IRON Kα FLUORESCENT LINE PROFILES FROM SPIRAL ACCRETION FLOWS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We present 6.4 keV iron Kα fluorescent line profiles predicted for a relativistic black hole accretion disk in the presence of a spiral motion in Kerr geometry, the work extended from earlier literature motivated by recent magnetohydrodynamic (MHD) simulations. The velocity field of the spiral motion, superposed on the background Keplerian flow, results in a complicated redshift distribution in the accretion disk. An X-ray source attributed to a localized flaring region on the black hole symmetry axis illuminates the iron in the disk. The emissivity form becomes very steep because of the light-bending effect from the primary X-ray source to the disk. The fluorescent line is calculated for various spiral waves with different X-ray source height. It is found, regardless of the source height, in the predicted broad-line profile that (1) a ubiquitous multiple peak along with a classical double-peaked structure generally appears; (2) such a multiple peak can be categorized into two types, sharp subpeaks and periodic spiky peaks; (3) a tightly packed spiral wave tends to produce more spiky multiple peaks, whereas (4) a spiral wave with a larger amplitude seems to generate more sharp subpeaks; (5) the effect seems to be less significant when the spiral wave is centrally concentrated; and (6) the line shape may show a drastic change (forming a double-peaked, triple-peaked, or multiple-peaked feature) as the spiral wave rotates with the disk (phase-dependent line). Our results emphasize that around a rapidly rotating black hole an extremely redshifted iron line profile with a noticeable spikelike feature can be realized in the presence of the spiral wave. Future X-ray observations, from Astro-E2, for example, will have sufficient spectral resolution for testing our spiral-wave model, which exhibits unique spikelike features. Furthermore, they may be able to allow us to identify the characteristics of the spiral wave occurring in the innermost accretion disk.

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

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1 INTRODUCTION

It is generally known that Seyfert 1 galaxy spectra exhibit reprocessed X-ray emission, such as broad Fe Kα fluorescence at 6.4 keV and Compton reflection (high-energy hump) around ~30 keV, from an illuminated accretion disk around a supermassive black hole. If the origin of such a reflection component can be attributed to a surrounding accretion disk (disk-line model), more precise spectral observations might allow us to better understand the physics in the vicinity very close to the central black hole. In standard disk-line models (Fabian et al. 1989; Laor 1991; Kojima 1991), accreting matter is normally considered to be in Keplerian orbit around a central black hole. The disk is then illuminated by an external X-ray source located somewhere near the innermost disk region and produces a broad, skewed fluorescent emission line at a particular photon energy (6.4 keV for neutral-like iron, 6.7 keV for He-like iron, and 6.9 keV for H-like iron, for instance) depending on the ionization state. See Fabian et al. (2002) and Reynolds & Nowak (2003) for a comprehensive review.

Past X-ray observations with the Japan/USA X-ray satellite ASCA (the best resolving power of ~120 eV) revealed such a relativistically broadened iron line from various Seyfert 1 galaxies, particularly from a very bright source, MCG –6-30-15 (Tanaka et al. 1995; Fabian et al. 1995). The observational data seem to be well fitted with the standard disk-line model in terms of the characteristic double-peaked feature, which is thought to be due to the longitudinal Doppler motion of the emitting matter in the disk, and the asymmetry in the profile is also believed to originate from the special relativistic, directional beaming effect. Furthermore, the observed emission line occasionally contains a very extended red tail that is interpreted to be a consequence of the general relativistic effect (i.e., gravitational redshift).

Apart from the standard disk-line models in which an axially symmetric flow with Keplerian circular motion is assumed under no perturbations, some authors have argued other accretion theories from different aspects. According to the past literatures, there seem to be three distinct issues of studies involved with such modifications: those focusing on (1) modified disk geometry instead of a simplified thin disk in the equatorial plane, (2) more complex X-ray source geometry, and (3) perturbed accretion flow (i.e., non-Keplerian flows). Issues 1–3 seem to be independent of each other, but they all modify the standard line profiles in terms of the redshift of photons, the line shape, and/or the line variabilities. As far as issue 1 is concerned, the actual disk geometry may not be so simple as geometrically thin in the equatorial plane. For instance, Hartnoll & Blackman (2000) have discussed warping of the disk where a part of the disk surface is geometrically skewed and tilted from the equatorial plane. On the other hand, a thin disk might become hotter as the gas approaches
the hole, forming a geometrically thick disk (or an accretion torus). Such a thick-disk model (accretion torus) has been studied by a number of authors, e.g., Shapiro et al. (1976), Tritz & Tsuruta (1989), and Kojima & Fukue (1992), while dense clouds embedded in a thick disk have been discussed by Guilbert & Rees (1988), Sivron & Tsuruta (1993), and Hartnoll & Blackman (2001). Issue 2 includes a stationary/dynamical, off-axis X-ray source (i.e., a nonaxisymmetric point source) instead of a typically postulated axisymmetric X-ray source. That is, the primary source (e.g., an orbiting flare in a corona or high-energy particles due to shock accelerations) is either located off-axis or moving around with some bulk motion relative to the disk (Reynolds & Begelman 1997; Ruszkowski 2000; Dabrowski & Lasenby 2001; Lu & Yu 2001). A flaring activity induced in the disk itself might irradiate the Keplerian matter to produce iron fluorescence (Nayakshin & Kazanas 2001). They found a very narrow line resulting from the small height of the flare.

With regard to issue 3, Keplerian motion may not be a very practical assumption since a thin disk is known to be subject to various kinds of instabilities to perturbations. For instance, disk oscillations can be triggered in the form of the \((p, g, c)\)-mode in the innermost disk region (Kato 2001a, 2001b), in which case the local emissivity is no longer axisymmetric (Yamada & Fukue 1993; Sanbuichi et al. 1994; Karas et al. 2001). Also, some MHD instabilities can induce spiral density waves in the presence of the magnetic field. This has been phenomenologically confirmed by two-dimensional numerical studies of a magnetized disk in Newtonian gravity in which a multiple-armed spiral wave evolves into a single-armed spiral over some time (Caunt & Tagger 2001, hereafter CT01) because of the accretion-ejection instability (AEI). On the other hand, a recent three-dimensional MHD simulation of the black hole accretion by Machida & Matsumoto (2003, hereafter MM03) suggests that an X-ray flare via magnetic reconnections could take place in the plunging region (i.e., the region inside the marginally stable orbit) as a result of the non-axisymmetric (one-armed) spiral density structure, which is initially caused by the magnetorotational instability (MRI) due to a differential rotation of frozen-in plasma. Hawley (2001, hereafter H01) has independently predicted a similar formation of tightly wrapped spiral waves using the pseudo-Newtonian potential. It is also demonstrated by Armitage (2002) that the intensity of the magnetic fields in the accretion disk tends to be amplified by shearing, which could be a potential source of the observed X-rays. In addition, a gravitational perturbation (tidal force) by a nearby star or a massive gas can trigger such a spiral wave, which eventually steepens into shocks (Chakrabarti & Wiita 1993a). Line profiles under such spiral patterns have been found by several authors (Chakrabarti & Wiita 1993b, 1994) in Newtonian geometry. The temporal variability of the iron line from a turbulent magnetized disk has recently been studied by Armitage & Reynolds (2003) using MHD simulations in a pseudo-Newtonian potential. They found a highly variable emission-line profile due to the turbulence. In all these cases, the accreting flow is no longer Keplerian because of a substantial radial velocity component. Therefore, the velocity field should be somewhat deviated from a circular one. For instance, Hartnoll & Blackman (2002, hereafter HB02) considered the possible effects of such a spiral motion on the effective line profile in an approximate Schwarzschild geometry. HB02 found a quasi-periodic bump and many steplike features purely due to the velocity field of spiral waves. In their work, predicted profiles are obtained for various spiral-wave parameters, and these authors concluded that the multiple subpeaks are generally more prominent for larger spiral-wave numbers.

In the current paper we focus our attention on issues 2 and 3, where an X-ray source geometry and the velocity field are both important ingredients for determining the iron line. Our model, being motivated by both HB02 and MM03, postulates a localized X-ray flare via a relatively small magnetic reconnection (small enough not to destroy the main structure) somewhere above the innermost region of the accretion disk around a rapidly rotating black hole, in the presence of the spiral accretion flow superposed onto the background Keplerian motion, which is a different setup from HB02. We also consider a different height of the flare. The X-ray flare will then illuminate the nearby disk material and produce cold iron fluorescent emission line at 6.4 keV in the rest frame. The iron is considered to be either neutral or only weakly ionized (i.e., Fe i–Fe xvi) in the case of a moderately weak flare. Thus, the effective iron line profile in our model will be determined primarily by both the spiral velocity field and the location of the flare.

The structure of this paper is as follows. In § 2 we introduce the assumptions made and establish our flare model in the context of the thin-disk line model in the presence of the spiral motion. The results are presented in § 3, where we show our theoretical line profiles for various situations including all the special/general relativistic effects, both from the flare source to the disk and from the disk to the observer. The apparent disk image (redshift and blackbody temperature) are also presented. The discussion and concluding remarks are given in § 4.

2. Assumptions and Basic Equations

First, we construct a spiral motion, superposed onto the unperturbed Keplerian orbit, in such a way that it qualitatively mimics to some degree the characteristic velocity field found in H01 and MM03. Then we introduce the geometry of our postulated flare X-ray source. For computing relativistic geodesics of emitted photons from the iron line to the observer, the ray-tracing method is employed. All the general/special relativistic effects (longitudinal Doppler shift, relativistic beaming effect, bending of light, and the gravitational redshift) are included in our computations, both from the flare to the disk and from the disk to the flare.

2.1. Spiral Motion with the Keplerian Flow in the Disk

Let us first assume that the spacetime is stationary \((\partial / \partial t = 0)\) and axially symmetric \((\partial / \partial \phi = 0)\) in the equatorial plane \((\theta = \pi / 2)\). Following the standard thin-disk models, the disk is considered to be geometrically thin \((h / r \sim 0.1)\) and optically thick \((\tau_e > 1)\), ranging from an inner radius \(r_{in}\) to an outer radius \(r_{out}\). Here, \(h\) is the scale height of the thin disk and \(\tau_e\) is the electron scattering optical depth. The schematic geometry of our model is illustrated in Figure 1. It shows a schematic view of the innermost region along with a local flare at height \(h_f\) above the disk surface at \((r, \pi / 2, \phi)\). The physical meaning of the illustrated notations will be explained later.

The background geometry is described in the Boyer-Lindquist coordinates as

\[
ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right)dt^2 + \frac{4aMr \sin^2 \theta}{\Sigma} dt d\phi + \frac{4 \sin^2 \theta}{\Sigma} d\phi^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2,
\]  

(1)
where $\Delta \equiv r^2 - 2Mr + a^2$, $\Sigma \equiv r^2 + a^2 \cos^2 \theta$, $A \equiv (r^2 + a^2)^2 - a^2 \Delta \sin^2 \theta$, and $M$ and $a$ are the black hole mass and its specific angular momentum, respectively. The metric signature is $(\cdot, +, +, +)$. Geometrized units are used such that $G = c = M = 1$, where $G$ and $c$ are the gravitational constant and the speed of light, respectively. In this paper, distance is normalized by the gravitational radius $r_g \equiv GM/c^2$. For instance, $r_g \sim 1.5 \times 10^{12}$ cm for a $10^7 M_\odot$ black hole mass. The unperturbed accretion disk possesses the Keplerian accretion flow with the angular velocity $\Omega_k = 1/(r^{3/2} + a)$, where $r$ is the position of the emitter (i.e., iron) in the disk surface. In order to discuss physical quantities, let us introduce a zero angular momentum observer (ZAMO) in a locally nonrotating reference frame (LNRF), which is a locally flat space. As seen by a ZAMO, the physical three-velocity (radial and azimuthal components) of the unperturbed Keplerian flow is described by

$$ v^r_{k} = 0, $$

$$ v^\phi_{k} = \frac{A}{\Sigma^{1/2}}(\Omega_k - \omega), $$

where $\omega \equiv 2a r / A$ is the angular velocity of the ZAMO with respect to a distant observer and the subscript $k$ denotes the Keplerian value and the hat represents quantities measured by the ZAMO. We set $r_{\text{out}} = 30r_g$ in our calculations for two reasons: both because we are interested in the relativistic line broadening in the inner region of the disk and because our attention is focused on the broad red tail. The inner radius $r_{\text{in}}$ coincides with the marginally stable circular orbit at $r_{\text{ms}}$ below which the accreting flow starts spiraling in toward the event horizon at $r_h$ along geodesics (free fall with $u^r \neq 0$). Since the radial gradient of the density within $r_{\text{ms}}$ (in the plunging region) is very large because of the free-fall trajectory, the optical depth $\tau_{\text{ds}}$ there is not large enough to maintain the optically thick assumption. Thus, we do not consider the accreting matter within $r_{\text{ms}}$ for fluorescence.

As suggested by H01 and MM03, the accretion disk is no longer Keplerian in the presence of magnetic fields because the field lines, which the accreting particles are frozen-in to, start interacting with one another. The MRI under differential rotation is then expected to occur and trigger the perturbations on the otherwise ordered Keplerian flow. As a result, the density distribution starts appearing as an asymmetric, tightly wrapped spiral pattern. There could be multiple-armed spiral waves, but H01, MM03, and CT01 show that the spiral structure will eventually evolve into a single-armed pattern after a certain rotation period. For instance, in MM03 a one-armed spiral starts appearing at $t \sim 10t_0$ (where $t_0$ is one orbital time at $r \sim 50r_g$) via the MRI, while CT01 have found a single-armed spiral pattern after about 200 orbits due to the AEI. Because of these findings by various previous authors, we only consider a one-armed spiral wave here. In H01 the specific angular momentum of the flow tends to fluctuate around the Keplerian value because of the MRI, and therefore we will phenomenologically include a similar effect caused by the spiral perturbations in the velocity. In order to qualitatively reproduce similar spiral motions found in their numerical results, we follow HB02 and use a simple representation of the bulk velocity field (radial and azimuthal components) of the spiral wave in the LNRF as

$$ v^r_{\text{sw}} = -A e^{-(r - r_{\text{ms}})/\Delta_{\text{sw}}} \sin \gamma_0 [(r - r_{\text{ms}}) + m\phi/2 - \phi_{\text{sw}}/2], $$

$$ v^\phi_{\text{sw}} = A e^{-(r - r_{\text{ms}})/\Delta_{\text{sw}}} \sin [(r - r_{\text{ms}}) + m\phi - \phi_{\text{sw}}], $$

where the subscript sw denotes the spiral wave. Such a spiral motion can qualitatively mimic the velocity perturbation discovered by H01 and MM03, and hence it is not an arbitrary choice. The characteristic structure of the spiral motion is thus uniquely determined by a set of parameters ($A_r, A_\phi, m, k_r, \Delta_{\text{sw}}, \gamma_0, \phi_{\text{sw}}$).

The number of parameters can be reduced by making reasonably acceptable assumptions in the following way. CT01 and MM03 both show that the azimuthal wave number $m$ is fixed to be $m = 1$ for a single-armed spiral wave in a late stage of the spiral evolution; $\gamma_0$ determines the width of the spiral pattern and turns out to be ineffective to the qualitative features of the line profile. Therefore, it is held constant at $\gamma_0 = 2$. Given these fixed parameters, the actual free parameters are ($A_r, A_\phi, k_r, \Delta_{\text{sw}}, \phi_{\text{sw}}$). MM03 show that the wave amplitude $A_r$ and $A_\phi$ are unlikely to be very large ($u^r$ only exceeds 0.1c). Besides, a large amplitude could perturb and destroy the whole disk structure. Therefore, the amplitude is chosen to be relatively small ($A_r = A_\phi = 0.1$) in most of our calculations in § 3.1. However, we look for the possible effects of amplitude variations; $k_r$ characterizes a tightness (the number of winding) of the spiral pattern, and the effective (radial) range of the spiral motion is controlled by $\Delta_{\text{sw}}$. For instance, the spiral is more tightly packed when $k_r$ is large, and it is more centrally (i.e., radially inward) concentrated when $\Delta_{\text{sw}}$ is small; $\phi_{\text{sw}}$ denotes the phase of the spiral and becomes an important factor for determining the line profile in the phase-dependent case. It is fixed otherwise. It is clear that the spiral motion is nonaxisymmetric and dependent on its phase $\phi_{\text{sw}}$. To avoid the phase dependence of the line profile, we hold the spiral phase constant, leaving us the few free parameters ($A_r, A_\phi, k_r, \Delta_{\text{sw}}$) for specifying a spiral motion. However, we will later investigate the phase-evolved line profile holding every parameter fixed except for $\phi_{\text{sw}}$. Note that $\phi = 270^\circ$ (equivalently $-90^\circ$) coincides with the observer’s azimuthal angle, and $v^r_{\text{sw}} < 0$ for accretion; $v^r$ and $v^\phi$ are set to be in-phase in equations (4) and (5), which turns out to be unimportant to the end results.

We assume that the effective accretion flow seen by a ZAMO in the LNRF is described as the sum of these velocity fields, the spiral orbit being superposed onto the unperturbed
Keplerian orbit. By adding each physical three-velocity field in the LNRF, we get

$$v^\phi = v_k^\phi + v_{sw}^\phi,$$  \( \tag{6} \)

$$v^\delta = v_k^\delta + v_{sw}^\delta.$$  \( \tag{7} \)

Since \((v^\phi, v^\delta)\) is not axisymmetric, the net velocity field is also nonaxisymmetric. The corresponding four-velocity field of the effective flow is then written as

$$(u', u', u^\theta, u^\phi) = u' \left( 1, \frac{\Delta}{A^{1/2}}, v^\phi, 0, \frac{\Sigma \Delta^{1/2}}{A \sin \theta} v^\phi + \omega \right),$$  \( \tag{8} \)

where \(u' = \sqrt{-\hat{\nabla}^2 \Delta A/\Sigma + 1 - 2r/\Sigma + \Lambda \omega^2/\Sigma} \) and \(\hat{\nabla}^2 \equiv (\nabla^2)^2 + (v^\delta)^2\) is the square of the physical three-velocity of the perturbed flow in the LNRF. Thus, the effective velocity field including the spiral motion in Keplerian background orbit is determined once we specify \(v_{sw}^\phi\) and \(v_{sw}^\delta\) through a set of free parameters \((A_A, A_\phi, k_r, \Delta_{sw})\). Figure 2 shows an example of a perturbed accreting flow where the radial four-velocity component \(u'\) described by equation (8) is plotted in the equatorial plane \((-30 \leq X \leq 30\) and \(-30 \leq Y \leq 30\)). The adopted parameters are \(k_r = 1.0, \Delta_{sw} = 30r_g\) for illustration purposes. The corresponding velocity profile at \(\phi = 0^\circ\) (along \(Y = 0\) in Fig. 2) is shown in Figure 3. From the top left clockwise, the radial three-velocity \(v^r\), azimuthal three-velocity \(v^\phi\), specific angular momentum of the gas \(l\), and the effective angular velocity \(\Omega\) are displayed. For comparison, the dotted curves are also shown for Keplerian motion.

2.2. A Localized X-Ray Flare Source

In our model the X-ray flare source is a locally stationary active region (e.g., flaring sites in corona) at some height \(h_f\) on the symmetry axis above the innermost disk. Following the practice adopted in many standard disk-corona models for the Fe fluorescent lines, we also approximate such a source as a pointlike X-ray source on the black hole symmetry axis (see Fig. 1). This assumption should be justified because the hottest region should be above the innermost disk because the multicolor disk temperature scales as \(\propto r^{-3/4}\). That should be very close to the rotation axis of the hole. We also assume that the entire disk is neutral or at most only weakly ionized by such a radiation source, producing a neutral-like fluorescence at 6.4 keV in the source frame. In this manner we can investigate the effects exclusively due to the spiral wave alone, by comparing our results with those obtained for the standard Keplerian disk model without spiral waves.

2.3. Relativistic Disk Emissivity

In Newtonian geometry, specifying the height of the X-ray source \(h_f\) would simply allow us to compute the emissivity law of the illuminated disk. In addition, it is also important, especially in the innermost region in the relativistic disk, to take into account the general relativistic bending effect (either redshift or blueshift) on the photons from the flare to the disk. Because of this effect, the intensity of the illuminating photon flux at the disk should be subject to a significant deviation from the Newtonian case. Reynolds & Begelman (1997) calculated this effect for their iron lines predicted for Schwarzschild geometry, whereas Martocchia & Matt (1996) calculated the photon trajectories from an on-axis source to the underlying accretion disk in Kerr geometry. We adopt and modify the work of the latter authors, who found the redshift factor \(g_{ad}\) measured in a local disk frame (i.e., ZAMO) as

$$g_{ad} = \sqrt{\frac{(r^2 + a^2 - 2r)(r^2 + a^2 + 2a^2/r)}{(1 - \nabla^2)(r^2 + a^2 - 2r)(h_f^2 + a^2)}},$$  \( \tag{9} \)

where we adopt the extreme Kerr parameter \(a = 0.998\) according to recent theoretical/observational speculations that a black hole is likely to rotate rapidly in some active galactic.
nuclei (Iwasawa et al. 1996a, 1996b; Young et al. 1998; Fabian et al. 2002; Wilms et al. 2001). Given the canonical photon power-law index ($\Gamma_{PL} \approx 1.9$) for Seyfert 1 galaxies (Nandra & Pounds 1994), the actual local emissivity is weighted by the factor of $g_{sd}^{1.9}$, which yields the net local axisymmetric emissivity as

$$\tilde{\epsilon}_d = \epsilon_d g_{sd}^{1.9},$$

where $\epsilon_d$ is the local Newtonian emissivity of the disk expressed as

$$\epsilon_d = \frac{h_f}{(r^2 + h_f^2)^{3/2}},$$

(11)

Here, $r$ is the radial position of the emitter (iron) in the disk.

### 2.4. Photon Trajectories

When fluorescent photons emitted from the disk reach a distant observer or telescope, the following geodesic equation in the integral form must be satisfied (Carter 1968; Chandrasekhar 1983):

$$\int_{r_{em}}^{r_{obs}} \frac{1}{\sqrt{R(r)}} \, dr = \pm \int_{\theta_{obs}}^{\theta_{em}} \frac{1}{\Theta(\theta)} \, d\theta,$$

(12)

where

$$R(r, \lambda, Q) = r^4 + (\lambda^2 - Q^2) + 2(Q + \lambda^2)r - Q,$$

$$\Theta(\theta, \lambda, Q) = Q - (\lambda \cot \theta)^2.$$  

(13)

(14)

Here an observer’s distance $r_{obs}$ and its inclination angle $\theta_{obs}$ need to be specified; $r_{em}, \theta_{em}$ is the emitter’s (i.e., iron) position on the disk. For a distant observer, we take $r_{obs} = \infty$; $\lambda$ and $Q$ are two constants of motion along a geodesic, which are closely related to the axial component of the angular momentum of photons (Carter 1968). We will make full use of the elliptic integrals to numerically evaluate equation (12) in the ray-tracing approach (Cadez et al. 1998; Fanton et al. 1997) for efficient computations. We will first search for an observable photon emitted from $r_{em}$ in the disk and then calculate the corresponding redshift $g_{sd}$. Given the four-velocity of the perturbed flow (iron) and the four-momentum of the null geodesic (photon), we obtain the redshift by

$$g_{sd} = \frac{E_{obs}}{E_{em}} = \frac{1}{u' \left(1 - \lambda \Omega - \sqrt{v^2 + \Omega^2} \right),}$$

(15)

where the observer at a distant location $r_{obs}$ is stationary; $E_{em}$ and $E_{obs}$ are the local photon energy and its observed energy, respectively. We consider a photographic plate of the observer’s (or telescope’s) window at $r_{obs}$ facing straight the accretion disk with the inclination angle $\theta_{obs}$. Images of the disk are projected onto this window with ($\alpha, \beta$), where $\alpha, \beta$ are the impact parameters of the observed photons in observer’s sky. In our calculations, the window roughly contains 280 x 280 pixels (corresponding to the spatial resolution of $\sim 0.23 r_g$) in which the images of the disk are generated in false color. We only consider the observed photons normal to this window.

### 2.5. Predicted Fluorescent Emission Lines

Once we know the redshift factor $g_{sd}$ and the surface emissivity of the disk $\tilde{\epsilon}_d$ including the bending effect expressed by $g_{sd}$, the observed photon flux is obtained by

$$F_{obs}(E_{obs}) = \int_{\Delta \Omega} g_{sd} I_{em} \, d\Omega,$$

(16)

where $d\Omega$ is the solid angle subtended by the disk in the observer’s frame. Here, the local intensity is approximated by the $\delta$-function of the monochromatic photon energy $E_{em}$ in the source frame as

$$I_{em} = \tilde{\epsilon}_d g_{sd} \delta(E_{obs} - g_{sd} E_{em}).$$

(17)

Broadening of the line photons due to turbulence may be insignificant (Fabian et al. 2000). The local emitting region is assumed to be optically thick in the absence of a thick electron scattering atmosphere above the disk so that the limb-darkening effect is unimportant, especially for a small inclination angle $\theta_{obs}$ (Chen & Eardley 1991; Laor 1991; Bao et al. 1994). In a statistical sense, it seems to be favored that the averaged $\theta_{obs}$ for Seyfert 1 galaxies is around $\sim 30^\circ$ (Antonucci & Miller 1985; Schmitt et al. 2001). Therefore, we adopt $\theta_{obs} = 30^\circ$ throughout this paper. Note that the additional redshift factor $g_{sd}$ due to the photon bending (from the source to the disk plane) is included via our emissivity prescription $\tilde{\epsilon}_d$ in the modified local intensity $I_{em}$.

Using the obtained fluorescent flux, we can estimate the equivalent blackbody temperature measured by a distant observer $T_{obs}$ from the Stefan-Boltzmann law,

$$T_{obs} = \left(\frac{F_{obs}}{\sigma_{SB}}\right)^{1/4},$$

(18)

which is a function of the redshift factor $g_{sd}$, the position of the emitter in the disk ($r, \pi/2, \phi$) for a given height of the flare $h_f$; $T_{obs}$ will allow us to see the temperature distribution in the perturbed disk. If the spiral wave is fixed in the rotating disk frame, the line profile becomes phase-dependent on $\phi_{sw}$ and its characteristic rotational period should be the Keplerian value.

### 3. RESULTS

Since there are a few degrees of freedom in our parameter space that primarily characterize the line shape, we need to carefully and systematically examine the effects of each parameter alone. First, we will see the effects of various spiral patterns by varying $(k_r, \Delta_{sw})$ for a given spiral phase $\phi_{sw} = 0^\circ$. In § 3.1.2 the spiral phase $\phi_{sw}$ is varied under the assumption that the spiral structure is fixed in the rotating disk frame. Our primary goal in the present paper is to demonstrate any detectable features seen in the iron line exclusively caused by a spiral perturbed velocity field, but for comparison purposes let us consider two different source heights: $h_f = 4r_g$ (a flare close to the hole) and $h_f = 10r_g$ (a relatively distant flare). The selected parameters for various models are tabulated in Table 1. In all cases we set $A_r = A_\phi$ (equal amplitude) unless otherwise stated.

#### 3.1. Predicted Iron Line Profile

Using the ray-tracing method, we are able to find roughly $\sim 6 \times 10^4$ photon trajectories between the accretion disk and the
Table 1
Adopted Model Parameters

| Model | \(k_r\) | \(\Delta r_{sw}\) | \(A_r\) | Description of Model | Figure |
|-------|--------|----------------|--------|---------------------|--------|
| 1     | 0.4    | 30             | 0.1    | Mildly packed       | 4a     |
| 2     | 1.0    | 30             | 0.1    | Moderately packed   | 4b     |
| 3     | 1.5    | 30             | 0.1    | Tightly packed      | 4c     |
| 4     | 0.4    | 30             | 0.01   | Rotation dominated* | 4d     |
| 5     | 0.4    | 5              | 0.1    | Centrally concentrated | 6a     |
| 6     | 0.4    | 15             | 0.1    | Centrally concentrated | 6b     |
| 1     | 0.4    | 30             | 0.1    | Centrally concentrated | 6c     |
| 7     | 0.4    | 5              | 0.01   | Rotation dominated* | 6d     |
| 1     | 0.4    | 30             | 0.1    | Small amplitude     | 7a     |
| 8     | 0.4    | 30             | 0.15   | Intermediate amplitude | 7b     |
| 9     | 0.4    | 30             | 0.2    | Large amplitude     | 7c     |
| 10    | 0.4    | 30             | 0.02   | Rotation dominated* | 7d     |

* We set \(A_r = 0.1A_g\) for these models. Unless otherwise stated, \(A_r = A_g\) and \(\phi_{sw} = 0°\) at all times.

To better illustrate an observational difference associated with a currently available spectral resolution, the same line profiles are obtained with \(E/\Delta E = 50\) (corresponding to \(\sim 120\) eV already achieved with *ASCA*). In Figure 5, where for comparison the same parameter sets are adopted as in Figure 4. With such an energy resolution, it seems very difficult to differentiate one
model from the other (for instance, the one with low $k_r$-value and the one with high $k_r$-value) and even impossible to distinguish the present model (with perturbations) from the standard disk-line model. This, however, will be distinguishable observationally with a much better spectral resolving power that should be available in the next-generation X-ray telescopes such as Astro-E2.

Figure 6 displays the profiles for various $\Delta_{sw}$ with $k_0 = 0.4$, where $\Delta_{sw}$ determines the effective (radial) distance of the spiral perturbation. We use $\Delta_{sw}/r_g = 5, 15, 30$ for Figures 6a, 6b, and 6c, respectively, while in Figure 6d we adopt $\Delta_{sw}/r_g = 5$ and $A_r = 0.1A_0 = 0.01$. The degree of the byky multiple peak looks roughly unchanged in every case regardless of $\Delta_{sw}$, and those multiple peaks are already present even when the spiral is centrally concentrated in Figure 6a. However, the overall line shape in Figure 6a is similar to that of the standard model in terms of the double-peaked structure (the third peak between the red one and the blue one is almost unseen). Therefore, it may be difficult to detect significant spiral effects when the perturbation is concentrated radially inward. Again, the radial component of the spiral motion appears to be unimportant in this case, too.

As we mentioned earlier, more effects of the spiral motion are intuitively expected when the amplitude is large. In Figure 7, $A_r = A_0$ = 0.1, 0.15, and 0.2 in Figures 7a, 7b, and 7c, respectively, while in Figure 7d $A_r = 0.1A_0 = 0.02$. As expected, a large amplitude tends to complicate the line shape more effectively. Specifically, the number of sharp subpeaks appears to increase, whereas the degree of the spiky multiple peaks remains almost unchanged when the amplitude increases. For example, the number of subpeaks can be as high as ~6 when $A_r = 0.2$ in Figure 7c, while it is ~3 when $A_r = 0.1$ in Figure 7a. For a small radial component in Figure 7d, there seems to be no significant difference from Figure 7a.

From what we find so far, it seems reasonable to say that the resulting line profile can be made very different from the classical one basically in two ways: (1) a tightly packed spiral wave with large $k_r$ tends to produce more spiky multiple peaks (wiggling), or (2) a large azimuthal amplitude $A_0$ tends to produce more sharp subpeaks, unless the spiral wave is restricted to the very inner region (small $\Delta_{sw}$).

### 3.1.2. Phase Dependence

In Figure 8 we show the phase dependence of the line profiles for a fixed spiral structure, with $k_0 = 0.4$, $\Delta_{sw} = 30r_g$, and $A_r = A_0 = 0.1$, varying $\phi_{sw}$ from $0^\circ$ to $300^\circ$ by $60^\circ$. The source height is $h_f = 4r_g$. The spiral wave is now fixed to the rotating disk frame. In other words, the spiral is corotating with the accreting gas. The distant observer at $r_{obs} \sim \infty$ is situated at $270^\circ$ (or equivalently $-90^\circ$) in its azimuthal position.

First of all, the profile appears to be constantly broadened over the photon energy $E_{obs}$ (≥4 keV) for the entire phase of the spiral wave $\phi_{sw}$ probably because of a small radius of the marginally stable orbit $r_m$. The line shape also normally contains a triple-peaked structure (left-end peak, middle-peak, and right-end peak) with the dominating blue peak (or right-end peak) at all the times. It can be classified as belonging to roughly two categories depending on its characteristic shape: (a) the left-end peak above 5 keV as in panels 1, 2, 3, and 6, and (b) the left-end peak below 5 keV as in panels 4 and 5. The line energy of each peak then shifts toward either higher energy or lower energy depending on the phase $\phi_{sw}$ (i.e., peak transition). This trend can be viewed in relation to the spiral phase $\phi_{sw}$ in the following. The main cause of this complicated variation primarily originates from the fact that some parts of the accretion disk are more redshifted while the other parts, on the other hand, are more blueshifted depending on the phase $\phi_{sw}$. Hence, nonaxisymmetry in the net velocity field is directly responsible for producing such a variability for a fixed X-ray source $h_f$. As discussed earlier, a choice of nearby source (smaller $h_f$) tends to generate more frequent subpeaks because of more exclusive contribution from the innermost gas where the spiral perturbation is greater. On the other hand, spiky quasi-periodic peaks do not seem to change very much over the phase $\phi_{sw}$. We have also confirmed that the above variation (or the transition of peaks) with phase $\phi_{sw}$ is not so obvious when $k_0$ is large because the velocity field becomes somewhat quasi-axisymmetric (that is, the perturbation becomes more or less uniform everywhere). Hence, the noticeable line variability would be more expected when the perturbing spiral wave is not so tightly packed (i.e., small $k_r$). The corresponding global variation with $\phi_{sw}$ can also be seen in Figure 9, where the normalized line intensity is plotted as a
function of the observed photon energy $E_{\text{obs}}$ (in keV) and the spiral phase $\phi_{\text{sw}}$ (in degrees), corresponding to Figure 8. The intensity is normalized between 1 (its minimum) and 2 (its maximum). An interesting pattern here is the existence of four distinct arcs (i.e., the transition of peaks) present at different energy $E_{\text{obs}}$: arc 1 ($E_{\text{obs}} \approx 4.5 - 5.3$ keV), arc 2 (5.3–5.7 keV), arc 3 (6.3–6.5 keV), and arc 4 (~6.6 keV). They individually correspond to the sharp peaks seen in Figure 8. Besides such arcs, a randomly distributed, wiggling variation of the line intensity is clearly present, especially at $E_{\text{obs}} \approx 6$ keV, because of the perturbed velocity field. This corresponds to the quasi-periodic multiple peaks in Figure 8.

3.2. Redshift and Temperature Distribution

Assuming the blackbody emission from the fluorescent photons, we estimate the equivalent temperature $T_{\text{obs}}$ measured by a distant observer. Figure 10 displays the spatial distribution of the redshift $g_{\text{do}}$ and the temperature $T_{\text{obs}}$ of the accreting gas for $k_r = 1.0$, $\Delta_{\text{sw}} = 30r_g$, $A_r = A_g = 0.1$, and $\phi_{\text{sw}} = 0^\circ$, where the redshift $g_{\text{do}}$ is scaled between 0 (maximum redshift) and 2 (maximum blueshift), whereas the temperature $T_{\text{obs}}$ is normalized by 1 (minimum temperature) and 2 (maximum temperature). The source height is at $h_f = 4r_g$. The phase of the spiral $\phi_{\text{sw}}$ is progressing from (1) 0° to (6) 300° by 60°. The horizontal axis is the observed photon energy $E_{\text{obs}}$ (keV), while the vertical axis shows the observed photon flux in arbitrary units.

Fig. 8.—Phase-evolved iron line profiles from a spiral wave with $k_r = 0.4$, $\Delta_{\text{sw}} = 30r_g$, and $A_r = A_g = 0.1$. The source height is at $h_f = 4r_g$. The phase of the spiral $\phi_{\text{sw}}$ is progressing from (1) 0° to (6) 300° by 60°. The horizontal axis is the observed photon energy $E_{\text{obs}}$ (keV), while the vertical axis shows the observed photon flux in arbitrary units.

Fig. 9.—Intensity map of the global evolution of the iron line in the energy phase $E_{\text{obs}}$-$\phi_{\text{sw}}$ space corresponding to Fig. 8 with the same parameter set being used. The phase of the spiral wave $\phi_{\text{sw}}$ is progressing from 0° to 345° by 15°. The intensity is normalized between 1 and 2. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 10.—Redshift distribution $g_{\text{do}}$ of the emitted photons in the disk (left) and the equivalent blackbody temperature distribution $T_{\text{obs}}$ of the disk (right) for $k_r = 1.0$, $\Delta_{\text{sw}} = 30r_g$, and $A_r = A_g = 0.1$. The phase of the spiral is $\phi_{\text{sw}} = 0$, and the source is at $h_f = 4r_g$. A distant observer is situated in the direction of 270° (or equivalently −90°). The redshift $g_{\text{do}}$ of the observed photons is scaled between 0 and 2 (left), while the apparent disk temperature $T_{\text{obs}}$ is normalized between 1 and 2 (right). The inner circle denotes the event horizon $r_h$, while the outer circle denotes the Newtonian circle with the radius of 30$r_g$. The arrow (left) indicates the rotational direction of the disk. A distant observer is situated in the illustrated azimuthal position. [See the electronic edition of the Journal for a color version of this figure.]
apparent. In the right panel the apparent blackbody temperature $T_{\text{obs}}$ is shown for the same parameter set. Again, the spiral pattern is present because of $T_{\text{obs}} \propto \Omega_{\text{ms}}$. The inner edge of the disk shows a rapid temperature drop because of the extreme gravitational Doppler redshift. The approaching side appears to be hotter than the other regions mainly because of the classical Doppler blueshift, even under the spiral perturbation. Such a hot region appears to be spatially narrow, forming an interesting two-dimensional shape (“hot spot”) in the approaching side of the disk (this can be better seen in the color version of Fig. 10). Interestingly, the spatial size of this hot spot is variable as the spiral phase $\Phi_{\text{sw}}$ progresses, whereas in the unperturbed disk it is constant. Although we do not show the exact variable temperature map here, it is found that the effective area of the hot spot appears to vary periodically as the spiral wave rotates with the accreting gas, which is due to the perturbed velocity field (and thus the perturbed redshift distribution). The variation is found to be larger when the spiral wave is mildly wounded (i.e., small $k_z$). In the case of $h_1 = 10r_g$, we also find a similar periodicity except that the hot spot appears farther out. This may imply that such a variation can be manifested as a quasi-periodic change in the observed photon flux with the Keplerian frequency of $\Omega_k/(2\pi) \sim 4 \times 10^{-4}$ Hz at $r \sim 6r_g$.

4. DISCUSSION AND CONCLUDING REMARKS

We modified and extended the work of HB02 on the iron lines under spiral perturbation by carrying out fully relativistic (both special and general) calculations in the Kerr geometry. We furthermore assume realistically that the net velocity field of the accreting gas should be the sum of Keplerian motion and the perturbing orbit in our model. The presence of spiral waves in the magnetized accretion disk has been suggested already by various previous numerical simulations (e.g., CT01; H01; MM03). The primary motivation of our current work is based on the numerical results by these previous authors, which indicate that the one-armed spiral velocity field may be produced at a late stage of the disk evolution because of the MRI and/or AEI for a differentially rotating disk. We carefully chose the spiral velocity field in such a way that it does qualitatively mimic the velocity perturbation already found by H01 and MM03.

Our results in many respects confirm the work of HB02. However, there are some important differences due to new results. Our present work is new and original in various ways. For instance, we extended the work of HB02 under an approximate Schwarzschild geometry, to a full Kerr geometry. As a consequence, first of all, our model generally allows for a very long red tail (below 4 keV), whereas the lines by HB02 extend at most only down to 4.5 keV. This is clearly due to our adoption of the Kerr geometry, which allows a smaller radius of marginal stability $r_{\text{ms}}$. In terms of comparison with observations, our model is more realistic than that of HB02 since observed lines sometimes exhibit such a very long red tail.

Moreover, we included general relativistic bending of photons, both from the X-ray source to the disk and from the disk to the observer. Bending of photons from the source to the disk enables us to account for a more realistic centrally concentrated emissivity profile. Because of this effect, the net intensity of the photon flux is altered from the Newtonian case. On the other hand, HB02 does not include this bending effect, although a similar source geometry is assumed here.

Let us note that our time-invariant treatment of the reprocessed photons should be valid as long as the characteristic timescale of the spiral rotation is much smaller than the light crossing timescale across the emitting region of the disk, which is our case. Thus, we feel that our approach is justified.

We confirm that quasi-periodic peaks in the profile due to the spiral motion in the accreting gas, which was reported by HB02 for an approximate Schwarzschild geometry, are exhibited in the Kerr geometry also. In addition, we newly find that the standard iron line (meaning a broadened line with a double-peaked structure) could be dramatically modified depending on the type and/or degree of such a spiral perturbation. Our results show that (1) the profile may commonly exhibit a multiple peak (or nonstandard double peak) even under a relatively small spiral perturbation, (2) the produced peaks can be divided into two kinds: sharp subpeaks and spiky multiple peaks, (3) the profile may possess many spiky multiple peaks for a tightly packed spiral wave, (4) a larger amplitude of the perturbation may produce more sharp subpeaks rather than spiky multiple peaks, (5) the effect of the spiral may not be significantly large enough for detection when the perturbation is centrally concentrated, and from the phase evolution we have learned that (6) the characteristic line shape (i.e., relative position of the line peaks) seems to be very sensitive to the azimuthal phase of the spiral wave, especially for large $k_z$ and/or a small $h_1$.

Result 1 is qualitatively similar to what HB02 have found. However, in addition we find more new features in our results 2–5 for various spiral patterns. We further find clearer line variability (e.g., peak transition) in result 6, assuming that the spiral wave is fixed in the rotating disk frame, although this is not so obvious in HB02. If such a periodicity is found from future observations, it may be attributed to the presence of such a spiral rotation.

Finally, one of our goals is to find any possible observable signatures due to the spiral motion imprinted in the iron fluorescent line. It is beyond the sensitivity of the current X-ray missions, such as Chandra and XMM-Newton, to detect some of our predicted features, such as the sharp subpeaks and/or very narrow multiple peaks. However, it will be observationally feasible to detect such signatures by future X-ray missions—if the spiral wave is actually involved in the production of fluorescent emission line. For instance, we choose the spectral resolving power to be $E/\Delta E \sim 600$ (equivalent to $\sim 10$ eV) in all the computations, which can be reached by next-generation X-ray missions. For instance, Japan/USA Astro-E2, scheduled to be launched in 2005, should be able to achieve $E/\Delta E \sim 500–700$ (equivalent to the spectral resolution of $10–13$ or 6 eV of FWHM) around 6.4 keV, and NASA’s Constellation-X is designed to accomplish $E/\Delta E \sim 300–1500$. Also, the next European X-ray satellite, XEUS, a potential successor to XMM-Newton, will have $E/\Delta E \sim 1000$ at 6 keV. These energy resolutions should be more than sufficient to identify the predicted multiple subpeaks in the profile. Therefore, our model can be tested with these future observations (e.g., Reynolds & Nowak 2003). Then it will allow us to evaluate whether our proposed model (perturbed accreting gas) can correctly describe the observed line profiles. If so, further, careful comparison with observation may enable us to narrow down some of the parameters for the spiral-wave structure.

So far, the standard disk-corona models explain well various Seyfert 1 galaxy iron line features already observed. However, these models do not include the effect of spiral waves, which have already been shown to be a natural outcome of the presence of magnetic fields in the accretion disk. Note that
magnetic fields must be present to produce corona. Before closing, we emphasize that inclusion of spiral waves in a realistic disk-corona model, as shown in our current paper, gives rise to new features, such as multiple fine peak structures, which can be tested by future observations.

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