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Recent results on microlensing

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Abstract This paper reviews recent results on Galactic structure obtained by microlensing surveys. The status of searches for compact Galactic halo objects towards the Magellanic Clouds and M31 is given. Recents measurements of the microlensing optical depth towards the Galactic Centre are reported.

Key words: dark matter – Galaxy: fundamental parameters – Galaxy: halo – gravitational lensing – surveys

1 INTRODUCTION

The first microlensing candidates were found ten years ago by the EROS (Aubourg et al. 1993) and MACHO (Alcock et al. 1993) collaborations towards the Magellanic Clouds and the OGLE (Udalski et al. 1993) survey towards the Galactic Centre. Microlensing is now a standard astrophysical technique. It has been giving results on subjects ranging from stellar atmospheres (see e.g Afonso et al. 2001, Fields et al. 2003) to planets (see e.g Gaudi et al. 2002), black holes (see e.g Bennett et al. 2002), exotic celestials objects or interactions (see e.g. Glicenstein 2002, Rahvar and Nouri-Zonoz 2003) or Galactic mass distribution. This paper reports only on recent results on searches for compact halo objects and on Galactic structure. A brief introduction to microlensing theory is given in section 2. The status of searches for compact Galactic halo objects is then presented in section 3. Finally, I discuss the most recent measurement of the microlensing optical depth towards the Galactic Centre.

2 MICROLENSING

2.0.1 Basics of microlensing

Gravitational lensing is a consequence of the deflection of light by massive bodies ("lenses"). General gravitational lensing systems produce multiple images of a distant source. Compact lenses like MACHOs distort the light beam from background sources and create two images. The typical separation between the images is $\theta \simeq \theta_E = r_E/d_{OL}$ where r_E defined by

$$r_E = \sqrt{\frac{4Gm_L}{c^2}\frac{d_{OL}(d_{OS} - d_{OL})}{d_{OS}}} \quad (1)$$

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is the Einstein radius, d_{OL} and m_L are the distance and mass of the lens and d_{OS} the distance of the source. For sources located in the Magellanic Clouds and lenses in the Galactic halo with masses less than 100 $M_\odot$, the typical separation of the images is less than 1 *mas*, too small to be resolved with present ground or space based telescope technology. The source is said to be "microlensed". However, it turns out that the flux coming from background sources undergoes an apparent amplification (magnification). This magnification is independent of wavelength (achromaticity) and is detectable when lenses move in front of sources. In a first approximation, the finite radius of the lens and source disks are negligible (point lens-point source or PLPS model) and the relative velocities are constant. The light curve (magnification, A, versus time, t) is given in this approximation by

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}\,, \tag{2}$$

$$u^2 = u_o^2 + \left(\frac{t-t_o}{t_E}\right)^2\,, \tag{3}$$

where u_o, t_o are parameters and t_E (the Einstein radius crossing time of the event) depends on r_E and the transverse velocity v_t of the lens as

$$t_E = \frac{r_E}{v_t} = \frac{1}{v_t}\sqrt{\frac{4Gm_L}{c^2}\frac{d_{OL}(d_{OS}-d_{OL})}{d_{OS}}}\,. \tag{4}$$

The PLPS model works well for most microlensing events. The basic physics observable is the distribution of Einstein radius crossing times t_E. This distribution can be predicted from specific lens models. Most of the time, only the first two moments of the t_E distribution, the event rate Γ and the optical depth τ are compared to the data. Equation (4) shows that t_E scales like $m_L^{1/2}$. To estimate the lens mass from t_E, one has to know d_{OL} and v_t. Since these are unknown, one has to rely on galactic modelling. For instance, for LMC sources and MACHO lenses in a standard isothermal halo, the lens mass is related to $\langle t_E\rangle$ by:

$$\langle t_E\rangle \simeq 75\sqrt{\frac{m_L}{M_\odot}}\text{days}\,. \tag{5}$$

2.0.2 Optical depth and event rates

The optical depth τ is the probability for a lens to be located at less than the Einstein angle θ_E from a source. It is thus given by

$$\tau = \int_O^S dl\rho(l)\pi r_E^2(l)\,, \tag{6}$$

where $\rho(l)$ is the number density of compact objects at a distance l. The optical depth is independent of individual lens masses and depends only on the number density $\rho(l)$. Assuming point sources and lenses, the optical depth is obtained from the measured events by

$$\tau = \frac{\pi}{2N_{\rm obs}T_{\rm obs}}\sum_{\rm events}\frac{t_E}{\epsilon(t_E)}\,, \tag{7}$$

where $\epsilon(t_E)$ is the experimental efficiency of observing an event with Einstein crossing time t_E, $N_{\rm obs}$ is the number of observed stars and $T_{\rm obs}$ is the total observation time. In the case of "exotic" events (section 3.2.5), equation (7) is no longer valid and may have important corrections (Glicenstein 2003). The event rate is in general harder to predict than the optical depth because it depends on modelling details such as the velocity distribution (e.g the lensing rate is higher for a rotating halo) and the mass distribution of lenses. For lenses with a mass m_L and no experimental efficiency corrections, the rate scales like $(\tau/\langle t_E\rangle) \propto m_L^{-1/2}$.

3 MACHO SEARCHES

3.1 MACHOs and the Galactic dark matter problem

At the galactic level, the strongest evidence for dark matter comes from the measurements of the rotation curves of neutral hydrogen and the motion of satellite galaxies. For instance, the mass of the Wilky Way M_{MW} has been estimated by Wilkinson and Evans (1999) from the motion of satellite galaxies

$$M_{\rm MW} \sim 5\ 10^{11} \left(\frac{R_{\rm halo}}{50{\rm kpc}}\right) M_{\odot} , \qquad (8)$$

where $R_{\rm halo}$ is the extent of the Galactic halo. The visible mass in the disk $M_{\rm disk} \sim 6\ 10^{10}\ M_{\odot}$ is an order of magnitude smaller than this. If the Milky Way is typical, the mass density in halos is

$$\rho_{\rm halo} \sim n_{\star} M_{\rm MW} \sim 10^{-31}\ {\rm g\ cm}^{-3} , \qquad (9)$$

where $n_{\star} \sim 10^{-2} h^3\ {\rm Mpc}^{-3}$ is the number density of galaxies per unit volume of the Universe. Since this is comparable to the density of baryons in the Universe ρ_b, a large fraction of the Dark Matter in galactic halos could be composed of baryons. Possible candidates for galactic baryonic dark matter are reviewed by Hegyi and Olive (1986) and Carr (1994). They can be divided in two classes, diffuse (cold molecular clouds) or compact objects, the so-called MACHOs (acronym for “Massive Astrophysical Compact Halo Object”). Diffuse objects are cold molecular clouds whose sizes range from 1 AU to 10 AU (Pfenniger et al. 1994, Kerins et al. 2002). Examples of compact objects include snowballs, planets, brown dwarfs, red dwarfs and dead stars such as white dwarfs and neutron stars, and black holes. As suggested by Paczyński (1986), microlensing is an ideal tool to search for massive compact objects. Two techniques have been developed, using either resolved or unresolved sources. Searches for MACHOs towards the Large (LMC) and Small (SMC) Magellanic Clouds monitor tens of millions sources. Alternatively, searches towards M31 use unresolved source stars and the technique of “pixel lensing”.

3.2 Searches towards the Magellanic Clouds

The two major surveys towards the Magellanic Clouds are the MACHO and EROS collaborations. Both have been monitoring the Magellanic Clouds for a decade and have completed their data taking. Both surveys have analyzed and published only a subset of their data. The status of MACHO and EROS data analysis is shown in table 1. The EROS survey has analyzed all its data towards the SMC, but only 1/4 of its data towards the LMC. The number of monitored stars is similar, but EROS LMC data are scattered over a larger area than MACHO data. The MACHO collaboration has published almost all its data towards the LMC, but (except for the discovery of the 2 microlensing alerts MACHO-SMC-97-1 and MACHO-SMC-98-1) no microlensing analysis towards the SMC.

3.2.1 Optical depth and rate predictions

Microlensing optical depth calculations use a dark halo model. Since very little is known about the dark halo except for its mass (equation (8)), the halo model is very uncertain. The so-called “standard isothermal halo model”, which is widely used, predicts

$$\tau_{\rm LMC} = 5.1\ 10^{-6}\ \ , \qquad \tau_{\rm SMC} = 6.8\ 10^{-6} . \qquad (10)$$

Other, more realistic models such as Evans (1994) models have been investigated by the microlensing surveys. Their predictions for $\tau_{\rm LMC}$ range from 1.5 10^{-6} to 5 10^{-6}. The values of

Table 1 Status of the EROS and MACHO surveys towards the Large (LMC) and Small (SMC) Magellanic Cloud. "Prediction" shows the expected number of events assuming a standard isothermal halo model filled with $0.5 M_\odot$ MACHOs (see text).

	EROS2 LMC	EROS2 SMC	EROS1 LMC	MACHO
Sources (x 10^6)	25.5	5.3	4.1	10.7
Area (deg^2)	39	9	27	15
Years analyzed	3	5	3	5.7
Prediction	21	12	2.4	55
Candidates	4	4	1	13 (17)

$\tau_{\mathrm{SMC}}/\tau_{\mathrm{LMC}}$ range from 0.9 to 1.4, as first noted by Sackett and Gould (1993). The predicted event rate is proportional to the optical depth for a given MACHO mass. Predictions for microlensing rates assuming a MACHO mass of $0.5 M_\odot$ and a standard isothermal halo are given in table 1. These rates are on the high side of the range of rates predicted by Galactic models. Rates per source star are similar towards the LMC and the SMC.

3.2.2 Results

The MACHO team did two independent analyses of their data and found 13 (17) microlensing candidates. The EROS team found 5 candidates in their LMC analysis and 4 candidates in their SMC analysis. As illustrated in figure 1, the observed t_E distributions towards the LMC seems compatible with the theoretical distribution assuming a standard isothermal halo and $0.5 M_\odot$ MACHOs. Note that the expected t_E distribution would be very similar for SMC sources. On the other hand, the 4 events observed by EROS towards the SMC and the event MACHO-SMC-98-1 do not fit well to the expected t_E distribution.

The EROS and MACHO teams give to the data a strikingly different interpretation. The MACHO collaboration is claiming a dark halo signal. The microlensing optical depth towards the LMC is, according to the MACHO collaboration:

$$\tau_{\mathrm{LMC}}^{MACHO} = 1.2^{+0.4}_{-0.3}\, 10^{-7}\,. \tag{11}$$

The typical t_E of the candidates is one month, which (from equation (5)) gives a MACHO mass of 0.6 $M_\odot$. Assuming a standard isothermal halo model, the halo mass fraction in MACHOs is $\sim 20\%$. The EROS survey, on the other hand, makes no claim for a signal and gives only upper limits. None of the EROS microlensing candidates is truly convincing and the t_E of the 2 gold-plated candidates towards the SMC (the other candidates are likely variable stars) is hardly compatible with the distribution observed towards the LMC. The results obtained towards the Magellanic Clouds are summarized in figure 2. The solid line shows the 95 % acceptance region from the MACHO survey. The region bounded from below by the dashed curve is the EROS 95 % exclusion zone. The region bounded from below by the dotted curve is the 95% exclusion zone of the MACHO "high mass" analysis.

The events seen by MACHO and EROS towards the Magellanic Clouds can be either variable stars or true microlensing events. If they are true microlensing events, they may be caused by dark halo stars or by a more conventionnal stallar populations.

3.2.3 Background from variable stars

Several types of variable stars have been identified as potential backgrounds to the microlensing search.

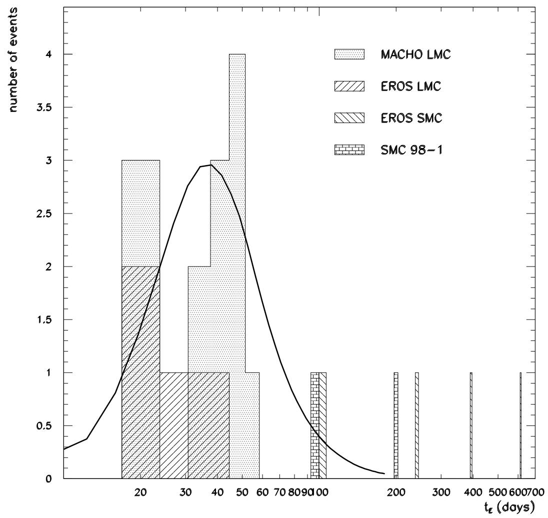

Fig. 1 Einstein crossing time (t_E) distribution for the microlensing candidates observed by the MACHO and EROS collaborations towards the Magellanic Clouds. The binary event MACHO-SMC-98-1 is compatible with two lensing models with different t_E (see Afonso et al. (2000) for details). The solid curve shows the expected t_E distribution for $0.5M_\odot$ MACHOs in a standard isothermal halo using EROS $\epsilon(t_E)$ efficiencies and LMC sources.

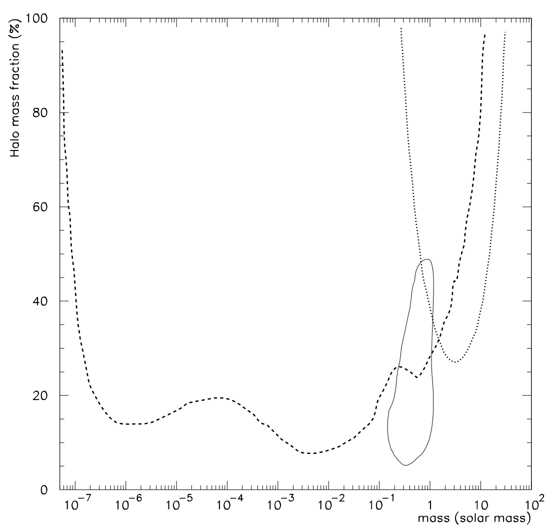

Fig. 2 Results of MACHO searches by microlensing surveys. The dark halo mass fraction accepted or excluded is plotted versus the MACHO mass. The solid line is the 95 % acceptance region from the MACHO survey (Alcock et al. 2000a). The region bounded from below by the dashed contour is the 95% exclusion zone from EROS (Afonso et al. 2003a). The region bounded from below by the dotted curve is the 95% exclusion zone of the MACHO "high mass" analysis.

- Young stars The "blue bumpers" are variable stars from the upper main sequence of the LMC CMD which were first discovered by the MACHO group (Alcock et al. (1996)). Their light curves show low amplication bumps compatible with PLPS microlensing shapes. The "blue bumpers" light curves are chromatic: the fluctuation is larger in the red pass-band than in the visible pass-band. This cannot be interpreted as the amplification of a faint star blended with the source, since the faint component would have to be bluer than the LMC main sequence as noted in Lasserre et al. (2000).
- Novæ Cataclysmic variable (CV) eruptions is another source of potential contamination for microlensing events. Dwarf novae outbursts can be observed as symmetric and achromatic to within the accuracy of microlensing surveys. They can have a recurrence time of ~ 1 year. The rate of dwarf novae outbursts is very uncertain, but could account for a non-negligible fraction of the detected microlensing events, according to della Valle and Livio (1996). Other types of novae may also contribute to the CV background. An exemple is given by nova GK Per (Nova Per 1901) which has roughly time symmetric flares separated by period of years. Cataclysmic variables can be identified and rejected by taking spectra of the microlensing candidates. Spectra of MACHO microlensing candidate LMC-1 taken by DellaValle (1994) showed that the source star was not in a known variable star class. Beaulieu et al. 1995 have taken spectra of the two EROS1 candidates. These spectra could not rule out the interpretation of the microlensing candidate EROS1 LMC-2 as a pre-nova outburst.
- Background supernovæ The MACHO group shows evidence that some of its microlensing candidates could be supernovæ exploding in galaxies behind the LMC. These candidates are rejected when their light curves make a better fit to type Ia supernova templates than to microlensing light curves. EROS rejects this background by cutting on the asymmetry of the light curve.

However a few "gold plated" microlensing events have been found by EROS and MACHO towards the SMC and the LMC (e.g., MACHO alert LMC-99-2, event SMC-98-1). Thus variable stars can explain at most a fraction of the signal.

3.2.4 Background from known stellar populations

Ordinary stellar populations contribute to microlensing. The Galactic disk should contribute one to three lenses to the signal of the MACHO group. The situation is much less clear for the contribution of the Magellanic Clouds ("self-lensing"). The LMC self-lensing background was calculated in Jetzer et al. (2002) using the most up-to-date knowledge of the LMC structure. The authors found that 3–4 events should contribute to the signal of the MACHO collaboration. However, self-lensing is found to be more important (and even make the whole signal up) in other LMC models (see e.g. Salati et al. (1999)). The SMC is known to have a complicated, elongated structure. Because of this, self-lensing is expected to give a sizable contribution. Palanque-Delabrouille et al. (1998) have estimated the SMC self-lensing background to contribute an optical depth of $\tau_{\rm self} \sim 1.5\ 10^{-7}$, comparable to the expected halo signal (equation (10)).

3.2.5 Clues from exotic lensing

Deviations from the simple PLPS lensing model are sometimes observable. Source stars have finite angular sizes which, whenever observed, can be compared to θ_E. This effect has been observed for binary event SMC-98-1, and also possibly for MACHO-LMC-1, according to Witt and Mao (1994). The rotation of binary sources may also be detected (e.g event MACHO-LMC-14). This effect allows for the comparison of the projected orbit of the source with r_E. Binary lenses have spectacular caustic crossing signatures. The modelling of binary lensing events gives informations such as the distance (in units of r_E) and the mass ratio of the 2 components of the lens. At least two clear binary lensing events, SMC-98-1 and MACHO-LMC-9, have been found towards the Magellanic Clouds. The "parallax" (distorsion of the light curve caused by the Earth acceleration) is observable when the lens is near the observer and when t_E is longer than a few months. This effect provides the ratio of the projection of r_E on the observer plane to the astronomical unit. The "parallax" effect was observed on event MACHO-LMC-5 and allowed the MACHO group to predict that the MACHO-LMC-5 lens was in the Galactic disk. The prediction was checked by the direct detection of the lens (Alcock et al. (2001)). No "parallax" effect could be detected on the long t_E SMC-97-1 event. This allowed the EROS group to constrain this lens to be either very heavy (a black hole) or located in the SMC. The analysis of "exotic" microlensing events shows no evidence for halo lenses. One lens was proven to be in the Galactic disk lens (MACHO-LMC-5), another was shown to be most likely in the SMC (98-SMC-1). For all other exotic lenses, no clear conclusion could be reached, but the "self-lensing" interpretation seems to be always somewhat favored.

4 SEARCHES TOWARDS M31

Microlensing surveys towards M31 are sensitive to MACHOs located either in the Galactic halo or in the halo of M31. The tilt of the M31 disk w.r.t the line of sight provides a signature for MACHO detection. If MACHOs make up a significant fraction of halo masses, more microlensing events should be seen towards the"far side" of the M31 disk than towards the "near side". M31 has also a bulge component towards which "self-lensing" is expected to dominate. Pixel lensing surveys do not measure t_E but rather the time at half maximum $t_{1/2}$. This quantity is only weekly dependent on the lens mass and is in the 10-20 days range for halo lenses. Two major microlensing surveys POINT-AGAPE and MEGA are now under way. Event detection rates for these surveys have been estimated by various authors (Baltz et al. (2003), Kerins et al. (2001)). For example, the POINT-AGAPE survey expects around 10 M31 halo events, 3.5 Galactic halo event and 2.2 self-lensing events (outside the bulge region) for one year of data-taking, assuming that halos have a 20% component in $0.3 M_\odot$ MACHOs. Both POINT-AGAPE and MEGA have already published analyses of subsets of their data. In particular, the POINT-AGAPE collaboration has published a first analysis of its 1999-2000 season (Paulin-Henriksson et al. 2003). More than 300 microlensing candidates have been found, out of which only 8 had $t_{1/2} < 25$ days. Four of these events are clear microlensing events. They can be interpreted as MACHOs, but an explanation as self-lensing events cannot be ruled out.

5 GALACTIC CENTRE

Hundreds of microlensing events have been observed towards the Galactic Centre (GC). The lenses responsible for these events are expected to be low mass stars from the Galactic disk or bulge.

5.1 Optical depth

The major input to the optical depth predictions are mass densities of various stellar populations. The fields of view towards the Galactic Centre have bright bulge sources, but are contaminated by disk stars. It is best from both a theoretical and an experimental point of view to study only bulge sources. The microlensing optical depth to bulge source τ_b is not affected by uncertainties on light absorption by dust. Depending on models, it is predicted to be $\tau_b \sim (1-2)\ 10^{-6}$ in the stellar fields monitored by the microlensing collaborations. For instance,

Table 2 Most recent Measurements of the Microlensing Optical Depth towards the GC (bulge sources only).

Author	τ_b ($\times 10^{-6}$)	($\bar{l}$ (deg), $\bar{b}$ (deg))	Method
Alcock et al. (2000b)	3.2 ± 0.5	(2.7, 3.3)	Diff. Phot., $f_{\rm disk} = 0.25$
Popowski et al. (2000)	2.0 ± 0.4	(3.9, –3.8)	PSF Phot.
Popowski (2000)	2.2 ± 0.4	(2.2, –3.2)	Diff. Phot., $f_{\rm disk} = 0.1$
Sumi et al. (2003)	$3.4^{0.9}_{-0.7}$	(3, –3.8)	Diff. Phot., $f_{\rm disk} = 0.25$
Afonso et al. (2003b)	0.94 ± 0.26	(2.5, –4)	PSF Phot.

a recent calculation of the optical depth towards the Baade Window by Han and Gould (2003) gives

$$\tau_b = \tau_{bb} + \tau_{db}, \qquad \tau_{bb} = 0.96\ 10^{-6}, \qquad \tau_{db} = 0.65\ 10^{-6}\,. \tag{12}$$

where τ_{bb} is contributed by bulge lenses and τ_{db} by disk lenses. An interesting constraint on τ has been noted by several authors (Kuijken (1997), Binney et al. (2000)). The microlensing optical depth towards the GC is related to the total mass in compact objects in the inner galaxy and cannot take arbitrarily large values. For an axisymmetric galaxy, one has:

$$\tau = \frac{GM(h)}{fhc^2} = 4.3\ 10^{-6} \left(\frac{2}{f}\right) \left(\frac{500 \text{ pc}}{h}\right) \left(\frac{M(h)}{9\ 10^{10} M_\odot}\right) \tag{13}$$

while for a barred galaxy one has:

$$\tau = 8.6\ 10^{-6} \left(\frac{g}{2}\right) \left(\frac{2}{f}\right) \left(\frac{500\,\text{pc}}{h}\right) \left(\frac{M(h)}{9\ 10^{10} M_\odot}\right)\,. \tag{14}$$

In these equations, h is the height of line of sight above the Galactic Centre, $M(h)$ is the total mass in compact objets, f parametrizes the transverse mass profile and g is related to the orientation of the Galactic bar. Most microlensing surveys monitor fields at a latitude $|b| \simeq 4°$ so that $h \simeq 500\,\text{pc}$. The total mass inside the solar radius is $M_o \sim 8.9\ 10^{10} M_\odot$. Values of the optical depth in the $(3-4)\ 10^{-6}$ range, if confirmed, would almost rule out axisymmetric Galactic models. They would also imply that stars make up most of the mass in the inner Galaxy.

5.2 Recent results

The first measurements of the microlensing optical depth towards the GC by the OGLE (Udalski et al. (1994)) and MACHO (Alcock et al. (1997)) collaborations were as high as $\tau_b = 3.9^{+1.8}_{-1.2}\ 10^{-6}$. Since reliable predictions of the optical depth are obtained on bulge sources only, two types of analysis are possible. Large samples of microlensing events (Alcock et al. 2000b, Sumi et al. (2003)) can be obtained by analyzing the GC fields with differential photometry. Unfortunately, the fraction of disk sources $f_{\rm disk}$ has to be estimated independently and used to correct the observed optical depth $\tau_{\rm obs}$ with $\tau_b = \tau_{\rm obs}/(1 - f_{\rm disk})$. The other possibility is to perform the photometry of resolved stars with PSF fitting programs (Alcock et al. (2000b), Afonso et al. (2003b)). This leads to smaller samples of microlenses, but bulge sources can be selected by their location in the local color-magnitude diagram. The five most recent measurements of the microlensing optical depth towards the GC are listed in table 2.

It is obvious from table 2 that there is still no consensus on the value of τ_b, but some of the most recent measurements do now agree with the theoretical expectations. The basic reason for the disagreement in the optical depth estimates can be traced down to the t_E distributions of

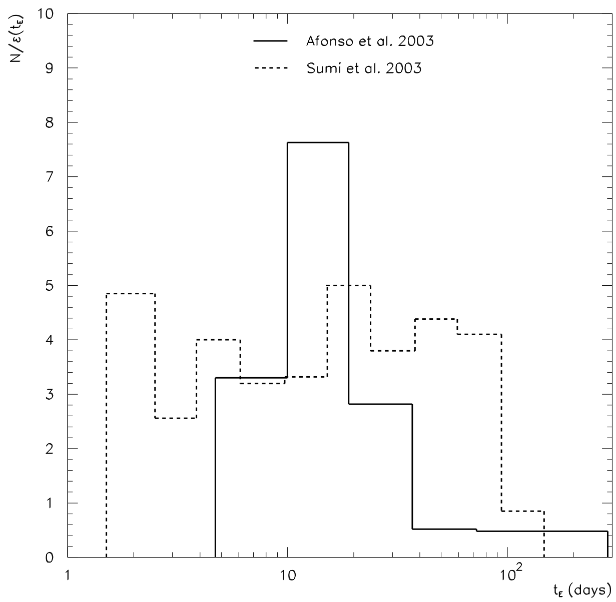

Fig. 3 Distributions of Einstein crossing times t_E measured by 2 surveys towards the GC. The solid line shows is taken from Afonso et al. (2003b) and the dashed line from Sumi et al. (2003). Both results are corrected for the experimental efficiency.

the various surveys. For example, the t_E distributions from Afonso et al. (2003b) and Sumi et al. (2003) are shown in figure 3.

The t_E distribution from Sumi et al. (2003) has a long t_E events tail, which is absent from the Afonso et al. (2003a) distribution. These events make the major contribution to τ_b, since they are weighted by t_E in the estimation (equation (7)) of the optical depth. The nature of these events is still unclear, since the t_E distribution cannot be reproduced by standard (e.g. Scalo (1986)) mass functions, as shown by Sumi et al. (2003).

6 CONCLUSIONS

The microlensing technique has made huge advances in the last decade. However, the status of MACHO searches, either towards the Magellanic Clouds or M31 is still unclear. One firm conclusion is that compact objects are not the major component of the Galactic halo. Hundreds of microlensing events have been found toward the Galactic Centre. The various optical depths measurements do not yet agree with each other. Recent measurements by the MACHO and EROS collaboration are in agreement with the theoretical expectations from galactic models.

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