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CORRELATION BETWEEN X-RAY CONTINUUM AND Fe Kα LINE VARIATION DUE TO MICROLENSING

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Abstract. The correlation between X-ray continuum and Fe Kα line variation due to microlensing event (MLE) is investigated. Concerning the shape of observed X-ray variations in three lensed quasars (MG J0414+0534, QSO 2237+0305, BAL QSO H1413+117 AT), we conclude that the Fe Kα forming region should be different in dimension than X-ray continuum emission region.

1. INTRODUCTION

The X-ray variability in continuum as well as in spectral lines (e.g. Fe Kα) is often present in the spectra of Active Galactic Nuclei - AGN (see e.g. Marshall et al. 1981, Turner et al. 1999, Manners et al. 2002).

Zakharov et al. (2003) found the significant probability that the high-redshifted QSOs are microlensed. Moreover, the microlensing effect in three macrolensed QSOs has been recently observed (Chartas et al., 2002; Dai et al., 2003; Oshima et al., 2001).

The influence of microlensing on Fe Kα spectral line shape was discussed in Popović et al. (2003), where it was noted that microlensing effect can be used for investigation of Fe Kα and continuum emission region structure.

The aim of this paper is to investigate the correlation between X-ray continuum and Fe Kα line variations due to microlensing, and to use the obtained results for discussion about the structure of Fe Kα and continuum emission region in AGN.

2. THEORY

The effects of microlensing on a compact accretion disk are analyzed using the ray tracing method (Bao et al, 1994; Bromley et al, 1997; Fanton et al, 1997; Čadež et al, 1998) considering only those photon trajectories that reach the sky plane at a given observer's angle $\theta_{\rm obs}$. If X and Y are the impact parameters that describe the apparent position of each point of the accretion disk image on the celestial sphere as seen by an observer at infinity, the amplified brightness is given by

$$I_p = I\left(T(X,Y)\right)\delta(x - g(X,Y))A(X,Y) \tag{1}$$

where $x = \nu_{\rm obs}/\nu_0$ (ν_0 and $\nu_{\rm obs}$ are the transition and observed frequencies, respectively); $g = \nu_{\rm em}/\nu_{\rm obs}$ ($\nu_{\rm em}$ is the emitted frequency from the disk). $A(X,Y)$ is the amplification caused by microlensing.

In the case of microlensing by an isolated compact object (point-like microlens), the amplification is given by the relation (see e.g. Narayan and Bartelmann, 1999):

$$A(X,Y) = \frac{u^2(X,Y) + 2}{u(X,Y)\sqrt{u^2(X,Y) + 4}}, \tag{2}$$

where $u(X,Y)$ corresponds to the angular separation between lens and source in Einstein Ring Radius (ERR) units and is obtained from

$$u(X,Y) = \frac{\sqrt{(X - X_0)^2 + (Y - Y_0)^2}}{\eta_0}, \tag{3}$$

X_0, Y_0 are the coordinates of the microlens with respect to the disk center (given in gravitational radii), and η_0 is the Einstein Ring Radius (ERR) expressed in gravitational radii.

To express I(T(X,Y)) we started from the standard Newtonian model of an accretion disk around a supermassive black hole. This model is based on the supposition that the locally released gravitational energy is emitted as a blackbody radiation of the temperature (Shalyapin et al, 2002):

$$T\left(r\right) = \left[\frac{3}{8\pi}\frac{GM}{\sigma r^3}\dot{M}\left(1 - \sqrt{\frac{r_{in}}{r}}\right)\right]^{\frac{1}{4}}, \tag{4}$$

where σ is the Stefan constant, G is the gravitational constant, M is the central black hole mass, $\dot{M}$ is the accretion rate, and r_{in} is the inner radius of the accretion disk. The above formula can be approximated by the following expression (Takahashi et al, 2001):

$$T\left(r\right) \approx 2.2 \times 10^5 \dot{M}_{26}^{1/4} M_8^{1/4} r_{14}^{-3/4}\left(1 - \sqrt{\frac{r_{in}}{r}}\right)^{\frac{1}{4}} K, \tag{5}$$

where $\dot{M}_{26} = \dot{M}/10^{26}{\rm gs}^{-1}, M_8 = M/10^8 M_\odot, r_{14} = r/10^{14}{\rm cm}$. The emitted intensity in Eq. (1) is a Planck function of the temperature:

$$I\left(T(X,Y)\right) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT(X,Y)} - 1}, \tag{6}$$

where c is the speed of light, h - Planck constant, k - Boltzmann constant and T is temperature.

The total observed flux is then given by

$$F(x) = \int_{\rm image} I_p(x)d\Omega, \tag{7}$$

where $d\Omega$ is the solid angle subtended by the disk in the observer's sky and the integral extends over the whole emitting region.

3. RESULTS

Recent observations of gravitationally lensed quasars QSO 2237+0305 (Dai et al, 2003), MG J0414+0534, (Chartas et al, 2002) and BAL QSO H1413+117 AT (Oshima et al, 2001) suggest that sudden enhancements of Fe Kα line, characteristical only for some of the source images, are possibly caused by microlensing.

In order to study the influence of microlensing on the variations of X-ray continuum and Fe Kα spectral line shape, we adopted the standard black body radiation model of a relativistic accretion disk with inclination $i = 35^o$. In our analysis we used the masses and accretion rates for AGNs given by Bian and Zhao (2002). In their Table 1, accretion rates are given in units of Eddington accretion rate: $\dot{m} = \frac{1.578\dot{M}_{26}}{3.88M_8}$, and we used them to determine the effective temperature distribution. According to Bian and Zhao (2002), we assumed the central black hole with mass $M = 10^8 M_\odot$ and accretion rate $\dot{m} = 0.4$ units of Eddington accretion rate. The variations of normalized line flux and normalized continuum are calculated for different positions of the point-like microlens with ERR = 10 R_g and for a disk in both, Schwarzschild and Kerr metrics. Normalization is made by dividing the perturbed flux by its unperturbed value.

Concerning possible dimensions of the X-ray line and continuum sources, the three cases were considered:

1. The radii of both continuum and line emission region are the same; $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$,
2. The radus of the continuum emission region is smaller than that for line emission, but the inner part of accretion disk emits in the line as well as in the continuum. In this case for continuum accretion disk we choose the inner and outer radii $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$, respectively. The corresponding radii for line emission accretion disk are $R_{in} = R_{rms}$ and $R_{out} = 80\ R_g$,
3. The dimension of the line emitting region is larger than continuum one, and they are separated. The radii of continuum emission accretion disk are $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$ and those of the line emission disk are $R_{in} = 20\ R_g$ and $R_{out} = 80\ R_g$.

As one can see from Fig. 1., in the first case, there is a very high correlation between line flux variation and continuum variation.

In the second case (Fig. 2), the correlation is less but still significant. The main reason for such significant correlation could be that continuum emission region coincides with the inner part of line emission region

Both of cases are not in good agreement with observations of gravitationally lensed quasar MG J0414+0534. Chartas et al. (2002) found that the continuum emission component does not follow the enhancement of the iron line. Considering the third case (Fig. 3) one can say that this case may be compared with observed variation due to MLE observed by Oshima et al. (2001), Chartas et al. (2002) and Dai et al. (2003), where the amplification is observed only in the Fe Kα line. As one can see in

Fig. 3, the microlensing effect is strong in X-ray continuum, but when the microlens crosses the outer region, the amplification of Fe Kα line flux stays stronger, while continuum is also amplified, but stays nearly constant during the MLE. These results also follow the explanation given in Chartas et al. (2002) that non-enhancement of the continuum suggests that the continuum emission region is concentrated closer to the center of the accretion disk than the iron line emission region, and that the microlens does not reach close enough to the continuum region to amplify it.

4. CONCLUSION

In order to investigate the influence of microlensing on the variations of X-ray continuum and Fe Kα line profile, we used the ray tracing method and considered the standard black body radiation model for a relativistic accretion disk around a supermassive black hole in both, Schwarzschild and Kerr metrics.

From our investigation we can conclude that the satisfactory explanation for the fact that we observe only Fe Kα line flux amplification (the absence of corresponding

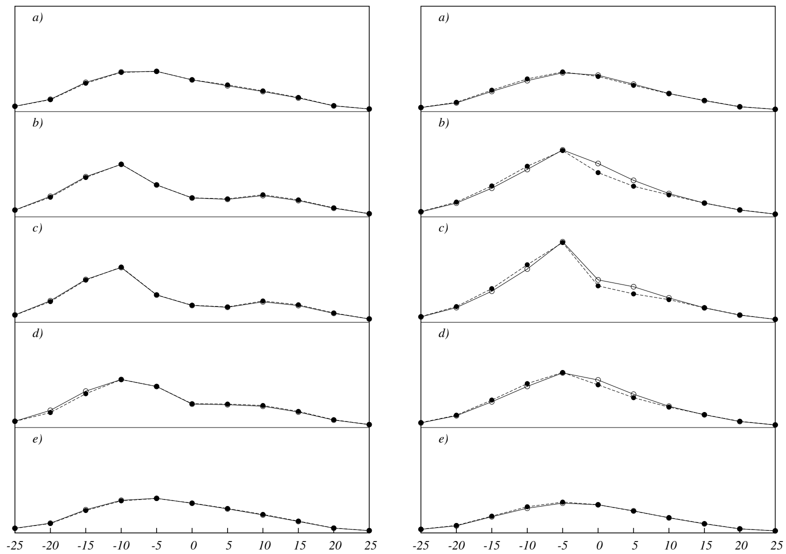

Fig. 1: The variations of normalized line flux (dashed line with full circles) and normalized continuum (solid line with open circles) for a disk in the Schwarzschild metric (left) and Kerr metric (right) with $i = 35^o$ and for different positions of the point-like microlens with ERR = 10 R_g. The radii of continuum and line emission regions of disk are $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$ in both cases. The central BH mass is $10^8 M_\odot$ and the accretion rate is 0.4 units of Eddington accretion rate. Case a) corresponds to the postion of MLE $Y_0 = 10$, case b) to $Y_0 = 5$, case c) to $Y_0 = 0$, case d) to $Y_0 = -5$, case e) to $Y_0 = -10$. The normalized flux is presented in range from 1 to 2.5.

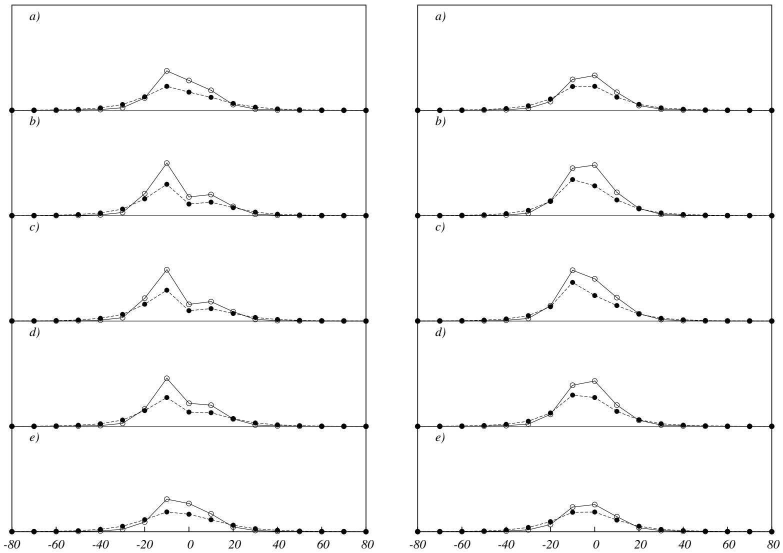

Fig. 2: The same as in Fig. 1, but the radii of continuum emission region are $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$ and the radii of line emission region are $R_{in} = R_{rms}$ and $R_{out} = 80\ R_g$.

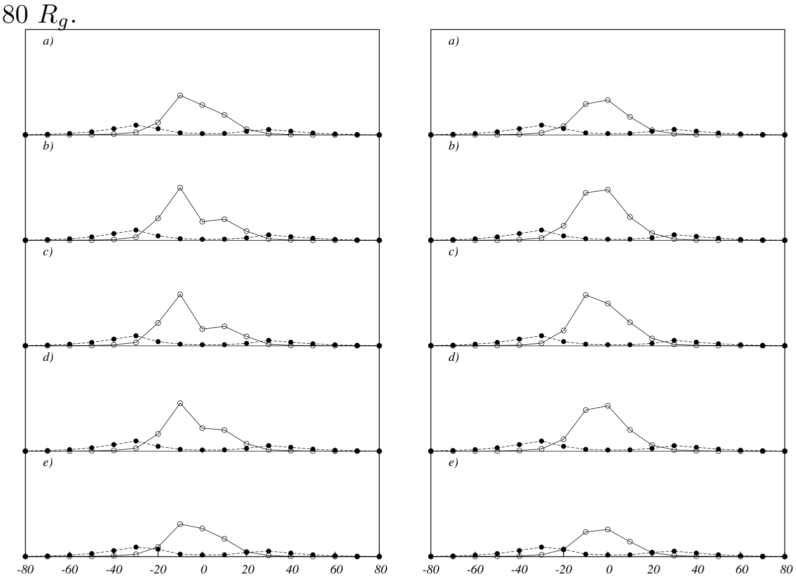

Fig. 3: The same as in Fig. 1, but the radii of continuum emission region are $R_{in} = R_{rms}$ and $R_{out} = 20\ R_g$ and the radii of line emission region are $R_{in} = 20\ R_g$ and $R_{out} = 80\ R_g$.

continuum variations) is that the Fe Kα emission region has different dimension than continuum one.

The more detailed discussion will be given in Jovanović et al. (2003).

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References

Bao, G., Hadrava, P., Ostgaard, E.: 1994, *Astrophys. J.*, **435**, 55.

Bian, W., Zhao, Y.: 2002, *Astron. Astrophys.*, **395**, 465.

Bromley, B.C., Chen, K., Miller, W.A.: 1997, *Astrophys. J.*, **475**, 57.

Chartas, G., Agol, E., Eracleous, M., Garmire, G., Bautz, M.W., Morgan, N.D.: 2002, *Astrophys. J.*, **568**, 509.

Čadež A., Fanton, C., Calvani, M.: 1998, *New Astronomy*, **3**, 647.

Dai, X., Chartas, G., Agol, E., Bautz, M.W., Garmire, G.P.: 2003, *Astrophys. J.*, **589**, 100.

Fanton, C., Calvani, M., Felice, F., Čadež, A.: 1997, *Publ. Astron. Soc. Japan*, **49**, 159.

Jovanović, P., Popović, L.Č., Mediavilla, E., Muñoz, J.A.: 2003, *Astron. Astrophys.*, in preparation.

Manners, J., Almaini, O., Lawrence, A.: 2002, *Mon. Not. Roy. Astron. Soc.*, **330**, 390.

Marshall, N., Warwick, R.S., Pounds, K.A.: 1981, *Mon. Not. Roy. Astron. Soc.*, **194**, 987.

Narayan, R., Bartelmann, M.: 1999, *Formation of Structure in the Universe* (Eds. A. Deker, J.P. Ostriker), Cambridge University Press, 360.

Oshima, T., Mitsuda, K., Fujimoto, R., Iyomoto, N., Futamoto, K., et al.: 2002, *Astrophys. J.*, **563**, L103.

Popović, L.Č., Mediavilla, E.G., Jovanović, P. and Muñoz, J.A.: 2003, *Astron. Astrophys.*, **398**, 975.

Shalyapin, V.N., Goicoechea, L.J., Alcalde, D., Mediavilla E., Muñoz J.A., Gil-Merino, R.: 2002, *Astrophys. J.*, **579**, 127.

Takahashi, R., Yonehara, A., Mineshige, S.: 2001, *Publ. Astron. Soc. Japan*, **53**, 387.

Turner, T.J., George, I.M., Nandra, K., Turcan, D.: 1999, *Astrophys. J.*, **524**, 667.

Zakharov, A.F., Popović, L.Č., Jovanović, P.: 2003, *Astron. Astrophys.*, submitted.