IRON K LINE EMISSION IN AGN: OBSERVATIONS

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ABSTRACT Iron Kα lines are key diagnostics of the central regions of AGN. Their profiles indicate that they are formed deep in the potential well of the central black hole, where extreme broadening and red shift occur. The profiles are most easily reproducible in an accretion disk: the lack of significant emission blue-ward of the rest energy is difficult produce in other geometries. In one source an apparent (and perhaps variable) absorption feature in the red wing of the line may represent rare evidence for inflow onto the black hole. Sample analysis has defined the mean properties, showing a strong concentration of the emission in the central regions and face-on accretion disks, at least in Seyfert 1 galaxies. Surprising results have been obtained from examination of the line variability. Strong profile changes may be accounted for by changes in the illumination pattern of the central, relativistic part of the disk. In at least the case of MCG-6-30-15, there is evidence for emission from within 6R_g, possibly indicating a spinning black hole. Developing an understanding of these complex changes has the potential to reveal the geometry and kinematics of the inner few gravitational radii around extragalactic black holes.

KEYWORDS: accretion, accretion disks; line:profiles; galaxies: active; galaxies: Seyfert

1. INTRODUCTION

The first iron Kα lines were discovered in NGC 4151, and a few source with large absorbing columns, in which the line was thought to originate ((Mushotzky, Holt & Serlemitsos 1978; Mushotzky 1982). The first unobscured AGN to show line emission was MCG-6-30-15 (Nandra et al. 1989; Matsuoka et al. 1990) and Ginga subsequently found iron Kα emission to be extremely common in Seyfert galaxies (Pounds et al. 1990; Nandra & Pounds 1994). Line emission had been predicted from optically-thick material close to the nucleus (Guilbert & Rees 1988), including the accretion disk (Fabian et al. 1989). Detailed predictions of the line strength from the disk (George & Fabian 1991; Matt, Perola & Piro 1991) were found to be in excellent agreement with the observations (Nandra & Pounds 1994), but the Ginga data were unable to determine the width or profile of these lines. This is of clear importance, as the profiles allow the location and geometry of the material to be constrained. Specifically, in the case of an accretion disk, large widths and distinctive profiles are expected due to the rotation and gravitational effects of the black hole (Fabian et al. 1989; Stella 1990; Laor 1991; Matt et al. 1992). The launch
FIGURE 1. Iron Kα profiles for MCG-6-30-15 (left panel; Tanaka et al. 1995) and NGC 3516 (right panel; Nandra et al. 1999). The ASCA SIS data, derived from interpolating a local continuum, are shown as the crosses. The profiles for both sources are very similar, and are extremely broad. They exhibit a relatively-narrow core peaked at the rest energy of near-neutral iron ($\sim 6.4$ keV) and a very broad wing to lower energies. These profiles are characteristic of Doppler and gravitational effects in an accretion disk orbiting a black hole and the lines show various models of such emission, which fit the data extremely well. In NGC 3516, the best model includes an absorption line around 5.8 keV. This feature may be due to resonance scattering in material inflowing into the central regions.

of ASCA offered an opportunity to test these models, with the SIS detectors having good sensitivity and a factor $\sim 4$ improvement in energy resolution compared to Ginga.

2. PROFILES OF INDIVIDUAL SOURCES

The early ASCA data did indeed show evidence that the iron Kα lines in AGN were broad with velocity widths of $\sim 50,000$ km s$^{-1}$, characteristic of material extremely close to the central black hole (Fabian et al. 1994; Mushotzky et al. 1995). Uncertainties in calibration, limited sensitivity above $\sim 7$ keV and the short exposures of these early observations made it difficult to determine the profiles, however. Long observations have provided the best constraints:

**MCG-6-30-15:** The first high signal-to-noise ratio profile was obtained in a $\sim 150$ ks observation of the Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al. 1995). These data provided strong confirmation of the hypothesis that the iron Kα line arises from the inner accretion disk (Fig. 1). The profile is extremely broad, with FWZI$\sim 0.3c$, and is skewed to the red. This is characteristic of accretion disk models in which the disk is observed close to face-on, where the dominant broadening process is the strong gravitational field of the black hole, rather than Doppler motions. Indeed,
the particular characteristics of the line in MCG-6-30-15 are extremely difficult to explain without the invocation of a black hole and accretion disk (see, e.g. Fabian et al. 1995). The line profile of MCG-6-30-15 has therefore rightly received much attention and scrutiny, as it presents arguably the most direct evidence we have for the existence of black holes in active galaxies. The broad profile in MCG-6-30-15 has been confirmed by BeppoSax (Guainazzi et al. 1999).

**NGC 4151:** Yaqoob et al. (1995) presented a profile very similar to MCG-6-30-15 for NGC 4151, based on another long ASCA exposure. In this case the origin of the line is less clear-cut, as the complexity of the continuum in NGC 4151 makes the line difficult to model (Zdziarski et al. 1996). Nonetheless, the similarity of the two profiles is highly suggestive of a common origin.

**NGC 3516:** A third example (Nandra et al. 1999; Fig. 1), which again shows a profile remarkably similar to MCG-6-30-15. Once more, an origin in a face-on accretion disk orbiting a black hole is indicated and in this case there is also evidence for an absorption feature in the red wing of the line. This feature may be due to resonance scattering by iron, redshifted from the rest energy. If the redshift is due to kinematic effects, this feature presents rare evidence for material inflowing into the black hole and could be an important tracer of accretion. The interpretation is not unique, however, as it is possible that redshift is gravitational, in which case it indicates that there may be an ionized “skin” above or around the accretion disk. Ruzkowski & Fabian (these proceedings) show that this also fits the data.

## 3. ACCRETION DISK MODELS

Fig. 1 shows various models of line emission from an accretion disk, which are used to fit the ASCA data. The disk line models such as those of Fabian et al. (1989) and Laor (1991) are characterized by a number of parameters, which can in principle be constrained by the data (Table 1). It has already been mentioned that the very red profiles of MCG-6-30-15 and NGC 3516 favor low inclinations for the disk. Because the emission tends to be centrally-concentrated, the inner radius of the disk is usually better constrained than its outer radius. The former is of particular interest because it can help constrain the black hole spin. The innermost stable orbit around the black hole metric: for a Schwarzschild (non-rotating) hole this occurs at $6 R_g$;

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Typical range</th>
</tr>
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<tbody>
<tr>
<td>Rest Energy</td>
<td>$E$</td>
<td>6.4-6.9 keV</td>
</tr>
<tr>
<td>Inclination</td>
<td>$i$</td>
<td>0-90 degree</td>
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<tr>
<td>Inner radius</td>
<td>$R_i$</td>
<td>1-6 $R_g$</td>
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<tr>
<td>Outer radius</td>
<td>$R_o$</td>
<td>20-1000 $R_g$</td>
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<tr>
<td>Emissivity Index</td>
<td>$q$</td>
<td>0-3</td>
</tr>
<tr>
<td>Equivalent Width</td>
<td>$EW$</td>
<td>100-500 eV</td>
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**TABLE 1. Disk line parameters**
FIGURE 2. The top panels shows the light curves of MCG-6-30-15 from the long ASCA observations in 1994 and 1997 (Iwasawa et al. 1996, 1999). The integrated line profiles of both observations are very similar (middle panels). In both observations, however, the line profile was found to vary. In the earlier data, a very broad and redshifted profile was observed during a deep minimum in the flux. In 1997, a similarly extreme profile was observed, but this time during a flare. The profile variations may be attributed to changes in the illumination pattern of the disk due to localized flares.

for a rapidly rotating hole, however, the stable orbits exist close to the gravitational radius. Another crucial parameter is the line emissivity law, which parameterizes the X-ray illumination of the disk. In the models of Fabian et al. (1989) and Laor (1991), a power-law emissivity assumed, which is a useful parameterization, if somewhat unphysical. The true emissivity depends on the geometry of the X-ray source and accretion disk and their relationship, modified by relativistic effects and ionization. As the geometries are very poorly known, what is really required is to formulate specific physical models and compare them with the data. Alternatively, one can attempt to “invert” the problem and derive the emissivity from the line profile (Dabrowski et al. 1997; Cadez & Calvani, these proceedings).
4. **AGN SAMPLES**

The profiles of individual sources provide strong constraints, but studying samples has also been extremely informative. The widespread applicability of the disk line models has been demonstrated by the fact that they fit the data better than symmetric profiles, such as a gaussian (Nandra et al. 1997a hereafter N97; Reynolds 1997). The parameters can also be constrained.

N97 presented ASCA iron Kα data for 18 Seyfert 1 galaxies and found good constraints on the inclination of a number of these. Low inclinations are very strongly preferred, with a mean of ∼ 30 deg. As these are Seyfert 1 galaxies, this may not be considered surprising, as in standard unification schemes, highly inclined sources would be expected to be obscured, and seen as Seyfert 2 galaxies (Lawrence & Elvis 1982; Antonucci & Miller 1995). It is puzzling then, that Turner et al. (1998) also found low inclinations to be preferred for a sample of Seyfert 2s and NELGs. A possible solution to this is suggested by Weaver & Reynolds (1998), who fitted the spectra with an additional, narrow line at 6.4 keV, presumed to arise from the obscuring torus (Ghiselini, Haardt & Matt 1994; Krolik, Madau & Zycki 1994). If such a line is allowed, then so is a higher inclination of ∼ 50 deg.

The mean emissivity was found by N97 to be proportional to $R^{-2.5}$ for Seyfert 1 galaxies. This rather steep function implies that the illumination - and therefore the line emission - is strongly concentrated in the inner regions of the AGN, with ∼ 50 % of the line coming from within $20R_g$ and 80 % from within $100R_g$. Such an emissivity is roughly consistent with that of a centrally-illuminated disk. No universal emissivity law was found, however, suggesting that there is no single geometry.

The emission line usually peaks at 6.4 keV, and for low-inclination disks this implies a low state of ionization, typically $<\text{Fe }\text{XX}$. If the peak is due to a contribution from a narrow line from another source, however, no constraint can be placed on the line rest energy (N97), and therefore ionization. Standard accretion disks are expected to be very dense, and can therefore remain cool despite the intense illumination. Nonetheless, significant ionization might be expected especially in the central regions, where the X-rays are most strongly concentrated (e.g. Matt, Fabian & Ross 1993). A range of ionization states throughout the disk is certainly consistent with the current data. The inner disk could be highly ionized, with the gravitational and Doppler shifts dominating and making it difficult to tie down the rest energy.

The observed profiles are well-fit with a disk line alone, and in Seyfert 1s there is no strong requirement from line emission from other regions (N97). In Seyfert 2s, however, there is evidence for an additional component (Weaver & Reynolds 1998) and it is quite plausible that the optical BLR or obscuring torus could contribute to the line emission in all AGN. The difficulty is in distinguishing such emission from that of the low-velocity outer disk, which requires high spectral resolution.
FIGURE 3. Light curves of NGC 3516. In descending order they are the 2-10 keV continuum, and the excess flux above the continuum in three line bands. Neither the core nor the blue wing flux is consistent with a constant and though the red wing is formally consistent with no variability, it appears strongly correlated (at 95% confidence) with the blue wing.

4.1. Differences and similarities

All of the high quality profiles obtained so far show profiles which are remarkably similar, and similar to the composite profile of Seyfert 1s. There are a few cases where it has been claimed that the line is narrow (e.g. NGC 4051 Mihara et al. 1994; NGC 7469 Guainazzi et al. 1994; Mrk 766 Leighly et al. 1996) but it is very difficult to exclude a broad component with the ASCA data, and none of these case is clear cut. Nonetheless there do appear to be differences in the profiles comparing different sources. The lack of a universal emissivity law is one suggestion of this (N97). Good quality data for more sources is required to confirm this, and investigate the origin. They may, for example, represent differences in geometry. Alternatively, they could be as simple as variations in the relative contributions of narrow and disk-line components.

5. VARIABILITY STUDIES

Variability studies often contribute fundamentally to our understanding of AGN. The line emission is no exception, and here some of the observations are reviewed.
• **MCG-6-30-15:** During the observation reported by Tanaka et al. (1995) the profile of the line was found to be variable (Fig. 3). Iwasawa et al. (1996) reported an unusually broad and redshifted profile during a “deep minimum” in continuum flux. Another long observation in 1997 showed a similar mean profile but this time exhibited the extreme broadening during a flare (Iwasawa et al. 1999). The profile variability was interpreted as being due to changes in the illumination pattern of the disk. If, instead of a single coherent source, localized flares produce the X-rays, then at certain times a few or even a single flare could dominate the emission. If that flare occurred in the very innermost regions, the line profile would temporarily appear more redshifted than the average. In MCG-6-30-15 the line is so broad during the deep minimum that it implies that the line emission arises within $\sim 6 R_g$ thus implying a Kerr black hole (Iwasawa et al. 1996; see also Reynolds & Begelman 1997; Dabrowski et al. 1997; Young et al. 1999).

• **NGC 3516:** Nandra et al. (1999) have noted profile variability in NGC 3516 also (Fig. 3). The absorption feature at 5.8 keV (Fig. 1) was found to be prominent only in the middle part of the observation, where the flux was high. Furthermore, while the core of the line appeared to follow the variations in the continuum, the red and blue wings did not. They were well correlated with each other, however, and showed strong variability (factor $\sim 2$). This was in excess of the variations in the driving continuum and therefore very difficult to explain in standard models. An interpretation similar to MCG-6-30-15 remains valid, where a localized flare beamed towards the inner disk causes the variation. Alternatively, or additionally, flares could cause an increase in the ionization of the inner disk. This could cause on over-response because the effective fluorescence yield increases sharply in the helium-like and hydrogen-like ionization states. Nandra et al. (1997b) also noted significant variability of the line flux in NGC 3516 over a 1 year baseline, with no obvious change in profile.

• **Other sources:** Yaqoob et al. (1996) found evidence for rapid variability of the broad wing in NGC 7314 but no obvious changes were seen in the core. This is consistent with the simple disk model, where the red wing is expected to come from close in. In NGC 4051 Wang et al. claimed a significant flux change comparing two ASCA observations, though some portion of the line flux is constant and comes from a more distant region (Uttley et al. 1999). Chiang et al. (1999) found no evidence for changes in the line flux of NGC 5548 despite large variability of the continuum.

6. PROBLEMS AND OPEN ISSUES

Some of the iron Kα line observations - particularly in the realm of variability - have been surprising in the context of the standard disk-line model. Depending on ones viewpoint, this may be interpreted as a further demonstration of their diagnostic
power (see above) or as being problematic for the disk line model (e.g., Sulentic, Marziani & Calvani 1998a). Alternatives to the relativistic disk have been suggested and we review those briefly here. Many of these issues have been discussed by Fabian et al. (1995). They include:

**Alternative geometries:** in the original paper predicting the iron Kα lines, Guilbert & Rees (1988) suggested that they may come from optically thick clouds, sheets or filaments, rather than the disk. Such material can produce the observed line strengths, as long as the covering fraction is high, but less than unity to avoid obscuring the continuum (e.g. Bond & Matsuoka 1993; Nandra & George 1994). Detailed calculations of the profiles in a pseudo-spherical geometry have not been carried out and it is therefore difficult to make a definite statement as to whether the observations can be reproduced. It does, however, seem unlikely. In MCG-6-30-15 and NGC 3516 (Fig. 1), there is very little evidence for emission blue-ward of the rest energy, and it is hard to envisage a non-disk geometry in which the blue emission is suppressed. The details depend on the geometry, kinematics and self-covering of the cloud system but, for example rotating blobs are almost certainly excluded, given that the high velocities would cause Doppler boosting of the blue wing. Inflowing or outflowing cloud distributions are another possibility, but once again it seems hard to suppress the emission from material moving towards us without a special geometry.

**Complex continuum:** As mentioned above, Zdziarski et al. (1996) have suggested that an apparently-broad line in NGC 4151 can be accounted for by a complex continuum - in particular complex absorption. Many AGN have material in their lines-of-sight, such as “warm absorbers” (e.g. Reynolds 1997; George et al. 1998) but typically these are not thought to affect the spectrum above about 3 keV. As in all other wavebands, a great challenge in determining the line strengths and profiles is determining the underlying continuum. Although different continuum-deconvolution methods tend to produce similar results, unknown complexities add additional uncertainty to the profile determination.

**Comptonization:** Kinematics and gravitation are not the only mechanisms by which lines can be broadened. A particular alternative suggestion has been that Compton scattering can broaden the line (e.g., Misra & Khembavi 1998). Fabian et al. (1995) argued against such a model, as the Comptonizing medium must be finely-tuned to generate the observed profile. In particular a very compact, high optical depth (τ ~ 5), cool (~ 0.2 keV) medium is required. Such a medium would down-scatter the X-ray continuum also, producing a spectral break at ~ 20 keV which is not observed.

**Line blending:** Combinations of numerous lines can appear broad when observed at low resolution. Differently-ionized species of iron-K, for example, result in emission from 6.4-6.9 keV. This cannot explain the observed profiles, as the broad emission occurs below 6.4 keV. No abundant element produces line emission in the 4-6 keV region where the red wing is observed, but Skibo (1997) has suggested that spallation of iron nuclei by > 10 MeV photons could result in significant amounts of V, Ti, Cr and Mn. There are numerous difficulties with such a model. For example,
the observed profile changes (see above) argue forcefully against such a suggestion, as all the fluorescence lines should vary together.

6.1. Open issues
None of these alternatives is as compelling as the standard disk, but some open questions remain. The broad lines have been confirmed by BeppoSax (Guainazzi et al. 1999), but we await further confirmation and definition of the profiles. In particular, it is important to quantify and deconvolve the disk line contribution from narrower components from the BLR and obscuring torus. ASCA observations have shown some differences comparing objects, but the high signal-to-noise profiles all show common features, and in particular the derived inclinations are often very similar. This, and possible disagreements with other inclination indicators (Sulentic et al. 1998b) are not yet significant problems, but it will be important in the future to relate the properties derived from iron Kα with other AGN observables. With large collecting area, it may be possible to discover the weak and very broad lines expected from edge-on accretion disks, which have so far eluded us. Deconvolution from a (potentially-complex) continuum is the key here.

The Kα observations so far have been of great importance, but have shown unexpected complications. The interpretation of future observations is therefore likely to be challenging. Two particular issues are the emissivity and ionization of the disk as a function of radius. These are both arbitrary from an observational standpoint, and difficult to predict theoretically. Detailed interpretation of, e.g., variability data - including reverberation mapping (e.g. Reynolds et al. 1999) - will require an understanding of these effects. Iron Kα observers can therefore look forward to developing the kind of complex physical models and advanced data analysis techniques that many other astronomers have been enjoying for many years. We hope and expect the rewards to be substantial.

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