Influences of magnetic coupling process on the spectrum of a disk covered by the corona

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ABSTRACT

Context. Recently, much attention has been paid to the magnetic coupling (MC) process, which is supported by very high emissivity indexes observed in Seyfert 1 galaxy MCG-6-30-15 and GBHC XTE J1650-500. But the rotational energy transferred from a black hole is simply assumed to be radiated away from the surrounding accretion disk in black-body spectrum, which is obviously not consistent with the observed hard power-law X-ray spectra.

Aims. We intend to introduce corona into the MC model to make it more compatible with the observations.

Methods. We describe the model and the procedure of a simplified Monte Carlo simulation, compare the output spectra in the cases with and without the MC effects, and discuss the influences of three parameters involved in the MC process on the output spectra.

Results. It is shown that the MC process augments radiation fluxes in the UV or X-ray band. The emergent spectrum is affected by the BH spin and magnetic field strength at the BH horizon, while it is almost unaffected by the radial profile of the magnetic field at the disk.

Conclusions. Introducing corona into the MC model will improve the fitting of the output spectra from AGNs and GBHCs.

Key words. accretion – accretion disks – black hole physics – magnetic field – corona

1. INTRODUCTION

Tenuous hot plasma (corona) is commonly believed to exist in the inner region of the accretion flow, which is produced and heated by magnetic activities, such as reconnection and flare etc. (e.g. [Liang & Price 1977] [Galeev et al. 1979]). The influences of the disk corona on the emergent spectrum from active galactic nuclei (AGNs) and galactic black-hole candidates (GBHCs) have been discussed by many authors (e.g. Haardt & Maraschi 1991, hereafter [HM91] Haardt & Maraschi 1993, Field & Rogers 1993, Esin 1999, Zhang et al. 2000, Liu et al. 2002). Corona explains the power-law X-ray spectra very well, and reprocessing of the coronal X-rays

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by cold disk gives rise to the observed emission lines naturally, in which iron $K\alpha$ fluorescence line provides us a diagnostic of the geometry of the accretion flow and the property of the space-time around the black hole (BH). However, only gravitational energy of the accreting matter is invoked to heat the disk and its corona in previous works.

Recently, much attention has been paid to the magnetic coupling (MC) process in which energy is transferred from a rotating BH to its surrounding disk (Blandford 1999; van Putten 1999; Li & Paczynski 2000; Wang et al. 2002; Wang et al. 2003a, b, hereafter W03a and W03b respectively), which is in fact a variant of the Blandford-Znajek (BZ) process. The existence of the MC process has been supported by very high emissivity indexes observed in Seyfert 1 galaxy MCG-6-30-15 and the GBHC XTE J1650-500, which cannot be explained by the standard accretion disk (Wilms et al. 2001; Miller et al. 2002; Li 2002b).

However, in the previous MC models all the energies that deposit on the disk, both the gravitational energy of the accreting matter and the rotational energy transferred from the BH, are simply assumed to be radiated away in black-body spectrum, which is obviously not consistent with the observed hard power-law X-ray spectra. In this paper we intend to introduce corona into the MC model and discuss the spectrum affected by the MC process. It is shown that the MC process augments the radiation fluxes, while corona makes MC model more reasonable and more consistent with the observations than the previous MC model.

The paper is arranged as follows: Sect.2 gives the description of our model. Sect.3 shows the procedure and results of our simplified Monte Carlo simulation and in Sect.4 we discuss the applications of our model to observations. Throughout this paper the geometric units $G = c = 1$ are used.

### 2. DESCRIPTION OF OUR MODEL

The poloidal profile of the large-scale magnetic field and the geometry of the corona are illustrated in Fig. 1. The central BH is fast rotating and surrounded by axisymmetric magnetosphere. It is assumed that the disk is geometrically thin and optically thick, while the corona is geometrically thick and optically thin. The poloidal magnetic field is assumed to be constant on the horizon and it varies as a power-law with the radial coordinate on the disk, i.e.,

$$B_H = \text{const}, \quad B_D \propto r^{-n}. \quad (1)$$

In Fig. 1 the angle $\theta_M$ indicates the angular boundary between the open and closed field lines at the BH horizon, which can be determined by the mapping relation derived in W03b. The angle $\theta_L$ is the lower angular boundary of the closed field lines, and it is supposed to be less than $0.5\pi$ to avoid the singularity of the closed field lines at the equatorial plane. The magnetic field powers the jet via the BZ process and transfers energy between the BH and the disk via the MC process.

Both large- and small-scale magnetic fields are involved in our model though the latter is not shown in Fig. 1. The large-scale magnetic field plays a key role in transferring energy and angular...
momentum from a fast-rotating BH to its surrounding disk or remote astrophysical load in the MC and BZ processes, respectively. While the small-scale magnetic field energizes the corona above the disk by virtue of some physical processes, such as magnetic reconnection and buoyancy (HM91). Moreover, the large-scale field can be produced from the small-scale field created by dynamo processes (e.g. Tout & Pringle 1996). Livio et al. (1999) argued that the strength of the large-scale field threading a black hole is very weak if the field is created in the thin disk, because the ratio of the large-scale field to the small-scale field is \( \sim H/R \ll 1 \), where \( H \) is the disk thickness and \( R \) is the radial size of the field. This greatly confines the BZ and MC powers. Since the thickness of the corona is about the radius of the disk, the large-scale magnetic fields created by dynamo processes in the corona are significantly stronger than those in the thin disk (Cao 2004), and the strong BZ and MC powers are maintained. For simplicity, we suppose that these two kinds of magnetic fields exist independently.

The energy deposited in the corona and disk consists of two parts: (i) the gravitational energy of the accreting matter, and (ii) the rotational energy of the BH transferred in the MC process. Some authors (e.g. [HM91] Merloni & Fabian 2002) have mentioned physical processes in which the gravitational energy converts to the thermal energies of the corona and disk. However, nobody has proposed any mechanism to describe how the rotational energy of the BH transferred in the MC process dissipates to date. In this paper, we deal with this issue based on the following two considerations.

(i) Based on BH magnetosphere theory [Macdonald & Thorne 1982, Thorne et al. 1986, Li 2002a, W03b], the disk can be regarded as an electromotive force (EMF) in an equivalent circuit due to its rotation, which is opposite to the BH EMF. If the angular velocity of the BH is greater than that of the disk, Poynting flux would flow from the BH to the disk (W03b). Although the disk is commonly supposed to be a perfect conductor, its interior resistance may not be zero. Part
of the MC power may heats the disk, just as Poynting flux gets into the resistance and heats it in a circuit;

(ii) The flux of the angular momentum transferred magnetically from the BH to the disk decreases rapidly with disk radius (see Eq. (3) below), and it results in the differential rotation of the accreted matter. Thus the electromagnetic energy converts to thermal dissipation, just as the gravitational energy of accreting matter converts to thermal dissipation in disk accretion.

Detailed discussions of these physical processes are beyond the scope of this paper, and we assume that both the gravitational energy of the disk and the rotational energy of the BH can dissipate into thermal energy of the corona and disk.

The scenario of the emergent spectrum is described as follows. Thermal soft seed photons are emitted from the disk, and when they cross the rarefied hot corona, some may go through the corona directly without being scattered, some may escape after one or several times of scattering, and others may be down-scattered to the disk by the corona. The fate of the X-ray photon that returns to the disk depends critically upon its energy $E$: (a) if $E > 100\text{keV}$, the photon loses its energy by Compton recoil, (b) if $E < a\text{ few keV}$, the photon is absorbed by ionization or free-free absorption, and (c) it may be both Compton scattered and bound-free absorbed for $a\text{ few keV} < E < 100\text{keV}$ [Field & Rogers 1993]. Bound-free absorption or ionization results in a vacancy in the inner shell of an atom, which leads to a fluorescence photon or the ejection of an Auger electron (for details see George & Fabian 1991, hereafter GF91). Unscattered photons form the component of the UV/soft X-ray band, photons escaping the corona after inverse Compton scatterings constitute the power-law X-ray spectrum, while reprocessed photons by the disk produce fluorescence lines and a reflection hump.

Here we neglect cyclo-synchrotron radiation since it is less important than Compton radiation in the slab corona [Di Matteo et al. 1997, Ghisellini et al. 1998]. We also neglect the bremsstrahlung radiation, assuming that the corona is tenuous enough.

From the above scenario it can be found that part of the energy dissipated in the corona is conveyed to the disk via hard X-rays, i.e., the disk is heated by three kinds of energies: (1) gravitational energy of the accreting matter, (2) rotational energy of the BH transferred to the disk and (3) the absorbed energy of X-rays coming from the corona. Since the energy of the X-rays comes eventually from the gravitational and rotational energies, we suppose the fraction of the total energy dissipate in the disk to be $\eta$, which includes the contribution of the downward X-rays. As shown in [HM91] the soft emission is derived almost only from absorption and reprocessing of the high-energy flux impinging on the disk. Roughly half of the Comptonized photons in the corona irradiate and heat the disk, and the rest half radiate away. So we take $\eta = 0.5$ in calculations.

Additionally, for simplicity of simulation, the disk is assumed to be “cold”, with hydrogen and helium being fully ionized, but all other elements being neutral or weakly ionized. Moreover, the energetic and spatial distributions of free electrons in the corona is postulated to be thermal and homogeneous.
3. SIMULATION OF DISK SPECTRUM

3.1. Multicolor Black-Body Spectrum of the Disk Affected by the MC Process

Based on the conservation laws of mass, angular momentum and energy, the local radiation flux from the disk around a rotating BH is given by Page & Thorne (1974) and Li (2002a),

$$ F = \frac{M_D}{4\pi r} f + \left( -\frac{d\Omega_D}{rdr} \right) \left( E^+ - \Omega_D L^+ \right) H r dr, $$

(2)

where $M_D$, $\Omega_D$, $r_{ms}$, $E^+$ and $L^+$ are respectively the accretion rate, the angular velocity of the disk, the radius of the marginally stable orbit, the specific energy and angular momentum at the disk radius $r$. The function $f$ is related to the radiation flux due to disk accretion, and $H$ is the flux of angular momentum transferred between the BH and the disk (W03a),

$$ H(a_\ast; \xi, n)/H_0 = \begin{cases} A(a_\ast, \xi) \xi^{-n}, & 1 < \xi < \xi_{out} \\ 0, & \xi > \xi_{out} \end{cases}, $$

(3)

$$ A(a_\ast, \xi) = \frac{a_\ast (1 - \beta)}{2\pi [2\csc^2 \theta - (1 - q)]} \sqrt{1 + a_\ast^2 \chi_{ms}^4 \xi^{-2} + 2a_\ast^2 \chi_{ms}^4 \xi^{-3} - \frac{1}{1 - 2\chi_{ms}^2 \xi^{-1} + a_\ast^2 \chi_{ms}^4 \xi^{-2}}}, $$

(4)

where $H_0 \equiv (B_H^0)^2 M$, $\beta$ is the ratio of the angular velocity of the disk to that of the BH, i.e. $\beta \equiv \Omega_D/\Omega_H$, $\xi = r/r_{ms}$ is a radial parameter of the disk defined in terms of $r_{ms}$, and $\chi_{ms} \equiv \sqrt{r_{ms}/M}$.

The relation between the magnetic field and the accretion rate is given by Moderski et al. (1997) based on the balance between the pressure of the magnetic field on the horizon and the ram pressure of the innermost parts of an accretion flow, i.e.,

$$ (B_H^0)^2/(8\pi) = \rho c^2 \sim \dot{M}_D/(4\pi r_H^2), $$

(5)

where $r_H$ is the radius of the horizon. From Eq. we can define $F_0 \equiv (B_H^0)^2 = 2\dot{M}_D/[M^2 \left(1 + \sqrt{1 - a_\ast^4}\right)^2]$. For the presence of corona the dissipated power in the unit area of the disk, $F_d$, is related to $F(r)$ by

$$ F_d(r) = \eta F(r), $$

(6)

where $F(r)$ is the local radiation flux expressed by Eq. According to Stefan-Boltzmann law we have the local effective temperature on the disk expressed by

$$ T_d(r) = (F_d/\sigma_{SB})^{1/4}, $$

(7)

where $\sigma_{SB}$ is the Stefan-Boltzmann constant. The local radiation spectrum is defined by Planck function:

$$ B_v(r) = \frac{2h}{c^2} \frac{v^3}{\exp [hv/k_B T_d(r)] - 1}. $$

(8)

Thus the multicolor black-body spectrum of the disk is

$$ L_v = \int_{r_{in}}^{r_{out}} B_v(r) 2\pi r dr. $$

(9)
3.2. Monte Carlo Simulation

If the disk is covered by corona, we need to resolve the radiative transfer in the hot corona to get the emergent spectrum. Radiative transfer has been computed in different ways. One approach is to solve the radiative transfer equation either numerically or analytically (e.g. Sunyaev & Titarchuk 1980, Poutanen & Svensson 1996). Another approach is the Monte Carlo simulation (e.g. Pozdnyakov et al. 1983, hereafter P83; Gorecki & Wilczewski 1984, GF91; Stern et al. 1995; Hua 1997, hereafter H97; Yao et al. 2005). The emergent spectrum can be also obtained by some approximate semi-analytical formulae (e.g. Zdziarski 1986; Hua & Titarchuk 1995). In this paper we calculate the spectrum by using the Monte Carlo simulation.

Compared with H97, photon absorption in the disk is taken into account in our model, which makes the simulation slightly more complex. The steps of the simulation are: (i) sample a seed photon including its position, energy and direction; (ii) draw a value for its free path and test whether it can leave the disk or corona; (iii) simulate the interaction of the photon with the medium; (iv) repeat steps (ii), (iii) till the photon leaves the system of the corona and disk.

3.2.1. Sampling the seed photons

The probability density of the seed photon can be written as

\[
p(r, v) = 2\pi r dr \cdot F_v(r)/L, \tag{10}
\]

where \( F_v(r) \) is the flux density at \( r \), \( L \equiv \int_r^{r_{\text{out}}} L(r) dr \) is the total luminosity of the disk, and \( L(r)dr = 2\pi r F_d(r) dr \) is the luminosity of the ring \( r \sim r + dr \). Obviously, \( p(r, v) \) can be expressed as follows,

\[
p(r, v) = \frac{L(r)dr}{L} \cdot \frac{2\pi r \cdot F_v(r) dr}{L(r)dr} = \frac{L(r)dr}{L} \cdot \frac{F_v(r)}{F_d(r)} = \tilde{p}(r) B_v(r) \tag{11}
\]

where \( \tilde{p}(r) \) is the probability of a photon emitted in the ring \( r \sim r + dr \), which can be sampled by tabulation. The Planck function \( B_v(r) \) can be sampled in the way described in P83.

3.2.2. Drawing the free path

For the photon scattered in the corona, the probability it travels at least an optical depth \( \tau \) is \( e^{-\tau} \), so the optical depth that the photon travels between the \( i \)-th and \((i+1)\)-th scatterings can be drawn with \( \tau_i = -\ln \lambda \), where \( 0 \leq \lambda \leq 1 \) is a random number corresponding to a random event. Then the free path of the photon can be drawn with \( \frac{r_i}{n_e \sigma_T} = \frac{-\ln \lambda}{\sigma} \cdot \frac{H_e}{\tau} \), where \( n_e \), \( \sigma \) and \( \sigma_T = 6.65 \times 10^{-24} \text{cm}^2 \) are the number density of the electrons, cross-sections of scattering and Thomson Scattering, respectively. The parameters \( H_e \) and \( \tau_e \) are the vertical height and optical depth of the corona, respectively. Because the corona is very hot, electrons in it are relativistic, which means that \( \sigma \) depends not only on the energy of the photon but also on the energy and
direction of the electron. So the cross-section averaged over the distribution of the electrons in [H97] is used to draw the free path of the photon.

Since the disk is assumed to be “cold”, with hydrogen and helium being fully ionized, and all other elements being neutral or weakly ionized, hard X-ray photons irradiating the disk from the corona can be absorbed by the atoms, as well as being scattered by the free electrons. In this case, there are two viable ways to draw the free path of the photon: (i) choose the lesser of the two free paths that are drawn with $\sigma_a$ and $\sigma_s$, where $\sigma_a$ and $\sigma_s$ are respectively the cross sections of absorption and scattering [GF91]; (ii) draw the free path with $\sqrt{\sigma_a(\sigma_a + \sigma_s)}$, and determine the interaction by drawing a random number $\lambda$ and comparing it with the probability that a free path ends with absorption, i.e., $\zeta = \frac{\sigma_a}{\sigma_a + \sigma_s}$. If $\lambda \leq \zeta$, the photon will be absorbed and otherwise be scattered [Rybicki & Lightman 1979]. We follow the first way in our simulations. Since electrons in the disk is nonrelativistic, $\sigma_s$ can be given by the Klein-Nishina formula:

$$\sigma_s = \frac{3\sigma_T}{4} \frac{1}{x} \left( \left[ 1 - \frac{4}{x} - \frac{8}{x^2} \right] \ln(1 + x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1 + x)^2} \right), \tag{12}$$

where $x = 2\hbar v / m_e c^2$ is the energy of the incident photon in unit of electron-rest-energy. The cross section of absorption $\sigma_a$ is taken from Morrison & McCammon (1983).

As the free path is known, the position that the photon arrives before the next interaction can be calculated. If the photon is outside the corona-disk system, it will escape away from the system and its energy and direction are recorded. But if the photon transfers from the disk to the corona or inverse, the point where the trajectory of the photon cross the interface between the disk and corona should be regarded as the next initial position of the photon in calculations (see [H97] for details).

### 3.2.3. Simulating the interaction

If the photon is scattered in the corona or disk, we can first sample an electron from thermal distribution, and then calculate the energy and direction of the scattered photon, following the procedure described in [P83].

The bound-free absorption of hard X-rays by the atoms in the disk will lead to ionization and vacancy, and induce emission of fluorescence lines with the probability called fluorescence yield, $Y$, rather than ejection of Auger electrons. In the simulations, if the photon is absorbed by a certain atom or ion, we can draw a random number $\lambda$ ($0 \leq \lambda \leq 1$) and compare it with the corresponding fluorescence yield. If $\lambda < Y$, an emission line is brought out, whose direction can be sampled from the isotropic distribution. If $\lambda > Y$, an Auger electron is sent out, the photon vanishes and its trajectory ends.

Because of the large abundance and cross-section of absorption of iron, only the 6.4keV Fe Kα fluorescence line is considered in our simulations. If the energy of the absorbed photon is less than the iron K-shell absorption edge, i.e. $E < 7.1$keV, no emission line is produced, while Fe Kα lines emanate with $Y = 0.34$ for $E > 7.1$keV.
3.3. Parameters of Corona and Results of Simulations

Optically thin thermal Compton scattering spectra are well represented by power-laws with exponential cut-offs, and the spectral index can be approximately given by (e.g. Rybicki & Lightman 1979)

$$\alpha = -\ln \frac{P}{\ln A_1}. \quad (13)$$

In Eq. (13) $A_1 = 1 + 4\Theta + 16\Theta^2$ is the average photon energy amplification per scattering, where $\Theta = kT_c/m_e c^2$ with $T_c$ being the coronal temperature. The average scattering probability $P$ for a uniform slab is given by Zdziarski et al. (1994) as

$$P = 1 + \exp\left(-\frac{\tau}{2}\left(\frac{1}{\tau} - 1\right) - \frac{1}{2\tau} + \frac{\tau}{2} E_1(\tau)\right), \quad (14)$$

where $E_1$ is the exponential integral (Press et al. 1992).

Observations of Seyfert galaxies show that their spectral indexes and the coronal Thomson optical depths are about 0.9 and 1, respectively (HM91; Zdziarski 1998), and we take $\alpha = 0.9, \tau = 1$ in simulations. From Eq. (13), we estimate the temperature of the corona to be $T_c \approx 60$keV.

In the following calculations, the radii of the inner and outer edges of the corona and disk are taken as $r_{ms}$ and $20r_{ms}$, respectively. The half heights of the disk and the corona are assumed to be $H_d = 0.02r_{ms}$ and $H_c = r_{ms}$, respectively. The value of $H_d \ll r_{ms}$ does not affect the final results. The radial range of the disk is taken to be rather small, because the MC power concentrates in the innermost region of the disk, and it can be easily verified that at least 80% of the radiation is emanated within $20r_{ms}$.

Since the typical magnetic field of the supermassive and stellar BHs are respectively about $10^4$ G and $10^8$ G, we take the middle value, $10^6$ G, in simulations. A large number ($10^9$) of photons are traced to get one spectrum in simulations, and the result of $10^9$ events costs about 100 minutes in running the program on a PC with 2.8 GHz Pentium 4 CPU. All the spectra in this paper are given in forms of curves rather than histogram to make the curves look smooth.

The simulation results are given in Fig. 2. The spectrum of the disk-corona system comprises three components, the black-body spectrum formed by unscattered photons, the power-law spectrum formed by photons that escape from the corona after several times of inverse Compton scatterings, and the reflected spectrum characterized by iron fluorescence line and reflection hump.

In order to study the effects of the MC process and corona, the spectra of the disk-corona system with and without the MC process and those with and without corona are simulated as shown in Fig. 3.

From Fig. 3 we find: (i) the disk can at most emit soft X-rays with $E < \text{fewkeV}$ without corona, while the spectrum becomes much more complex and much harder when corona exists; (ii) the MC process can increase the flux and extend the spectrum to higher energy when the corona does not exist, but it can only augment the flux and has no influence on the cutoff energy and the index of the spectrum.
Fig. 2. The spectrum of the disk-corona system (solid line) and its components. The black-body, power-law and reflected components are shown in dot-dashed, dotted and dashed lines, respectively. The parameters $a_* = 0.998$, $n = 3$ and $B = 10^6$G are taken.

Fig. 3. Multicolor spectra of the disk and the simulated spectra of the disk-corona system. Thick and thin lines correspond to the spectra with and without the MC process, respectively. Solid and dashed lines correspond to the spectra with and without corona, respectively. The parameters $a_* = 0.998$, $n = 3$ and $B = 10^6$G are taken.

The fact that the cutoff energy and index of the spectrum are indifferent with the MC process when corona exists is because the spectral cutoff $h\nu_{\text{cut}}$ and index $\alpha$ are determined by $\Theta$ and $\tau$, which are independent of the MC process in our model.

Spectra with different $a_*$, $n$ and $B$ are given in Fig. 4, from which we find (i) the fluxes increase with $a_*$ and $B$ no matter the MC process exists or not; (ii) the parameter $n$ has little influence on the flux.
Fig. 4. Spectra corresponding to different values of the parameters $a_*$, $n$ and $B$ in (a), (b) and (c), respectively. Thick and thin lines correspond to the states with and without the MC process, respectively.

It can be easily explained why the fluxes increase with $a_*$ and $B$ no matter the MC process exists or not. For pure accretion without the MC process, as $a_*$ increases the inner edge of disk approaches the BH horizon, and more gravitational energy can be released if the accretion rate is
the same. So the fluxes of the disk-corona system increase with $a_\ast$. According to Eq. (5), stronger magnetic field corresponds to a greater accretion rate $\dot{M}_D$, and thus higher fluxes. At the presence of the MC process, higher fluxes are produced for greater $a_\ast$ and $B$ since the MC power increases with both $a_\ast$ and $B$. The flux is almost unaffected by $n$ because the MC power is not significantly affected by $n$.

4. APPLICATION TO ASTROPHYSICS

In this paper corona is introduced into our model, and it is helpful to interpret the following observations.

4.1. Jet

The same as our previous model, the BZ and MC processes can coexist in the present model, provided that the parameters $a_\ast$ and $n$ are greater than some critical values, and their powers are derived by using a modified equivalent circuit and expressed as follows (W03b).

\[
\frac{P_{BZ}}{P_0} = 2a_\ast^2 \int_{0}^{\theta_M} \frac{k(1 - k) \sin^3 \theta d\theta}{2 - (1 - q) \sin^2 \theta}, \quad 0 < \theta < \theta_M,
\]

\[
\frac{P_{MC}}{P_0} = 2a_\ast^2 \int_{\theta_M}^{\theta_L} \frac{\beta(1 - \beta) \sin^3 \theta d\theta}{2 - (1 - q) \sin^2 \theta}, \quad \theta_M < \theta < \theta_L,
\]

where $P_0 \equiv (B_H^0)^2 M^2$.

An important feature of our model is the strength of the BZ power relative to the MC power can be adjusted by virtue of the angle $\theta_M$, which is the angular boundary between the open and closed field lines at the BH horizon as shown in Fig.1. As argued in W03b, $\theta_M$ is eventually determined by the parameters $a_\ast$ and $n$ contained in the mapping relation between the angular coordinate on the BH horizon and the radial coordinate on the disk.

Combining accretion with the MC process, the luminosity of the disk can be expressed as

\[
L = (1 - E_{ms}) \dot{M}_D + P_{MC}.
\]

The first term in Eq. (17) comes from disk accretion, and the second term from the contribution of the MC process. The quantity $E_{ms}$ is the specific energy of the accreting matter corresponding to the marginally stable orbit and it reads (Novikov & Thorne 1973)

\[
E_{ms} = \frac{1 - 2\chi_{ms}^{-2} + a_\ast \chi_{ms}^{-3}}{(1 - 3\chi_{ms}^{-2} + 2a_\ast \chi_{ms}^{-3})^{3/2}}.
\]

Our model can be applied to the observations of some sources, fitting the jet power in radio band driven by the BZ process and fitting the bolometric luminosity driven by disk accretion and the MC process.

Here we apply our model to fit the observational data of 3C 273. The BH mass contained is estimated as $6.59 \times 10^9 M_\odot$ by reverberation method, the bolometric luminosity $L$ is estimated
Fig. 5. The numbers of iron fluorescence photons at different radii and different incline angles. Solid lines, dashed lines and dotted lines correspond to \( \mu = \cos i = 0.95, 0.75, 0.35 \), respectively. Thick lines and thin lines correspond to the cases with and without the MC effects, respectively. The parameters, \( a_s = 0.998, n = 3 \) and \( B = 10^6 \)G are given.

to be \( \sim 10^{47} \text{erg} \cdot \text{s}^{-1} \) (Paltani \& T{"u}rler 2005), and the minimum jet power is given as \( P_{\text{jet}}^{\text{min}} = 6.61 \times 10^{45} \text{erg} \cdot \text{s}^{-1} \) (Celotti et al. 1997). If the magnetic field at the BH horizon is considered to be \( B_H^{\beta} \approx 10^4 M_9^{-1/2} \)G (Beskin 1997), we can estimate some parameters of our model as \( a_s \approx 0.76, n \approx 6.13 \) and \( \theta_M \approx 48^\circ \) by combining Eqs. (15)–(18) with the relation (5).

The spectral index, \( \alpha \approx 0.77 \), and luminosity of the X-rays in the range of 3-10keV, \( L_{3-10} \approx 0.81 \times 10^{46} \text{erg} \cdot \text{s}^{-1} \) can be derived from Page et al. (2004), where some X-ray observational results of 3C273 are listed. Combining Eq. (13) with the assumption that \( \tau = 1 \), we have \( T_c \approx 73 \)keV. It can then be obtained by Monte Carlo method that \( L_{3-10} \approx 0.72 \times 10^{46} \text{erg} \cdot \text{s}^{-1} \), which is a little less than the observational data. Since 3C273 is a well known radio-loud quasar with a jet showing superluminal motion, the X-rays emitted by synchrotron self-Comptonization of high-energy electrons in the jet should be considered. Moreover, the degree of ionization of the disk is supposed to be low in our model, which means higher absorption in the range \( \sim 10 \)keV. If these reasons are considered, the luminosity of the X-rays could be well fitted with our model.

4.2. Steep Emissivity Index

Wilms et al. (2001) assumed that the reflected flux has an emissivity profile \( \propto r^{-\beta} \) in fitting the 2-10keV observational data of Seyfert I galaxy MCG-6-30-15, and found a very interesting result. The emissivity profile is very steep with \( \beta = 4.3 - 5.0 \), which is too high to be explained by the standard accretion disk model.
In W03a and W03b, we explained the very steep emissivity profile by the local radiation flux emitted in black-body spectrum by virtue of the MC process. However, the spectra of previous models cannot extend to \( \sim 10 \) keV for AGNs, which is not consistent with the observations. This inconsistency can be removed in the MC model with corona.

Taking Fe K\( \alpha \) fluorescence as an example, we find in Fig. 5 that the photon numbers produced in our model reduce more quickly with the disk radius than those produced in the standard disk with corona. It turns out that the very steep emissivity produced in the MC process could not be changed at the presence of the corona.

### 4.3. QPOs

Wang et al. (2003c) explained kilohertz quasi-periodic oscillations (QPOs) in BH binaries by virtue of rotating hotspots arising from non-axisymmetric magnetic fields. When corona is introduced into our model, although the rotational energy of the BH is shared by the disk and the corona, i.e., the temperature of the hotspot on the disk decreases, the total flux from the region of higher magnetic field remains unchanged. So, as the high-magnetic-field region rotates, the fittings to the frequency of the QPOs are still valid. An interesting phenomenon different with previous model is that we can not see a hotter spot in the corona because of the cooling of more soft photons from the disk. Additionally, the introduction of corona into our model is helpful to interpret QPOs which are usually observed in steep power-law state (McClintock & Remillard 2003).

Although the introduction of the corona into our model is helpful to fitting the observations, our model needs to be improved in some aspects. For example, the more reasonable geometry and parameters of the corona should be adopted (e.g. Haardt et al. 1993; Liu et al. 2002), the cooling of synchrotron radiation should be considered, and gravitational effects on the trajectories of photons need to be taken into account since it cannot be ignored in the inner region of the disk around a rapidly spinning BH. We shall deal with these problems in future works.

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