PROPERTIES OF IRON LINE EMISSION FROM ACCRETION DISCS AROUND SPINNING BLACK HOLES

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Abstract

The study of line emission is a powerful diagnostic of the kinematics of matter accreting onto compact objects. Here we discuss how it is in principle possible with this method to "see" black holes, and even to discriminate between static and rotating. The most spectacular example of a line from a relativistic disc is the iron line from the Seyfert Galaxy MCG–6-30-15, whose properties can be explained if the hole is spinning.

1 Searching for black holes

The formation and even the very existence of Black Holes (BH) has been a matter of debate for several decades, owing to the impossibility to directly detect this kind of objects.

Stellar mass BH are usually searched for by measuring the mass function in binary systems (usually X-ray binaries) in which one of the star is known to be collapsed. If the mass of the compact object exceeds the Rhoades-Ruffini limit ($\sim 3.2 M_\odot$), it can no longer be a neutron star, and therefore it is very likely to be a black hole. However, recent works have suggested that the mass upper limit for a neutron star can be as high as about $11 M_\odot$; moreover, the existence of exotic objects like Q stars cannot presently be rejected altogether (see Miller [1] for a review).

Evidence for the presence of supermassive BH in the center of galaxies (in particular in the Nuclei of Active Galaxies, AGN) is very strong, based both on energy budget considerations and velocity measurements of circumnuclear matter (see the paper by Miyoshi et al. [2] for the most spectacular example), but also in these cases the arguments are rather indirect or based on reasonable but not completely proven assumptions (virialization, keplerian motion), and in any case, in these like in the stellar masses BH, the observations refer to distance from the black hole such that strong General Relativistic (GR) effects, which would give stronger and more direct evidence for a BH, are not actually tested.

It would therefore be of the utmost importance to probe matter very close (i.e. at a few $r_g = GM/c^2$) to the BH. The study of line emission (in particular of the iron fluorescent $K\alpha$ line at 6.4 keV) is particularly promising in this respect, and has already given fundamental results.

2 Iron $K\alpha$ line profiles

The method is based on the study of the distortions induced by kinematic and gravitational effects on the iron $K\alpha$ line profile from accretion discs orbiting around BH. The line is produced by $L \rightarrow K$ fluorescent transition, following external X–ray illumination of the accretion disc with consequent possible photoabsorption by a K–shell electron in an iron atom.

The profiles for lines emitted by accretion discs around BH have been discussed in several papers, both in Schwarzschild [3,4] and Kerr [5,6] metrics. The profiles are usually double–horned because of the Doppler effect, with a "blue" ($E > E_0$, being E_0 the rest energy of the line) horn due to approaching matter and a "red" ($E < E_0$) one due to receding matter; the former is more intense due to Doppler boosting, but the red part has a wide wing due to both transverse Doppler and gravitational redshift effects. At high inclination angles, further features due to light bending of photons coming from the other side of the disc also arise.[4]

The main difference between line profiles in Schwarzschild and Kerr metric is due to the fact that, in the latter case, the disc can extend down to 1.23 r_g (for a maximally rotating BH)[7,8], while in the former case the innermost stable orbit is at 6 r_g. Therefore, in the Kerr case the GR effects are stronger, and their imprint on the profile is basically a particularly enhanced red wing, with the double peaked structure almost disappearing.[5] However, if the emissivity law were such that most of the line photons come from radii exceeding 6 r_g, the differences between static and rotating BH would be rather small, and practically undetectable with present X–ray detectors.[6]

The recent ASCA observation of the Seyfert 1 galaxy MCG–6-30-15,[9] revealing a clearly double–peaked, asymmetric iron $K\alpha$ line profile, have provided the best evidence of the existence of BH so far (no convincing alternative explanations do presently exist for such a line broadening and skewness [10]). It is worth stressing that never before matter has been probed so deeply in a gravitational field; it is also the first time that so strong GR effects have been directly tested. The profile reported by Tanaka et al.[9] is averaged over the whole 4.5 day observation, and is consistent with an innermost emitting radius of slightly more than 6 r_g; therefore, it is not possible to determine whether the black hole is spinning or not.

Broad iron lines have also been clearly detected in many other Seyfert galaxies, but the quality of the data are usually not good enough to unambiguously reveal the asymmetry in the profile. However, in most sources, including MCG–6-30-15, the line equivalent width (i.e. the ratio between the total line intensity and the flux density at the line centroid energy) is larger by a factor 2 or 3 [11] with respect to the model predictions.[12] Many explanations of this effect are possible, anisotropy in the primary emission and iron overabundance being the most likely ones. We have explored another possibility based on pure GR effects in Kerr metric. The model and the relative results are presented in the next section.

3 Disc illumination and line intensity in Kerr metric.

We have studied the geodetics of photons emitted by a point source on the black hole axis at height h above the equatorial plane (where the accretion disc is assumed to lie) and illuminating the disc. A maximally rotating black hole (i.e. $a \equiv J/m^2 = 0.9981$, $a = 1$ being prevented by the capture of photons by hole itself [8]) has been assumed.

Introducing the *Boyer–Lindquist* (B-L) coordinates t, ξ, θ and ϕ, the projection of the photon trajectory on the $\xi - \theta$ plane is determined by the equation of motion[13]:

$$\int_\xi V_\xi^{-1/2} d\xi = \pm \int_\theta V_\theta^{-1/2} d\theta. \tag{1}$$

Here V_ξ, V_θ are quartic functions of ξ and $\cos\theta$ respectively, depending also on a and the constants of motion λ, i.e. the component of the angular momentum along the rotation axis, and q^2, the so-called *Carter's* or *fourth* constant. (The other two constants of motion are the energy E and the mass μ of the moving particle. Of course $\mu = 0$ for a photon.) The initial conditions are given by the angles formed by the energy-momentum 4-vector $\mathbf{p}$ of the photon with the unit vectors of the emitting point reference frame. We used the direction cosines determined by the 4-D scalar products of $\mathbf{p}$ with each vector of the orthonormal co-moving tetrad $(\mathrm{e}_{[\mu]}, \mu = 0, \ldots 3)$:

$$\cos\delta_i = \frac{p_\mu e^\mu_{[i]}}{p_\mu e^\mu_{[0]}} = \frac{p_{[i]}}{p_{[0]}}(\lambda, q^2). \tag{2}$$

As we are interested here in photons emitted on the hole axis, λ has always been taken equal to zero. In Fig. 1 we show some of the trajectories, for both Schwarzschild and extreme Kerr metrics. It is worth noticing that for low h the illumination is not very effective in Schwarzschild metric, due to the rather large value of the innermost stable orbit.

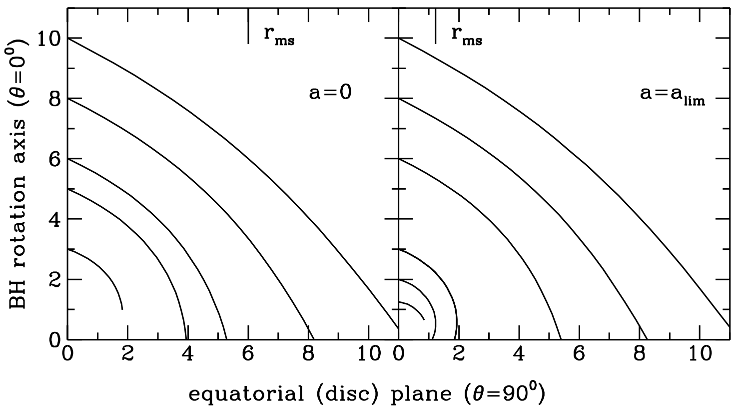

Figure 1: Primary photons geodesics in the $\xi - \theta$ plane, for various source heights h and an emission angle $\delta = 60^o$. Both Schwarzschild and extreme Kerr metric cases are shown. Even if they seem not to differ very much, note that in Kerr metric 1) it does also exist a deflection in the ϕ direction, i.e. perpendicular to the sheet plane, and 2) most of the photons can actually illuminate the disc, owing to the much smaller innermost stable orbit $r_{\rm ms}$.

The results on the line emissivity are discussed in detail elsewhere.[14,15] The main result is that the line emission can be much higher than in the Schwarzschild case due to mainly two reasons: *a*) the light bending, when the source is very close to the black hole, increases significantly the fraction of photons illuminating the disc (which would have been, in absence of relativistic effects, equal to 1/2); *b*) photons arriving to the disc at a radius smaller than $\sim h$ are blueshifted, and the fraction of photons with energies above the photoionization threshold is therefore increased.

4 Discussion

In the previous section we have shown that, in our model, the line emission can be greatly enhanced provided that the primary source is very close to the black hole. In this situation, most of the line is emitted in the innermost part of the disc, and the profile is expected to be very broad and redshifted.

Actually, the line profile (averaged over the whole observation) of MCG–6-30-15 requires an inner emitting radius for which the effects described in the previous section are not much effective in enhancing the line intensity. The large equivalent width is therefore to be attributed to a different cause, most likely iron overabundance. However, the flux of the source varied significatively during the observation. Iwasawa et al.[16] therefore divided the observation into 7 time intervals corresponding to different flux levels. In one of these phases, when the flux was particularly low, the profile was rather different than the mean one, exhibiting a huge red tail, while the blue peak completely disappeared: such a shape can be fitted only if the emitting region has a minimum radius smaller than 6 r_g, i.e. the black hole is spinning (calculation of line profiles in the Kerr metric can be found in several papers [5,6,17]). In this situation, our model predicts that the line equivalent width is enhanced, and in fact it was observed at about a factor 3 greater than the average value. An explanation for this behaviour is that, while generally the X–ray primary source is not very close to the black hole and therefore the innermost regions are not effectively illuminated, sometimes the mean distance of the emitting particles from the black hole suddenly diminishes; as a consequence, the line intensity increases while the profile drastically changes.

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