THE EMISSION FROM AN INNER DISK AND A CORONA IN THE LOW AND INTERMEDIATE SPECTRAL STATES OF BLACK HOLE X-RAY BINARIES

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ABSTRACT

Recent observations reveal that a cool disk may survive in the innermost stable circular orbit (ISCO) for some black hole X-ray binaries (BHXRBs) in the canonical low/hard state. The spectrum is characterized by a power law with a photon index $\Gamma \sim 1.5$–2.1 in the range of 2–10 keV and a weak disk component with a temperature of $\sim 0.2$ keV. In this work, we revisit the formation of such a cool, optically thick, geometrically thin disk in the innermost region of BHXRBs at the low/hard state within the context of disk accretion fed by condensation of the hot corona. By taking into account the cooling process associated with both Compton and conductive processes in a corona and the irradiation of the hot corona to the disk, we calculate the structure of the corona. For viscosity parameter $\alpha = 0.2$, it is found that the inner disk can exist for an accretion rate ranging from $M \sim 0.006$ to $0.03 M_{\text{Edd}}$, over which the electron temperatures of the corona are in the range of 1–5 $\times$ 10^9 K producing the hard X-ray emission. We calculate the emergent spectra of the inner disk and corona for different mass accretion rates. The effect of viscosity parameter $\alpha$ and albedo $a$ ($a$ is defined as the energy ratio of reflected radiation from the thin disk to incident radiation upon it from the corona) on the emergent spectra is also presented. Our model is used to explain the recent observations of GX 339-4 and Cyg X-1, in which the thin disk may exist at the ISCO region in the low/hard state at a luminosity around a few percent of $L_{\text{Edd}}$. It is found that the observed maximal effective temperature of the thermal component and the hard X-ray photon index $\Gamma$ can be matched well by our model.

Key words: accretion, accretion disks – black hole physics – X-rays: individual (GX 339-4, Cyg X-1) – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

Black hole X-ray binaries (BHXRBs) are binary star systems that are luminous in the X-ray part of the spectrum. These X-ray emissions are generally thought to be caused by one of the companion stars being a black hole accreting matter from the companion. The properties of these systems have been reviewed by several authors (Remillard & McClintock 2006; Done et al. 2007; Gilfanov 2010, p. 17). It is well known that various spectral states have been exhibited in BHXRBs. In particular, two basic X-ray spectral states are presented, with a high/soft spectral state occurring at high luminosities and a low/hard spectral state occurring at low luminosities. Generally, at the high/soft state, with a higher accretion rate, the accretion is dominantly via a standard thin disk extending to the innermost stable circular orbit (ISCO; Pringle & Rees 1972; Shakura & Sunyaev 1973; Mitsuda et al. 1984; Frank et al. 2002). The ISCO is at $3 R_S$ (where $R_S = 2GM/c^2$, $G$ is the gravitational constant, $c$ is the light speed, and $M$ is the central black hole mass) for non-rotating black holes and 0.615 $R_S$ for rotating black holes with a limiting spin rate $a_\text{sc} = 0.9982$, where $a_\text{sc}$ is the specific angular momentum (Thorne 1974). With the decline of the accretion rate to some transition rate, BHXRBs enter the low/hard spectral state, in which the standard thin disk is replaced by hot, optically thin, geometrically thick advection-dominated accretion flows (ADAFs) in the innermost region around the black hole, i.e., the thin disk truncates at some radius off the ISCO (Rees et al. 1982; Narayan & Yi 1994, 1995a, 1995b; Abramowicz et al. 1995; Narayan 2005; Narayan & McClintock 2008; Kato et al. 2008; Esin et al. 1997; Kawabata & Mineshige 2010; Qiao & Liu 2009, 2010; Zhang et al. 2010). However, the picture of a truncated outer thin disk + inner ADAF model in the low/hard state is challenged by the recent observations of some BHXRBs. Reis et al. (2010) investigate a sample composed of eight BHXRBs in the low/hard state observed with XMM-Newton and Suzaku. Although the hard X-ray continuum is characterized by a power law with a photon index in the range of $\Gamma \sim 1.5$–2.1, a thermal component with a color temperature consistent with $L \propto T^4$ is detected in all eight sources; meanwhile, a broad iron Kα fluorescence line is also observed in half of the sample. Both the $L \propto T^4$ relation and the broad iron line profile suggest that a cool disk extends to ISCO. The observed thermal component is around 0.2 keV. Observations of GX 339-4 were made with Swift and RXTE in 2007 May when the transition to the low/hard state occurred (Kalemci et al. 2007). Fits to the observed broad iron Kα line profile with a relativistic reflection model at luminosity $0.8\% L_{\text{Edd}}$ suggest that a cool disk resides in the region very close to the ISCO. A thermal component with a disk temperature $\sim 0.165$ keV at luminosity $0.8\% L_{\text{Edd}}$ is detected. The X-ray spectra are roughly characterized by a power law with a photon index $\Gamma = 1.63^{+0.04}_{-0.03}$ (Tomsick et al. 2008).

A disk accretion model maintained by the recondensation of the hot corona has been proposed to explain the presence of the cool disk in the innermost region around the black hole in the low/hard state by Liu et al. (2006) and Meyer et al. (2007). In this model, when the accretion rate decreases just below the transition rate between the high/soft state and low/hard state, as a consequence of efficient evaporation, the thin disk truncates at a distance where the maximum evaporation rate occurs (Meyer et al. 2000a, 2000b; Liu et al. 1999, 2002). The remnant disk from the truncation radius inward can be steadily
fed by the condensation of the hot corona/ADAF rather than swallowed by the black hole within the viscous timescale (Liu et al. 2007; Taam et al. 2008; Liu et al. 2011). The size of the inner remnant disk is governed by the accretion rate. The geometry of the accretion flows is allocated as an inner disk and a much cooler outer disk, which are separated by an ADAF. With a decrease of the accretion rate, the inner disk shrinks and eventually vanishes completely at a certain accretion rate.

The dynamical interaction between the inner disk and corona is established between the conductive flux from the upper corona, bremsstrahlung radiation, and vertical enthalpy flux.

For a given distance from the black hole, a fraction of the disk gas is heated and evaporated to the corona when the conduction flux is too large to be radiated away. On the other hand, a certain amount of coronal gas is cooled down, condensing to the disk if the bremsstrahlung radiation is more efficient than the conduction. At accretion rates around a few percent of the Eddington value, gas evaporates from the disk to the corona, the disk vanishes at around a few hundred Schwarzschild radii, and the coronal gas partially condenses back to the disk in the innermost region.

The cooling of the corona is classified as the conduction-dominated case and Compton-dominated case at different radii (Liu et al. 2007). Here, we follow the work of Taam et al. (2008), in which the conduction-dominated case is modified by adding the Compton cooling and the Compton-dominated case is modified by adding the conductive cooling. Meanwhile, in our calculation the irradiation of the corona to the disk is added to obtain a self-consistent disk–corona system (Liu et al. 2011). Throughout the paper, we scale some quantities as follows: \( m \) is the central black hole mass scaled with solar mass \( M_\odot \); \( \dot{m} \) is the accretion rate scaled with Eddington accretion rate \( \dot{M}_{\text{Edd}} \); \( \dot{M}_{\text{Edd}} = 1.39 \times 10^{18} \text{m s}^{-1} \); and \( r \) is the distance from the black hole scaled with Schwarzschild radius \( R_S \), \( R_S = 2GM/c^2 = 2.95 \times 10^8 \text{m cm} \). For the sake of clarity, we list the basic results of the disk–corona model in the following.

### 2.1. Corona Dominated by Conductive Cooling

In the case of conduct-domination cooling, the condensation rate is given as (Taam et al. 2008)

\[
\dot{m}_{\text{cond}}(x) = 3.23 \times 10^{-3} \alpha^{-7/3} \dot{m}^3 f(x),
\]

where \( \alpha = (q_{\text{Cmp}}/dF_*/dz) \) is the ratio of the Compton cooling rate to the conductive cooling rate, which weighs the modification of the neglected cooling process compared with the dominated cooling process. The ratio can be reexpressed as

\[
\lambda = 1.4052 \times 10^4 \dot{m} r^{-3/2} [1 - (3/r)] T_{\text{eff, max}}^{-4},
\]

where \( T_{\text{eff, max}} \) is the maximum effective temperature of the accretion disk (Taam et al. 2008). \( r_1 \) and \( r_o \) represent the size of the inner disk without and with modification in the conduction-dominated case, respectively. \( r_1 \) and \( r_o \) are expressed as

\[
\begin{align*}
\dot{m}_{\text{cond}}(x) &= 3.23 \times 10^{-3} \alpha^{-7/3} \dot{m}^3 f(x), \\
\lambda &= (q_{\text{Cmp}}/dF_*/dz) T_{\text{eff, max}}^{-4}.
\end{align*}
\]

The electron temperature distribution of the corona in the radial direction is

\[
T_{\text{ec}} = 2.01 \times 10^{10} \alpha^{-2/5} \dot{m}^{2/5} r^{-2/5} (1 + \lambda(r_o))^{-2/5} \text{K}.
\]

The bremsstrahlung luminosity from the transition layer is

\[
\frac{L_{\text{brem}}}{L_{\text{Edd}}} = 0.0642 \alpha^{-7/3} \dot{m}^{5/3} \left[ 1 - \left( \frac{3}{r_o} \right)^{1/2} \right],
\]

2. THE MODEL

The disk–corona model adopted here is based on the study of Taam et al. (2008) and Liu et al. (2011). It is assumed that an ADAF-like hot corona (described by the self-similar solution of Narayan & Yi 1995b, with \( \alpha = 0.2, \beta = 0.8 \)) lies above a thin disk. The corona is heated by the viscous release of gravitational energy of accreted gas and cooled by vertical conduction and inverse Compton scattering of soft photons emitted by the underlying disk. For the Compton cooling of the corona, the upward hard photons escape from the corona directly; the downward hard photons are partially reflected and partially absorbed by the underlying optically thick disk. The absorbed photons are reprocessed in the optically thick disk and reemitted as a thermal emission providing the soft photons for the Compton scattering in the corona. This procedure is iterated until a stable disk–corona system forms. In the vertical transition layer between the disk and the corona, an equilibrium is established between the conductive flux from the upper corona, bremsstrahlung radiation, and vertical enthalpy flux.
and the Compton luminosity from the corona is
\[
\frac{L_{\text{Cmp}}}{L_{\text{Edd}}} = 1.349 \alpha^{-7/5} m^{7/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{4} \times \int_{r_i/3}^{r_o/3} \left( 1 + \lambda \right)^{-2/5} x^{-29/10} (1 - x^{-1/2}) \, dx.
\]
\[
\times \left( \frac{T_{\text{em}, \max}}{0.3 \text{ keV}} \right)^{16/7} \left[ 1 + \frac{1}{\lambda (r_o)} \right]^{4/7}.
\]
(6)

Note that the emission from the outer pure ADAF is not included here, as it would cause the coronal luminosity to deviate from the true value when the inner disk is very small, which occurs at accretion rates less than 0.01.

### 2.2. Corona Dominated by Compton Cooling

In the case of Compton-dominated cooling, the condensation rate is given as
\[
m_{\text{cnd}}(x) = A \left[ 2B \left( \left( \frac{r_o}{r_i} \right)^{1/2} - 1 \right) - \int_{r_i/3}^{r_o/3} \left( 1 + \frac{1}{\lambda} \right)^{-2/5} \right] \times x^{1/5} (1 - x^{-1/2})^{-2/5} \, dx,
\]
(7)

where
\[
A = 6.164 \times 10^{-3} \alpha^{-7/5} m^{-2/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{-8/5},
\]
\[
B = 3.001 \alpha^{-14/15} m^{2/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{8/5} \left( \frac{r_i}{r} \right),
\]
(8)

and the condensation radius \( r_o \) meets the following requirement:
\[
r_o \left[ 1 - \left( \frac{3}{r_o} \right)^{1/2} \right]^{-4/7} = 14.417 \alpha^{-4/3} m^{4/7} m_{\text{cnd}}^{-8/21} \times \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{16/7} \left[ 1 + \frac{1}{\lambda (r_o)} \right]^{4/7}.
\]
(9)

The electron temperature distribution of the corona in the radial direction is
\[
T_{\text{em}} = 3.025 \times 10^{9} \alpha^{-2/5} m^{-2/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{-8/5} \times \left[ 1 - \left( \frac{3}{r} \right)^{1/2} \right]^{-2/5} x^{-29/10} \left( 1 + \frac{1}{\lambda} \right)^{-2/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{-8/5}.
\]
(10)

The expression of bremsstrahlung luminosity from the transition layer is the same as Equation (5), and the Compton luminosity from the corona is
\[
\frac{L_{\text{Cmp}}}{L_{\text{Edd}}} = 0.392 \alpha^{-7/5} m^{3/5} \left( \frac{T_{\text{eff}, \max}}{0.3 \text{ keV}} \right)^{12/5} \times \int_{r_i/3}^{r_o/3} \left( 1 + \frac{1}{\lambda} \right)^{-2/5} x^{-23/10} (1 - x^{-1/2}) \, dx.
\]
(11)

For a given black hole mass \( m \), accretion rate \( \dot{m} \), viscosity parameter \( \alpha \), and a presumed value of \( T_{\text{eff}, \max} \), quantities describing the inner disk and corona are determined by Equations (1)–(6) in the case of conduction-dominated cooling and by Equations (7)–(11) in the case of Compton-dominated cooling. Iterative calculations are carried out until a self-consistent \( T_{\text{eff}, \max} \) is obtained.

### 2.3. Iterative Calculations with Irradiation

The surface effective temperature of the accretion disk with irradiation from the corona is expressed as
\[
\sigma T_{\text{eff}}^4(r) = F_{\text{cnd}} + F_{\text{irr}},
\]
(12)

where \( F_{\text{cnd}} \) refers to the flux that originates from disk accretion fed by condensation per unit area, i.e.,
\[
F_{\text{cnd}} = \frac{3GM M_{\text{cnd}}}{8\pi R^3} \left[ 1 - \left( \frac{3R_S}{R} \right)^{1/2} \right].
\]
(13)

\( F_{\text{irr}} \) refers to the illumination flux from the corona to the disk surface per unit area (Liu et al. 2011),
\[
F_{\text{irr}} = \frac{1}{2} L_{\text{c.in}} (1 - a) \frac{H_s}{4\pi (R^2 + H_s^2)^{1/2}} L_{\text{c.in}} = L_{\text{brems}} + L_{\text{Cmp}},
\]
(14)

where the ADAF-like corona is assumed above the disk as a point source at a height \( H_s \), the covering factor of the point source to a disk ring at distance \( R \) is given as \( f = H_s/(4\pi (R^2 + H_s^2)^{1/2}) \), and \( a \) is albedo. \( L_{\text{c.in}} \) is the total intrinsic luminosity of the corona and the transition layer above and below the disk.

Combining Equations (12)–(14), the effective temperature of the accretion disk can be reexpressed as
\[
T_{\text{eff}}(r) = 2.05 T_{\text{eff, max}} \left( \frac{3}{r} \right)^{3/4} \left[ 1 - \left( \frac{3}{r} \right)^{1/2} \right]^{1/4} \times \left[ 1 + 6L_{\text{c.in}} (1 - a) \frac{H_s}{M_{\text{cnd}}^{2}} \right]^{1/4}
\]
\[
= 2.05 T_{\text{eff, max}} \left( \frac{3}{r} \right)^{3/4} \left[ 1 - \left( \frac{3}{r} \right)^{1/2} \right]^{1/4},
\]
(15)

where
\[
T_{\text{eff, max}} = T_{\text{eff, max}} \left[ 1 + 6L_{\text{c.in}} (1 - a) \frac{H_s}{M_{\text{cnd}}^{2}} \right]^{1/4}.
\]
(16)

\( T_{\text{eff, max}} \) refers to the maximum effective temperature from disk accretion, which is reached at \( r_{\text{max}} = (49/12) \). The expression of \( T_{\text{eff, max}} \) is given as (Liu et al. 2007)
\[
T_{\text{eff, max}} = 0.2046 \left( \frac{m}{10} \right)^{-1/4} \left( \frac{m_{\text{cnd}}(r_{\text{max}})}{0.01} \right)^{1/4} \text{ keV}.
\]
(17)

At a lower accretion rate \( \dot{m} \), it is assumed that the corona is dominated by conductive cooling. An effective temperature \( T_{\text{eff, max}} \) is presumed to calculate the condensation rate from Equations (1) and (2) and the luminosity of the transition layer and the corona from Equations (5) and (6), with which a new effective temperature \( T_{\text{eff, max}} \) is derived from Equations (16) and (17) by assuming a value of albedo \( a \). An iteration is made until the presumed temperature is consistent with the derived value. From the derived effective temperature, the Compton-dominated region is determined by the following equation (Liu et al. 2007):
\[
r_{\text{Cmp}} \left[ 1 - \left( \frac{3}{r_{\text{Cmp}}} \right)^{1/2} \right]^{2/3} \leq 23.487 \dot{m}^{2/3} \left( \frac{T_{\text{eff, max}}}{0.3 \text{ keV}} \right)^{8/3}.
\]
(18)
If Equation (18) has no solution, it means that the corona is dominated by conductive cooling throughout the corona, and we find a self-consistent solution of the disk–corona system. Otherwise, the Compton-dominated region is determined by Equation (18). We recalculate the condensation rate by combining Equations (1), (2) and (7), (8) and recalculate the luminosity of the transition layer and the corona from Equations (5), (6), and (11) until the presumed temperature is consistent with the derived value and we find a solution of the disk–corona system. With an increase of the mass accretion rate, the Compton-dominated region extends inward and outward until Compton cooling dominates throughout the corona at some accretion rate. An effective temperature $T_{\text{eff, max}}$ is assumed to calculate the condensation rate from Equations (7) and (8) and the luminosity of the disk–corona system. The frequency-integrated flux from the transition layer is

$$F_{\text{brem}} = \int_0^\infty f T_{\text{eff}}(v, T_{\text{cpl}})e^{-h\nu/kT_{\text{cpl}}}d\nu$$

Solving Equation (20), we can get

$$f = \frac{F_{\text{brem}}h}{kT_{\text{cpl}}} \frac{1}{\int_0^\infty g_f(v, T_{\text{cpl}})e^{-\nu/kT_{\text{cpl}}}d\nu}$$

where the expression of $F_{\text{brem}}$ is given as (Liu et al. 2007)

$$F_{\text{brem}} = \frac{1}{2} \times 6.391 \times 10^{24} \alpha^{-7/3} m^{-1} m^{5/3} r^{-5/2} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$$

and the integral $\int_0^\infty g_f(v, T_{\text{cpl}})e^{-\nu/kT_{\text{cpl}}}d\nu$ is a frequency average of the velocity-averaged Gaunt factor, which is in the range 1.1–1.5. Choosing a value of 1.2 will give an accuracy to within 12% (Rybicki & Lightman 1979).

By combing Equations (19) and (21), we get the local emergent bremsstrahlung spectra from the transition layer, which is given as

$$F_{\text{brem}} = \frac{F_{\text{brem}}h}{kT_{\text{cpl}}} \frac{1}{\int_0^\infty g_f(v, T_{\text{cpl}})e^{-\nu/kT_{\text{cpl}}}d\nu} \times g_f(v, T_{\text{cpl}})e^{-h\nu/kT_{\text{cpl}}} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}.$$  

By integrating the local Compton spectra from the corona and the bremsstrahlung spectra from the transition layer along the radial direction, we get the total emergent spectra of the inner disk–corona system.

3. NUMERICAL RESULTS

Given a black hole mass $m$, the mass accretion rate $\dot{m}$, the viscosity parameter $\alpha$, and the albedo $\alpha$, the structure of the corona in the radial direction is solved self-consistently as described in Section 2. Throughout the calculation, $m = 10$ is adopted.

For viscosity parameter $\alpha = 0.2$ and albedo $\alpha = 0.15$, it is found that the inner disk can survive for the accretion rate in the range of $\dot{m} \sim 0.006$–0.03, which is consistent with the results of Liu et al (2011), where the modification to the cooling of the corona is not considered. This is because the corona is dominated by the Compton cooling and the modification of conductive cooling to the corona can be neglected at the upper limit of the accretion rate, and the corona is dominated by the Conductive cooling and the modification of Compton cooling to the corona can be neglected at the lower limit of the accretion rate. The size of the accretion disk as a function of the mass accretion rate is plotted in the left panel of Figure 1 with a red
The size of the inner disk is defined by a critical radius, where neither the evaporation nor the condensation process occurs. Outside the critical radius, the matter is evaporated to the corona from the disk (if the disk is not evaporated completely), and inside the critical radius, the corona matter condenses onto the disk. An increase of the mass accretion rate leads to more gas condensation onto the disk, and the corresponding critical radius of the inner disk increases. The maximum temperature of the inner disk is plotted in the right panel of Figure 1 with a red line. It is evident that the maximum temperature of the disk increases with the mass accretion rate. This is because an increased value of the mass accretion rate results in the increase of the condensation rate and the luminosity of the hot corona, and the maximum temperature of the inner disk heated up by accreting condensed gas and the irradiation of the hot corona integrated throughout the inner disk increases. The ratio of the luminosity dissipated in the corona to the luminosity dissipated in the disk, $L_c/L_d$, as a function of the mass accretion rate $\dot{m}$ is plotted in Figure 2 with a red line. With an increase of the accretion rate $\dot{m}$, the relatively quick increase of the emission from the accretion disk to the emission from the corona leads to a decreased value of $L_c/L_d$. The electron temperature and the optical depth for the Compton scattering of the hot electron in the vertical direction as functions of radius are plotted in Figure 3 with a red line. The solid line is for $\dot{m} = 0.03$ (dotted line: $\dot{m} = 0.02$; dashed line: $\dot{m} = 0.01$). We can see that the electron temperatures are in the range of $\sim 1-5 \times 10^9$ K for different accretion rates $0.01 \leq \dot{m} \leq 0.03$. It is clear that the temperature of the corona decreases with the increase of the mass accretion rate for $\dot{m} = 0.15$. This is because, with the increase of the mass accretion rate, the Compton cooling of the soft photons from the disk to the corona becomes more efficient, and the temperature of the corona decreases. To clearly show the mass distribution of the inner disk–corona system in the radial direction, we plot the mass accretion rate in the accretion disk and the mass accretion rate in the corona as functions of radius in Figure 4. It can be seen that, with the increase of the mass accretion rate, more gases in the corona recondense back to the disk, and the accretion rate in the disk increases.

The emergent spectra of the inner disk and corona for different mass accretion rates are plotted in Figure 5. The X-ray spectrum in the range of $2-10$ keV is roughly characterized by a power law with a photon index $\Gamma = 1.63$ at $\dot{m} = 0.01$ (solid green line). With the increase of the mass accretion rate, the hard X-ray photon index is $\Gamma = 1.75$ at $\dot{m} = 0.02$ (solid blue line) and $\Gamma = 1.92$ at $\dot{m} = 0.03$ (solid red line). It is obvious that the X-ray spectra become softer with the increase of the mass accretion rate. This can be understood as the hard X-rays being dominated by bremsstrahlung at the low accretion rate but by Compton radiation at the high accretion rate. In Figure 5, the dashed line shows the contribution of the Compton scattering of the soft photons from the underlying cool disk by the electrons in the hot corona (Compton radiation), and the dotted line shows the contribution from the bremsstrahlung of the transition layer. At the lower accretion rate $\dot{m} = 0.01$, the cooling of the corona is dominated by the conductive cooling and fewer soft photons
from the underlying thin disk are scattered to the hard X-ray band, so the Compton emission to the hard X-ray band is weak, and the hard X-ray emission is dominated by the bremsstrahlung of the transition layer. With the increase of the mass accretion rate to $\dot{m} = 0.02$, the Compton emission of the corona to the X-ray band becomes dominant compared with the bremsstrahlung of the transition layer, as shown by the blue dashed line and the dotted line in Figure 5. With a further increase of the accretion rate, the Compton $y$-parameter decreases, which results in a large photon index and small luminosity ratio between the corona and the disk, as shown by the red solid line in Figures 2 and 5.

In order to study the effect of albedo $a$ on the spectra, we plot the emergent spectra of the inner disk and the corona with albedo in Figure 6. The size and the maximum effective temperature of the inner accretion disk with $a$ can also be seen in Figure 1. The electron temperature and the optical depth for the Compton scattering of the hot electron in the vertical direction as functions of radius are plotted in Figure 3. The red line, blue line, and green line are for $a = 0.15$, $a = 0.6$, and $a = 1$ (without irradiation), respectively. For
viscosity parameter $\alpha = 0.2$ and mass accretion rate $\dot{m} = 0.02$, we plot the emergent spectra for different albedo $a$ in Figure 6. For albedo $a = 0.15$, the hard X-ray photon index $\Gamma = 1.75$. With the increase in the value of albedo, the hard X-ray photon index is $\Gamma = 1.63$ and $1.53$ for $a = 0.6$ and $1$, respectively. It can be seen clearly that the X-ray spectrum becomes harder with the increase of albedo. This is because for larger albedo, fewer X-ray photons of the irradiation from the corona to the disk are absorbed and reprocessed as thermal seed photons to be scattered in the corona, the temperature of the electron in the corona is higher, and a harder X-ray spectrum is predicted. We plot the emergent spectra with albedo $a$ for different mass accretion rates in Figure 7. We can see, for both $\dot{m} = 0.01$ and $\dot{m} = 0.03$, that the hard X-ray spectra become harder with the increase of $a$. From Figure 6, it is also very clear that the positive dependence of the hard X-ray spectrum index on the mass accretion rate holds for different albedo $a$.

From theory, the value of albedo $a$ is uncertain and has been investigated by several authors, e.g., George & Fabian (1991) and White et al. (1988). The value of albedo $a$, which depends on how the incident photons from the corona interact with the underlying accretion disk, is defined as the energy in the reflective spectrum divided by the energy in the incident spectrum. The value of albedo is energy dependent. White et al. (1988) study the Compton scattering of the incident photons by the electrons in the disk. In their calculations, the X-ray is assumed to be incident upon a semi-infinite, plane–parallel, zero-temperature, purely scattering medium. They show that the monochromatic albedo $a(x_0)$ changes from 95% to 1% for the energy $x_0$ in the range of $\sim 10^{-3}$ to $\sim 30$ ($x_0$ is the energy of the incident photons scaled with the rest energy of electrons). If the mean energy of the photons is around 50 keV, $\sim 40\%$ of the irradiation flux is absorbed by the disk through the Compton scattering of the electron in the disk (White et al. 1988). The K-shell absorption of the metals is negligible for the incident photons at $\sim 50$ keV. However, because the K-shell absorption of the metals is proportional to $(m_e c^2/h\nu)^{7/2}$, at lower energy, the K-shell absorption becomes important. For the distribution of $N_e \propto \nu^{-1.6}$, $\sim 30\%$ of the incident energy is absorbed (Taam et al. 2008). Thus, $\sim 70\%$ of the total irradiation flux is absorbed by the Compton scattering and K-shell absorption, so the value of albedo $a$ is around 0.3. However, it is highly uncertain for the calculation of the value of albedo, e.g., the ionization state of the surface of the accretion disk. In this paper, we only take albedo as a parameter to fit the observations.

To test the effect of the viscosity parameters $\alpha$ on the shape of the spectra, we plot the emergent spectra of the inner disk and corona with the viscosity parameter $\alpha$ in Figure 8. In our calculation, albedo $a = 0.15$ and mass accretion rate $\dot{m} = 0.03$ are adopted. For $\alpha = 0.2$, the hard X-ray photon index is $\Gamma = 1.92$. With the increase of $\alpha$, the hard X-ray photon index is $\Gamma = 1.67$ and $1.57$ for $\alpha = 0.25$ and $0.3$, respectively. It is found that the luminosity of the disk–corona system decreases systematically with the value of $\alpha$; meanwhile, the X-ray spectra in the range of $2 \sim 10$ keV become harder with the value of $\alpha$. This is because, for the fixed mass accretion rate, the surface density in the corona decreases with the increase of $\alpha$. With a lower density, the heat flux to the transition layer decreases; meanwhile, the bremsstrahlung cooling rate is decreased even more. The energy balance between heating and cooling results in a decreased heating rate associated with a lower enthalpy flux. The net effect results in a decreased condensation rate. The energy conversion efficiency of the inner disk + corona/ADAF can be expressed as $\eta = (L/L_{\text{Edd}})/(M/M_{\text{Edd}})$. The efficiency of the thin disk is 0.1; however, for the hot corona/ADAF, owing to the strong advection effect, the efficiency is much less than 0.1. With the increase of $\alpha$, owing to the decrease of the condensation rate, less matter is accreted...
in the form of the thin disk, and the luminosity of the inner disk + corona/ADAF system decreases. Meanwhile, owing to a relative lack of photons from the underlying thin disk being scattered in the corona, the temperature of the corona is higher, so a harder X-ray spectrum is predicted.

To show the effect of the different parameters (accretion rate $\dot{m}$, viscosity parameter $\alpha$, and albedo $a$) on the condensation features and the corresponding spectral features of the inner disk and corona clearly, we list the numerical results for different parameters in Table 1.

### Table 1

| $\alpha$ | $a$  | $\dot{m}$ | $r_d$   | $\dot{m}_{\text{cnd}}$ | $L_{\text{ISCO}}/L_{\text{Edd}}$ | $L_{\text{c}}/L_d$ | $T_{\text{eff,max}}$ (keV) | $\Gamma_{\text{mod}}$ |
|---------|-----|----------|---------|------------------------|-----------------------------|-----------------|--------------------------|------------------|
| 0.2     | 0.15| 0.01     | 19.2    | $9.66 \times 10^{-3}$ | $1.02 \times 10^{-3}$     | 3.04            | 0.10                      | 1.63             |
| 0.2     | 0.15| 0.02     | 124.2   | $2.98 \times 10^{-3}$ | $9.18 \times 10^{-3}$     | 1.56            | 0.19                      | 1.75             |
| 0.2     | 0.15| 0.03     | 350.0   | $1.29 \times 10^{-2}$ | $3.32 \times 10^{-2}$     | 1.45            | 0.27                      | 1.92             |
| 0.2     | 0.6  | 0.01     | 15.8    | $5.92 \times 10^{-3}$ | $8.22 \times 10^{-4}$     | 6.50            | 0.08                      | 1.52             |
| 0.2     | 0.1  | 0.01     | 13.1    | $3.60 \times 10^{-3}$ | $6.79 \times 10^{-4}$     | 4.30            | 0.05                      | 1.40             |
| 0.2     | 0.6  | 0.02     | 106.2   | $2.25 \times 10^{-3}$ | $6.71 \times 10^{-3}$     | 2.27            | 0.16                      | 1.63             |
| 0.2     | 0.1  | 0.02     | 92.9    | $1.66 \times 10^{-3}$ | $5.05 \times 10^{-3}$     | 4.06            | 0.13                      | 1.53             |
| 0.2     | 0.6  | 0.03     | 308.2   | $1.07 \times 10^{-2}$ | $2.48 \times 10^{-2}$     | 1.93            | 0.23                      | 1.77             |
| 0.2     | 0.1  | 0.03     | 278.3   | $8.72 \times 10^{-3}$ | $1.83 \times 10^{-2}$     | 2.72            | 0.20                      | 1.62             |
| 0.2     | 0.15 | 0.03     | 350.0   | $1.29 \times 10^{-2}$ | $3.32 \times 10^{-2}$     | 1.45            | 0.27                      | 1.92             |
| 0.25    | 0.15| 0.03     | 83.0    | $3.19 \times 10^{-3}$ | $1.35 \times 10^{-3}$     | 1.79            | 0.21                      | 1.67             |
| 0.3     | 0.15| 0.03     | 22.2    | $4.66 \times 10^{-4}$ | $4.25 \times 10^{-4}$     | 2.80            | 0.15                      | 1.57             |

**Notes.** With black hole mass $m = 10$, viscosity parameters $\alpha$, albedo $a$, and the mass accretion rate $\dot{m}$, the size of the inner disk $r_d$, condensation rate $\dot{m}_{\text{cnd}}$ integrated from the condensation radius to $3 R_\bullet$, the luminosity dissipated in the corona $L_{\text{ISCO}}/L_{\text{Edd}}$, the ratio of the luminosity dissipated in the corona to the luminosity dissipated in the disk $L_{\text{c}}/L_d$, the maximum temperature of the inner disk $T_{\text{eff,max}}$, and the hard X-ray photon index $\Gamma_{\text{mod}}$ in the range of 2–10 keV are listed.
from our model. The detailed fitting results are shown in Table 2.

From the calculation above, it is found that the hard X-ray photon index calculated by taking $\alpha = 0.3$ can match the observed one better than that of taking $\alpha = 0.4$. Here, we want to show that the observed X-ray luminosity and the maximum effective temperature of the disk can only be fitted in a very narrow range for the value of $\alpha$. For instance, for $\alpha = 0.2$, we cannot fit the X-ray luminosity and the maximum effective temperature simultaneously, i.e., by taking $\tilde{m} = 0.0251$, the observed X-ray luminosity can be matched; however, even by taking the limited value of albedo $a = 1$, the theoretical value of $T_{\text{eff,max}}$ is 0.1825 keV, which is bigger than the observed value 0.165 keV.

4.2. Cyg X-1

Cyg X-1 is a well-known BHXRB and has been well studied by several authors. The distance to Cyg X-1 was very early estimated at 2 kpc (Murdin & Webster 1971; Reis et al. 2010) and confirmed by Massey et al. (1995), who found a distance of 2.1 ± 0.1 kpc. The mass of Cyg X-1 is found in the range of 7–15 $M_\odot$ (Shaposhnikov & Titarchuk 2009). In this paper, a distance $d = 2$ kpc and $m = 10$ are adopted (Reis et al. 2010). We compare our result with the recent observations of Cyg X-1 (Reis et al. 2010). They find that an X-ray luminosity

![Figure 9](https://example.com/figure9.png)  
**Figure 9.** Emergent spectra of GX 339-4 calculated by different fitting parameters of our model. The solid line shows the emergent spectrum for $m = 5.8$, $\alpha = 0.3$, $\tilde{m} = 0.0456$, and $a = 0.782$; the dotted line shows the emergent spectrum for $m = 5.8$, $\alpha = 0.4$, $\tilde{m} = 0.0773$, and $a = 0.617$. (A color version of this figure is available in the online journal.)

![Figure 10](https://example.com/figure10.png)  
**Figure 10.** Emergent spectra of Cyg X-1 calculated by different fitting parameters of our model. The solid line shows the emergent spectrum for $m = 10$, $\alpha = 0.3$, $\tilde{m} = 0.044$, and $a = 0.398$; the dotted line shows the emergent spectrum for $m = 10$, $\alpha = 0.4$, $\tilde{m} = 0.064$, and $a = 0.267$.

| $\alpha$ | $m$ | $\tilde{m}$ | $a$ | $r_d$ | $m_{\text{surf}}$ | $L_{\text{accretion}}/L_{\text{Edd}}$ | $L_c/L_d$ | $\Gamma_{\text{mod}}$ |
|----------|-----|----------|-----|------|-----------------|---------------------------|-----------|---------------|
| 0.3      | 0.0456 | 0.782   | 34.9 | 16.05 | $1.40 \times 10^{-3}$ | 0.8 $\times 10^{-2}$ | 5.0 | 1.50 |
| 0.4      | 0.0773 | 0.617   | 16.05| 5.98 $\times 10^{-4}$ | 0.8 $\times 10^{-2}$ | 6.59 | 1.40 |

| $\alpha$ | $m$ | $\tilde{m}$ | $a$ | $r_d$ | $m_{\text{surf}}$ | $L_{\text{accretion}}/L_{\text{Edd}}$ | $L_c/L_d$ | $\Gamma_{\text{mod}}$ |
|----------|-----|----------|-----|------|-----------------|---------------------------|-----------|---------------|
| 0.3      | 0.044 | 0.398   | 55.0 | 2.73 $\times 10^{-3}$ | 1.47 $\times 10^{-2}$ | 2.57 | 1.60 |
| 0.4      | 0.064 | 0.267   | 30.4 | 1.55 $\times 10^{-3}$ | 1.47 $\times 10^{-2}$ | 2.89 | 1.52 |

**Table 2**  
Fitting Results for GX 339-4 and Cyg X-1

| $\alpha$ | $m$ | $\tilde{m}$ | $a$ | $r_d$ | $m_{\text{surf}}$ | $L_{\text{accretion}}/L_{\text{Edd}}$ | $L_c/L_d$ | $\Gamma_{\text{mod}}$ |
|----------|-----|----------|-----|------|-----------------|---------------------------|-----------|---------------|
| 0.3      | 0.0456 | 0.782   | 34.9 | 16.05 | $1.40 \times 10^{-3}$ | 0.8 $\times 10^{-2}$ | 5.0 | 1.50 |
| 0.4      | 0.0773 | 0.617   | 16.05| 5.98 $\times 10^{-4}$ | 0.8 $\times 10^{-2}$ | 6.59 | 1.40 |

| $\alpha$ | $m$ | $\tilde{m}$ | $a$ | $r_d$ | $m_{\text{surf}}$ | $L_{\text{accretion}}/L_{\text{Edd}}$ | $L_c/L_d$ | $\Gamma_{\text{mod}}$ |
|----------|-----|----------|-----|------|-----------------|---------------------------|-----------|---------------|
| 0.3      | 0.044 | 0.398   | 55.0 | 2.73 $\times 10^{-3}$ | 1.47 $\times 10^{-2}$ | 2.57 | 1.60 |
| 0.4      | 0.064 | 0.267   | 30.4 | 1.55 $\times 10^{-3}$ | 1.47 $\times 10^{-2}$ | 2.89 | 1.52 |

**Notes.** With the black hole mass $m$, the X-ray luminosity $L_{\text{accretion}}/L_{\text{Edd}}$ and the effective temperature $T_{\text{eff,max}}$ of the accretion disk derived from the observation, and assuming a value of $\alpha$, the two quantities accretion rate $\tilde{m}$ and albedo $a$ are adjusted simultaneously to match the observed X-ray luminosity and the effective temperature of the accretion disk. $r_d$, $m_{\text{surf}}$, $L_{\text{accretion}}/L_{\text{Edd}}$, and $L_c/L_d$ are the corresponding size of the inner disk, the integrated condensation rate from the condensation radius to 3 $R_g$, the luminosity dissipated in the corona, and the ratio of the luminosity dissipated in the corona to the luminosity dissipated in the disk, respectively. $\Gamma_{\text{mod}}$ is the hard X-ray photon index in the range of 2–10 keV calculated by the corresponding parameters.

- $^a$ The central black hole mass.
- $^b$ The observed X-ray luminosity.
- $^c$ The observed temperature of the accretion disk.
- $^d$ The observed X-ray photon index in the range of 2–10 keV.
\(L_x/L_{\text{Edd}} = 5 \times 10^{-3} (m/10) \times (d/2 \text{kpc})^2\) in the range of 0.5–10 keV and a hard power-law photon index \(\Gamma = 1.71 \pm 0.01\) (2–10 keV). Extrapolating the luminosity to 100 keV, we get an X-ray luminosity \(L_x/L_{\text{Edd}} = 1.47 \times 10^{-2} (m/10) \times (d/2 \text{kpc})^2\). By fitting the spectra with the Diskbb+power-law model, they reveal a cool disk component with a temperature \(kT \approx 0.194\) keV; meanwhile, it is found that the inner boundary of the accretion disk is very close to the ISCO, i.e., \(r_{\text{in}} = 5.7^{+7.0}_{-3.0}\) (Reis et al. 2010).

With \(m = 10\), the X-ray luminosity \(L_x = 1.47 \times 10^{-2} L_{\text{Edd}}\) and an effective temperature of the disk \(kT \approx 0.194\) keV derived from observations, and assuming viscosity parameter \(\alpha = 0.3\), it is found that the observed X-ray luminosity and effective temperature are matched by taking \(m = 0.044\) and albedo \(a = 0.398\), respectively. We plot the emergent spectrum of the inner disk and corona with the fitting parameters in Figure 10 (solid line). It is found that the hard X-ray spectra in the range of 2–10 keV are characterized by a power law with a photon index \(\Gamma_{\text{mod}} = 1.60\) from our model. The fitting results for bigger viscosity parameter \(\alpha = 0.4\) are also listed in Table 2.

5. CONCLUSION

We study the formation of a cool, optically thick, geometrically thin disk in the innermost region of BHXRBs in the low/hard spectral state within the context of the disk accretion fed by condensation of the hot corona. By taking into account the cooling process associated with both Compton scattering and vertical conduction in a corona and the irradiation of the hot corona to the disk, we obtain a self-consistent solution of the inner disk and corona. We calculate the emergent spectra of the inner disk and corona for different accretion rates and vertical conduction in a corona and the irradiation of the cooling process associated with both Compton scattering and albedo \(a\). Our model is used to explain the spectral features of BHXRBs GX 339-4 and Cyg X-1 in the low/hard spectral state, in which the thin disk resides in the region very close to the ISCO. Our results are roughly in agreement with the observations characterized by a weak disk component with a temperature of \(\sim 0.2\) keV and hard power-law X-ray spectra with \(\Gamma \sim 1.5\)–2.1 for the sources in the low/hard spectral state.

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