Research in Astron. Astrophys. **2009** Vol. **9** No. **4**, 401–408
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in
Astronomy and
Astrophysics

The advection-dominated accretion flow+thin accretion disk model for two low-luminosity active galactic nuclei: M81 and NGC 4579 [*]

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Received 2008 May 9; accepted 2008 July 17

Abstract It was found that advection-dominated accretion flow (ADAF)+thin disk model calculations can reproduce the observed spectral energy distributions (SEDs) of two low-luminosity active galactic nuclei (AGNs), provided they are accreting at $\sim 0.01 - 0.03$ Eddington rates and the thin disks are truncated to ADAFs at $\sim 100R_{\rm S}$ ($R_{\rm S}$ is the Schwarzschild radius) for M81 and NGC 4579 (Quataert et al. 1999). However, the black hole masses adopted in their work are about one order of magnitude lower than recent measurements on these two sources. Adopting the well estimated black hole masses, our ADAF+thin disk model calculations can reproduce the observed SEDs of these two low-luminosity AGNs, if the black hole is accreting at 2.5×10^{-4} Eddington rates with the thin disk truncated at $R_{\rm tr} = 120R_{\rm S}$ for M81 ($\dot{m} = 3.3 \times 10^{-3}$ and $R_{\rm tr} = 80R_{\rm S}$ are required for NGC 4579). The transition zones with temperature from the thin disk with $\sim 10^4 - 10^5$ to $\sim 10^9 - 10^{10}$ K in the ADAF will inevitably emit thermal X-ray lines, which provides a useful diagnosis of their physical properties. The observed widths of the thermal X-ray iron lines at $\simeq 6.8$ keV are consistent with Doppler broadening by Keplerian motion of the gases in the transition zones at $\sim 100R_{\rm S}$. We use the structure of the transition zone between the ADAF and the thin disk derived by assuming the turbulent diffusive heat mechanism to calculate their thermal X-ray line emission with the standard software package Astrophysical Plasma Emission Code (APEC). Comparing them with the equivalent widths of the observed thermal X-ray iron lines in these two sources, we find that the turbulent diffusive heat mechanism seems to be unable to reproduce the observed thermal X-ray line emission. The test of the evaporation model for the accretion mode transition with the observed thermal X-ray line emission is briefly discussed.

Key words: accretion, accretion disks — black hole physics — galaxies:active — radiation mechanisms: thermal — galaxies: individual (M81, NGC 4579)

1 INTRODUCTION

It is well accepted that many astrophysical systems are powered by black hole accretion. Standard thin disks (i.e., geometrically thin and optically thick accretion disks) can successfully explain most observational features of the black hole accretion systems (Shakura & Sunyaev 1973). The ultraviolet/optical continuum emission observed in luminous quasars is usually attributed to thermal radiation

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[*] Supported by the National Natural Science Foundation of China.

from the standard disks (SDs) surrounding the massive black holes in quasars (e.g., Sun & Malkan 1989). However, the SD model is unable to reproduce the spectral energy distributions (SEDs) of many sources (e.g., Sgr A*) accreting at very low rates, and advection-dominated accretion flows (ADAF) have been suggested to be present in these sources (Narayan & Yi 1994, 1995). In the ADAF model, most released gravitational energy of the gases in the accretion flow is converted to the internal energy of the gas, and the ADAF is hot, geometrically thick, and optically thin. Only a small fraction of the released energy in the ADAF is radiated away, and their radiation efficiency is therefore significantly lower than that of standard thin disks (see Narayan et al. 1998, for a review and references therein). The ADAF model can successfully reproduce the observed SEDs in many black hole systems accreting at low rates (e.g., Lasota et al. 1996; Narayan et al. 1996, 1998).

There is a critical accretion rate $\dot{m}_{\rm crit}$, above which the ADAF is suppressed and a standard thin disk is present. The ADAF can co-exist with the standard thin disk, when it is accreting at rates slightly lower than the critical value $\dot{m}_{\rm crit}$. In this case, the ADAF is present in the inner region near the black hole and connects to a standard thin disk at a certain transition radius $R_{\rm tr}$ (see Narayan et al. 1998, for a review and references therein). Narayan et al. (1996) proposed the ADAF+standard thin disk systems to model the observed spectra of the black hole accretion systems with moderate accretion rates. Narayan (1996) found that many different spectral states observed in black hole X-ray binaries can be understood as a sequence of ADAF+thin disk models with varying $\dot{m}$ and $r_{\rm tr}$ (where $r_{\rm tr}$ is the outer radius of ADAF in units of Schwarzschild radii, $R_{\rm S} = 2GM_{\rm bh}/c^2$). This scenario has been explored in more detail by several authors (Esin et al. 1997, 1998), and they found that the different spectral states of X-ray binaries (i.e., the quiescent state, low state, intermediate state or high state) correspond to different accretion rates. It is believed that standard thin disks (or slim disks) are present in luminous active galactic nuclei (AGNs), while ADAFs are present in those low-luminosity AGNs accreting at relatively low rates. The ADAF+thin disk systems are required for modeling on a variety of observations of AGNs accreting at moderate rates (e.g., Quataert et al. 1999; Cao 2003).

The physical mechanisms of the transition from a thin disk to an ADAF and its structure are still quite uncertain, though a few different scenarios have been suggested (e.g., Meyer & Meyer-Hofmeister 1994; Honma 1996; Liu et al. 1999). Meyer & Meyer-Hofmeister (1994) proposed an "evaporation" mechanism, in which the disk is evaporated as it is heated by electron conduction from a hot corona, and then a quasi-spherical hot accretion flow is formed. An alternative scenario was suggested by Honma (1996), in which a "turbulent diffusive heat" mechanism is employed to explore the structure of the ADAF+thin disk system. This model was further developed and the global structure of the ADAF+thin disk system was derived numerically (Manmoto & Kato 2000; Manmoto et al. 2000). All of these model calculations show that a rapid decrease in temperature occurs within a narrow zone between the inner ADAF and the outer standard thin disk at $\sim r_{\rm tr}$.

Quataert et al. (1999) showed that the optical/UV to X-ray emission detected from the nuclei of M81 and NGC 4579 can be well explained by an optically thick, geometrically thin accretion disk which extends down to $\sim 100\ R_{\rm S}$ (inside which an ADAF is present), provided their accretion rates are $\dot{m} \sim 0.01$. The optical/UV bumps observed in these two sources can be attributed to thermal emission from the outer standard thin disks, while their hard X-ray emissions are dominantly from the inner ADAFs. In their model calculations, the same central black hole mass $M_{\rm bh} = 4 \times 10^6\ M_\odot$ is adopted for these two sources, which is underestimated by about an order of magnitude compared with recent estimates (Devereux et al. 2003; Barth et al. 2001). Iron Kα lines were observed in these two sources (Ishisaki et al. 1996; Terashima et al. 1998). In addition to narrow iron Kα lines at 6.4 keV, the broad line components centered at $E_{{\rm K}\alpha} = 6.79$ keV were also observed in these two sources (Dewangan et al. 2004). Thermal X-ray line emission is a useful diagnosis of black hole accretion systems (e.g., Narayan & Raymond 1999; Xu et al. 2006). Dewangan et al. (2004) found that the observed lines from these two sources are too broad to be thermal line emission from the host galaxy, and they suggested that these broad emission lines are probably from the transition zones between the ADAFs and the outer standard thin disks. The temperature of the inner edge of the thin disk is around 10^4 K, and therefore the temperature of the transition zone extends from $\sim 10^4$ to $\sim (10^8 - 10^9)$ K while connecting to the ADAF. Thus, thermal X-ray line emission can naturally originate from such transition zones. The observed widths of the broad lines are roughly consistent with Doppler broadening by Keplerian motion of the gases in the transition zones at $\sim 100\ R_{\rm S}$ (Quataert et al. 1999).

In this work, we re-investigate the ADAF+thin disk systems in these two low-luminosity active galactic nuclei, NGC 4579 and M81, adopting the black hole masses estimated by Devereux et al. (2003); Barth et al. (2001). The thermal iron Kα line emissions from the transition zones of the ADAF to the thin disk in these two low-luminosity active galactic nuclei, NGC 4579 and M81, are calculated with the transition model based on the turbulent diffusive heating mechanism developed by Honma (1996).

2 THE ADAF+THIN DISK MODEL

The observed SEDs of two low-luminosity AGNs, M81 and NGC 4579, were reproduced with the ADAF+standard thin disk model by Quataert et al. (1999). In this ADAF+standard thin disk model, no smooth physical connection between the ADAF and the outer standard thin disk at $r_{\rm tr}$ has been included. The resulting spectra are simply the combination of the spectra from the ADAF and the outer thin disk. Quataert et al. (1999)'s model calculations showed that the best fits to the observed SEDs of these two sources require a transition radius $r_{\rm tr} \simeq 100$ for both sources. The accretion rates are $\dot{m} = 0.03$ and $\dot{m} = 0.01$ for NGC 4579 and M81, respectively. The viscosity parameter $\alpha = 0.1$, the ratio of gas to total pressure $\beta = 0.9$ and the fraction of the released energy directly heating the electrons $\delta = 0.01$ are adopted in their calculations. In their model calculations, the same central black hole mass $M_{\rm bh} = 4 \times 10^6\ M_\odot$ is adopted for these two sources, which is underestimated by about an order of magnitude. The masses of these two black holes were estimated as $M_{\rm bh} \simeq 7 \times 10^7\ M_\odot$ for M81 and $M_{\rm bh} \sim 5 \times 10^7\ M_\odot$ for NGC 4579 (Devereux et al. 2003; Barth et al. 2001). Thus, we have to re-calculate the global structures of the ADAFs surrounding the black holes in these two sources. We employ the approach suggested by Manmoto (2000) to calculate the global structure of an accretion flow surrounding a Schwarzschild black hole in a general relativistic frame. All the radiation processes are included in the calculations of the global accretion flow structure (see Manmoto 2000, for details and references therein). It was pointed out that a significant fraction of the viscously dissipated energy could go into electrons by magnetic reconnection, if the magnetic fields in the flow are strong (Bisnovatyi-Kogan & Lovelace 1997, 2000). They argued that δ can be as high as ~ 0.5. Therefore, we adopt a conventional value of $\delta = 0.3$ (e.g., Wu, Yuan & Cao 2007), and tune the accretion rates $\dot{m}$ to fit their observed optical/UV/X-ray continuum spectra. The irradiation of the outer thin disk by ADAF is included in our calculations. We include an empirical color correction given by Chiang (2002) for the thermal emission from the outer thin disk, which can reproduce the non-LTE disk spectral model of Hubeny et al. (2001).

The flux due to viscous dissipation in the outer region of the disk is

$$F_{\rm vis}(R) \simeq \frac{3GM_{\rm bh}\dot{M}}{8\pi R^3}, \tag{1}$$

which is a good approximation for $R_{\rm tr} \gg R_{\rm in}$. The outer thin disk may be irradiated by the incident photons from the inner ADAF region. The flux due to the irradiation in the outer thin disk $F_{\rm irr}(R)$ can be calculated by assuming the incident photons are reprocessed as thermal radiation from the thin disk, while the global structure of the inner ADAF is available (see Cao & Wang 2006, for details). The local disk temperature of the thin cold disk is

$$T_{\rm disk}(R) = \frac{[F_{\rm vis}(R) + F_{\rm irr}(R)]^{1/4}}{\sigma_{\rm B}^{1/4}}, \tag{2}$$

by assuming local blackbody emission. In order to calculate the disk spectrum, we include an empirical color correction for the disk thermal emission as a function of radius. The correction has the form (Chiang 2002)

$$f_{\rm col}(T_{\rm disk}) = f_\infty - \frac{(f_\infty - 1)[1 + \exp(-\nu_{\rm b}/\Delta\nu)]}{1 + \exp[(\nu_{\rm p} - \nu_{\rm b})/\Delta\nu]}, \tag{3}$$

where $\nu_p \equiv 2.82 k_B T_{\rm disk}/h$ is the peak frequency of a blackbody with temperature $T_{\rm disk}$. This expression for $f_{\rm col}$ goes from unity at low temperatures to f_∞ at high temperatures with a transition at $\nu_{\rm b} \approx \nu_{\rm p}$. Chiang (2002) found that $f_\infty = 2.3$ and $\nu_b = \Delta\nu = 5 \times 10^{15}$ Hz do a reasonable job of reproducing the model disk spectra of Hubeny et al. (2001). The disk spectra can therefore be calculated by

$$L_\nu = 8\pi^2 \left(\frac{GM}{c^2}\right)^2 \frac{h\nu^3}{c^2} \int\limits_{r_{\rm tr}}^{\infty} \frac{rdr}{f_{\rm col}^4[\exp(h\nu/f_{\rm col}k_B T_{\rm disk}) - 1]}. \qquad (4)$$

We find that the best fits to the SEDs of these sources require: $\dot{m} = 3 \times 10^{-4}$ and $r_{\rm tr} = 120$ for M81; $\dot{m} = 3.3 \times 10^{-3}$ and $r_{\rm tr} = 80$ for NGC 4579. We find that the observations in optical/UV and X-ray bands of these two sources can be fitted quite well (see Fig. 1).

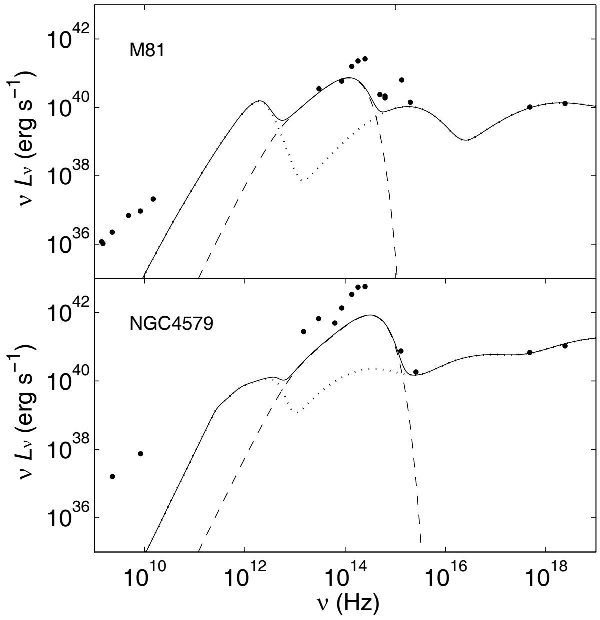

Fig. 1 ADAF+standard thin disk spectral models for M81 and NGC 4579 (solid lines). The dotted lines represent the spectra of ADAFs, while the dashed lines are the spectra of the outer standard thin disks. The observed data points are taken from Ho (1999).

3 TRANSITION ZONE OF THE THIN DISK TO THE ADAF

The global structure of ADAF+standard thin disk systems based on the assumption of additional turbulence viscosity in the transition zone was derived by Honma (1996). Manmoto et al. (2000) performed numerical calculations on the ADAF+thin disk system based on Honma (1996)'s model, and obtained the global structure of the ADAF which smoothly connects to the outer thin disk. They extended Honma's analytical solution to be able to describe the global structure of the ADAF+thin disk system including the transition zone quite well compared with the numerical results (see Manmoto et al. 2000, for more details). Honma's analytical solution for the ADAF+standard thin disk system is only valid for fully advection-dominated flows ($f = 1$), where f is the ratio of the advected energy to the viscously dissipated energy in the ADAF. By introducing a new parameter a, the extension of Honma's analytical solution derived by Manmoto et al. (2000) can deal with ADAFs with partial cooling ($f < 1$),

$$v = -\alpha \frac{(3-a)}{5}[1-(R/R_{\rm tr})^a]v_{\rm K}(R)\,,$$

$$\Omega = \sqrt{\frac{a+5}{5}}(R/R_{\rm tr})^{a/2}\Omega_{\rm K}(R)\,,$$

$$c_{\rm s} = \sqrt{\frac{2}{5}}[1-(R/R_{\rm tr})^a]^{1/2}v_{\rm K}(R)\,. \tag{5}$$

The relation between f and a is

$$f = \frac{12a(3-a) - 24(\alpha_{\rm T}/\alpha)(1-a)a}{(a+5)(3-a)^2}. \tag{6}$$

As we are focusing on the transition zone, $\alpha_{\rm T} = 0$ is adopted, because the structure of the transition zone is almost independent of the value of this parameter (corresponding to turbulent energy transport) (Manmoto et al. 2000). Their derived global structure (either the analytical one or that derived numerically) is one temperature (i.e., the temperature of the electrons is the same as that of the ions), which prevents us from calculating the spectrum of the accretion flow directly. In this work, we include all the radiation processes in our calculations for the global structure of the inner ADAF, while we only use Manmoto et al. (2000)'s model to connect our ADAF solution to the outer thin disk. We assume the efficiency of the released gravitational energy $\eta = 0.1$, and a fraction f of it is advected in the flow. We have

$$L_{\rm ADAF} = \eta\dot{m}(1-f)\dot{M}_{\rm Edd}M_{\rm bh}c^2, \tag{7}$$

which can be derived by integrating their observed continuum emission (subtracting the optical/UV bumps from the outer thin disk regions). Thus, the value of f can be estimated if the accretion rate $\dot{m}$ is known. The value of f can also be derived from our calculation of the global structure of the inner ADAF, because the radiation processes have been considered in the global solution of the ADAF. We find that the value of f, which is estimated with Equation (7), is consistent with that derived from the global solution of the ADAF. In order to explore how thermal line emission varies with accretion rate $\dot{m}$, we loosen the constraints on the accretion rates $\dot{m}$, i.e., allowing $\dot{m}$ to vary by about an order of magnitude from the values derived from the model fits of the SEDs from these two sources, in our calculation of the thermal line emission from the transition zone. We can estimate f as a function of the accretion rate $\dot{m}$, provided $L_{\rm ADAF}$ is derived from the observed SEDs. The value of a can be calculated with Equation (6) after f is known. The structure, and then the thermal line emission, of the transition zone can be calculated as a function of the accretion rate $\dot{m}$. Using Equations (5) and (6), the structure of the transition zone is available for calculating its thermal X-ray line emission as a function of the accretion rate.

4 THERMAL X-RAY LINE EMISSION FROM THE TRANSITION ZONES

Besides the narrow iron Kα lines at 6.4 keV, broad line components centered at $E_{\rm K\alpha} = 6.79$ keV with equivalent width EW=287 eV for NGC 4579, and EW=101 eV for M81, were observed with XMM-Newton by Dewangan et al. (2004). The widths of these two lines with Gaussian fittings are $\sigma = 231$ eV and 188 eV for NGC 4579 and M81, respectively.

Thermal X-ray line emission can be calculated when the physical properties of the plasma, i.e., the temperature, density and metallicity, are specified. Using the models of the ADAF+thin accretion disk systems described in the previous section, we can calculate their thermal X-ray line emission from the accretion flows surrounding the black holes in these two low-luminosity active galactic nuclei, NGC 4579 and M81. In the ADAF+standard thin disk system, the inner ADAF is very hot ($T_e \sim 10^9 - 10^{10}$ K) and the outer thin disk is cold ($T_e \sim 10^4 - 10^5$ K). Thus, the inner ADAF is too hot

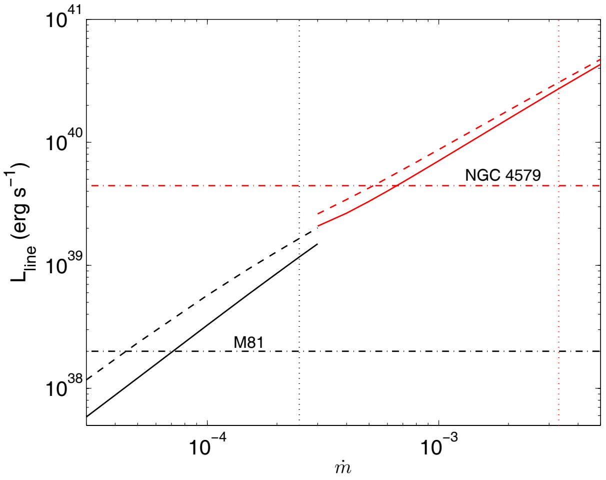

Fig. 2 Total H-like and He-like iron line luminosities as functions of accretion rate $\dot{m}$ calculated using Honma (1996)'s model. The solid lines correspond to cases with solar metallicity, while the dashed lines are for cases with five times solar metallicity. The observed values for these two sources are marked in the figure (dash-dotted lines). The dotted lines represent the accretion rates derived from the ADAF+SD model fitting of the observed SEDs.

to produce thermal X-ray line emission since the plasma is almost completely ionized, while the outer thin disk is too cold to generate thermal X-ray line emission. For the H-like and He-like iron line emission that we are interested in, they are most probably emitted from the transition zone of the ADAF to the outer thin disk, because the temperature of the transition zone is between $\sim (10^{\,4}-10^5)-(10^9-10^{10})$ K.

The line luminosity $L_{\rm line}$ can be calculated by integrating over the transition zone,

$$L_{\rm line} = \int_{r_{\rm tr}-\delta r}^{r_{\rm tr}} n_e(r)^2 \epsilon_{\rm line}(r) \frac{1-e^{-\tau_{\rm line}(r)}}{\tau_{\rm line}(r)} 4\pi r H(r) R_{\rm S}^2 {\rm d}r \,, \qquad (8)$$

where n_e is the electron number density, δr is the width of the transition zone connecting the inner ADAF to the thin disk, $r_{\rm tr}$ is the inner radius of the thin disk, $H = c_s/\Omega$ is the vertical half-thickness of the transition zone and $\tau_{\rm line} = 2Hk_{\rm line}$ is the optical depth of the emission line in the vertical direction ($k_{\rm line}$ is the line absorption coefficient). The line emissivity $\epsilon_{\rm line}(r)$ as a function of temperature is calculated with the standard software package Astrophysical Plasma Emission Code (APEC) (Smith et al. 2001). The APEC code includes collisional excitation, recombination to excited levels and dielectronic satellite lines (see Smith et al. 2001, for details). It ignores photo-ionization, which is not important in these two low-luminosity AGNs (see discussion in Dewangan et al. 2004). We assume ionization equilibrium in the plasma. In the transition zone, the density/temperature of flow changes by orders of magnitude from the inner optically-thin ADAF to the outer optically-thick thin disk. The optical depth of the flow can be very large in the outer part of the transition region, and the absorption and radiative transfer of the line is considered in our calculation. The X-ray continuum emission of the ADAF+thin disk system is dominated by the bremsstrahlung and the Comptonization of the soft photons in the ADAF. Considering that the energy resolution of the observations of the X-ray line emission is quite low, we only calculate the total equivalent widths of H-like and He-like iron lines.

In Figure 2, we plot the thermal X-ray line luminosity as functions of accretion rate $\dot{m}$ based on the transition model given by Manmoto et al. (2000). Besides the solar metallicity, we also calculate the X-ray line emission from these two sources for five times solar metallicity for comparison.

5 DISCUSSION

Our best fits to the observed continuum spectra of these two sources show that the outer thin disks are truncated at $r_{\rm tr} = 120$ and 80, for M81 and NGC 4579, respectively. The two important disk parameters, $\dot{m}$ and $r_{\rm tr}$, are mainly determined from the comparison of the outer disk spectra with the observed optical/UV continuum emission in these two sources, and the observed X-ray continuum spectra can then be naturally reproduced by the ADAF models. The observed widths of the broad lines are roughly consistent with Doppler broadening by Keplerian motion of the gas in the transition zone at $\sim 50 - 150\ R_{\rm S}$ (Dewangan et al. 2004). The ratio of the transition radii of these two sources is 1.5, which is consistent with the observed line width ratio $\simeq 0.814$, because the width $\sigma \propto r_{\rm tr}^{-1/2}$.

Comparison of our calculations based on the transition zones given by Manmoto et al. (2000) (see Fig. 2, and Sections 3 and 4 for a detailed description) with the observations show that the accretion rates are $\dot{m} \sim 7.1 \times 10^{-5}$ and 6.5×10^{-4} for M81 and NGC 4579, respectively (see Fig. 2). These seem to be inconsistent with the optical/UV spectra observed in these two sources, which require the accretion rates to be $\dot{m} = 2.5 \times 10^{-4}$ (M81) and 3.3×10^{-3} (NGC 4579), unless the transition radii deviate significantly from ~ 100 (e.g., an order of magnitude smaller than 100). However, the widths of the thermal X-ray lines provide strict constraints on the transition radii, if the thermal X-ray line emission does originate from the transition zones. The dependence of our results on the metallicity can be understood with Equation (8). A larger metallicity will increase the line emissivity and line optical depth at the same time, while the line luminosity and EW will slightly increase by a factor $1 - e^{-\tau_{\rm line}}$. Of course, the structure of ADAF+thin disk systems based on this model is rather simplified, in which only one temperature is considered (i.e., the electrons have the same temperature as the ions). Thus, we cannot rule out this model from the thermal X-ray line emission only. In the transition zone, the density is very high so that one temperature flow is a good approximation, as the Coulomb interaction between ions and electrons in this region is very efficient. Our calculations of the thermal X-ray line emission from the transition zone have not been affected by this one temperature assumption. More detailed calculations of the ADAF+thin disk systems, including energy equilibrium between electrons and ions in accretion flows, may help to test this model, which is beyond the scope of this work.

An alternative model for the transition of a thin disk to an ADAF is the "evaporation" mechanism initially suggested by Meyer & Meyer-Hofmeister (1994), in which the thin disk is evaporated as it is heated by electron conduction from a hot corona, and then a quasi-spherical hot accretion flow is formed. There is a very thin layer between the cold thin disk and the hot corona, in which the electron temperature may vary from $\sim 10^{6.5}$ K to $\sim 10^{9}$ K in the corona (e.g. Liu et al. 1995, 1997, 2002). Such a layer, of course, will emit thermal X-ray line emission. In principle, the evaporation model for the transition of a thin disk to an ADAF can be tested by the observed thermal X-ray line emission. However, the structure of this disk-corona system is complicated and is only available by numerically integrating a set of ordinary differential equations (e.g., Liu et al. 2002), which prevents us from testing this model in this paper.

Acknowledgements We thank the anonymous referee for his/her helpful comments/suggestions. We are grateful to R. Narayan and B. F. Liu for helpful discussion. This work is supported by the NSFC (Nos. 10778621, 10703003, 10773020, 10821302 and 10833002), the CAS (No. KJCX2-YW-T03), and the National Basic Research Program of China (No. 2009CB824800).

References

Barth, A. J., Ho, L. C., Filippenko, A. V., Rix, H.-W., & Sargent, W. L. W. 2001, ApJ, 546, 205
Bisnovatyi-Kogan, G. S., & Lovelace, R. V. E. 1997, ApJ, 486, L43
Bisnovatyi-Kogan, G. S., & Lovelace, R. V. E. 2000, ApJ, 529, 978
Cao, X. 2003, ApJ, 599, 147
Cao, X., & Wang, T. -G. 2006, ApJ, 652, 112
Chiang, J. 2002, ApJ, 572, 79

Devereux, N., Ford, H., Tsvetanov, Z., & Jacoby, G. 2003, AJ, 125, 1226
Dewangan, G. C., Griffiths, R. E., Di Matteo, T., & Schurch, N. J. 2004, ApJ, 607, 788
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Esin, A. A., Narayan, R., Cui, W., Grove, J. E., & Zhang, S.-N. 1998, ApJ, 505, 854
Ho, L. C. 1999, ApJ, 516, 672
Honma, F. 1996, PASJ, 48, 77
Hubeny, I., Blaes, O., Krolik, J. H., & Agol, E. 2001, ApJ, 559, 680
Ishisaki, Y., Makishima, K., Iyomoto, N., et al. 1996, PASJ, 48, 237
Lasota, J.-P., Abramowicz, M. A., Chen, X., Krolik, J., Narayan, R., & Yi, I. 1996, ApJ, 462, 142
Liu, B. F., Meyer, F., & Meyer-Hofmeister, E. 1997, A&A, 328, 247
Liu, B. F., Mineshige, S., Meyer, F., Meyer-Hofmeister, E., & Kawaguchi, T. 2002, ApJ, 575, 117
Liu, B. F., Yuan, W., Meyer, F., Meyer-Hofmeister, E., & Xie, G. Z. 1999, ApJ, 527, L17
Liu, F. K., Meyer, F., & Meyer-Hofmeister, E. 1995, A&A, 300, 823
Manmoto, T. 2000, ApJ, 534, 734
Manmoto, T., & Kato, S. 2000, ApJ, 538, 295
Manmoto, T., Kato, S., Nakamura, K. E., & Narayan, R. 2000, ApJ, 529, 127
Meyer, F., & Meyer-Hofmeister, E. 1994, A&A, 288, 175
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Narayan, R. 1996, ApJ, 462, 136
Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. 1998, ApJ, 492, 554
Narayan, R., Mahadevan, R., & Quataert, E. 1998, in Theory of Black Hole Accretion Disks, eds. M. A. Abramowicz, G. Bjornsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 148
Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
Narayan, R., & Raymond, J. 1999, ApJ, 515, L69
Quataert, E., Di Matteo, T., Narayan, R., & Ho, L. C. 1999, ApJ, 525, L89
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91
Sun, W.-H., & Malkan, M. A. 1989, ApJ, 346, 68
Terashima, Y., et al. 1998, ApJ, 503, 212
Wu, Q., Yuan, F., & Cao, X. 2007, ApJ, 669, 96
Xu, Y.-D., Narayan, R., Quataert, E., Yuan, F., & Baganoff, F. K. 2006, ApJ, 640, 319