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Microlensing effect on Fe Kα line and X-ray continuum in the case of three gravitationally lensed quasars: MG J0414+0534, QSO 2237+0305 and H1413+117

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Abstract. The observed enhancements of the Fe Kα line in three gravitationally lensed QSOs: MG J0414+0534, QSO 2237+0305 and H1413+117 are interpreted in terms of microlensing, even if an equivalent X-ray continuum amplification is not observed. To understand these observations we have studied the effects of microlensing on the quasar spectra produced by the crossing of a straight fold caustic across a standard relativistic accretion disk. To describe the disk emission we used a ray tracing method considering both metrics, Schwarzschild and Kerr.

Key words. Microlensing: Fe Kα line – Microlensing: X-ray continuum – Quasar: Gravitationally lensed – Quasar: MG J0414+0534 – Quasar: QSO 2237+0305 – Quasar: H1413+117

1. Introduction

Recent observational and theoretical studies suggest that gravitational microlensing can induce variability in the X-ray emission of gravitationally lensed QSOs. Microlensing of the Fe Kα line has been reported at least in three macrolensed QSOs: MG J0414+0534 (Chartas et al. 2002), QSO 2237+0305 (Dai et al. 2003), and H 1413+117 (Oshima et al. 2001a; Popović et al. 2003a; Chartas et al. 2004). Chartas et al. (2002) detected an increase of the Fe Kα equivalent width in the image B of MG J0414+0534 which was not followed by the continuum and explained this behavior by assumption that the thermal emission region of the disk and the Compton up-scattered emission region of the hard X-ray source lie within smaller radii than the iron-line reprocessing region. Analyzing the X-ray variability of QSO 2237+0305A, Dai et al. (2003) also measured amplification of the Fe Kα line in component A of QSO 2237+0305 but not in the continuum and suggested that the larger size of the continuum emission region in comparison to the Fe Kα emission region could explain this result. In the case of H 1413+117, Chartas et al. (2004) found that the continuum and the Fe Kα line were enhanced by a different factor. Popović et al. (2005) analyzed this different behavior of line and continuum variability in the observed events in context of the microlensing hypothesis. The influ-

Send offprint requests to: P. Jovanović ence of microlensing on the Fe Kα spectral line shape was also discussed in Popović et al. (2001a,b); Chartas et al. (2002) and Popović et al. (2003a,b). Popović et al. (2003a,b) showed that objects in a foreground galaxy with even relatively small masses can produce observable changes in the Fe Kα line flux.

The aim of this paper is to discuss microlensing of the X-ray emitting region in the case of three lensed quasars (MG J0414+0534, QSO 2237+0305 and H1413+117) where microlensing of the Fe Kα line was observed.

2. Microlensing of a compact accretion disk

To study the effects of microlensing on a compact accretion disk we used the ray-tracing method (see e.g. Popović et al. (2003a) and references therein). The amplified brightness (at energy E) with amplification $A(X, Y)$ for the continuum is given by

$$I_C(X, Y; E) = I_P(E, T(X, Y)) \cdot A(X, Y), \tag{1}$$

and for the Fe Kα line by

$$I_L(X, Y; E) = I_P(E_0 \cdot g(X, Y), T(X, Y)) \cdot \delta(E - E_0 \cdot g(X, Y)) \cdot A(X, Y), \tag{2}$$

where $I_P(E, T(X, Y))$ is the disk emissivity, $T(X, Y)$ is the temperature, X and Y are the impact parameters which describe the apparent position of each point of the accretion disk image on the celestial sphere as seen by an observer at infinity; E_0 is the the line transition energy ($E_0^{\mathrm{Fe\ K}\alpha} = 6.4$ keV) and the energy shift $g(X, Y) = E_{\mathrm{obs}}/E_{\mathrm{em}}$ (E_{obs} is the observed energy and E_{em} is the emitted energy from the disk). The line shape, as well as the continuum distribution, depend on emissivity law, so we will use here the black body and modified black body emissivity laws for both; the Fe Kα and X-ray continuum emission.

The total observed flux for the continuum and the Fe Kα line is given as

$$F(E) = \int_{\mathrm{image}} [I_C(X, Y; E) + I_L(X, Y; E)] d\Omega, \tag{3}$$

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. As one can see from the above equation, the total observed flux is a sum of the continuum and the line fluxes and consequently, the amplification in the continuum and in the Fe Kα line can be considered separately as two independent components, originating from their own emitting regions in an accretion disk.

2.1. Microlens and accretion disk parameters

In most cases micro-deflector is located in an extended object (typically, a lens galaxy) and its influence can be described by crossing of the straight fold caustic over accretion disc. The expression for caustic amplification $A(X, Y)$ is given in e.g. (Chang & Refsdal 1984). For other microlens parameters, such as Einstein ring radus (ERR), the amplification outside of the caustic (A_0), caustic amplification factor (β) and the direction of caustic motion (κ) we adopted the same values as in Popović et al. (2005). For the disk inclination we used the averaged values given by Nandra et al. (1997) from the study of the Fe Kα line profiles of 18 Seyfert 1 galaxies: $i = 35°$. The inner radius of the disk, R_{in}, can not be smaller than the radius of the marginally stable orbit, R_{ms}, that corresponds to $R_{ms} = 6R_g$ (gravitational radii, $R_g = GM/c^2$, where G is gravitational constant, M is the mass of central black hole, and c is the velocity of light) in the Schwarzschild metric and to $R_{ms} = 1.23R_g$ in the case of the Kerr metric with angular momentum parameter $a = 0.998$. To select the outer radius, R_{out}, we took into account some previous investigations of the X-ray variability, supporting a very compact X-ray emitting disks ranging from 10 to 100 R_g for black hole masses in the range $10^7 - 10^9$ $M_\odot$. This range of sizes is also acceptable for the Fe Kα emission region (see e.g. Nandra et al. (1997)).

In order to explain the lack of adequate response of the X-ray continuum to the microlensing events detected in the Fe Kα line, we considered two cases:

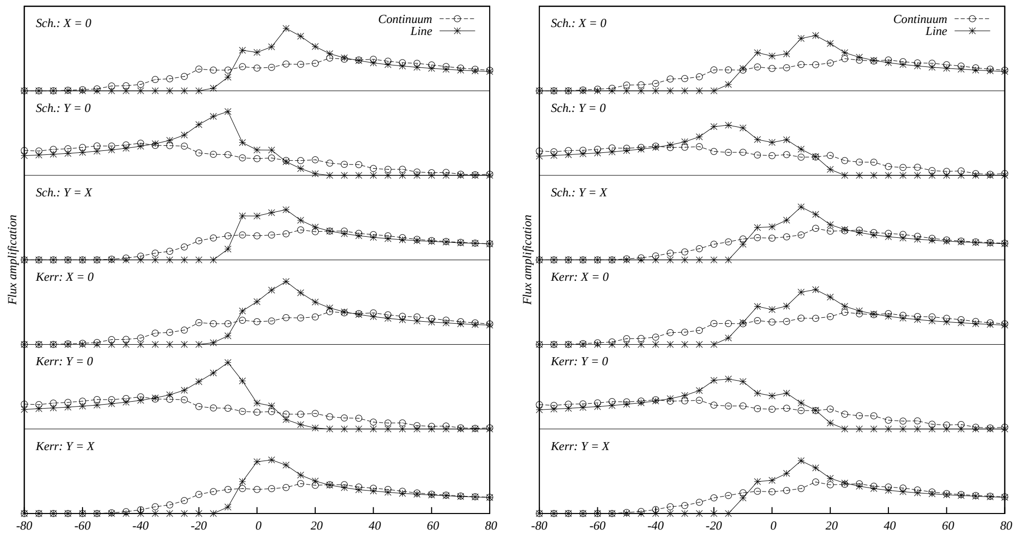

Fig. 1. Variations of integrated Fe Kα line and X-ray continuum flux during a caustic crossing (ERR=50 R_g) over accretion disk in the case 1. of §2.1. Three different directions of caustic crossing are considered: X=0, Y=0 and X=Y. Left and right panels correspond to the black body and modified black body law, respectively. From top to bottom, the three first panels (left and right) correspond to Schwarzschild and the last three to Kerr metrics. The flux axis ranges from 1 to 1.7.

1. the continuum emission region has radii $R_{in} = 20\ R_g$, $R_{out} = 80\ R_g$ and the line emission region $R_{in} = R_{ms}$ and $R_{out} = 20\ R_g$ (i.e. the Fe Kα emission is located in the inner disk and the continuum emission in the outer annulus);
2. the continuum emission region has radii $R_{in} = R_{ms}$, $R_{out} = 20\ R_g$ and the line emission region $R_{in} = 20\ R_g$ and $R_{out} = 80\ R_g$ (i.e. the continuum emission takes place in the inner part of disk surrounded by the annulus of Fe Kα emission).

3. Results

The variations of the integrated X-ray continuum and Fe Kα line flux due to caustic crossing ($ERR = 50\ R_g$) over the accretion disk in the case 1. of §2.1 are presented in Fig. 1, and the corresponding variations due to crossing of caustic with $ERR = 2000\ R_g$ over a highly inclined accretion disk in the case 2. of §2.1 are presented in Fig. 2. Taking into account that the observed BAL QSOs could have accretion disks with high inclination, here we adopted the value $i = 75°$. The results presented on Figs. 1 and 2 correspond to the black body and modified black body emission laws, respectively. When the continuum and line emission are separated (Figs. 1 and 2), considering that inner disk contributes to the continuum and an outer annulus to the Fe Kα line (or vice-versa), there is a significant differences between the continuum and the line amplification. Also, the amplified component is mainly very narrow (Fig. 2) in comparison with the undeformed line. This result is in agreement with the observations of Chartas et al. (2002, 2004) and Dai et al. (2003) and supports the conclusions of these authors that enhancements of the Fe Kα line observed in only one image of quasars MG J0414+0534, QSO 2237+0305 and H1413+117 were caused by microlensing. The lack of observed associated enhancement of the X-ray continuum in objects with the microlensed Fe Kα line can be expected in the case 1. of §2.1 when the microlens crosses the inner part of the disk (Fig. 1). However, the continuum never remains strictly constant during a complete Fe Kα microlensing event. In

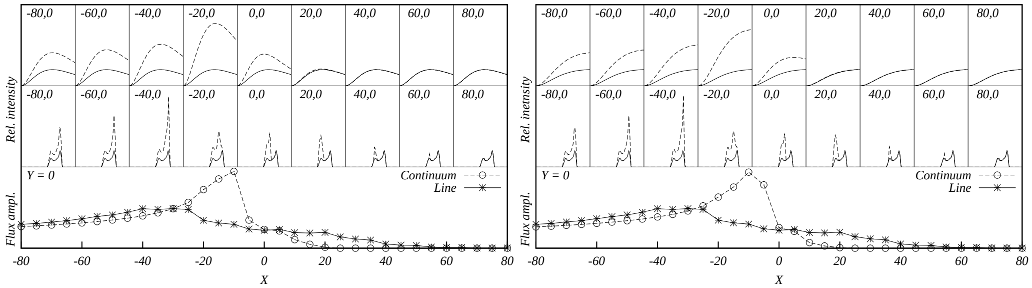

Fig. 2. Variations of the X-ray continuum and the Fe Kα line flux for a highly inclined disk (i = 75°) due to microlensing by a caustic with ERR=2000 R_g in the case 2. of §2.1. Black body (left) and modified black body (right) emission laws are considered. The flux axis ranges from 1 to 4.

the best case there is a significant and relatively quick change of the Fe Kα emission while the continuum experiences only a slow increase. This behavior could well approximate non-varying continuum only for observations in a limitited temporal window, during the maximum of the Fe Kα line microlensing event. In such case, the amplification of slowly changing or almost constant continuum of quasar's microlensed image, in respect to the continua of the other images, is practically indistinguishable from the global macrolensing amplification. This, as well as the shapes of the line and continuum total flux amplification, indicate that the observed microlensing amplification of the Fe Kα in three lensed quasars may be explained if the line is originated in the innermost part of the disk and the X-ray continuum in some larger region.

4. Conclusions

In order to discuss the observed enhancements of the Fe Kα line and absence of corresponding continuum amplifications in the case of quasars MG J0414+0534, QSO 2237+0305 and H1413+117, we performed the numerical simulations and obtained the following results:

1. Both, the Fe Kα line and the X-ray continuum may experience significant amplification by a microlensing event;
2. Segregation of the emitters allows us to reproduce the Fe Kα enhancement without equivalent continuum amplification (the case of the inner Fe Kα disk plus an outer continuum annulus), but only during the limited time intervals.

More detailed discussion about microlensing of the X-ray emitting region will be given in Popović et al. (2005).

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