IRON LINE EMISSION FROM ACCRETION DISCS AROUND KERR BLACK HOLES

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ABSTRACT. The study of iron line emission is a powerful diagnostic of the kinematics of matter accreting onto compact objects. In this contribution we show how it can in principle be possible not only to "see" black holes, but also to discriminate between rotating and non-rotating ones by studying line emission from relativistic accretion discs.

1. Introduction

The width and asymmetry in the iron Kα line profile recently discovered by ASCA in the spectrum of MCG–6-30-15 (Tanaka et al. 1995) has confirmed theoretical models attributing the iron Kα line emission at 6.4 keV (a very common feature in Seyfert 1 galaxies) to fluorescence, following external X-ray illumination of a relativistic accretion disc orbiting around the putative black hole (e.g. Fabian et al. 1989; Laor 1991; Matt et al. 1992). A detailed analysis of a sample of Seyfert 1's observed by ASCA indicates that this line is indeed usually broad in this class of objects (Nandra et al. 1996), as expected in the relativistic disc models. The equivalent widths of the observed lines are, however, often significantly greater than expected from discs accreting onto static black holes (which in turn is expected to be at most 160 eV, see Matt et al. 1992). Several explanations for the large equivalent widths are possible, asymmetries in the illuminating radiation and iron overabundance being the most likely. We show here that a significant and even dramatic enhancement of the line intensity can be obtained as a pure General Relativistic effect if the disc is rotating around a spinning (Kerr) black hole. Details on the computational method and results can be found in Martocchia & Matt (1996, 1997). For a recent and detailed work on line profiles in Kerr metric see Fanton et al. (1996).

2. Line emission

We assume a geometrically thin, optically thick accretion disc around a maximally rotating black hole (Bardeen et al. 1972), illuminated by an isotropic (in its reference frame) X–ray point source on the symmetry axis of the hole at height h. The photon trajectories between the source and the disc are calculated by numerically solving the equation of motion (Carter 1968). The matter in the disc is assumed to be neutral with cosmic chemical abundances. Photons impinging to the disc can either be photoabsorbed or reflected; photoabsorption from a K–shell of an iron atom has a 31% probability to be followed by a $K\alpha$ fluorescent emission at 6.4 keV (see e.g. Matt, Perola & Piro 1991)

The most relevant difference, as far as line emission is concerned, between accretion discs orbiting around static (Schwarzschild) and rotating (Kerr) black holes is that the radius of the innermost stable orbit in the Kerr case can be as low as about 1.23 times the gravitational radius (r_g=GM/c^2; Bardeen et al. 1972; Thorne 1974), to be compared to a value of 6 r_g for a static black hole. Therefore, in a Kerr black hole line photons can be emitted very deeply in the gravitational field, where the relativistic effects are strongest. Among these effects, the most relevant in increasing the line intensity are:

I) If the primary source is very close to the black hole, a fraction of photons emitted towards infinity can be deflected by the black hole gravitational field and come back to illuminate the accretion disc. (For static black holes this effect is not very important because the disc cannot extend below 6 r_g, and most of the deflected photons are lost.) Therefore, the number of X-rays illuminating the disc increases while the primary radiation observed at infinity diminishes.

II) Photons arriving to the disc at a radius smaller than about h are blueshifted: the fraction of photons with energies greater than the photoionization threshold therefore increases. Of course, at great radii photons are redshifted, but for small h these regions do not contribute much to the total line emission because of light deflection.

III) Photons arrive to the disc preferentially with high incident angles (e.g. Cunningham 1976; Martocchia & Matt 1997). The efficiency of line emission increases with this angle (e.g. Matt et al. 1991).

The most important observational quantity is not, however, the line intensity but its equivalent width (EW), i.e. the ratio between the total line intensity and the flux density at the line centroid energy. This quantity is further increased by another General Relativistic effect, i.e. gravitational redshift of the primary radiation. Summing all these effects, we obtain, for a maximally rotating black hole, the relation between the EW and h shown in the figure. The EW is normalized to the "classical" value, i.e. the value that would have been obtained with the same geometrical, physical and chemical assumptions in the absence of any relativistic effect. It can be seen from the figure that the EW can be much higher than in the classical case. On the contrary, in the Schwarzschild case the enhancement never exceeds 10–20% (Matt et al. 1992).

The line intensity has been obtained by comparing the local line emissivity derived in the Kerr case with that in the 'classical' case, after averaging over the emission angles. The angular dependence of the line intensity and shape will be dealt with in a forthcoming paper (Martocchia & Matt 1997).

The values of EW plotted in the figure refer to the primary radiation continuum only. However, the enhanced illumination will increase the Compton reflection continuum too, and the observable EW is expected to never exceed about 1 or 2 keV (the shaded area in the figure). A more precise evaluation of the reflected continuum also requires a General Relativistic treatment, and will be discussed in Martocchia & Matt (1997).

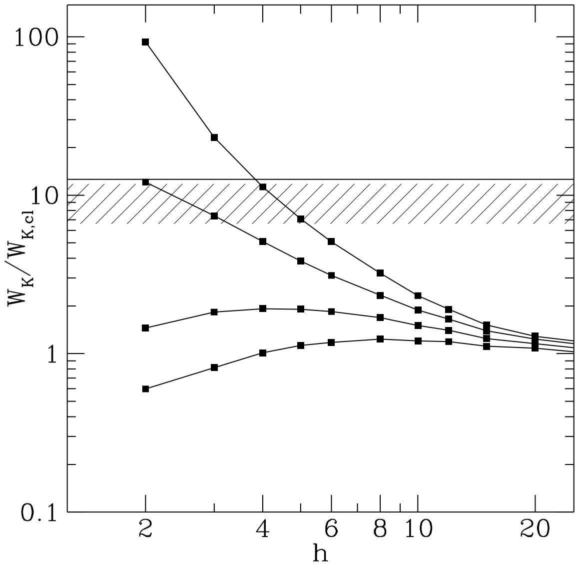

Fig. 1. The EW with respect to the primary continuum, normalized to the 'classical' value, as a function of h. Four different values of the inner disc radius are considered: 1.23 (the innermost stable orbit), 2, 4 and 6 (from top to bottom). The shaded area indicates the maximum values when the Compton reflection continuum is taken into account.

3. Discussion

Most of the Seyfert 1 galaxies observed by ASCA have broad iron Kα lines (e.g. Tanaka et al. 1995; Nandra et al. 1996), a fact which is currently explained in terms of emission from relativistic discs (see Fabian et al. 1995 for a critical discussion of alternative models). However, their equivalent widths are often in excess by a factor 2–3 of that expected from an accretion disc around a Schwarzschild black hole (Matt et al. 1992), which in turn is only slightly greater than the 'classical' value (George & Fabian 1991; Matt et al. 1991).

One possible explanation is that the iron in AGN is overabundant with respect to the mean cosmic value. To explain the observed EW, an iron overabundance (with respect to the elements responsible for the photoabsorption at 6.4 keV) of a factor 3–4 would be required (Matt, Fabian & Reynolds 1996 and references therein).

Here we have proposed an alternative explanation in terms of General Relativistic effects, which is viable if the black hole is significantly rotating, and the accretion disc can therefore extend down to almost the event horizon.

The best method to discriminate between the two explanations is by the study of the line profile. The present model is effective in significantly increasing the line emission only if most of the photons come from the innermost region of the disc; the profile is then expected to be very broad and redshifted, without any clear peak (Laor 1991; see e.g. Fabian et al. 1989 and Matt et al. 1992 for profiles in Schwarzschild metric).

A good candidate for hosting a rotating black hole is the radiogalaxy 3C 120, where the line is particularly intense (EW > 400 eV) and broad ($\sigma > 0.8$ keV; Grandi et al. 1996). For this and all the sources with claimed broad lines, apart from MCG–6-30-15, the quality of the data is however insufficient to allow for a direct search for relativistic profiles.

Different is the case of MCG–6-30-15 which is, thanks to a very long observation performed by ASCA (Tanaka et al. 1995), the best example of a relativistic line yet. The profile, averaged over the whole observation, is consistent with that expected from the Schwarzschild metric, and the large EW ($\sim$300 eV) is therefore likely due to iron overabundance. However, the profile changed during the observation (Iwasawa et al. 1996). In particular, during a phase of deep minimum of the total flux the profile could only be fitted with a Kerr model, while the EW increased by a factor $\sim$3, qualitatively in agreement with the present model. An intriguing possibility is that usually the geometry of the X–ray emitting source is such that the illumination favours disc regions with radii greater then $6r_g$ (where differences between Kerr and Schwarzschild metric, as far as both intensity and profile are concerned, are small), while sometimes the mean distance from the black hole of the emitting particles suddenly diminishes, with consequent increasing of the line intensity and change of the profile, and decreasing of the continuum flux due to gravitational redshift.

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