equals D, revealing that parameter A corresponds to the value where the spectral index remains constant. Parameter B is introduced to control the speed of functional form transition. Considering the defined scaling factor, the transformation yields:

$$M_t = M_r s_\nu = M_r \frac{\nu_{\mathrm{tr;t}}}{\nu_{\mathrm{tr;r}}} \tag{5}$$

where M_t and M_r are target and reference source masses, and $\nu_{\mathrm{tr;t}}$ and $\nu_{\mathrm{tr;r}}$ are target and reference source cutoff frequencies, respectively. This method can determine target source mass based on observed correlations between QPO frequency and spectral index, given a reference source. As mentioned, relationships exist not only between spectral index and frequency but also between model normalization parameters and frequency, with the latter usable for distance estimation using consistent methodology, which we won’ t elaborate on further. We compare some results with dynamical measurements in Table 1.

4 Black Hole Spin Measurement

Spin is a fundamental physical quantity of black holes that affects spacetime around them. Spin magnitude influences the innermost stable orbit around the black hole, thereby affecting the accretion process. Therefore, spin is also an important physical quantity to consider when studying black hole accretion disk properties and evolution. Two widely applied methods for measuring black hole spin currently exist: the thermal continuum fitting method and the X-ray reflection feature fitting method. Additionally, there are methods using QPOs to measure black hole spin, but these have high requirements for observed QPOs, limited applicability, and have not been widely adopted. Thus, the following sections focus on introducing the two mainstream methods.

4.1 Thermal Continuum Fitting

The thermal continuum fitting method is based on the fact that black hole spin affects inner disk temperature, which is highest during black hole accretion. Since spin influences the location of the innermost stable circular orbit, it affects the inner edge position of the accretion disk. Under the context of specific accretion disk models, this influence can be quantified, enabling spin determination. This method is particularly suitable for systems with geometrically thin, optically thick, steady accretion disks and weak X-ray coronae. The accretion disk structure is calculated by Novikov et al. [**?**], with main model assumptions being steady state, constant inward mass flow (i.e., negligible mass loss due to disk winds), angular momentum loss through internal disk stresses (i.e., negligible external torque due to large-scale magnetic fields), and locally radiated energy in the flow. Finally, an inner boundary condition must be specified for the disk model, typically assuming internal stress vanishes at the innermost stable circular orbit (the so-called zero-torque boundary condition).

Applying the thermal continuum fitting method to measure spin requires several elements. First, the system description must conform well to the disk model proposed by Novikov et al. [**?**], meaning no (or weak) disk winds and spectra dominated by thermal radiation from the optically thick accretion disk. Then models with color correction factor $f_{\rm col}$ are used for fitting, a function derived from detailed radiative transfer calculations [**?**]. Black hole X-ray binaries cycle through different states during outbursts, including the so-called thermal dominant state [**?**], which closely resembles the aforementioned disk model. Therefore, for stellar-mass black holes, we can monitor and wait for the system to enter the thermal dominant state before using the obtained spectrum to determine spin.

Insight-HXMT’ s exceptional detection capabilities across a broad energy range provide significant advantages for spectral research, particularly in studying black hole X-ray binary spins through spectroscopy. MAXI J1820+070 is a Galactic black hole X-ray binary that outburst on May 11, 2018, exceeding 4 Crab units in brightness and becoming one of the brightest X-ray transient sources [?]. Guan et al. [?] analyzed MAXI J1820+070' s spectrum during the soft state (from MJD 58310 to MJD 58380), conducting detailed analysis of 49 observations from Insight-HXMT. Table 2 shows the models and energy bands used in the study, with continuum fitting employing both low-energy and medium-energy bands, demonstrating Insight-HXMT's advantage of wide energy coverage in spectral research. The main parameters required in the models are black hole mass $M = 8.48M_\odot$, inclination $i = 63^\circ$, and distance $D = 2.96$ kpc [?].

We present the fitting results in [Figure 5: see original paper]. The results show a clear evolutionary trend in spin during the selected time period. However, since the physical spin evolution timescale for stellar-mass black holes due to accretion is approximately 3×10^5 yr [?], we infer that MAXI J1820+070' s spin evolution is clearly non-physical and must be related to problems in estimating the innermost stable circular orbit radius, i.e., related to R_{in} in model M1. [Figure 5: see original paper] indeed shows R_{in} decreasing around MJD 58330, then remaining stable in the third epoch. Therefore, during the third epoch the disk extends to the inner stable circular orbit radius, and spin values obtained during this period ($a^* = 0.2^{+0.2}_{-0.3}$) are reliable.

Zhao et al. [?] also measured MAXI J1820+070' s spin using continuum fitting, studying spectra in intermediate and soft states with both non-relativistic (constant$TBabs$(diskbb+powerlaw)) and relativistic (constant$TBabs$simpl*kerrbb2) models. TBabs describes interstellar medium absorption of X-rays, simpl is an empirical model describing Compton scattering, and kerrbb2 is an improved version of the multi-blackbody disk model that more accurately simulates radiation from rotating black hole accretion disks through a hardening factor. The final spin parameter range was $a^* = 0.14 \pm 0.09$, showing basic consistency with Guan et al. [?]' s results.

In addition to MAXI J1820+070 research, spins of other sources have been measured using Insight-HXMT spectral observations, such as GRS 1915+105, MAXI J1348-630, and Cygnus X-1. We list only these sources' results below.

Zhao et al. [?] used Insight-HXMT observations of Cygnus X-1 from August 24, 2017, to August 5, 2018, employing both non-relativistic (constant$TBabs$(diskbb+powerlaw)) and relativistic (constant$TBabs$simpl*kerrbb) models for spectral fitting. They reported a spin of $a^* > 0.967$ (under different mass-distance parameters), confirming this is an extreme spin black hole. Wang et al. [?, ?] used Insight-HXMT observations to study GRS 1915+105' s spectral characteristics throughout the observation period, finding spectra could be well fitted with a combined model containing disk components (diskbb/kerrbb) and power-law components (simpl). The black hole spin lower limit from the kerrbb model was 0.9990, close to the maximum value of 1, confirming GRS 1915+105 as an extreme spin black hole. Wu et al. [?] used Insight-HXMT observations in the 2-20 keV range from MJD 58588 to MJD 58596 to measure the spin of the stellar-mass black hole in MAXI J1348-630 through continuum fitting, confirming this source' s spin value as $a^* = 0.42^{+0.13}_{-0.50}$. Yorgancioglu et al. [?]

used Insight-HXMT and Neutron star Interior Composition Explorer (NICER) spectral data to measure 4U 1543-47' s spin through thermal continuum fitting, obtaining a spin result of $a^* = 0.65^{+0.14}_{-0.24}$. Subsequently, Chen et al. [?] fitted Insight-HXMT spectra of this source in the soft state, selecting 11 observations and considering uncertainties in black hole mass, distance, and orbital inclination on spectral fitting. They performed fitting with 50 mass values in the 8-11 $M_\odot$ range, 50 distance values in the 6-9 kpc range, and 100 uniformly distributed inclination values in the 20-42° range. [Figure 6: see original paper] shows the final spin distribution from fitting 11 observed spectra, yielding a spin result of $a^* = 0.456 \pm 0.126$ (68% confidence level).

4.2 Reflection Component Fitting

The X-ray reflection model applies to optically thick, geometrically thin accretion disk systems, measuring spin through gravitational redshift of spectral lines near the innermost stable orbit. Therefore, it is suitable for systems with accretion rates between 0.01-0.3 times the Eddington rate, though this limit can extend to near the Eddington limit when accretion energy is partially transferred to the corona. Most Seyfert galaxies, moderately luminous quasars, and black hole X-ray binaries in high-luminosity hard states are believed to be in this accretion rate range.

In active galactic nuclei and some black hole X-ray binaries, their X-ray power-law components can extend to 100 keV, comprising a large fraction of total luminosity. For active galactic nuclei, optically thick accretion disks can produce quasi-blackbody spectra; for stellar-mass black holes, quasi-blackbody spectra temperatures are generally around 1 keV. Early black hole studies recognized that a hot, high-energy corona must exist above the accretion disk, producing hard X-rays through inverse Compton scattering of disk thermal radiation. X-rays generated in the corona subsequently irradiate the accretion disk, causing photoionization of some material in the optically thick disk. Therefore, the disk' s surface layer radiates an energy spectrum rich in X-ray fluorescence and recombination emission lines, commonly called the X-ray reflection spectrum, featuring many soft X-ray emission lines, iron emission line features, and a peak formed by iron photoionization and Compton scattering.

The observed X-ray reflection spectrum is distorted by Doppler effects from orbital motion of material in the inner disk and gravitational redshift from the black hole. These effects are stronger closer to the black hole. On the side of the accretion disk moving toward the observer, emission lines form a sharp blue-shifted peak, while material near the black hole creates an extended redshifted wing. Assuming a black hole spin of 0.9, the result is shown in [Figure 7: see original paper]. The X-ray reflection spectrum is truncated at the innermost stable orbit; inside this orbit, accretion material density drops sharply due to radial acceleration, leading to complete photoionization of electrons in the plasma. Therefore, the innermost stable orbit and black hole spin manifest through the intensity of Doppler and gravitational broadening effects in the

X-ray reflection spectrum.

By convolving the X-ray reflection spectrum with relativistic (Doppler or gravitational) broadening and redshift effects, precise models of accretion disk reflection spectra have been constructed. Overall, disk reflection models mainly include the following parameters: accretion disk inclination to the observer, inner disk ionization parameter, accretion disk elemental abundance (primarily iron abundance), spectral index of X-ray continuum irradiating the accretion disk, and black hole spin. Black hole mass is independent of the disk reflection spectrum model because the accretion disk' s velocity field and gravitational potential are dimensionless when expressed in gravitational radii.

Liu et al. [**?**] studied Insight-HXMT observations of the X-ray binaries MAXI J1535-571 and 4U 1630-472 during their 2017 and 2020 outbursts. They first fitted spectral data using constant$tbabs$nthcomp, finding clear structures at 5-7 keV. As shown in [Figure 8: see original paper], obvious iron emission line features exist between 5-8 keV, confirming the presence of reflection components in these two sources, followed by final fitting using the relxillCp model. relxillCp [**?**] is a widely used model for describing reflection spectra. At 90% confidence level, the fitting results are: MAXI J1535-571 spin $a^* = 0.9916 \pm 0.0012$, and 4U 1630-472 spin $a^* = 0.817 \pm 0.014$. Song et al. [**?**] used reflection models to fit Insight-HXMT observations of MAXI J1348-630, with best-fit results showing this source' s spin as $a^* = 0.82^{+0.04}_{-0.03}$. Finally, we present in the black hole spin parameter measurement results obtained from Insight-HXMT observations using both continuum fitting and reflection component fitting methods, along with energy band information.

5 Summary and Outlook

We briefly introduced relevant research methods and progress in measuring stellar-mass black hole masses and spins. For black hole mass measurement, we described three methods. Currently, results obtained through dynamical methods are considered most accurate. We also used MAXI J1820+070 as an example to demonstrate main procedures and results—if sufficient optical observations provide companion star parameters and orbital inclination, black hole mass can be well determined. In contrast, results from spectral fitting and QPO methods have larger uncertainties, making precise measurements difficult. Particularly for the source MAXI J1348-630 we listed, spectral fitting gave a mass of about $9.1M_{\odot}$, while the QPO method gave $14.8M_{\odot}$. Currently, our understanding of QPO phenomena remains incomplete, with many unresolved questions about the relationship between QPO origins and black hole surrounding environments and their physical properties. First, QPO origin mechanisms remain unknown, likely involving complex dynamical processes of matter in black hole accretion disks and observational effects. Second, QPO characteristics such as frequency and amplitude may be closely related to properties of black hole environments. Understanding matter distribution, geometric structure, and accretion disk and corona shapes near black holes is crucial for interpreting QPO phenomena. Meanwhile, QPO frequencies may have some relationship with black hole spin and mass. Through more accurate black hole mass measurements and extensive QPO observational data, we hope to establish more precise connections between them. In summary, comprehensive understanding of QPOs has potential importance for black hole mass measurement. Through in-depth QPO research, we hope to achieve more precise black hole property measurements. Insight-HXMT’ s time resolution is very suitable for QPO research and long-term monitoring, and it will play a significant role in this area in the future.

Black hole spin research has always been a very popular topic. We introduced the two mainstream methods for measuring black hole spin—thermal continuum fitting and reflection component fitting—and briefly described important measurement results obtained using these methods with Insight-HXMT. Insight-HXMT’ s broad energy band characteristics enable better constraints on many model fitting parameters, yielding more credible results. In the thermal continuum fitting method, we briefly introduced two results from MAXI J1820+070 studies, which obtained basically consistent results. Many other works have used Insight-HXMT spectra meeting model assumptions to measure spins of other sources such as GRS 1915+105, MAXI J1348-630, and 4U 1543-47, with basically similar procedures. Reflection component fitting for spin measurement is also a widely applied field for Insight-HXMT data. We mainly introduced the theoretical basis and briefly described fitting results for MAXI J1535-571 and 4U 1630-472.

Since Insight-HXMT officially began scientific observations on December 1, 2017, it has produced massive observational data, conducting long-term monitoring of multiple transient sources. Further in-depth mining of these data can help us better understand black hole physical properties. The future Einstein Probe satellite will be able to systematically discover and explore high-energy transient sources, even searching for X-ray signals from gravitational wave sources, greatly enhancing our understanding of extreme compact objects and their merger processes. Additionally, polarization observations of black hole transient sources can reveal properties of accretion disks and corona structures around black holes. Combined with Insight-HXMT’ s broad energy band, this can provide a relatively complete picture of geometric structures around black holes. Future astronomy is gradually entering the multi-messenger era, meaning astronomical research will no longer rely solely on single-type observational data but will require comprehensive multi-wavelength information. In the past, X-ray observations have been one of the main methods for studying transient sources. Development of new-generation astronomical observation equipment provides more observational means, including radio, optical, infrared, and gravitational waves. By integrating observational data from different wavelengths, we can more comprehensively understand black hole properties and physical processes. Through this multi-wavelength comprehensive observational approach, we hope to solve many outstanding questions in black hole research and gain deeper understanding of their formation, evolution, and interaction with surrounding environments. This will advance our scientific understanding of one of the most mysterious and fascinating objects in the universe to new heights.

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