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The X-ray view of the AGN inner regions

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Abstract. Recent results, mainly from *Chandra* and XMM-*Newton* observations, on the inner regions of AGN are reviewed. In particular, two topics are discussed: the innermost regions of the accretion disc, as probed by relativistic iron line features; and the obscured AGN, with particular emphasis on the pc-scale torus.

Key words. Galaxies: active – X-rays: galaxies

1. Introduction

X-rays are the privileged band to study the inner regions of AGN. *Chandra* and XMM-*Newton* have recently provided the sensitivity and spectral resolution necessary to make a step forward. Among the several possible topics in this review, for reasons of space, I will concentrate myself on two of them: the innermost regions of the accretion disc, as probed by relativistic iron line features; and the obscured AGN, with particular emphasis on the pc-scale torus.

2. The innermost regions of the accretion disc

Iron lines are the best tool to study emission from the innermost regions of accretiond discs. (e.g. Fabian et al. 2000 and references therein). They can offer the possibility to determine the angular momentum (or, better, the adimensional angular momentum per unit mass, a; note that $0\leq a \leq 1$) and the mass of the Black Hole. The spin can be derived from the inner radius of the emitting regoin, if assumed to be equal to the innermost stable orbit, which depends on a (see Fig. 1); the Black Hole mass from reverberation mapping (e.g. Stella 1990; Matt & Perola 1992) or from orbiting spots (see below).

We first discuss the observational status for "classic" relativistic lines (i.e. those emitted from the entire, or at least large portions of the disc), then we will discuss evidence for emission from orbiting spots.

2.1. "Classic" relativistic lines

XMM-*Newton* is, thanks to its combination of large sensitivity and good energy resolution at 6 keV, definitely the best satellite so far (at least before the launch of *S uzaku*) to search for and study relativistic lines from accretion discs (see Fabian et al. 2000 and references therein). It is quite disappointing, therefore, that these lines turned out to be present only in a minority of sources (e.g. Bianchi et al. 2004 and references therein), while a narrow iron line, likely coming from the torus, is almost ubiquitous (see e.g. Fig. 2. Apart from MCG-6-

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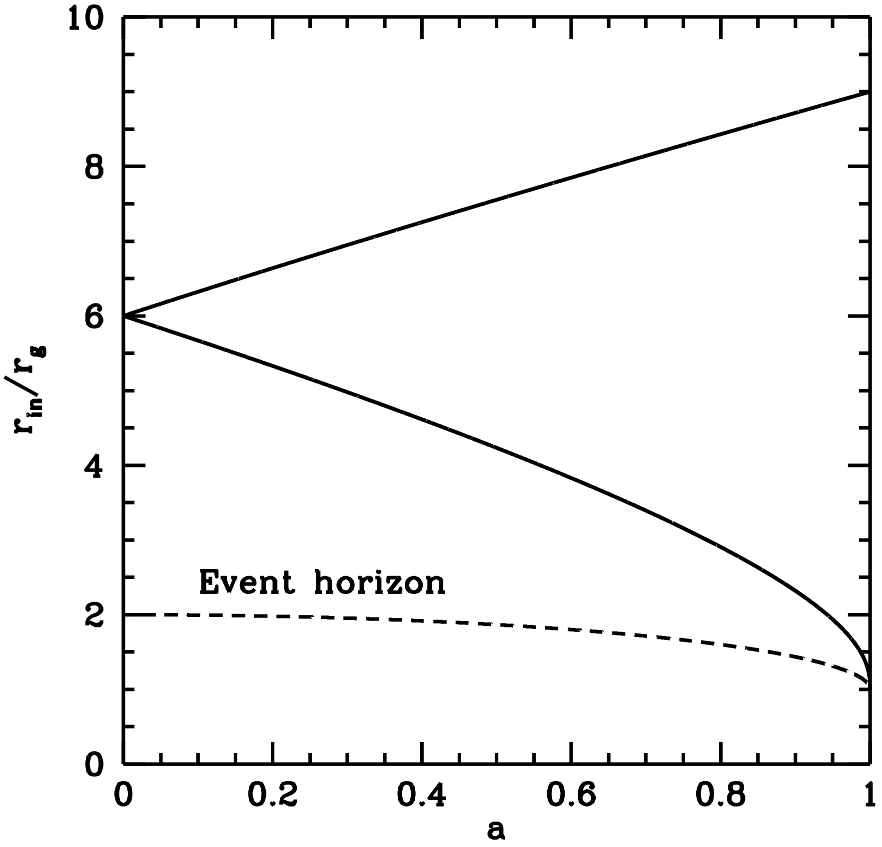

Fig. 1. The radius of the innermost stable orbit of an accretion disc as a function of the Black Hole "spin", a. The lower (upper) curve refers to a co- (counter-) rotating disc. The radius of the event horizon is also shown for comparison.

30-15, whose relativistic line, discovered by ASCA (Tanaka et al. 1995), was afterwards confirmed by all other satellites (BeppoSAX: Guainazzi et al. 1999; XMM-*Newton*: Wilms et al. 2001, Fabian et al. 2002; *Chandra*: Lee et al. 2002; *Suzaku*: Takahashi 2005: note that the inner radius derived from XMM-*Newton* observation is below $6r_g$, implying a spinning Black Hole), only in a few other bright sources (e.g. NGC 3516: Turner et al. 2002; MCG-5-23-16: Balestra et al. 2004) the relavistic line has been detected with good confidence. On the other hand, these findings raise a new interesting problem, i.e. why the relativistic line is sometimes present, and sometimes not. A few possible solutions to this problem have been proposed, none of them fully satisfactory in my opinion.

One possibility is that the disc is ionized. The properties of the line emission depends

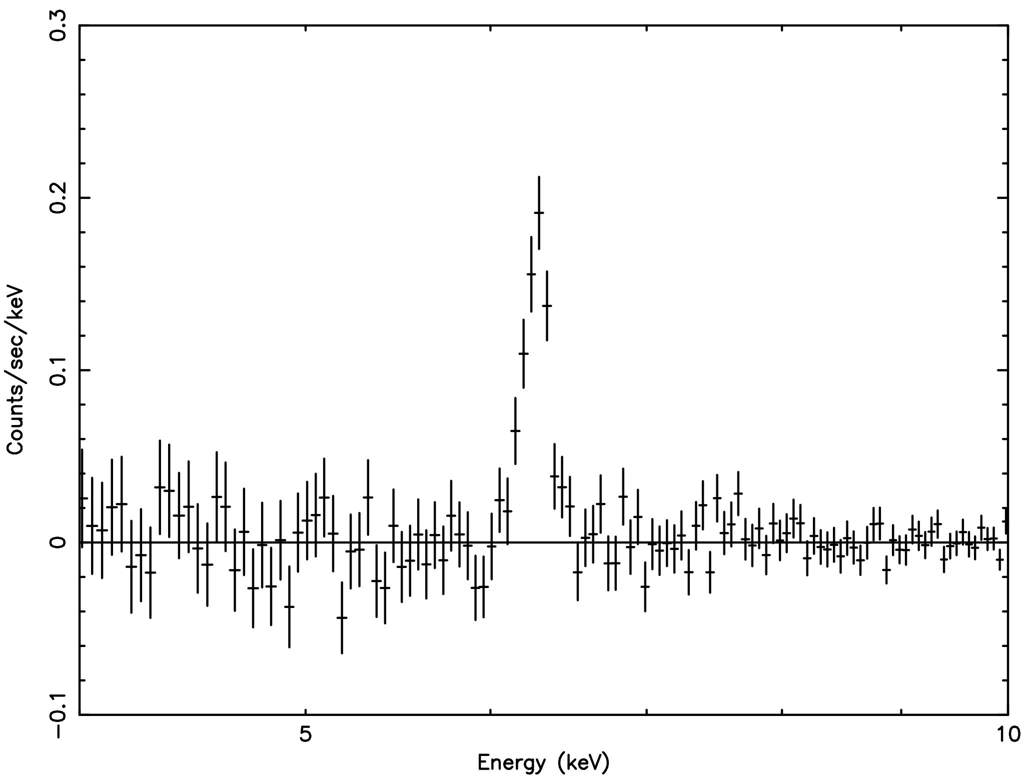

Fig. 2. The iron line in the bright Seyfert 1 galaxy MCG+8-11-11. The line is unresolved, with no evidence for relativistic broadening. From Matt et al. (2006).

on the disc model adopted. In the simple constant density model (Ross & Fabian 1993), four different regimes for line emission are present (Matt et al. 1993, 1996): for low ionization parameters the matter is basically neutral, and standard calculations apply (George & Fabian 1991; Matt et al. 1991). When the iron is mildly ionized, with vacancies on the L shell, the line photons get resonantly trapped, and the Auger effect ensures effective line destruction. For higher ionization parameters iron is mainly in He– and H–like states, and Auger effect is of course no longer possible; reduced photoabsorption at the line energy, due to ionization of lower Z elements, makes line emission more prominent than in the neutral case. Finally, for still higher ionizations matter is completely ionized and there is no more line emission. The latter case requires very large ionization parameters, unlikely to occur in Seyfert galaxies. The mildly ionized case is instead well possible, but as a general solution is a bit unpalatable, as there is no obvious reason why the majority of sources should have the ionization parameters in the required interval.

Another possibility is simply that the inner disc is not there, i.e. that the disc is truncated, due to some instability, at a radius larger than the innermost stable orbit. This was first suggested by Zdziarski et al. (1999) to explain the correlation between the photon index and the amount of Compton reflection. In Galactic Black Hole systems, it is believed that the disc is truncated during the so-called hard states (e.g. Fender et al. 2004 and references therein), and indeed the analogy between Seyfert galaxies and GBH systems has been suggested many times, even if this point is still highly controversial (e.g. Uttley & McHardy 2005). Possible evidence for disc truncation has been recently found in the luminous quasar Q0056-363 (Matt et al. 2005). The source has been observed twice by XMM-*Newton*, about three years apart. In the second observation, the UV and soft X-ray flux was lower, the hard X-ray spectrum harder, and the iron line equivalent width about halved (see Fig. 3). All these findings can be explained, at least qualitatively, if the disc, in the second observation, has an inner radius significantly larger than in the first observation.

Finally, it is in principle possible that the relativistic lines are so broad to be impossible to distinguish from the continuum. This could occur if most of line emission would come from the very innermost regions of an accretion disc around a maximally rotating Black Hole. Such a situation can occur if the illuminating source is very close to the Black Hole event horizon. However, in this case the iron line equivalent width should be very large (Martocchia & Matt 1996, Martocchia et al. 2002, Miniutti & Fabian 2004), much larger than the upper limit that can be put to the line EW in bright sources without the relativistic line (e.g. Bianchi et al. 2004). Therefore, this cannot be a general solution.

Of course, it is well possible that the explanation is different from source to source. More information may will come from population studied, and one can alwayw hope for a stroke of luck which may suddenly shed more light, but it is not inconceivable that we will have to wait for an answer until the next generation of X-ray satellites.

2.2. Orbiting spots

While "classic" relativistic lines were found by Chandra and XMM-*Newton* to be less common than expected, other features, possibly interpreted in terms of relativistically distorted iron lines, have been recently discovered. These features are narrow, transient, and usually found between 5 and 7 keV (which immediately suggests identification with iron lines). They were first discovered by Turner et al. (2002) in the Seyfert galaxy NGC 3516, and then found in several other sources (see e.g. Pechacek et al. 2005 and references therein). As these features are often detected at a few σ level, some skepticism exists about their very existence. After all, it would not be surprising to find sometimes a few σ feature simply by statistical fluctuations. A blind search for such features, performed by Longinotti et al. (2005), is however suggesting that they are too frequent to be simply explained by statistical fluctuations. Even if the reality of the faintest of these features may still be questionable, we then assume it is a real phenomenon.

The most popular interpretation is that they are the blue peak of the iron line from an "orbiting spot" (Matt et al. 2004, Dovciak et al. 2004). Let us suppose to have a bright flare (possibly due to magnetic reconnection) just above the accretion disc. Let us also assume that the size of the flare is small (i.e. $\Delta r \ll r$) and that it corotates with the disc. The flare illuminates the disc region just below it, producing an iron line which, due to Doppler, SR and GR effects will change its brightness and centroid energy (as seen from the distant observer) along the orbit. In particuar, due to Doppler boosting, the line will appear particularly prominent when the emitting matter is approaching. At the same time, due to Doppler effect, the line energy will appear maximally blueshifted ("blue peak"). It is important to note that for low radii and inclination angles even the blue peak may actually be redshifted, Doppler effect being overcompensated by gravitational redshift. Then, the detected features may be the blue peak of the orbiting spot, the rest of the emission being below detectablity. The transient nature of most of these features is consistent with such a scenario.

If this intepretation is true, it also offers the possibility to measure the Black Hole mass. Assuming Keplerian motion, the orbital period is given by:

$$T_{\rm orb} \simeq 310\, r\ \sqrt{r-2}\, M_7 \quad s \tag{1}$$

where M_7 is the Black Hole mass in units of 10^7 solar masses, a is the Black Hole adimentional angular momentum per unit mass, and r is the radius in units of the gravitational radius (=GM/c^2). Because a cannot exceed 1, its measurement is relevant only for

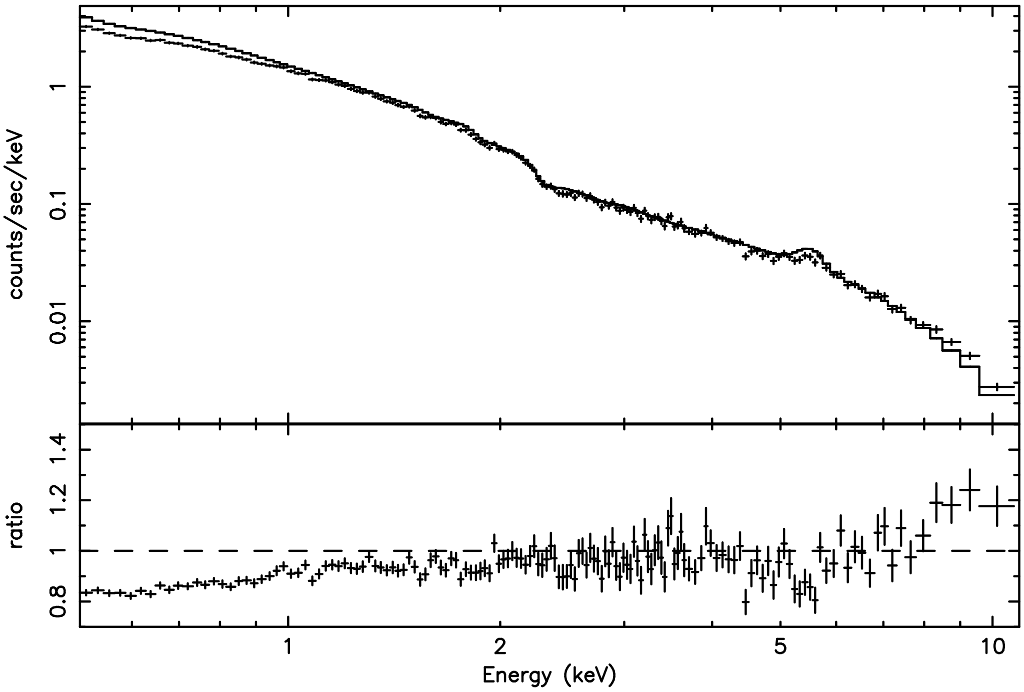

Fig. 3. The spectrum of the 2003 observation of Q0056-363 fitted with the best fit model of the 2000 observation. Note the fainter soft X-ray emission, the flatter hard X-ray emission and the smaller iron line.

small radii. If one could follow the line emission along the entire orbit, than r and a[1] can be estimated (Dovciak et al 2004), and the orbital period would then give the Black Hole mass. Even with XMM-*Newton* this task is almost impossible, due to the combination of limited sensitivity and often insufficient exposure time. In most cases, only a rough estimate of the emitting radius is possible. Pechacek et al. (2004) have found that for the best studied cases the emission must came from small radii, but not so small to require a spinning Black Hole: a solution in terms of a Schwarschild Black Hole always exists (see Table 1). In any case, the fact that the features seem to arise from the innermost disc regions provides an argument against disc truncation as a general explanation for the paucity of "classic" relativistic lines (see previous section).

It is worth remarking that in one case an estimate of the Black Hole mass has been possible. In a long look of NGC 3516, in fact, Iwasawa et al. (2004) discovered emission redwards of 6.4 keV, variable in time consistently with periodic emission. The derived Black Hole mass is 1-5$\times 10^7$ $M_\odot$, in agreement with other, independent estimates. In the Constellation-X and XEUS era, this method will promise to become the most precise to measure the Black Hole mass in AGN.

3. Obscured AGN

3.1. The pc-scale torus

With 'torus' we mean the optically thick matter located at distances from the Black Hole of the order or a parsec, whatever its actual shape (which may well not remind a doughnut, even

[1] For large radii, the dependence of the properties of the line emission on a is very weak, and therefore this parameter may be difficult to estimate. Fortunately, its relevance for determining the Black Hole mass is also negigible in this case.

Source	$E_{\rm line}$ [keV]	r [GM/c^2]	$\theta_{\rm o}$ [deg]	$r_{\theta_{\rm o}={\rm const}}$ [GM/c^2]	Reference
NGC 3516	5.57	6–12	0–23	6.6 ($\theta_{\rm o}$ = 20°)	(Turner at al. 2002)
	6.22	6–50	0–35	12.4 ($\theta_{\rm o}$ = 20°)	
		6–46	>74 *		
	6.53	>6	20–40	56/93 ($\theta_{\rm o}$ = 20°)	
		6–14	65–80 *		
ESO 198-G024	5.70	6–14	0–26	7.2 ($\theta_{\rm o}$ = 20°)	(Guainazzi 2003)
	5.96	6–21	0–30	8.9 ($\theta_{\rm o}$ = 20°)	(Dovčiak et al. 2004)
		8–20	>85 *		
NGC 7314	5.84	6–17	0–28	6.3 (θ_0 = 27°)	(Yaqoob T., et al. 2003)
	6.61	>6	27–41	20/93 (θ_0 = 27°)	
		6–12	65–78 *		
Mrk 766	5.60	6–12.5	0–24	6.7 ($\theta_{\rm o}$ = 20°)	(Turner et al. 2004)
	5.75	6–15	0–27	7.4 ($\theta_{\rm o}$ = 20°)	
ESO 113-G010	5.40	6–10	0–20	6 ($\theta_{\rm o}$ = 20°)	(Porquet D. et al. 2004)

Table 1. The narrow features detected so far in AGN which may be intepreted as the blue horns of a 6.4 keV iron line arising from an orbiting spot. The interpretations with higher inclination angles, denoted with asterisk, are due to the amplification caused by the lensing effect and bending of light rays. From Pecháček et al. (2005).

if some sort of axial simmetry is probably preserved; see Elvis 2000 for an alternative view).

In X-rays, the torus can be studied not only in absorption but also, and I would say mainly, in reflection. This is best done in Compton-thick sources, where the nuclear radiation is fully obscured up to at least 10 keV, leaving the reflection components as the only visible ones. Both *Chandra* and XMM-*Newton* have observed the brightest Compton-thick AGN, in particular Circinus, NGC 1068 and Mrk 3. The main results can be summarized as follows:

3.1.1. Circinus

High quality gratings and CCD spectra with *Chandra* and XMM-*Newton* have revealed a wealth of emission lines (Sambruna et al. 2001; Bianchi et al. 2002; Molendi et al. 2003; Massaro et al. 2006). The iron Kα Compton shoulder was detected (Bianchi et al. 2002, Molendi et al. 2003); its relative flux implies that the line emitting matter is Compton-thick (Matt 2002), supporting the view that the emission comes from the far side of the torus. Evidence for iron overabundance, (when compared to solar values), with respect to lower Z elements, and of nickel with respect to iron, were also found (Molendi et al. 2003).

3.1.2. NGC 1068

The XMM-*Newton* EPIC observation (Matt et al. 2004) revealed possible evidence for flux variability in both the neutral (supposed to originate in the torus) and ionized reflectors with respect to a BeppoSAX observation taken 3.5 years before, implying distances of the order of few parsecs. Again, the relative intensity of the iron Kα Compton shoulder implies that the neutral reflector is Compton-thick, likely the visible inner wall of the $N_H > 10^{25}$ cm^{-2} absorber. An iron (nickel) overabundance of about 2 (4) with respect to lower Z elements, was also found.

3.1.3. Mrk 3

The XMM-*Newton* EPIC observation is discussed by Bianchi et al. (2005) and Pounds & Page (2005). The source is dominated by a pure Compton reflection component and an iron Kα line, both likely produced by the Compton-thick matter responsible also for the large line–of–sight column density (about 1.4×10^{24} cm^{-2}). Interestingly, the iron line is marginally resolved (σ=32^{+13}_{-14} eV, Bianchi et al. 2005). If interpreted in terms of Doppler broadening due to the Keplerian rotation of the torus, an estimate of its inner radius of $r \sim 0.6 sin2i$ pc is derived.

3.2. How many reflecting/absorbing regions?

The column densities measured in absorbed AGN span an interval of several orders of magnitude, from about 10^{21} cm^{-2} (smaller values are difficult to measure because of the Galactic absorption) up to several times 10^{24} cm^{-2} and even more (above 10^{25} cm^{-2} the nuclear radiation is completely absorbed, e.g. Matt et al. 1999, and only a lower limit to the column density can be put). A natural question is: are these absorbers always to be identified with one and the same structure (e.g. the torus), or are there more than one circumnuclear regions? There is increasing evidence that the latter is the correct answer (e.g. Matt et al. 2003), and that in particular the torus is quite thick, while thinner matter is probably associated to more distant regions, or to the host galaxy itself (even if in some cases the Compton-thin matter is definitely close to the nucleus, see e.g. Elvis et al. 2004 and Risaliti et al. 2005).

Let us discuss one of the clearest case, i.e. NGC 5506, one of the brightest AGN in the X-ray sky. It is a Compton-thin AGN ($N_H \sim 10^{22}$ cm^{-2}) with: a) a narrow (σ <40 eV) and costant iron line, despite large nuclear flux variations (Bianchi et al. 2003); b) a strong reflection component (Matt et al. 2001), necessarily produced in Compton–thick matter (Matt et al. 2003). Clearly, the absorbing (Compton-thin) matter must be different than the reflecting (Compton-thick) matter. Because the iron line is narrow and costant, the latter is likely to be quite distant from the Black Hole, and an identification with a pc-scale torus seems to be the most natural (much larger distances would imply too large masses: note that the covering factor must be large to explain the intensity of the reflection components). It is also worth noting that in Seyfert 1s, when the relativistic line is not present, a Compton reflection component and a narrow iron line are usually still there (Bianchi et al. 2004), again suggesting the presence of substantial circumnuclear Compton–thick matter.

3.3. Beyond the nucleus

If the Compton-thin matter is far away, can it be related to the host galaxy? Lamastra et al. (2006) have proposed a simple model in which the Compton-thin obscuration is provided by the molecular disc of the host galaxy. Taking into account the effect on the shape of the disc of the gravitational force exerted by the Black Hole, the relation between the fraction of Compton-thin absorbed AGN and the luminosity, as found from X-ray surveys (Ueda et al. 2003, La Franca et al. 2005 and references therein) is naturally explained, provided that the surface mass density is large enough.

4. Conclusions

X-ray observations from *Chandra* and XMM-*Newton* of AGN are providing some answers to old questions, as well as new questions to be answered by new observations and/or by theoretical efforts. Probably the most fundamental new question, which is indeed a challenge for our understanding of accretion processes in AGN, is: why in some sources there is evidence (as expected from simple models) of relativistic iron lines, while in other sources (probably the majority) such lines are not there (at least with the expected intensity)? None of the proposed explanation is, in my opinion, fully satisfactory, and it is possible that, to have an answer, we have to wait for the next generation of X-ray satellites.

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