Irradiation of an Accretion Disk by a Jet: Spin Measurements of Black Holes

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X-ray irradiation of an accretion disk around a black hole leads to strong fluorescent reflection features, which are then broadened and distorted by relativistic effects. Analyzing the shape of this reflection spectrum allows to determine the spin of the black hole. Generally, broad reflection features are identified with rapidly spinning black holes. As the shape also depends on the location and size of the irradiating source, we study how different irradiation geometries affect the determination of the spin. We find that broad reflection features are produced only for compact irradiating sources situated close to the black hole. This is the only case where the black hole spin can be determined unambiguously. In all other cases the line shape is narrower, which could either be explained by a low spin or an elongated irradiating source. Hence, for those cases no unique solution for the spin exists and therefore only a lower limit of the spin value can be given.

1 Introduction

In Active Galactic Nuclei (AGN) and Galactic Black Holes (GBH) X-rays are emitted very close to the central compact object. Some of this radiation is intercepted by gas in the accretion disk around the black hole, in a process called "X-ray reflection". Because the reflected spectrum comes from the inner parts of the accretion disk, it shows signs of relativistic effects (Fabian et al. 1989)[6]. The strongest X-ray reflection feature observed in these objected is the fluorescent Fe Kα line at 6.4 keV. This is the reason why a relativistically distorted line shape could first be seen by analyzing solely this reflection feature (Tanaka et al. 1995[25]; Reynolds at al. 2003[2[illegible]]; and references therein). In the past decade, such "relativistic lines" have been observed in many GBH (Miller 2007[16]; Duro et al. 2011[5]; Fabian et al. 2012[7]) and AGN (Guainazzi, Bianchi & Dovčiak 2006[12]; Nandra et al. 2007[18]; Patrick et al. 2011[19]) systems. Recently a more self-consistent approach has been used (see, e.g., Zoghbi et al. 2010[29]; Duro et al. 2011[5]; Fabian et al. 2012[8]; Dauser et al. 2012[3]), where the relativistic effects were applied to the full reflection spectrum. These reflection spectra are calculated by detailed simulations (`relionx`, Ross & Fabian 2007[22]; `xillver`, Garcia et al. 2013[11]) and also allow for an ionization of the accretion disk.

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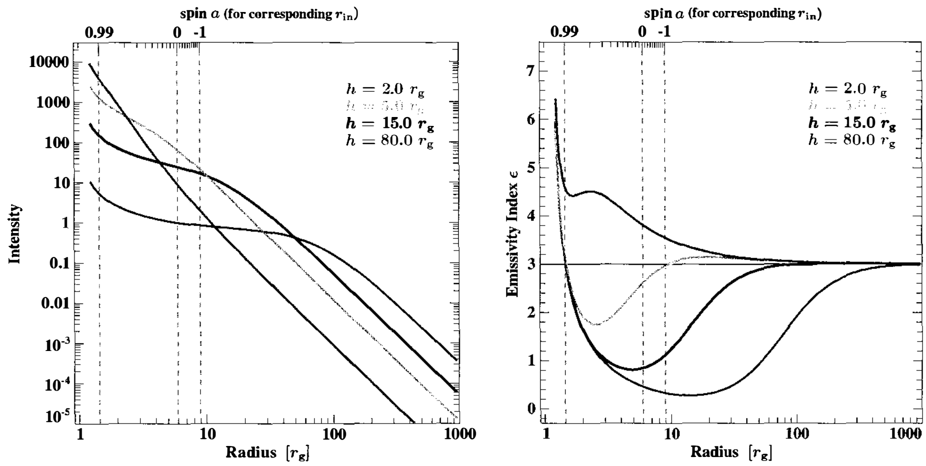

Figure 1: The irradiated intensity I on the accretion disk (left) and the emissivity index ϵ (right), which are connected by the relation $I \propto r^{-\epsilon}$. Note that for large radii all emissivity profiles converge towards the canonical value of r^{-3}. We assume that the primary spectrum has a spectral shape $\propto E^{-\Gamma}$ with $\Gamma = 2$, which is a common value for AGN.

2 A jet irradiating the accretion disk

The shape of the relativistically distorted line depends on parameters like the black hole spin a, or the inclination of the system. Additionally, also the location and size of the primary source of radiation does affect the line profile. Initially, the idea was that a corona of hot electrons around the inner accretion disk produces the primary radiation by Comptonization of soft disk photons, as this leads to the observed shape in form of a power law (Haardt 1993[13]). In the simplest case, this leads to an intensity irradiating the disk which is proportional to r^{-3} (Shakura & Sunyaev 1973)[23]. However, in more detailed spectra (e.g., by *XMM-Newton*) a much steeper emissivity at the inner parts of the disk was found for most sources (e.g., Wilms et al. 2001[28]). Further interpretation of the hard X-ray source may be a the base of a jet or the jet itself, emitted along the rotational axis of the black hole. Such a setup can also describe the power law continuum generally observed in black hole systems (Markoff & Nowak 2004[14]). Moreover the strong light bending effects close to the black are capable in explaining the observed anti-correlation in flux between the direct and the reflected radiation (e.g., Miniutti et al. 2003[17]). Finally, the steep emissivity observed is naturally predicted by the jet base geometry (see, e.g., Fukumura et al. 2007[10]; Wilkins & Fabian 2012[27]; Dauser et al. 2013[2]).

In order to analyze the impact of the jet base geometry, we calculate the irradiation of the disk for different heights of the jet base. The general relativistic calculations used for the following results are presented in more detail in Dauser et al. (2013)[2] and are based on the `relline`-code (Dauser et al. 2010)[4]. Figure 1 shows how the irradiated intensity I and the emissivity index ϵ, which is defined by $I \propto r^{-\epsilon}$, evolves with distance to the black hole and depending on the height of the jet base. Generally one can see that for larger heights of the jet base, there is a growing zone on the accretion disk which gets irradiated by the same intensity ($\epsilon \approx 0$). Using a similar approach, one can also simulate the irradiation of a jet, which is extended along the rotational axis of the black hole. Such an extended jet produces an irradiation profile, which is similar to a jet base at an intermediate height (detailed description and results can be found in Dauser et al. 2013[2]).

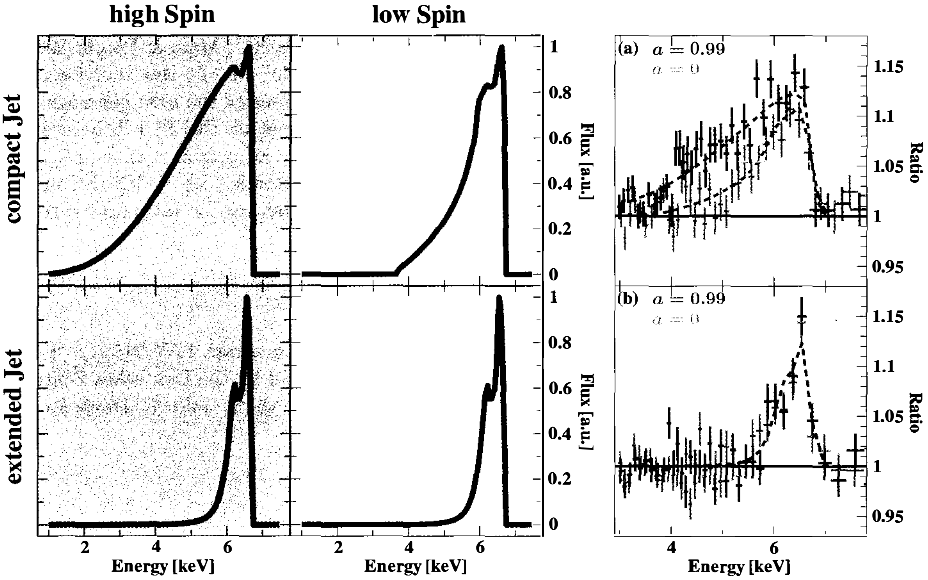

Figure 2: (left) Line profiles for high and low spin ($a = 0.99$ and $a = 0$) and a compact (point source at $3\,r_g$) and an extended jet (3-$100r_g$). (right) Simulated 100 ksec *XMM-Newton* observation for a compact source (a) and an extended jet (b). Figure adapted from Dauser et al. (2013).

3 Determining the Spin

The relativistic line profile also depends on the spin of the black hole, as the location of the inner edge of the accretion disk strongly depends on the spin. Namely, for high spin the accretion disk extends to smaller radii. Photons reflected in this additional area are shifted to lower energies due to the strong gravitational redshift and therefore broaden the line shape (see, e.g., Dauser et al. 2010[4]). Hence, we associate broad reflection features with highly spinning black holes (upper panel in Fig. 2). However, this is only true for a compact emission region. Figure 2 also shows that if we allow the primary emission region to be extended, the resulting relativistic line will be narrow, independent of the spin of the black hole. Hence, only for a compact emission region close to a rapidly rotating black hole, a broad line will be observed. Simulations of observations with current X-ray satellites (see Fig. 2, right column) reveal that for a compact emission region we are able to distinguish between low and high spin, while for an extended source there is little difference expected in the spectrum.

4 Conclusions

We showed that if we observe a broad emission line, we are in principle able to measure the spin of this object. Such observations also indicate that the emission region of the primary source must be compact and at low height and that the black hole is rapidly rotating. Simulations also revealed that an observation of a narrow relativistic reflection feature alone does not allow to draw firm conclusions on the spin from spectral fitting alone, as such a feature is not sensitive on the spin if produced by an extended primary source. Hence, if we wrongly assume a compact emission region in this case when modeling such data, the wrong spin may be determined. We therefore conclude that in order constrain the spin from a narrow reflection feature, additional information on the geometry of the system are necessary. Such information can be provided by a time lag analysis (so-called "reverberation mapping"), where the time difference between the primary and reflected radiation is measured (see, e.g., Stella 1990[24]; Matt & Perola 1992[15]; Reynolds et al. 1999[21]; Uttley et al. 2011[26]; and references therein). While this reverberation could only be measured for a few sources yet, the large collection area of the next generation of X-ray satellites (*LOFT*, Feroci et al. 2012[9]; *ATHENA+*, Barcons et al. 2012[1]) will be able to determine the emission geometry for a larger sample of AGN. The new extension of the `relline` model[b], presented in Dauser at al. (2013)[2], allows to model an extended jet. With this model the uncertainties on the size and the location of the emission region can be estimated directly for the first time by spectral analysis.

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[b]download at `http://www.sternwarte.uni-erlangen.de/research/relline/`