Can EROS/MACHO be detecting the galactic spheroid instead of the galactic halo?

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Abstract

Models of our galaxy based on dynamical observations predict a spheroid component much heavier than accounted for by direct measurements of star counts and high velocity stars. If, as first suggested by Caldwell and Ostriker, this discrepancy is due to a large population of faint low-mass stars or dark objects in the spheroid, the spheroid could be responsible for microlensing events for sources in the Large Magellanic Cloud (LMC). We show that, although the rate of events is lower than predicted by a galactic halo made of microlensing objects, it is still significant for EROS/MACHO observations. Because of the different matter distributions in the halo and spheroid components, a comparison between microlensing event rates in the LMC, future measurements of microlensing in the galactic bulge and, possibly, in M31 can provide information about the amounts of dark objects in the different galactic components. If the EROS/MACHO collaborations find a deficiency with respect to their halo expectation, when more statistics are available, their detected events could be interpreted as coming from spheroid microlenses, allowing for a galactic halo composed entirely of non-baryonic dark matter.
1 Introduction

The recent detection by the EROS \[1\] and MACHO \[2\] collaborations of microlensing events in the Large Magellanic Cloud (LMC) seems to support the hypothesis that at least part of the dark matter in our galaxy is baryonic, appearing in the form of massive astrophysical objects. Indirect evidence for the presence of galactic dark matter existed from several observations like measurements of the rotation curves of spiral galaxies, including our own, or velocity dispersions measured in elliptical galaxies.

At present, all dynamical observations in our galaxy are well fitted by models with at least three galactic components. These are: (i) the (relatively thin and flat) disk, with a surface mass density decreasing exponentially with $r$, the distance from the galactic centre, (ii) the (approximately spherical) halo, with density asymptotically falling as $r^{-2}$, which gives the main contribution to the total mass of the Galaxy and ensures the flatness of the rotation curve at large distances, and (iii) the (approximately spherical) spheroid, which contributes sizeably to the central part of the galaxy but has a faster radial decrease than the halo. In some models, additional components are also introduced.

The total mass in spheroid stars with mass $m$ larger than the minimum mass for hydrogen burning was estimated, on the basis of star counts at high galactic latitudes and of high velocity stars by Bahcall, Schmidt and Soneira \[3\], to be $M_S(m > 0.085 M_\odot) = 0.9 - 3.2 \times 10^9 M_\odot$. On the other hand, the galactic models based on dynamical measurements and on 2.2 $\mu$m infrared (IR) surveys of the galactic centre predict a much larger total mass for the spheroid, $M_S = 5 - 7 \times 10^{10} M_\odot$, which is comparable to the mass of the disk \[4, 3, 5\]. As recognized by Caldwell and Ostriker \[4\] and by Bahcall, Schmidt and Soneira \[3\], these two results can be made compatible by assuming that most of the mass of the spheroid is non-luminous, in the form of faint low-mass stars, neutron stars, brown dwarfs or Jupiters. An alternative solution \[3\] to this apparent discrepancy is to consider a light spheroid, as determined by star counts and high velocity stars, together with a new galactic component, a central core with large mass density and a sharp cut-off at about 1 kpc, which accounts for the innermost galactic observations. One should note however that there is no reason for the stellar mass function to become negligible just below the hydrogen burning limit. In fact, recent measurements of spheroid field stars \[7\] indicate a steeply increasing mass function towards low masses, with no indications of flattening or of a cutoff near 0.1 $M_\odot$, and this provides support for the heavy spheroid models constituted mainly by brown dwarfs.

We consider here the implications of the scenario with a heavy, mostly dark, spheroid for the ongoing microlensing searches, showing that it can give rise to a significant rate of events both for stars in the LMC and in the galactic bulge. The paper is organized as follows. In Sec. 2 we compare different galactic models and give the corresponding density profiles for the spheroid and the halo which will be used in our study. In Sec. 3 we discuss the prediction for the microlensing event rate at the LMC and compare the results with the EROS/MACHO data. Sections 4 and 5 are devoted to microlensing in the galactic bulge and in M31, where further signatures for spheroid dark objects can be found. Our conclusions are drawn in Sec. 6.
2 Galactic models and density profiles

We will use four different galactic models which provide good fits to the observed rotation curves and the results from 2.2 µm IR surveys, and which predict a heavy spheroid. As stressed by Caldwell and Ostriker the dynamical galactic measurements lead to a spheroid component much heavier than accounted for by the brighter visible stars [4]. We use their best-fit models C(150) and D(150) [8], which we will call OC1 and OC2. Model OC1 includes in the fit the inner peak in the rotation curve and not the measured bulge velocity dispersion, while model OC2 does the reverse. These models consist of three components. The disk has an exponentially falling surface density, and the spheroid has a density (obtained from a deconvolution of the “Hubble Law”)

$$\rho_S^{(OC)}(r) = \rho_S \left\{ \begin{array}{ll}
\frac{3.75\rho}{2^{2/3}Z^{1/2}} \ln \left( \frac{1+Z^{1/2}}{1-Z^{1/2}} \right) - 3, & r < r_s \\
\frac{3.75\rho}{2^{2/3}Z^{1/2}} \frac{\arctan \left( \frac{-1}{2^{1/2}} \right) + \pi}{2} - 3, & r > r_s
\end{array} \right. $$

(1)

where $Z = [(r/r_S)^2 - 1]$. In model OC1, $r_S = 0.09929$ kpc, $\rho_S = 136.0 M_\odot$ pc$^{-3}$, while, for the model OC2, $r_S = 0.1004$ kpc, $\rho_S = 101.8 M_\odot$ pc$^{-3}$. The asymptotic behaviour at large radius is $\rho_S^{(OC)} \sim r^{-3}$ and the total spheroid masses are $M_S^{(OC1)} = 5.9 \times 10^{10} M_\odot$ and $M_S^{(OC2)} = 4.6 \times 10^{10} M_\odot$, assuming a density cut-off at 150 kpc. Finally, there is a dark halo with density

$$\rho_H^{(OC)}(r) = \frac{\rho_c}{1 + (r/r_c)^2},$$

(2)

where $r_c = 3.697$ kpc, $\rho_c = 7.815 \times 10^{-2} M_\odot$ pc$^{-3}$ for OC1 and $r_c = 2.332$ kpc, $\rho_c = 20.03 \times 10^{-2} M_\odot$ pc$^{-3}$ for OC2.

We will also consider the models 5 and 6 of Rohlfs and Kreitschmann [4], here called RK1 and RK2, which are also based on dynamical observations and 2.2 µm IR surveys, and predict a heavy spheroid as well. The two models differ only in that in model RK1 all data points of the rotation curves are included, whereas in model RK2, the data for 1 kpc $< r < 3$ kpc are omitted. Here the spheroid follows a spherical Brandt profile

$$\rho_S^{(RK)}(r) = \rho_b \left[ 1 + 2(r/r_b)^{n_b} \right]^{-(1+3/n_b)},$$

(3)

where $r_b = 0.68$ kpc, $n_b = 0.54$, $\rho_b = 2.59 \times 10^3 M_\odot$ pc$^{-3}$ for RK1 and $\rho_b = 2.25 \times 10^3 M_\odot$ pc$^{-3}$ for RK2, with a total mass $M_S^{(RK1)} = 7.2 \times 10^4 M_\odot$ and $M_S^{(RK2)} = 6.3 \times 10^4 M_\odot$. In their models the halo has the density

$$\rho_H^{(RK)}(r) = \rho_h \frac{1 + n_h x^{-n_h}}{x^2} \exp(-x^{-n_h}),$$

(4)

where $x = r/r_h$, $r_h = 14.53$ kpc, $n_h = 3.40$, $\rho_h = 3.27 \times 10^{-3} M_\odot$ pc$^{-3}$ for RK1 and $r_h = 14.64$ kpc, $n_h = 3.00$, $\rho_h = 3.55 \times 10^{-3} M_\odot$ pc$^{-3}$ for RK2. These models contain also a central core with constant density $\rho_k$ and cut-off $r_k$, where $\rho_k = 27 M_\odot$ pc$^{-3}$ and $r_k = 0.237$ kpc for RK1 and $\rho_k = 11 M_\odot$ pc$^{-3}$ and $r_k = 0.390$ kpc for RK2.

The general structure of RK1 and RK2 is substantially similar to OC1 and OC2, for which the central core is mimicked by a logarithmic rise in $\rho_S^{(OC)}(r)$ at small $r$. The main difference is the halo density minimum of RK1 and RK2 at the galactic centre, which however plays no significant role in our discussion.
In Ref. [6], models with lighter spheroids are also proposed. However, for comparison, we will consider the galactic model of Bahcall, Schmidt, and Soneira [3] (here called BSS) for which the density profile of the spheroid is determined by non-dynamical observations. BSS is a four-component model with a spheroid having a “de Vaucouleurs” density

$$\rho_{\text{S}}^{(\text{BSS})}(r) = \frac{\rho_D(R_0)}{800} \left\{ \begin{array}{ll}
1.25Y^{-3} \exp[10.093(1 - Y)], & r < 0.03R_0 \\
Y^{-7/2} \left( 1 - \frac{0.08669}{Y} \right) \exp[10.093(1 - Y)], & r \geq 0.03R_0,
\end{array} \right. \quad (5)$$

with $$Y \equiv \left( \frac{r}{R_0} \right)^{1/4}$$, $$\rho_D(R_0) = 0.15M_\odot \text{ pc}^{-3}$$ and $$R_0 = 8 \text{ kpc}$$, the galactocentric solar distance, and with total mass $$M_S^{(\text{BSS})} = 4.2 \times 10^9 M_\odot$$. The halo density in their model is given by

$$\rho_{\text{H}}^{(\text{BSS})}(r) = \rho_H(R_0) \left( \frac{a^{1.2} + R_0^{1.2}}{a^{1.2} + r^{1.2}} \right) \times \left\{ \begin{array}{ll}
1, & r \leq R_C \\
(R_C/r)^{1.5}, & r > R_C,
\end{array} \right. \quad (6)$$

with $$\rho_H(R_0) = 0.009 M_\odot \text{ pc}^{-3}$$, $$R_C = 30 \text{ kpc}$$, and $$a = 2 \text{ kpc}$$. Besides the disk, there is also a central core, which is important at $$r \approx 1 \text{ kpc}$$.

The density profiles for halo and spheroid in the different models are compared in Fig. 1. Notice the clear discrepancy between the spheroid mass density in models OC and RK and in the BSS model.

We will assume, as suggested by Caldwell and Ostriker [4] and by Bahcall, Schmidt and Soneira [3], that the difference between the predictions of the spheroid mass based on dynamical observations and that based on star counts and high-velocity stars is due to a large spheroid population of very faint stars or dark objects. Given the large numerical discrepancy between the two values of $$M_S$$, we will take $$\rho_S(r)$$ in the heavy spheroid models as describing the density of microlensing objects to a good approximation and proceed to estimate the predicted event rates for EROS/MACHO.

## 3 Microlensing in the LMC

The optical depth $$\tau$$ for microlensing, which is just the number of objects inside the microlensing tube, can easily be computed following Paczyński [8]:

$$\tau = \frac{4\pi G u_T^2}{c^2 L} \int_0^L dx x(L-x)\rho(r). \quad (7)$$

In Eq. (7) $$L$$ is the distance to the source, $$x$$ is the distance to the lensing object, $$u_T$$ is the experimental threshold for $$u \equiv d/R_e$$, where $$d$$ is the impact parameter of the lensing object, i.e. its minimum distance from the line-of-sight and

$$R_e = 2\sqrt{\frac{Gm(L-x)x}{c^2L}} \quad (8)$$

is the Einstein radius for an object with mass $$m$$. Since $$u$$ is related to the image amplification $$A$$ by the relation [4]

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \quad (9)$$
by choosing, e.g., $A_T = 1.34$ one finds $u_T = 1$. In Eq. (4), the distance of the lensing object to the galactic centre is

$$r = \sqrt{x^2 + R_0^2 - 2xR_0 \cos b \cos l}$$

with $(b, l)$ the angular galactic coordinates of the source (we have taken $R_0 = 8.5$ kpc except for the BSS model).

Figure 2 shows the optical depth $\tau$ as a function of $\cos b \cos l$, for three different source distances $L$ (corresponding to the distance to the galactic centre, the LMC, and M31) and for microlensing objects distributed as the spheroid and halo density profiles of the OC1 model. Notice that, as $\cos b \cos l$ increases and the line-of-sight comes closer to the galactic centre, the optical depth for spheroid lensing objects becomes larger and can overcome the value of $\tau$ from halo lensing objects. Also, as $L$ increases, the optical depth for spheroid objects saturates much faster than for halo objects, because of the steeper decrease with the radius of the spheroid density.

For the LMC ($L = 55$ kpc, $b = -32.8^\circ$, $l = 281^\circ$), the optical depths for the spheroid models considered here, as well as the prediction for a halo of lensing objects, are given in Table 1.

To compute the rate of events $\Gamma$, which corresponds to the flux of objects entering the microlensing tube, it is necessary to know the velocity dispersion of the spheroid population. This has been measured by Hartwick and Sargent [10] at distances of about $10$ kpc and $60$ kpc and found a value of $\sigma$, the one-dimensional velocity dispersion, $\sigma \simeq 125$ km/s. Note that for an isothermal and isotropic velocity distribution with a mass density $\rho \sim r^{-n}$, the velocity dispersion is related to the circular velocity $v_c$ through $\sigma = v_c/\sqrt{n}$ [10, 16] giving, for $\sigma = 125$ km/s and $v_c = 220$ km/s, $n = 3.1$, in agreement with the asymptotic behaviour of the models considered ($n = 3$ for OC, $n = 3.54$ for RK).

Following Griest [11], we compute $\Gamma$ from the expression

$$\Gamma = 8u_T \sigma^2 \sqrt{\frac{G}{c^2 mL}} \int_0^L dx \sqrt{x(L-x)} \rho(r) e^{-\eta^2} \int_0^\infty dz e^{-z^2} I_0(2z\eta),$$

where $I_0$ is the modified Bessel function of order 0. In Eq. (11) $\eta = v_t(x)/(\sqrt{2}\sigma)$ and $v_t(x)$ is the transverse velocity of the microlensing tube at a distance $x$ given by

$$v_t(x) = \sqrt{\left(1 - \frac{x}{L}\right)^2 |\vec{v}_{\odot\perp}|^2 + \left(\frac{x}{L}\right)^2 |\vec{v}_{s\perp}|^2 + 2 \frac{x}{L} \left(1 - \frac{x}{L}\right) |\vec{v}_{\odot\perp}| |\vec{v}_{s\perp}| \cos \theta},$$

where $\vec{v}_{s\perp}$ and $\vec{v}_{\odot\perp}$ are the source and solar velocities transverse to the line-of-sight, and $\theta$ is the angle between them.

The values of $\Gamma$ for the LMC are shown in Table 1 for the different models. To allow easier comparison with the existing literature, we also present the predicted rates in the case of a halo made of lensing objects, in which we have chosen $\sigma = 155$ km/s (corresponding to a 3-dimensional velocity dispersion of 270 km/s). Notice that the predicted halo event rates vary by as much as a factor of 1.7 among different models. In particular, the rate quoted in Ref. [11] lies in the lower end of the range shown in Table 1.

The differential rate distribution in event duration $t$ is

$$\frac{d\Gamma}{dt} = \frac{8u_T \sigma^2}{m} \int_0^L dx \rho(r) z^4 e^{-(z^2+\eta^2)} I_0(2z\eta) z, \quad (13)$$
with
\[ z \equiv \sqrt{\frac{2Gmx(L-x)}{c^2L\sigma^2t^2}}. \tag{14} \]

The event time duration \( t \) is defined as the time taken by the dark object to travel a distance equal to \( R_e \) in a direction orthogonal to the line-of-sight. We can compute the average time duration
\[ \langle t \rangle \equiv \int_0^\infty dt \frac{t}{\Gamma} \frac{d\Gamma}{dt} = \frac{2\tau}{\pi u_T \sigma}, \tag{15} \]
which is given in Table 1. One can also estimate the most probable event duration as the time \( t_P \) at which \( \Gamma^{-1}d\Gamma/dt \) reaches a maximum. The values of \( t_P \) for the different models are shown in Table 1.

For a given time duration \( t \), we can compute the most probable mass \( m_P \) of the object responsible for that microlensing event as the value which maximizes the distribution \( \Gamma^{-1}d\Gamma/dt \), taken now as a function of \( m \). The results for \( m_P \), shown in Table 1, can only be understood as indicative, and masses three times smaller or three times larger are roughly half as probable. For large statistics, information on the lensing object mass distribution could be extracted using the technique proposed in Ref. [12]. Notice that the results contained in Table 1 have been derived under the simplifying assumption that all lensing objects have the same mass.

The expected number of events is then simply
\[ N_{ev} = \Gamma N_\star T \epsilon \tag{16} \]
with \( N_\star \) the number of monitored stars, \( T \) the total observation time, and \( \epsilon \) the experimental efficiency. For the microlensing events due to dark objects of the spheroid, we estimate from Table 1:
\[ N_{ev} = 0.16u_T \epsilon \sqrt{\frac{M_\odot}{m}} \frac{N_\star}{10^6} \frac{T}{\text{years}}, \tag{17} \]
where we have chosen the most favorable case of model RK1. Results from the other models can be easily extracted from Table 1.

MACHO has observed one event with a duration of 17 days and EROS has observed two events with durations of 27 and 30 days. From the results of Table 1 we estimate the most likely mass range \( 2 \times 10^{-2} < m/M_\odot < 2 \times 10^{-1} \) for \( t = 15 \) days, and an interval of masses four times heavier for \( t = 30 \) days. For the MACHO collaboration, which has monitored 1.8 million stars during one year, the expected number of events is about \( N_{ev} = 1\sqrt{0.1M_\odot/m} u_T \epsilon \), while for EROS, with 3 million stars monitored during three observing seasons of about six months each, the expected number is about \( N_{ev} = 2.2\sqrt{0.1M_\odot/m} u_T \epsilon \).

The experimental efficiency \( \epsilon \) can only be computed with a specific knowledge of the experimental apparatus and of the details of the observational procedures, and has not been fully presented by the two groups. The predictions from spheroid microlensing seem to be lower than the preliminary observations of EROS/MACHO, unless either their efficiencies are not much smaller than 1 or the lensing objects are lighter than what suggested by the observed event durations. Only with improved experimental statistics and a careful study of the efficiencies can more conclusive statements be made. Nevertheless, the
rate in Eq. (17) is still significant and could allow for a determination of the amount of spheroid dark matter, especially if observations from different sources are compared, as discussed in the next section.

Finally we want to mention that a larger event rate could be expected if the LMC contained a spheroid of dark objects similarly to the Milky Way. Since the LMC is an irregular galaxy, we cannot draw analogies with our galaxy and we do not attempt to make any estimates. We can only expect that, if microlensing events from LMC spheroid dark objects indeed occur, they should be rather sensitive to the distance of the line-of-sight with the centre of the LMC galaxy.

4 Microlensing in the galactic bulge

Since the galactic spheroid is highly concentrated towards the galactic centre, where it becomes the dominant component, microlensing of bulge (central spheroid) stars could be a strong test of the heavy dark spheroid models that we are considering. This is particularly interesting as the OGLE group \[20\] is currently attempting to detect microlensing of bulge stars and MACHO is planning to do so during the southern winter, when the LMC is low. Microlensing of bulge stars by the halo and disk dark matter and by faint stars in the disk has already been studied by Paczyński \[13\] and by Griest et al. \[14\].

Due to the strong radial dependence of the spheroid density, both the optical depth and the event rate are sensitive functions of the angle between the source and the galactic centre. The optical depth has already been given in Eq. (7). The computation of the event rate is analogous to the one that has led to Eq. (11); here, however, one has to average not only over the velocity distribution of the lenses, but also over the velocity distribution of the sources $\vec{v}_{s\perp}$. The total event rate is

$$\Gamma_B = \frac{1}{2\pi \sigma_b^2} \int_0^{2\pi} d\theta \int_0^\infty dv_s v_s \exp \left(-\frac{v_s^2}{2\sigma_b^2}\right) \Gamma,$$

where $v_s \equiv |\vec{v}_{s\perp}|$, $\Gamma$ is given in Eq. (11), and an isotropic Maxwellian velocity distribution has been assumed. Since the velocity dispersion measured for bulge stars is slightly smaller than for spheroid stars at larger radius \[10\], we take for the one-dimensional velocity dispersion the value $\sigma_b = 105$ km/s, in accordance with the value obtained by Rich \[16\] for Baade’s window $(l, b) = (0.9^\circ, -3.9^\circ)$. We have neglected in our computations the effect of the bulge rotation, which may affect the microlensing rates by spheroid objects by as much as $\sim 20\%$. However, the effect is more important for lensing from disk dark objects \[14\].

The rates for bulge star microlensing from spheroid dark objects are plotted in Fig. 3 as a function of the angle $\alpha$ between the source and the galactic centre ($\alpha = 4^\circ$ for Baade’s window) for the spheroid models OC1 and RK1. We also show for comparison the results for the halo dark matter in model OC1 and those obtained in Ref. \[14\] for disk dark matter (DDM). The rate from halo dark matter is independent of the angle between the line-of-sight and the galactic centre (for small angles) since, for $r \lesssim r_c = 3.7$ kpc, $\rho_H^{(OC)}$ is roughly constant, see Eq. (2). For DDM, the angle coordinate in the plot is the absolute value of the galactic latitude $b$ (and not $\alpha$) and the rate is almost independent.
of the galactic longitude $l$ (for not too large values of $l$). The existence of DDM claimed for many years [15] is still very controversial. A more established source of microlensing comes from faint low-mass stars in the disk. The predictions for the optical depth and the event rate are rather uncertain, depending on the extrapolation of the mass distribution function [14]. Since the event rate is computed by integrating over all faint stars masses, we do not show it in Fig. 3, where a fixed value of $m$ has been assumed. Its angular dependence is qualitatively similar to the one of DDM. The predictions for the optical depth, microlensing event rate and average event duration for faint disk stars, DDM, halo and spheroid dark matter are shown in Table 2 for stars in Baade’s window. The uncertainties in the fit of the faint disk stars mass distribution, as computed in Ref. [14], are shown in Table 2. We have not considered the RK halos, since they predict a negligible rate, because of their “holes” in the galactic centre, see Eq. (4) and Fig. 1.

A realistic range accessible to observations is $\alpha \sim 4^\circ–10^\circ$, since the galactic centre is heavily obscured. As shown in Fig. 3, for $l \simeq 0$, the spheroid dark matter event rate is comparable to, and even larger than, the event rates expected from both DDM and halo dark matter. It should be emphasized that the halo rate is very sensitive to the assumed value of the core radius, decreasing for larger $r_c$.

As mentioned above, we have plotted in Fig. 3 the spheroid microlensing event rate as a function of $\alpha$, whereas the DDM microlensing event rate is plotted as a function of $|b|$. The different and very strong dependence on the galactic longitude $l$ provides the “smoking gun” signature that allows one to distinguish spheroid microlensing events from those coming from DDM or faint disk stars.

5 Microlensing in the Andromeda galaxy

Although M31 is much further away ($L = 650$ kpc) than the Magellanic Clouds, it has been suggested that microlensing of M31 stars could be a good probe of the presence of baryonic dark matter around that galaxy [17]. In particular, the large inclination of its disk ($75^\circ$ with respect to the face on position) makes the optical depth of stars in the far side larger than that in the near side since the line-of-sight crosses a larger fraction of the halo. This effect will be even more pronounced if the lensing objects belonged to a spheroid population rather than to a halo one, because of the steeper $r$-dependence of the spheroid density profile.

Recent fits to dynamical observations in M31 show the presence of a significant spheroid besides the disk. In Ref. [18], a “de Vaucouleurs” spheroid law was assumed, as resulting from luminosity measurements [19], and fits to the rotation velocities resulted in a total spheroid mass $M_S \sim 5 - 8 \times 10^{10} M_\odot$. Due to the great similarity between our galaxy and M31, we will just use the OC1 spheroid model (which has a comparable total mass) to estimate the optical depth for microlensing of M31 stars as a function of the impact parameter $d$, i.e. the distance between the line-of-sight and the M31 galactic centre. This is done by using Eq. (7) where now the distance $r$ between the lensing object and the M31 galactic centre can be written as:

$$r = \sqrt{(L - x - d \cos \Phi \tan i)^2 + d^2},$$  

(19)
where $L$ and $x$ are defined in Sec. 3. Here $i \simeq 75^\circ$ is the inclination of the M31 disk, while $\Phi$ is the position angle relative to the far minor axis. The resulting optical depth for spheroid lensing objects is shown in Fig. 4 as a function of the impact parameter, for stars located along the minor axis, with positive values of $d$ representing the far side ($\Phi = 0$) and negative ones the near side ($\Phi = \pi$).

There is no convincing evidence for a halo in M31. Nevertheless, for comparison, we also show in Fig. 4 the optical depth for lensing objects forming an M31 halo described by the OC1 halo, as well as the contribution to the optical depth from a Milky Way spheroid and halo populations described by the same models. In the computation of the optical depth for Milky Way lensing objects, a cut-off of 150 kpc has been used for both spheroid and halo mass densities.

It is apparent from Fig. 4 that the M31 spheroid microlensing is the most significant for small impact parameters and has a very different profile from the one of the halo, providing a possible observational test. We note, however, that the proximity between the sources and the lensing objects could make the associated Einstein radius quite small; its angular extent can therefore be smaller than the angle subtended by some very large source stars. This could be a drawback for the microlensing of red giant stars by very light objects [17].

6 Conclusions

Galactic models obtained by fitting dynamical observations predict a spheroid component considerably heavier than is accounted for by estimates of the brighter visible stars, suggesting that a “missing mass” problem exists in the spheroid. If such a spheroid dark matter really exists, it will certainly be baryonic. In this paper we have assumed, following Caldwell and Ostriker, that the spheroid population consists mainly of low-mass faint stars or dark objects and we have computed the rate for microlensing events for stars in the LMC. This rate is lower than the corresponding one for microlensing events coming from a galactic halo of dark objects, but it is still significant for observations of EROS/MACHO. We also note that, if the LMC has a heavy spheroid component, this could give an additional considerable contribution to the total rate of events, since the line-of-sight can pass very close to the LMC galactic centre. The example of M31, presented in Sec. 5, is illustrative of such an effect. Unfortunately, poor knowledge of the properties of the LMC does not allow us a reliable estimate.

It is very interesting that the rates for spheroid and halo microlensing vary considerably depending on the source. Searches towards the galactic centre seem particularly promising for distinguishing between them, since the rate for spheroid microlensing is larger than for halo microlensing and has a characteristic dependence on the galactic longitude. The much more challenging search in M31 can also provide important information, since the rate for spheroid microlensing can be very large and can present a strong dependence on the impact parameter, if M31 has indeed a spheroid component similar to the one of the Milky Way, as suggested by observations.

Therefore microlensing searches can map the distributions of dark heavy objects contained in the different galactic components, especially if results from different sources are compared. Knowledge of the amount of dark matter in the spheroid is of great interest.
for understanding the structure of our galaxy and for building reliable galactic models. Finally, we want to mention that the dark spheroid contributions to the total mass of the Universe are not cosmologically very significant, since the mass of the spheroid is comparable to the mass of the galactic disk.

While Turner [21] has suggested that the preliminary EROS/MACHO data already point towards some deficiency with respect to the halo expectation, EROS [1] has claimed that their result is consistent with their expectation, and MACHO [2] has made no statement about it. Only improved statistics and a complete study of the experimental efficiencies (which has not been presented by the EROS/MACHO groups in their papers describing the discovery events [1, 2]) can resolve the question. However, if a deficiency is indeed found, this could be interpreted as microlensing entirely due to dark objects in a heavy spheroid rather than in the halo. In this scenario, therefore, the galactic halo can consist entirely of non-baryonic dark matter and the EROS/MACHO observations could be reconciled with the presently favoured model of structure formation in a critical Universe. This of course would also have important consequences for the currently running experiments searching for halo dark matter from nuclear recoil and from annihilation products. The different distributions of the two dark matter components, with the baryonic one more concentrated towards the galactic centre, could naturally be accounted for by the dissipative processes undergone by the baryons during the galaxy collapse. This is in contrast to the picture proposed by Turner and Gates [22], in which the same galactic component, the halo, is formed by a mixture of baryonic and non-baryonic dark matter.

Note added: After submitting this paper we received a preprint by Gould, Miralda-Escudé and Bahcall [23] where they discuss the possibility that the microlensing events are caused by dark objects in a thick (or a thin) disk.

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Figure captions

Fig. 1. Spheroid and halo density distributions as a function of the radius $r$, for the various models considered. Model RK2 (not shown) is very similar to RK1.

Fig. 2. Optical depth as a function of $\cos b \cos l$, with $(l, b)$ the angular galactic coordinates, for three different values of $L$, the distance to the source, corresponding to the galactic centre ($L = 8.5 \text{ kpc}$), to the LMC ($L = 55 \text{ kpc}$) and to M31 ($L = 650 \text{ kpc}$). Solid lines refer to spheroid lensing objects while dashed lines refer to halo objects, as described by model OC1. The locations of LMC and M31 are indicated.

Fig. 3. Microlensing event rates ($\times \sqrt{m/M_\odot}$) expected for bulge star sources. For the spheroid and the halo, the rate is plotted as a function of $\alpha$, the angle between the source and the galactic centre, which is the only relevant angle because of the spherical symmetry of the density distribution. For disk dark matter, the rate is plotted as a function of the absolute value of the galactic latitude $b$ and the rate is independent of the galactic longitude $l$, in the range of interest. The location of Baade’s window (BW) is indicated.

Fig. 4. Optical depth for microlensing of stars along the minor axis of M31, as a function of the impact parameter $d$ ($d > 0$ for the far side and $d < 0$ for the near side). Solid lines refer to spheroid lensing objects and dashed lines to halo objects, with the contribution from M31 and the Milky Way (MW) plotted separately. The OC1 model was used.
Table 1: The optical depth ($\tau$), the event rate ($\Gamma$), the average event duration ($\langle t \rangle$), the most probable event duration ($t_P$), and the most probable mass ($m_P$), for microlensing events in the LMC. We have taken $\sigma = 125$ km/s for the spheroid and $\sigma = 155$ km/s for the halo. The lensing object mass $m$ is in units of $M_\odot$ and $t_{10}$ is the event duration in units of 10 days. We have taken $u_T = 1$ and $\tau \propto u_T^2$, $\Gamma \propto u_T$.

|             | $\tau$         | $\Gamma_{\text{events}}$ [yr$^{-1}$ $10^6$ stars] | $\langle t \rangle$ [days] | $t_P$ [days] | $m_P$ [$M_\odot$] |
|-------------|----------------|-----------------------------------------------|-----------------|--------------|------------------|
| Spheroid OC1| $4.0 \times 10^{-8}$ | $0.13 \sqrt{m}$                           | $71 \sqrt{m}$   | $44 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Spheroid OC2| $3.1 \times 10^{-8}$ | $0.10 \sqrt{m}$                           | $71 \sqrt{m}$   | $44 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Spheroid RK1| $4.9 \times 10^{-8}$ | $0.16 \sqrt{m}$                           | $69 \sqrt{m}$   | $42 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Spheroid RK2| $4.2 \times 10^{-8}$ | $0.14 \sqrt{m}$                           | $70 \sqrt{m}$   | $42 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Spheroid BSS| $3.5 \times 10^{-9}$ | $0.01 \sqrt{m}$                           | $66 \sqrt{m}$   | $40 \sqrt{m}$ | $0.04 t_{10}^2$  |
| Halo OC1    | $7.5 \times 10^{-7}$ | $2.7 \sqrt{m}$                            | $65 \sqrt{m}$   | $43 \sqrt{m}$ | $0.04 t_{10}^2$  |
| Halo OC2    | $8.0 \times 10^{-7}$ | $2.8 \sqrt{m}$                            | $66 \sqrt{m}$   | $42 \sqrt{m}$ | $0.04 t_{10}^2$  |
| Halo RK1    | $5.4 \times 10^{-7}$ | $1.6 \sqrt{m}$                            | $77 \sqrt{m}$   | $49 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Halo RK2    | $5.8 \times 10^{-7}$ | $1.8 \sqrt{m}$                            | $76 \sqrt{m}$   | $49 \sqrt{m}$ | $0.03 t_{10}^2$  |
| Halo BSS    | $8.4 \times 10^{-7}$ | $2.7 \sqrt{m}$                            | $71 \sqrt{m}$   | $46 \sqrt{m}$ | $0.03 t_{10}^2$  |

Table 2: The optical depth ($\tau$), the event rate ($\Gamma$), and the average event duration ($\langle t \rangle$), for microlensing events in Baade’s window. The results for disk DM and faint disk stars are taken from Ref. [13]. The lensing object mass $m$ is in units of $M_\odot$. We have taken $u_T = 1$ and $\tau \propto u_T^2$, $\Gamma \propto u_T$.

|             | $\tau$         | $\Gamma_{\text{events}}$ [yr$^{-1}$ $10^6$ stars] | $\langle t \rangle$ [days] |
|-------------|----------------|-----------------------------------------------|-----------------|
| Spheroid OC1| $5.0 \times 10^{-7}$ | $6.1 \sqrt{m}$                           | $19 \sqrt{m}$   |
| Spheroid OC2| $3.9 \times 10^{-7}$ | $4.6 \sqrt{m}$                           | $19 \sqrt{m}$   |
| Spheroid RK1| $6.2 \times 10^{-7}$ | $7.1 \sqrt{m}$                           | $20 \sqrt{m}$   |
| Spheroid RK2| $5.4 \times 10^{-7}$ | $6.3 \sqrt{m}$                           | $20 \sqrt{m}$   |
| Spheroid BSS| $5.0 \times 10^{-8}$ | $0.6 \sqrt{m}$                           | $21 \sqrt{m}$   |
| Halo OC1    | $2.7 \times 10^{-7}$ | $2.4 \sqrt{m}$                           | $26 \sqrt{m}$   |
| Halo OC2    | $4.4 \times 10^{-7}$ | $4.0 \sqrt{m}$                           | $25 \sqrt{m}$   |
| Halo BSS    | $1.3 \times 10^{-7}$ | $1.2 \sqrt{m}$                           | $26 \sqrt{m}$   |
| Disk DM     | $9.8 \times 10^{-7}$ | $5.1 \sqrt{m}$                           | $46 \sqrt{m}$   |
| Faint Disk Stars | $(2.9 - 9.6) \times 10^{-7}$ | $2.2 - 7.5$                          | $30$            |
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