Black Holes from Stars to Galaxies – Across the Range of Masses
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Strong gravity effects: X-ray spectra, variability and polarimetry

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Abstract. Accreting black holes often show iron line emission in their X-ray spectra. When this line emission is very broad or variable then it is likely to originate from close to the black hole. The theory and observations of such broad and variable iron lines are briefly reviewed here. In order for a clear broad line to be found, one or more of the following have to occur: high iron abundance, dense disk surface and minimal complex absorption.

Several excellent examples are found from observations of Seyfert galaxies and Galactic Black Holes. In some cases there is strong evidence that the black hole is rapidly spinning. Further examples are expected as more long observations are made with XMM-Newton, Chandra and Suzaku. The X-ray spectra show evidence for the strong gravitational redshifts and light bending expected around black holes.

Keywords. Black hole physics – X-rays – line: formation – accretion, accretion disks

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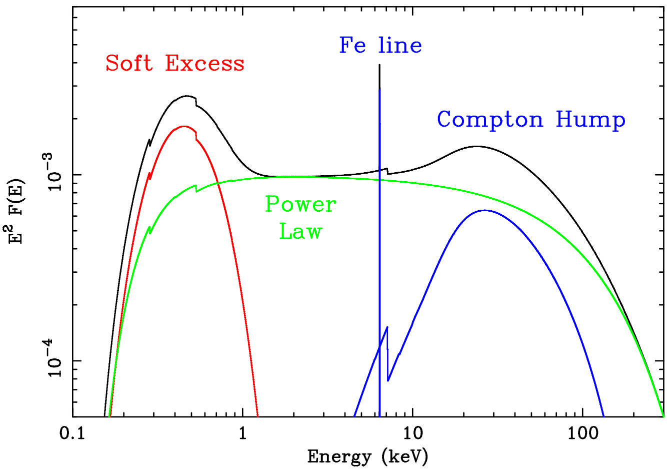
1. Introduction

Much of the radiation from luminous accreting black holes is released within the innermost 10-20 gravitational radii (i.e. 10–$20r_{\rm g} \equiv$ 10–$20GM/c^2$). In such an energetic environment, iron is a major source of line emission, with strong emission lines in the 6.4–6.9 keV band. Observations of such line emission then provides us with a diagnostic of the accretion flow and the behaviour of matter and radiation in the strong gravity regime very close to the black hole (Fabian *et al.* 2000; Reynolds & Nowak 2003; Fabian & Miniutti 2005).

The rapid X-ray variability found in many Seyfert galaxies is strong evidence for the emission originating at small radii. The high frequency break in their power spectra, for example, corresponds to orbital periods at $\sim 20r_{\rm g}$ and variability is seen at still higher frequencies (Uttley & McHardy 2004; Vaughan *et al.* 2004). Key evidence that the very innermost radii are involved comes from Soltan's (1982) argument relating the energy density in radiation from active galactic nuclei (AGN) to the local mean mass density in massive black holes, which are presumed to have grown by accretion which liberated that radiation. The agreement found between these quantities requires that the radiative efficiency of accretion be 10 per cent or more (Yu & Tremaine 2002; Marconi *et al.* 2005). This exceeds the 6 per cent for accretion onto a non-spinning Schwarzschild black hole and inevitably implies that most massive black holes are rapidly spinning with accretion flows extending down to a just few $r_{\rm g}$. Moreover, this is where most of the radiation in such accretion flows originates.

The X-ray spectra of AGN are characterized by several components: a hard power-law which may turnover at a few hundred keV, a soft excess and a reflection component (Fig. 1). This last component is produced from surrounding material by irradiation by the power-law. It consists of backscattered X-rays, fluorescence and other line photons, bremsstrahlung and other continua from the irradiated surfaces. Examples of reflection



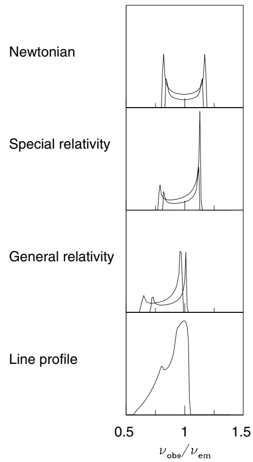


Figure 1. Left: The main components of the X–ray spectra of unobscured accreting BH are shown: soft X–ray emission from the accretion disc (red); power law from Comptonization of the soft X–rays in a corona above the disc (green); reflection continuum and narrow Fe line due to reflection of the hard X–ray emission from dense gas (blue). Right: The profile of an intrinsically narrow emission line is modified by the interplay of Doppler/gravitational energy shifts, relativistic beaming, and gravitational light bending occurring in the accretion disc (from Fabian *et al.* 2000). The upper panel shows the symmetric double–peaked profile from two annuli on a non–relativistic Newtonian disc. In the second panel, the effects of transverse Doppler shifts (making the profiles extend to lower energies) and of relativistic beaming (enhancing the blue peak with respect to the red) are included. In the third panel, gravitational redshift is turned on, shifting the overall profile to the red side and reducing the blue peak strength. The disc inclination fixes the maximum energy at which the line can still be seen, mainly because of the angular dependence of relativistic beaming and of gravitational light bending effects. All these effects combined give rise to a broad, skewed line profile which is shown in the last panel, after integrating over the contributions from all the different annuli on the accretion disc. Detailed computations are given by Fabian *et al.* (1989), Laor (1991), Dovčiak *et al.* (2004) and Beckwith & Done (2004).

spectra from photoionized slabs are shown in Fig. 2. At moderate ionization parameters ($\xi = F/n \sim 100$ erg cm s^{-1}, where F is the ionizing flux and n the density of the surface) the main components of the reflection spectrum are the Compton hump peaking at ~ 30 keV, the iron line at 6.4–6.9 keV (depending on ionization state) and a collection of lines and reradiated continuum below 1 keV. When such a spectrum is produced from the innermost parts of an accretion disk around a spinning black hole, the outside observer sees it smeared and redshifted (Fig. 2) due to doppler and gravitational redshifts.

Another, potentially powerful, diagnostic of the strong gravity regime is the study of timing and Quasi-Periodic Oscillations (QPOs). Despite the richness of the data (e.g. Strohmayer 2001), there is no consensus on how to interpret them and they will not be discussed further here.

2. Observations

All three main parts of the reflection spectrum have now been seen from AGN and Galactic Black Holes (GBH). The broad iron line and reflection hump are clearly seen in the Seyfert galaxy MCG–6-30-15 and in the GBH J1650-400. More recently it has been realised that the soft excess in many AGN can be well explained by smeared reflection (Crummy *et al.* 2006). It had been noted by Czerny *et al.* (2003) and by Gierlinski &

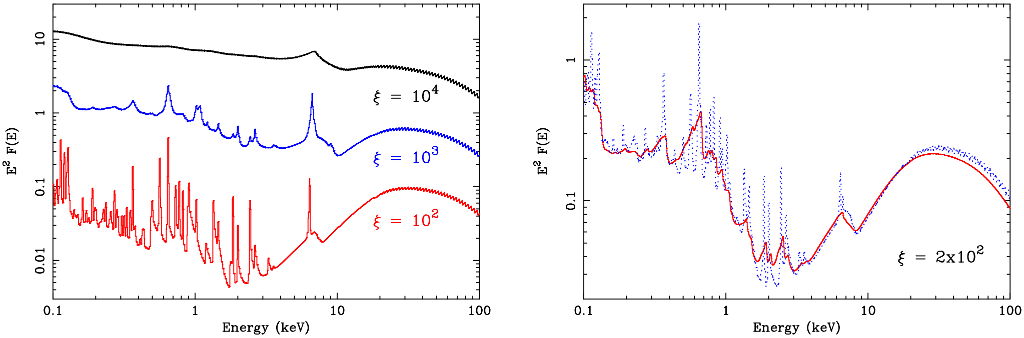


Figure 2. Left: Computed X-ray reflection spectra as a function of the ionization parameter ξ (from the code by Ross & Fabian 2005). The illuminating continuum has a photon index of $\Gamma = 2$ and the reflector is assumed to have cosmic (solar) abundances. Right: Relativistic effects on the observed X-ray reflection spectrum (solid line). We assume that the intrinsic rest-frame spectrum (dotted) is emitted in an accretion disc and suffers all the relativistic effects shown in Fig. 1.

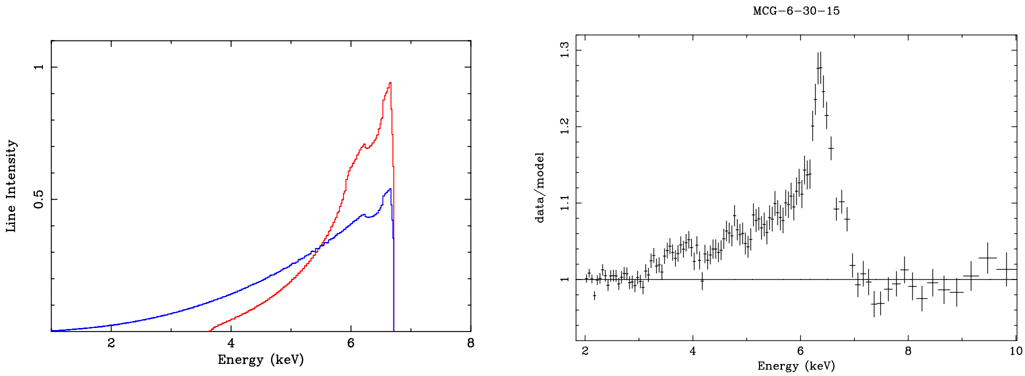


Figure 3. Left: The line profile dependence on the inner disc radius is shown for the two extremal cases of a Schwarzschild BH (red, with inner disc radius at 6 r_g) and of a Maximal Kerr BH (blue, with inner disc radius at $\simeq 1.24\ r_g$). Right: The broad iron line in MCG–6-30-15 from the XMM observation in 2001 (Fabian *et al.* 2002a) is shown as a ratio to the continuum model.

Done (2004) that the soft excess posed a major puzzle if thermal since the required temperature was always about 150 eV, irrespective of black hole mass, luminosity etc. Explaining it as a feature due to smeared atomic lines resolves this puzzle. An alternative interpretation involves smeared absorption lines (Gierlinski & Done 2004).

The extent of the blurring of the reflection spectrum is determined by the innermost radius of the disk (Fig. 3). Assuming that this is the radius of marginal stability enables the spin parameter a of the hole to be measured. Objects with a very broad iron line like MCG–6-30-15 are inferred to have high spin $a > 0.95$ (Dabrowski *et al.* 1997; Brenne-mann *et al.* 2006). Some (Krolik & Hawley 2002) have argued that magnetic fields in the disk can blur the separation between innermost edge of the disk and the inner plunge re-gion so that the above assumption is invalid. This probably makes little difference for the iron line however since the low ionization parameter of most observed reflection reflection requires that the disc matter is very dense. The density of matter in the plunge region drops very rapidly to a low values (Reynolds & Begelman 1997) and only very strong magnetic fields, much larger than are inferred in disks, can stop this steep decline in

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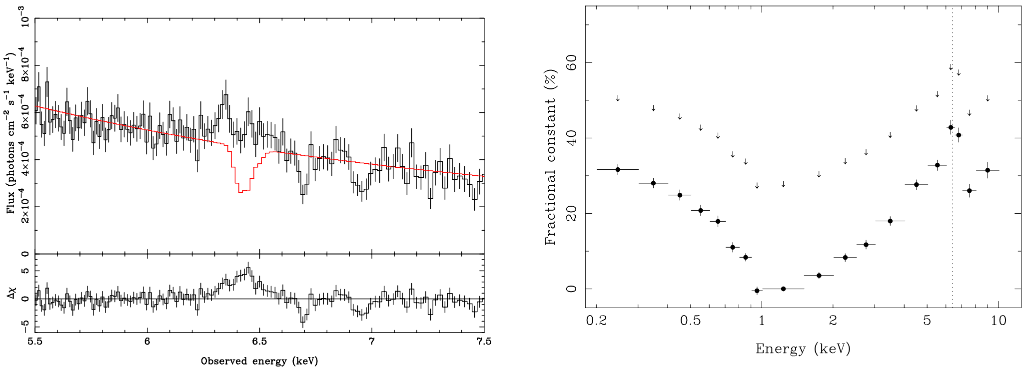

Figure 4. Left: The Chandra HEG spectrum overlaid with an ionized absorber model for the red wing (Young *et al.* 2005). Note that the absorption between 6.4 and 6.5 keV predicted by the absorber model is not seen. Right: The fractional spectrum of the constant component of MCG–6-30-15, constructed from the intercept in flux–flux plots (Vaughan & Fabian 2004). This component strongly resembles reflection.

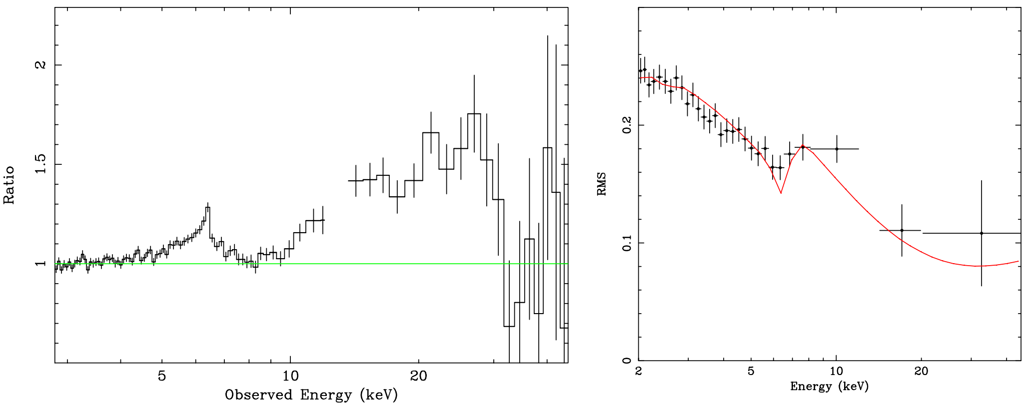

Figure 5. Left: Broad iron line and Compton hump in MCG–6-30-15 from Suzaku. Right: Fractional r.m.s. variability as a function of energy compared with model (solid line) in which the power-law is assumed to change in normalization whilst the reflection component is fixed.

density. Any reflection from the plunge region will be very highly ionized and so produce little iron emission.

Broad iron lines and reflection components are seen in both AGN (e.g. Tanaka *et al.* 1995; Nandra *et al.* 1997) and GBH (Martocchia & Matt 2002; Miller *et al.* 2002abc, 2003ab, 2004ab). A recent exciting development are the reports that broad iron lines are present in 50 per cent of all XMM AGN observations where the data are of high quality (more than 150,000 counts; Guainazzi *et al.* 2006; Nandra *et al.* 2006). They are not found in all objects or in all accretion states. There are many possible reasons for this, including over-ionization of the surface, low iron abundance, and beaming of the primary power-law away from the disk (e.g. if the power-law originates from the mildly-relativistic base of the jet).

In many cases there is a narrow iron line component due to reflection from distant matter. Absorption due to intervening gas, warm absorbers and outflows from the AGN, as well as the interstellar medium in both our Milky Way galaxy and the host galaxy must be accounted for. Moreover, if most of the emission emerges from within a few

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gravitational radii and the abundance is not high, then the extreme blurring can render the blurred reflection undetectable (Fabian & Miniutti 2005).

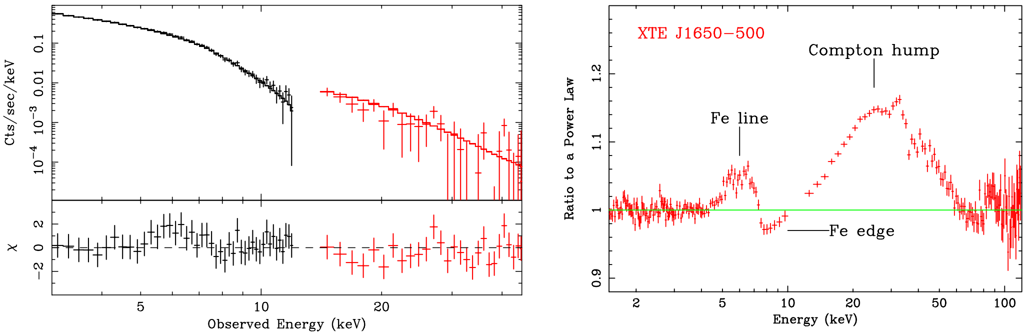

Figure 6. The broadband BeppoSAX spectrum of XTE J1650–500 (plotted as a ratio to the continuum). The signatures of relativistically-blurred reflection are clearly seen (Miniutti *et al.* 2004).

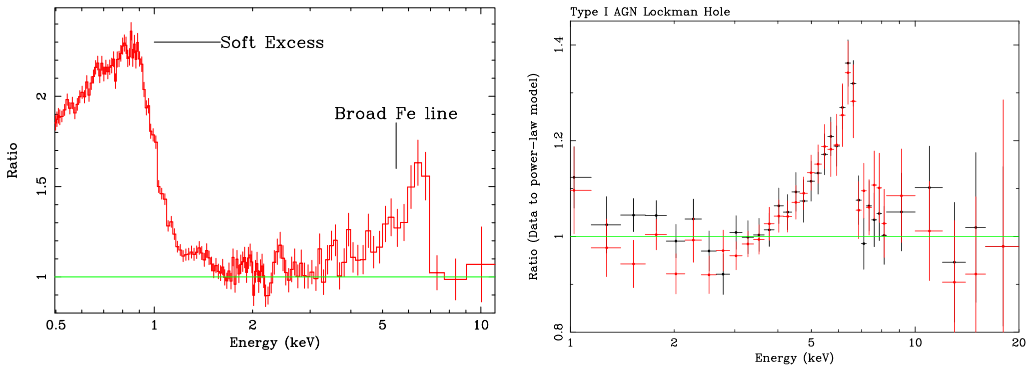

Figure 7. Left: Ratio of the spectrum of the NLS1 galaxy 1H0707 to a power-law. Spectral fits with either a very broad iron line or a partial covering with a steep edge are equally good for this object (Fabian *et al.* 2004; Boller *et al.* 2002). Right: Ratio plot of the mean unfolded spectrum for type–1 AGN in the Lockman Hole with respect to a power law (Streblyanska *et al.* 2005).

In order to distinguish between the various spectral components, both emission and absorption, we can use higher spectral resolution, broader bandwidth and variability. An example of the use of higher spectral resolution is the work of Young *et al.* (2005) with the Chandra high energy gratings (Fig. 4). Observations of MCG–6-30-15 fail to show absorption lines or feature associated with iron of intermediate ionization. Such gas could cause some curvature of the apparent continuum mimicking a very broad line. A broader bandwidth is very useful in determining the slope of the underlying continuum. This has been shown using BeppoSAX (e.g. Guainazzi *et al.* 1999) and now in several sources with Suzaku (Fig. 5, Miniutti *et al.* 2007; Reeves *et al.* 2007).

3. Variability

In the best objects where a very broad line is seen (e.g. MCG–6-30-15 – Fabian *et al.* 2002; NGC4051 – Ponti *et al.* 2006) the reflection appears to change little despite large variations in the continuum. The spectral variability can be decomposed into a highly

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variable power-law and a quasi-constant reflection component. This behaviour is also borne out by a difference (high-low) spectrum which is power-law in shape and the reflection-like shape of the spectrum of the intercept in flux-flux plots (Figs. 6–7).

This behaviour was initially puzzling, until the effects of gravitational light bending were included (Fabian & Vaughan 2003; Miniutti *et al.* 2004; Miniutti & Fabian 2005). Recall that the extreme blurring in these objects means that much of the reflection occurs with a few $r_{\rm g}$ of the horizon of the black hole. The enormous spacetime curvature there means that changes in the position of the primary power-law continuum have a large effect on the flux seen by an outside observer (Martocchia & Matt 1996; Martocchia *et al.* 2002). What this means is that an intrinsically constant continuum source can appear to vary by large amounts just be moving about in this region of extreme gravity. The reflection component, which comes from the spatially fixed accretion disc, appears relatively constant in flux in this region. Consequently, the observed behaviour of these objects may just be a consequence of strong gravity.

Some of the Narrow-Line Seyfert 1 galaxies such as 1H0707, IRAS13224 and 1H0439 appear to share this behaviour (Fabian *et al.* 2002b, 2004, 2005) and can be interpreted in terms of extreme light bending. Some of these objects can show sharp drops around 7 keV that may be alternatively interpreted as due to absorption from something only partially covering the source (Boller et al 2002). (If the covering was total then no strong soft emission would be seen, contrary to observation.) The GBH XTE J1650-500 behaved in a manner similar to that expected from the light bending model (Rossi *et al.* 2005).

4. Polarization

The X-ray emission from accreting black holes is expected to be polarized (Rees 1975), with general relativistic effects influencing the degree and angle of polarization of emission from the innermost regions (Stark & Connors 1977; Dovčiak *et al.* 2004, Fig. 8). Hopefully, a mission in the near future will carry a sensitive polarimeter so that this powerful information channel can be opened up.

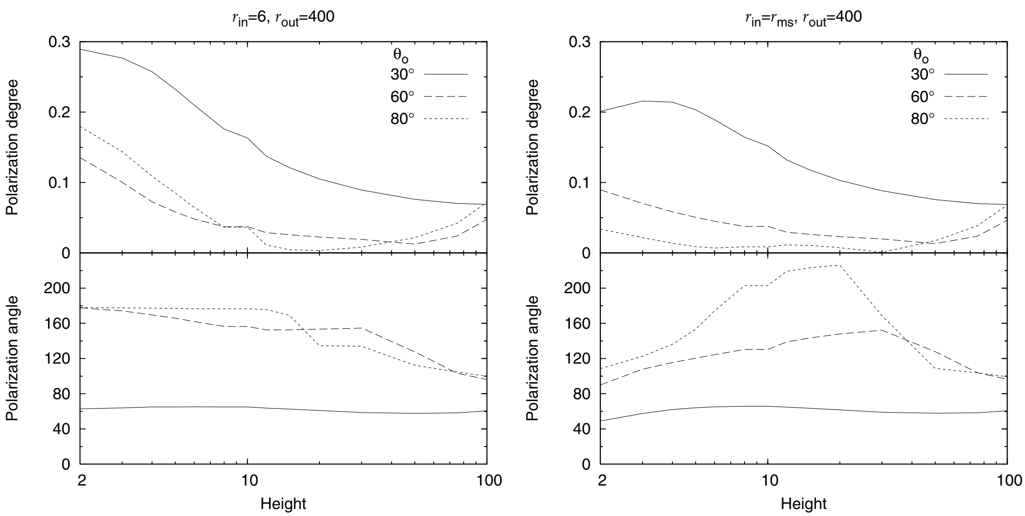

Figure 8. Polarization properties in the 9–12 keV band expected from a disc around a rapidly spinning black hole as a function of the height of the source above the disc in gravitational radii (Dovčiak, Karas & Matt 2004). The different lines are for different inclination angles. The inner radius of the disc is $6r_{\rm g}$ on the left and $1.2r_{\rm g}$ on the right.

5. Discussion

Clear examples of relativistically-broadened iron lines are seen in some AGN and GBH in some states. Such objects must have dense inner accretion disks in order that the gas is not over-ionized. Detection of a line is helped greatly if the iron abundance is super-Solar and if there is little extra absorption due to very strong warm absorbers or winds. Where broad lines are seen and can be modelled satisfactorilly then the spin of the central black hole can be reliably determined.

The study of absorption and emission variability of iron-K lines is in its infancy, with some interesting and tantalising results produced so far. The inner regions of accretion flows are bound to be structured and so give rise to variations. Some may be due to motion or transience in the corona or primary power-law source while others may reflect structure, e.g. spiral waves, on the disk itself, intercepting primary radiation from much smaller radii.

The number of broad lines detected is increasing and will continue to expand with the improved broad band coverage from Suzaku. Hints that broad lines are common in fainter objects such as in the Lockman Hole (Streblyanska *et al.* 2005) and Chandra Deep Fields (Brusa *et al.* 2005) could indicate that the conditions necessary for strong line production, perhaps high metalicity, are common in typical AGN at redshifts 0.5–1.

X-ray astronomers have an excellent tool with which to observe the innermost regions of accretion disks immediately around spinning black holes. The effects of redshifts and light bending expected from strong gravity in this regime are clearly evident. This can and should be exploited by future X-ray missions. To make significant progress we need large collecting areas. The count rate in the broad iron line of MCG–6-30-15 is about 2 ph m^{-2} s^{-1}, which means that square metres of collecting area are required around 6 keV in order to look for reverberation effects. GBH are much brighter but the orbital periods of matter close to the black hole are much, much smaller so reverberation is difficult here. Instead, variations with mass accretion rate and source state are accessible.

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Felix Mirabel: Could you comment on the possibility of probing empirically the connection between black-hole spin derived from the skewed iron lines and the observed jets power?

Andy Fabian: Not at the present time. Such correlation is possible, but it cannot be currently probed with, say, MCG–6-30-15 which is the one I have worked on most. This

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galaxy does have a radio source – it's virtually unresolved and I know of no study of its variability, but I have also learned that radiative efficiency of jets can be as low as $\sim 10^{-4}$. So the radio emission does not clearly tell us about power of the jet. In terms of Galactic black holes there has been very little work on correlating broad iron line properties with radio properties.

Marek Abramowicz: Comment: I would like to remark that there is another example of the effect described by the speaker – namely, the QPO variability in microquasars may also be caused or influenced by motion of the source in cooperation with the strong-gravity light bending (and *not* by the intrinsic variations of the flux). This is part of the model described by Michal Bursa who is also present here in the room.

Thaisa Storchi-Bergmann: When you and others discuss observations of the Fe $K\alpha$ line, always the same source MCG–6-30-15 is presented. Why is that – what about other sources with broad iron K lines?

Andy Fabian: Broad lines are seen in other sources, but MCG–6-30-15 is the clearest. The fraction of sources (AGN) with broad lines is discussed in the work on XMM–Newton data by Paul Nandra *et al.* Also recently at a workshop on broad iron lines at VILSPA, Matteo Guainazzi *et al.* showed the fraction of sources with broad iron lines is similar to that found with ASCA ($\sim$ 30%). It turns out that MCG–6-30-15 happens to have, I believe, high iron abundance – we can see that also from the reflection hump in Suzaku data. Perhaps one has to be somewhat lucky with the objects that show high iron abundance.

Alexander Zakharov: Are the images of accretion discs – those images which were presented in the first part of your talk – an artist's view? If computed, the images should exhibit a bended part of the image from behind the black hole, especially in case of Kerr black hole.

Andy Fabian: Yes, these were artist's impressions apart from the simulation by Armitage & Reynolds.

Gregory Beskin: What about magnetic field influence on the iron lines, especially in binary systems?

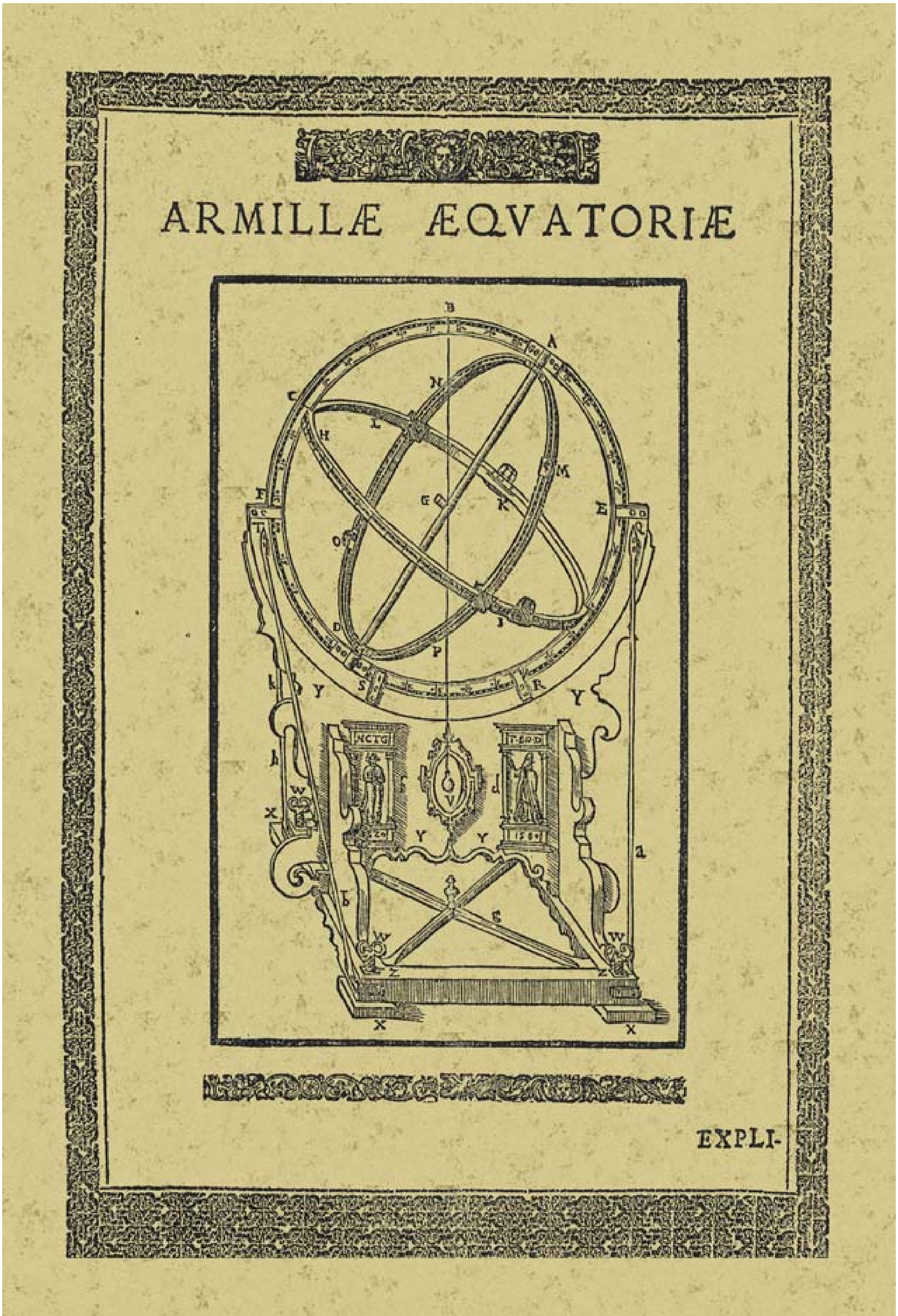
Andy Fabian: I don't think there is any direct influence, although we do believe that the power-law continuum is powered by magnetic energy from the disc.

Boris Komberg: I would like to know your opinion about the nature of X-ray sources that appear very high above of the accretion disc (primary sources of X-rays).

Andy Fabian: I believe they are connected with magnetic field twisting and reconnection, but we still do not understand details of that process. Perhaps the primary X-ray emission is generated at the base of the jet, but I would stress that's still a speculation.

Margarita Safonova: Is it possible to quantify the dependence of the spin of the black hole with the iron line broadening?

Andy Fabian: Yes; for this the entire shape of the line and the continuum have to be fitted.



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