Black Hole Spin in AGN and GBHCs

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Abstract. We discuss constraints on black hole spin and spin-related astrophysics as derived from X-ray spectroscopy. After a brief discussion about the robustness with which X-ray spectroscopy can be used to probe strong gravity, we summarize how these techniques can constrain black hole spin. In particular, we highlight XMM-Newton studies of the Seyfert galaxy MCG–6-30-15 and the stellar-mass black hole GX 339–4. The broad X-ray iron line profile, together with reasonable and general astrophysical assumptions, allow a non-rotating black hole to be rejected in both of these sources. If we make the stronger assertion of no emission from within the innermost stable circular orbit, the MCG–6-30-15 data constrain the dimensionless spin parameter to be $a > 0.93$. Furthermore, these XMM-Newton data are already providing evidence for exotic spin-related astrophysics in the central regions of this object. We conclude with a discussion of the impact that Constellation-X will have on the study of strong gravity and black hole spin.

1. Introduction

With evidence for the existence of black holes and the dynamical measurement of their mass becoming almost passé, an increasing focus is being placed on detecting the effects of black hole spin. Spin truly is a creature of the relativistic Universe, and the observational investigation of spin puts us one step closer to being able to genuinely test strong-field General Relativity (GR). Even if GR passes all of these tests (which, of course, would be the most “boring” possibility), black hole spin gives us crucial insight into how black holes of all masses are born, and may well be an important ingredient in powering some of the most energetic sources in the Universe.

At the current time, the best evidence for the effects of black hole spin come from X-ray observations, both timing and spectroscopy. X-ray variability studies, particularly investigations of quasi-periodic oscillations (QPOs) have produced tantalizing hints that we might be witnessing the effects of black hole spin (Stella, Vietri & Morsink 1999; Strohmayer 2001). However, the lack of any agreed upon theoretical framework for the high-frequency QPOs prevents us from drawing robust conclusions at this time. For this reason, the most compelling studies of black hole spin have originated from X-ray spectroscopy.

In this contribution, we describe constraints on black hole spin from X-ray spectroscopy. We will align our discussion around three questions;
“Have we seen the effects of strong gravity at all?”, “Have we seen the effects of black hole spin?”, and “Can we probe the exotic astrophysics associated with spinning black holes?” For the impatient reader, the answers to these questions are “Yes!”, “Very probably”, and “We’re maybe just starting to...”. We conclude by discussing future prospects for probing black hole spin and testing strong-field GR with both X-rays and gravitational waves.

2. Strong gravitational effects in X-ray spectra

The principal spectroscopic tool used to date to study strong gravity is the characterization of the broad iron-Kα fluorescent emission line (see reviews by Fabian et al. 2000 and Reynolds & Nowak 2003). The essential physics underlying this phenomenon is straightforward. Moderate-to-high luminosity black hole systems accrete via a radiatively-efficient disk. Even in the region close to the black hole, such a disk will (apart from a hot and tenuous X-ray emitting corona) remain optically-thick, geometrically-thin, almost Keplerian, and rather cold ($T < 10^7$ K). X-ray irradiation of the surface layers of the disk by the corona will excite observable fluorescence lines, with iron-Kα being most prominent due to the combination of its astrophysical abundance and fluorescent yield. This emission line is then subject to extreme broadening and skewing due to the both the normal and transverse Doppler effect (associated with the orbital velocity of the disk) as well as the gravitational redshift of the black hole (see Fig. 1).

So, have we seen these effects in the X-ray spectra of real accreting black holes? Broad emission features that can be modeled as iron emission lines from the central regions of a Keplerian accretion disk are present in the XMM-Newton data for over half of the moderate-to-high luminosity Seyfert galaxies, as well as many Galactic Black Hole Candidates (GBHCs) in their intermediate and high state. Given the breadth of these features, it is valid to ask whether continuum curvature and/or unmodeled complex absorption might be mimicking a broad emission line. In some cases, detailed scrutiny of high signal-to-noise XMM-Newton data allows one to reject these alternatives, further validating the relativistic line interpretation (e.g. MCG–6-30-15 [Vaughan & Fabian 2004, Reynolds et al. 2004, also see Fabian et al. 1995], GX 339–4; Miller et al. 2004). In other cases, absorption by large columns of photoionized material appears to be important. In the case of NGC 4151, for example, much of the broad iron line reported by Wang et al. [1999] was probably an artifact of not modeling the complex absorber later identified by Schurch & Warwick (2002) and Schuch et
al. (2003). In many other cases, the role that complex absorption has on the presence of a broad iron line remains uncertain. It is important to stress, however, that the role of photoionized absorption in masking or mimicking broad iron lines is knowable, and will be elucidated by the high-resolution and high count-rate spectra that Astro-E2 will be obtaining on a regular basis starting in early 2005.

To summarize this section, there are robust examples of broad iron emission lines that are giving us a clean probe of the strong gravity region around both stellar and supermassive black holes. However, while broad iron lines are not rare, the precise fraction of objects in the various classes of accreting black holes that display these features is still uncertain. In addition to obtaining new high-resolution and high count-rate spectra with Astro-E2, significant progress is possible in this field via a large and unbiased survey of current XMM-Newton data.

3. Constraining black hole spin with X-ray spectroscopy

Having established that at least some accreting black holes display broad iron lines that cleanly probe the strong gravity region, we now ask whether we can constrain the black hole spin using these features. To sharpen the discussion, we will address whether one can rule out a Schwarzschild metric (i.e., non-spinning black hole) for any given black hole system.

Even with XMM-Newton, we cannot probe the iron line on the dynamical timescale of the very centralmost regions of the accretion disk where spin effects are dominant. We are driven to study line profiles that have been time-averaged over several dynamical timescales — hence, our primary information on black hole spin at the current time will originate from the breadth and redshift of these time-averaged line profiles.

There is a common misconception that rapidly spinning black holes invariably produce broader and more highly redshifted emission lines than slowly spinning black holes. This stems from the fact that the innermost stable circular orbit (ISCO; $6GM/c^2$ for a non-rotating black hole) for a prograde accretion disk pulls-in towards the horizon as the spin-parameter of the black hole is increased. Hence, the line broadening will increase with black hole spin if the line emission is always truncated at the ISCO. But it is important to realize that we can produce arbitrarily redshifted and broadened emission lines from around even a non-rotating black hole if nature had the freedom to produce line emission from any radius beyond the horizon (Reynolds & Begelman 1997). This discouraging fact has led some authors to conclude that
current iron line profiles contain essentially no information on the black hole spin (Dovciak, Karas & Yaqoob 2004).

This would be an overly bleak assessment of our ability to constrain black hole spin. Even the application of some rather weak (i.e., general) astrophysical constraints can impose an inner limit on the radii at which spectral features can be produced. In order to produce any significant iron emission line from the region within the ISCO (which we shall refer to as the plunging region), the disk in this region must be optically-thick, not too highly ionized (i.e., a significant fraction of the iron cannot be fully ionized), and illuminated by the hard X-ray continuum. While much work remains to be done on the physical state of matter in the plunging region, it is challenging to construct a model for a non-rotating black hole in which there are appreciable spectral features produced by matter inside of $4-5GM/c^2$ (Reynolds & Begelman 1997). If we require an emitting radius less than this when fitting a non-rotating black hole model to a particular dataset, we can claim to have found good evidence for a spinning black hole.

This is exactly the situation we find when attempting to fit the XMM-Newton data for the Seyfert-1 galaxy MCG–6-30-15. The June-2000 observation of this source (reported by Wilms et al. [2000] and Reynolds et al. [2004]) caught it in its enigmatic “Deep Minimum State” first identified with ASCA data by Iwasawa et al. (1996) during which the iron line is known to be particularly broadened and red-shifted. Fitting the Reynolds & Begelman (1997) Schwarzschild iron line model which includes emission from within the plunging region results in essentially all of the emission being placed at $3GM/c^2$. It is extremely hard to understand how this could be a physical result — the relativistic inflow at this location demands (through mass continuity) that the density be low and, hence, that this material be completely photoionized if it were to experience the irradiation suggested by this fit. Thus, the extreme parameters derived from a fit to a Schwarzschild-based model leads to the conclusion that we are seeing the effects of black hole spin.

Given an observation of a very broad iron line such as that detected in the Seyfert-1 galaxy MCG–6-30-15 or the GBHC GX 339–4 (Miller et al. 2004), we can place constraints on the black hole spin given certain astrophysical assumptions. The systematic exploration of these constraints has only just begun and is still a work in progress. To facilitate this work, we have constructed a new iron line profile code kerr (that employs the Kerr metric ray-tracing code of Speith, Riffert & Ruder 1995) which treats the black hole spin as a free parameter. This code also takes advantage of modern computing speeds and performs the necessary calculations in real time as the spectrum is being fit.
Figure 1. Theoretical lines profiles from a Keplerian accretion disk around a Kerr black hole. We assume an observed inclination angle of $i = 40^\circ$ and a line emissivity that falls off as $r^{-3}$ between the ISCO and $r_{\text{out}} = 50GM/c^2$.

with xspec. The user may therefore tune the spectral resolution and numerical accuracy of the model to suit the data at hand, a feature that is not available in the tabular models such as laor that have been extensively employed to date.

Preliminary fitting of kerr to the highest signal-to-noise data for MCG–6-30-15 (from the June-2001 observation) demonstrates that the black hole must possess a dimensionless spin parameter of $a > 0.93$ (Brenneman & Reynolds, in prep) if we impose the condition that no spectral features are produced from within the ISCO. See Fig. 1 for examples of line profiles calculated under this assumption. Current work is focused on obtaining spin constraints once that assumption is relaxed. Note that these fits assume a broken power-law form for the line emissivity as a function of radius. Hence, our limit of $a > 0.93$ is a stronger constraint than the $a > 0.94$ deduced by Dabrowski et al. (1997) from ASCA data who assumed the line emissivity tracks the radial dissipation profile of a “standard” (Novikov & Thorne 1974; Page & Thorne 1974) accretion disk. As will be discussed below, the XMM-Newton data are of sufficient quality to actually falsify the Dabrowski et al. assumption.
4. The exotic astrophysics of spinning black holes

Rapidly-spinning black holes are undoubtedly amongst the most exotic objects in the current-day universe. In this section, we focus on one particular facet of their behaviour — the magnetic interactions between the spinning black hole and surrounding matter including the accretion disk. We argue that XMM-Newton data are already hinting at evidence for the magnetic extraction of spin energy from the black hole in MCG–6-30-15.

Analytic (Krolik 1999, Gammie 1999) and numerical (Hawley & Krolik 2001, Reynolds & Armitage 2002) studies have shown that magnetic forces can couple material within the plunging region to the body of the accretion disk, thereby extracting energy and angular momentum from that region. In an extreme limit, a Penrose process\(^\dagger\) might be realized in which the innermost regions of the accretion flow are placed on negative energy orbits by these magnetic torques (Agol & Krolik 2000). Together with any Blandford-Znajek process (Blandford & Znajek 1977) that might result from field lines directly connecting to the (stretched) horizon, these magnetic torques can in principal extract a black hole’s spin energy, depositing it either in the body of the disk or in the form of an outflow of mass and/or Poynting flux. Note that all of this behaviour is in stark contrast to standard black hole disk models (Shakura & Sunyaev 1973, Novikov & Thorne 1974, Page & Thorne 1974) in which material follows conservative orbits once inside the ISCO.

Can we see evidence for any of these processes in the current data? Again, we return to the Deep Minimum State of MCG–6-30-15 which displays one of the broadest and most highly redshifted iron lines known. This immediately tells us that the X-ray reflection features are originating from a region that is extremely centrally-concentrated in the accretion disk. For the moment, we assume that the primary continuum X-ray source is located a small distance above the disk surface (the “local corona approximation”) and radiates a fixed fraction of the energy dissipated in the underlying disk. Then, even assuming a near-maximal rotating black hole (with \(a = 0.998\)), these data cannot be adequately described with a model consisting of a standard Novikov & Thorne (1974) accretion disk — the model simply cannot reproduce the centrally concentrated emission pattern inferred from these data (Fig. 2a). One can attempt to rescue the standard disk model by supposing that a larger portion of the total dissipation in the disk is channeled into the X-ray emitting corona as one moves to smaller radii.

\(^\dagger\) We note that Williams [2003] has also argued for the importance of a non-magnetic, particle-particle and particle-photon scattering mediated Penrose process.
However, since 30–50% of the bolometric power of MCG–6-30-15 seems to emerge through the X-ray emitting corona, one cannot decouple it entirely from the dissipation distribution. In the most extreme model (which provides an adequate but not the best fit to the data), all of the dissipated energy is channeled into the X-ray emitting corona within the central $5GM/c^2$, while the X-ray production efficiency is zero beyond that radius.

Our best-fitting model consists of a strongly torqued accretion disk in which the extreme central concentration originates from a magnetic torque by the plunging region or the rotating black hole (Reynolds et al. 2004; Fig. 2b) — the work done by the torque is dissipated in the main body of the accretion disk and, with some efficiency, energizes the inner regions of the X-ray emitting corona. If this is really the correct description of the physics at play, the data argue that the accretion disk is in an extreme torque-dominated state, i.e., the disk is predominately shining through the release of black hole spin energy.

MHD simulations suggest that magnetic connections between the plunging region and the body of an accretion disk tend to be rather sporadic. It is then tempting to identify MCG–6-30-15’s transition into the Deep Minimum State as the (temporary) onset of a significant inner torque. The fact that the overall luminosity of a disk necessarily increases when an inner torque is applied (due to the dissipation of the extra work done by the inner torque), in contrast to X-ray flux drop observed during the Deep Minimum State, may be a problem for this model. However, the enhanced returning radiation associated with the torque-induced emission will strongly Compton cool the X-ray corona.

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*Figure 2.* Broad iron line fit assuming that the line emission tracks the underlying disk dissipation of (a) a standard (Novikov & Thorne 1974) accretion disk and, (b) an Agol & Krolik (2000) torqued accretion disk. Modified from Reynolds et al. (2004).
leading to a steepening of the X-ray continuum and (possibly) a large-
scale condensation-driven collapse of the corona. Such effects may be
responsible for the X-ray flux decrease (Garofalo & Reynolds 2004).

It is also possible that the local-corona approximation is not valid.
If the X-ray emitting source is a significant height above the optically-
thick part of the accretion disk, the hard X-ray continuum photons
will be gravitationally focused into the central regions of the accretion
disk (see Andy Fabian’s contribution in these proceedings). Aspects of
this scenario have been explored by many authors including Martocchia
& Matt (1996), Reynolds & Begelman (1997) and Miniutti & Fabian
(2004). This suggests an alternative picture in which the Deep Mini-
imum State is produced when the X-ray source is located at mid/high
latitudes very close to the black hole. The centrally concentrated X-
ray reflection results from the gravitational focusing, and the decrease
in the observed continuum X-ray flux is a natural consequence of the
fact that the continuum photons are focused away from the observer
(Reynolds & Begelman 1997; Miniutti & Fabian 2004). We note that
this scenario does not diminish the need for exotic spin-related astro-
physics — the base of a spin-driven magnetic jet is an obvious candidate
for this elevated continuum X-ray source.

5. Conclusion and the future of black hole studies

Current data are already allowing us to probe black hole physics within
a few gravitational radii of the event horizon, and may well be giving
us the first observational glimpses of physics within the ergosphere.
But this is just the beginning of X-ray astronomy’s exploration of
strong gravity, not the end of the road. The enormous throughput
of Constellation-X will allow us to probe detailed time variability of
the iron line. Dynamical timescale line variability, an easy goal for
Constellation-X, will allow us to follow non-axisymmetric structures in
the disk as they orbit (Armitage & Reynolds 2003; also see Iwasawa,
Miniutti & Fabian [2003] for the first hint of such structure in XMM-
Newton data). This gives us a direct probe of an almost Keplerian
orbit close into a black hole. Furthermore, line variability on the light
crossing time will allow us to probe relativistic reverberation signatures
(Reynolds et al. 1999; Young & Reynolds 2000), essentially giving us
a direct probe of the null geodesics in the space-time. Together, these
variability signatures will allow true tests of strong-field GR.

There is no compelling reason to believe that GR fails on the macro-
scoplic scales probed by either X-ray or gravitational wave studies of
astrophysical black holes. In the event that GR is verified, both X-ray
and gravitational wave observations will allow unambiguous measurements of black hole spins. Gravitational wave observations with \textit{LISA} of a stellar mass black hole spiraling into a $10^6 M_\odot$ black hole (a so-called Extreme Mass Ratio Inspiral; EMRI) will allow precision measurement of the supermassive black hole’s spin as well as tests of the no-hair theorem and the Kerr metric. The event rates of such sources is quite uncertain, however, partially due to the recent evidence for “anti-hierarchical” black hole growth (e.g., Marconi et al. 2004) and its implications for the number density of $10^6 M_\odot$ black holes in the cosmic past. X-ray spectroscopy with \textit{Constellation-X} provides a crucial parallel track of study in which we can obtain measurements of black hole spin across the whole mass range of astrophysical black holes (i.e., stellar, intermediate, and supermassive) using spectral features that are already known to exist. Only then can the demographics and astrophysical relevance of black hole spin truly be gauged.

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