The Future of Fe-K Line Diagnostics for Probing Strong Gravity

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Abstract. We review what we have learnt with ASCA from studying the Fe-K lines in AGN and describe a program to deconvolve the narrow, non-disk components of the lines with Chandra. This is necessary to derive the correct profiles of the broad, relativistic lines obtained using data from XMM and other high-throughput instruments. Since reverberation techniques are now not looking promising, we present Constellation-X simulations showing an alternative way we might be able to measure black-hole mass and spin.

1. The Fe-K Lines in AGN

Given the potential of the Fe-K line in AGN to yield constraints on black-hole mass and spin (e.g. Fabian et al. 2000), what have we actually learnt so far? One thing which has been clear since soon after the launch of ASCA in 1993, is that there is a large variety of line profiles. In some objects the line is very broad while in others it is not so broad. Obviously it is the broadest lines that have the potential for measuring black-hole parameters since the broadening is believed to be due to extreme Doppler and gravitational energy shifts close to the hole. Unfortunately only a handful of AGN are bright enough to yield ASCA data with sufficient signal-to-noise to provide useful constraints on models of the Fe-K line profile generated in an accretion disk rotating around a black hole. For these, time-averaged spectra can produce fairly tight constraints on the disk inclination angle but this parameter is degenerate with the rest energy of the line. Unless the line is not very broad, we cannot constrain the rest energy of the line. Thus, even in MCG−6−30−15, we cannot yet tell from the Fe-K line profile what the dominant species of Fe ions in the disk are. Since we have little information on what the radial distribution of Fe-K line emission from the disk is, the shape of the line between the extreme energies of the profile does not yet provide useful constraints.

We do not even know whether the line emission is axisymmetric. If the fluorescent Fe-K line is energized by local flares on the disk (as opposed to a central source), it is likely not to be axisymmetric. Moreover, we can only constrain the inner radius in a few cases. If the Fe-K line is not very broad we can get a lower limit on the radius of the line-emitting region (below this the disk may be completely ionized or non-existent). If the Fe-K line is extremely broad or redshifted, we may deduce an upper limit on the smallest radius contributing
to line emission. On two occasions (∼ 40 ks episodes in ASCA observations of MCG−6−30−15) it has been possible to deduce that the inner radius is inside the marginally stable orbit of a Schwarzschild black hole. Whether this provides evidence for a Kerr hole has been debated. Robust and unambiguous, model-independent measurements of black-hole spin, one of the ultimate goals of these studies, has not yet been achieved.

Nonaxisymmetric events are also a likely factor in accounting for another major result that has come out of Fe-K line studies. That is, rarely does the line intensity (and shape, when it can be measured) respond to changes in the continuum in a way which would be expected from a simple unionized uniform disk responding to the luminosity variations of a single, localized continuum source, or one which uniformly covers the whole disk (e.g. Reynolds 2000; Vaughan & Edelson 2001). Ionization of the disk could also play a role but whether this is the case or not, reverberation techniques to measure the black-hole mass and spin will not be possible until we understand the physics of the line variability. When we do, reverberation mapping of the disk using the Fe-K line may be impractical even with Constellation-X.

2. Deconvolving the Narrow, Non-relativistic Fe-K Line

Table 1. The Narrow Fe-K Line Component in Some AGN

| Source  | $E_{\text{Fe-K}}$ (keV) | EW (eV) | FWHM (km/s) |
|---------|------------------------|--------|-------------|
| NGC 5548 | 6.402 (+0.027, −0.025) | 133 (+62, −54) | < 8040 |
| NGC 3783 | 6.347 (+0.050, −0.021) | 86 (+35, −28) | < 6665 |
| NGC 4151 | 6.386 (+0.014, −0.016) | 330 (+63, −67) | < 8169 |
| Mkn 509  | 6.389 (+0.082, −0.030) | 61 (+35, −21) | < 6290 |
| NGC 4051 | 6.4 (fixed) | 135 (+57, −53) | - |
| NGC 3327 | 6.4 (fixed) | < 85 | - |
| 3C 273   | 6.4 (fixed) | < 25 | - |

The Chandra HETG, combined with a high-throughput instrument such as EPIC/XMM, or PCA/RXTE, currently offers the best possibility of deconvolving any component of the Fe-K line which originates far from the central black hole. Since the EW of such a narrow component can be a significant fraction of the total Fe-K line emission, it is important to measure, in order to correctly model the relativistic component (see Yaqoob et al. 2001; Reeves et al., these proceedings). Table 1 shows some preliminary Chandra measurements for some AGN (errors and upper limits are for 90% confidence, one parameter; energies are in the rest-frame). We have initiated a program to simultaneously measure the Fe-K line profiles of the brightest AGN with the strongest Fe-K lines using Chandra and/or RXTE and/or XMM, results of which will be forthcoming.

Figure 1 shows the HEG data directly against (non-simultaneous) ASCA data for four of these sources. Note that in some cases, such as 3C 273, a narrow component is weak or absent. It is likely that the narrow component does not vary on timescales of weeks or perhaps much longer. However, we do not know, and should attempt to constrain the variability with ASTRO-E2 and even XMM in some cases. Even if the narrow component varies, folding the Chandra results
back into non-simultaneous ASCA (or XMM) data is still useful because it is unlikely that the energy and width of the narrow Fe-K line varies.

3. Measuring Black-Hole Spin

Suppose there is an enhancement of the Fe-K line emission from the disk at a few gravitational radii out from the marginally stable orbit, due to a local magnetic flare. Further suppose that this hot spot co-rotates with the disk for at least one orbit. The result is that if we examine the time-averaged line profile over the whole disk, the enhanced annulus will produce two very sharp spikes corresponding to the extreme red and blueshifts. They are sharp because the annulus is thin. The energies of these spikes are a function of the black-hole spin ($a$), the inclination angle of the disk ($\theta$), and the radius of the annulus ($r$).

We can obtain $\theta$ from the overall line profile. That leaves two unknowns ($a$, $r$) and two observables (the energies of the spikes). Hence we can measure $a$. The largest uncertainty will be the rest energy of the Fe-K line. Simulations show that Constellation-X will easily be able to measure the energies of these spikes, superimposed on the overall line profile. For example, Figure 2 shows a 40 ks simulation of an AGN in which $r = 6.5r_g$, $a = 0$, and $\theta = 10^\circ$; the 2–10 keV flux is $9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The EW of the overall Fe-K line is 300 eV and the hot spot contains only a mere 10% of the total line emission. How will we know whether we have integrated over more than one orbit? We could split the observation, into two, for example. The positions of the spikes should not change. The Keplerian orbital timescale is $314(r/r_g)^{3/4} M_7$ s ($r_g \equiv GM/c^2$). For $M_7 = 1$, at $6r_g$ this is 4.6 ks and at $30r_g$ it is 50 ks. For $a > 0$ these timescales will be shorter, corresponding to smaller inner disk radii.

If such hot spots exist, the advantage of this method for measuring spin is that it does not rely on having to compute the detailed transfer function of
the disk in the face of complex ionization physics, nor on knowledge of the line-emissivity function over the disk. Note that measuring the extrema of the main profile to obtain the same information is not practical. Even future missions will have trouble distinguishing the low-energy end of the Fe-K line from the continuum. In contrast the narrow spikes will be easy to measure. Time-resolved ASCA spectra show evidence that these may exist, although the bumps and wiggles which come and go are at the $2 - 3\sigma$ level (e.g. Wang, Wang, & Zhou 2001). XMM should be able to pull them out of the noise if they are real.

With Constellation-X, we could time-resolve the data into intervals as small as the statistics allow and follow the energy of the narrow line from the hot spot as it rotates, as suggested by Nayakshin & Kazanas (2001). This will directly constrain the black-hole mass. Sensitivity to this depends on the size of the hot spot (i.e. width of the line). For example, taking a Gaussian with $\sigma = 20$ eV, and the same parameters as in the time-averaged model above, simulations show that $\sim 500$ s intervals with Constellation-X will yield robust measurements of the line energy in each time frame, with a 90% confidence error of only 3 eV.

I thank my collaborators, I. George, J. Turner, K. Nandra, K. Weaver, & J. Gelbord.

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Figure 2. 40 ks Con-X simulation of a 10% intensity hot spot.