Mass Measurement of Black Hole X-ray Transient Sources (Postprint)

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Full Text

Preamble

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Mass Measurements of Black Hole X-ray Transients

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Abstract

To date, 72 black hole X-ray transients and candidates have been detected, of which 19 have been dynamically confirmed. These transients are X-ray binary systems composed of stellar-mass black holes and low-mass companion stars. Measuring the fundamental parameters of stellar-mass black holes not only enhances our understanding of binary evolution and black hole formation but also provides crucial evidence for key questions in the field, such as whether a strict mass gap exists between stellar-mass black holes and neutron stars. This review introduces the basic theory of black hole X-ray binaries, describes in detail the common methods and software used to measure stellar-mass black hole masses, analyzes potential sources of error in dynamical modeling, and finally summarizes the statistical properties of the existing sample of black hole X-ray transients while offering perspectives on future research directions.

Keywords: X-rays; black hole binaries; transients; dynamical studies

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1 Introduction

One of the most famous predictions of Einstein' s general relativity (GR) is the existence of black holes (BHs). In a black hole, gravity completely dominates, creating a spacetime singularity within [1]. The essential attribute of a black hole is its event horizon, an immaterial surface that bounds the interior region from which no communication with external spacetime is possible. The extremely strong gravitational field of black holes provides astronomers with a unique laboratory to observe and study high-energy physical phenomena in the universe, such as accretion, relativistic jets, and gamma-ray bursts. Consequently, black holes play important roles in many areas of astrophysical research, including massive star evolution, X-ray binaries, and active galactic nuclei.

Black holes are the simplest macroscopic objects in the universe. GR' s no-hair theorem states that when an isolated black hole forms, the final object' s properties are completely characterized by its mass, angular momentum, and charge [2, 3]. It is generally believed that charged black holes in realistic cosmic environments would be neutralized by their surroundings, so astrophysical black holes are defined solely by mass and angular momentum. Accurate measurements of these two parameters are fundamental to probing spacetime structure in strong gravitational fields. For black holes, mass is the basic parameter, and black hole identification is achieved by constraining their mass. Reliable black hole mass values are also prerequisites for measuring black hole spin through X-ray continuum fitting methods [4]. Confirmed black holes in the universe include stellar-mass black holes (mass range 3 M   100 M), supermassive black holes (mass range 10^6 M   10^{10} M), and intermediate-mass black holes (mass range 10^2 M   10^5 M) that lie between the former two categories.

Dynamical modeling is one of the primary pathways to confirm black holes. Its basic principle is to constrain the mass of the central compact object through the Keplerian motion of observable stars or gas. Currently, all stellar-mass black holes confirmed in the Milky Way reside in binary systems. By observing the companion star in a binary, we can obtain the system' s orbital solution and precisely constrain the mass of the compact object. In 1939, Oppenheimer and Snyder [5] performed the first rigorous calculation of black hole formation. When a compact object’ s mass exceeds the Tolman-Oppenheimer-Volkoff limit, it can only collapse into a black hole. The exact value of this limit remains an active research area, but it is generally believed to be no more than 3 M . Therefore, when a compact object’ s mass is reliably determined to be greater than 3 M , it can be identified as a stellar-mass black hole. Supermassive black holes are similarly identified by studying the orbits of stars around them to determine their mass lower limits. The radio source Sgr A* at the Galactic Center was the first supermassive black hole confirmed through this method, with the most recent mass measurement yielding M_{BH} = (4.297 ± 0.012) × 10^6 M [6]. For active galactic nuclei, reverberation mapping (RM) is the primary method for measuring supermassive black hole masses. Its basic principle involves measuring the velocity of broad-line region gas and its distance from the black hole through spectroscopic and variability observations, making it essentially a dynamical method [7, 8]. Recent reverberation mapping studies of dwarf galaxies have found evidence for intermediate-mass black holes at galactic centers, such as NGC 4395, whose central black hole has a mass on the order of 10^4 M . In addition to dynamical methods, gravitational wave detection has observed nearly a hundred stellar-mass binary black hole merger events [9] and found evidence for intermediate-mass black holes produced by the merger of stellar-mass black holes (for example, in the GW190521 event, the product of the binary black hole merger was a 142 M black hole [10, 11]). Gravitational lensing methods can also be used to probe isolated black holes in the universe [12].

The physical processes around black holes of different masses exhibit remarkable similarities. Meanwhile, compared to supermassive black holes, stellar-mass black holes have shorter variability timescales, allowing astronomers to conduct in-depth studies of their properties through various accretion mechanisms [13]. Stellar-mass black holes are important for many areas of astronomy. For instance, they are one of the final products of massive star evolution, and the collapse of their progenitor stars enriches the universe with heavy elements [14]. Black hole mass can also reflect information about the progenitor star’ s mass and wind loss. A rich sample of stellar-mass black holes helps us understand how massive stars end their lives and transform into black holes. The mass distribution of stellar-mass black holes in galaxies has complex and close relationships with the number and evolution of massive stars, the energy sources of supernova explosions, and the boundary between neutron stars and black holes. Furthermore, complete binary orbital parameters are crucial for understanding compact binary evolution theory and comparing the merits of various models [15–17]. X-ray binary systems with known three-dimensional space velocities can provide further constraints on black hole formation mechanisms, allowing us to explore the kicks experienced during black hole formation and providing evidence for binary evolution and supernova models [18].

Stellar-mass black holes detected through gravitational waves follow different mass distributions from those confirmed dynamically, suggesting they may represent different black hole populations. To date, stellar-mass black holes confirmed dynamically are primarily located in X-ray binary systems [19]. Most black hole X-ray binaries are first discovered through X-ray outbursts and then confirmed as stellar-mass black holes through dynamical modeling. After such outbursts, these binary systems typically return to a weak X-ray radiation state on timescales of months to years—the "quiescent state." Consequently, these X-ray binaries are called black hole X-ray transients (XRT). Black hole X-ray transients constitute the main body of stellar-mass black holes confirmed dynamically to date. This review will focus on the dynamical modeling and mass measurement of black hole X-ray transients.

2.1 History of X-ray Binary Research

Isolated black holes are difficult to detect through observable radiation, making binary systems composed of black holes and normal stars effective pathways for finding and observing black holes. When a black hole resides in a close binary system and actively accretes matter from its companion, it produces bright X-ray radiation that is easily detectable in the X-ray band. Therefore, the first compelling evidence for a stellar-mass black hole came from observations of the X-ray binary Cygnus X-1 [20, 21]. X-rays are high-energy radiation released when companion star matter is transported through the accretion disk around the black hole and heated to extremely high temperatures, providing extremely valuable information for in-depth investigation of black hole properties and surrounding accretion behavior. Through detailed analysis of these X-ray signals, we can constrain multiple parameters of black hole binary systems based on their light curves and energy spectra. X-rays also help reveal accretion disk structure, temperature distribution, thickness, and matter transport processes, while observed rapid X-ray variations and outburst activities help scientists understand various aspects such as instabilities and turbulence within the accretion disk [19]. The optical radiation of Cygnus X-1 primarily comes from its companion star, and observations of optical band spectra enable measurement of the companion’ s radial velocity and physical parameters (such as mass), thereby allowing estimation of the black hole mass through dynamical modeling.

X-ray binaries are binary systems with a neutron star or black hole as the primary and a normal star as the companion. Based on the companion’ s mass, they are divided into high-mass X-ray binaries (HMXB) and low-mass X-ray binaries (LMXB). HMXB companions are typically O/B-type massive stars with masses M 10 M . Strong stellar winds from the companion directly flow toward the compact object, which accretes matter through wind accretion, producing continuous X-ray bright sources. Cygnus X-1 and the second black hole X-ray binary discovered later—LMC X-3 in the Large Magellanic Cloud [22]—both belong to this category. However, among HMXB systems confirmed in the Milky Way, only Cygnus X-1 is a black hole system; most known HMXBs are neutron star binaries. LMXB companions are mostly G/K/M-type stars (mass less than about 1 M). After the companion’ s material fills its Roche lobe, it is transported to the accretion disk through Lagrange points. The third black hole binary system discovered, A 0620-00, is a representative source of black hole LMXBs. Unlike Cygnus X-1, it is not a persistent X-ray source. A 0620-00 was first detected through an X-ray outburst event, with peak brightness on the order of 10^−9 W • m^−2 [23]. After the outburst, over approximately one year, A 0620-00’ s brightness gradually returned to quiescent X-ray levels, eventually stabilizing at 10^−17 W • m^−2 and becoming a relatively faint X-ray source [24]. For the X-ray outbursts from black hole LMXBs that last for months, the driving force is widely believed to originate from some physical instability mechanism within the accretion disk [25, 26]. During this process, when the accretion mass flow provided by the companion to the black hole is insufficient, matter in the outer accretion disk begins to accumulate because internal material cannot continuously and effectively transport angular momentum outward through viscous mechanisms to move toward the black hole center. After reaching a critical point, the accretion disk’ s equilibrium is disrupted, triggering a large-scale release of matter and energy—this is the X-ray outburst we observe [27]. This outburst mechanism helps us understand various astrophysical processes such as accretion disk dynamics, matter transport, and interactions between compact objects and their companions. Consequently, black hole LMXBs exist as X-ray transients [19]. Such systems spend most of their time in X-ray quiescent states (with typical X-ray luminosities below 10^{25} J • s^−1).

The spatial distribution differences of these two types of X-ray binaries in the Milky Way reflect their associations with different stellar populations. HMXBs tend to be associated with young stars and are commonly found in the galactic disk regions, which often contain abundant gas and dust and thus active star formation. LMXBs are more concentrated in the central bulge region of the Milky Way and within globular clusters, which contain large populations of old stars that are more likely to form LMXB systems over long evolutionary timescales.

2.2 X-ray Spectral Properties of Black Hole Binaries

The X-ray energy spectra of black hole binaries can typically be decomposed into thermal and non-thermal components. The thermal component primarily originates from blackbody radiation of the accretion disk with characteristic temperatures near 1 keV. The non-thermal component mainly comes from inverse Compton scattering, manifesting as a power-law spectrum. X-ray photons with power-law spectra irradiating the accretion disk are reflected by it. Although this accretion disk reflection component is ubiquitous, it is more easily observed in black hole binaries with smaller accretion disk inclinations (i.e., smaller angles between the disk normal and line of sight) [28]. In addition to these continuum spectral features, black hole binary X-ray spectra also contain line features, such as relativistically broadened Fe Kα emission lines. Current research is exploring the feasibility of using Fe Kα fluorescence lines to measure black hole mass [29]. The companion star in black hole binary systems may produce narrow Fe Kα emission lines when irradiated by X-rays. If the narrow line component can be separated from the observed Kα emission line, the companion’ s radial velocity curve can be generated. The feasibility of this method depends on other system parameters such as mass ratio q and orbital inclination i. Additionally, practical implementation faces limitations such as shielding by complex stellar wind configurations. Nevertheless, in the era of high-resolution X-ray astronomy represented by micro-calorimeters, if the feasibility of such methods can be observationally confirmed, it will significantly improve the precision of stellar-mass black hole mass measurements.

3 Mass Measurement of Black Hole X-ray Transients

Dynamical modeling of black hole binaries is primarily accomplished through optical spectroscopic and photometric observations of the companion star. Unlike conventional observations, dynamical observations uniquely focus on time-domain analysis, requiring multiple measurements over extended periods to ensure coverage of most orbital phases, thereby enabling accurate modeling of periodic radial velocity curves and light curves. Photometric studies measure periodic variations in the system’s optical brightness, while spectroscopic studies primarily measure the line center shifts of absorption lines from the companion star’ s atmosphere (corresponding to radial velocity) and their broadening (corresponding to the companion’ s rotational velocity). The companions in black hole HMXBs are O/B-type stars that dominate the system’ s optical radiation. For black hole LMXBs, during outbursts, the optical radiation from the low-mass companion is completely overwhelmed by the bright accretion disk. Only during X-ray quiescent states can the companion’s optical radiation be detected, enabling dynamical modeling through optical spectroscopic and photometric observations to measure the black hole mass. Therefore, optical observations for dynamical studies of black hole X-ray transients must be conducted during their X-ray quiescent states.

3.1 Methodology

Dynamical studies of binary systems rely on Kepler’ s third law of motion, expressed in the form of the mass function defined by equation (1):

$$f(M) = \frac{PK_2^3}{2\pi G} = \frac{M \sin^3 i}{(1+q)^2}$$

This equation naturally applies to compact object binary systems, where M represents the mass of the compact object, and the defined mass function f(M) represents the lower limit of the compact object’ s mass. If this lower limit exceeds 3 M , the compact object is identified as a black hole. Note that equation (1) implicitly assumes a circular orbit, which is a reasonable assumption because the orbital circularization timescale for X-ray binaries is much shorter than their expected lifetimes [30].

Starting from the definition of the mass function, the process for measuring black hole mass in X-ray transients follows these steps: (1) Identify features in the companion star' s optical spectrum, determine its spectral type, and select appropriate stellar spectral templates; (2) Fit the companion' s radial velocity measured from optical spectra covering multiple orbital phases to obtain its semi-amplitude K2 and orbital period P, then calculate the compact object' s mass function f(M); (3) Measure the companion' s projected rotational velocity v sin i from optical spectra to calculate the mass ratio q = M_c/M; (4) Obtain the optical light curve through photometry, model the companion' s ellipsoidal modulation to derive the binary orbital plane inclination i, and finally calculate the black hole mass M.

The period P can also be obtained from optical light curves. However, in certain special cases (see Section 3.2.2), the photometric period derived from light curves does not reflect the true orbital period and must be precisely constrained through fitting of the companion' s radial velocity curve. We elaborate on these steps in detail below.

3.1.1 Measuring P and K2 from the Companion' s Radial Velocity Curve

We first select appropriate template spectra that have absorption line features nearly identical to the companion star for measuring radial and rotational velocities. The most effective technique is cross-correlation spectroscopy. Specifically, we can obtain a series of stellar spectra of known spectral types using telescopes or directly select spectra from the PHOENIX stellar spectral template library published by Husser et al. in 2013 [32]. This work first performs cross-correlation analysis between the average spectrum of the black hole binary system and numerous template spectra to select the spectrum with the highest correlation as the template for subsequent processing. Then, each spectrum of the black hole binary is cross-correlated with the template spectrum to measure the corresponding radial velocity [33]. Many software packages can perform cross-correlation analysis between spectra, such as IRAF/fxcor [34, 35], all based on the method proposed by Tonry and Davis [36]. The specific process involves setting a series of velocity values as the velocity difference between the template and actual spectra, then correcting wavelengths according to the Doppler effect, and finally calculating the correlation between the two spectra using a cross-correlation function. The velocity value with the best correlation is the relative radial velocity between the two spectra.

For black hole binaries, the radial velocity obtained directly from cross-correlation between observed and template spectra is the companion' s velocity relative to the ground-based telescope and must be corrected to the heliocentric reference frame. We typically use the pyasl.helcorr module in the PyAstronomy library [37] for this operation, which implements velocity correction by inputting telescope coordinates and observation times along with Earth’ s motion. Finally, the thejoker package [38] in Python can be used to fit the companion’ s radial velocity curve. This is a Monte Carlo sampler specifically designed to simulate radial velocity curves of binary systems, selecting optimal parameters (i.e., model curves) based on ˆ2 results between different model curves and actual data points. The fitted parameters include the orbital period P and companion radial velocity semi-amplitude K2 required for mass function calculation.

[Figure 1: see original paper] shows an example of radial velocity fitting, where the horizontal axis represents phase distribution after period folding and the vertical axis shows radial velocity data and residuals from the model curve. The black line is the optimal radial velocity model curve obtained from fitting. This example demonstrates the radial velocity curve of the black hole X-ray transient Nova Muscae 1991, consisting of radial velocity values measured from 72 spectra obtained over two observing nights, covering complete orbital phases [31]. The mass function f(M) is the basis for identifying stellar-mass black holes and can typically be measured with a precision of a few percent. This requires the spectrograph’ s resolving power to be higher than $\lambda/\Delta\lambda$ 1500 [13], where λ represents wavelength and $\Delta\lambda$ is the minimum resolvable wavelength interval of the spectrograph. Additionally, to more accurately fit the radial velocity curve, the orbital phases corresponding to spectroscopic observations should uniformly cover the complete orbital period.

3.1.2 Measuring Mass Ratio q through v sin i

The mass function f(M) only provides a lower limit for the compact object’s mass. The accurate value of the compact object’ s mass also requires measurements of the mass ratio q and binary orbital plane inclination i. The primary method for determining the mass ratio is measuring the rotational broadening (v sin i) of absorption lines from the companion’ s photosphere. This method exploits the fact that for short-period, mass-transferring binary systems, the companion often fills its Roche lobe and is tidally locked, with its rotation period equal to its orbital period, making its absorption lines significantly broader than those of slowly rotating single stars. Under spherical approximation, the relationship between rotational broadening and binary mass ratio can be quantified by the formula [39]:

$$v \sin i \approx 0.462 K_2 q^{1/3} (1+q)^{2/3}$$

Therefore, by measuring v sin i and combining it with K2 obtained from previous steps, we can constrain the range of q.

The measurement of v sin i can be performed using the optimal subtraction method implemented by the molly software [40]. The basic idea is to process template spectra (such as broadening absorption lines) to simulate the actual companion star spectrum. When comparing the optical spectrum of a black hole binary with the corresponding template (i.e., a spectrum of a field star with the same spectral type), the black hole binary’ s spectrum shows broader and shallower absorption lines. The line broadening is caused by the faster rotation of the tidally locked companion as described above, while the shallowness results from additional continuum emission from the accretion disk that often dilutes the companion’ s absorption line features in black hole binary systems. The optimal subtraction method can simultaneously measure the companion’ s rotational velocity v sin i and the spectral fraction of the companion fs (0 < fs < 1), with the accretion disk fraction being fd = 1 - fs.

The specific procedure involves setting a series of rotational velocity v sin i values, broadening the template spectrum’ s absorption lines according to the v sin i values, multiplying by the fs factor, and subtracting the resulting spectrum from the black hole binary’ s spectrum. Ideally, if the set v sin i and fs values match the actual parameters of the black hole binary system, the resulting residual spectrum will contain no companion absorption lines, only noise. We perform a ˆ2 test on the residual spectrum, and through ˆ2 minimization, we find the optimal broadening velocity v sin i while also obtaining the companion fraction fs in the spectrum. Based on the measured v sin i value, the mass ratio q can be calculated using equation (2). [Figure 2: see original paper] shows a graphical illustration of measuring v sin i for the black hole X-ray transient Nova Muscae 1991 using the optimal subtraction method. The middle spectrum is the template spectrum. After processing through the aforementioned steps and subtracting from the upper black hole binary spectrum, the residual spectrum at the bottom contains only noise (plus non-companion features like accretion disk emission lines and interstellar medium absorption) when the most appropriate v sin i and fs values are used.

Several technical details require attention when measuring v sin i and fs using the optimal subtraction method. Black hole binary spectra often contain interstellar medium absorption features and accretion disk spectral features (such as Balmer emission lines), requiring these wavelength ranges to be masked. Additionally, during the rotational broadening measurement process that places template and target average spectra in the same rest frame, we need to apply limb darkening correction to the template spectrum and also blur the template spectrum according to exposure time and instantaneous radial velocity to simulate the smearing effect caused by absorption line center movement during continuous exposure. In black hole X-ray transients, typical companion rotational broadening ranges from 30 150 km · sˆ−1, requiring high spectral resolution to obtain accurate v sin i values; otherwise, measurement errors will be large, affecting the accurate calculation of the mass ratio.

3.1.3 Constraining Inclination i through Ellipsoidal Modulation of Light Curves

Binary system orbital inclinations are typically determined by fitting ellipsoidal modulation models to optical or near-infrared band light curves. First, to obtain the target source' s magnitude in photometric images, aperture photometry can be performed using the IRAF/DAOPHOT tool, typically choosing an aperture size of 1.5 times the point source image' s full width at half maximum (FWHM). In special cases where nearby sources contaminate photometry, image subtraction can be used for more accurate variability measurement. This widely-used data processing method in galaxy research focuses on variable components by subtracting constant parts from images. Common software includes SFFT (saccadic fast fourier transform) [41], HOTPANTS, and ZOGY. These methods match point spread functions between images at different times and subtract pixels based on matched PSF characteristics, with SFFT performing these operations in Fourier space for faster processing.

After obtaining the light curve, periodicity analysis of photometric results is needed. We recommend using the Lomb-Scargle method [42] to find the time frequency with the strongest periodic signal. This method, based on Fourier transform algorithms, first calculates power at different temporal frequencies, then phase-folds the data according to the derived period to nicely display the periodic light curve.

In black hole X-ray transients, the companion star fills its teardrop-shaped Roche lobe. At different orbital phases, the surface area of the companion facing the observer varies, accompanied by non-uniform surface brightness distribution, resulting in a characteristic double-peaked modulation phenomenon in the light curve (called "ellipsoidal modulation"). [Figure 3: see original paper] shows the light curve of the black hole X-ray transient GRO J1655-40, where the horizontal axis represents orbital phase, the vertical axis shows V-band magnitude, the solid line is the best-fit light curve model, and black dots represent data including error bars. This is a very typical example of ellipsoidal modulation. Within one orbital period, two equal brightness peaks represent the phases when the companion' s surface area facing the observer is maximum (i.e., when the companion' s radial velocity absolute value is maximum), while two unequal brightness troughs represent phases when the companion appears in front of (shallower trough) or behind (deeper trough) the black hole. The amplitude of this modulation has a close functional relationship with the binary system' s orbital inclination i: larger inclination i means the binary orbital plane' s normal is closer to perpendicular to our line of sight, i.e., the orbital plane faces the observer "edge-on," resulting in larger ellipsoidal modulation amplitude. GRO J1655-40 is a black hole X-ray transient with an F6 IV intermediate-mass companion whose system orbital inclination has been precisely measured [43]. However, more common are black hole X-ray transients with fainter K-M type companions, where light curves may be severely contaminated by other non-stellar light sources (see Section 3.2).

To obtain accurate light curve models, researchers must consider the local intensity at each point on the companion’ s surface, affected by factors such as limb darkening and gravity darkening. Limb darkening refers to the phenomenon where regions near the edge of a star’ s surface appear darker than the central region, while gravity darkening refers to the phenomenon where a star’ s equatorial region expands due to centrifugal force, decreasing density and causing reduced surface temperature and brightness. By comprehensively considering the distribution of local intensity over the Roche lobe geometry and correcting for effects from limb darkening and gravity darkening, light curve models can be obtained. Kurucz and NEXTGEN atmospheric models [44] are commonly used for optimal results. Various methods exist for measuring binary system orbital inclinations through ellipsoidal modulation, including the ELC (eclipsing light curve) [44], W-D (Wilson-Devinney) [45], or PHOEBE [46] software packages.

3.1.4 Other Feasible Methods

In some systems with highly active accretion disks, black hole X-ray binary optical light curves may exhibit “superhump” modulation, where the period derived from the light curve slightly deviates from the orbital period (see Section 3.2.2 for explanation). For such systems, if the mass ratio q is in the range 0.04 0.30, there exists a relationship between period and q:

$$\Delta P = (P_{sh} - P_{orb})/P_{orb} \simeq (0.216 \pm 0.018)q[47, 48]$$

This empirical formula was obtained by fitting strongly correlated data and is physically reasonable because superhump modulation from orbital precession should not occur when q = 0. This method can both test the reasonableness of q values and directly estimate them.

In addition to fitting ellipsoidal modulation of light curves, binary orbital inclination i can also be constrained through several other methods. For black hole binary systems where radio jets can be detected, the angle between the jet and observer’ s line of sight is used to substitute for orbital inclination, based on the assumption that the jet is perpendicular to the binary orbital plane. However, evidence suggests that jets are not necessarily perpendicular to the accretion disk direction. Poutanen et al. [49] demonstrated using the black hole binary MAXI J1820+070 as an example that the line of sight, jet, and orbital plane normal point in different directions.

Additionally, Hα emission line features produced in the accretion disk around the black hole can be used to measure mass ratio q and orbital inclination i. Based on existing results from 11 black hole X-ray transients, Casares [50] used least squares fitting in 2016 to derive the relationship:

$$\log q = -(6.88 \pm 0.52) - (23.2 \pm 2.0) \log W_{FWHM}$$

where DP and W_{FWHM} represent the double-peak separation and full width at half maximum of the Hα emission line profile, respectively. There is also a correlation between Hα double-peak trough depth T and orbital inclination i [51]:

$$i = (93.5 \pm 6.5)T + (23.7 \pm 2.5); \quad T = 1 - 2^{1-(DP/W)}$$

where W represents the FWHM value of a single Gaussian curve when fitting the Hα emission line with a double-Gaussian symmetric model. However, parameters in these methods are fitted from limited data points and may require more data to verify their accuracy.

3.2.1 Accretion Disk Optical Radiation Contamination

As seen in equation (1), black hole mass calculation depends on sin^3 i, so uncertainties in black hole mass measurements mainly originate from errors in measuring the system orbital plane inclination. The primary source of error for orbital inclination i is contamination of the system' s light curve by optical radiation from the accretion disk, causing rapid, non-periodic variations in the light curve. High time-resolution optical monitoring of black hole X-ray transients shows that quiescent-state systems can exhibit significant optical variability on timescales as short as minutes [52, 53]. This variability shows no obvious regularity and interferes with light curve modeling (both periodicity analysis and ellipsoidal modulation analysis). Such irregular variability is more prominent in black hole binary systems with cooler companions, and its characteristic timescale increases with longer orbital periods. These features suggest the variability likely originates from the accretion disk. Lower companion temperature means its thermal radiation is weaker than the accretion disk' s radiation, while in systems with hotter companions, the companion' s radiation increases the system' s total luminosity, making accretion disk variations relatively less significant. Although no definitive evidence currently points to the physical mechanism of such rapid variations, evidence shows that irregular variability amplitude correlates positively with the proportion of accretion disk radiation measured spectroscopically: the higher the accretion disk' s contribution to the system' s optical radiation, the larger the irregular variability amplitude [54], confirming that this irregular variability mainly comes from the accretion disk.

Assuming accretion disk optical radiation follows a negative power-law spectrum [55], previous work chose to observe and analyze in the near-infrared band, ignoring accretion disk radiation in this band to facilitate precise extraction of binary orbital parameters through ellipsoidal fitting. However, near-infrared observations of some black hole X-ray transients show that the accretion disk' s contribution in the near-infrared spectrum remains high, and its contamination of light curves cannot be ignored [56, 57], challenging the validity and reliability of using only near-infrared light curves for pure ellipsoidal fitting [31].

Research proposing solutions to accretion disk contamination originated from over a decade of optical variability monitoring of the quiescent black hole X-ray transient A 0620-00. Cantrell et al. [58] identified three main states in A 0620-00’ s optical light curve: “active state,” “loop state,” and “passive state,” as shown in [Figure 4: see original paper]. These three states can be distinguished based on average magnitude, color, and variability amplitude at different times and also apply to other black hole binary systems. In the passive state, the binary system’ s radiation flux is lowest and exhibits minimal irregular variability, with its light curve most closely approximating ideal ellipsoidal modulation. As the system evolves toward the loop and active states, it brightens while irregular variability increases significantly, making the ellipsoidal modulation signal less apparent. Therefore, light curves in the passive state are most suitable for ellipsoidal modulation fitting to determine binary system orbital inclinations. Cantrell et al. [59] reanalyzed A 0620-00’ s V, I, and H-band light curves in the passive state and found the system’ s orbital inclination to be about 10° higher than previous results after applying ellipsoidal fitting. Earlier studies directly performed ellipsoidal fitting on near-infrared light curves without considering contamination from light sources other than the companion (such as the accretion disk). Consequently, neglecting accretion disk contamination effects could lead to overestimation of the black hole mass in A 0620-00 by about a factor of two. This study emphasizes that to accurately measure binary system orbital inclinations, it is crucial to use light curves with minimal flickering activity during passive states. Another study of black hole X-ray transients also shows that quiescent black hole binary systems have a long-term gradual brightening trend in the optical band [60], indicating gradual accumulation of accretion disk density and increasing radiation [26, 27]. When black hole X-ray transient systems just enter quiescence after X-ray outbursts, their optical radiation is faintest and accretion disk contamination is minimal; thus, this period is the optimal time for dynamical studies of black hole X-ray transients through optical spectroscopy and photometry [60].

3.2.2 Superhump Modulation Phenomenon

Superhump modulation is another effect that introduces systematic errors in binary orbital inclination. This is caused by period offsets due to precession of the accretion disk. The disk’ s precession period is much longer than the binary orbital period, and the mixing of these two periodic signals causes us to detect a signal in the light curve with a period slightly longer than the orbital period, which we call the superhump period (P_{sh}). The relationship between these three can be expressed as: P_{pr} = (P_{sh}^−1 - P_{orb}$^{-1)}$−1 [61-63], where P_{pr} represents the disk precession period, P_{orb} and P_{sh} are the orbital and superhump periods, respectively. Superhump modulation causes long-term variations in the shape and amplitude of ellipsoidal light curves, potentially creating offsets between orbital inclinations constrained from such ellipsoidal modulation curves and true inclination values. The period measured in this case is inaccurate and should not be used to constrain inclination. The period from radial velocity curves is unaffected by superhump modulation and represents the true orbital period.

3.2.3 Systematic Errors in Measuring v sin i

When modeling data to fit orbital parameters, models often cannot perfectly reproduce binary motion. Therefore, researchers typically assume reasonable approximations that have minimal impact on results in areas beyond observational and theoretical reach. When a star fills its Roche lobe, it is very close to the compact object and no longer maintains a perfect spherical shape, with the side near the compact object being stretched. However, when measuring rotational broadening, a model spectrum with fixed velocity broadening is typically used without considering the star' s actual shape variation with phase, so the derived v sin i values often underestimate the mass ratio q [40]. Additionally, commonly used limb darkening and gravity darkening laws [64, 65] may lead to underestimation of true rotational broadening, resulting in underestimated mass ratios [66]. Despite these potential systematic error sources, statistical errors in measuring v sin i are usually larger than systematic errors [13]. Furthermore, considering that companions in black hole X-ray transients are much less massive than black holes (q 1), systematic errors in q have relatively small impact on final black hole mass estimates.

4 Statistical Properties of Black Hole X-ray Transients

The statistical properties of black hole X-ray transients can provide important clues about black hole formation mechanisms. Over the past decades, using dynamical studies of these systems, researchers have constructed models for the mass and spatial distributions of stellar-mass black holes [67, 68], which can be compared and validated against predictions from supernova theory and observations of gravitational wave sources [15, 69].

4.1 Statistics of Confirmed Black Holes

summarizes the basic parameters of the 19 currently known dynamically confirmed black hole X-ray transients (sorted by discovery time). Typically, uncertainties listed in the table are 1σ standard deviations, though orbital inclination errors sometimes provide data at 90% or 95% confidence levels. Since some sources have been observed multiple times over past decades, multiple measurement results often exist for the same parameter, with varying credibility due to observational limitations. Parameter values in favor results with cleaner, more reliable data—for example, higher spectral resolution and signal-to-noise ratio for measuring radial velocity and companion rotational broadening, and lower irregular variability amplitude in light curves used to constrain system orbital inclination. The mass function is obtained from the companion' s radial velocity curve during X-ray quiescence. However, for the GX 339-4 system, although the companion was not yet detected in quiescence in the earliest studies, researchers derived a lower limit for the mass function using emission lines excited from the companion' s irradiated hemisphere during outburst [70]. Subsequently, in 2017, Heida et al. [71] performed more complete parameter constraints on this system using its companion spectrum. Binary system orbital inclinations primarily come from model fitting of ellipsoidal light curves in quiescence, but for GRS 1915+105, the inclination was inferred from radio jet direction [72]. For a few sources without obvious X-ray eclipses in their light curves but with measured mass ratios, upper limits on orbital inclination can be provided.

[Figure 5: see original paper] shows the historical changes in the number of discovered and confirmed black hole X-ray transients, also indicating the operational periods of major X-ray satellites. In the past decade, more than ten black hole X-ray transient candidates have been added, yet only two have received dynamical confirmation: MAXI J1305-704 and MAXI J1820+070. MAXI J1820+070 exhibits relatively special properties, still producing smaller outbursts three to four years after its X-ray outburst, indicating its accretion disk may remain relatively active.

As seen from , there are no systems with particularly high orbital inclinations among confirmed black hole X-ray transients. In fact, this characteristic is also observed in other black hole candidates, possibly implying observational selection effects or methodological biases. Some studies suggest that because outwardly curved, highly obscuring accretion disks exist around black holes, the central X-ray source in high-inclination binary systems is effectively blocked, making direct observation difficult [74]. This warped disk phenomenon may be related to accretion processes and surrounding environments, such as heat distribution within the disk and magnetic field structure, collectively causing the warped morphology that affects observations of such high-inclination systems. The importance of discovering high-inclination black hole X-ray transients lies in the fact that uncertainties in black hole mass from inclination are small in these systems, promising relatively precise black hole mass measurements. Therefore, they will play key roles in constructing the mass distribution of compact objects. Swift J1357.2-0933 has a very broad Hα emission line profile, extremely low peak X-ray brightness, and brightness trough signals in its optical light curve, suggesting it may be a high orbital inclination black hole X-ray transient [75]. However, it shows no observed orbital modulation in X-rays (neither eclipses nor X-ray dimming features), and no strong emission or absorption lines were found in X-ray spectra obtained by the XMM-Newton satellite, casting doubt on its high-inclination hypothesis [76].

4.2 Spatial Distribution in the Milky Way

[Figure 6: see original paper] shows 35 black hole X-ray transients and candidates with distance estimates from a galactic polar perspective [73]. Dynamically confirmed black holes are marked with solid orange circles, while yellow star symbols represent massive black hole candidates not yet dynamically confirmed. Notably, about half of the dynamically confirmed black holes are distributed within a small region about 4.5 kpc from the Sun, indicating that interstellar extinction severely affects dynamical confirmation of more distant black holes. Interstellar extinction refers to intensity attenuation and color changes when starlight passes through Milky Way dust clouds, posing a serious challenge to methods relying on optical spectroscopy and photometry to determine black hole dynamical masses. Additionally, an obvious regular distribution pattern is observed (see [Figure 6: see original paper]): confirmed black holes (orange symbols) are not uniformly distributed throughout the Milky Way but are concentrated near specific spiral arm structures. This discovery provides new clues for further exploring the distribution patterns of black holes in galactic evolution and their relationship with star-forming environments. Based on this pattern, for black hole binary systems with large distance uncertainties, we can set credible distance ranges according to the approximate distance ranges of their located spiral arms, effectively improving the accuracy and reliability of distance parameter determinations for such black hole systems. Black hole X-ray transient candidates (yellow symbols) are mainly distributed in the bulge, possibly related to higher stellar densities in this region.

[Figure 7: see original paper] shows the distribution of black hole X-ray transients perpendicular to the galactic plane, where the horizontal axis represents the distance from the transient to the galactic plane and the vertical axis represents its space-time density. The vertical distribution of black hole binary systems theoretically should follow a similar exponential law as ordinary stars, i.e., spatial density decreases exponentially with increasing height above the galactic plane [97]. As shown in [Figure 7: see original paper], the black solid line is the fitting result for exponential decay. Furthermore, modern X-ray astronomy detection techniques for searching and identifying black hole binary systems show no obvious bias or selection effect in the vertical direction relative to the galactic plane [67]. That is, as long as certain X-ray radiation intensity conditions are met, the probability of detection is relatively high regardless of the black hole binary system' s location above the galactic plane. Therefore, the existing sample can reflect the vertical distribution characteristics of black hole X-ray transients in the Milky Way. Gandhi et al. [98] explored the relationship between this spatial distribution characteristic and the orbital periods of black hole X-ray transients, finding an anti-correlation: the farther from the galactic plane, the shorter the system' s orbital period. They proposed two possible physical mechanisms to explain this phenomenon: (1) Black hole X-ray binary systems originate in the galactic disk, and their spatial scattering is caused by birth kicks, with only compact binary systems surviving strong kicks; (2) Binaries originate in the galactic halo, and interactions in globular clusters shorten system orbital periods. We anticipate that more correlations between spatial distribution and binary parameters will be discovered in the future, providing important observational constraints on binary system formation and evolution.

4.3 Black Hole Mass Distribution

Based on data from , the black hole mass distribution in X-ray transients is derived (shown in [Figure 8: see original paper]), with most black hole mass uncertainties within 2 M . For black holes in that only provide a mass range (often with large error bars), we use the midpoint of that range as the black hole mass value. The neutron star mass distribution [17] is also marked in [Figure 8: see original paper] for comparison. An obvious gap exists in the (2 5) M interval between neutron star and black hole mass distributions, known as the "mass gap" problem [67, 99]. Whether this mass gap truly exists has been extensively studied. This issue is important not only because it represents a blank region but also because some theoretical predictions for supernova explosions generating stellar-mass black holes suggest more black holes should exist in this interval [15]. Özel et al. [67] demonstrated that selection effects from detection sensitivity to X-ray outbursts cannot fully explain the existence of the "mass gap" when considering black hole mass measurement errors. This provides constraints for supernova explosion models (e.g., references [16, 17, 100, 101]). From an observational perspective, Kreidberg et al. [102] pointed out that accretion disk contamination in optical/infrared bands for black hole X-ray transients (see Section 3.2) causes underestimation of binary system orbital inclinations, leading to overestimation of black hole masses. After considering this issue, black hole masses in some black hole X-ray transients, such as GRO J0422+32, may fall within the mass gap region. Precise mass measurements of more stellar-mass black holes can make the statistical distribution of black hole masses more accurate, provide more samples for mass gap research, and further constrain supernova explosion mechanisms and binary evolution.

5 Summary and Outlook

Black hole X-ray transients are X-ray binary systems composed of stellar-mass black holes and low-mass stars. This review introduced the background and dynamical research methods for such systems. We primarily search for low-mass black hole X-ray binaries from detected X-ray outbursts. Generally, binary systems return to X-ray quiescence within months after outbursts, allowing us to study the entire binary system' s orbital parameters from the companion' s spectrum and photometry. Combining Kepler' s third law and stellar atmospheric models, we derive the mass range of the central compact object. If the measured mass exceeds 3 M , we can confirm the compact object as a black hole. For different systems, the measurement process inevitably involves more or less error, often determined by the nature of observational data itself. We must carefully identify and select the most reliable data, analyzing reasonable error ranges to ensure result reliability. Additionally, we performed statistical analysis on the black hole X-ray transient sample, studying its spatial distribution within the Milky Way and black hole mass distribution patterns. Stellar-mass black holes and their candidates tend to be distributed near galactic spiral arms and bulge regions, with most systems concentrated near the disk plane. For the existing sample' s mass distribution, the mass gap between neutron stars and black holes remains significant, but whether this gap is caused by sample incompleteness and selection effects remains to be determined.

For the existing sample, many black holes or candidates in X-ray transient systems have not received sufficient mass constraints and require further photometric monitoring to select phases with less accretion disk contamination for precise dynamical modeling. Regarding X-ray outburst frequency, we find that most black hole transients have only been observed to outburst once, with repeated outbursts being rare. The relationship between X-ray outburst periods and black hole fundamental parameters has also been studied. Lin et al. [103] found that a 12-hour orbital period is a turning point for outburst frequency: transient systems with periods below this show only one outburst in X-ray observational history, while sources with multiple outbursts generally have orbital periods longer than 12 hours. This phenomenon may be related to different mass transfer rates from companions at different orbital periods. Therefore, continued X-ray monitoring in the future is of great significance for studying the evolution of black hole X-ray transients.

Stellar evolution theory predicts that the number of stellar-mass black holes that may exist in the Milky Way is greater than 10ˆ8 [104]. In comparison, the proportion of discovered stellar-mass black holes and candidates in the Milky Way is extremely small. Traditional stellar-mass black hole detection methods rely on X-ray observations. X-ray satellites with higher detection sensitivity and wider field coverage, such as China' s Einstein Probe, are expected to discover more black hole X-ray binaries. Meanwhile, given that most black hole binaries are in X-ray quiescence (or even lack mass exchange), breaking free from X-ray observation limitations and directly searching for and confirming black holes from a dynamical perspective is an effective means to substantially expand the stellar-mass black hole sample. An increasing number of telescopes are now operational, such as China' s Large Area Multi-Object Spectroscopic Telescope (LAMOST), China Space Station Telescope (CSST), Multiplexed Survey Telescope (MUST), and Europe's Gaia satellite, which can provide large-scale stellar spectroscopic, photometric, and astrometric databases through surveys, thereby discovering more black holes and candidates and promising to produce representative samples of stellar-mass black holes to provide important evidence for black hole formation and evolution studies. Algorithms and software for processing large-scale survey data are also flourishing. Based on these survey databases, several black hole binaries or candidates have already been discovered, such as LB-1 [105, 106], 2MASS J05215658+4359220 [107], V723 Mon [108], Gaia BH1 [109], BH2 [110], and BH3 [111]. Such systems typically have long orbital periods (hundreds of days to decades) and high orbital eccentricities (up to 0.5). Comprehensive analysis combining stellar-mass black holes discovered through optical surveys with samples obtained through gravitational wave detection (nearly 100 cases), gravitational lensing, X-ray transients, and other methods can greatly expand the stellar-mass black hole sample, yield more accurate stellar-mass black hole mass distributions, and provide better constraints on black hole formation mechanisms.

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