NARROW MOVING FE Kα LINES FROM MAGNETIC FLARES IN AGN.

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ABSTRACT

We point out that luminous magnetic flares, thought to occur in standard AGN accretion disks, cannot be located much higher than few pressure scale heights above the disk. Using this fact, we estimate the fraction of the disk surface illuminated by a typical flare. This fraction turns out to be very small for geometrically thin disks, which implies that the instantaneous Fe Kα emission line from a specific magnetic flare is narrow. The line is red- or blue-shifted depending on the position of the observer relative to the flare and sweeps across the line band with time. We present several examples of theoretical time-resolved line profiles from such flares for Schwarzschild geometry. The observations of such moving features with future X-ray telescopes will present a powerful test of the accretion disk geometry and may also test General Relativity in the strong field limit.

Subject headings: accretion, accretion disks — radiative transfer — line: formation — X-rays: general

1. INTRODUCTION

There is much current debate about the structure of the inner part of the accretion flow in Active Galactic Nuclei (AGN). One of the possibilities often discussed is the standard (geometrically thin, optically thick) accretion disk in which the X-ray activity is provided by magnetic flares above the disk (e.g., Galeev, Rosner & Vaiana 1979; Haardt, Maraschi & Ghisellini 1994). The main difficulty of this model is its intrinsic physical complexity, which does not naturally relate the X-ray emission to the global disk parameters, such as the accretion rate in the disk, black hole mass, etc. However the model is attractive because of the physical parallel with the Solar magnetic flares, and the fact that it naturally explains the broad Fe Kα lines observed in a number of AGN — see the recent review by Fabian et al. (2000). Any robust observational prediction that can be used to test the model is thus of a substantial value.

Herein we show that time-resolved Fe Kα line profiles of the magnetic flare model should consist of relatively narrow features due to the limited extent (in radius and height) of the active regions. As they circle the black hole, the corresponding Fe Kα line features should sweep across ~ 4 – 8 keV energy band. This pattern is unique to the magnetic flare model (in particular, the line width is much narrower than the profiles of the lamppost-like models calculated by Reynolds et al. [1999], Young & Reynolds [2000] and Ruszkowski [2000]), and it could be used in the future to verify or falsify the basic premises of this model.

2. THE FLARE HEIGHT AND THE ACTIVE REGION SIZE

The size of a single magnetic reconnecting region, ΔR, and its height above an accretion disk are of theoretical and observational import, yet there is no clear discussion of this issue in the literature. If one assumes that magnetic field pressure in the flux tube greatly exceeds the gas pressure there, then its equilibrium structure should be dictated by a force-free equilibrium. Parker (1979, §8.4) computes the force-free equilibrium for a flux tube not bounded by any external pressure. He shows that, mathematically speaking, the magnetic field fills all the available (empty) space. However, one can check that most of the magnetic energy is confined within a volume of roughly same linear size as the separation between the footpoints of the tube, i.e., in close proximity to the footpoints. Further, it is generally believed that the size of a magnetic flux tube inside the disk should be no larger than the size of the largest turbulent cell, which is ~ H, the disk pressure height scale (e.g., Galeev et al. 1979). These considerations thus require that both the size and the height of a magnetic flare be ΔR ~ H.

At the same time, one could argue that the magnetic field need not completely dominate the energy (and pressure) content of the flux tube above the disk, and hence maybe the gas pressure expands the flux tube much above H. While this is in principle possible dynamically (e.g., Romanova et al. 1998), one can show that the coronal region has to be magnetically dominated or the energy balance conditions will require unrealistically large size for the emitting region (e.g., Merloni & Fabian 2001). These authors derive also a limit on the size of a magnetic flare (see their equation 8), which however depends on the average number of magnetic flares, N; this is not a well determined quantity since the usual variability arguments (e.g., Haardt et al. 1994) may not be applied if a single flare in the light curve is produced by a multitude of reconnecting flux tubes (e.g. as in the flare avalanche model of Poutanen & Fabian 1999; also see below).

We now show that one can derive an even tighter limit on the flux tube size. The magnetic flux, Ψ, is a constant along a flux tube (e.g., Parker 1979). Since any flux tube is anchored in the disk mid-plane, the maximum of the magnetic flux is Ψ ~ B_c H^2 where B_c is the equipartition magnetic field in the disk mid-plane, and H^2 is the order of magnitude estimate of the maximum tube cross section within the disk. The magnetic pressure in the loop above

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the disk is thus
\[
\frac{B^2}{8\pi} \sim \beta \lambda^2 P_d \left( \frac{H}{\Delta R} \right)^4, \quad (1)
\]
where we introduced parameter \( \beta \equiv B_{\text{max}}^2 / B_0^2 \leq 1; \) \( B_{\text{max}} \)
and \( \lambda^2 H^2 \) are the actual magnetic field and the tube’s cross section in the mid-plane (\( \lambda < 1 \)), and \( P_d \) is the total disk pressure there.

The constraint on the size of the active region comes from the demand that the mechanism responsible for the formation of the resulting spectrum be the Comptonization of seed photons by an optically thin, mildly relativistic plasma (e.g., Poutanen & Svensson 1996), a process known to yield power law spectra in agreement with those observed in AGN. In order for Comptonization to be the dominant emission mechanism, the compactness parameter, \( l / l_f \), of the emission region must be greater than about \( \sim 0.1 \) (Fabian 1994; Nayakshin 1998, §2). To estimate the value of \( l \) we assume that the luminosity of a flare, \( L_f \), is given by \((4\pi/(3\Delta R)^2)B^2(8\pi)^2t_r^{-1}\), where \( t_r \) is the reconnection time scale, here parameterized as \( b \Delta R / c \) with \( b > 1 \). With this assumption, the X-ray flux from the active region is \( F_x \sim (B^2/(8\pi))c/3b \), which with the use of Eq. (1) yields for the compactness
\[
l \equiv \frac{\sigma T F_x \Delta R}{m_e c^3} = \beta \lambda^2 \frac{P_d \sigma T H}{3 m_e c^2} \left[ \frac{H}{\Delta R} \right]^3. \quad (2)
\]
It is a simple matter to show, using equations of Svensson & Zdziarski (1994; SZ94), that for both radiation- and gas-dominated disks,
\[
\frac{P_d \sigma T H}{3 m_e c^2} = \frac{1}{6\sqrt{2}} (m_p/m_e) \alpha^{-1} \eta^{-1} r^{-3/2} \dot{m} J(r), \quad (3)
\]
where \( \alpha \) is the viscosity parameter; \( \dot{m} \) is the dimensionless accretion rate (for \( \dot{m} = 1 \) the disk luminosity equals that of Eddington \( L_{\text{Edd}} \); \( \eta \approx 0.06 \) is the efficiency of accretion; \( J(r) \equiv 1 - \sqrt{3/r}, \) and \( r = Rc^2/2GM \). The function
\[
J(r)/r^{3/2} \text{ has a maximum at } r = 16/3, \text{ with the value } \approx 0.02.
\]
Therefore, for any radius in the disk,
\[
l \leq 73 \beta \lambda^2 \frac{\dot{m}}{\alpha b} \left[ \frac{H}{\Delta R} \right]^3. \quad (4)
\]
The corresponding limit on the size of the active region is
\[
\frac{\Delta R}{H} \leq 4.2 \left[ \frac{l}{0.1} \right]^{-1/3} \left[ \frac{\beta}{\alpha b} \right]^{1/3} \lambda^{4/3} \left[ \frac{\dot{m}}{0.01} \right]^{1/3}. \quad (5)
\]
where \( \alpha_2 \equiv \alpha/100 \) and \( b_1 \equiv b/10 \). Thus, the requirement of sufficiently large compactness for an active region limits its height to no more than several times the disk scale height \( H \). This limit can be even tighter if one demands larger values for \( l \) (e.g., \( l \approx 10 \) was assumed by Poutanen & Fabian 1999).

Let us now compare \( H \) with the radius, \( R \). Using equation (7) of SZ94, one finds
\[
\frac{H}{R} = \frac{1}{16} \frac{\dot{m}}{0.01} \frac{J(r)}{r} = \frac{\dot{m}}{16 \times 0.01} \frac{J(r)}{r}. \quad (6)
\]
This is a tiny number: for \( r = 5 \), i.e., for radii around which the radiation flux in the Shakura-Sunyaev disk reaches maximum, \( H/R \approx 0.003 \) for \( \dot{m} = 0.01 \). Note that our considerations do not preclude the presence of larger size magnetic loops, but they show that these loops will have very weak magnetic fields and hence are unlikely to be responsible for the X-ray radiation that we observe from AGN.

Let us now consider the area of the disk illuminated by a flare. A source that is a height \( \Delta R \) above the disk will illuminate area \( \sim \pi(\Delta R)^2 \) immediately below the flare, and the rest of the disk will receive a negligible amount of X-ray illumination. This area, \( \pi(\Delta R)^2 \), is a very small fraction of the disk full area, according to Eq. (3). This fact has an important observational implication: the instantaneous Fe Kα line profile from a single magnetic flare should be narrow (see below). With an estimate of the extent \( \Delta R \) of a magnetic flare (Eq. (1)) one can now estimate its luminosity as a fraction of the total disk luminosity \( \dot{m} L_{\text{Edd}} \) (at \( r = 6 \)):
\[
\frac{L_1}{L} \approx 1.4 \times 10^{-2} \frac{\beta \lambda^4}{\alpha b_1} \left[ \frac{H}{\Delta R} \right]^2 \frac{\dot{m}}{0.01}. \quad (7)
\]
Because both \( \lambda \) and \( \beta \) must be smaller than one by definition, the above relation shows that if the X-ray luminosity is a good fraction of the bolometric luminosity, then one needs \( N \) (the number of such X-ray emitting regions) \( \sim \) from tens up to few thousand at any one time. If flares occurred completely randomly, independently of each other, then one would expect an RMS variability amplitude \( \sim 1/\sqrt{N} \). This latter number seems to be too small given that it is not atypical for AGN to exhibit variations in X-ray flux by factors of 2 or so.

To account for the observed variability one needs to invoke avalanches of magnetic flares, i.e., require that each observed X-ray flare consists of many correlated (in time and space) individual active regions (e.g., Poutanen & Fabian 1999). Physically, it is likely that magnetic flux tubes rise above the disk but do not immediately reconnect, settling down into a quasi-static equilibrium state. However, with time, more and more magnetic flux tubes arise from the disk, covering the disk surface. Additionally, the tubes that are already above the disk are sheared by differential rotation of the foot-points and hence some of them will be taken out of equilibrium (i.e., the reconnection will start). If some region of the disk is particularly closely packed with flux tubes, then it is possible that the active magnetic flares will affect its neighbors, setting them off as in a chain reaction, producing the flare avalanche and leading to a flare-like event in the observer’s light curve.

Note that for this scenario to be plausible, the magnetic flares taking part in the avalanche must be near each other, otherwise it is hard to see how they can interact over distances greater than their own size, \( \Delta R \). Therefore, from now on, we will accept that the active flares contributing to a particular observer’s flare in the light curve (which can be as large as \( \sim 50\% \) of the average X-ray luminosity of an AGN) closely pack a disk region of area \( A \). Assume that the active region produces a fraction \( \zeta \) of the bolometric luminosity, \( L \). The maximum X-ray flux produced by flares in the active region is \( F_x \sim c P_d b^{-1} \). The area of
the disk covered with magnetic flares responsible for the luminosity \( \zeta L \) is thus \( A \sim \zeta L/F_c \). We can compare this area with the effective area of the inner accretion disk \( \pi R^2 \) if we note that \( L \sim F_\Omega \pi R^2 \), where \( F_\Omega = (9/8)\alpha c_s P_d \) is the Shakura-Sunyaev disk flux, and \( c_s \) is the mid-plane sound speed:

\[
A \sim \zeta \alpha b c_s c \sim 10^{-4}\alpha c_b ,
\]

where we used \( T \sim 10^5 \) to estimate \( c_s \). The combination of the remaining factors in the equation above is probably less than unity, and so clearly \( A \ll R^2 \). If we assume that the active region has about the same dimensions in the radial (\( \delta R \)) and azimuthal (\( R \delta \phi \)) directions, then we conclude that \( \delta R/R \sim \delta \phi/2\pi \sim 0.01 \).

3. TIME RESOLVED Fe Kα LINE PROFILE

An immediate implication of the discussion of the previous section is the prediction that the instantaneous Fe Kα line profile as seen by an observer at infinity should be narrow. Indeed, for a non-rotating black hole, and neglecting photon ray bending due to strong gravitational fields for a moment, the observer sees Fe Kα line photons of energy \( E(R, \phi) \) from a point source at \( (R, \phi) \)

\[
E(R, \phi) = E_0(1 - 2/r)^{1/2} [\gamma(1 - v \cos \alpha_0)]^{-1} ,
\]

where \( v \) is the orbital velocity in units of speed of light at radius \( r \), \( \alpha_0 \) is the angle this velocity makes with the direction to the observer, \( \gamma \equiv (1 - v^2)^{-1/2} \), and \( E_0 \) is the photon rest frame energy. Approximately, the width of the line profile will be

\[
\delta E = \frac{\partial E}{\partial R} \delta R + \frac{\partial E}{\partial \phi} \delta \phi .
\]

For a pole-on observer the second term vanishes and \( \delta E \sim 0.1E_0(\delta R/R) \sim 6 \text{ eV} \) for the chosen values of \( \delta R, \delta \phi \), much smaller than the red or blue-shift of the line centroid itself. \( \delta E \) generally increases with increasing inclination angle. The maximum of the second term in eq. (9) is for an equatorial observer when \( \alpha = \pi/2 \) or \( 3\pi/2 \):

\[
\text{max} |\partial E/\partial \phi| = E(R, \phi) v \approx E_0(r - 2)^{-1/2} ,
\]

which yields \( \delta E \approx 130\text{eV}(\delta \phi/0.01\pi) \). Hence the width of Fe Kα line profile from a Schwarzschild disk flare should vary between as little as \( \sim 6 \text{ eV} \) to \( \sim 100 \text{ eV} \), with a “reasonable” value of \( \sim 30 \text{ eV} \) for Seyfert 1 Galaxies that are thought to be nearly pole-on. Note that the contrast of these features to the continuum flux is larger (by a factor of \( \sim 10 \)) for nearly face-on than for nearly edge-on disks.

Let us now calculate the time-resolved Fe Kα line profile from a single rotating spot. We will assume that its radial size \( \delta R \) is negligible, and \( \delta \phi/(2\pi) = 0.01 \). Note that the time delay between the start of a magnetic flare and the Fe Kα line emission from the flare is very small, i.e., it is \( \sim H/c \), and so we can neglect it. For this first study, we will assume that the Fe Kα line emissivity is isotropic in the rest frame and is also constant over the active region’s life time. Finally, we will consider the case of a flare lasting exactly one rotation for a non-rotating black hole at a radius \( R = 12GM/c^2 \).

In polar spherical coordinates with the black hole at the center and the disk treated as a plane at \( \theta = \pi/2 \), we place the observer at \( r_o = 10^3 \), azimuthal angle \( \phi = 0 \) and polar angle \( \theta = \theta_o \). The active region turns on at \( \phi = -\pi \) and turns off at \( \phi = \pi \) by assumption. We consider three different values of the observer inclination angles: \( \theta_o = 4, 27 \) and 63 degrees. To calculate the time dependent line profiles, we isotropically (in the rest frame of the active region) emit a large number of photons and then trace their trajectories until they reach radius \( r_o \). The photon ray tracing is performed using appendices A3 and A4 of Reynolds et al. (1999). Only the photons that arrived within angle \( \theta = \theta_o \pm 2\circ \) and \( \phi = \pm 0.005 \times 2\pi \) are recorded. Figure 1 shows the resulting Fe Kα line trajectory in the energy-time diagram for the three chosen angles. One can easily derive an analytical expression for these tracks neglecting photon ray bending (e.g., eq. 14) with \( \alpha \) calculated as a function of photon arrival time). This expression agrees with the curves shown in Figure 1 quite well (because for \( r = 12 \) and not too large \( \theta_o \), the ray bending is relatively weak).

When the observer is nearly pole-on, there is almost no Doppler boost, so the photon line trajectory in Figure 1 is a straight line. At larger angles, line photons can be either red or blue shifted depending on the azimuthal separation of the source and the observer. Finally, one should note that the larger the inclination angle, the shorter (in time) the blue-shifted section of the S-shaped trajectory is. This is simply due to the fact that the source moves towards the observer for \( -\pi < \phi < 0 \) and then it moves away from the observer for \( 0 < \phi < \pi \). Also note that similar trajectories can be noticed in some of the response functions calculated by Ruszkowski (2000; see his Figures 5, 7 & 9). The latter are however much broader because the X-ray source is located much higher above the disk.

4. DISCUSSION

In this Letter we showed that the area illuminated by X-rays from an active magnetic flare is small compared to the total disk area. The time-resolved Fe Kα line profile from this active region should then be a narrow feature sweeping with the rotation period across the entire range of red(blue)-shift associated with the given radius and inclination angle. We calculated several examples of such line profiles for a non-rotating black hole. We now discuss the implications of our results assuming that such a narrow moving Fe Kα line trajectory can be observed in the future with observatories such as XMM-Newton or (more realistically) Constellation-X.

(1) The trajectories of the Fe Kα feature in the energy-time diagram are very different from those obtained by Reynolds et al. (1999), Young & Reynolds (2000) and Ruszkowski (2000) for the lamp-post model or highly elevated flares. Indeed, these latter profiles are considerably broader – i.e., \( \delta E \sim 1 \text{ keV} \) with the red- and blue-shifted wings of the line appearing simultaneously. This is due to the fact that a highly elevated X-ray source illuminates a large fraction of the disk area. In contrast, we found \( \delta E \lesssim 100 \text{ eV} \) with the line being either red- or blue-shifted at any particular time. Future observations of sufficient energy and time resolution should be able to confirm these results thereby setting limits on the size and height of X-ray emitting regions in accretion disks.

(2) The much more restricted extent of the X-ray emitting region argued for in this note compared to that of e.g. the lamp-post model presents a much more unequivocal
probe of the underlying geometry. In the lamp-post case, one of the complications is that even if the accretion disk proper does not exist at radii smaller than the last stable orbit, there is still gas there. This gas is thought to be free-falling into the black hole. As shown by Reynolds & Begelman (1997), the vertical Thomson depth of this material can be significant, thus suggesting that it will also produce a fluorescent Fe Kα line emission if it is illuminated by X-rays. And indeed, if the X-ray source is located on the height $\sim$ few $GM/c^2$ above the disk, then this region also contributes to the observed line profile (Reynolds & Begelman 1997). Young, Ross & Fabian (1998) argued that a detailed account of disk photo-ionization can still constrain the location of the innermost radius of the disk in the particular case of the well known AGN MCG-6-30-15. For time-dependent reflection, the distinction between rotating and non-rotating holes is in a red-ward moving bump in the line profile, as shown by Reynolds et al. (1999) and Young & Reynolds (2000). However, recently, it was realized that thermal ionization instability plays a crucial role in the photo-ionized reflection (Nayakshin, Kazanas & Kallman 2000). Recent modeling of time-dependent reflection that included thermal ionization instability (Nayakshin & Kazanas 2001) shows that the physics of the problem is far richer than it has been thought based on constant density models. We therefore feel that distinguishing between rotating and non-rotating black holes in the lamp-post geometry can be non trivial in practice.

In contrast, magnetic flares can only occur where there is a continuous energy production in the underlying disk, that is at radii greater than the last stable orbit. Since the flares illuminate only the disk immediately below them, the region inwards of the last stable orbit receives a negligible amount of X-rays and hence emits no line. Observation of a Fe Kα line shifted by an amount only consistent with $R < 6GM/c^2$, would strongly argue for a rotating black hole, then.

(3) Fe Kα line trajectories similar to those in Figure 1 could be used to constrain circular orbits of test particles in the gravitational field, as well as photon ray bending. In principle, this information can be used to test General Relativity in the strong field limit. Note that, as long as the line profile is sufficiently narrow, this procedure would require knowledge of only the Fe Kα line energy versus time and not the amplitude of the line emission; hence complications due to anisotropy of the magnetic flare emissivity or photo-ionization physics may be neglected (this is not so for the lamppost case because it may be hard to define the peak of the line if the profile is broad and is overlayed on the top of a continuum emission).

The real Fe Kα line profiles should be produced by many magnetic flares (see eq. 8). If they occur randomly, at completely independent locations, then it will be perhaps impossible to distinguish individual line “trails” if of sufficiently large number. However, as we discussed in §2, this would also preclude any substantial variability in the X-ray continuum flux, while one often observes variations of up to $\sim 50\%$ in the continuum flux (e.g., Edelson et al. 2000). Therefore, we believe that observed large amplitude excursions of the AGN X-ray flux can only be accounted by magnetic flares if the latter are not independent of each other, i.e., if they take part in flare avalanches (Poutanen & Fabian 1999). Further, it is difficult to see how small scale flares can affect each other unless they are in physical proximity. Therefore, the line profile from a magnetic flare avalanche should also be narrow and hence the points made above hold true. On the other hand, the active region (the avalanche region) may be sheared by the differential rotation in the disk (although magnetic field can also be strong enough throughout the active region to inhibit differential rotation [E. Vishniac, private communication]). Thus, the region may become larger in extent and the point-source approximation will be invalid. Whether this is the case or not could be determined directly from time-resolved Fe Kα line spectroscopy.

In summary, we conclude that instantaneous Fe Kα line profiles from magnetic flares and highly elevated X-ray sources, such as a lamppost, are very much different (e.g., compare Fig. 1 to Figures in Reynolds et al. 1999), and hence time-resolved Fe Kα line observations have an
enormous potential for constraining accretion disk theo-
ries. Given this, Astrophysics community should spare
no effort in developing future space observatories such as
Constellation-X.

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