Broad Iron Lines in AGN and X-ray Binaries

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Abstract.

Several AGN and black hole X-ray binaries show a clear very broad iron line which is strong evidence that the black holes are rapidly spinning. Detailed analysis of these objects shows that the emission line is not significantly affected by absorption and that the source variability is principally due to variation in amplitude of a power-law. Underlying this is a much less variable, relativistically-smeared, reflection-dominated, component which carries the imprint of strong gravity at a few gravitational radii. The strong gravitational light bending in these regions then explains the power-law variability as due to changes in height of the primary X-ray source above the disc. The reflection component, in particular its variability and the profile of the iron line, enables us to study the innermost regions around an accreting, spinning, black hole.

1. Introduction

Radiatively-efficient accreting black holes are expected to be surrounded by a dense disc radiating quasi-blackbody thermal EUV and soft X-ray emission. Hard X-ray emission originates via Comptonization of that soft radiation in a corona above the disc, fed by magnetic fields from the body of the disc. Irradiation of the dense disc material by hard X-rays then gives rise to a characteristic ‘reflection’ spectrum, computed examples of which are shown in Fig. 1 (from Ross & Fabian 2004).

Most of the power is radiated from close to the smallest disc radii which for a non-spinning black hole is 6$r_g$, where $r_g = GM/c^2$. For a spinning (Kerr) black hole it reduces as the spin increases (Bardeen et al. 1972) to 1.23 $r_g$ for what is assume to be maximal spin (Thorne 1972). Relativistic effects then affect the appearance of the reflection spectrum through Doppler, aberration, gravitational redshift and light bending effects (Fabian et al. 1989; Laor 1991). The dominant feature in the spectrum seen by a distant observer is an iron line with a broad skewed profile.

Broad iron lines seen in the spectrum of several active galaxies and Galactic black hole binaries are reviewed here. The cases for relativistic lines in the Seyfert galaxy MCG–6-30-15 and the X-ray binary GX 339-4 are very strong, indicating that those black holes are rapidly spinning. The puzzling spectral variability of such sources is now beginning to be understood within the context of emission from the strong gravity regime (Miniutti & Fabian 2004). Some active galactic nuclei (AGN)
Figure 1. Computed reflection spectrum as a function of $\xi = F/n$, where $n$ is the density of the surface (Ross & Fabian 2004).

and X-ray black hole binaries show either no line or only a narrow one. This is discussed within the context of state changes and jetted emission observed in the Galactic black holes.

2. MCG-6-30-15

The X-ray spectrum of the bright Seyfert 1 galaxy MCG–6-30-15 ($z = 0.00775$) has a broad emission feature stretching from below 4 keV to about 7 keV. The shape of this feature, first clearly resolved with *ASCA* by Tanaka et al. (1995), is skewed and peaks at about 6.4 keV. This profile is consistent with that predicted from iron fluorescence from an accretion disc inclined at 30 deg extending down to within about 6 gravitational radii ($6r_g = 6GM/c^2$) of a black hole (Fabian et al. 1989; Laor 1991). In part of the *ASCA* observation the line extended below 4 keV (Iwasawa et al. 1996) which means that the emission originates at radii much less than $6r_g$, probably due to the black hole spinning. *XMM-Newton* has observed MCG–6-30-15 twice (in 2000, Wilms et al. 2001 and 2001; Fabian et al. 2002a) and in both cases the line extended down to about 3 keV (Fig. 2a), implying the spin parameter $a > 0.93$ (Dabrowski et al. 1997; Reynolds et al. 2004). This raises the exciting possibility that the spin energy of the hole is being tapped (Wilms et al. 2001).
The X-ray continuum emission of MCG–6-30-15 is highly variable (see Vaughan, Fabian & Nandra 2003, Vaughan & Fabian 2004 and Reynolds et al. 2004 for recent analyses). If the observed continuum drives the iron fluorescence then the line flux should respond to variations in the incident continuum on timescales comparable to the light-crossing, or hydrodynamical time of the inner accretion disc (Fabian et al. 1989; Stella 1990; Matt & Perola 1992; Reynolds et al. 1999). This timescale ($\sim 100M_6$ s for reflection from within $10r_g$ around a black hole of mass $10^6M_6$ M$_\odot$) is short enough that a single, long observation spans many light-crossing times. This has motivated observational efforts to find variations in the line flux (e.g. Iwasawa et al. 1996, 1999; Reynolds 2000; Vaughan & Edelson 2001; Shih, Iwasawa & Fabian 2002). These analyses indicated that the iron line in MCG–6-30-15 is indeed variable on timescales of $\sim 10^4$ s (e.g. Fig. 3), but that the general amplitude of the variations was considerably less than expected and not directly correlated with the observed continuum.
The long *XMM-Newton* observation (Fabian et al. 2002) showed that a simple two-component model (Shih et al. 2002) is sufficient to explain the observed spectral variability (Fig. 1b; Fabian & Vaughan 2003; Taylor et al. 2003). The model consists of a highly variable power-law component (PLC) plus a much less variable harder component carrying the iron line (RDC, Fig. 2a). It gives an excellent fit to the data, with the harder, line-carrying component dominating lowest flux states of the observation (Fabian & Vaughan 2003). That the variation is driven by a power-law is evident from difference spectra made by subtracting the spectra of fainter parts of the lightcurve from those of brighter parts and fitting the resulting ‘difference spectrum’. It is a power-law from 3–10 keV with no iron-K features. On the assumption that this power-law continues to lower energies, where attenuation at low energies due to both Galactic absorption and the warm absorber in MCG–6-30-15 is seen. This demonstrates that there is no subtle additional absorption influencing the shape of the extensive low-energy “red” wing to the iron line. Small variations in the amplitude of the RDC are seen.

A detailed analysis of the *XMM-Newton* 2001 data by Turner et al. (2003, 2004) shows, from a curve of growth analysis of the absorption lines and difference spectra, that the warm absorber accounts for most of the soft X-ray spectral features and that any distinct relativistically-broadened CNO lines (Branduardi-Raymont et al. 2001; Sako et al. 2003) are weak.

2.1. Interpretation

Explaining the relatively small variability of the RDC, compared with that of the PLC, provides a significant challenge. It appears to be mostly due to reflection but it is not simple reflection of the observed power-law component since that repeatedly varies by factors of two or more on short timescales; the RDC and PLC appear partially dis-
connected. Since however both show the effects of the warm absorber they must originate in a similar location. As the extensive red wing of the iron line in the RDC indicates emission peaking at only a few gravitational radii \( (GM/c^2) \) we assume that this is indeed where that component originates. In such extreme gravity the general relativistic bending of light is very large, boosting the strength of reflection (Martocchia et al. 2000, 2002; Dabrowski & Lasenby 2001) and can account for the behaviour of the components (Fabian & Vaughan 2003; Miniutti et al. 2003, 2004). How bright the PLC appears depends strongly on its height above the disc. Much of the radiation is bent down to the disc and black hole when the PLC is at a height of a few \( r_g \) but less so above 20\( r_g \) (Fig. 5a).

Part of the source variability can thus be explained by an intrinsically constant PLC changing height above the disc. Intrinsic variability of the PLC might also be present. The RDC is expected to change little during PLC variations due to source position but will change with intrinsic variability. Line profile changes with source height is a discriminant (Fig. 5b).

Tapping of black holes spin by magnetic fields in the disc is a strong possibility to account for the peaking of the power so close to the hole (Wilms et al. 2001; Reynolds et al. 2004).

3. Galactic Black Hole binaries and NLS1

Broad iron lines have been found in several Galactic black hole binaries (or Black Hole Candidates BHC). The lines in GX 339-4 (Fig. 6a, Miller et al. 2004a,b) and XTE J1650-500 (Fig. 6b, Miller et al. 2002; Miniutti et al. 2004) are among the best examples (see also Miller et al. 2003, 2002a,b; Martocchia et al. 2002). That in GX 339-4 shows a very broad red wing indicating that the black hole is rapidly spinning. Changes in
the strength of the iron line as the power-law continuum varied during the outburst of XTE J1650-500 (Rossi et al. 2003) follow the sense of the variation expected from the light-bending model (Fig. 5a).

Figure 6. Left panel: The line in the BHC GX 339-4 (Miller et al. 2004). Right panel: The broad iron line in XTE J1650-500 (Miniutti et al. 2004).

Figure 7. Left panel: Ratio of the spectrum of the NLS1 1H0707 to a power-law fitted between 2 and 3 keV and above 7.5 keV. Right panel: Spectral decomposition of 1H0707-495 in terms of a variable power-law (dashed) and a blurred reflection component (dot-dashed) (from Fabian et al. 2004).

Narrow Line Seyfert 1 galaxies tend to show steep soft X-ray spectra and sometimes broad iron emission features. One extreme such object is 1H0707-495 which has a marked drop in its spectrum above 7 keV. This is either an absorption edge showing partial-covering in the source (Boller et al. 2002, 2004) or the blue wing of a massive, very broad, iron line (Fig. 7a, Fabian et al. 2002, 2004). A two component, relativistically-blurred reflection plus power-law, model explains all the complex spectrum, including its soft excess and broad line, together with its rapid spectral variability. 1H0707-495 is therefore an extreme Kerr hole.
4. Broad-line-free sources

Some objects show no evidence for a broad line. Good examples from long XMM-Newton exposures are Akn120, which has no warm absorber (Vaughan et al. 2004), and the broad line radio galaxy 3C 120 (Ballantyne et al. 2004).

Various possibilities for the lack of any line have been proposed by the authors of those papers including: a) the central part of the disc is missing; b) the disc surface is fully ionized (ie the iron is); c) the coronal emissivity function is flat, which could be due to d) the primary X-ray sources being elevated well above the disc at say 100rg.

There are also intermediate sources where the data are either poor or there are complex absorption components so that one cannot argue conclusively that there is a relativistic line present. Some narrow line components are expected from outflow, warm absorbers and distant matter in the source. One common approach in complex cases, which is not recommended, is to continue adding absorption and emission components to the spectral model until the reduced $\chi^2$ of the fit is acceptable, and then claim that model as the solution. Very broad lines are difficult to establish conclusively unless there is something such as clear spectral variability indicating that the power-law is free of Fe-K features, as found for MCG–6-30-15, or for GX 339-4 where the complexities of an AGN are not expected.

5. Generalization of the light-bending model

Our interpretation of the spectral behaviour of MCG–6-30-15 and some other sources means that we are observing the effects of very strong gravitational light bending within a few gravitational radii of a rapidly spinning black hole. The short term (10–300 ks) behaviour is explained, without large intrinsic luminosity variability, through small variations in the position of the emitting region in a region where spacetime is strongly curved.

This implies that some of the rapid variability is due to changes in the source position. Now BHC in the (intermediate) high/soft state have high frequency breaks at higher frequency, for the same source, than when in the low/hard state (cf. Cyg X-1, Uttley & McHardy 2004). This additional variability when in the soft state is identified with relativistic light-bending effects on the power-law continuum.

This picture suggests a possible generalization of the light-bending model to unify the AGN and BHC in their different states. Note the work of Fender et al. (2004) which emphasises that jetted emission
occurs commonly in the hard state of BHC. The key parameter may be the height of the main coronal activity above the black hole. Assume that much of the power of the inner disc passes into the corona (Merloni & Fabian 2002) and that the coronal activity is magnetically focussed close to the central axis. Then at low Eddington ratio the coronal height is large (say $100r_g$ or more), the corona is radiatively inefficient and most of the energy passes into an outflow; basically the power flows into a jet. Reflection is then appropriate for Euclidean geometry and a flat disc and there is only modest broadening to the lines. If the X-ray emission from the (relativistic) jet dominates then X-ray reflection is small (see e.g. Beloborodov 1999). The high frequency break to the power spectrum is low ($\sim 0.001c/r_g$).

When the Eddington fraction rises above say ten per cent, the height of the activity drops below $\sim 20r_g$, the corona is more radiatively efficient and more high frequency variability occurs due to light bending and the turnover of the power spectrum rises above $0.01c/r_g$. The X-ray spectrum is dominated at low heights by reflection, including reflection-boosted thermal disk emission, and a broad iron line is seen. Any jet is weak.

The objects with the highest spin and highest accretion rate give the most extreme behaviour. Observations suggest that these include NLS1 and some very high state, and intermediate state, BHC. Some broad-line-free sources do not however fit this model, so more work is required.

6. Summary

A relativistically-broadened iron line is unambiguous in the spectra and behaviour of a few objects. The strength and breadth of reflection features is strong evidence for gravitational light bending and redshifts from a few $r_g$. They indicate that a dense disc extends close to the black hole, which must therefore be rapidly spinning ($a/m > 0.8$).

The potential for understanding the accretion flow close to a black hole is enormous. Current observations are at the limit of XMM-Newton’s powers, which nevertheless has enabled a breakthrough in understanding the spectral behaviour of MCG–6-30-15 and similar objects. Similarities in the spectral and timing properties of AGN and BHC is enabling further progress to be made. Studies in the near future with ASTRO-E2 followed by XEUS and Constellation-X in the next decade will continue to open up the immediate environment of accreting black holes, within just a few gravitational radii, to detailed study.
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