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On the contribution of microlensing to X-ray variability of high-redshifted QSOs

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Abstract. We consider a contribution of microlensing to the X-ray variability of high-redshifted QSOs. Such an effect could be caused by stellar mass objects (SMO) located in a bulge or/and in a halo of this quasar as well as at cosmological distances between an observer and a quasar. Here, we not consider microlensing caused by deflectors in our Galaxy since it is well-known from recent MACHO, EROS and OGLE observations that the corresponding optical depth for the Galactic halo and the Galactic bulge is lower than 10^{-6}. 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. As a result of our analysis, we obtained that the optical depth for microlensing caused by stellar mass objects is usually small for quasar bulge and quasar halo gravitational microlens distributions ($\tau \sim 10^{-4}$). On the other hand, 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.

Key words. accretion, accretion disks – gravitational lensing – galaxies: quasars: general

1. Introduction

The X-ray radiation of Active Galactic Nuclei (AGNs), in the continuum as well as in spectral lines, has rapid and irregular variability (see e.g. Marshall et al. 1981; Barr & Mushotzky 1986; Lawrence & Papadakis 1993; Green et al. 1993; Turner et al. 1999; Weaver et al. 2001; Manners et al. 2002, etc.). 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. 1993, 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 observed in the ∼0.1−10 keV band. It was first suggested by Barr & Mushotzky (1986) that the flux variation of an AGN is inversely proportional to its luminosity. Lawrence & Papadakis (1993) and Green et al. (1993) confirmed the variability-luminosity relationship, finding that the variability amplitude (σ) varies with luminosity as $\sigma = L_X^{-\beta}$ with $\beta \approx 0.3$. 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 were 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. 2003; Dai et al. 2003). Taking into account that the X-rays of AGNs are generated in the innermost and very compact region of an accretion

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disc, the X-ray radiation in the continuum as well as in a line can be strongly affected by microlensing (Popović et al. 2003)[1].

Recent observations of three lensed QSOs seem to support this idea (Oshima et al. 2002; Chartas et al. 2002a; Dai et al. 2003). Popović et al. (2003) 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. 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. 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.

The aim of this paper is to discuss the contribution of microlensing to the relation σ vs. z for X-ray radiation considering the recent results given by Manners et al. (2002) and Popović et al. (2003). In the next section we will consider the optical depth.

2. The optical depth

The optical depth τ (the chance of seeing a microlens (ML)) is the probability that at any instant of time a source is covered by the Einstein ring of a deflector. Here we will consider deflectors from the host bulge and halo as well as at cosmological distances between observer and source. We will not consider microlensing caused by Galactic microlenses since it is well-known from recent MACHO, EROS and OGLE observations that the corresponding optical depth for Galactic halo and Galactic bulge is lower than 10^{-6}. Therefore, by analogy, one could expect that the optical depth for microlensing due to objects in the halo or/and bulge of a quasar is small (similar to the optical depth for microlensing in the Galaxy). However, it would be appropriate to present some more accurate estimates for optical depths for microlensing by bulge/halo objects assuming reasonable values for density distribution of QSO bulges/halos. This is because, as we mentioned above, the X-ray emission regions are much smaller than UV/optical ones, and even small mass deflectors from a QSO bulge/halo can produce significant magnification in the X-ray radiation (Popović et al. 2003), while it will not happen in the UV/optical band.

2.1. Quasar bulge microlenses

In this section we consider gravitational microlensing caused by stellar mass objects in the bulge of an observed quasar. Of course, to calculate an optical depth we have to know the radial mass density distribution in the QSO bulge. In this case the optical depth could be evaluated by the integral

$$\tau \sim \frac{4\pi G}{c^2} \int_0^R \rho(r) r \, \mathrm{d}r, \tag{1}$$

where R is the bulge radius. For qualitative discussions of the optical depth range we make the assumption of constant mass density (see also Popović et al. 2003). Evaluating this integral, we obtain

$$\tau \sim \frac{2\pi G}{c^2} \rho_0 R^2 = \frac{3G}{2c^2} \frac{M_{\rm bulge}}{R}, \tag{2}$$

where $\rho_0 = \frac{3\,M_{\rm bulge}}{4\pi R^3}$ is the average density of the bulge. It is clear that the maximal optical depth corresponds to the most compact galactic bulge for a fixed bulge mass. For an estimate of the bulge mass use can be made of scaling from the black hole mass; McLure & Dunlop (2002) give $M_{\rm bh} = 0.0012\ M_{\rm bulge}$, and Shields et al. (2003) $M_{\rm bulge} = 10^{2.8} M_{\rm bh}$. However, for Seyfert 1 galaxies ratios of the central black hole mass and the bulge mass could be about 1×10^{-4} (Bian & Zhao 2003). We can derive an upper limit from the estimate by Czerny et al. (2001) that for AGN $M_{\rm bulge} \approx 10^{12}\ M_\odot$ (with $M_{\rm AGN} \sim 10^{13}\ M_\odot$, Shields et al. 2002). Schade et al. (2000) found typical values for the radii of AGN bulges in the range 1−10 kpc. So, using the lower limit for the AGN bulge radius and the total mass estimation $M_{\rm tot}$, we obtain an upper limit of the optical depth for microlensing by bulge stellar mass objects of $\tau_{\rm bulge} \sim 3.5 \times 10^{-5}$. This upper limit is about the value evaluated earlier (Popović et al. 2003) and the contribution to the total optical depth for microlensing is small. Microlensing would thus be detectable only in a small fraction of quasars.

2.2. Quasar halo microlenses

2.2.1. Singular isothermal sphere model

Here we assume a mass density distribution described by a singular isothermal sphere model, namely

$$\rho(y) = \begin{cases} \frac{\rho_0 r}{y^2}, & r \le y \le R, \\ 0, & y > R \text{ or } y < r, \end{cases} \tag{3}$$

where r is the inner and R is the outer radius of halo, and ρ_0 is the mass density at the inner radius r,

$$\tau_{\rm halo} \sim \frac{4\pi G}{c^2} \int_r^R \rho \frac{D_d (D_{\rm s} - D_d)}{D_{\rm s}} \mathrm{d}D_d. \tag{4}$$

Evaluating this integral, we obtain

$$\tau_{\rm halo} \sim \frac{4\pi G}{c^2} \rho_0 r^2 \ln \frac{R}{r}. \tag{5}$$

The halo mass can be expressed as

$$M_{\rm halo} = \int_r^R \frac{\rho_0 r^2}{y^2} 4\pi y^2 \mathrm{d}y = 4\pi \rho_0 r^2 R. \tag{6}$$

Thus,

$$\rho_0 = \frac{M_{\rm halo}}{4\pi r^2 R} \tag{7}$$

[1] Simulations of X-ray line profiles are presented in a number of papers, see, for example, Zakharov & Repin (2002a,b,c, 2003a,c) 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.

and

$$\tau_{\rm halo} \sim \frac{G}{c^2}\frac{M_{\rm halo}}{R}\ln\frac{R}{r}\cdot \quad (8)$$

Typical halo masses are in the range 10^{11}–10^{14} $M_\odot$ range (Bullock et al. 2001; Ferrarese 2002) and typical halo radii are R are ~few $\times 10^2$ kpc (Klypin et al. 2002; Ferrarese 2002), and typical inner radii $r \sim$ a few $\times 10$ kpc (Ferrarese 2002), we can estimate the optical depth using these values. Assuming that $M_{\rm halo} = 10^{14}\ M_\odot$, $R \sim 10^2$ kpc and $r \sim 5$ kpc we obtain $\tau_{\rm halo} \sim \tau_{\rm bulge} \sim 7\times10^{-5}$.

2.2.2. Navarro–Frenk–White halo (NFW) profiles

Let us calculate the optical depth for Navarro–Frenk–White (NFW) halo profiles of mass density distributions. A two-parameter form for halo profiles was proposed by Navarro et al. (1995, 1996, 1997)

$$\rho_{\rm NFW}(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \quad (9)$$

where $r_{\rm s}$ is a characteristic inner radius and $\rho_{\rm s}$ is the corresponding inner density, $\rho_{\rm s} = 4\rho_{\rm NFW}(r_{\rm s})$ and $\rho_{\rm s} = \rho_{\rm NFW}(0.466 r_{\rm s})$ (Bullock et al. 2001), where $0.466 r_{\rm s}$ is the approximate solution of the equation

$$(r/r_{\rm s})^3 + 2(r/r_{\rm s})^2 + (r/r_{\rm s}) - 1 = 0. \quad (10)$$

Navarro et al. (1995, 1996, 1997) showed that these halo profiles provide a good fit over a large range of masses and for several cosmological scenarios (including a flat cosmological model with $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$). Bullock et al. (2001) confirmed the success of this model at $z = 0$, but mentioned that the NFW model significantly over-predicts the concentration of halos at early times $z > 1$ and suggested some modifications of the NFW model. However, we will use the standard NFW model.

One can calculate the halo mass

$$M_{\rm halo} = 4\pi\rho_{\rm s} r_{\rm s}^3 A(c_{\rm vir}), \quad (11)$$

where

$$A(c_{\rm vir}) = \ln(1+c_{\rm vir}) - \frac{1+c_{\rm vir}}{c_{\rm vir}} \quad (12)$$

and $c_{\rm vir} = R/r_{\rm s}$. Using Eq. (4) and the NFW halo profile, one obtains

$$\tau_{\rm halo} \sim \frac{2\pi G}{c^2}\rho_{\rm s} r_{\rm s}^2 \quad (13)$$

and substituting $\rho_{\rm s}$ from Eq. (11)

$$\rho_{\rm halo} = \frac{M_{\rm halo}}{4\pi r_{\rm s}^2 A(c_{\rm vir})} \quad (14)$$

we obtain

$$\tau_{\rm halo} \sim \frac{G}{c^2}\frac{M_{\rm halo}}{2 r_{\rm s} A(c_{\rm vir})}\cdot \quad (15)$$

Since typical $c_{\rm vir}$ values are in the range 5–30, $A(c_{\rm vir})$ varies in the range 1–3, and $r_{\rm s} \sim$ a few $\times 10$ kpc (Ferrarese 2002). Assuming $M = 10^{14}\times M_\odot$, $r_{\rm s} = 3$ kpc, $A(c_{\rm vir}) = 2$, we obtained $\tau_{\rm halo} \sim 4\times10^{-4}$. Therefore, the optical depth estimates by Popović et al. (2003) are realistic if we consider objects inside the halo and/or bulge. We recall that they found the optical depth to be in the range 10^{-4}–10^{-3}.

2.3. 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. This 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)

$$r_{\rm EC} = \sqrt{\frac{4GM}{c^2}\frac{D_{\rm s}D_{\rm ls}}{D_{\rm l}}} \sim 4\times10^{16}\sqrt{M/M_\odot}\ {\rm cm}, \quad (16)$$

where "typical" lens and source redshift of $z \sim 0.5$ and $z \sim 2$ were chosen, M is the lens mass, $D_{\rm l}$, $D_{\rm s}$ and $D_{\rm ls}$ are angular diameter distances between observer and 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 an approximation for X-ray sources. However, let us make some estimates. The relevant length scale for microlensing in the source plane for this sample

$$R_{\rm EC} = r_{\rm EC}\frac{D_{\rm s}}{D_{\rm l}} \sim 1\times10^{17}\ {\rm cm}. \quad (17)$$

Even if we consider a supermassive black hole in the center of the quasar $M_{\rm SMBH} = 10^9\ M_\odot$, then its Schwarzschild radius is $r_g = 3\times10^{14}$ cm and assuming that the emission region for the X-ray radiation is located near the black hole $r_{\rm emission} < 100\, r_g = 3\times10^{16}$ cm, we obtain that $r_{\rm emission} < R_{\rm EC}$, therefore the point size source approximation can be adopted for the X-ray emitting region[2]. Note that sometimes this approximation cannot be used when the microlens lies in the bulge or halo of a quasar (see previous subsections), because then the Einstein–Chwolson radius would be about several astronomical units, since we have $D_{\rm l} \sim D_{\rm s}$, $D_{\rm ls} \ll D_{\rm s}$ from Eqs. (16) and (17),

$$R_{\rm EC} \sim r_{\rm EC},$$

and

$$R_{\rm EC} \sim 9\ {\rm au}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_{\rm ls}}{10\,{\rm kpc}}\right)^{1/2} \sim 10^{14}\ {\rm cm}. \quad (18)$$

In this case one has to take into account the size of the X-ray emission region.

To evaluate the optical depth, we assume a source located at redshift z.

[2] 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 $M_{\rm SMBH}$ is in the range $3.6\times10^6(\beta/0.2)^2$ and $1.1\times10^7(\beta/0.2)^2\ M_\odot$ ($\beta \sim 1$). Therefore a typical emission region is much smaller than the Einstein–Chwolson radius $R_{\rm EC}$, since following Chartas et al. (2002a) one could assume that the emitting region corresponds to (10–1000) r_g or $\sim1.5\times10^{14}$–1.5×10^{16} cm for a $10^8\ M_\odot$ black hole.

The expression for optical depth has been taken from Wang et al. (1996); Turner et al. (1984); Fukugita & Turner (1991)

$$\tau_{\rm L}^{p} = \frac{3}{2}\frac{\Omega_{\rm L}}{\lambda(z)}\int_0^z {\rm d}w \frac{(1+w)^3[\lambda(z)-\lambda(w)]\lambda(w)}{\sqrt{\Omega_0(1+w)^3+\Omega_\Lambda}}, \quad (19)$$

where $\Omega_{\rm L}$ is the matter fraction in compact lenses,

$$\lambda(z) = \int_0^z \frac{{\rm d}w}{(1+w)^2\sqrt{\Omega_0(1+w)^3+\Omega_\Lambda}}, \quad (20)$$

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

We will use some realistic cosmological parameters to evaluate the integral (19). 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; Bond et al. 2001; Balbi 2001; Lahav 2002; Peebles 2002). 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 (see also Bridle et al. 2003 for discussion). Therefore we will assume $\Omega_0 = 0.3$ and $\Omega_0 = 0.2$ as realistic cases. 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 (O'Meara et al. 2001; Burles et al. 2001; Turner 2002)

$$\Omega_{\rm b}h^2 = 0.02 \pm 0.002, \quad (21)$$

taking into account the Hubble constant estimation $h = 0.72 \pm 0.08$ (Freedman et al. 2001). However, Parodi et al. (2000); Tammann & Reindl (2002a,b) give lower limits for $h = 0.585 \pm 0.063$. Therefore, using for example the estimate by Freedman et al. (2001) one could obtain for the cosmic baryon density (Turner 2002)

$$\Omega_{\rm b} = 0.039 \pm 0.0075. \quad (22)$$

Using CMB anisotropy data of the BOOMERANG and MAXIMA-1 experiments Stompor et al. (2001) found that

$$\Omega_{\rm b}h^2 = 0.033 \pm 0.013. \quad (23)$$

An analysis of recent WMAP data on CMB anisotropy gives as the best fit (Spergel et al. 2003)

$$\Omega_{\rm b}h^2 = 0.0224 \pm 0.0009, \quad (24)$$

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

Therefore, the cases with $\Omega_0 = 0.3$ and $\Omega_{\rm L} = 0.05$ ($\Omega_{\rm L} = 0.01$) can be adopted as realistic (the top panel in Fig. 1, here we assume that almost all baryon matter and a small fraction of non-baryon matter can form microlenses ($\Omega_{\rm L} = 0.05$), or, alternatively, that about 25% of baryon matter forms such microlenses ($\Omega_{\rm L} = 0.01$)). However, for both cases and for distant objects ($z \sim 2.0$) the optical depth could reach ~0.01–0.1 (see Table 1 and Fig. 1). If about 30% of non-baryonic dark matter forms objects with stellar masses, $\Omega_{\rm L} = 0.1$ can be adopted, and then $\tau \sim 0.2$ at $z \sim 2$. The optical depths for realistic values of $\Omega_{\rm L}$ as a function of redshift are presented in Table 1. The middle and bottom panels of Fig. 1 show the optical depth as a funciton of redshift for chosen cosmological parameters (densities).

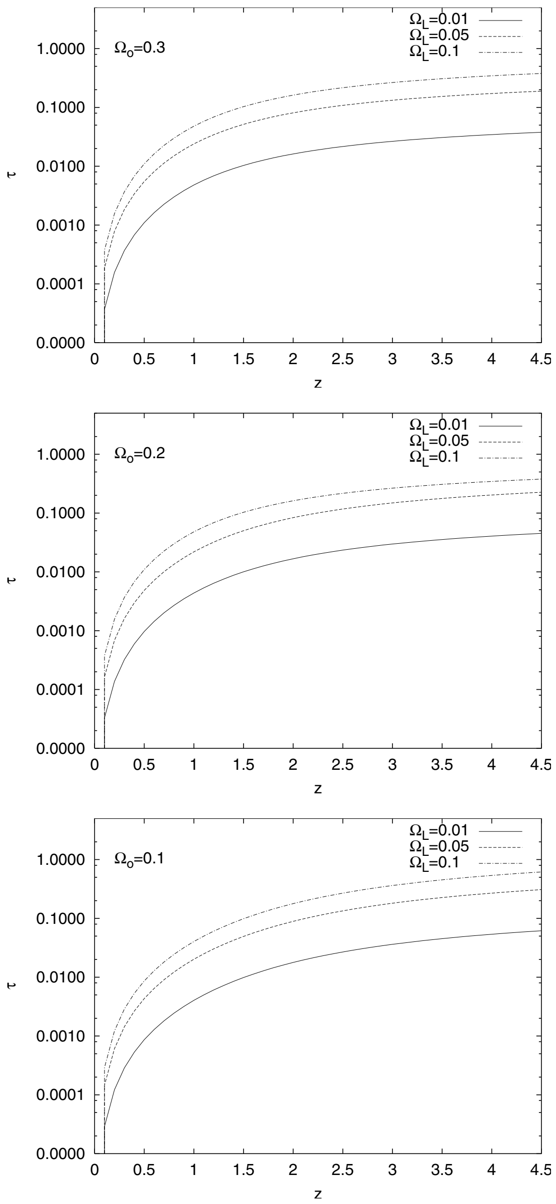

Fig. 1. The calculated optical depth as a function of redshift for different value $\Omega_{\rm L}$ and Ω_0.

Recently, Wyithe & Turner (2002a) considered probability distributions for the cases when lensing objects are concentrated in galaxies. The authors found that about 1% of high-redshift sources ($z \sim 3$) are microlensed by stars at any time. The microlensing rate by stars in elliptical/S0 galaxies is 10 times higher than in spiral galaxies. Multiple imaged sources dominate the stellar microlensing statistics. However, if CDM halos are composed of compact objects, Wyithe & Turner (2002a) concluded that the microlensing rate should be

Table 1. The calculated optical depth as a function of redshift for different values of Ω_L and $\Omega_0 = 0.3$.

$z \backslash \Omega_L$	0.01	0.05	0.10
0.5	0.001100	0.005499	0.010998
1.0	0.004793	0.023967	0.047934
1.5	0.010310	0.051550	0.103100
2.0	0.016196	0.080980	0.161959
2.5	0.021667	0.108334	0.216669
3.0	0.026518	0.132590	0.265180
3.5	0.030770	0.153852	0.307703
4.0	0.034504	0.172521	0.345042
4.5	0.037804	0.189018	0.378037
5.0	0.040742	0.203712	0.407424

about 0.1, i.e. ∼1 high-redshift source out of 10 is microlensed at any time.

Wyithe & Turner (2002b) calculated variability rates for a hypothetical survey. Let us recall their results. For a limiting quasar magnitude $m_B = 21$ the authors found that the probability that a quasar could show a variability larger than $m_B = 0.5$ due to microlensing by stars is about 2×10^{-3} (the cosmological density of stars is assumed to be equal to $\Omega_* = 0.005$). 90% of these events are in multiple-imaged systems. Therefore, microlenses in gravitational lenses forming multiple-imaged quasars dominate in these statistics. Assuming that a dark halo (truncated so that the total mass density equals the critical density) is also composed of compact objects, the fraction of quasar images which exhibit microlensing variability larger than $m_B = 0.5$ rises to ∼10%. Thus, Wyithe & Turner (2002b) pointed out that the comparison of lensed and unlensed quasars will provide a powerful test for dark compact objects in the halo.

2.4. Microlensing of gravitationally lensed objects

Just after the discovery of the first multiple-imaged quasar QSO 0957+561 A,B by Walsh et al. (1979) the idea of microlensing by low mass stars in a heavy halo was suggested by Gott (1981). First evidence of quasar microlensing was found by Irwin et al. (1989). Now there is a number of known gravitational lens systems (Claeskens & Surdej 2002; Browne et al. 2003) and some of them show evidence for microlensing (Wambsganss 2001a).

In this subsection we consider the optical depth for gravitational microlensing in multiple-imaged quasars. There is many approaches to calculate probability for this case. See for example, the papers by Deguchi & Watson (1987); Seitz et al. (1994); Seitz & Schneider (1994); Neindorf (2003). Here we will present some rough estimates for such a phenomenon, using calculations by Turner (1990); Wang et al. (1996) for a flat universe with Λ-term. According to Turner (1990)

$$\tau_{\rm GL} = \frac{F}{30}\left[\int_1^y \frac{{\rm d}w}{(\Omega_0 w^3 - \Omega_0 + 1)^{1/2}}\right]^3, \qquad (25)$$

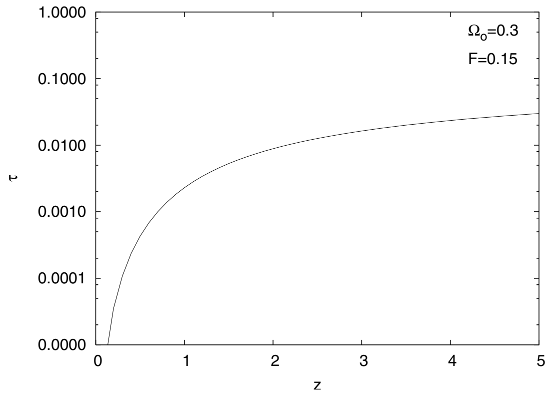

Fig. 2. The calculated optical depth for gravitational macrolensing $\tau_{\rm GL}$ as a function of redshift for the most realistic cosmological matter density $\Omega_0 = 0.3$.

where $z_Q = y - 1$ (z_Q is the quasar redshift) and

$$F = 16\pi^3 n_0 \left(\frac{c}{H_0}\right)^3 \left(\frac{\sigma}{c}\right)^4, \qquad (26)$$

F characterizes the gravitational lens effectiveness, σ is the one-dimensional velocity dispersion and n_0 is the co-moving space density. According to Turner (1990); Turner et al. (1984) the effectiveness F can be chosen to be $F = 0.15$. As was shown by Turner (1990), for the most popular cosmological model $\Omega_0 = 0.3$ and a distant quasar $z_Q = 2$ the optical depth could be about 0.01. In Fig. 2 the optical depth as a function of cosmological redshift is given. As one can see from Fig. 2, the optical depth has similar trend as in the case of cosmologically distributed objects.

If we try to find the microlensing phenomenon in multiply imaged quasars, we should recall that Wyithe & Turner (2002b) showed that if we restrict ourselves to quasars for which the sum of the macro-images is brighter than $m_B = 21$, one image in three multiply imaged quasars should vary by more than 0.5 mag during 10 years of monitoring. This means that roughly speaking the probability of microlensing for multiple imaged quasars is about 0.3.

2.5. Observed features of microlensing for quasars

More than 10 years ago Hawkins (1993) (see also Hawkins 1996, 2002) put forward the idea that nearly all quasars are being microlensed. Recently, Hawkins (2002) considered three basic models to explain AGN variability: the disc instability model proposed by Rees (1984), the starburst model developed by Aretxaga & Terlevich (1994) as an alternative, and finally the idea that the observed variations are not intrinsic to the AGN, but a result of gravitational microlensing by stellar mass objects along the line of sight (Hawkins 1993). Suggesting that different mechanisms dominate in different luminosity regimes Hawkins (2002) divided AGN into two categories, quasars with $M_B < -23$ and Seyfert galaxies with $M_B > -23$.

To distinguish different models of variability Hawkins (2002) used quantitative predictions for the statistics of AGN variability based on structure functions of Kawaguchi et al. (1998). Hawkins (2002) analyzed about 1500 quasars in the central 19 $\deg^2$ of ESO/SERC Field 287 up to magnitude $B_J = 22$, and 610 have been confirmed with redshifts. The structure function was calculated for a sample of 401 quasars from the survey of Hawkins (1996). For comparison he considered the results of monitoring Seyfert galaxy NGC 5548 and a sample of 45 Seyfert galaxie from the survey of Hawkins (1996). He calculated structure function slopes of two classes of AGN and found that the slope is 0.36 ± 0.02 for Seyfert galaxies and 0.2 ± 0.01 for quasars. Since the model prescriptions give structure function slopes of 0.83 ± 0.08 for the starburst model, 0.44 ± 0.03 for the disc instability model and 0.25 ± 0.03 for microlensing, the observational results favor the disc instability model for Seyfert galaxies, and the microlensing model for quasars. The starburst and disc instability models are ruled out for quasars, while the microlensing model is in good agreement with the observations. As was shown by Hawkins (1996) the cosmological density of microlenses should be comparable with the critical density or at least with $\Omega_m \sim 0.3$. However, the analysis of the structural function only cannot confirm or rule out the hypothesis of microlensing origin of quasar variability, but it is an additional argument in favor of the microlensing model.

3. Discussion

As was mentioned earlier by Popović et al. (2003) 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, 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 ($z \sim 2$). Moreover, it is in good agreement with the trend in the variability amplitude with redshift found by Manners et al. (2002), where AGNs of the same X-ray luminosity are more variable at $z > 2$.

To investigate distortions of spectral line shapes due to microlensing (Popović et al. 2003) the most promising candidates are multiply imaged quasars, since the corresponding probability could be about 0.3 (for magnification of one image $\Delta m = 0.5$ during 10 years). 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 Wambsganss (Wyithe & Turner 2002b), 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. 2003) is a powerful tool to confirm or rule out Hawkins' (2002) conclusions.

Table 2. The calculated optical depths (τ_{GL} and τ_L^p for 3 gravitational lensed objects). The used parameters are: $\Omega_0 = 0.3$, $\Omega_L = 0.05$, $F = 0.15$. τ_{GL} is the optical depth for macrolensing for quasars located at the same redshifts as the gravitational lensed objects.

Object	z	τ_{GL}	τ_L^p
MG J0414+0534	2.64	0.013652	0.1151256
QSO 2237+0305	1.695	0.006635	0.0626277
BAL QSO H1413+117 AT	2.56	0.013049	0.1112457

As it was mentioned, the probability that the shape of the Fe Kα line is distorted (or amplified) is highest in gravitationally lensed systems. Actually, this phenomenon was discovered by Oshima et al. (2002); Dai et al. (2003); Chartas et al. (2002a,b, 2004) who found evidence 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 ($z = 3.91$). Let us consider quasars located at the same redshifts as the gravitational lensed objects. The probabilities that these quasars are gravitationally microlensed by objects in a foreground galaxy (τ_{GL}) and by cosmologically distributed objects (τ_L^p) are given in Table 2 (if we have no a priori information about gravitational macrolensing for the quasars). One can see from Table 2 that the optical depth for microlensing by cosmologically distributed microlenses are one order higher than for microlensing by objects in a foreground galaxy. So the observed microlensing in the X-ray Fe Kα line from these objects should be caused by cosmologically distributed objects rather than by the objects from a lensed galaxy. For example, in the case of the redshift corresponding to the famous Einstein Cross QSO 2237+0305 where the optical depth is smaller than for other two redshifts. 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; Ostensen et al. 1997; Turnshek et al. 1997; Chae et al. 2001). Therefore, in future may be a chance 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. On the other hand, one can see from Table 2 that, if we have no a priori information about gravitational lensing of distant quasars, the expected variabilities in the X-ray band due to microlensing tend to be the same for the lensed and unlensed QSOs at the same redshift. This means that cosmologically distributed deflectors play the main role in microlensing of high redshifted QSOs. The comparison of X-ray variation in lensed and unlensed QSOs at the same redshift can provide a powerful test for the cosmologically distribution of the dark compact objects. The observed rate of microlensing can be used for estimates of the cosmological density of microlenses (see, for example, Sect. 2.3), but durations of microlensing events could be used to estimate microlens masses (Wambsganss 2001a,b).

4. Conclusions

For a discussion of the contribution of microlensing to the X-ray variability of high-redshift QSOs we calculated optical depth considering the density of deflectors in the halo and bulge of the host galaxy as well as for a cosmological distribution of microdeflectors.

From our calculations we can conclude:

i) The optical depth in the bulge and halo of host galaxy is $\sim 10^{-4}$. This is in good agreement with previous estimates by Popović et al. (2003). Microlensing by deflectors from the host galaxy halo and bulge makes a minor contribution to the X-ray variability of QSOs.

ii) 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.

iii) 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).

iv) 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 (see Sect. 2.3) the fraction of dark matter microlenses, but the durations of microlensing events could be used for gravitational microlens mass estimations.

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