OBSERVING THE EFFECTS OF STRONG GRAVITY WITH FUTURE X-RAY MISSIONS

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ABSTRACT Spectroscopy of the broad iron iron with ASCA and BeppoSAX has up opened the innermost regions of accreting black hole systems to detailed study. In this contribution, I discuss how observations with future X-ray missions will extend these studies and all us to observationally address issues which are currently only in the realm of the theorists. In particular, high-throughput spectroscopy with XMM and, eventually, Constellation-X will allow the full diagnostic power of iron line variability to be realized. Instabilities of the inner accretion flow, the geometry of the variable X-ray source, and the black hole mass and spin will all be open to study. Eventually, X-ray interferometry will allow direct imaging of the black hole region in nearby active galaxies, thereby providing the ultimate probe of black hole astrophysics.

KEYWORDS: accretion, accretion discs – black hole physics – galaxies: active – X-rays: general – line: profiles

1. INTRODUCTION

As we have heard in this meeting, X-ray spectroscopy with ASCA and BeppoSAX are providing probes of the region very close to the supermassive black holes in active galactic nuclei (AGN). In particular, detailed observations and modeling of the broad Kα fluorescence emission line of iron, which is thought to originate from the surface layers of the inner accretion disk, allow us to probe the inner disk structure and strong-field gravity in completely new ways. The current observational status of this field has been summarized in Dr. Nandra’s contribution in this volume. In this paper, I will discuss what there still is to learn, and how observations with future X-ray missions will help us understand the environment near an accreting supermassive black hole (SMBH).

As one might expect, the region close to an accreting SMBH is complex, with many basic issues still unknown to us. At a fundamental level, the mass of most active SMBHs is very uncertain. Furthermore, there are essentially no robust indicators of black hole spin. Many models for the radio-loud/radio-quiet dichotomy of AGN postulate that the black hole mass and, especially, the spin are the control parameters that determine the radio-loudness of the object. However, without

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observational signatures of black hole masses and spins, it will be difficult or im-
possible to test such models. In addition, the physics governing the interaction
of the accreting matter with the SMBH is far from clear. Some of the outstanding
questions are:

1. Does the inner accretion disk in some objects become hot and geometrically-

thick (see Dr. Sambruna’s contribution in this volume for a suggestion that
this might be the case in broad line radio galaxies)?

2. Is the violently variable X-ray emission due to magnetic flares on the accre-
tion disk surface, or changes within a central corona sitting within the cold
accretion disk?

3. What happens within the radius of marginal stability? Does this region have
observational relevance? For example, Krolik (1999) recently suggested that
the magnetic field becomes very strong in this region, and as a result Alfén
waves might plausibly transport significant amounts of energy from this region
into an inner corona or the rest of the disk.

4. How are jets launched from the black hole region and collimated, and what
contribution do they make to the emissions observed from non-blazar AGN.

This article describes how future X-ray observations may attempt to disentangle
these phenomena.

2. CURRENT UNCERTAINTIES AND PURE SPECTRAL STUDIES

The accretion disk model is highly successful at explaining the X-ray reprocessing
spectrum observed in many AGN. A small number of AGN (MCG–6-30-15, Tanaka
et al. 1995; NGC 3516, Nandra et al. 1999; NGC 4151, Wang et al. 1999) have
been the subject of very long integrations with ASCA yielding high quality iron
line profiles which match the predictions of the accretion disk model well (Fabian
et al. 1995). However, there are still ambiguities present.

Firstly, a time-averaged iron line profile contains no information about the mass
of the central black hole. All parameters relevant to determining the line profile scale
with the gravitational radius. Secondly, and more interesting from an astrophysics
point of view, the line profile is sensitive to the X-ray source geometry, accretion disk
structure (including the region inside the innermost stable orbit), and the spin of the
SMBH. Degeneracies exists in the sense that different astrophysical assumptions and
space-time geometries can produce very similar iron line profiles. The best studied
element of this degeneracy is the case of the very-broad state of the iron line in
MCG–6-30-15 found by Iwasawa et al. (1996). Making the standard assumptions
that the line emission is axisymmetric, and there is only emission from outside of the
radius of marginal stability, Iwasawa et al. (1996) suggested that the SMBH in this
object must be rapidly rotating to produce a line as broad and redshifted as that
seen. Dabowski et al. (1996) computed grids of iron line profiles for various values
FIGURE 1. Density structure in a slice through an MHD simulation of disk accretion in a pseudo-Newtonian potential. The inner edge of the simulated wedge is at \( r = 4GM/c^2 \) and the outer edge is at \( r = 12GM/c^2 \). Strong clumping can be seen at all radii, and especially within the radius of marginal stability at \( r = 6CM/c^2 \). From Armitage & Reynolds (2000).

of the SMBH spin with the same assumptions and set a formal limit of \( \alpha > 0.94 \) on the spin of this SMBH. However, Reynolds & Begelman (1997) showed that the same iron line profile can result from a non-rotating SMBH if a high-latitude X-ray source illuminates disk material within the radius of marginal stability. This is an explicit demonstration of how uncertainties in the assumed astrophysics (e.g. the X-ray source geometry) leads to the degeneracy between models with very different space-time geometries (i.e. Schwarzschild vs. extremal Kerr). In a rather different vain, Weaver & Yaqoob (1998) showed that non-axisymmetric obscuration of the line emitting region could also reproduce these data.

The first question to address is whether better spectroscopy with much higher signal-to-noise and/or larger bandpass than ASCA and BeppoSAX will remove these degeneracies. Returning to the example of MCG–6-30-15, Young, Fabian & Ross (1998) showed that iron fluorescence from material within the radius of marginal stability would be accompanied by a large iron edge. While it is questionable whether the current ASCA data are of sufficient quality to rule out the presence of such an edge, one might think that this would be a tell-tale signature that could be used to distinguish the Schwarzschild and extremal-Kerr models for this object. However,
it is important to realize that such conclusions are at the mercy of extra epicycles of astrophysical theory. Both the Reynolds & Begelman (1997) and Young et al. (1998) models assume a smooth accretion flow within the radius of marginal stability. But strong magnetic fields in that region will inevitably produce clumping of the material which will in turn lower the ionization parameter of the material which produces the X-ray reflection signatures (Armitage & Reynolds 2000; also see Fig. 1). This, in turn, may diminish the depth of the iron edge that one would expect in the spectrum.

3. IRON LINE VARIABILITY
Spectral variability, and in particular variability of the broad iron line, is a powerful probe of AGN central engines. Many of the degeneracies described above can be broken by considering line variability. In this section, I shall distinguish three types of line variability and discuss how the study of each may help unravel the complexities of these systems.

3.1. Structural changes in the source
As has already been mentioned above, ASCA has already seen broad iron line variability in several objects, e.g. MCG–6-30-15 (Iwasawa et al. 1996) and NGC 4051 (Wang et al. 1999). Figure 2 shows the line variability in MCG–6-30-15 in which the line changed from its ‘normal’ state (shown with open squares) to a very broad and strong state (shown by filled circles). This change in line profile accompanied a sharp drop in the continuum flux level during an event that lasted at least 60 ksec (which is greater than the dynamical timescale \( t_{\text{dyn}} \) for the inner accretion disk by a factor of \( \sim 100 \) or more for any plausible SMBH mass; Reynolds 1999). Unless the occultation scenario of Weaver & Yaqoob (1998) is correct, some dramatic change in the structure of the accretion disk and/or the geometry of the illuminating X-ray source is required to produce such dramatic and long-lived line changes. Changes in the thermal structure of the disk, which occur on a timescale of \( t_{\text{th}} \sim t_{\text{dyn}}/\alpha \) (where \( \alpha \sim 0.1 - 0.01 \) is the standard viscosity parameter), may produce this type of variability.

Even given the long-lived nature of these events, ASCA cannot produce high signal-to-noise line profiles in the different states. This hampers our ability to probe details of the disk/corona variability using these line changes. XMM will completely change this situation. With an effective area at iron line energies more than a factor of 10 greater than ASCA, very high quality iron line profiles will be obtained at different times as a source such as MCG–6-30-15 undergoes one of these events. While I dare not predict what these observations will find, these studies will undoubtedly revolutionize our understanding of the kind of instabilities suffered by the inner accretion disk and X-ray emitting corona.
FIGURE 2. Iron line variability in MCG–6-30-15 detected by ASCA by Iwasawa et al. (1996). The open squares show the ‘normal’ state of the line whereas the filled circles show the ‘very-broad’ state of the line, during which time the continuum level was seen to drop dramatically.
3.2. Orbiting flares

The X-ray emission from most AGN is observed to be highly variable on timescales down to (our best estimate for) the dynamical timescale. Whether the X-ray emission is due to magnetic flares exploding out of the accretion disk or some other instability in a hot disk corona, the instantaneous X-ray emission is likely to be non-axisymmetric. If these non-axisymmetric structures are long lived (i.e. survive at least a couple of dynamical timescales), the iron line will be observed to undergo distinct profile changes as the system orbits the central SMBH.

The computation of observables from an orbiting hot-spot on an accretion disk around a black hole is a classical problem and has been worked on by many authors (e.g. Ginzburg & Ozernoi 1977, Bao et al. 1994, Bromley et al. 1997). Most recently, Ruszkowski (1999; also see contribution in this volume) has computed the observed iron line variability when it is powered by an X-ray flare that is co-rotating with the disk. XMM should be able to track these profile changes and measure several key parameters. Firstly, the period and amplitude of energy variations in the peak energy of the iron line are an easy and robust way of determining the black hole mass. Note that the inclination can be measured from the time-averaged iron line profile and so is a known quantity in this calculation. Secondly, departures from sinusoidal time-dependence of the iron line peak can be attributed to relativistic effects and used to probe, for example, the spin parameter of the black hole. Such observations may yield signatures of a spinning black hole: if iron line variations are found that imply a flare orbiting on a circular orbit at a radius less the Schwarzschild radius of marginal stability \( r = 6GM/c^2 \), a rapidly rotating black hole is will be implied.

3.3. Reverberation

If some X-ray flares are very short lived, or activate rapidly (as compared to the light-crossing time of the inner accretion disk), line profile changes due to the finite speed of light will occur. This then raises the possibility of performing ‘reverberation mapping’ of the central regions of the SMBH accretion disk (Stella 1990; Reynolds et al. 1999).

In principal, reverberation provides powerful diagnostics of the space-time geometry and the geometry of the X-ray source. When attempting to understand reverberation, the basic unit to consider is the point-source transfer function, which gives the response of the observed iron line to an X-ray flash at a given location. As a starting point, one could imagine studying the brightest flares in real AGN and comparing the line variability to these point-source transfer functions in an attempt to measure the SMBH mass, spin and the location of the X-ray flare. By studying such transfer functions, it is found that a characteristic signature of rapidly rotating black holes is a ‘red-tail’ on the transfer function. This feature corresponds to highly redshifted and delayed line emission that originates from an inwardly moving ring of illumination/fluorescence that asymptotically freezes at the horizon (see Reynolds et al. 1999 for a discussion of this feature).
FIGURE 3. *Constellation-X* simulations of iron line reverberation. Panel (a) shows the case of a rapidly rotating SMBH whereas panel (b) shows a non-rotating SMBH. In both cases, an X-ray flash on axis at a height of $10GM/c^2$ has been assumed and the iron line response calculated for an accretion disk inclination (away from normal) of $30^\circ$. Sequential 1000s *Constellation-X* observations of the time varying iron line are then simulated, continuum subtracted, and stacked in order to make an observed transfer function. Figure from Young & Reynolds (1999).

The primary observational difficulty in characterizing iron line reverberation will be obtaining the required signal-to-noise. One must be able to measure an iron line profile on a timescale of $t_{\text{reverb}} \sim GM/c^3 \approx 500M_8\text{s}$, where we have normalized to a mass of $10^8M_\odot$. This requires an instrument such as *Constellation-X*. Figure 3 shows that *Constellation-X* can indeed detect reverberation from a bright AGN with a mass of $10^8M_\odot$. Furthermore, the signatures of black hole spin may well be within reach of *Constellation-X* (Young & Reynolds 1999). Although these simulations make the somewhat artificial assumption that the X-ray flare is instantaneous and located on the axis of the system, it provides encouragement that reverberation signatures may be observable in the foreseeable future.

Of course, the occurrence of multiple, overlapping flares will also hamper the interpretation of iron line reverberation. The best way to disentangle these flares is still the subject of current work. However, *Constellation-X* may have the required signal to noise to allow the direct fitting of multiple transfer functions to real data (see Young & Reynolds 1999).

4. DIRECT IMAGING OF BLACK HOLE ACCRETION DISKS

I will end by briefly discussing an exciting idea which will allow us to image the central regions of nearby AGN with sufficient angular resolution to probe structure on scales smaller than the size of the event horizon. By combining diffraction limited X-ray optics with the interferometric technologies that are currently being developed for the Space Interferometer Mission (*SIM*), it is within our technological
FIGURE 4. Theoretical image of a nearly edge-on accretion disk around a Schwarzschild black hole. The hole in the center of the image corresponds to the radius of marginal stability at $r = \frac{6GM}{c^2}$. The distortions in the image of the far side of the accretion disk are due to strong light bending effects. In the future, X-ray Interferometry will allow us to obtain such images for real systems.

reach to construct an X-ray interferometer capable of achieving sub-microarcsecond resolution (this concept has become known as MAXIM, the Micro-arcsec X-ray Interferometer Mission; see [http://maxim.gsfc.nasa.gov]).

As well as the obvious appeal of directly imaging an accreting black hole, an observatory capable of achieving $0.1\mu$ arcsec would yield major scientific return. The geometry of the X-ray source (and the spatial nature of the X-ray flares) would be open to direct imaging studies. X-ray activity or fluorescence from within the radius of marginal stability could be easily seen (this region would be well resolved). We might also expect there to be X-ray emission from the base of the jet in the region where the magnetic field couples to the black hole spin via the Blandford-Znajek process. Such emission could be imaged, thereby providing the first look at these exotic physical mechanisms at work. If an interferometer can be constructed with sufficient effective area, we will be able to use the fluorescent iron line to make detailed velocity maps across the image. These velocity fields would provide direct constraints of the black hole mass and spin, and implicitly provide a stringent test of strong field General Relativity.

5. CONCLUSIONS

The immediate environment of an accreting supermassive black hole is extremely exotic. Broad iron lines provide us with the best tool to date for studying these regions. ASCA and BeppoSAX observations have already shown us that the accretion disk in at least some AGN extends very close to the black hole (and maybe so close as to suggest that the black hole must be rotating). Furthermore, the detection of broad iron line variability by ASCA is most likely tracking structural changes in the accretion disk and/or X-ray emitting corona. However, large effective area
detectors are required to make further progress. XMM will allow these structural changes to be characterized in detail, thereby probing the instabilities that affect the inner accretion disk/corona. Furthermore, XMM will allow us to study iron line variability caused by the accretion disk rotation, allowing us to measure the mass of the black hole and constrain the location/lifetime of the X-ray flares. Eventually, Constellation-X will allow us to search for iron line reverberation. The detection of reverberation will give robust signatures of black hole spin and provide the tools to study the inner disk structure in unprecedented detail.

Further in the future, direct imaging of the inner disk and black hole region in nearby AGN will be possible using X-ray interferometry. This will provide the ultimate observational probe of black hole astrophysics.

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