Iron K Line Diagnostics in Active Galactic Nuclei

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**Abstract.** We discuss some topical issues related to the study of Fe K emission lines in Active Galactic Nuclei (AGNs). We show remarkable agreement between non-contemporaneous ASCA and Chandra grating data and explain why there has been terrible confusion about the ASCA and post-ASCA results on the relativistic components of the Fe K line emission. We point out that in fact the number of sources (not the percentage) that have been reported to exhibit relativistic effects in the Fe K line is now larger than it was in the ASCA era. Thus, the case for Constellation-X as a probe of strong gravity is even more compelling than it was a decade ago. One of the primary goals of these studies is to establish the foundations for future missions to map the spacetime metric around black holes. A prerequisite first step is to measure the black-hole angular momentum in a robust manner that does not rely on assumptions about the accreting system. In addition, probing the Fe K lines out to high redshifts will pave the way for studying the accretion history and evolution of supermassive black holes. However, we point out some issues that need to be resolved, pertaining to spin measurement and to the relativistic Fe K line emission found from AGN in deep X-ray surveys.

1. **Introduction**

Black holes have “no hair” and have only three measurable parameters (not including the Hawking temperature): charge, mass, and angular momentum. We do not yet know how to measure the charge. Measurements of black-hole mass are well underway and constitute a field in itself and we do not discuss it here (e.g., see Peterson & Bentz 2006, and references therein). That leaves black-hole angular momentum, or spin. This is a property of the space-time metric, and measurement of the spin would be a first step towards mapping the metric. If one cannot measure the spin there is little hope of mapping the metric in order to compare with the predictions of general relativity (or other theories of gravity).

Currently, detailed Fe K line spectroscopy is limited to low-redshift AGNs, plus a handful of high-redshift objects. Eventually we would like to be able to routinely measure the black-hole spin for AGNs out to all observable redshifts. The spin may be a function of some other physical property of accreting black-hole systems that may also be time-dependent and evolving. For example, according to Thorne (1974), disk accretion increases the angular momentum of a black-hole, reaching a maximal value of $a/M = 0.9982$ (but see Gammie, Shapiro, & McKinney 2004). Thus, the Fe K line emission in AGN could even-
Figure 1. Left: (a) The mean ASCA Fe K line profile (see Yaqoob et al. 2002). Middle: (b) The ASCA (AO6) Fe K line profile of 3C 120 (solid) compared with (a). Right: (c) The highest luminosity, highest redshift ($z = 0.297$) radio-quiet AGN with a reported Fe K line ($E1821+643$). Note the redshifted absorption line in $E1821+643$ (see Yaqoob & Serlemitsos 2005).

Eventually be used to study accretion in a cosmological context, in particular the accretion history, and the evolution of accreting black holes.

The Fe K emission line is also a probe of the physics and structure of the accretion flow itself. In particular, the inclination angle of the disk with respect to the observer, the ionization state of the disk (and its dependence on the source X-ray luminosity and accretion rate), and its inner radius are important physical properties that still remain largely elusive. Finally, the narrow Fe K line emission from more distant matter beyond the accretion disk carries important information on the structure and physical state of matter in the outer regions of the AGN central engine, possibly originating from the putative parsec-scale “obscuring torus” that is a key component of standard AGN unification schemes.

Although relativistic Fe K lines are observed in X-ray binaries (e.g. see Miller 2006, and references therein) and do not suffer from the problem of deconvolution from a distant-matter Fe K line, in this work we focus on AGNs.

2. Did the ASCA Broad Fe K Lines Go Away?

Since the first reports of the observation of relativistically broadened Fe K emission lines in AGN, many studies have been done of the same and additional sources using BeppoSAX (e.g. Perola et al. 2002), XMM-Newton (e.g. Reynolds & Nowak 2003; Page et al. 2004; Porquet et al. 2004; Jiménez-Bailón et al. 2005; Fabian and Miniutti 2005; Jiang, Wang & Wang 2006 and references therein), and Suzaku (e.g. Miniutti et al. 2006; Reeves et al. 2006; Yaqoob et al. 2006). There is a myth that the post-ASCA results are somehow inconsistent with ASCA, and that the broad Fe K lines are less common than ASCA had found. Lubiński & Zdziarski (2001) began the important process of re-examining the ASCA data. Changes in the ASCA calibration were shown to have a negligible impact on the Fe K line profiles (Yaqoob et al. 2002), yet the myth and confusion still prevail.

The myth arose because, given the currently available data (ASCA and post-ASCA), the “percentage of AGN with a relativistically broadened Fe K line” is a model-dependent quantity that also depends on the criterion used to define “broad”. Despite many ASCA results appearing after Nandra et al. (1997 – hereafter, N97), it is this paper that the confusion is centered around. The
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claim in N97 was that fourteen out of eighteen type 1 AGN have a resolved Fe K line. “Resolved by ASCA” does not mean that all fourteen sources have an enormous red wing on the Fe K line as does MCG $-6-30-15$. The lines were parameterized by Gaussian models, the data were fitted between 3–10 keV only, and the broad Gaussian could in part be modeling complexity in the continuum (e.g. due to ionized absorption). Of these fourteen AGN at least four should not have been counted. NGC 7469 has a 68% confidence error (table 3 in N97) that does not exclude the line being unresolved. Interestingly, the line profile has a strong blue wing and virtually no red wing. For NGC 6814, the signal-to-noise is so low that no actual line is apparent in the spectrum and the Gaussian component was in fact modeling the continuum. The signal-to-noise in the brighter Mkn 841 observation was also too low to distinguish line emission from continuum emission - this can be seen by eye. The line profile for NGC 5548 shows a small excess on the blue side of the peak but, after accounting for the spectral resolution, there appears to be no excess on the red side. We note that excess emission blue-ward of the Fe K line peak can be caused by complexity in the continuum. For example, it can clearly be seen from the photoionization models applied to MCG $-6-30-15$ by Lee et al. (2001) that continuum curvature and edge features are apparent all the way up to the Fe K band and are not just restricted to below 3 keV. Thus, we are left with ten or less possible broad lines in the ASCA sample and this corresponds to 56% or less. This is not inconsistent with post-ASCA results. Guainazzi, Bianchi, & Dovčiak (2006) found that $\sim 25 - 50\%$ of low-redshift AGN show broad relativistic lines, the actual value depending on sample selection (see also Nandra et al. 2006). Model-dependence of the broad-line detections and measurements contributes additional uncertainty. If post-ASCA results are compared with the ASCA results on a source-by-source basis, as opposed to some sample property or mean line profile, no problem arises.

Another factor is over-interpretation of mean Fe K line profiles from the ASCA sample. Figure 1a shows a later version of one of the mean profiles in N97 (see Yaqoob et al. 2002 for details). It excludes MCG $-6-30-15$, NGC 4151, and NGC 6814 (the latter because it is so dim). There is a red wing but it is weak and its relative strength is sensitive to the continuum level. However, the version of the profile that most people associate with ASCA is the one that did not exclude the above three sources and shows a much stronger red wing, biased by MCG $-6-30-15$ and NGC 4151. Although N97 showed a profile excluding these latter two (that is consistent with Figure 1a), it is not the version people recall. However, we emphasize that there are now a larger number of AGN with reported broad Fe K lines than in the ASCA era even though that number as a fraction of a class may have been revised. There are still strong candidates in the original ASCA sample. Figure 1b shows the Fe K line profile from an ASCA AO6 observation of 3C 120 (N97 used a shorter, AO1 observation). These data show one of the broadest lines in the sample (but this is not a unique interpretation). A significant number of new broad Fe K lines have been found with post-ASCA data. Figure 1c shows the (broad) Fe K line profile found in the highest luminosity, highest redshift quasar yet, $E 1821 + 643$ ($z=0.297, L_{2-10\text{ keV}} \sim 3 \times 10^{45}$ ergs s$^{-1}$; see Fang et al. 2002; Yaqoob & Serlemitsos 2005).
Figure 2. The Chandra High Energy Grating (HEG) Fe K line profiles for twelve AGN in the Yaqoob & Padmanabhan (2004) sample (black) compared with non-contemporaneous ASCA data (red).

Figure 2 shows heavily binned Chandra High Energy Grating (HEG) data directly compared to ASCA data for twelve type 1 AGN. The spectral resolution of the HEG data is $\sim 1800$ km s$^{-1}$ FWHM but here we have binned it to approximately CCD resolution. All except Mkn 279 were members of the N97 sample and all are members of the Chandra HEG sample of Yaqoob & Padmanabhan (2004) in which the Fe K line core was studied. In cases where there were multiple ASCA observations, only the highest signal-to-noise observation is shown in Figure 2. The data/model ratios in Figure 2 were made by fitting the
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3–10 keV band with a simple power law continuum, but excluding the 5–7 keV data. What is remarkable about Figure 2 is that even though the ASCA and Chandra observations were not contemporaneous (typically separated by years), the apparent ASCA and Chandra Fe K line profiles are largely consistent with each other, except for some energy regions in a few sources. The ASCA data were not flawed. Although most of the Fe K line profiles in Figure 2 appear to be broad, this does not of course prove that broad Fe K lines are present because the continuum is not modeled. One needs to model the continuum rigorously in order to determine any conclusions about the Fe K line parameters. Certainly, however one chooses to model the ASCA data, the Chandra data can in general be fitted well with that same model.

3. The Deconvolution Problem

In general, that part of the Fe K line emission from a relativistic accretion disk that is near the line rest-frame energy (e.g. from the outer regions and/or line-emission observed at small inclination angles to the disk normal) is degenerate with line emission from distant matter (e.g. see Weaver & Reynolds 1998). MCG –6–30–15 is one of the exceptions, having a narrow Fe K line that is relatively weak. Although the Chandra HEG has the best spectral resolution, it is challenged by a small effective area. Some progress in decoupling the broad and narrow Fe K line intensities has been made with CCD data, but the narrow line is then even harder to resolve (e.g. Reeves et al. 2006; Yaqoob et al. 2006).

The origin of the distant-matter Fe K emission line remains elusive. The peak line energies can be measured extremely well and strong clustering around 6.4 keV indicates that the Fe is not highly ionized (e.g. Sulentic et al. 1998; Yaqoob & Padmanabhan 2004). If the Fe Kβ line is detected with a good signal-to-noise ratio, the ionization state of Fe can be determined to a very high precision due to the redundancy of information (e.g. see Yaqoob et al. 2006). The Fe K line core widths measured by even the Chandra gratings may still be affected by a contribution from any underlying broad Fe K line emission. Nevertheless, in specific cases where one can show that the Fe K line width is less than the optical, BLR line width (such as that of Hβ) with a high statistical significance, one can deduce that the distant-matter line in such sources originates in matter farther out than the BLR. Nandra (2006) illustrates some key examples, which are actually more important than the lack of a correlation between the Fe K and Hβ line widths. It is often argued that a Compton-thin origin for the distant-matter Fe K line is ruled out because the EW of the line is too large but this argument assumes a time-steady situation over many years. However, in any individual case it is not usually possible to rule out continuum-line time delays as the cause for an artificially high EW. Higher effective area as well as spectral resolution is needed to unambiguously measure or rule out a “Compton-shoulder” in order to further constrain the origin.

4. Disk Ionization and Other Suppressors of Relativistic Lines

When a broad Fe K emission line is detected, given the current typical signal-to-noise ratio even of XMM-Newton and Suzaku data, it is not generally possible
to robustly constrain the rest-frame energy of the line (and therefore the ionization state of the relativistic line-emitting matter). This is because there is degeneracy between the line rest energy and the disk inclination angle and, to some extent, the line radial emissivity function. The notion that the broad relativistic Fe K lines originate predominantly in cold, neutral matter is another myth. When disk-line plus Gaussian models are fitted to data, the disk-line rest energy generally has to be assumed and cannot be derived.

There are notable cases where a peak in the Fe K complex is clearly higher than 6.4 keV and indicative of highly ionized Fe. Obviously, for such line energy constraints to be measurable, these emission lines that are unambiguously from ionized Fe are never too broad – if they were they could be modeled with disk lines from neutral Fe with parameters that make the apparent line centroid shift to higher energies. In other cases, XMM-Newton or Chandra (grating) data reveal that what was previously thought to be a single, broad line is in fact composed of multiple narrower lines, involving multiple ionization stages of Fe (e.g. see Bianchi et al. 2005, and references therein). These narrow lines do not necessarily originate from distant matter, based on variability and/or redshifting (e.g. see Turner et al. 2002; Petrucci et al. 2002; Yaqoob et al. 2003). It also appears to be the case that Fe K emission lines from highly ionized Fe are more likely to be found in NLS1s (Dewangan 2002), which have steeper hard X-ray continua than “regular” Seyfert 1 galaxies.

The fact that there are a significant number of radio-quiet, low-luminosity AGN that have no detected broad Fe K line but have sufficient signal-to-noise to place tight upper limits on the EW of such a line (e.g. Guainazzi et al. 2006 and references therein) implies that there is an important factor missing in our understanding. The explanation often invoked is that the accretion disk is truncated so that the Fe K line emission does not extend down to small enough radii to cause sufficient line broadening (e.g. see Müller & Camenzind 2004; Matt et al. 2005, and references therein). The truncation may be real or apparent (for example if the Fe in the innermost region of the disk is completely ionized). Either way, this does not address the question of what the fundamental driver is that causes the apparent truncation. The answer may not be simple because there are examples of radio-quiet high-luminosity AGN that do have broad Fe K lines (see §5), yet ionized disks are usually invoked to explain the lack of broad Fe K lines in high-luminosity AGN. An effect that has not received much attention is that if a broad Fe K line emitted by a disk encounters a hot corona with sufficient optical depth on the way to the observer, it may be broadened so much that it may be undetectable against the continuum. We emphasize that in order to obtain a complete understanding of the broad Fe K lines that are detected, it will be just as important for future missions such as Constellation-X to observe the AGN in which no broad line is currently detected.

5. High Luminosity and High Redshift

The Fe K emission lines (broad or narrow) in AGN become scarce at high luminosity \((L_{2-10\,\text{keV}} > 10^{44}\,\text{ergs s}^{-1}\) or so\) and at redshifts higher than \(\sim 0.1\) or so. The apparent anti-correlation of the Fe K emission line EW with the X-ray continuum luminosity has been dubbed the “X-ray Baldwin effect” (Iwa-
sawa & Taniguchi 1993) and has been revisited many times (e.g. Jiang et al. 2006, and references therein). However, both the measurement errors for the EW, and the scatter in the correlation are large. Also, the highest luminosity AGN that have had pointed X-ray observations tend to be mostly radio loud. The presence of strong Fe K lines in the high luminosity radio-quiet quasars E 1821+643 (e.g. Fang et al. 2002; Yaqoob & Serlemitsos 2005) and Q0056−363 (Matt et al. 2005) destroys the X-ray Baldwin effect, at least for radio-quiet AGN. E 1821+643 (z = 0.297) has $L_{\text{2-10 keV}} \sim 3 \times 10^{45}$ ergs s$^{-1}$ so it is the highest redshift, highest luminosity individual AGN known that has a broad Fe K emission line (see Figure 1c). In comparison, Q0056−363 (z = 0.162) has $L_{\text{2-10 keV}} \sim 2 \times 10^{44}$ ergs s$^{-1}$. Thus, it appears that the X-ray Baldwin effect may only be telling us that radio-loud AGN have weak or no Fe K line emission. For radio-quiet AGN there appears to be no relation between the EW of the Fe K line and X-ray continuum luminosity. The EW of the Fe K line in E 1821+643 is $209^{+51}_{-57}$ eV (Yaqoob & Serlemitsos 2005) which is comparable to (actually larger than) the typical EW for AGN with luminosities at the low end of the range, $L_{\text{2-10 keV}} \sim 10^{42}$ ergs s$^{-1}$ (e.g. see Page et al. 2004).

6. The Fe K Line in the Cosmological Context

Figure 3. Monte Carlo simulations of XMM-Newton spectra of 200 AGN with a range in cosmological redshift. Left: (a) Input spectra with a narrow, unresolved Fe K emission line. Middle: (b) Data to power-law model ratio for mean spectrum made using conventional methods: the spectral features are artifacts of the averaging procedure. Right: (c) As (b) but using the new averaging procedure in Yaqoob (2006). The narrow Fe K line is recovered.

The finding of broad relativistic Fe K lines in the spectra of high-redshift sources found in deep X-ray surveys would represent an extremely important milestone because one could then use them to study the history and evolution of accreting black holes. Streblyanska et al. (2005) have presented evidence for such from the summed spectra of both type 1 and type 2 AGN found in the Lockman Hole with XMM-Newton (each source was too weak to yield line detection in any individual source). The peak redshifts were $\sim 1.7$ for the type 1 AGN and $\sim 0.7$ for the type 2 AGN respectively. However, there is a fundamental problem with summing low signal-to-noise spectra over a range of redshifts. This can introduce artificial features into the mean spectrum that look just like relativistic line broadening and a hard tail, mimicking a Compton reflection continuum (see Yaqoob 2006). For example, Figure 3 shows the result
of XMM-Newton Monte Carlo simulations of 200 type 1 AGN with a redshift distribution similar to that of the Streblyanska et al. (2005) sample, but with input spectra that were simple power laws, with only narrow, unresolved, Fe K emission lines. A new averaging method is given in Yaqoob (2006) and Figure 3c shows that it successfully recovers the input narrow line. The new method should now be applied to real data. Brusa, Gilli, & Comastri (2005) studied Fe K lines from Chandra deep field sources, but summed the data in the observed frame so they could not measure intrinsic line widths.

7. Black-Hole Angular Momentum

A fundamental problem in measuring black-hole spin from the Fe K emission lines is that the radial emissivity of the Fe K line from the accretion disk is unknown. This leads to ambiguity in $a/M$. All claims to measure or constrain $a/M$ so far are based on the argument that there is no Fe K line emission inside the radius of marginal stability (which varies from $6r_g$ for $a/M = 0$ to $1.23r_g$ for $a/M = 0.9982$), and that at $6r_g$ one cannot get a large enough gravitational redshift to account for the strength of the red wing in MCG −6−30−15. Combined with assumptions about the radial emissivity, this can lead one to derive near-maximal values of $a/M$ with tiny statistical errors. However, Figure 4a (solid line) shows that at $6r_g$, even for $a/M=0$, a 6.4 keV line can be redshifted down to $\sim 3.7$ keV (for a disk inclination angle of $\theta_0 = 30^\circ$; even lower energies are possible for greater $\theta_0$ – see e.g. Zakharov & Repin 2006). Even with the highest signal-to-noise data currently available it is difficult to tell where the Fe K line profile joins the continuum at low energies in a model-independent way. Thus, a Schwarzschild black hole can produce a large enough redshift, without invoking line emission inside the marginally stable radius, or plunge region.

From a $\sim 290$ ks XMM-Newton spectrum for MCG −6−30−15 Dovciak, Karas, & Yaqoob (2004) first derived constraints on $a/M$ from the counts spectrum (as opposed to unfolded spectra which already assume a value for $a/M$). From one of the classes of models fitted, Figure 4b shows confidence contours of...
\[ \theta_0 \text{ versus } a/M, \text{ and they are flat, covering all possible values of } a/M \text{ from 0 to 1.} \]

Details of the model and parameters can be found in Dovčiak et al. (2004) but note that the best-fit inner disk radius was \((7.0 \pm 0.2)r_g – \text{i.e. not inside the plunge region. Fe K line emission inside the plunge region (e.g. Krolik \\& Hawley 2002) may indeed be expected to be weak (e.g. Brenneman \\& Reynolds 2006, and references therein) but the reduction in line emission with radius must be quantified. To demonstrate why this is important, Figure 4c shows a “devil’s advocate” solution to the same data. It has a Schwarzschild black hole \((a/M = 0), \text{ and no emission inside } 6r_g \text{ (the outer radius fitted is } \sim 7r_g)\). Obviously this is too simplistic but any radial emissivity profile that provides sufficient enhancement near \(6r_g \text{ will work. This kind of scenario must be shot down first before measurements of } a/M \text{ can be placed on a robust footing. The model includes a complex photoionized absorber and relativistically blurred Compton reflection consistent with the emission line.}

In order to robustly constrain black-hole spin using Constellation-X we need to utilize information that is not all radially integrated over the disk and that does not require knowledge of how the Fe K line responds to the X-ray continuum. One can constrain \(\theta_0\) from the persistent, time-averaged line profile. Then one can probe azimuthal, non-axisymmetric enhancements in the line emission by time-slicing and look for events in which the extreme centroids (say \(E_- \text{ and } E_+\)) of such hotspots (located at a radius \(r\)) could be measured on their orbit (other scenarios such as spiral density wave enhancements also may be relevant – see Fukumura \\& Tsuruta 2004). In addition, if the signal-to-noise is sufficiently high to measure the broad Fe K\(\beta\) line parameters, one could obtain reasonable constraints on \(E_0\). Then one has four observables, two unknowns, and two equations: \(E_\pm = f_\pm(r, a/M, \theta_0, E_0)\), so that one could in principle determine \(a/M\). Even with one piece of information missing one could obtain constraints on \(r\) versus \(a/M\). The method does not require: (1) any knowledge of the line radial emissivity function; (2) the continuum to behave in a certain way, and (3) an understanding of how the line emission responds to continuum variability (it is not reverberation). Such calculations have been discussed at length in the literature (e.g. Nayakshin \\& Kazanas 2001; Pecháček et al. 2005, and references therein) and observational evidence from currently available data for the sought-after non-axisymmetric enhancements is now accumulating fast (e.g. see Turner et al. 2002, 2006; Iwasawa, Miniutti, \\& Fabian 2004; Fabian \\& Miniutti 2005). Along with the sources that show persistent broad Fe K lines, the number of AGN exhibiting relativistic effects in the X-ray spectra is larger now than it was in the ASCA era, making the case for Constellation-X as a probe of strong gravity more compelling than ever.

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