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Black Holes: theory versus observations - analysis of the Fe K_α Lines and precise astrometrical observations

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Abstract. Recent X-ray observations of microquasars and Seyfert galaxies reveal the broad emission lines in their spectra, which can arise in the innermost parts of accretion disks. A theoretical analysis of observations and their interpretations were discussed in a number of papers. We consider a radiating annulus model to simulate spectral line shapes. That is a natural approximation for narrow emitting circular rings without extra astrophysical assumptions about emissivity laws. Recently Müller & Camenzind (2004) presented results of their calculations and classified different types of spectral line shapes and described their origin. We clarified their hypothesis about an origin of double peaked and double horned line shapes. Based on results of numerical simulations we showed that double peaked spectral lines arise almost for *any* locations of narrow emission rings (annuli) although Müller & Camenzind (2004) suggested that such profiles arise for relatively flat space-times and typical radii for emission region about 25 r_g. We showed that triangular spectral lines could arise for nearest annuli and high inclination angles. We discuss a possibility of appearance of narrow spectral line shapes as a result of spiralling evolution of matter along quasi-circular orbits which could be approximated by narrow annuli.

Key words. black hole physics; line: profiles; X-ray galaxies – Cosmology: observations

1. Introduction

Several years ago it was predicted that profiles of lines emitted by AGNs and X-ray binary systems[1] could have asymmetric double-peaked, double horned or triangular shape according to Müller & Camenzind (2004) classification (e.g. Chen et al. (1989); Fabian et al. (1989); Robinson, Perez & Binette (1990); Dumont & Collin-Souffrin (1990); Matt, Perola & Stella (1993)). Generation of the broad K_α fluorescence lines as a result of irradiation of cold accretion disk was discussed by many authors (see, for example, Matt et al. (1991); Matt et al (1992a,b); Matt & Perola (1992); Matt et al. (1993); Bao (1993); Martocchia at al. (2002b) and references therein). Recent X-ray observations of

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[1] Some of them are microquasars (for details see, for example, Greiner (1999); Mirabel (2000); Mirabel & Rodriguez (2002)).

Seyfert galaxies, microquasars and binary systems (Fabian et al. (1995); Tanaka et al. (1995); Nandra et al. (1997a,b); Malizia et al. (1997); Paul et al. (1998); Sambruna et al. (1998); Cui et al. (1998); Sulentic, Marziani & Calvani (1998b); Sulentic et al. (1998a); Yaqoob et al. (1996, 1997, 2001); Ogle et al. (2000); Miller et al. (2002); Bianchi et al. (2004) and references therein) confirm these considerations in general and reveal broad emission lines in their spectra with characteristic two-peak profiles. Comprehensive reviews by Fabian et al. (2000); Fabian (2004) summarize the detailed discussion of theoretical aspects of possible scenarios for generation of broad iron lines in AGNs. These lines are assumed to arise in the innermost parts of the accretion disk, where the effects of General Relativity (GR) must be taken into account, otherwise it appears very difficult, if any, to find the natural explanation of the observed line profile. A formation of shadows (mirages) is another sample when relativistic effects are very important and there is a chance to evaluate parameters of black holes (Zakharov et al. 2005a,b,c).

Numerical simulations of the line structure could be found in a number of papers, see Kojima (1991); Laor (1991); Bao & Stuchlik (1992); Karas et al. (1992); Bao (1993); Bao et al. (1994); Rauch & Blandford (1993, 1994); Bromley et al. (1997); Fanton et al. (1997); Pariev & Bromley (1997, 1998); Pariev, Bromley & Miller (2001); Ruszkowski (2000); Ma (2002); Müller & Camenzind (2004). They indicate that the accretion disks in Seyfert galaxies are usually observed at the inclination angle θ close to 30° or less. It occurs because according to the Seyfert galaxy models, the opaque dusty torque, surrounds the accretion disk, so that, such structure does not allow us to observe the disk at larger inclination angles.

Recently Müller & Camenzind (2004) presented results of their calculations and classified different types of spectral line shapes and described their origin. In particular Müller & Camenzind (2004) claimed that usually "... triangular form follows from low inclination angles...", "...double peaked shape is a consequence of the space-time that is sufficiently flat. This is theoretically reproduced by shifting the inner edge to the disk outwards... A relatively flat space-time is already reached around 25 r_g..." We clarified their hypothesis about an origin of double peaked and double horned line shapes. Based on results of numerical simulations we showed that double peaked spectral lines arise for *almost any* locations of narrow emission rings (annuli) (except closest orbits as we could see below) although Müller & Camenzind (2004) suggested that such profiles arise for relatively flat space-times and typical radii for emission region about 25 r_g. Using a radiating annulus model we checked the statements claimed by Müller & Camenzind (2004) and clarified it for the case. We could note here that in the framework of the model we do not use any assumptions about an emissivity law, but we only assume that radiating region is a narrow circular ring (annulus). Thus, below we do not use some specific model on surface emissivity of accretion (we only assume that the emitting region is narrow enough). But general statements (which will be described below) could be generalized on a wide disk case without any problem.

In Section 2° we describe briefly our model. In Section 3° we discuss Shakura – Sunyaev disk model. In Section 4° we present the results of simulations for narrow annulus model. In Section 5° we discuss results of calculations and present conclusions.

2. Numerical methods

We used an approach which was discussed in details in papers by Zakharov (1991, 1994); Zakharov & Repin (1999, 2002a); Zakharov & Repin (2002b); Zakharov et al. (2003); Zakharov & Repin (2003a, 2004a). The approach was used in particular to simulate spectral line shapes. For example, Zakharov et al. (2003) used this approach to simulate an influence of magnetic field on spectral line profiles. This approach is based on results of qualitative analysis (which was done by Zakharov (1986, 1989) for different types of geodesics near a Kerr black hole). Using first integrals found by Carter (1968) (see also Misner et al. (1973);

Sharp (1981)). The equations of photon motion in Kerr metric are reduced to the following system of ordinary differential equations in dimensionless Boyer – Lindquist coordinates (Zakharov (1991, 1994, 1995); Zakharov & Repin (1999)).

3. Shakura – Sunayev Disk model

Here we analyze the inner wide part of accretion disk with a temperature distribution which is chosen according to the Shakura & Sunyaev (1973) (see also Lipunova & Shakura (2002)) with fixed inner and outer radii r_i and r_o. Usually a power law is used for a wide disk emissivity (see, for example, Laor (1991); Matt et al. (1991); Martocchia & Matt (1996); Martocchia et al. (2000, 2002a)). However, another models for emissivity could not be excluded for so wide class of accreting black holes, therefore, just to demonstrate how another emissivity law could change line profiles we exploit such emissivity law. Details of the disk models are described by Zakharov & Repin (2003a,b); Zakharov (2004).

In spite of the fact that Müller & Camenzind (2004) noted that double horned spectral lines arise for power emissivity functions we showed that also such profiles are typical for Shakura – Sunayev model (see typical spectral line shapes in Fig. 1 for selected position angles $\theta = 40°, 50°, 60°$ from left to right, see also other spectral line shapes for the Shakura – Sunayev model presented by Zakharov & Repin (2003b,c, 2004a) (using as templates Zakharov et al. (2003) calculated distortions of the spectral line shape by a strong magnetic field, line shapes for non-flat accretion flows were discussed by Zakharov & Repin (2003a)).

For simulation we assume that the emitting region lies entirely in the innermost region of α-disk (zone a) from $r_{out} = 10\,r_g$ to $r_{in} = 3\,r_g$ and the emission is monochromatic in the comoving frame.[2] The frequency of this emission set as a unity by convention.

[2] We use as usual the notation $r_g = 2GM/c^2$.

4. Results of calculations

Presenting their classification of different types of spectra line shapes Müller & Camenzind (2004) noted that double peaked shapes arise usually for emission regions located far enough from black holes. Earlier, we calculated spectral line shapes for annuli for selected radii and distant observer position angles and found that an essential fraction of spectral line gallery correspond to double peaked profiles Zakharov & Repin (1999). To check the Müller & Camenzind (2004) hypothesis about an origin of double peaked profiles we calculated a complete set of spectral line shapes for emitting annuli. Below we discuss results of our calculations for rapidly rotating black holes (a = 0.998).

First, let us assume that an observer is located at the black hole axis. In this case spectral line shapes look like simulated δ-function with a redshift corresponding to an annulus radius, of course the smallest redshift corresponds to the largest radius (see the first row in Fig. 2).

If inclination angles are small ($\theta = 15°, \theta = 30°$), spectral line shapes are double peaked however one could mention that for radii $r \in (0.7, 1)r_g$ the intensity of the line is not very high (second and third rows in Fig. 2) since almost all photons emitted by annuli are captured by a black hole (see corresponding number of photons reaching infinity at the selected angle). Since the number of photons detecting by distant observer is low, there is natural statistical noise in the spectral line shapes. For larger radii the statistical noise disappears since a number of photons is much higher.

For intermediate angle $\theta = 45°$ and shortest radius $r = 0.7$ a red peak is very low and it is hardly ever distinguishable from background, however even for the next considered radius $r = 0.8$ and larger radii the spectral line shapes have the double peak structure (see fourth row in Fig. 2).

For another intermediate angle $\theta = 60°$ and smallest radius $r = 0.7$ the spectral line shape has triangular structure, for longer radii $r = 0.8$ and $r = 1.$ a red peak arises and it is low and probably it could be distinguished from a back-

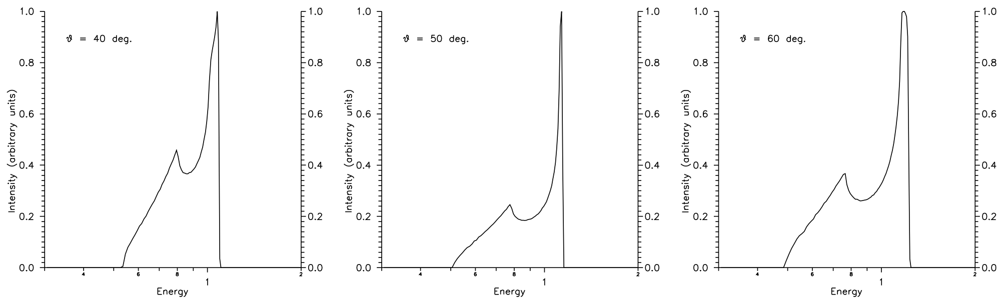

Fig. 1. Samples of Fe K_α line profiles for Shakura - Sunyaev emissivity disk model.

ground, but for $r = 2.$ a red peak is quit clear (see fifth row in in Fig. 2).

For high inclination angles $\theta = 75°, \theta = 80°, \theta = 85°, \theta = 88°, \theta = 89°$ and small radii $r = 0.7, 0.8, 1$ spectral line shapes have triangular structure (see first three columns in Fig. 3). For larger radius $r = 2.$ and angles $\theta = 75°, 80°, 85°$ spectral line shapes have triangular structure. For higher inclination angles $\theta = 88°, 89°$ and $r = 2.$ an extra (third) peak arises as it was discussed earlier by Zakharov & Repin (2003a) (see last panels in fourth and fifth rows in Fig. 3).

For radius $r = 3.$ and angle $\theta = 85°$ features of extra peaks arise (there is a bump) and features are more clear demonstrated for increasing radii and inclination angles (approaching the equatorial plane) and the features are clearly seen if radii tend to about $10r_g$. The effect was discussed earlier by Zakharov & Repin (2003a) (see also Dovčiak et al. (2004)).

5. Discussion and conclusions

As it was shown in the framework of the simple model the double peaked spectral line shape arise almost for all parameters r and a except the case when radii are very small ($r \in (0.7, 2)r_g$) and inclination angles are in the band $\theta \in [45°, 90°]$ (for these parameters the spectral line shape has triangular structure). The phenomenon could be easyly understood, since for this case the essential fraction of all photons emitted in the opposite direction in respect to the emitting segment of annulus is captured by a black hole, therefore a red peak is strongly dumped. For other radii and angles spectral line profiles have double peaked structure. Therefore we clarify the statement by Müller & Camenzind (2004) that double peaked structure arises if radiation region is far enough.

If we assume that radiation spot evolved along quasi-circular orbits from outer to inner radii, then temporal behavior of profiles could be characterized by a motion from right to left along each row at each Figs. If we assume that there is a weak dependence of emissivity function on radius, then a number of photons characterizes relative intensity in the line (roughly speaking for $r = 0.7$ an intensity (in counts) in 10 times lower then an intensity for $r = 2.$) therefore in observations for small radii one could detect only a narrow blue peak but another part of spectra is non-distinguishable from a background.

One could note also that for fixed radius there is a strong monotone dependence of intensity on inclination angle (maximal intensity corresponds to photon motion near equatorial plane and only a small fraction of all photons reach a distant observer near the polar axis). That is a natural consequence of a photon boost due to a circular motion of emitting fragment of annulus in the equatorial plane and an influence of spin of a rotating black hole (see also Dabrowski et al. (1997); Miniutti & Fabian (2004)).

In the framework of the simple model one could understand that sometimes the Fe K_α line

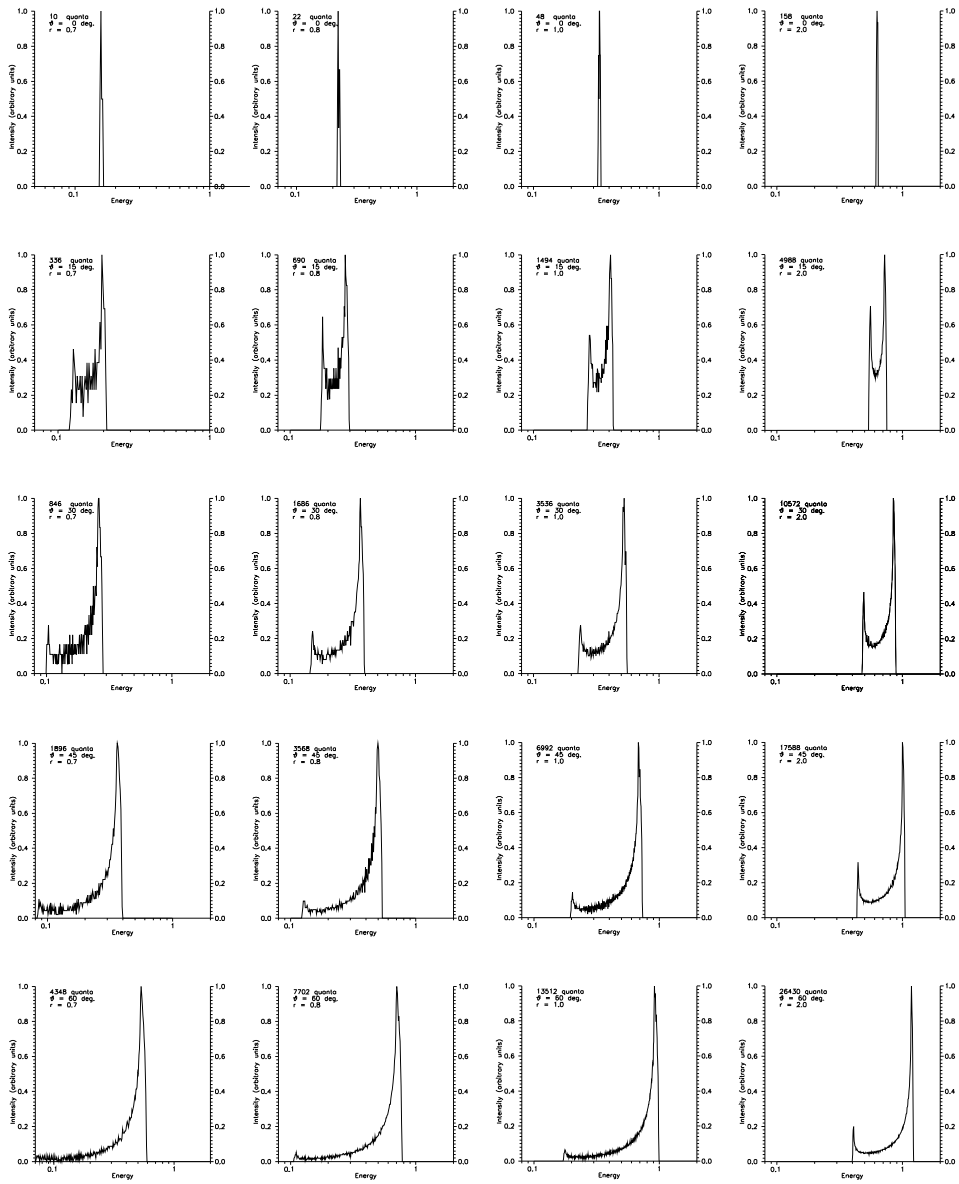

Fig. 2. A set of spectral line shapes for narrow emitting rings (annuli) is shown for different short radii and observer position angles. Radii take values 0.7, 0.8, 1, 2 r_g(from left to right); angles take values $0, 15, 30, 45, 60$ degrees (from top to down).

has only one narrow peak like in observations of the Seyfert galaxy MCG-6-30-15 by the XMM-Newton satellite Wilms et al. (2001). If radiating (or illuminating) region is a narrow annulus evolving along quasi-circular orbits, then initial two peak structure of the spec-

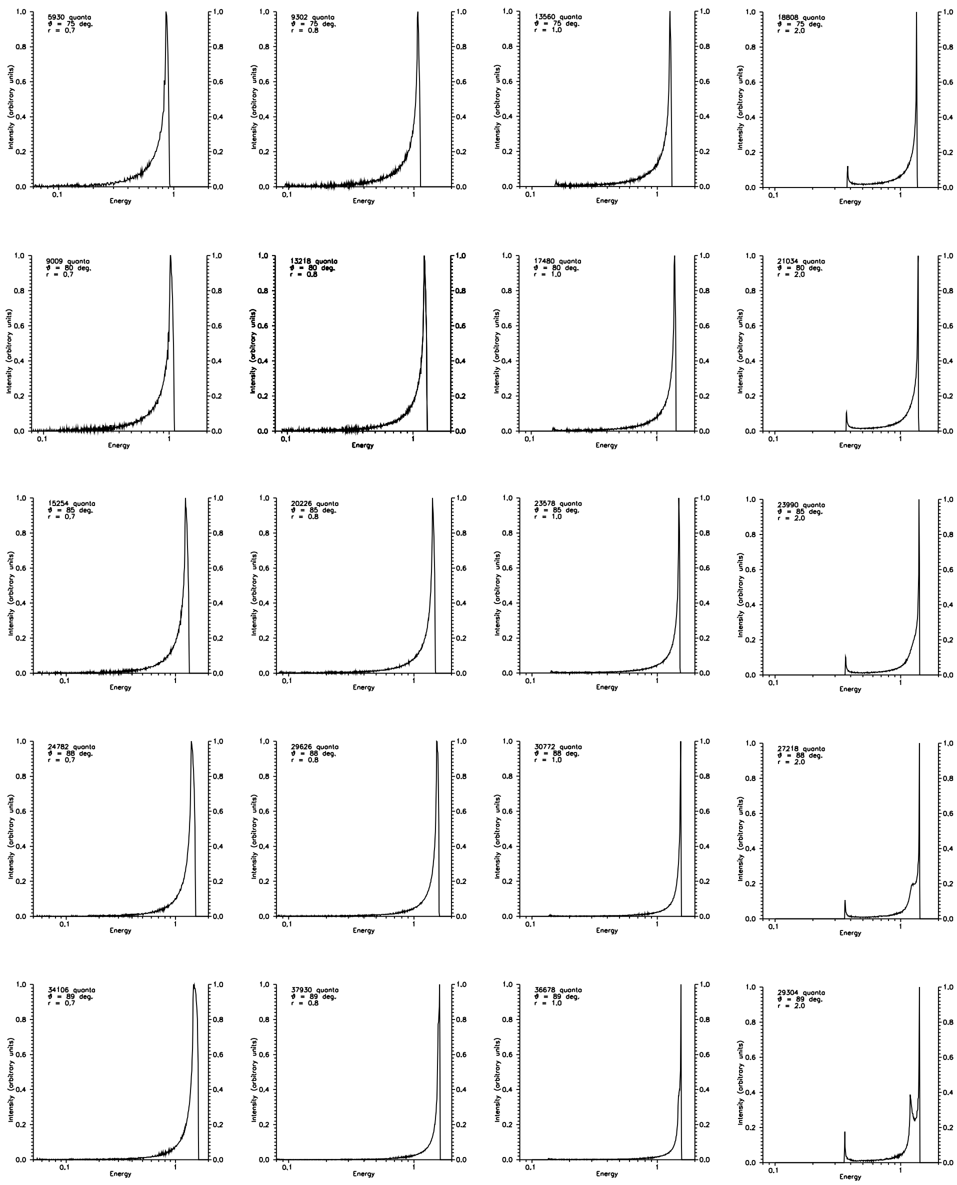

Fig. 3. A set of spectral line shapes for narrow emitting rings (annuli) is shown for different short radii and observer position angles. Radii take values 0.7, 0.8, 1, 2 r_g (from left to right); angles take values 75, 80, 85, 88, 89 degrees (from top to down).

tral line profile transforms in one peaked (triangular) form. Moreover, an absolute intensity in the line is increased for smaller radii since a significant fraction of emitted photons are captured by a black hole during the evolution of emitting region toward to black hole in observations we could detect only narrow blue peak and its height is essentially lower than its height was before for larger radii. Another part of the triangular spectral line shape could be non-distinguishable from a background. A relative low intensity for a triangular spectral line shape could give a narrow single peak structure in observations.

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