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The Broad Fe Kα Line in MCG–6-30-15

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Abstract. Fluorescent iron Kα lines in active galactic nuclei serve as probes for the behavior of material under the extreme conditions close to the supermassive black hole. We discuss the evidence for such relativistic effects in observational data from Seyfert galaxies taken with the EPIC cameras on board *XMM-Newton*.

Key words. black hole physics - galaxies: active - accretion, accretion disks

1. Introduction

One of the "holy grails" of modern astrophysics is the search for observational evidence of the existence of black holes (BHs). A first step towards finding this "holy grail" would be the proof that the behavior of material close to large mass concentrations is consistent with what is predicted by general relativity. X-ray observations of Fe Kα lines from active galactic nuclei (AGN) are currently one of the most likely means to achieve this goal. In this contribution we first describe how broad Fe Kα lines are produced (§2) and then give an overview of our results from *XMM-Newton* guaranteed time observations of the broad Fe Kα line source MCG–6-30-15 (§3).

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2. Relativistic Fe Kα Lines

In the standard model of AGN, 1–2 $M_\odot\,\mathrm{yr}^{-1}$ accrete via an accretion disk onto a central supermassive BH (Antonucci, 1993, and therein). The detailed structure of the accretion flow is unknown. While the disk has likely a thermal spectrum – which is observed as the "big blue bump" in the UV and the soft X-rays – X-ray data show a further hard power law component that turns over into an exponential cutoff at $\sim$100 keV. Current thought is that this hard component is due to Comptonization of soft disk photons in a hot electron gas – the "accretion disk corona" (ADC) – which surrounds the disk (e.g., Haardt et al., 1997, see also Fig. 1). A possible origin of the ADC are the MHD instabilities thought to be responsible for the viscosity of the accreting material (Balbus & Hawley, 1998). Efficient Compton cooling of the electrons prevents the formation of an ADC which fully covers the accre-

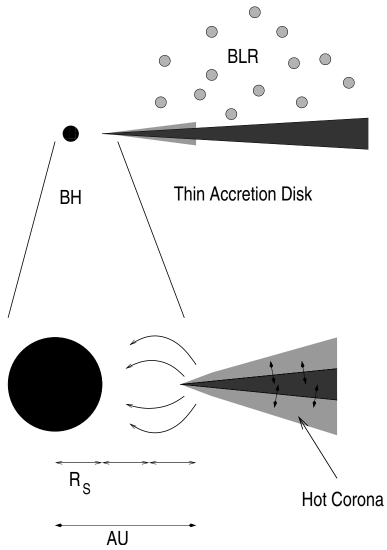

Fig. 1. Sketch of the inner region of an AGN accretion disk.

tion disk, so that patchy coronae or geometries where the disk and the ADC are separated are more likely (e.g., Dove et al., 1997).

Regardless of the geometry, a fraction of the hard ADC photons are expected to be intercepted by the disk. These photons are either downscattered by electrons in the accretion disk, or absorbed by the accretion disk material. The detailed physics of this process strongly depends on the ionization state of the accretion disk (see, e.g., Ballantyne et al. 2002 and Nayakshin & Kallman 2001), however, the X-ray spectrum from a disk irradiated by a power-law is roughly characterized by a Compton reflection hump peaking at ~30 keV (Lightman & White, 1988). Below ~10 keV, this "Compton reflection hump" is dominated by absorption and fluorescent line emission. The most prominent of these lines is the Fe Kα line at ~6.4 keV, which provides a very distinct spectral feature.

Since the reprocessing features (Fe Kα line and reflection hump) come from close to the BH, distant observers are able to see the influence of the large speeds (the Keplerian speed at the innermost stable circular orbit is a significant fraction of the speed of light) and the effects of strong gravity in the observed X-ray spectrum. As a result of these effects, the observed Fe Kα line shape is strongly broadened and skew-symmetric. As is shown elsewhere (e.g., Reynolds & Nowak, 2003; Wilms et al., 1998, and therein), the study of the Fe Kα line profile allows in principle the determination of the BH's angular momentum and of the Fe Kα emissivity.

The first secure detection of a relativistic Fe Kα line came from a long *ASCA* observation of the Seyfert galaxy MCG−6-30-15 (Tanaka et al., 1995). Later observations showed that broadened Fe Kα lines are common in the X-ray spectra of Seyfert galaxies (e.g., Nandra et al., 1997; Molendi et al., 1997; Lee et al., 1998). With the *Chandra* HETGS and the *XMM-Newton* EPIC, these earlier results have been confirmed and extended, e.g., with new detections of broad lines in sources such as the Seyfert 1.9 galaxy MCG−5-23-16 (Dewangan et al., 2003) or the quasar Q0056−363 (Porquet & Reeves, 2003). At the same time, some AGN thought to exhibit broad lines were shown to have more complex spectra (e.g., Reeves, 2003).

3. *XMM-Newton* Observations of MCG−6-30-15

With the launch of *XMM-Newton* in 1999, an instrument allowing one to measure the properties of Fe Kα lines with ~150 eV resolution and a high signal-to-noise ratio has become available. It was thus natural to use the *XMM-Newton* guaranteed time (GT) to further our understanding of MCG−6-30-15 with a 100 ksec long observation of the source in 2000 June. Luckily enough, the *XMM-Newton* GT observation caught the AGN during a time of low flux, where the Fe Kα line was expected to be broad (Iwasawa et al., 1996). Here, we summarize our Fe Kα line results from this observation, see Wilms et al. (2001) and Reynolds et al. (2004) for more detailed information. We note that a second and longer *XMM-Newton* observation of MCG−6-03-15 was performed as part of *XMM-Newton*'s open time program in 2001 July and August, when the source was 70% brighter than in the GT observation. The main results of the

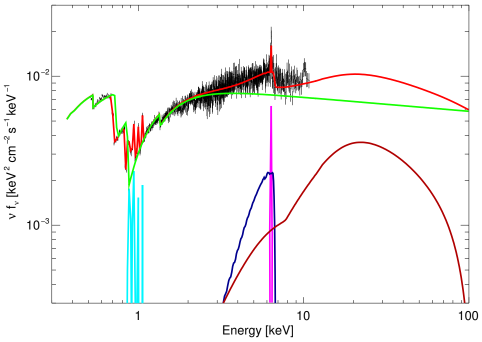

Fig. 2. Inferred νf_ν spectrum of MCG−6-30-15 from the EPIC pn data, showing the model components of the best fit model. Note that the data have been only slightly rebinned.

GT observation are confirmed by these data which have been analyzed in a series of papers by Fabian and collaborators (e.g., Fabian & Vaughan, 2003; Fabian et al., 2002, and therein).

In order to determine the Fe Kα parameters, an understanding of the underlying continuum spectrum is required. This determination of the continuum is complicated by features in the soft X-rays, which are thought to be either absorption edges caused by ionized material along the line of sight – the "dusty warm absorber" (Lee et al., 2001, and references therein) – or relativistically broadened O and Ni recombination lines (Branduardi-Raymont et al., 2001; Sako et al., 2003). The effect of these features is measurable at energies up to 2 keV. To gauge the effect the soft X-rays have on the modeling of the Fe Kα line, we model both the 2–10 keV and the 0.5–10 keV EPIC-pn data. Furthermore, in modeling the 0.5–10 keV data we gauge the stability of our interpretation of the > 2 keV spectrum by using both, an empirical warm absorber model and emission lines for describing the soft X-rays. The qualitative results of our data modeling are the same in both cases (Reynolds et al., 2004).

The continuum >2 keV is modeled by a power law, ionized reflection, and the Fe Kα complex. The data clearly show that the Fe Kα line is the superposition of a narrow feature at 6.4 keV, which has constant flux during the observation and likely originates from material far away from the central source, as well as the relativistic broadened feature. To describe the relativistic smearing of the Fe Kα line and the continuum we first assume a power law emissivity per disk unit area of the form $\epsilon \propto r^{-\beta}$ for the line. Fitting the data shows that $\beta > 3$, i.e., the emissivity of the Fe Kα line is strongly concentrated towards the inner rim of the accretion disk (Wilms et al., 2001) such that the observed Fe Kα line is strongly broadened (Fig. 2). Since simple ADC models predict that the Fe Kα line emissivity is proportional to the energy dissipated in the accretion disk, one would expect $\beta < 3$. This led us to the conclusion that a further energy dissipating process must be at work close the the central compact object, e.g., magnetic coupling between a Kerr BH and the accretion disk, possibly by torquing the inner edge of the disk (Agol & Krolik, 2000; Li, 2002). Based on such models, we have reanalyzed our GT data with more physical models, confirming our earlier conclusions and showing that the Fe Kα line can be well described by emission from a strongly torqued accretion disk which emits most X-rays from within a few gravitational radii (Reynolds et al., 2004).

4. Conclusion

We have described the results of the analysis of *XMM-Newton* guaranteed time data of MCG−6-30-15, showing that the instruments on *XMM-Newton* are well suited for the study of the behavior of material in the strong gravitational field close to a BH. Clearly, future theoretical and observational work is needed since *XMM-Newton* and other satellites have proven that MCG−6-30-15 is strongly variable. The study of this variability will improve our ability to understand the source, by studying correlations between the different spectral components. Furthermore, alternative models for the line broadening have to be investigated. At the moment, the only other model explaining the line shape is the "lamppost model" (e.g., Martocchia et al., 2002), where the the X-ray source is assumed to be close to the spin axis of the black hole and above the accretion disk.

Changes in the height of such an X-ray source can explain the correlation between the continuum intensity and the strength of the X-ray reflection feature (Fabian & Vaughan, 2003). Further high signal to noise data of MCG−6-30-15, however, both from *XMM-Newton* and *Chandra*, as well as from future missions such as *XEUS* or *Constellation-X*, are required to disentangle the spectral components in this complicated source and shed further light on the reality of relativistic effects in the universe.

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