Amplification and variability of the AGN X-ray emission due to microlensing

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We consider the contribution of microlensing to the AGN Fe Kα line and X-ray continuum amplification and variation. To investigate the variability of the line and X-ray continuum, we studied the effects of microlensing on quasar X-ray spectra produced by crossing of a microlensing pattern across a standard relativistic accretion disk. To describe the disk emission we used a ray tracing method considering both metrics, Schwarzschild and Kerr. We found that the Fe Kα and continuum may experience significant amplification by a microlensing event (even for microlenses of very small mass). Also, we investigate a contribution of microlensing to the X-ray variability of high-redshifted QSOs, finding that cosmologically distributed deflector may contribute significantly to the X-ray variability of high-redshifted QSOs (z > 2).

1 Introduction

The X-ray emission in Active Galactic Nuclei – AGN (the continuum as well as in the Fe Kα spectral line) has rapid and irregular variability (see e.g. Manners et al. 2002). X-ray flux variability has long been known to be a common property of AGN, i.e. X-ray flux variations are observed on timescales from ~1000 s to years, and amplitude variations of up to an order of magnitude are observed in the ~0.1-10 keV spectral band (see, for example reviews by Mushotzky et al. 1993; Ulrich et al. 1997, and references therein).

Recent observational studies suggest that gravitational microlensing can induce variability in the X-ray emission of microlensed QSOs. Microlensing of the Fe Kα line has been reported at least in three microlensed QSOs: MG J0414+0534 (Chartas et al. 2002), QSO 2237+0305 (Dai et al. 2003), and H1413+117 (Popović et al. 2003a, Chartas et al. 2004).

The influence of microlensing in the X-ray emission has been also theoretically investigated. Mineshiga et al. (2001) simulated the variation of the X-ray continuum due to microlensing showing that the flux magnifications for the X-ray and optical continuum emission regions are not significantly different during the microlensing event, while Yonehara et al. (1998,1999), Takahashi et al. (2001) found that simulated spectral variations caused by microlensing show different behavior, depending on photon energy. Also, microlensed light curves for thin accretion disks around Schwarzschild and Kerr black holes were considered in Jaroszyński (2002) and microlensing light curves for the Fe Kα line were simulated by Jaroszyński (1992). Moreover, the influence of microlensing in the Fe Kα spectral line shape was discussed in Popović (2001a), Chartas (2002), Popović et al. (2003ab, 2006) and Jovanović (2005,2006).

All of these investigations showed that monitoring of gravitational lenses may help us to understand the physics of the innermost part of AGNs, i.e. the physics of relativistic accretion disks. The aims of this work are to discuss of the X-ray variation due to microlensing (in the X-ray continuum and Fe Kα line) and consider the probability that the QSO X-ray emission may be affected by microlensing of cosmologically distributed deflector.

2 Theoretical model

The X-ray emitting region geometry.

According to the standard model of AGNs, a QSO consists of a black hole (BH) surrounded by a (X-ray and optical) continuum emitting region probably with an accretion disk geometry, a broad line region and a larger region that can be resolved in several nearby AGN that is the so called narrow line region (e.g., Krolik 1999). The X-ray emitting region is supposed to be the most compact and the closest to the massive black hole. Consequently, an initial assumption that we adopted was the existence of a super-massive BH \( (10^7-10^9 \text{ M}_\odot) \) surrounded by an accretion disk that radiates X-rays in the center of all types of AGNs. Accretion disks could have different forms, dimensions, and emission, depending on the type of central BH, whether it can be rotating (Kerr metric) or non-rotating (Schwarzschild metric) BH. Except for effects due to disk instability, its emission...
could also be affected by gravitational microlensing, especially in the case of gravitationally lensed QSOs (Chartas et al. 2002,2004; Dai et al. 2003).

The disk emission was analyzed using numerical simulations based on a ray-tracing method in a Kerr metric, taking into account only photon trajectories reaching the observer’s sky plane (see Popović et al. 2003ab and references therein). The assumption of a disk geometry for the distribution of the Fe Kα emitters is supported by the spectral shape of this line in AGN (e.g. Nandra 1997). Regarding the X-ray continuum emission, it seems that it mainly arises from an accretion disk. For instance, Fabian et al. (2003) have shown that the X-ray spectral variability of MCG-6-30-15 can be modeled by a two-component model where the one varying component is a power-law and the other constant component is produced by very strong reflection from a relativistic disk. Consequently, to study the effects of microlensing on a compact accretion disk we used the ray tracing method considering only those photon trajectories that reach the sky plane at a given observer’s angle θobs (see e.g. Popović et al. 2003ab and references therein). The amplified brightness with amplification A(X, Y) for the continuum and the line is given in Popović et al. (2006) as well as discussion about emissivity of the disk, and here will not be repeated.

**Microlens model.**

The influence of microlensing on a standard accretion disk was studied using three types of a microlensing model: point-like microlens, straight-fold caustic, and quadrupole microlens. Illustration of the point like microlens and straight-fold caustic crossing over an accretion disk in the Kerr/Sch. metric and the corresponding effects on the the X-ray continuum shapes and the Fe Kα line can be found in Popović et al. (2003ab, 2006) and Jovanović (2005,2006).

For the each lens system we are able to model the amplification maps (see e.g. Abajas et al. 2005, Popović et al. 2006 and Figs. 1 and 2). In order to apply an appropriate microlens model, we considered a standard microlensing magnification pattern (Figs. 1 and 2, upper) for different objects. The simulation was made employing ray-shooting techniques that send rays from the observer through the lens to the source plane (Kayser et al. 1986; Schneider & Weiss 1987; Wambsganss et al 1990a,b). We assume a flat cosmological model with Ω = 0.3 and H0 = 75 km s⁻¹ Mpc⁻¹.

As an example, the illustration of the amplification patterns for PG 1115+080A1,A2 images are given in Figs. 1 and 2 (upper panel). The dimensions of the patterns are 16 × Einstein radii (ERR) on a side, k=0.56, λ=0.11 and k=0.63, λ=0.11 are taken for A1 and A2, respectively (κ_e=0). The mass of microlens is taken to be 1M⊙.

3 **Probability of the X-ray emission microlensing**

The optical depth τ is the chance of seeing a microlens, i.e. the probability that at any instant of time a source is covered by the Einstein ring of a deflector. It was shown that deflectors from the host bulge and halo have a small optical depth τ ~ 10⁻⁴ – 10⁻³ (Popović et al. 2003a, Zakharov et al. 2004,2005). On the other hand, Zakharov et al. (2004,2005) showed that cosmologically distributed objects can have high optical depth (for the high red-shifted QSOs it may be τ ~ 0.1).

Moreover, one should take into account that, as it was mentioned above, the X-ray emission comes from the most compact part of the accretion disk. To demonstrate the differences in light curve (or amplification) of different spectral bands we investigate microlensing of the X-ray, UV and optical emission assuming that the source mass is 10⁸ M⊙. For modeling of emitting regions an accretion disk in Schwarzschild metric is used. The radii of emitting regions are taken as: Rin = 500 Rg, Rout = 5000 Rg – for the optical emitting region; Rin = 100 Rg, Rout = 1000 Rg – for the UV emitting region; and Rin = Rrms, Rout = 50 Rg –

![](image)

**Fig. 1** Top: The magnification map of the PG1115+080A1 image. The white solid line represents the center position of an accretion disk. Down: Corresponding variation in the X-ray (solid), UV (dotted) and optical (dash-dotted) spectral band.
The probability that the shape of the Fe Kα line is distorted (or amplified) is highest in gravitationally lensed systems. The probabilities that lensed QSOs, where microlensing of the Fe Kα were observed (QSO H1413+117, QSO 2237+0305 and J0414+0534), are gravitationally microlensed by objects in a foreground galaxy and by cosmologically distributed objects are calculated by Zakharov et al. (2004) (see their Table 2). It is interesting that the optical depth for microlensing by cosmologically distributed microlenses can be one order higher than for microlensing by objects in a foreground galaxy. So the observed microlensing in the X-ray, e.g. Fe Kα line, from these objects might be caused by cosmologically distributed objects rather than by the objects from a lens galaxy.

Taking into account this result and results from our simulations (Figs. 1 and 2) it seems that there is a big chance to find X-ray microlensing for gravitationally lensed systems that have signatures of microlensing in the UV/optical band. Moreover, considering the sizes of the sources of X-ray radiation, the variability in the X-ray range during microlensing event is more prominent than in the optical and UV band (see Figs. 1 and 2). Consequently, gravitational microlensing in the X-ray band is a powerful tool for dark matter investigations, as the upper limit of optical depth (τ ∼ 0.1) calculated by Zakharov et al. (2004,2005) corresponds to the case where dark matter forms cosmologically distributed deflectors.

From discussion above and our simulations, it seems that contribution of the X-ray radiation microlensing can have a significant part in the X-ray variations of lensed and un-lensed high red-shifted QSOs.

4 Discussion

Recent observations of three lensed QSOs seem to support idea about the X-ray microlensing (Chartas et al. 2002; Dai et al. 2003). Also, it seems that the Fe Kα line has been more affected by microlensing than the X-ray continuum. Popović et al. (2003a,2006) showed that objects in a foreground galaxy with very small masses can cause strong changes in the X-ray line profile. Our investigations indicate that the observational probability of X-ray variation due to microlensing events is higher than in the UV and optical radiation of QSOs. This is connected with the fact that typical sizes of X-ray emission regions are much smaller than typical sizes of those producing optical and UV bands. Typical optical and UV emission region sizes could be comparable or even larger than Einstein radii of microlenses and therefore microlenses magnify only a small part of the region emitting in the optical or UV band (see e.g. Abajas et al. 2002,2005; Popović et al. 2001b, for UV and optical spectral line region). This is reason that it could be a very tiny effect in UV/optical spectral band from an observer point of view. On the other hand, the variability and amplification of the X-ray spectra seems to be more prominent and it may be detectable. Note here, that expected microlensing time...
scales for X-ray microlensing are from several days to several months (e.g. from our X-ray microlensing simulations for several microlensed QSOs, we obtained the shortest time scale for Q2237+0305 of \( \approx 14 \) days, while for LBQS 1009-0252 we obtained the longest one \( \approx 320 \) days). Heaving in mind that the variation of optical/UV continua, which are weaker and much slower (the order of several years, see Fig. 2 in Jovanović 2006), one can expect that in a period of several years (during microlensing of the optical emission) a number of microlensing of the X-ray emission will occur. But, after a complete microlensing of the optical emission region, there should be a correlation between X-ray and optical/UV continua, which are in mind that the variation of optical/UV continua, which are stronger and much slower (the order of several years, see Fig. 2 in Jovanović 2006), one can expect that in a period of several years (during microlensing of the optical emission) a number of microlensing of the X-ray emission will occur. But, after a complete microlensing of the optical emission region, there should be a correlation between X-ray and optical emission amplification (see Figs. 1 and 2).

From theoretical investigation of the Fe K\( \alpha \) line microlensing there are several interesting results (see Popović et al. 2003ab):

i) Microlenses of very small projected Einstein radii (\( \sim 10 R_\odot \)) can give rise to significant changes in the iron line profiles. The effects may be an order of magnitude greater than the ones inferred for the UV and optical lines. Off-centered microlenses would induce strong asymmetries in the observed Fe K\( \alpha \) line profiles. In the case that a part of the Fe K\( \alpha \) line originates from the reflection on a distant matter, the amplification will be present only in the broad component from the disk, and the effects of microlensing will be similar as in the case of a pure disk emitted line.

ii) The effects of microlensing show differences in the Kerr and Schwarzschild metrics, the amplitude of the magnification being greater in the Kerr metric. The transit of a microlens along the rotation axis of the accretion disc would induce a strong amplification of the blue peak in the Schwarzschild metric when the microlens was centered in the approaching part. In the Kerr metric the amplification will be greater but will not affect so preferentially the blue part of the line. This difference could be interesting to test the rotation of an accretion disc.

5 Conclusion

From recent investigation of the X-ray emitting region microlensing (Popović et al. 2003ab, 2006, Zakharov et al. 2004,2005, Jovanović 2005,2006) and simulations performed in this paper we give following conclusions:

1. Gravitational microlensing can produce significant variations and amplifications of the line and continuum fluxes. These deformations of the X-ray radiation depend on both, the disk and microlens parameters.

2. Microlensing can satisfactorily explain the excess in the Fe K\( \alpha \) line observed in three gravitational lens systems: MG J0414+0534 (Chartas et al. 2002), QSO 2237+0305 (Dai et al. 2003), and H1413+117 (Chartas et al. 2004).

3. On the basis of these investigations, one can expect that the Fe K\( \alpha \) line and X-ray continuum amplification due to microlensing can be significantly larger than the corresponding effects on optical/UV emission lines and continua.

4. The optical depth for gravitational microlensing by cosmologically distributed deflectors could be significant. The maximum optical depth could be expected if dark matter forms cosmologically distributed compact objects.

Results mentioned above and recent investigation of the X-ray microlensing show that monitoring of lensed and unlensed high-redshift QSOs in X-ray band can be very useful not only for investigation of the innermost structure of QSOs, but also of the cosmological parameters.

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