Advances in the Study of X-ray Reflection Components in Black Hole X-ray Binaries (Postprint)

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Abstract

Reflection is an important tool for studying black hole X-ray binaries, facilitating the understanding of numerous physical processes unique to strong gravitational fields. Integrating observational and theoretical research, we discuss recent advances in the X-ray reflection component in black hole X-ray binaries: (1) introducing the relevant physical processes and spectral morphological characteristics of the reflection component; (2) reviewing the reflection component and its features discovered in recent years across different spectral states of black hole X-ray binaries; (3) reviewing the developmental history of reflection models, with emphasis on existing models, particularly the recently developed relxill model; (4) exploring difficulties and challenges in reflection component research, such as uncertainties in accretion disk thickness and coronal properties; (5) providing prospects for future research on the reflection component in black hole X-ray binaries.

Full Text

Preamble

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Research Progress of X-ray Reflection Components in Black-Hole X-ray Binaries

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Abstract: Reflection is an important tool for studying black-hole X-ray binaries, helping to understand many physical processes unique to strong gravitational fields. This paper synthesizes observational and theoretical research to discuss recent advances in X-ray reflection components in black-hole X-ray binaries: (1) we introduce the relevant physical processes and spectral characteristics of reflection components; (2) we review reflection components discovered in recent years across different spectral states of black-hole X-ray binaries and their features; (3) we review the developmental history of reflection models, focusing on existing models with particular attention to the recently developed relxill model; (4) we explore challenges and difficulties in reflection studies, such as uncertainties in accretion disk thickness and coronal properties; and (5) we discuss future research directions for reflection components in black-hole X-ray binaries.

Keywords: black-hole X-ray binaries; accretion; reflection

1 Introduction

Black-hole X-ray binaries are important high-energy astrophysical systems consisting of a stellar-mass black hole and a companion star. The black hole accretes matter from its companion, and through viscous processes, forms an accretion disk orbiting the black hole [1]. As accreted material flows into the black hole, part of the gravitational energy is released as radiation, primarily in the X-ray band. Over the past several decades, through observations and theoretical simulations, researchers have gradually deepened their understanding of the accretion and radiation properties of black-hole X-ray binaries, revealing physical processes unique to strong gravitational fields. With improvements in X-ray telescope precision, energy coverage, and sensitivity, more data on black-hole X-ray binaries have become available, including X-ray spectra, timing, and polarization information, providing more detailed information for studying these systems.

In recent years, research on reflection components in black-hole X-ray binaries has attracted widespread interest. Reflection components form when high-energy X-rays irradiate the accretion disk and are reflected. Here, reflection refers to the process where material in the accretion disk interacts with incident X-rays (including photoelectric absorption and Compton scattering) and re-radiates. Reflection components thus provide rich information for studying the physical properties of accretion disks (such as density, temperature, and composition) and the geometry of accretion flows. Reflection components generally originate from the inner regions of the accretion disk, very close to the black hole, and are therefore subject to strong gravitational field effects. Consequently, reflection components can be used to measure important parameters such as black hole spin. However, analyzing reflection components requires modeling various influencing factors, posing challenges to model accuracy and precision.

2 Physical Basis of Reflection Components

[Figure 1: see original paper] shows a schematic diagram of reflection component production, where photons from the incident source (generally the corona) irradiate the accretion disk surface, interact with material in the disk, and are ultimately re-radiated.

Note: Corona photons irradiate the accretion disk surface, interact with disk material, and are re-radiated to form the reflection spectrum.

2.1 Interaction of X-rays with Matter

When high-energy X-rays irradiate the accretion disk, they interact with atoms, ions, and electrons in the disk, primarily through photoelectric absorption and Compton scattering. Photoelectric absorption, also called bound-free absorption, occurs when an atom or ion absorbs a photon, causing a bound electron to gain energy and escape as a free electron. Absorption only occurs when the photon energy is greater than or equal to the atomic energy level, and the absorption cross-section decreases rapidly with photon frequency ω to the third power. Therefore, photoelectric absorption from a given atomic energy level creates an absorption edge structure. Different atomic species have different ionization energies for their ground-state electrons. The most abundant atoms in accretion disks are hydrogen and helium, with ground-state ionization energies of 13.6 eV and 24.6 eV [2], respectively, primarily absorbing ultraviolet radiation and contributing little to X-ray absorption. Although heavy elements are less abundant, their ground-state electron ionization energies correspond to the X-ray band, making heavy elements dominate X-ray photoelectric absorption. For a given atomic species, electrons at different energy levels have different ionization energies. These processes are important for interpreting X-ray radiation from accretion disks.

Compton scattering refers to the process where X-ray photons collide with stationary or slow-moving electrons, transferring part of their energy to the electrons and changing their propagation direction. Compton scattering can thus reshape the X-ray energy spectrum. Other interactions between X-rays and matter include inverse Compton scattering and electron-positron pair production, but these effects are not important for accretion disk reflection.

2.2 Accretion Disk and Corona

In 1973, Shakura and Sunyaev [1] established the optically thick, geometrically thin disk model. In this model, the disk gas reaches local thermal equilibrium, with each local region radiating a blackbody spectrum; the total disk radiation is the superposition of blackbody radiation from all regions. The temperature of a local region relates to its radius as $T \propto R^{-0.75}$. In the quiescent state or early outburst (low/hard state) of black-hole X-ray binaries, the accretion disk is generally considered to be truncated [3]. When the inner edge of the accretion disk extends to the innermost stable circular orbit, the temperature in the innermost region can reach 1 keV for a 10 $M_\odot$ black hole. The optically thick, geometrically thin disk model applies to luminosities below $0.3L_{\rm Edd}$ (where $L_{\rm Edd}$ is the Eddington luminosity). At higher luminosities, radiation pressure increases the disk thickness, and the accretion disk is no longer geometrically thin [1, 4].

To describe accretion disks in such situations, researchers proposed the "Polish doughnuts"model [5], the slim disk model [4], and the supercritical disk model [6]. In the slim disk model, advection effects are considered, and the disk thickness is lower than in the "Polish doughnuts" model. In these models, if the viewing angle is large relative to the disk normal, the innermost region of the accretion disk may be occulted by the outer disk.

The corona refers to high-energy plasma clumps near the black hole. When soft photons from the accretion disk enter the corona, they undergo inverse Compton processes that increase their energy before radiating to infinity, producing a power-law spectrum with a high-energy cutoff: $F(E) \propto E^{1-\Gamma}$ [7], where $F(E)$ is the radiation flux and Γ is the photon index. The corona is therefore also called the Comptonization region. The corona may be the base of a jet [8, 9], an advection-dominated hot inner flow (ADAF) between the inner disk boundary and the innermost stable circular orbit [10], or hot plasma atmosphere above the accretion disk surface [11]. [Figure 2: see original paper] shows several possible coronal geometries.

2.3 Spectral Features of Reflection

When X-rays irradiate different regions of the accretion disk, both intensity and photon energy distribution vary, so each local region has its own reflection spectrum, and the total reflection spectrum is the sum of contributions from all regions. The main features of reflection spectra include fluorescence lines, Fe absorption edges, and the Compton hump [13].

When X-rays irradiate the accretion disk surface, they interact with atoms in the disk through the photoelectric effect, causing electrons to transition to higher energy levels or ionized states. When electrons return to lower energy levels, they emit photons with energies corresponding to the energy difference between the levels—these emitted photons are fluorescence lines. In black-hole X-ray binaries, fluorescence lines refer primarily to the Fe K-line series, with the Fe Kα line being the most prominent. The energy of Fe fluorescence lines varies with the ionization degree of Fe atoms, ranging from 6.4 keV for neutral Fe to 6.97 keV for fully ionized Fe. Other heavy element fluorescence or absorption lines also appear near 6 keV, but Fe fluorescence lines are more prominent because Fe is the most abundant heavy element in the universe.

Photoelectric absorption of X-rays by Fe elements creates characteristic absorption edges in the 7-10 keV range, primarily caused by K-shell electron absorption. The strength of absorption edges is affected by the Fe ionization degree at the disk surface, disk density, and the photon energy distribution of the incident spectrum. Higher disk surface temperatures lead to greater gas ionization and weaker absorption edges, while higher gas densities at the disk surface produce stronger absorption edges.

When high-energy photons above 10 keV irradiate the accretion disk, they undergo downward Compton scattering, while lower-energy photons below 10 keV experience photoelectric absorption, forming a Compton hump in the reflection spectrum above 10 keV. In black-hole X-ray binaries, the peak of the Compton hump from coronal reflection geometry typically appears in the 20–30 keV range.

Due to the strong gravitational field near the black hole, the observed reflection spectrum is generally obtained after passing through general relativistic effects (gravitational redshift, light bending, photon capture, etc.). The reflection spectrum consists of contributions from all local regions of the accretion disk, which exist in different gravitational environments. Additionally, because the accretion disk rotates around the black hole, Doppler effects must also be considered. These effects cause the observed photon energies to differ from those emitted in the disk coordinate system (see [Figure 3: see original paper]) [14]. Furthermore, due to light bending, the emission direction of photons reaching the observer in the disk coordinate system may not align with the line of sight. These effects influence Fe fluorescence lines most significantly, causing line broadening and distortion. [Figure 4: see original paper] shows the observed Fe fluorescence line structure for different black hole spins. Conversely, we can study the properties of the gravitational field near black holes by observing Fe fluorescence lines.

3 Observational Studies of Reflection Components

Reflection is an important aspect of studying black-hole X-ray binaries, providing crucial information about physical processes of accreting matter in strong gravitational fields. With the development of modern X-ray telescopes, observational studies of reflection components have made great progress, enabling deeper understanding of accretion processes and black hole properties. This chapter discusses reflection components in hard, intermediate, and soft states across different sources to explore their important role in black-hole X-ray binaries.

3.1 Reflection in Hard and Intermediate States

The capabilities of the Chandra [15] (launched 1999) and XMM-Newton (X-ray Multi-Mirror Mission) [16] (launched 2000) satellites made it possible to resolve the broad Fe fluorescence line structure in stellar-mass black holes. These satellites observed Fe fluorescence lines in outbursts of multiple black-hole X-ray binaries [17], such as Cygnus X-1, XTE J1650-500, and GX 339-4, advancing understanding of strong gravitational fields near black holes. In hard and intermediate states, Fe fluorescence lines have been extensively studied. [Figure 5: see original paper] shows the Fe fluorescence line of black-hole X-ray binary GX 339-4 in the steep power-law state observed by Chandra. The Fe fluorescence line is broad, asymmetric, and has a long redshifted tail. Only regions very close to the black hole can produce such structure, indicating that GX 339-4 is a rotating black hole with spin no less than 0.8–0.9 [18]. Additionally, Miller [17] reanalyzed ASCA/GIS (Advanced Satellite for Cosmology and Astrophysics/Gas Imaging Spectrometers) satellite (1993–2000) observations of broad Fe lines. [Figure 6: see original paper] shows Fe fluorescence lines of black-hole X-ray binaries XTE J1550-564, GRO J1655-40, Cygnus X-1, and GRS 1915+105 observed by ASCA/GIS. The spins of XTE J1550-564 and GRO J1655-40 are no less than 0.9 [19], while Cygnus X-1 and GRS 1915+105 appear to have lower spins based on ASCA/GIS Fe fluorescence lines, perhaps due to data quality issues.

NuSTAR (Nuclear Spectroscopic Telescope Array) [20] satellite (launched 2012) has a broader effective energy range of 3–79 keV and excellent energy resolution above 10 keV, enabling simultaneous study of Fe fluorescence lines, Fe absorption edges, and Compton scattering. [Figure 7: see original paper] shows Fe fluorescence lines and Compton humps of black-hole X-ray binaries V404 Cyg [21] and MAXI J1535-571 [22] observed by NuSTAR. The reflection features of V404 Cyg and MAXI J1535-571 are very clear and representative, typical of reflection features from power-law hard X-ray irradiation, with Compton hump peaks in the 20–30 keV range.

NICER (Neutron star Interior Composition Explorer) satellite [23] (launched 2017) has high signal-to-noise photon counting capability in the 0.2–12 keV band. [Figure 8: see original paper] shows fluorescence emission lines discovered by NICER in black-hole X-ray binary MAXI J1535-571 [24]. Miller et al. [24] found through spectral analysis that besides the relativistically broadened line structure from the innermost disk region, the Fe fluorescence line also exhibits an asymmetric, weak narrow-line component. They suggested this asymmetric weak Fe fluorescence line may originate from larger radii in the accretion disk, broadened by Doppler effects or weak gravitational fields, proposing that a warped disk [25] might provide a physical explanation. This demonstrates NICER’ s capability to reveal more features of both inner and intermediate disk regions.

Based on numerous observational facts, researchers have developed a mature understanding of reflection components in black-hole X-ray binaries. Hard photons from the corona irradiate the accretion disk and reflect to form reflection spectra. In low/hard and intermediate states, strong hard photon radiation indicates the corona is important during these periods, and reflection components frequently appear in these states. However, considerable controversy remains regarding coronal geometry and its evolutionary properties. Studying reflection spectra, especially their evolution, can help understand coronal geometry and physical properties. You et al. [9] studied the 2018 outburst of black-hole X-ray binary MAXI J1820+070 and found that Fe fluorescence lines and Compton humps evolve with time (see [Figure 9: see original paper]). This evolution can be described by the reflection fraction parameter (the ratio of coronal intensity irradiating the accretion disk to that radiating to infinity). They found the reflection fraction gradually decreases during the decay phase of the first outburst, indicating more coronal photons radiate to infinity than irradiate the disk. However, Kara et al. [26] found through timing analysis that the corona gradually approaches the black hole as the outburst decays. Assuming isotropic coronal radiation, more photons should irradiate the accretion disk. This contradicts the evolution of the reflection fraction, indicating the isotropy assumption is incorrect. They suggested that if the corona' s relativistic velocity along the black hole spin axis increases as it approaches the black hole, it could explain the evolution of the reflection fraction.

During reflection, features like Fe fluorescence lines are produced when hard photons from the corona irradiate the accretion disk and reflect. Therefore, reflection components should arrive at detectors later than direct coronal radiation. In 2012, Zoghbi et al. [27] first discovered Fe emission line time lags in black hole systems. In NGC 4151, they found photons at 5–6 keV lagged those at 2–3 keV and 7–8 keV by approximately 2000 s. The peak energy of the lag spectrum is lower than that of the fluorescence line (see [Figure 10: see original paper]), which they explained as photons from the redshifted tail arriving later at the detector. The lag spectrum peak shifts to lower energies at higher frequencies, consistent with relativistic expectations that the redshifted tail of Fe fluorescence lines originates from regions closer to the black hole, with greater redshift indicating closer proximity.

3.2 Reflection in the Soft State

Reflection components typically appear in low/hard and intermediate states, and are less frequently found in the soft state. However, in recent years, reflection components have been discovered in the high soft state of some black-hole X-ray binary sources. Since the hard photon component from the corona is very weak in the high soft state and cannot serve as the incident source for reflection components, other models are needed to explain reflection occurring in the high soft state. Below we enumerate reflection features in the high soft state of several black-hole X-ray binaries.

3.2.1 Black-Hole X-ray Binary XTE J1550-564 XTE J1550-564 is a Galactic black-hole X-ray binary discovered by the RXTE satellite in 1998, with a black hole mass of $(9.1 \pm 0.6)M_{\odot}$ and distance of $4.4^{+0.6}_{-0.4}$ kpc [28]. Connors et al. [28] performed detailed analysis of RXTE/PCA spectra from one high soft state observation during the 1998–1999 outburst. [Figure 11: see original paper] shows spectral fitting results using reflection models. They found the relxillNS model could fit the reflection component well. The incident spectrum in the relxillNS reflection model is a single-temperature blackbody with temperature around 1 keV, contributing 5.2% of the total flux. They interpreted the high soft state reflection component as partial disk photons being bent by the strong gravitational field back onto the disk, where reflection occurs (referred to as disk self-reflection).

3.2.2 Black-Hole X-ray Binary EXO 1846-031 EXO 1846-031 is a Galactic black-hole candidate discovered by the EXOSAT satellite in 1985 [29]. Wang et al. [29] discovered reflection components in high soft state observations from the Insight-HXMT satellite during the source' s 2019 outburst. They fitted the spectrum using multiple models; the spectral models and fitting residuals are shown in [Figure 12: see original paper]. Both relxilllp and relxillNS models could fit the reflection component well. However, they noted that using the coronal hard component as the incident source for reflection components is unreasonable in the high soft state, and suggested that disk self-reflection is a possible reflection mechanism.

3.2.3 Black-Hole X-ray Binary MAXI J1631-479 MAXI J1631-479 is a Galactic black-hole X-ray binary discovered by the MAXI satellite in 2018 [30]. Xu et al. [30] discovered very strong reflection components in the high soft state during the 2018–2019 outburst. [Figure 13: see original paper] shows the broad Fe line residual structure and correlation between Fe line flux and power-law component flux from the disk-dominated to power-law-dominated states. In the high soft state, the Fe line flux is maximum while the power-law component flux (10–79 keV) is very low. Therefore, they noted that using Comptonization region irradiation geometry to explain the high soft state reflection component is unreasonable.

3.2.4 Black-Hole X-ray Binary MAXI J0637-430 MAXI J0637-430 is a Galactic black-hole X-ray binary discovered by the MAXI satellite in 2019 [31]. Lazar et al. [31] performed detailed analysis of high soft state spectra from the 2019–2020 outburst. They found that thermal radiation from the accretion disk plus a weak thermal Comptonization component could not fit the high soft state spectra. They adopted two approaches to fit the remaining residuals: (1) adding an additional blackbody component describing radiation from the plunging region, with fitted spectrum and residuals shown in [Figure 14: see original paper]; and (2) adding the relxillNS model, considering possible disk self-reflection, with fitted spectrum and residuals shown in [Figure 15: see original paper].

3.2.5 Black-Hole X-ray Binary 4U 1543-47 4U 1543-47 is a Galactic black-hole X-ray binary and one of the few dynamically confirmed black holes [32]. Its black hole mass is $(9.4 \pm 1.0)M_{\odot}$, companion mass is $(2.45 \pm 0.15)M_{\odot}$, and distance to the source is (7.5 ± 0.5) kpc [33, 34]. During its 2021 outburst, the source' s peak intensity exceeded the Eddington luminosity [35], and it showed reflection features in the soft state [36]. The Insight-HXMT satellite conducted long-term intensive observations of the decay phase [37]. Detailed analysis of spectra provided by Insight-HXMT [37] revealed that the source remained in the soft state for an extended period during outburst decay, with strong broad Fe reflection lines present in the soft state. [Figure 16: see original paper] shows reflection features observed by Insight-HXMT in the early decay phase. During the decay, several flaring events above 15 keV occurred, but we found Fe fluorescence line intensity was independent of these hard photon flares, suggesting that using coronal irradiation models to explain soft state reflection components is unreasonable.

4 Development of Reflection Models

In 1974, Basko et al. [38] first considered both photoelectric absorption and Compton scattering simultaneously when studying X-ray reflection and reprocessing by the atmosphere of a normal companion star in X-ray binary systems. They simulated reflection spectra from hard X-ray irradiation of neutral atmospheres, where main reflection features—Fe fluorescence lines, Fe absorption edges, and Compton humps—were clearly visible. X-ray reflection studies of accretion flows near black holes began with Guilbert and Rees [39] in 1988. They noted that accretion flows near black holes could remain non-ionized while effectively radiating, producing reflection spectra when irradiated by hard X-rays.

In the innermost disk regions, hard X-ray irradiation intensity may ionize gas at the disk surface, making it non-neutral. In 1979, Ross [40] calculated spectra after hard X-rays passed through Compton-thick atmospheres. In such atmospheres, atoms with low proton numbers are ionized, resulting in many free electrons that down-Compton scatter hard X-rays, softening the emergent spectrum. These calculations were further developed to treat ionization of different atomic species more carefully, eventually evolving into the frequently used reflection spectral fitting model reflionx [41]. Ionization also affects emission line features, as discussed in García and Kallman [42].

In 1995, Tanaka et al. [43] first discovered relativistically broadened Fe fluorescence lines in observational data. In the active galactic nucleus MCG-6-30-15, they observed a very broad, asymmetric Fe fluorescence line with a redshifted tail. They noted this line most likely originated from regions between (3–10) R_s (where R_s is the Schwarzschild radius), thus being subject to strong gravitational field effects. Broad Fe fluorescence lines are also common in stellar-mass black holes [17] and neutron star systems [44], sharing the same characteristics as those in active galactic nuclei. Therefore, relativistic effects on reflection spectra are universal in compact object systems.

4.1 Hard X-ray Reflection Models

The reflection process can be divided into three steps [13]: first, irradiation of the accretion disk by the incident source; second, reprocessing and re-radiation of incident X-rays by gas at the disk surface; and third, the influence of general relativistic effects such as gravitational redshift and light bending on the radiation. For the incident source, both the shape of the incident spectrum and the irradiation intensity distribution on the disk must be considered. The irradiation intensity distribution depends on the geometry of the incident source, which has considerable uncertainty—the source may be a point source or a geometrically extended diffuse source relative to the accretion disk. Relativistic effects also play a role. If the incident source moves at relativistic speeds, beaming effects will concentrate radiation in its direction of motion. If the incident source is very close to the black hole, light bending caused by the strong gravitational field will also alter the angular distribution of radiation from the source.

To study the physical properties of reflection components, the geometry and physical properties of the accretion disk must be considered. The disk geometry may be truncated or extend to the innermost stable circular orbit; it may be geometrically thin or thick. For geometrically thick disks, the location of reflection also changes. The disk’ s temperature, density, metallicity, and ionization degree all affect the reflection spectrum. Doppler and gravitational redshift effects alter the energy distribution of the reflection spectrum. Light bending effects in strong gravitational fields cause different emission angles from each point on the disk. The reflection spectrum seen by an observer in a given line of sight is the sum of reflected radiation from different emission angles.

Since Fe fluorescence lines are the most prominent reflection features, the first relativistic reflection models focused on fitting Fe fluorescence lines. The first generation of relativistic Fe line models were diskline [45] and laor [46]; diskline applies to non-rotating black holes, while laor applies to black holes with spin 0.998. The relativistic Fe line model relline [14] works for any spin value. These models treat the angular distribution of reflected radiation in the disk coordinate system crudely (for example, in laor assuming $I_e \propto 1 + 2.06\cos\vartheta_e$, where I_e is radiation intensity in the disk frame and ϑ_e is the emission angle relative to the disk normal), leading to approximately 20% uncertainty in estimating the disk inner boundary region [47].

State-of-the-art reflection models can correctly calculate reflection spectra in the accretion disk coordinate system, including reflionx [41] and xillver [42, 48]. These models use a high-energy cutoff power-law spectrum as the incident spectrum and consider the metallicity and ionization degree of gas at the disk surface. The main parameters of these non-relativistic reflection models and their descriptions are listed in .

These non-relativistic reflection models can generate relativistic reflection spectra when convolved with relativistic smearing models. The commonly used relativistic convolution model is relconv. Due to uncertainties in incident source geometry, relconv adopts a phenomenological approach to describe the irradiation intensity distribution on the accretion disk, assuming reflection intensity decays as a power law with radius, expressed as $\epsilon \propto r^{-\epsilon}$, where ϵ is the emissivity index. For more complex irradiation geometries, relconv uses a broken power law with break radius R_{br}. The main parameters of relconv and their descriptions are listed in .

Light bending effects cause different emission angles for reflection spectra from different disk regions, but this effect is not considered in the relconv model. To address this, García et al. [49] in 2014 combined relconv and xillver to create a complete relativistic reflection model: relxill. In the relxill model, they considered emission angle differences caused by light bending, noting that without angle-resolved reflection spectra, estimates of some model parameters could be affected by systematic uncertainties with maximum deviations of 20%. Today, the relxill family of models has become one of the most commonly used reflection models.

The relxill model applies to relativistic reflection spectra from irradiated accretion disks around compact objects (black holes or neutron stars). This family of models is publicly available and can be used in Xspec; please consult its official website for details. The relxill family includes relxill [49], relxillCp, relxillNS [50], relxilllp, and relxilllpCP, among other sub-models applicable to different scenarios such as different incident source geometries, incident source spectral shapes, and disk densities. lists the main differences among these models.

The relxill family differs primarily in physical assumptions about the incident source, reflected in two aspects: incident source geometry and incident source spectrum. For geometry, there are two different descriptions. The first phenomenologically describes the distribution of reflected radiation intensity on the disk rather than assuming specific incident source geometry, with intensity varying as a power law with radius ($\epsilon \propto r^{-\epsilon}$). For more complex cases, a broken power law can be used, with r^{ϵ_1} between R_{in} and R_{br}, and r^{ϵ_2} between R_{br} and R_{out}. The second is the lamp-post geometry assumption, where the incident source is point-like and located on the black hole spin axis, irradiating the disk like a street lamp—hence the name. Models relxilllp and relxilllpCp adopt this geometry, using two parameters to describe the source geometry: (1) height h above the black hole, and (2) the source' s relativistic velocity β. These parameters jointly determine the irradiation intensity distribution on the disk. Higher source height increases the range of outer disk regions that can be irradiated but decreases irradiation intensity in inner regions ($\propto 1/h^2$). Even for an isotropic source, relativistic motion changes the angular distribution of radiation, thereby altering the irradiation intensity distribution on the disk.

For coronal spectra, the relxill family provides two options: high-energy cutoff power-law and thermal Comptonization continuum (nthcomp) [51, 52]. nthcomp is a hot electron Comptonization model that can give the coronal electron temperature. In relxillNS, the incident spectrum is a blackbody, commonly used for neutron star systems to describe irradiation of the disk by surface radiation. In the relxill models, the accretion disk is assumed to be optically thick and geometrically thin, with metallicity, ionization degree, and density as variable parameters. A major advantage of the relxill model is that the reflection fraction is one of its parameters [53]. The reflection fraction is the ratio of coronal intensity irradiating the disk to that radiating directly to infinity, thus reflecting coronal geometry and other properties. For lamp-post coronae, general relativistic effects tend to bend radiation toward the disk. Therefore, assuming isotropic coronal radiation, we expect a larger reflection fraction when the corona is closer to the black hole. Other features of the relxill family can be found in the user manual on its official website.

4.2 Soft X-ray Reflection Models

In recent years, reflection components have also been discovered in the high soft state of black-hole X-ray binaries, and some researchers [29, 30, 37] have noted that these components cannot be explained by coronal irradiation. Currently, there is considerable controversy regarding accretion disk structure and coronal properties at high luminosities. At high luminosities, the accretion disk may be thick [4, 6], yet existing reflection models assume geometrically thin disks. In reflection models constructed for black-hole X-ray binaries, coronal irradiation is assumed, with high-energy, power-law-shaped photons. However, whether coronae exist in the high soft state and in what form remains undetermined [12]. In some sources, the blackbody incident spectrum reflection model relxillNS can fit spectra well [28, 29]. Since the incident spectrum in this case is a ~1 keV blackbody, reflection is considered to be disk self-reflection. Observations of high-luminosity Galactic black-hole X-ray binaries are also rare, leaving our understanding of reflection at high luminosities limited and requiring further observational study.

5 Summary and Outlook

Reflection components are powerful tools for studying accreting black holes. The reflection process occurs primarily in the inner disk region, and reflection spectra contain information about strong gravitational fields. Therefore, analysis of reflection components can be used to study accretion processes and physical properties of black holes in strong-field regions. Over the past decade, tremendous progress has been made in reflection research, and excellent models now exist for fitting observed reflection spectra in black-hole X-ray binaries. In this article, we have reviewed progress in reflection research from observational and theoretical perspectives and introduced the commonly used relxill reflection model.

Modeling reflection requires consideration of multiple factors, including incident source geometry and radiation spectrum, accretion disk geometric features and physical properties, and effects of strong gravitational fields on reflection components. However, understanding of disk and coronal properties in the soft state of black-hole X-ray binaries, especially when sources are very bright, remains limited, posing great difficulties for studying reflection in these cases. Even the successful relxill model for low/hard and intermediate states makes many simplifying assumptions about these factors.

Reflection research depends heavily on telescope energy resolution capabilities. Microcalorimeters are the core technology for next-generation high-resolution X-ray imaging spectrometers, offering ultra-high energy resolution. They will provide high-resolution X-ray spectra and boost reflection research. The XRISM (X-Ray Imaging and Spectroscopy Mission) [54] satellite’ s Resolve payload uses microcalorimeters with an effective energy range of 0.3-12 keV and energy resolution of 5-7 eV. The Athena (Advanced Telescope for High-ENergy Astrophysics) [55] satellite’ s I-XFU (X-ray Integral Field Unit) payload also uses microcalorimeters, with an effective energy range of 0.2-12 keV and energy resolution better than 2.5 eV below 7 keV. The enhanced X-ray Timing and Polarimetry mission (eXTP) space observatory is China’ s next-generation X-ray space telescope [56], with main scientific payloads including the Spectroscopic Focusing Array (SFA), Polarimetry Focusing Array (PFA), Large Area Detector (LAD), and Wide Field Monitor. SFA has a detection band of 0.5-10 keV with energy resolution better than 180 eV, suitable for studying fluorescence lines of heavy elements; LAD has timing precision of 1.0 s and effective energy range of 2-30 keV, advantageous for studying short-timescale variability near black holes and conducting timing studies of reflection components; PFA can measure photon polarization, effectively constraining accretion flow geometry such as disk inclination. These telescopes are expected to advance understanding of reflection processes in black-hole X-ray binaries.

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