DISK EVAPORATION–FED CORONA: STRUCTURE AND EVAPORATION FEATURES WITH MAGNETIC FIELD

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ABSTRACT

The disk-corona evaporation model naturally accounts for many observational phenomena in black hole X-ray binaries, such as the truncation of an accretion disk and the spectral state transitions. On the other hand, magnetic fields are known to play an important role in transporting angular momentum and producing viscosity in accretion flows. In this work, we explicitly take the magnetic field in the accretion disk corona into consideration and numerically calculate the coronal structure on the basis of our two-temperature evaporation code. We show that the magnetic field influences the coronal structure through its contribution to the pressure, energy, and radiative cooling in the corona and by decreasing the vertical heat conduction. We find that the maximum evaporation rate stays more or less constant (~3% of the Eddington rate) when the strength of the magnetic field changes, but that the radius corresponding to the maximum evaporation rate decreases with increasing magnetic field. This suggests that spectral state transitions always occur at a few percent of the Eddington accretion rate, while the inner edge of the thin disk can be at ~100R\text{Edd} or even less in the hard state before the transition to the soft state. These results alleviate the problem of previous evaporation models’ predicting too large a truncation radius and are in better agreement with the observational results for several black hole X-ray binaries, although discrepancies remain.

Subject headings: accretion, accretion disks — black hole physics — conduction — magnetic fields — X-rays: binaries

1. INTRODUCTION

X-ray binaries and active galactic nuclei (AGNs) are interesting objects in astrophysics and have drawn a great deal of attention since their discovery. Accretion is widely accepted to be the main energy source driving these objects (Shakura & Sunyaev 1973, hereafter SS73; Pringle 1981; Rees 1984). The thin-disk model proposed by SS73 not only successfully solves the energy problems in both X-ray binaries and AGNs but also well reproduces some key features of dwarf novae (Meyer & Meyer-Hofmeister 1984). With the advancement of observing techniques in recent decades, various types of broadband spectra have been observed from X-ray binaries, as well as AGNs. These spectra usually have a two-component structure, that is, a thermal component together with a nonthermal component (see Remillard & McClintock 2006 for a review of X-ray binaries; see Mushotzky et al. 1993 for a review of AGNs). It is difficult to explain the observed broadband spectra with a thin disk alone, which emits a multicolor blackbody spectrum. An additional hot accretion flow is required in order to produce the high-frequency nonthermal spectrum. Therefore, a two-component model, consisting of an inner advection-dominated accretion flow (ADAF; Narayan & Yi 1994) or radiatively inefficient accretion flow (RIAF; Yuan et al. 2003) and an outer Shakura-Sunyaev disk (SSD; SS73), was proposed to explain the observed spectra and has since been widely adopted in the study of black hole binaries (e.g., Esin et al. 1997; Quataert et al. 1999). However, there is still some debate over what causes the transition between these two physically different kinds of accretion flow and how to determine the transition properties, such as the critical accretion rate, the disk truncation radius, and so on.

These problems have been extensively discussed in many previous studies (Narayan & Yi 1995; Honma 1996; Meyer et al. 2000a; Lu et al. 2004). Among these models, only Meyer et al. (2000a) considered the detailed vertical structure (a thin disk sandwiched by the corona) as regards the transition between SSD and RIAF. Their model also predicts a scale-free evaporation rate–radius (\text{in}-\text{r}) relation, from which the disk truncation radius can be determined for a given accretion rate, which has been found to be consistent with observations (Liu et al. 1999; Liu & Meyer-Hofmeister 2001). Further investigations have shown that the disk evaporation model can also account for the hysteresis in accretion rate between the hard-to-soft and soft-to-hard transitions that has been observed in quite a number of low-mass X-ray binaries (Meyer-Hofmeister et al. 2005; Liu et al. 2005). Recent studies (Liu et al. 2006; Meyer et al. 2007) show that the disk evaporation model can explain the existence of an inner disk during intermediate states.

The original disk evaporation model was proposed by Meyer & Meyer-Hofmeister (1994), who did not include a magnetic field since that work aimed at explaining the UV lag observed in dwarf novae. But magnetic fields have long been realized to play an important role in accretion disks (SS73). Recently, observations have also revealed the magnetic nature of disk accretion onto black holes (Miller et al. 2006). Meyer & Meyer-Hofmeister (2002) included magnetic pressure in the disk evaporation model in order to explain the different truncation radii of the outer thin disks between...
the nuclei of elliptical galaxies and low-luminosity AGNs, which have similar Eddington-scaled accretion rates (normalized by the Eddington accretion rate $M_{\text{Edd}}L_{\text{Edd}}/L^2$, where $L_{\text{Edd}}$ is the Eddington luminosity and $L$ is the efficiency of energy conversion). A one-temperature (1T) model (meaning that the electrons and ions in the corona have the same temperature) was used in that study. Besides the contribution of the magnetic pressure to the total pressure, magnetic field can also affect the heat conduction. Meyer-Hofmeister & Meyer (2006) took this effect into account, together with irradiation and Comptonization processes, and found that variations in heat conduction can change the $\dot{m}$-$r$ relation significantly.

In this paper, we investigate in detail the influence of magnetic field on both the pressure and heat conduction with a more realistic two-temperature (2T) model (meaning that the electrons and ions in the corona have different temperatures; Liu et al. 2002). We present more detailed numerical results and also give fitting formulae for the numerical results, which enable a much easier comparison between theory and observations. In § 2, we briefly describe the model and the basic equations; in § 3, we present the numerical results, and in § 4, our results are compared with observations. In § 5, we discuss the model itself, and our conclusions are presented in § 6.

2. DESCRIPTION OF THE MODEL

Following previous work on disk evaporation (Meyer & Meyer-Hofmeister 1994; Liu et al. 1995; Meyer et al. 2000b; Liu et al. 2002), we direct most of our attention to the transition region between SSD and RIAF, which is characterized by a thin disk sandwiched by the coronal flow. The viscous heat of ions is partially transferred to electrons through collisions and is conducted down by the electrons to the transition layer, which is cooler and denser. Part of the cool matter in the transition layer is heated and evaporates into the corona until an equilibrium density is reached. The gas in the corona carries a similar amount of angular momentum to that in the disk and is continuously accreted by the central black hole as a result of viscous angular momentum transfer, similar to the situation in accretion disks. The drifting-in gas is steadily re-supplied by the gas evaporating from the transition layer between the corona and the thin disk, and an equilibrium state can be reached in the system.

There are three factors crucial to the evaporation rate—the heating of the corona, thermal conduction, and radiative cooling in the transition layer. Any new physical process related to these three factors can influence the evaporation rate and eventually change the final configuration of the accretion flow (see, e.g., Liu et al. 2005). One relevant factor is the magnetic field, because it has an overall influence on accretion disks. First, it enhances the viscosity (Balbus & Hawley 1991). Second, a magnetic field will contribute to the total pressure. The viscous heating changes with both the viscous coefficient and the pressure. Third, a strong, entangled magnetic field can greatly modify the heat conduction in the plasma (Tao 1995; Chandran & Cowley 1998; Narayan & Medvedev 2001). Fourth, in the presence of a magnetic field, there should be cyclosynchrotron radiation. In addition, magnetic dissipation and reconnection can be an additional mechanism to heat the corona.

However, how a magnetic field influences the viscosity parameter $\alpha$ is still unclear. The contribution could already be included if $\alpha$ is as large as 0.3. The dependence of evaporation rate on the viscosity parameter has been discussed by Meyer-Hofmeister & Meyer (2001). Here we concentrate on the influence of magnetic pressure and heat conduction on the disk evaporation process. The cyclosynchrotron radiation is optically thick in our corona and can only be important when the electron temperature is higher than $10^9$ K, which is the case in the upper boundary layers. Compared with the cooling from heat conduction, cooling from optically thick synchrotron radiation in the upper layers can be neglected as long as the electron temperature is not too much higher than $10^9$ K, which is indeed the case in our computations (see also Meyer & Meyer-Hofmeister 2002). Thus, cyclosynchrotron radiation is not be included in our calculations. For simplicity, we assume a chaotic magnetic field, which provides an isotropic magnetic pressure in the corona.

The basic equations and boundary conditions we adopt in this work are the same as those in Liu et al. (2002), with some minor changes. The viscosity parameter ($SS73$) is set to $\alpha = 0.3$. As has been shown in many previous works, the characteristics of disk evaporation are independent of the mass of the central black hole; the results are the same for systems with stellar-mass or with supermassive black holes. For clarity, we reproduce the basic equations here.

The mass continuity equation is

$$\frac{d}{dz}(\rho v_z) = \eta \frac{2}{r} \left( \frac{\rho v_z}{r^2 + z^2} - \frac{2\pi}{r^2 + z^2} \rho v_z \right), \quad (1)$$

where $\rho$, $v_z$, and $v_r$ are the gas density and the vertical and radial components of the velocity, respectively. The factor $\eta \frac{2}{r}$ is equal to 1 in the evaporation model (Meyer-Hofmeister & Meyer 2003).

The $z$-component of the momentum equation is

$$\rho \frac{d v_z}{dz} = - \frac{dP}{dz} + \rho \left( \frac{GMz}{(r^2 + z^2)^{3/2}} \right), \quad (2)$$

where the total pressure $P$ includes both the gas pressure $P_g$ and the magnetic pressure $P_m$. The equation of heat conduction is

$$F_c = -\kappa T_e^{3/2} d T_e / dz, \quad (3)$$

where $\kappa$ is the heat conduction coefficient and $T_e$ is the electron temperature.

The ion energy equation is

$$\frac{d}{dz} \left( \rho v_z \left[ \frac{v^2}{2} + \frac{\gamma}{\gamma - 1} \frac{P_i}{\rho_i} - \frac{GM}{(r^2 + z^2)^{1/2}} \right] \right) = \frac{3}{2} \alpha P \Omega - q_e + \eta e \frac{2}{r} \rho v_z \left[ v^2 + \frac{\gamma}{\gamma - 1} \frac{P_i}{\rho_i} - \frac{GM}{(r^2 + z^2)^{1/2}} \right]$$

$$- \frac{2\pi}{r^2 + z^2} \left( \rho v_z \left[ v^2 + \frac{\gamma}{\gamma - 1} \frac{P_i}{\rho_i} - \frac{GM}{(r^2 + z^2)^{1/2}} \right] \right). \quad (4)$$

Here $v$ is the modulus of the velocity vector, $P_i$ and $P_e$ are the contribution of ions to the density and pressure, respectively, $\Omega$ is the angular velocity of the gas in the corona, and $q_e$ is the rate of heat transfer from ions to electrons due to Coulomb coupling (Liu et al. 2002), which can be expressed as

$$q_e = \left( \frac{2}{\pi} \right)^{1/2} \frac{m_e}{m_p} \ln \Delta \sigma T_cn_n(k T_i - k T_e) \left[ 1 + \frac{T_e^{1/2}}{T_i^{1/2}} \right], \quad (5)$$

where $m_e$, $m_p$, $T_i$, and $T_e$ have their usual meaning, $\sigma_T$ is the Thomson scattering cross section, and $\ln \Delta = 20$ is the Coulomb logarithm. $T_e = (k T_e/m_e c^2)(1 + (m_e/m_p)(T_i/T_e))$, $\gamma$ is the ratio of specific heats, and $k$ is the Boltzmann constant (rather than the heat conduction coefficient $\kappa$). The factor $\eta e$ is equal to $\eta + 0.5$ (Meyer-Hofmeister & Meyer 2003).
The combined energy equation for ions and electrons is

\[
\frac{d}{dz} \left\{ \rho v_e \left[ \frac{ve^2}{2} + \frac{\gamma - 1}{\gamma - 1} \rho - \frac{GM}{r^2} \right] + F_c \right\} = \frac{3}{2} \alpha P \Omega - n_e n_i L(T_e) + \frac{\eta \varepsilon}{r} \rho v_e \left[ \frac{v_e^2}{2} + \frac{\gamma - 1}{\gamma - 1} \rho - \frac{GM}{r^2} \right] - \frac{2 \varepsilon}{r^2 + z^2} \left\{ \rho v_e \left[ \frac{ve^2}{2} + \frac{\gamma - 1}{\gamma - 1} \rho - \frac{GM}{r^2 + z^2} \right] \right\},
\]

where \( \Lambda(T) \) is the radiative cooling function for a low-density, optically thin gas of cosmic abundances in the temperature range \( 10^4 - 10^6 \) K, taken to be the bremsstrahlung radiation function for \( T > 10^8 \) K (Raymond et al. 1976).

Note that the last terms on the right-hand sides of equations (1), (4), and (6) are the flaring terms (Meyer & Meyer-Hofmeister 1994). The pressure \( P \) in these equations is no longer the gas pressure but the total pressure, so the sound speed \( (P/\rho) \) has an additional factor of \( 1 + \beta^{-1} \) compared with the sound speed without the magnetic pressure \( (P/\rho) \) (where \( \beta \equiv P_g/P_m \) is the ratio of gas to magnetic pressure). The ratio of specific heats \( \gamma \) also changes with \( \beta \), following the relation \( \gamma = (5\beta + 8)/(3\beta + 6) \) (cf. Appendix A of Esin 1997), but note that the definition of \( \beta \) is different there.

Both \( \beta \) and \( \kappa \) affect the lower boundary conditions in the corona, which are

\[
T_l = T_e = 10^{6.5} \, \text{K},
\]

\[
F_c = -2.73 \times 10^6 P \lambda^{1/2} \left( 1 + \beta^{-1} \right)
\]

(Meyer-Hofmeister & Meyer 2006), where \( \lambda \equiv \kappa/\kappa_{Sp} \) is the fraction of the standard value (the Spitzer value, \( \kappa_{Sp} = 10^{-6} \, \text{g cm}^{-3} \, \text{K}^{-7/2} \)) of the heat conduction coefficient (Meyer-Hofmeister & Meyer 2006). We integrate equations (1)–(6) until the upper boundary conditions

\[
v_e = c_s, \quad F_c = 0
\]

are fulfilled.

3. NUMERICAL RESULTS

We consider a chaotic magnetic field and parameterize it by \( \beta \equiv P_g/P_m \) (where \( P_m \equiv B^2/24\pi \)). So, a smaller \( \beta \)-value means a stronger magnetic field. Under the assumption of equipartition between the gas pressure and magnetic pressure, we have \( \beta = 1 \); MHD simulations yield \( \beta \approx 12 \) (Sharma et al. 2006), and the case without a magnetic field corresponds to \( \beta = \infty \). Assuming different strengths of the magnetic pressure and heat conduction, we can numerically solve for the vertical structure of the corona at different radii. Our main results are discussed in what follows.

3.1. Vertical Structure of the Magnetized Corona

Figure 1 shows the vertical structure of the corona above a thin disk at a radius \( R = 214.3 \). The left panel shows the structure without magnetic field, \( \beta = \infty \) and \( \kappa = \kappa_{Sp} \). The right panel shows the influence of a magnetic field on the structure, with \( \beta = 10/3 \) and \( \kappa = 0.5\kappa_{Sp} \). Comparing the two cases, we find that the vertical profiles of the coronal quantities do not change much when magnetic field is included, although the absolute values, for example, the density and evaporation rate, do change. This is a typical feature in disk coronae also seen in earlier works (e.g., Meyer et al. 2000b), which indicates that the corona above a thin disk undergoes very steep changes in temperature and density and cannot be simply averaged in the vertical direction.

3.2. Meaning of the \( m-r \) Curve

Qualitatively similar to previous results (Meyer et al. 2000b; Liu et al. 2002), our new calculations with a magnetic field show that the mass evaporating from the disk to the corona increases...
toward the central black hole, reaching a maximum at a few hundred Schwarzschild radii and then dropping very quickly near the black hole. The distribution of evaporation rate with distance turns out to be independent of the black hole mass. We scale the evaporation rate by the Eddington accretion rate, $M_{\text{Edd}} \equiv L_{\text{Edd}} / 0.1c^2 = 1.39 \times 10^{18}M_\odot / c^2$, so $\dot{m} \equiv M / M_{\text{Edd}}$, and scale the distances by the Schwarzschild radius, $R_S = 2GM/c^2$ and $r \equiv R / R_S$. We will illustrate the dependence of $\dot{m}$ on $r$ so that the relations $\dot{m}(r)$ can be tested with observations from some black hole X-ray binaries.

The $\dot{m}$-$r$ curve can predict the configuration of the accretion flow at different accretion rates. If the mass accretion rate of the accretion disk is lower than the maximum evaporation rate, the disk will be depleted inside a radius where the accretion rate is equal to the evaporation rate. This truncation radius is outside the radius of the maximum evaporation rate. The accretion flow is then dominated by an inner pure corona or, more exactly, an ADAF or RIAF. Such a configuration corresponds to the low/hard spectral state in black hole X-ray binaries. However, it is also possible that there is an inner disk that is separated from the outer disk by a "pure coronal flow" if the accretion rate is close to the maximum evaporation rate (Liu et al. 2006). This configuration is thought to be related to the intermediate spectral state. If the mass accretion rate exceeds the maximum evaporation rate, the disk cannot be depleted anywhere, so it can extend to the marginally stable radius (Meyer et al. 2000b). The radiation is then predominantly from the standard thin disk, and the corona is suppressed by Compton cooling. This situation corresponds to the high/soft spectral state.

A change of mass accretion rate in the disk can also cause a transition between different spectral states. As an example, if the mass accretion rate in the disk increases from a value smaller than the maximum (critical) evaporation rate to a value larger than that, a hard-to-soft state transition will occur, and vice versa. So the maximum evaporation rate corresponds to a transition accretion rate (or a transition luminosity). This transition accretion rate and the truncation radius of the disk in the low/hard state, as shown in our predicted $\dot{m}$-$r$ curves, are the two parameters to be compared with observational results.

3.3. Influence of Magnetic Field on $\dot{m}(r)$

We investigate the influence of magnetic pressure by calculating the evaporation rate for a series of $\beta$-values. Our results based on both the 1T model and 2T model are present in the $\dot{m}$-$r$ curves.

The $\dot{m}$-$r$ relation for the 1T model is shown in Figure 2. The solid, dot-dashed, and long-dashed lines represent the cases of $\beta = \infty$ (no magnetic field), $\beta = 5$, and $\beta = 2$, respectively. We did not calculate curves for even smaller $\beta$, since the magnetic field would be too strong in those cases, invalidating the assumptions of our current model. The most obvious changes due to the inclusion of the magnetic field are in the value and location of the maximum evaporation rate. From Figure 2, one can see that in the 1T model the maximum evaporation rate increases with an increase of magnetic field, while its location moves inward. This can be understood as a consequence of enhanced viscous heating due to the contribution of magnetic pressure. The viscous heating cannot be efficiently consumed by radiative cooling until a higher density is reached in the inner region. There is also another influence in the outer region of the corona (at large radii): In contrast to the maximum evaporation rate, the evaporation rate at a fixed radius increases with a decrease in magnetic field. This is because viscous heating is balanced by advection rather than by radiation in the outer region of the corona. The viscous heating contributed by the magnetic pressure is mainly transferred to the enthalpy of the gas, which makes the gas hotter than in the case without a magnetic field, and hence radiative cooling is more efficient if the density is unchanged. This leads to a reduced evaporation rate. These trends are consistent with the qualitative estimates given by Meyer et al. (2000b; see their eqs. [56] and [57]). These evaporation features basically rely on the enhanced dissipation rate produced by the enhanced magnetic pressure, which might be true in other dissipation models as well, including those based on reconnection and shocks in a strongly magnetized corona.

Such a distribution of evaporation rate with distance as shown in Figure 2 implies that at a given accretion rate, truncation of the disk occurs at a smaller radius with the inclusion of magnetic field and that the disk can extend to a smaller radius before the system switches to the soft state.

In the 2T model, we take into account the decoupling of electrons and ions that probably occurs in the inner region. When electrons and ions are decoupled, the electron heating due to collisions with ions is inefficient. A large fraction of the heat is stored in ions, and the heat available to evaporate the gas in the disk is thus limited. Therefore, a smaller evaporation rate is expected in the 2T scenario than in the 1T case, especially in the inner region. Our numerical results are shown in Figure 3. The lines other than the short-dashed line represent the results calculated for the 2T model, with the same styles as in Figure 2 for the 1T model. As expected, the 1T and 2T results are similar in the outer region. However, there are clear differences in the inner region, where ions and electrons are not well coupled. Because the 2T model usually describes the real physics in the inner hot accretion flow, we concentrate our discussion on this model. Figure 3 shows that the curve for the evaporation rate shifts inward with an increase of magnetic field, while the maximum evaporation rates stay more or less the same, around 2%–3% of the Eddington rate. This indicates that the involvement of magnetic field results in a smaller truncation radius for the thin disk. The stronger the magnetic field, the smaller the radius at which the disk is truncated. However, our result implies that the transition from the hard state to the soft state occurs at almost the same accretion rate, no matter whether a magnetic field is included or not. Such an effect may explain why some objects
are truncated at smaller radii than predicted by previous models (see § 4). To show in more detail the influence of the magnetic field, we list the maximum evaporation rates and the corresponding radii for different $\beta$-values in Table 1A. The data can be linearly fitted by $\log \dot{m}_{\text{max}} = 0.143/\beta - 1.579$ and $\log r_{\text{max}} = -1.750/\beta + 2.299$.

3.4. Influence of Heat Conduction on $\dot{m}(r)$

Theoretical work has shown that a chaotic magnetic field should suppress heat conduction in the plasma (Tao 1995; Chandran & Cowley 1998; Narayan & Medvedev 2001). Recent work indicates that the coefficient of heat conduction can be reduced to one-fifth the Spitzer value (Narayan & Medvedev 2001). We calculate the influence of the magnetic field on the rate of reduced heat conduction by deflecting the motion of electrons, and the inclusion of such a field would greatly reduce the disk truncation radius, thereby leading to an outward shift of the evaporation curve $\dot{m}(r)$ (Liu et al. 2005), partially counteracting the effect of reduced heat conduction. For details of the combined effect of heat conduction and irradiation and Comptonization, we refer the reader to the work of Meyer-Hofmeister & Meyer (2006).

Figure 4 shows the dependence of the $\dot{m}-r$ relation on $\kappa$, based on the 2T model. The solid line represents the standard case with $\kappa = \kappa_{Sp}$. The dot-dashed line and the long-dashed line correspond to $\kappa = 0.5\kappa_{Sp}$ and $\kappa = 0.2\kappa_{Sp}$, respectively. For comparison, a curve with $\kappa = \kappa_{Sp}$ in the 1T model is also shown (short-dashed line). Figure 4 looks very similar to Figure 3. The location of the maximum evaporation rate moves inward with a decrease in $\kappa$, but the maximum evaporation rate is insensitive to $\kappa$. Detailed values from our calculations and the corresponding linear fit results are listed in Table 1B. Comparing the fit results for both the cases of magnetic pressure and heat conduction, we find that the influence of magnetic field is much stronger than that of heat conduction. Note that a chaotic magnetic field tends to decrease heat conduction by deflecting the motion of electrons, and the inclusion of such a field would greatly reduce the disk truncation radius through both $\beta$ and $\kappa$. We describe a composite result in the next subsection.

![Figure 4](image-url)
The 1T results with different \( \kappa \)-values are plotted in Figure 5, which shows a tendency similar to the influence of \( \beta \). Because of the decoupling of electrons and ions in the inner region, the 1T results are less meaningful than the 2T results.

### 3.5. The Combined Effect of \( \beta \) and \( \kappa \)

Qualitatively, the presence of a chaotic magnetic field can reduce the efficiency of heat conduction by electrons. But how \( \kappa \) changes with \( \beta \) remains unclear. As an example, we take \( 1/\beta = 0.3 \) and \( \kappa = 0.5 \kappa_{Sp} \) to calculate the evaporation rates at different radii. The results are shown in Figure 6 (dotted line). One can see that the magnetic pressure and the heat conduction play similar roles in shifting \( \dot{m}(r) \). That is, an increase in magnetic field or a decrease of heat conduction shifts the evaporation curve \( \dot{m}(r) \) inward. The combined effect is a superposition of the shifts caused separately by the magnetic pressure and the heat conduction. However, the maximum evaporation rate increases slightly with magnetic pressure and even more slightly with heat conduction. Since the magnetic field tends to reduce the efficiency of heat conduction, the two effects on the maximum evaporation rate counteract each other. The magnetic field tends to reduce the efficiency of heat conduction, and even more slightly with heat conduction. Since the magnetic field tends to reduce the efficiency of heat conduction, the two effects on the maximum evaporation rate counteract each other.

The maximum evaporation rate hardly changes with the inclusion of magnetic field and heat conduction, while the truncation radius depends strongly on both the magnetic pressure and heat conduction. This implies that if a magnetic field exists in the disk, the truncation of the disk could occur at much smaller radii, while the hard-to-soft state transition should occur at more or less the same accretion rate, \( \dot{m} \approx 0.03 \). For instance, in the case with \( 1/\beta = 0.3 \) and \( \kappa = 0.5 \kappa_{Sp} \) (Fig. 6, dotted line), the hard-to-soft transition occurs at \( \dot{m} = 0.028 \) and the disk can extend down to \( \sim 27R_s \) before the transition. Such a transition radius is much smaller than the prediction of \( \sim 209R_s \) without including a magnetic field.

If the dependence of \( \kappa \) on the magnetic field is known, we can more accurately determine the maximum evaporation rate and the corresponding radius and compare theoretical predictions with the accretion rate and inner disk radius determined by observations during hard-to-soft state transitions.

### 4. COMPARISON OF MODEL PREDICTIONS WITH OBSERVATIONS

Our numerical results can be compared with observations. Since the results predicted by the disk evaporation model are mass-scale-free, they can be used in various systems with different central black hole masses.

#### 4.1. Luminosities at Spectral State Transitions in X-Ray Binaries

The maximum evaporation rate in the \( \dot{m}-r \) curve predicts a critical accretion rate at which a transition occurs between the hard and soft spectral states. When the accretion rate in the disk is lower than the critical value, evaporation depletes the disk and the accretion flow is eventually replaced by an ADAF or RIAF. When the accretion rate is higher than the critical value, the standard thin disk can extend down to the last stable orbit and thus dominates the accretion flow. From Figures 3 and 4, one can see that this transition accretion rate is around \( 0.03 \dot{M}_{Edd} \) on the basis...
of the 2T model (the 1T model gives 0.02$\dot{M}_{\text{Edd}}$; see also Meyer et al. 2000b), which is weakly dependent on the strength of magnetic pressure and heat conduction. This quantity can be compared with the transition luminosities in black hole X-ray binaries if the efficiency of energy conversion, $\eta$, is similar.

The observed transition luminosities (scaled by the Eddington luminosity) for some black hole X-ray binaries are listed in Table 2. One can see that different objects have transition luminosities ranging from 1% to 15%. The average value is 0.036. However, when speaking about the transition luminosity, we must exercise caution. First, the luminosities of different sources are observed in different energy bands and may not represent the bolometric luminosities. Second, these observed transition luminosities suffer from uncertainties in some of the parameters, such as the mass of the central black hole and the source’s distance (Gierliński & Newton 2006). If these dimensionless transition luminosities represent the corresponding dimensionless mass accretion rates, we can estimate their average value as 0.036. This value predicted by the disk evaporation model ($\sim 0.03$) is quite consistent with this observational result.

4.2. Truncation Radius and Corresponding Accretion Rate in Hard States

In the hard state of black hole X-ray binaries, the accretion rate in the disk is lower than the maximum evaporation rate, and the thin disk will be truncated at a radius where the accretion rate in the disk equals the evaporation rate. So, the $\dot{m}$-$r$ relation can be tested with the truncation radius of the disk and the corresponding accretion rate estimated from observational data.

For this purpose, we collect data on some black hole X-ray binaries in Table 3. These data are based on spectral fitting with the ADAF+disk model (Narayan et al. 1997). The accretion rates in Table 3 are Eddington-scaled values ($\dot{m} = 0.1\dot{M}/\dot{M}_{\text{Edd}}$), which are converted from the Eddington ratios ($L/L_{\text{Edd}}$; Zdziarski et al. 2004) or from the rates scaled by the critical accretion rate ($\dot{m} \equiv \dot{M}/\dot{M}_{\text{Edd}}$; Wilms et al. 1999), or from $\dot{M}$ (in solar masses per year) (Poutanen et al. 1997). The data listed in Table 3 can then be compared with the theoretical results from our model.

Figure 7 shows the observational data together with our model predictions for different strengths of the magnetic pressure and heat conduction. One can see that the enhanced magnetic pressure and reduced heat conduction bring the model predictions much closer to the observations. We expect that theoretical results with a stronger magnetic field or further reduced heat conduction, or both, will yield predictions that are more consistent with observations. Here we do not give such an example, not only because we do not accurately know the magnetic field strength in the individual objects, but also because of the large uncertainties in the observational data. Care should be taken here, in that there are several sets of data given in the original papers; we just listed the best-fitted ones here. We also note that in the modeling of the low-state spectrum of XTE J1118+480 with an inner ADAF and an outer disk (Esin et al. 2001), the ratio $P_{\text{g}}/(P_{\text{g}} + P_{\text{m}})$ in the ADAF was set to 0.97, which corresponds to $\beta = 32$ in this work.

5. DISCUSSION

5.1. Comparison with Earlier Estimates

Our 1T calculations confirm the estimates by Meyer et al. (2000b), namely,

$$\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \propto \frac{\alpha^3}{\kappa_{1/2}} \left( 1 + \frac{1}{\beta} \right)^{5/2}, \quad \frac{R}{R_{\text{S}}} \propto \frac{\kappa}{\alpha^2} \left( 1 + \frac{1}{\beta} \right)^{-4}. \quad (14)$$
However, our results from the 2T model are different from those of the 1T model. The maximum evaporation rate remains almost the same with a decrease in both $\beta$ and $\kappa$, although the location of the maximum evaporation rate moves to smaller radii in a similar way to that in the 1T model. In the outer regions, both the 2T model and the 1T model give similar results, since the accretion flow is close to a 1T flow. However, in the inner region, ions and electrons are decoupled. The accretion energy is mainly stored in the ions, and the temperature of ions is higher than that of electrons. Therefore, the accretion flow is a 2T flow. There is little heat conducted by the electrons from corona to disk, and thus evaporation is inefficient compared with the 1T case.

5.2. Cooling by Cyclosynchrotron Radiation

With the inclusion of a magnetic field, one potential cooling mechanism is cyclosynchrotron radiation, which is negligible in the lower layers (Meyer & Meyer-Hofmeister 2002). In the highest part of the corona, this may influence the temperature (see the discussion of synchrotron radiation in Narayan & Yi 1995 and Mahadevan 1997). However, we expect little influence from cyclosynchrotron radiation on the main body of the coronal activity.

5.3. Heating by Magnetic Field Dissipation

Besides its influence on such physical processes as heat conduction, the magnetic field may play an important role in the formation of the corona (Galeev et al. 1979). Disk magnetic fields rising into the corona contain energy that originates in the disk accretion but which will be dissipated (e.g., by reconnection and shocks) in the corona. We take this very roughly into account by scaling the viscous dissipation in our modeling to the total pressure instead of the gas pressure, thus including parts that are related to the addition of disk-produced magnetic flux that raise the magnetic pressure (i.e., lead to a lower $\beta$ in the corona).

5.4. Comparison with MHD Simulations

Detailed investigations of the formation of a magnetized corona from MHD simulations (e.g., Miller & Stone 2000; Machida et al. 2000; Hawley & Balbus 2002) have shown that a strongly magnetized corona can form above an initially weakly magnetized disk. Miller & Stone (2000) showed that the magnetic field is amplified within 2 disk scale heights ($H = 0.01 R$) and that the energy is mostly dissipated within 3 to 5 scale heights, thereby heating up the corona. Machida et al. (2000) also showed that a low-$\beta$ corona can exist in the form of a “patchy corona” or active coronal regions. More recent work that includes radiation transport (Hirose et al. 2006) shows that magnetic dominance occurs deeper than the photosphere, where the medium is still relatively cool. Here we consider a slab corona in a large vertical extent where the structure is vertically stratified, in contrast to an isothermal torus in the MHD simulations. More importantly, vertical thermal conduction is taken into account in our model. This leads to efficient mass evaporation from the disk to the corona, feeding the corona to higher mass density than in the coronal envelope seen in MHD simulations. Therefore, we expect relatively higher $\beta$-values in our case.

6. CONCLUSION

We have investigated the influence of coronal magnetic fields on the structure of an accretion disk corona sustained by dissipative energy release and thermal coupling between corona and disk. Numerical calculations show that the relation between mass evaporation rate and radius (the $\dot{m}$-$r$ curve) systematically shifts to smaller radii with either an increase in magnetic pressure (decreasing $\beta$) or a decrease in heat conductivity (decreasing $\kappa$). The location of maximum evaporation rate lies between $30 R_S$ and $200 R_S$ when $\beta$ ranges from 2 to infinity, or $\kappa$ from $\kappa_{Sp}$ to 0.2$\kappa_{Sp}$. However, the maximum evaporation rate remains nearly unchanged (~0.03$\dot{M}_{Edd}$, with energy conversion efficiency $\eta = 0.1$) if the disk truncation and state transitions are indeed caused by an evaporation process, the transition luminosity predicted by our disk evaporation model is $L_{Edd} = 0.03L_{Edd}$ before the transition to the soft state. The inner edge of the outer thin disk can be from several tens to several hundreds of Schwarzschild radii, depending on the strength of the magnetic field and its effect on the heat conduction. This alleviates the problem of previous evaporation models predicting too large a disk truncation radius before the transition from the hard to the soft state. Our predictions with the inclusion of the coronal field are found to be in better agreement with the observational results for several black hole X-ray binaries, although discrepancies remain.

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