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Contribution of Microlensing to X-ray Variability of Distant QSOs

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Abstract. We consider a contribution of microlensing to the X-ray variability of high-redshifted QSOs. Cosmologically distributed gravitational microlenses could be localized in galaxies (or even in bulge or halo of gravitational macrolenses) or could be distributed in a uniform way. We have analyzed both cases of such distributions. We found that the optical depth for gravitational microlensing caused by cosmologically distributed deflectors could be significant and could reach $10^{-2} - 0.1$ at $z \sim 2$. This means that cosmologically distributed deflectors may contribute significantlly to the X-ray variability of high-redshifted QSOs ($z > 2$). Considering that the upper limit of the optical depth ($\tau \sim 0.1$) corresponds to the case where dark matter forms cosmologically distributed deflectors, observations of the X-ray variations of unlensed QSOs can be used for the estimation of the dark matter fraction of microlenses.

1. Introduction

X-ray flux variability has long been known to be a common property of active galactic nuclei (AGNs), e.g. Ariel 5 and HEAO 1 first revealed long-term (days to years) variability in AGNs and by uninterrupted observations of EXOSAT rapid (thousands of seconds) variability was also established as common in these sources (see, for example reviews by Mushotzky *et al.* (1993); Ulrich *et al.* (1997) and references therein). X-ray flux variations are observed on timescales from ∼1000 s to years, and amplitude variations of up to an order of magnitude are in the ∼ 0.1 - 10 keV spectral band. Recently, Manners *et al.* (2002) analyzed the variability of a sample of 156 radio-quiet quasars taken from the ROSAT archive, considering the trends in variability of the amplitude with luminosity and with redshift. They found that there was evidences for a growth in AGN X-ray variability amplitude towards high redshift (z) in the sense that AGNs of the same X-ray luminosity were more variable at $z > 2$. They explained the σ *vs.* z trend assuming that the high-redshifted AGNs accreted at a larger fraction of the Eddington limit than the low-redshifted ones.

On the other hand, the contribution of microlensing to AGN variability was considered in many papers (see e.g. Hawkins (1993, 2002); Wambsganss (2001a,b); Zakharov (1997a), and references therein). Moreover, recently X-ray microlensing of AGN has been considered (Popović *et al.* 2001a; Takahashi *et al.* 2001; Chartas *et al.* 2002a; Popović *et al.* 2003a,b; Dai *et al.* 2003). Taking into account that the X-rays of AGNs are generated

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in the innermost and very compact region of an accretion disc, the X-ray radiation in the continuum as well as in a line can be strongly affected by microlensing (Popović *et al.* 2003a).† Recent observations of three lens systems seem to support this idea (Oshima *et al.* 2001; Chartas *et al.* 2002a, 2004; Dai *et al.* 2003). Popović *et al.* (2003a,b) showed that objects in a foreground galaxy with very small masses can cause strong changes in the X-ray line profile. This fact may indicate that the observational probability of X-ray variation due to microlensing events is higher than in the UV and optical radiation of AGNs. It 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. Popović *et al.* (2001b); Abajas *et al.* (2002), for UV and optical spectral line region). This is reason that it could be a very tiny effect from an observer point of view, in spite of this fact recently Richards *et al.* (2004) observed microlensing of the C IV line in SDSS J1004+4112.

Microlenses in quasar bulge/halo give a small contribution into optical depth, therefore it would be reasonable to evaluate a contribution from cosmological distribution of microlenses (Zakharov *et al.* 2004b,c).

2. Cosmological distribution of microlenses

To estimate the optical depth we will use the point size source approximation for an emitting region of X-ray radiation. It means that the size of emitting region is smaller than this Einstein – Chwolson radius. This approximation is used commonly to investigate microlensing in optical and UV bands. The typical Einstein – Chwolson radius of a lens can be expressed in the following way (Wambsganss 2001a)

$$r_{\mathrm{EC}} = \sqrt{\frac{4GM}{c^2}\frac{D_s D_{ls}}{D_l}} \sim 4 \times 10^{16}\sqrt{M/M_\odot}\ \mathrm{cm}, \tag{2.1}$$

where "typical" lens and source redshift of $z \sim 0.5$ and $z \sim 2$ were chosen, M is the lens mass, D_l, D_s and D_{ls} are angular diameter distances between an observer and a lens, observer and source, lens and source respectively. A typical quasar size is parameterized in units of 10^{15} cm (Wambsganss 2001a). Since the point size source approximation for an emitting region is reasonable for optical and for UV bands, and as it is generally adopted that X-ray radiation is formed in the inner parts of accretion disks we can use this approximation for X-ray sources. However, let us present simple estimates. The relevant length scale for microlensing in the source plane for this sample

$$R_{\mathrm{EC}} = r_{\mathrm{EC}}\frac{D_s}{D_l} \sim 1 \times 10^{17}\ \mathrm{cm}. \tag{2.2}$$

Even if we consider a supermassive black hole in the center of the quasar $M_{\mathrm{SMBH}} = 10^9 M_\odot$, then its Schwarzschild radius is $r_g = 3 \times 10^{14}$ cm and assuming that the emission region for the X-ray radiation is located near the black hole $r_{\mathrm{emission}} < 100\, r_g = 3 \times$

† Simulations of X-ray line profiles are presented in a number of papers, see, for example, Zakharov & Repin (2002a,b,c,d, 2003a, 2004, 2003c,d) and references therein, in particular Zakharov *et al.* (2003) showed that an information about magnetic filed may be extracted from X-ray line shape analysis; Zakharov & Repin (2003b) discussed signatures of X-ray line shapes for highly inclined accretion disks, Zakharov *et al.* (2004a) calculated shapes of spectral lines for non-flat accretion flows.

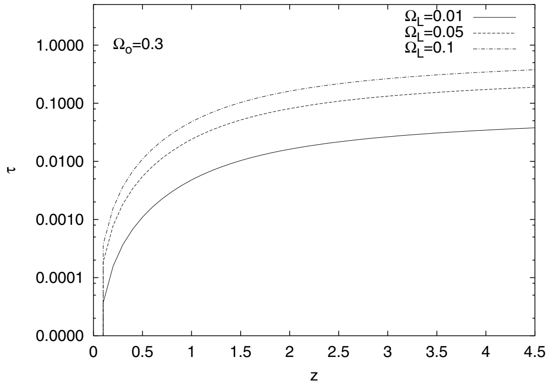

Figure 1. The calculated optical depth as a function of redshift for different values of Ω_L and Ω_0.

10^{16} cm, we obtain that $r_{\text{emission}} < R_{\text{EC}}$, therefore the point size source approximation can be adopted for the X-ray emitting region.†

To evaluate the optical depth, we assume a source located at redshift z. The expression for optical depth has been taken from Turner *et al.* (1984); Fukugita and Turner (1991)

$$\tau_L^p = \frac{3}{2}\frac{\Omega_L}{\lambda(z)}\int_0^z dw \frac{(1+w)^3[\lambda(z)-\lambda(w)]\lambda(w)}{\sqrt{\Omega_0(1+w)^3+\Omega_\Lambda}}, \tag{2.3}$$

where Ω_L is the matter fraction in compact lenses,

$$\lambda(z) = \int_0^z \frac{dw}{(1+w)^2\sqrt{\Omega_0(1+w)^3+\Omega_\Lambda}}, \tag{2.4}$$

is the affine distance (in units of cH_0^{-1}).

We will use some realistic cosmological parameters to evaluate the integral (2.3). According to the cosmological SN (Supernova) Ia data and cosmic microwave background (CMB) anisotropy one can take $\Omega_\Lambda \approx 0.7, \Omega_0 \approx 0.3$ (Perlmutter *et al.* 1999). Recent CMB anisotropy observations by the WMAP satellite team have confirmed important aspects of the current standard cosmological model, the WMAP team determined $\Omega_\Lambda \approx 0.73, \Omega_0 \approx 0.27$ (Bennett *et al.* 2003; Spergel *et al.* 2003) for the "best" fit of cosmological parameters. If we assume that microlensing is caused by stars we have to take into account cosmological constraints on baryon density. Big Bang Nucleosynthesis (BBN) calculations together with observational data about the abundance of ^{2}D give the following constraints on the cosmic baryon density (Turner 2002)

$$\Omega_b h^2 = 0.02 \pm 0.002, \tag{2.5}$$

taking into account the Hubble constant estimation $h = 0.72 \pm 0.08$ (Freedman *et al.* 2001). An analysis of recent WMAP data on CMB anisotropy gives as the best fit (Spergel *et al.* 2003)

$$\Omega_b h^2 = 0.0224 \pm 0.0009, \tag{2.6}$$

† For example, Chartas *et al.* (2002a) found evidence for X-ray microlensing in the gravitationally lensed quasar MG J0414+0534 ($z = 2.639$), where according to their estimates M_{SMBH} is in the range $3.6 \times 10^6(\beta/0.2)^2$ and $1.1 \times 10^7(\beta/0.2)^2 M_\odot$ ($\beta \sim 1$). Therefore a typical emission region is much smaller than the Einstein – Chwolson radius R_{EC}, since following Chartas *et al.* (2002a) one could assume that the emitting region corresponds to $(10-1000)\,r_g$ or $\sim 1.5 \times 10^{14} - 1.5 \times 10^{16}$ cm for a $10^8 M_\odot$ black hole.

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which is very close to the BBN constraints, but with much smaller error bars.

Therefore, the cases with $\Omega_0 = 0.3$ and $\Omega_L = 0.05$ ($\Omega_L = 0.01$) can be adopted as realistic. Here we assume that almost all baryon matter can form microlenses ($\Omega_L = 0.05$), or, alternatively, that about 25% of baryon matter forms such microlenses ($\Omega_L = 0.01$)).

3. Discussion and results

In Fig. we show the optical depth of cosmologically distributed microlenses assuming three cases of cosmoligically distributed microlenses: i) small fraction of baryonic matter (25 %) forms microlenses ($\Omega_L = 0.01$); ii) almost all baryonic matter forms microlenses ($\Omega_L = 0.05$); iii) about 30% of non-baryonic (dark) matter forms microlenses ($\Omega_L = 0.1$).

As was mentioned earlier by Popović *et al.* (2003a,b) the probability of microlensing by stars or other compact objects in halos and bulges of quasars is very low (about $10^{-4} - 10^{-3}$). However, as one can see from Fig. 1, for cosmologically distributed microlenses it could reach $10^{-2} - 0.1$ at $z \sim 2$. The upper limit $\tau \sim 0.1$ corresponds to the case where compact dark matter forms cosmologically distributed microlenses. As one can see from Fig. 1, in this case the optical depth for the considered value of Ω_0 is around 0.1 for $z > 2$. This indicates that such a phenomenon could be observed frequently, but only for distant sources ($z \sim 2$).

To investigate distortions of spectral line shapes due to microlensing (Popović *et al.* 2003a,b) the most real candidates are multiply imaged quasars. However, these cases the simple point-like microlens model may not be very good approximation (Wambsganss 2001a,b) and one should use a numerical approach, such as the MICROLENS ray tracing program, developed by J. Wambsganss or some analytical approach for magnification near caustic curves like folds (Schneider *et al.* 1992; Fluke & Webster 1999) or near singular caustic points like cusps (Schneider & Weiss 1992; Mao 1992; Zakharov 1995, 1997b, 1999) as was realized by Yonehara (2001).

If we believe in the observational arguments of Hawkins (2002) that the variability of a significant fraction of distant quasars is caused by microlensing, the analysis of the properties of X-ray line shapes due to microlensing (Popović *et al.* 2003a) is a powerful tool to confirm or rule out Hawkins' (2002) conclusions.

As it was mentioned, the probability that the shape of the Fe $K\alpha$ line is distorted (or amplified) is highest in gravitationally lensed systems. Actually, this phenomena was discovered by Oshima *et al.* (2001); Dai *et al.* (2003); Chartas *et al.* (2002a,b, 2004) who found evidencees for such an effect for QSO H1413+117 (the Cloverleaf, $z = 2.56$), QSO 2237+0305 (the Einstein Cross, $z = 1.695$), MG J0414+0534 ($z = 2.64$) and possibly for BAL QSO 08279+5255 ($z = 3.91$). One could say that it is natural that the discovery of X-ray microlensing was made for this quasar, since the Einstein Cross QSO 2237+0305 is the most "popular" object to search for microlensing, because the first cosmological microlensing phenomenon was found by Irwin *et al.* (1989) in this object and several groups have been monitoring the quasar QSO 2237+0305 to find evidence for microlensing. Microlensing has been suggested for the quasar MG J0414+0534 (Angonin-Willaime *et al.* 1999) and for the quasar QSO H1413+117 (Remy *et al.* 1996). Therefore, in future a chance may be to find X-ray microlensing for other gravitationally lensed systems that have signatures of microlensing in the optical and radio bands. Moreover, considering the sizes of the sources of X-ray radiation, the variability in the X-ray range during microlensing event should be more prominent than in the optical and UV. Consequently, gravitational microlensing in the X-ray band is a powerful tool for dark matter investigations, as the upper limit of optical depth ($\tau \sim 0.1$) corresponds to the case where dark matter forms cosmologically distributed deflectors.

Conclusions

From our calculations we can conclude (Zakharov *et al.* 2004b,c):

i) The optical depth for cosmologically distributed deflectors could be $\sim 10^{-2} - 0.1$ at $z \sim 2$ and might contribute significantly to the X-ray variability of high-redshift QSOs. The value $\tau \sim 0.1$ corresponds to the case where compact dark matter forms cosmologically distributed microlenses.

ii) The optical depth for cosmologically distributed deflectors (τ_L^p) is higher for $z > 2$ and increases slowly beyond $z = 2$. This indicates that the contribution of microlensing on the X-ray variability of QSOs with redshift $z > 2$ may be significant, and also that this contribution could be nearly constant for high-redshift QSOs. This is in good agreement with the fact that AGNs of the same X-ray luminosity are more variable at $z > 2$ (Manners *et al.* 2002).

iii) Observations of X-ray variations of unlensed QSOs can be used for estimations of matter fraction of microlenses. The rate of microlensing can be used for estimates of the cosmological density of microlenses, and consequently the fraction of dark matter microlenses, but the durations of microlensing events could be used for gravitational microlens mass estimations.

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