Iron Fluorescent Line Emission from Black Hole Accretion Disks with Magnetic Reconnection-Heated Corona

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We investigate the iron Kα fluorescent line produced by hard X-ray photons from magnetic reconnection-heated corona. In our model, X-ray photons are efficiently produced in the corona, irradiate the underlying disk, and drive iron fluorescence in the disk. We find the local emmisivity of iron line on the disk is approximated as $F_{\mathrm{K}\alpha}(r) \propto r^{-5}$. The profile derived from this model gives an excellent fit to the observational data of MCG-6-30-15 with the profile derived theoretically for $i = 29.4°$.

1. INTRODUCTION

Iron Kα line is one of the most useful probe of the vicinity of the black hole. It may be produced by X-ray irradiation on 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 beamings and gravitational redshifts, since the material is orbiting at high velocity in a strong gravitational field. So it is expected that we can get some information about the gravitational field and the accretion flow close to the central black hole from the shape of iron line profile (for comprehensive review, see [3]; [11]).

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, and some authors adopted a power-law emissivity distribution on the disk. Although one can reconstruct the observed iron line profiles and its time variability with these models, little can be known regarding the fundamental physics which describes the origins of X-ray irradiation in the black hole accretion disk system.

In this study, we adopt the corona model in which the magnetic flux loop emerging from the disk reconnects with other loops and heat the corona to a temperature around 10^9K [8]. The advantage of this model is that one can compute the iron line profile without any adjustment of free parameter but 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.

2. MODEL

We consider the disk-corona model constructed in [8], in which the corona is assumed to be plain-parallel and to be coupled tightly with underlying Shakura & Sunyaev disk [12]. Magnetic flux loops generated in the disk emerge into the corona by the 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.

$$\frac{B^2}{4\pi} V_A \approx \frac{4k_B T}{m_e c^2} n\sigma_T lcU_{\rm rad}, \qquad (1)$$

where $B, V_A, T, l, U_{\rm rad}$ are the magnetic field strength, the Alfvén speed, the coronal temperature, the scale height of the corona (=the length of the magnetic loop), and the soft photon field to be Compton scattered, respectively.

If the density of 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 evaporation of plasma in the disk (see [7]) .

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

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

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

$$\beta \equiv \frac{n_{\rm disk} kT_{\rm disk}}{B^2/8\pi} \sim 1 \qquad (3)$$

(although the results are not sensitive to β-values).

These equations determine the temperature and density in the corona as a function of energy densities of the magnetic field and seed radiation field. However, it is not sufficient to substitute the results into Shakura-Sunyaev disk model; we have to take into account the back reaction due to the energy transfer from the disk to the corona by magnetic reconnection. Defining f as the fraction of accretion energy released in the reconnected magnetic corona,

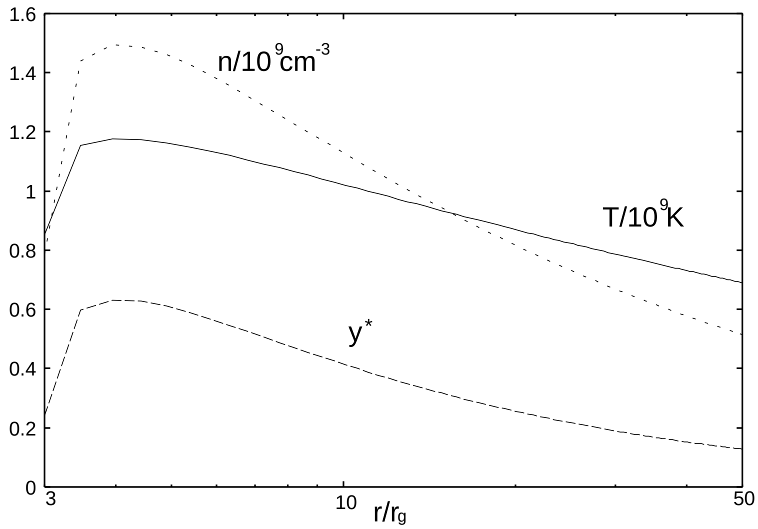

Figure 1: Coronal quantities along distance for $M = 10^8 M_\odot$ and $\dot{M} = 0.1\dot{M}_{\rm Edd}$. The coronal temperature is around 10^9K and density around $10^9{\rm cm}^{-3}$. $y^* = (4kT/mc^2)\lambda_\tau n\sigma_T l$ is the effective Compton y parameter of the corona.

$$f \equiv \frac{F_{\rm cor}}{F_{\rm tot}} = \frac{B^2}{4\pi} V_{\rm A} \left[\frac{3GM\dot{M}}{8\pi r^3} \left(1 - \sqrt{\frac{3r_S}{r}} \right) \right]^{-1}, \quad (4)$$

Liu et al. [8] found that in the expression of disk quantities, such as pressure and $U_{\rm rad}$, $\dot{M}$ should be replaced by $(1-f)\dot{M}$. With this modification, the coronal temperature and density can be derived.

With these assumptions, we can derive the equations which 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, $U_{\rm rad} \approx 0.4 U_B$, (see [5])where U_B is the magnetic field energy density.

Then we get an equation,

$$\begin{aligned} f &= 4.70 \times 10^4 (1-f)^{11/10} \alpha_{0.1}^{-99/80} \beta_1^{-11/8} m_8^{11/80} \\ &\quad \times (\dot{m}_{0.1}\phi)^{1/10} r_{10}^{-81/160} l_{10}^{3/8}, \end{aligned} \quad (5)$$

where $\phi \equiv 1-(R_*/R)^{1/2}$ and R_* is taken to be the last stable orbit $3R_{\rm S}$; and α_{-1}, β, m_8, $\dot{m}_{-1}$, r_{10}, l_{10} are the viscous coefficient, the plasma beta, the black hole mass, the accretion rate, the distance, the length of the magnetic loop in units of 0.1, 1, $10^8 M_\odot$, $0.1\dot{M}_{\rm Edd}$, $10R_{\rm S}$, $10R_{\rm S}$, 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 distances.

Figure 1 shows the coronal structures along distance for $M = 10^8 M_\odot$ and $\dot{M} = 0.1\dot{M}_{\rm Edd}$. The coronal temperature is $\sim 10^9$K and the density is $\sim 10^9{\rm cm}^{-3}$. In such 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 were calculated from Monte Carlo simulations in [7]. They showed that the X-ray specral 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 which are backscattered in the corona and do not escape the disk-corona system. They impinge the underlying disk and drive iron line fluorescence in it. Given such a condition, we can calculate the line profile from this disk-corona system.

3. COMPUTATIONS AND RESULTS

For deriving 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 [8] and [7], we can calculate the illumination spectrum on each radial grid of the disk by Monte Carlo simulations. We make use of the semi-analytical expression derived by George & Fabian [**?**], and derive the fluorescent line emissivity on the disk as the 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 $\propto r^{-\beta}$ with $\beta \sim 4-5$ down to $r/r_S \approx 6$.

To calculate the iron line profile from a given line emissivity law, we use the ray-tracing method [9] and take into account general relativistic energy shift in

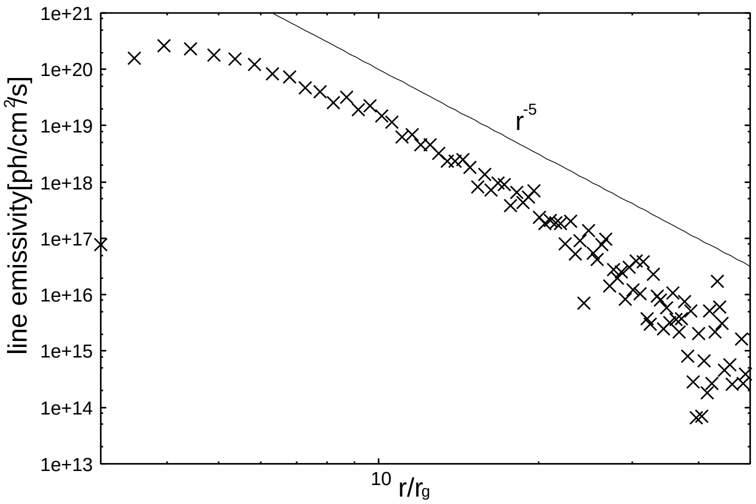

Figure 2: The iron line emissivity profiles on the disk for $M = 10^8 M_\odot$ and $\dot{M} = 0.1\dot{M}_{\rm Edd}$. The profile can be fitted with the power-law $\propto r^{-5}$. This dependence is the same for different black hole mass or mass accretion rate.

calculating the line intensity. In our model, the parameters 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 so sensitive to the first two parameters. With this reason, we show the line profiles for various viewing angles for fixed M and $\dot{M}$.

Figure 3 displays the best-fit profile of MCG-6-30-15 observational data [13]. One can excellent agreement between an observed profile and a theoretically calculated profile, especially in their red wing, for the viewing angle of 29.4°.

Although there are many previous results which agree with the data, this is the first calculation assuming no adjustable parameters regarding the emissivity distribution. This coincidence strongly supports our view of magnetic reconnection-heated corona.

4. DISCUSSION AND CONCLUSION

Using Monte Carlo simulation, we derive the X-ray irradiation from magnetic reconnection-heated corona onto the underlying disk, and find that the iron 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 [8], the fraction of accretion energy 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 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 $y = 4k_B T n \sigma l/(m_e c^2)$, so y also increases inward. In an optically thin corona, the spectral index can be expressed as $\alpha = (9/4 + 4/y)^{1/2} - 3/2$. Hence the spectrum of coronal radiation gets flatter as the distance from the black hole gets smaller. As a result, the fraction of photons whose energy are high enough to drive iron fluorescence decreases outward. Such effect results in a steep line emissivity profile on the disk, and makes the red wing of an iron line profile prominent.

MCG-6-30-15 also showed a very broad iron line profile which had a significant red tail extending to $\sim$ 2keV [6]. Wilms et al. [14] 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 $\beta \sim 4 - 5$. Some authors speculate that such a steep emissivity is the evidence of the extraction of rotation energy from the central black hole by Blandford-Znajek process [1]. Our model can reproduce a emissivity profile which is roughly proportional to r^{-5} without assuming any peculiar X-ray illumination process, and there are only two free parameters; M and $\dot{M}$. Besides, in order to explain extremely extended red wing in the iron line profile, it may be necessary to assume the disk around a Kerr black hole [2]. However, in the case of Kerr spacetime, we can construct the corona model with a relativistic disk model [10] and our model may have a great advantage in fitting the data because of the steep emissivity law derived from it.

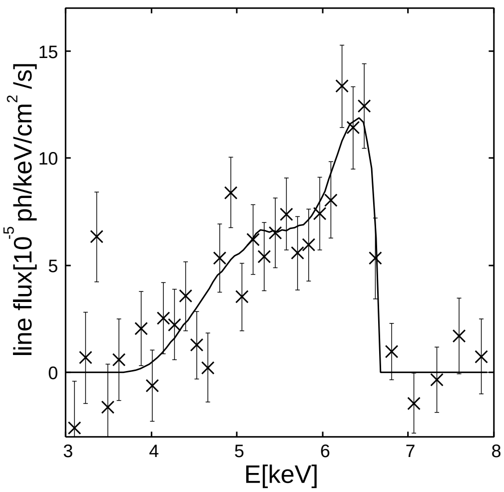

Figure 3: Best-fit iron line profile for the time-averaged line of MCG-6-30-15. The viewing angle is 29.4°.

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