Fe Kα emission from photoionized slabs: the impact of the iron abundance

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ABSTRACT
Iron Kα emission from photoionized and optically thick material is observed in a variety of astrophysical environments including X-ray binaries, active galactic nuclei, and possibly gamma-ray bursts. This paper presents calculations showing how the equivalent width (EW) of the Fe Kα line depends on the iron abundance of the illuminated gas and its ionization state — two variables subject to significant cosmic scatter. Reflection spectra from a constant density slab which is illuminated with a power-law spectrum with photon-index Γ are computed using the code of Ross & Fabian. When the Fe Kα EW is measured from the reflection spectra alone, we find that it can reach values greater than 6 keV if the Fe abundance is about 10× solar and the illuminated gas is neutral. EWs of about 1 keV are obtained when the gas is ionized. In contrast, when the EW is measured from the incident+reflected spectrum, the largest EWs are ∼800 keV and are found when the gas is ionized. When Γ is increased, the Fe Kα line generally weakens, but significant emission can persist to larger ionization parameters. The iron abundance has its greatest impact on the EW when it is less than 5× solar. When the abundance is further increased, the line strengthens only marginally. Therefore, we conclude that Fe Kα lines with EWs much greater than 800 eV are unlikely to be produced by gas with a supersolar Fe abundance. These results should be useful in interpreting Fe Kα emission whenever it arises from optically thick fluorescence.

Key words: gamma rays: bursts – line: formation – line: profiles – radiative transfer – galaxies: active – X-rays: galaxies – X-rays: general

1 INTRODUCTION
There are a number of different astrophysical environments where optically thick material may be irradiated by X-rays. If the incident spectrum has significant flux above 7.1 keV, then, as a result of its relatively high cosmic abundance and large fluorescent yield, the iron Kα line is predicted to be a significant feature in the resulting emission from the illuminated surface (e.g., George & Fabian 1991; Matt, Perola & Piro 1991). The presence of this line has been discussed for a number of different reprocessors including the solar surface (Bai 1979), the surface of the companion star in X-ray binaries (Basko, Sunyaev & Titarchuk 1974, Basko 1978, Pravdo 1979), and the surface of accreting magnetic white dwarfs (e.g., Swank, Fabian & Ross 1984, Done, Osborne & Beardmore 1993, van Teeseling, Kastra & Heise 1996). Most famously, Fe Kα emission has been observed in the X-ray spectra of many Active Galactic Nuclei (AGN) and black hole candidates (Nandra & Pounds 1994, Ebisawa et al. 1996). Here, the irradiated surface is likely the accretion disc feeding the black hole, and some of the observed Fe Kα lines have been observed to be broadened in a manner consistent with material orbiting in a relativistic gravitational potential (Tanaka et al. 1995, Nandra et al. 1997, Fabian et al. 2000). Finally, tentative detections of line emission, most likely from Fe Kα, have been found in recent observations of the X-ray afterglows of some γ-ray bursts (e.g., Piro et al. 1999, 2000, Antonelli et al. 2000). If this is confirmed then it implies that optically thick material may be in the vicinity — a possible constraint on the environment and progenitor of the burst (Rees & Mészáros 2000, Vietri et al. 2001, Ballantyne & Ramirez-Ruiz 2001).

As one of the few physical diagnostics in the X-ray spectra of these systems, it is important to understand how the Fe Kα emission line depends on the properties of the irradiated gas. Previous studies have examined the influence of changes in metal abundance (Matt, Fabian & Reynolds 1997), the inclination angle of the reflector (Chisellini, Haardt & Matt 1994), ionization state (Matt, Fabian & Ross 1993, 1996), and the density distribution of the gas (Ross, Fabian & Young 1999, Nayakshin 2000, Ballantyne & Ross 2001) on the line emission. This paper generalizes the results of Matt and colleagues by presenting how the strength of the Fe Kα line (presented as an equivalent width [EW]) depends on both the Fe abundance and the ionization state of the gas. These two variables have the greatest impact on the EW, and are likely to vary widely over...
different astrophysical environments. We anticipate that these results will be helpful in interpreting Fe Kα detections whenever it arises from an optically thick surface.

The following section details the calculations that were performed, and then Section 3 presents the results as contour plots of EW. A brief discussion concludes the paper in Section 4.

2 COMPUTATIONS

The calculations were performed using the code of Ross & Fabian (1993). A slab with a constant hydrogen number density $n_H = 10^{15}$ cm$^{-3}$ was illuminated with a power-law continuum with photon-index $\Gamma$ (i.e., so that photon flux $\propto E^{-\Gamma}$). Provided that they have comparable flux above 7 keV, other incident spectral forms (e.g., blackbody, Wien tail) will not significantly alter the results. As a crude approximation to isotropic illumination, the penetrating radiation was assumed to strike the slab at an angle of 54.7 degrees from the normal. Hydrogen and helium were assumed to be fully ionized, but C v–vii, O v–ix, Mg ix–xiii, Si xi–xv, and Fe xvi–xxvii were treated with abundances given by Morrison & McCammon (1983). The depth of the slab was increased as the illuminating flux was increased and had a minimum value of 6 Thomson depths and a maximum of 30 Thomson depths.

When the irradiated material reached thermal and ionization equilibrium, the angle-averaged reprocessed emission from the gas was calculated. As with all photoionized gas, the reflection spectrum can be characterized by an ionization parameter:

$$\xi = \frac{4\pi F_X}{n_H},$$

where $F_X$ is the incident flux between 0.01 and 100 keV, the energy range of the illuminating continuum. $\xi$ was varied by changing only the value of $F_X$. The evolution of the reflection spectrum with $\xi$ has been discussed by Ross et al. (1999). Here we calculate reflection spectra for $\log(\xi) = 1.0–6.0$ while also varying the Fe abundance from 0.1–10.1 times solar. When the illuminated gas is predominantly neutral, the Fe Kα line may be affected by variations in other metals, particularly oxygen (Matt et al. 1997). Of course, when $\log(\xi) \gtrsim 2.8$ all the metals other than Fe are fully ionized and will have little effect on the Fe emission lines. Therefore, we do not consider abundance effects due to other metals, and instead refer readers to Matt et al. (1997) where such results are presented for neutral reflectors. The iron emission features will also depend slightly on the slope of the incident continuum (due to the different number of ionizing photons), so we have performed these computations for $\Gamma = 1.7, 2.0$ and 2.3 to illustrate this effect.

The EWs were calculated by the following integral:

$$\text{EW} = \int_{5.5\text{ keV}}^{7.1\text{ keV}} \frac{E F_x(E) - E F_x(E)}{E F_x(E)} dE,$$

where $E F_x(E)$ is the spectral flux of the reflected spectrum, and $E F_x(E)$ is the estimated spectral flux of the continuum at energy $E$. The continuum was estimated by fitting a straight line to the reflection spectrum between 5.50 and 7.11 keV. The lower limit of the integration was chosen to take into account any Compton broadening of the line profile, and the upper limit was set to the energy of the photoelectric absorption edge of neutral Fe. Dividing the line-flux by the monochromatic continuum at 6.4 or 6.7 keV makes a negligible difference to the contour plots. Figure 1 shows several examples of this calculation at different $\xi$.

3 RESULTS

Figure 3 shows contours of constant Fe Kα EW in the $\log(\xi)$–Fe abundance plane for the case where the incident power-law has not been added to the reflected spectra, as if the reflected spectrum were viewed in isolation. Therefore, these EWs are the maximum that can be observed as they are not diluted by the incident power-law. Such reflection-dominated spectra may be observed in Seyfert 2 galaxies (e.g., NGC 6552; Reynolds et al. 1994). The plots show that the Fe Kα EW reaches two separate maxima in the vertical direction: one when the ionization parameter is low and the line is at 6.4 keV, and the other at $\log(\xi) \sim 3$ when the line is at 6.7 keV. Between these two maxima the line is suppressed due to Auger destruction (Ross, Fabian & Brandt 1996), and at higher $\xi$ the line weakens and disappears as all the iron becomes ionized.

Increasing the iron abundance does increase the Fe Kα EW, but, as is discussed in Sect. 4, its effect is greatest when the abundance is still relatively low. Nevertheless, Fig. 3 shows that the line can get very strong ($> 6$ keV in some cases) at high Fe abundance with the largest values occurring when the line is neutral. As is shown below, this is reversed when the incident power-law is added to the reflection spectrum.

As $\Gamma$ is increased the number of Fe ionizing photons decreases. This causes the contours to spread out vertically in the plot, because at a higher $\Gamma$ a larger flux is needed to ionize Fe. When $\log(\xi) \lesssim 2.5$ and $\Gamma > 1.7$ the dependence on the Fe abundance weakens and the EW grows more slowly. Again, this is due to the decrease in the number of ionizing photons.

In many X-ray observations unprocessed radiation with the spectrum of the incident power-law is simultaneously detected along with the reflection spectrum. Therefore, we have repeated all the EW calculations for the total power-law+reflection spectra...
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Figure 2. Each panel shows contours of constant Fe Kα EW in the log ξ-Fe abundance plane. The different panels separate the three different values of Γ that were considered. The contours are at 200, 400, 800, 1600, 3200, 6400 eV and notice that only every second contour is labeled. The incident power-law was not added to the reflection spectra before the line was measured, therefore these EWs are the maximum possible under these circumstances.

(AGN workers think of this as a reflection fraction of unity). These results are shown in Figure 3. As before, two maxima are found in the contours: one when iron is neutral and the other when the He-like Fe Kα emission line at 6.7 keV is prominent. Likewise, the contours spread out vertically as the photon-index is increased. However, there are a number of differences between this set of plots and the previous one. The first one is trivial but important: the Fe Kα EWs are now much smaller. The largest values are now just over 800 eV and occur when log ξ ∼ 3. At low values of ξ the 6.4 keV line dominates, and the EW cannot exceed 400 eV. This turn-around between the (apparent) strength of the neutral and ionized lines when the incident spectrum is added in is caused by the effects of absorption by other elements in the gas. When the slab is weakly illuminated much of the flux around 6 keV is absorbed by other metals in the gas, particularly oxygen, and is re-emitted as softer X-rays. This results in a large difference in flux between the incidence spectrum and the reflected spectrum at 6 keV. In contrast, when log ξ ∼ 3 all the metals except for iron are almost completely ionized, so there is very little absorption around the Fe Kα line. Thus, when the reflection and incident spectra are added together, the He-like 6.7 keV line is more prominent than the neutral line.

To summarize, when iron abundances up to 10.1 × solar were considered, the maximum Fe Kα EW is about 8.5 keV and is found when the gas is neutral and illuminated by Γ = 1.7 power-law. In the case when the power-law is just simply added to the reflection spectrum (i.e., a reflection fraction of 1), the EWs are much smaller (< 1 keV) with the largest values being found when the gas is ionized and the 6.7 keV line of He-like Fe is dominant. In this case, it seems to be very difficult to obtain Fe Kα lines with EWs greater than 700 eV.
4 DISCUSSION

The results presented in the previous section showed that increasing the iron abundance would increase the Fe Kα EW, but its influence seemed to weaken as it grew. It is interesting to investigate this point since we have only considered abundances up to 10.1× solar. Is it possible to obtain an arbitrarily large EW solely by increasing the Fe abundance?

The answer to this question is found in Figure 4. This plot shows contours of Fe Kα EW normalized by the Fe abundance for the case of Γ = 2.0 and a reflection fraction of one. In this case the contours show a maximum at low Fe abundance implying that the most “power” out of an Fe atom or ion occurs when its abundance is around solar. Increasing the amount of iron in the gas does permit the number of Fe Kα photons emitted to increase, but it also strengthens the line destruction mechanisms of photoabsorption and scattering. Therefore, for a given flux of ionizing photons, competing atomic processes in the gas eventually decreases the efficiency of iron fluorescence. This is seen particularly when the gas is neutral: the normalized Fe Kα EW falls slowly over a wide range in Fe abundance because Kα photons are destroyed by L shell absorption.

At higher values of the ionization parameter, there is a more rapid drop in the normalized Fe Kα EW. As is illustrated explicitly in Figure 3, an increase in the iron abundance from 1.1 to 5.1× solar causes a fairly big jump in the line strength, but then only a very small change from 5.1 to 10.1× solar. In this case, only K shell absorption is important, but due to the finite number of ionizing photons, the K edge will saturate when the Fe abundance is about solar (from Fig. 4). Increasing the Fe abundance beyond this...
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Figure 4. Contours of (Fe Kα EW/Fe abundance) in the log ξ-Fe abundance plane. The EWs were calculated using the total incident+reflected spectra and we only show the case of Γ = 2.0. The contour lines are at 50, 100, 200, 300, 500, 700 eV. The effect of increasing the iron abundance is greatest when it is less than 3× solar and when the slab is ionized.

point will not greatly increase the line emission because there are few photons available to ionize the newly introduced Fe atoms. Of course, increasing ξ allows more K shell ionizations to occur, and the normalized EW becomes more uniform with Fe abundance. Interestingly, the H-like Fe Kα line at 6.97 keV which is suppressed due to resonance scattering significantly strengthens as the abundance is increased.

These results illustrate that above an Fe abundance of ~ 5× solar there is only a very slow increase in the Fe Kα EW. Therefore, it seems unlikely that the EW of the line can be significantly increased by considering iron abundances larger than 10× solar.

ACKNOWLEDGMENTS

DRB acknowledges financial support from the Commonwealth Scholarship and Fellowship Plan and the Natural Sciences and Engineering Research Council of Canada. ACF and RRR acknowledge support from the Royal Society and the College of the Holy Cross, respectively. ACF and RRR thank A. Young for his work on this project.

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Figure 5. Explicit examples of how the Fe Kα line changes with Fe abundance. Total incident-reflection spectra are plotted for the three different values of Φ and three representative values of ξ. Reflection from a slab with a 1.1, 5.1 and 10.1× solar Fe abundance is plotted as the solid, short-dashed and long-dashed lines, respectively.

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