IRON FLUORESCENT LINE EMISSION FROM BLACK HOLE ACCRETION DISKS WITH MAGNETIC RECONNECTION–HEATED CORONA

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Received 2004 November 16; accepted 2005 August 18

ABSTRACT

We investigate the iron Kα fluorescent line produced by hard X-ray photons from the magnetic reconnection–heated corona. The hot corona with temperature of \( \sim 10^9 \) K can irradiate the underlying disk with a continuum X-ray spectrum produced via thermal Comptonization. Then the iron atoms in the disk photoelectrically absorb X-ray photons and radiate Kα line photons. Therefore, the activity of the corona is responsible for the iron line emission from the underlying disk. In previous studies, oversimplified X-ray photon sources were often assumed above the disk in order to compute the iron line profile or power-law line emissivity profiles were assumed with an index as a free parameter. We adopt the more realistic corona model constructed by Liu et al. in which the corona is heated by magnetic energy released through the reconnection of magnetic flux loops and which has no free parameter. Then the accretion energy is dominantly dissipated in the corona, in which X-ray photons are efficiently produced and irradiate the underlying disk. We find that the local emissivity of the iron line on the disk is approximated as \( F_{\rm K\alpha}(r) \propto r^{-2} \). The iron line profiles derived from this model give excellent fits to the observational data of MCG −6-30-15 with the profiles derived theoretically for \( i \sim 30^\circ \) for the 4–7 keV energy band. Possible origins of line variability are briefly discussed.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — line: profiles

1. INTRODUCTION

The iron Kα line is one of the most useful probes of the vicinity of a black hole. It might be produced by X-ray irradiation of cold iron atoms in an optically thick accretion disk. Although the line width is intrinsically small, the line profile is broadened by Doppler effects and distorted by relativistic beaming and gravitational redshifts, since the material is orbiting at high velocity in a strong gravitational field. Thus, we expect to be able to get some information about the gravitational field and the accretion flow close to the central black hole from the shape of the iron line profile (for comprehensive reviews, see Fabian et al. 2000; Reynolds & Nowak 2003).

In many previous studies, the relativistic effects that distort the iron line profile have been computed in detail. Most of them, however, used very simplified models of iron line emissivity distribution. Some authors assumed a point source above the disk whose position and luminosity vary with time (Ruszkowski 2000; Lu & Yu 2001), and some authors adopted a power-law emissivity distribution on the disk (Fabian et al. 1989; Laor 1991; Kojima 1991; Dovčiak et al. 2004). Although one can reconstruct the observed iron line profiles and their time variability with these models, little can be known regarding the fundamental physics that describes the origins of X-ray irradiation in the black hole accretion disk system. In order to get information about the physical processes around the black hole by analyzing the observed iron line profile, such overidealized models are of limited use, so one should construct a more realistic X-ray source model taking into account the physics of radiation and magnetic processes.

So what is the primal X-ray source and how does it illuminate the disk? If the mass accretion rate is sufficiently high, a disk-corona structure can be established. In this case, one can expect the X-ray photons that impinge on the cold disk to be produced in the corona through inverse Compton scattering of thermal soft photons from the disk. In fact, X-ray spectral features observed in ordinary active galactic nuclei (AGNs) and some galactic black hole candidates (GBHCs) show that there is hot gas coexisting with cold matter in the vicinity of an accreting black hole (see Mushotzky et al. 1993). There are many studies about the disk-corona system (e.g., Haardt & Maraschi 1991, 1993). However, few attempts to compute the line profile with such a corona as a realistic X-ray source have been done because the coronal heating process remains unclear.

In this study, we adopt a corona model in which the magnetic flux loop emerging from the disk reconnects with other loops and heats the corona to a temperature around \( 10^9 \) K (Liu et al. 2002, hereafter LMS02). It is known that emergent spectra calculated from this model through Monte Carlo simulations are close to the observed spectra in Seyfert galaxies and radio-quiet QSOs (Liu et al. 2003, hereafter LMO03). The advantage of this model is that one can compute the iron line profile without any adjustment of free parameters except for a black hole mass \( M \) and an accretion rate \( \dot{M} \). We assume that the iron line emissivity distribution on the disk is determined by the X-ray continuum emission in the corona right above the point of interest.

The plan of this paper is as follows: In § 2, we describe the magnetic reconnection–heated corona model that is used in our study. Then we calculate the iron line profile predicted from this corona model and make some fits to observations in § 3. A discussion and conclusions are given in § 4.

2. THE DISK-CORONA MODEL

We consider the disk-corona model constructed by LMS02, in which the corona is assumed to be plane-parallel and to be coupled tightly with an underlying Shakura & Sunyaev (1973) disk (with zero-torque inner boundary condition). Magnetic flux loops generated in the disk emerge into the corona by magnetic buoyancy and reconnect with other loops. As a result, the magnetic energy in the loops is released in the corona as thermal energy. This coronal heat is cooled down by Compton scattering, and thus the energy balance in the magnetic flux tube is attained.

\[
\frac{B^2}{4\pi} \frac{V_A}{c} \approx \frac{4k_B T}{m_e c^2} n \sigma T \gamma U_{\text{rad}} \lambda^{\gamma-1},
\]

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where $V_A$ is the Alfvén speed, $U_{\text{rad}} = U_{\text{rad}}^\text{in} + U_{\text{rad}}^\text{rep}$ is the soft photon field to be Compton scattered from both the intrinsic disk and reprocessed radiation, and $l$ is the length of the magnetic loop. Here $\lambda_r$ is introduced in order to take into account the isotropy of incident photons. If $\lambda_r = 1$, the effective optical depth in the corona is equal to the vertical scattering optical depth $\tau = n\sigma_T l$.

In a plane-parallel geometry, however, the actual optical depth should be larger than the vertical one, since the incident photons would not be necessarily injected in the vertical direction and would undergo a longer path than $l$. Then if $\lambda_r$ were set to be unity, we would overestimate the coronal temperature, and therefore too large an upscattered luminosity would be derived by Monte Carlo simulation (see below). In LMO03 and our study, the value of $\lambda_r$ is determined so that the integrated upward luminosity is equal to the released gravitational energy (see LMO03); other parameters and constants have their standard meanings.

If the density of the corona is not high enough for Compton cooling, heat is conducted by electrons from the corona to the chromosphere, which is dominantly cooled down by the evaporation of plasma in the disk:

$$\frac{k_0 T^{7/2}}{l} \approx \frac{\gamma}{\gamma - 1} nkT \left( \frac{kT}{m}\right)^{1/2},$$

(2)

where $k_0 \approx 10^{-6}$ ergs cm$^{-1}$ s$^{-1}$ K$^{-7/2}$ and $\gamma = 5/3$.

Moreover, we assume equipartition of gas energy and magnetic energy in the disk,

$$\beta \equiv \frac{n_{\text{disk}}kT_{\text{disk}}}{B^2/8\pi} \sim 1$$

(3)

(although the results are not sensitive to $\beta$-values).

With these assumptions, we can derive the equations that concern the fraction of accretion energy dissipated in the corona $f$, which has been treated as a fitting parameter in previous disk-corona models. For a gas pressure–dominant disk, the soft photon field is dominated by the reprocessed coronal radiations,

$$U_{\text{rad}} \approx 0.4\lambda u U_B,$$

(4)

where $U_B$ is the magnetic field energy density. This equation requires some explanation. Haardt & Maraschi (1991) showed that the fraction of Compton-scattered photons that illuminate the underlying disk is about 0.5–0.6, and the albedo of the disk is about 0.1–0.2 for a specific range of parameters. Then, in LMS02, the reprocessed soft photon energy density is set to be $U_{\text{rad}} \approx 0.4U_B$. However, the precise value of $U_{\text{rad}}$ generally depends on the coronal temperature and density. We introduce the parameter $\lambda$ in order to take this effect into account and adopt the value so that the downward luminosity is equal to the luminosity of soft photons reprocessed in the cold disk (see LMO03).

Then we get the equation

$$f = 4.70 \times 10^{4}(1 - f)^{11/10}\alpha_{0.1}^{-99/80}\beta_{-1}^{11/8}\alpha_{r1}^{1/4}\lambda_{10}^{1/4}/m_{10}^{11/80} \times (n_{0.1} \phi)^{1/10}r_{10}^{-1}160 \lambda_{r10}^{3/8},$$

(5)

where $\phi = 1 - (R_c/R)^{1/2}$, where $R_c$ is taken to be the last stable orbit $3R_S$; and $\alpha_{-1}, \beta, m_{8}, \alpha_{r1}, r_{10}$, and $l_{10}$ are the viscous coefficient, the plasma $\beta$, the black hole mass, the accretion rate, the distance, and the length of the magnetic loop in units of 0.1, 1, $10^8 M_\odot$, 0.1$M_{\text{Edd}}$, 10$R_S$, and 10$R_S$, respectively. By solving equation (5) for $f$ for a given black hole mass and accretion rate, we can calculate the coronal quantities (as well as the disk quantities) at any distance.

Figure 1 shows the coronal structures versus distance for $M = 10^8 M_\odot$ and $M = 0.1M_{\text{Edd}}$. The coronal temperature is $\sim 10^9$ K, and the density is $\sim 10^3$ cm$^{-3}$. In such a corona, continuum X-ray photons are efficiently produced via inverse Comptonization, and part of them are upscattered and escape from the disk-corona system. The emergent spectrum produced by such photons was calculated from Monte Carlo simulations in LMO03 (see also § 3). They showed that the X-ray spectral indices of the calculated spectrum between 2 and 20 keV are around 1.1, which are close to that of the observed spectra of Seyfert galaxies and QSOs.

On the other hand, there are also some photons that are back-scattered in the corona and do not escape the disk-corona system. They impinge on the underlying disk and drive iron line fluorescence in it. Given such conditions, we can calculate the line profile from this disk-corona system. We show the computational method and its results in detail in § 3.

3. COMPUTATIONS AND RESULTS

3.1. Iron Line Emissivity from the Disk

To derive the iron fluorescence emission law on the disk, it is necessary to derive the X-ray spectrum constructed by the photons downscattered in the corona. Since the coronal properties were determined by LMS02 and LMO03, we can calculate the illumination spectrum on each radial grid of the disk by Monte Carlo simulations.

For a typical AGN system with a black hole mass of $10^8 M_\odot$ and an accretion rate of $0.1M_{\text{Edd}}$, the magnetic field is $B \sim 10^3$ G under the assumption of energy equipartition among the gas in the disk. Then we can estimate the energy flux from the corona onto the disk using equation (1), and therefore the ionization parameter $\xi$ of the disk

$$\xi \equiv \frac{4\pi F_X(r)}{n_{\text{disk}}(r)} \leq \frac{4\pi F(r)}{n_{\text{disk}}(r)} \sim \frac{4\pi}{n_{\text{disk}}(r)} \left( \frac{1}{2} \right) \left( \frac{B^2 V_A}{4\pi} \right) \sim 0.1 \text{ ergs cm}^{-1} \ll 100 \text{ ergs cm}^{-1},$$

(6)
where $F_X(r)$ and $F(r)$ are the X-ray flux and the bolometric flux striking the unit area of the disk at radius $r$, respectively. Then, according to the investigation of Matt et al. (1993, 1996), we can assume that the disk material is sufficiently cold and dense that the ionization of metals in the disk can be neglected, although this is not always the case for a disk that is strongly illuminated by coronal X-rays.

According to the approximate expression derived by George & Fabian (1991), the number flux of iron fluorescent photons per unit time that emerge from the disk is given by

$$F_{K\alpha} = \frac{Z}{C_{25}} = 2 \frac{Z E_{\text{max}}}{E_{\text{min}}} G(E; \beta_{\text{in}}) N(E; \beta_{\text{in}}) dE d\beta_{\text{in}},$$

where $\beta_{\text{in}}$ is the incident angle, $N(E, \beta_{\text{in}})$ is the number spectrum of the incident photons as a function of $\beta_{\text{in}}$, and

$$G(E, \beta_{\text{in}}) = g(\beta_{\text{in}}) f(E),$$

$$g(\beta_{\text{in}}) = 10^{-2} (6.5 - 5.6 \cos \beta_{\text{in}} + 2.2 \cos^2 \beta_{\text{in}}),$$

$$f(E) = 7.4 \times 10^{-2} + 2.5 \exp \left( - \frac{E - 1.8}{5.7} \right)$$

(note that this expression is justified only when one adopts cosmic element abundances).

In equation (7), $E_{\text{min}}$ and $E_{\text{max}}$ should be equal to 7.1 keV, which is the energy of the iron K edge, and 30 keV, which is the upper application limit of the George & Fabian approximation, respectively. In this way we can derive the fluorescent line emissivity on the disk as a function of radius.

Figure 2 shows the radial dependence of the iron line photon flux on the disk. This profile can be fitted to a power law $\propto r^{-2}$ with $\beta \sim 4-5$ down to $r/r_g \approx 6$. We also take into consideration the anisotropy of the intensity of emerging iron line photons with the formula

$$I_{K\alpha} (\theta_{\text{out}}) d\Omega \propto \frac{\cos \theta_{\text{out}}}{\pi} \ln \left( 1 + \frac{1}{\cos \theta_{\text{out}}} \right) d\Omega$$

(Basko 1978; Haardt 1993; Ghisellini et al. 1994), where $\theta_{\text{out}}$ is the angle between the momentum vector of a photon and the vector normal to the disk surface in the corotating frame and it should be determined by

$$\cos \theta_{\text{out}} = -\frac{p_{\mu} n^{\mu}}{p_{\mu} u^{\mu}},$$

Fig. 2.—Iron line emissivity profiles on the disk for $M = 10^8 M_\odot$ and $M = 0.1 M_{\text{Edd}}$. The profile can be fitted with the power law $\propto r^{-3}$. This dependence is the same for different black hole mass or mass accretion rate.

Fig. 3.—Iron line profiles resulting from an accretion disk with magnetic reconnection–heated corona (left) and from a simple power law ($\propto r^{-3}$) emissivity distribution (right). The black hole mass and the mass accretion rate are assumed to be $10^8 M_\odot$ and $0.1 M_{\text{Edd}}$, respectively, and the outer radius of the disk is assumed to be $50 r_g$. Three inclinations are shown: $10^\circ$, $30^\circ$, and $60^\circ$. 
where \( \mathbf{p} \), \( \mathbf{n} \), and \( \mathbf{u} \) are four-vectors representing the photon’s momentum, the surface normal of the disk, and the velocity of the disk material, respectively.

### 3.2. Line Profiles

To calculate the iron line profile from a given line emissivity law, we use the ray-tracing method (Luminet 1979) and take into account the general relativistic energy shift in calculating the line intensity. In our model, the parameters that we can vary are the black hole mass, the mass accretion rate, and the inclination angle. In fact, however, the calculated line profiles are not that sensitive to the first two parameters. For this reason, we show the line profiles for various viewing angles for fixed \( M \) and \( \dot{M} \).

Figure 3 shows the line profiles observed from different viewing angles. The line photons are assumed to be emitted from the region extending between \( 6r_g \) and \( 50r_g \) from the black hole. With large inclination, the red wing of the line profile is more enhanced than that calculated with a power-law emissivity \( \propto r^{-3} \), which is the same distribution as the energy flux from the standard disk, because the emissivity profile obtained from this corona model is as steep as \( \propto r^{-5} \) and a large number of iron line photons are emitted from the innermost region where the gravitational redshift is significant.

The best-studied observation of iron line emission from an accretion disk is that by Tanaka et al. (1995), who showed the time-averaged iron line profile from the Seyfert 1 galaxy MCG –6-30-15. It is claimed to be evidence that there exists a strong gravitational field at the center of the galaxy. Figure 4 displays the best-fit profile of MCG –6-30-15 observational data from 1994.\(^3\) One can see excellent agreement between the observed profile and a theoretically calculated profile, especially in their red wing, for the viewing angle of 29\(^\circ\). Although there are many previous results that agree with the data, this is the first calculation performed taking into account the fundamental physics that may operate the X-ray illumination in an accretion disk system, and we do not assume any phenomenological parameters such as the power-law index of the emissivity distribution. This coincidence strongly supports our view of magnetic reconnection–heated corona.

Figure 5 shows the fits of our theoretical line profiles to a more recent XMM-Newton observation of MCG –6-30-15 in 2001.

\(^3\) In the following discussion, we assume that there is no narrow core component in the line profile, which is composed of the line emission coming from the gas with small velocity, i.e., located far from the central black hole.
Some authors speculate that such a steep emissivity profile be derived?

Hence, the spectrum of the coronal radiation gets flatter as the distance from the black hole gets smaller. As a result, the fraction of photons whose energy is high enough to drive iron fluorescence decreases outward. Such an effect results in a steep line emissivity profile on the disk and makes the red wing of the iron line profile rather prominent.

As seen in the recent observations, MCG −6-30-15 also showed a very broad iron line profile that had a significant red wing extending to ~2 keV (for example, see Fig. 5, right). Wilms et al. (2001) concluded that, to account for such a broad line profile, the line emissivity profile should be as steep as a power law \( \propto r^{-\beta} \) with \( \beta \approx 4-5 \). Some authors speculate that such a steep emissivity is evidence of the extraction of rotation energy from the central black hole by the Blandford-Znajek process (Blandford & Znajek 1977). Our model can reproduce an emissivity profile that is roughly proportional to \( r^{-3} \), although it is flattened inside \( r \approx 6r_g \). In order to reproduce such an extended red wing in the iron line profile, which we gave up making fit with our model perfectly, it may be necessary to assume the disk around a Kerr black hole (Dabrowski et al. 1997) or nonzero torque in the central region of the disk (Reynolds et al. 2004). We can construct a corona model with disk models taking these assumptions into account (Novikov & Thorne 1973; Agol & Krolik 2000), and our model may have a great advantage in fitting the XMM-Newton data shown in Figure 5 because of the steep emissivity law derived from it.

Both line profiles are intrinsically the same but made with different ways of subtracting the power-law continuum component. Roughly speaking, the left profile was obtained by ignoring any contribution from the red component, while the right profile was designed for the red tail to extend down to \( \sim 3 \) keV (see the figure legend for a detailed explanation of the line profiles). As these fits show, our model can explain the recent observational line profile with high signal-to-noise ratio in the 4–7 keV energy range, although it fails to explain the red wing found below \( \sim 4 \) keV (see § 4 for a discussion).

With our model, we can calculate both the strength of the continuum emission (LMO03) and that of the iron line emission, so we can evaluate the equivalent width (EW) of the iron line emission in the context of our model. Figure 6 shows the inclination dependence of the EW of the iron Kα line. In particular, the EW of the best-fit profile of the MCG −6-30-15 observation in 1994 is \( \sim 70 \) eV, which is much lower than the value implied in the analyses of Tanaka et al. (1995), 250–400 eV (i.e., we can fit the theoretical iron line profile with the observation but fail to fit its absolute strength). However, this does not mean the failure of our model (see below).

4. DISCUSSION AND CONCLUSION

Using a Monte Carlo simulation, we derive the X-ray irradiation from a magnetic reconnection–heated corona onto the underlying disk, and we find that the predicted iron line profile is consistent with past observations. According to our calculation, the line emissivity on the accretion disk is approximately proportional to \( r^{-5} \), where \( r \) is the distance from the central black hole.

As derived in LMS02, the fraction of the accretion energy that is dissipated into the corona is almost unity. In the standard model, the energy flux from the accretion disk is roughly proportional to \( r^{-3} \), so one would naively expect that the coronal illumination energy on the disk is also proportional to \( r^{-3} \). So how could such a steep emissivity profile be derived?

The answer to this question is obvious from the behavior of the Compton y-parameter, which is approximately proportional to \( r^{-1} \). The inward increase of \( y \) can be understood in this way: the coronal temperature \( T \) and density \( n \) increase inward, since in the inner region the coronal heating and chromospheric evaporation is more active than in the outer region. Now \( y = 4kTn_{\text{e}}r^{-1}/(m_e c^2) \), so \( y \) also increases inward. In an optically thin corona, the spectral index can be expressed as \( \alpha = (9/4 + 4/y)^{1/2} - 3/2 \).

We are grateful to B. F. Liu for providing part of the simulation code and to T. Tsuru, S. Nagataki, K. Ohsuga, K. Watarai, Y. Kato, A. Mizuta, and R. Takahashi for their useful discussions and comments. This work was supported in part by Grants-in-Aid of the Ministry of Education, Science, Sports, Technology, and Culture of Japan (14079205, 16340057, SM).
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