Proc. VI Serbian-Bulgarian Astronomical Conference, Belgrade 7-11 May 2008,
Eds. M. S. Dimitrijević, M. Tsvetkov, L. Č. Popović, V. Golev
Publ. Astr. Soc. "Rudjer Bošković", No. 9, 2009, 45-50

VARIATIONS IN AN ACCRETION DISK EMISSIVITY - REPERCUSSIONS TO THE Fe Kα LINE PROFILE

PREDRAG JOVANOVIĆ and LUKA Č. POPOVIĆ

Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
e-mail: pjovanovic@aob.bg.ac.yu

Abstract. The Fe Kα line of some Active Galactic Nuclei (AGN) shows certain irregularities which are not predicted by standard model of an accretion disk. Here we propose a modification of disk emissivity law in order to model the observed Fe Kα line profiles. The disk emission was analyzed using the ray-tracing method in Kerr metric, assuming a modification of power-law emissivity which allows us to include perturbations in the disk emission due to photoionization. When the emissivity law was modified in such way, we found that the corresponding variations in the disk emission could explain the observed Fe Kα line profiles if the line is emitted from the innermost part of the accretion disk.

1. INTRODUCTION

The X-ray spectrum and variability properties of AGN in most cases could be described with a two-component model consisting of a power-law continuum and a reflection component, containing a broad relativistic iron line from the accretion disk around a rapidly rotating Kerr black hole (Larsson et al., 2007). The most prominent feature in the resulting 3-10 keV reflection spectrum is the broad Fe Kα line extending from about 3 to 7 keV and peaking at 6.4 keV. The line arises as the power-law continuum irradiates the disk, and its asymmetric profile (narrow bright blue peak and wide faint red peak) is affected by relativistic effects close to the central black hole (BH). It was discovered in Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al., 1995) and later on observed in a number of AGN (Nandra et al., 1997; Nandra et al., 2007). In some cases the line width can correspond to one third of speed of light (as it is in case of MCG-6-30-15), indicating that its emitters rotate with relativistic velocities, close to the central BH. Therefore, observed Fe Kα line profiles represent a fundamental tool for investigating the plasma conditions and the space-time geometry in vicinity of the supermassive BH.

The observed Fe Kα line profiles of some Active Galactic Nuclei (AGN) show certain irregularities which are not predicted by standard Shakura-Sunyaev model of accretion disk (Shakura and Sunyaev, 1973). For example, a narrow component of the Fe Kα line is seen to vary in energy in NGC 3516 (Iwasawa et al., 2004) and Mrk 766 (Miller et al., 2006; Turner et al., 2006), possibly in a periodic manner (Fabian, 2006). On the other hand, in the best objects where a very broad Fe Kα line is seen (e.g. MCG–6-30-15 (Fabian and Vaughan, 2003) and NGC 4051 (Ponti et al. 2006)) amplitude of the line variations are considerably less than expected, despite large variations in the continuum (Fabian and Vaughan, 2003; Fabian, 2006). In such cases, the lack of variability of the line has been interpreted as an effect of strong gravitational light bending very close to the central black hole (Fabian and Vaughan, 2003; Ross and Fabian 2005).

To model the observed variability in the Fe Kα line profiles and intensities, here we consider the perturbations in the accretion disk emissivity, which is analyzed using ray-tracing method in Kerr metric (see Popović et al., 2003, and references therein).

2. MODELS OF DISK PERTURBING REGION

Surface emissivity of the disk is usually assumed to vary with radius as a power law: $\varepsilon(r) = \varepsilon_0 \cdot r^q$ where ε_0 is an emissivity constant and q - emissivity index. Total observed flux is then given by (Popović et al., 2006):

$$F_{obs}(E_{obs}) = \int_{image} \varepsilon(r) \cdot g^4\, \delta(E_{obs} - gE_0) d\Xi, \tag{1}$$

where g is the energy shift due to the relativistic effects: $g = \frac{\nu_{obs}}{\nu_{em}}$ and the rest energy of the Fe Kα line is: $E_0^{FeK\alpha} = 6.4$ keV. $d\Xi$ is the solid angle subtended by the disk in the observer's sky. In this paper we propose two modifications of the power-law disk emissivity in order to explain the observed profiles.

2.1. Model 1 of disk perturbing region

The following emissivity law of the disk is assumed:

$$\varepsilon_1(r) = \varepsilon(r) \cdot \left(1 + \varepsilon_p \cdot e^{-\left(\frac{r-r_p}{w_p}\right)^2}\right), \tag{2}$$

where $\varepsilon_1(r)$ is the modified emissivity of the disk at given radius r, $\varepsilon(r)$ is the power-law disk emissivity, ε_p - emissivity of perturbing region, r_p - central radius of perturbing region (in gravitational radii R_g) and w_p - width of perturbing region (in R_g). Under assumption that perturbation is moving by speed of light c, one can calculate time $t_p[s]$ that corresponds to current radius $r = \frac{r_p}{R_g}$:

$$t_p[s] = \frac{r_p[R_g]}{c[m \cdot s^{-1}]} = \frac{r \cdot GM_{BH}}{c^3}, \tag{3}$$

where G is Newton's gravitational constant and M_{BH} is the mass of central black hole.

2.2. Model 2 of disk perturbing region

In this model, the following emissivity law of the disk is assumed:

$$\varepsilon_2(x_p, y_p) = \varepsilon\left(r(x_p, y_p)\right) \cdot \left(1 + \varepsilon_p \cdot e^{-\left(\left(\frac{x-x_p}{w_x}\right)^2 + \left(\frac{y-y_p}{w_y}\right)^2\right)}\right), \tag{4}$$

where $\varepsilon_2(x_p, y_p)$ is the modified disk emissivity at the given position (x_p, y_p) of perturbing region (in R_g), ε_p is emissivity of perturbing region and (w_x, w_y) are its widths (also in R_g). Time $t_p[s]$ that corresponds to current position (x_p, y_p) can be estimated using the following expression:

$$t_p[s] = \frac{r(x_p, y_p)[R_g]}{c[m \cdot s^{-1}]} = \frac{r_{x,y} \cdot GM_{BH}}{c^3}, \tag{5}$$

where $r_{x,y} = \frac{r(x_p, y_p)}{R_g}$ G is Newton's gravitational constant and M_{BH} is the mass of central black hole.

3. PARAMETERS FOR NUMERICAL SIMULATIONS

For numerical simulations in the case of the first disk perturbing model, we adopted the following parameters: disk inclination i=35°, inner and outer radii of the disk R_{in}=R_{ms} and R_{out}=50 R_g (where R_{ms} is the radius of marginally stable orbit), emissivity constant ε_0=1, emissivity index q=-2.5 and emissivity of perturbing region ε_p=10. Central radius of perturbing region r_p was varied between 6 and 42 R_g and its width w_p between 1 and 5.5 R_g. The corresponding times t_p are calculated for black hole mass $M_{BH} = 1 \times 10^9\ M_\odot$.

In the case of the second perturbing model the disk parameters were the same, except that for its outer radius we took the value R_{out}=30 R_g. The emissivity of perturbing region in this case was ε_p=5. We made simulations for different positions of perturbing region along x-axis (i.e. for y_p=0) between x_p=8 and 26 R_g in both, positive and negative directions. At the same time the widths of perturbing region w_x=w_y were varied between 1 and 10 R_g. The times t_p are calculated for the same mass of central black hole as in previous case.

4. RESULTS

Two examples of disk perturbed emissivity in case of the first and the second perturbing models are presented in left panels of Figs. 1 and 2, respectively. The corresponding perturbed and unperturbed profiles of the Fe Kα line are given in the right panels of the same Figs. As one can see from these Figs, the first perturbing model affects the line flux in each of "red", "core" and "blue" spectral bands. Thus, it is not in good agreement with the most of observed variations of the Fe Kα line flux. On the other hand, in case of the second perturbing model (see Fig. 2), only "red wing" is affected while the "blue" one and the line core stay nearly constant. It is even more obvious if we analyze the corresponding simulated light

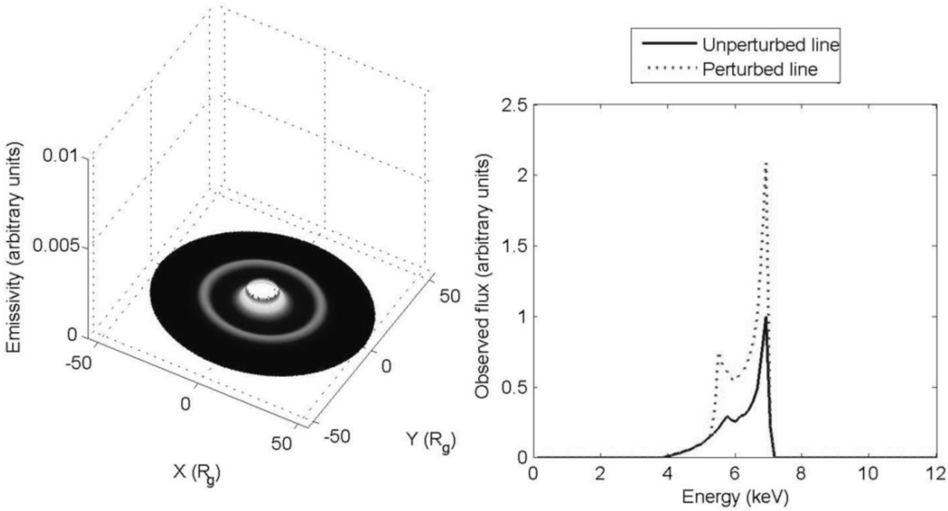

Figure 1: *Left*: shape of perturbed emissivity of an accretion disk in Schwarzschild metric in case of the first perturbing model for the following values of central radius of perturbing region and its width: r_p=26 R_g and w_p=3.5 R_g. The values of the other parameters are given in §3. *Right*: the corresponding perturbed (dashed line) and unperturbed (solid line) Fe Kα line profiles.

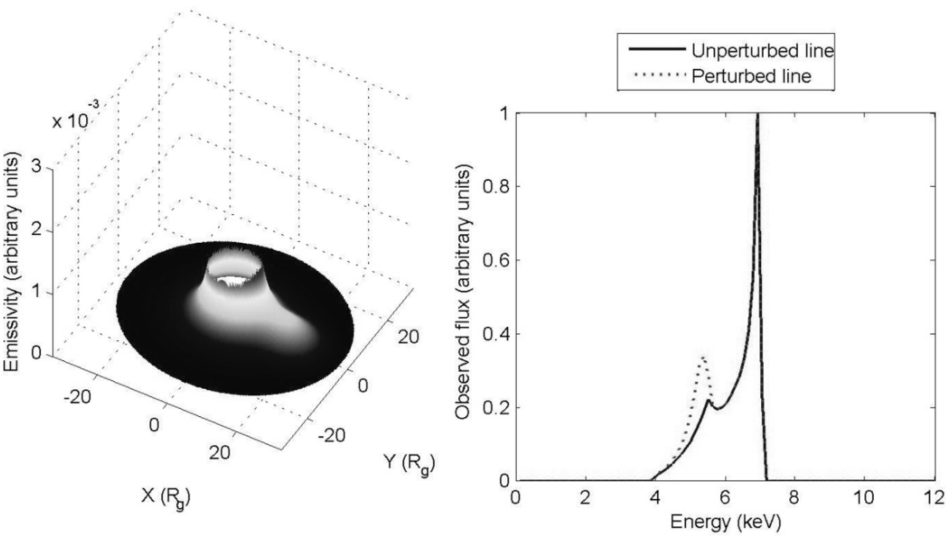

Figure 2: The same as in Fig. 1, but for the second perturbing model. The coordinates of perturbing region are x_p=20 R_g and y_p=0, its widths are w_x=w_y=7 R_g and the remaining parameters are described in §3.

curves which are presented in Fig. 3. From this figure it can be seen that the second model results in variations of only "red" light curve which are then reflected in total line flux in 0.1 - 12.8 keV energy band. Thus, this model could satisfactorily explain the observed variations of the Fe Kα line flux. Besides, in case of both models we are able to obtain the realistic durations of disk emissivity perturbations when we assume central supermassive black hole with mass $M_{BH} = 1 \times 10^9\ M_{\odot}$.

A detailed discussion will be given elsewhere (Jovanović et al., 2008).

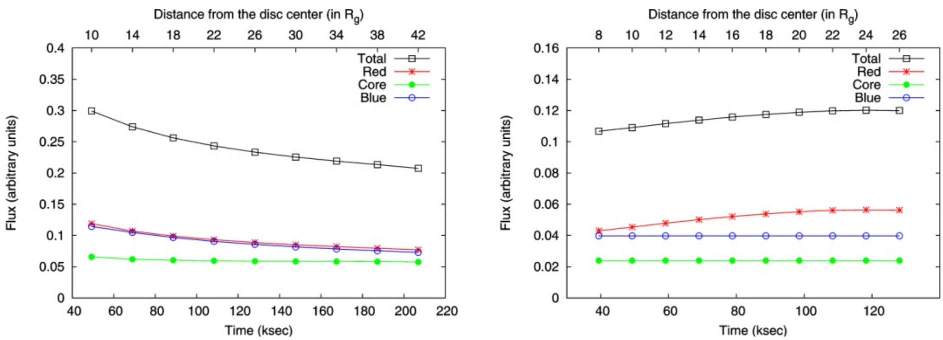

Figure 3: The simulated light curves in case of Model 1 (left) and Model 2 (right) of disk emissivity perturbations in Schwarzschild metric. Light curves correspond to the following spectral bands: total flux (black) to 0.1 - 12.8 keV, "red" to 0.1 - 6.1 keV, "core" to 6.1 - 6.7 keV and " blue" to 6.7 - 12.8 keV.

4. CONCLUSIONS

Perturbations of accretion disk emissivity were analyzed using numerical simulations based on a ray-tracing method in Kerr metric from wich we can preliminary conclude the following:

- i observed variations of the Fe Kα line flux could be caused by perturbations in the disk emissivity
- ii two models of disk perturbing regions were developed
- iii the first model affects the line flux in "red", "core" and "blue" spectral bands, and thus it is not in a good agreement with the most of observed variations of the Fe Kα line flux
- iv the second model results in variations of only one of "red" or "blue" light curves, while the other one stays nearly constant, as well as the line core. Thus, this model could satisfactorily explain the observed variations of the Fe Kα line flux
- v there are only small differences between the Fe Kα line flux variability in Schwarzschild and Kerr metrics for both models

vi realistic durations of disk emissivity perturbations in both analyzed models were obtained for central black hole mass $M_{BH} = 1 \times 10^9 \; M_{\odot}$.

The detailed analysis and results will be given in forthcoming paper (Jovanović et al. 2008).

Acknowledgments

This work is a part of the project (146002) "Astrophysical Spectroscopy of Extragalactic Objects" supported by the Ministry of Science and Technological Development of Serbia.

References

Fabian, A.C.: 2006, *AN*, **327**, 943.
Fabian, A. C., Vaughan, S.: 2003, *Mon. Not. R. Astron. Soc.*, **340**, L28.
Iwasawa, K., Miniutti, G., Fabian, A. C.: 2004, *Mon. Not. R. Astron. Soc.*, **355**, 1073.
Jovanović et al. 2008, in preparation.
Larsson, J., Fabian, A. C., Miniutti, G., Ross, R. R.: 2007, *Mon. Not. R. Astron. Soc.*, **376**, 348.
Miller, L., Turner, T. J., Reeves, J. N., George, I. M., Porquet, D., Nandra, K., Dovciak, M.: 2006, *Astron. Astrophys.*, **453**, L13.
Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J. and Yaqoob, T.: *1997, Astrophys. J.*, **477**, 602.
Nandra, K., O'Neill, P. M., George, I. M., Reeves, J. N.: 2007, *Mon. Not. R. Astron. Soc.*, **382**, 194.
Ponti, G., Miniutti, G., Cappi, M., Maraschi, L., Fabian, A. C., Iwasawa, K.: 2006, *Mon. Not. R. Astron. Soc.*, **368**, 903.
Popović, L. Č., Jovanović, P., Mediavilla, E. G., Zakharov, A. F., Abajas, C., Muñoz, J. A. and Chartas, G.: 2006, *Astrophys. J.*, **637**, 620.
Popović, L. Č., Mediavilla, E. G., Jovanović, P., Muñoz, J. A.: *2003, Astron. Astrophys.*, **398**, 975.
Ross, R. R., Fabian, A. C.: 2005, *Mon. Not. R. Astron. Soc.*, **358**, 211.
Shakura, N. I. and Sunyaev, R. A.: 1973, *Astron. Astrophys.*, **24**, 337.
Tanaka, Y., Nandra, K., Fabian, A. C., Inoue, H., Otani, C., Dotani, T., Hayashida, K., Iwasawa, K., Kii, T., Kunieda, H., Makino, F., Matsuoka, M.: 1995, *Nature*, **375**, 659.
Turner, T. J., Miller, L. J., George, I. M., Reeves, J. N.: 2006, *Astron. Astrophys.*, **445**, 59.