A new analysis of the MEGA M31 microlensing events

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Abstract. We discuss the results of the MEGA microlensing campaign towards M31. Our analysis is based on an analytical evaluation of the microlensing rate, taking into account the observational efficiency as given by the MEGA collaboration. In particular, we study the spatial and time duration distributions of the microlensing events for several mass distribution models of the M31 bulge. We find that only for extreme models of the M31 luminous components it is possible to reconcile the total observed MEGA events with the expected self-lensing contribution. Nevertheless, the expected spatial distribution of self-lensing events is more concentrated and hardly in agreement with the observed distribution. We find it thus difficult to explain all events as being due to self-lensing alone. On the other hand, the small number of events does not yet allow to draw firm conclusions on the halo dark matter fraction in form of MACHOs.

Key words. Gravitational Lensing; Galaxy: halo; Galaxies: individuals: M31

1. Introduction

Since the proposal of Paczyński (1986) gravitational microlensing has proved to be an efficient tool for the study of the MACHO contribution to the dark matter galactic halos. The first line of sight to be explored with this purpose has been that towards the Magellanic Clouds (Alcock et al., 1993, Aubourg et al., 1993, Udalski et al., 1993). As first discussed by Crotts (1992), Baillon et al. (1993) and Jetzer (1994) observations towards M31 have also been undertaken (Crotts & Tomaney, 1996, Ansari et al., 1997).

The interpretation of the results obtained so far remain, however, debated and controversial. Along the line of sight towards the LMC the MACHO collaboration (Alcock et al., 2000) reported the signal of a halo fraction of about 20\% in form of MACHOs with mass $\sim 0.5 \, M_\odot$, while the latest results of the EROS collaboration towards both the SMC and the LMC (Afonso et al., 2003, Tisserand, 2005, Tisserand et al., 2006) are even compatible with a no MACHO hypothesis. On the contrary the MEGA collaboration (de Jong et al., 2006) finds that their results, although not conclusive, are in agreement with a no MACHO hypothesis. Although the issues involved in the microlensing observations towards the LMC or the M31 are indeed rather different, the results on the halo fraction in form of MACHOs depend crucially on the prediction of the expected signal due to known luminous populations, this being dominated by the “self-lensing” signal where both source and lens belong to same star population residing respectively either in the LMC or in M31. This problem is indeed the main aspect we want to discuss in this paper.

The issue of the expected microlensing signal towards M31 has been discussed in a few works (e.g. Kerins et al., 2001, Baltz et al. 2003, Riffeser et al., 2003, de Jong et al. 2004, Belokurov et al. 2005, Joshi et al. 2005 and lately the first constraints on the halo fraction have been reported. The results of the POINT-AGAPE collaboration (Calchi Novati et al. 2003) are compatible with the ones of the MACHO group, by putting a lower limit on the halo fraction in form of MACHOs of $\sim 20\%$ for objects in the mass range $0.5 - 1 \, M_\odot$. On the contrary the MEGA collaboration (de Jong et al., 2006) finds that their results, although not conclusive, are in agreement with a no MACHO hypothesis. Although the issues involved in the microlensing observations towards the LMC or the M31 are indeed rather different, the results on the halo fraction in form of MACHOs depend crucially on the prediction of the expected signal due to known luminous populations, this being dominated by the “self-lensing” signal where both source and lens belong to same star population residing respectively either in the LMC or in M31. This problem is indeed the main aspect we want to discuss in this paper.

The case towards M31 is complicated by the further degeneration in the lensing parameter space due to the fact that sources at baseline are unresolved, a case referred to as “pixel-lensing” (Crotts, 1992, Baillon et al., 1993, Gould, 1996). Still, a handful of microlensing events have been observed in the meantime (Ansari et al. 1999, Auriere et al. 2001, Calchi Novati et al. 2002, 2003, Paulin-Henriksson et al. 2003, Riffeser et al. 2003, de Jong et al. 2004, Belokurov et al. 2005, Joshi et al. 2005).
simulation which we have used to investigate the nature and location of the microlensing candidates events towards M31 as reported in a first paper by the MEGA collaboration [de Jong et al. 2003]. In the present work our aim is to further explore these issues taking into account the latest MEGA results [de Jong et al. 2006]. In particular, we now go through a full characterisation of the expected signal, including the predicted number of events, that we then compare with the observational results. Our aim is to explore, in particular, the question whether the expected self-lensing signal due to stars belonging either to the bulge or the disc of M31 is able, as claimed by [de Jong et al. 2006], to fully explain their results.

The plan of the paper is as follows. In Sect. 2 we describe the microlensing rate, our main tool of investigation, and present its predictions. In Sect. 3 we critically discuss the models used to describe the different galactic components involved. In Sect. 4 we discuss our main results and give some concluding remarks.

2. Event rate prediction

In evaluating 1 the expected event number along a fixed line of sight we take into account the existence of two source populations (stars in the M31 bulge and disk) with number density \( n_s(D_{os}, M) \) and of five lens populations (stars in the M31 bulge, stars in the M31 and MW disks, MACHOs in M31 and MW halos) with density \( n_l(D_{ol}, \mu) \). Here \( D_{os} \) (\( D_{ol} \)) is the source (lens) distance from the observer, \( M \) is the source magnitude and \( \mu \) is the lens mass in solar units.

We assume, as usual, that the mass distribution of the lenses is independent on their position in M31 or in the Galaxy (factorization hypothesis). So, the lens number density (per unit of volume and mass) \( n_l(D_{ol}, \mu) \) can be written as [Jetzer et al. 2002]

\[
n_l(D_{ol}, \mu) = \left( \frac{\rho_l(D_{ol})}{\rho_l(0)} \right) \psi_0(\mu) ,
\]

where \( \rho_l(0) \) is the local mass density of the considered lens population in the Galaxy or the central density in M31, \( \psi_0(\mu) \) the corresponding lens number density per unit mass and the normalization is given by

\[
\int_{\mu_{\text{min}}}^{\mu_{\text{up}}} \psi_0(\mu) \mu \, d\mu = \frac{\rho_l(0)}{M_\odot} .
\]

Table 1. For the 14 MEGA events we give position, magnitude at maximum \( \Delta r \) and full-width half-maximum duration \( t_{1/2} \). The coordinate system we adopt has origin in the M31 center and the X axis oriented along the M31 disk major axis.

| MEGA | X arcmin | Y arcmin | \( \Delta r \) mag | \( t_{1/2} \) day |
|------|----------|----------|-------------------|-----------------|
| 1    | -4.367   | -2.814   | 21.8 ± 0.4        | 5.4 ± 0.7       |
| 2    | -4.478   | -3.065   | 21.51 ± 0.06     | 4.2 ± 0.7       |
| 3    | -7.379   | -1.659   | 21.6 ± 0.1       | 2.3 ± 2.9       |
| 7 (N2) | -21.164 | -6.248   | 19.37 ± 0.02     | 17.8 ± 0.4      |
| 8    | -21.650  | +7.670   | 23.0 ± 0.2       | 27.5 ± 1.2      |
| 9    | -33.833  | -2.251   | 21.97 ± 0.08     | 2.3 ± 0.4       |
| 10   | -3.932   | -13.847  | 22.2 ± 0.1       | 44.7 ± 5.6      |
| 11 (S4) | +19.193 | -11.833  | 20.72 ± 0.03     | 2.3 ± 0.3       |
| 13   | +22.072  | -22.022  | 23.3 ± 0.1       | 26.8 ± 1.5      |
| 14   | +19.349  | -29.560  | 22.5 ± 0.1       | 25.4 ± 0.4      |
| 15   | -6.634   | -0.697   | 21.63 ± 0.08     | 16.1 ± 1.1      |
| 16 (N1) | -6.886  | +3.843   | 21.16 ± 0.06     | 1.4 ± 0.1       |
| 17   | +21.214  | -5.161   | 22.2 ± 0.1       | 10.1 ± 2.6      |
| 18   | +6.995   | -13.533  | 22.7 ± 0.1       | 33.4 ± 2.3      |

where \( \mathcal{L}_s(0) \) is central luminosity density of the considered source population, \( \phi_s(M) \) is the source number density per unit magnitude in the M31 center and the normalization now reads

\[
\int_{M_{\text{min}}}^{M_{\text{up}}} \phi_s(M) L(M) \, dM = \mathcal{L}_s(0) .
\]

Here \( M_{\text{min}} \) and \( M_{\text{up}} \) are the lower and the upper limits for the source magnitude (see Subsection 3.1), \( M(L) \) is the luminosity in a given photometric band

\[
L(M) = \eta_{\nu_{\text{Vega}}} L_\odot 10^{-M/2.5} ,
\]

\( \eta_{\nu_{\text{Vega}}} \) being the Vega luminosity (in solar units) in the considered band.

We consider the volume element of the microlensing tube to be \( d^3x = (\mathbf{v}_\perp \cdot \mathbf{n}) R_E u_{\parallel} dD_{ol}, R_E \) being the Einstein radius, \( \mathbf{v}_\perp \) the relative transverse velocity between the lens and the microlensing tube with distribution function \( f(\mathbf{v}_\perp) \), \( \mathbf{n} \) the inner normal to the microlensing tube and \( \alpha \) the angle between \( \mathbf{n} \) and \( \mathbf{A}_\perp \) (see eq. 3).

Assuming perfect observational sensitivity to microlensing, the differential event rate \( dN_{\text{ev}}/d\Omega \) in units of event s\(^{-1}\) for microlensing by compact objects with impact parameter below a certain threshold \( u_{\parallel} \), during the time interval \( dt \), is given by [Griest [1991], De Rújula et al. 1991]

\[
\frac{dN_{\text{ev}}}{d\Omega} = D_{os}^2 u_{\parallel} R_E d\alpha v_{\parallel} f(\mathbf{v}_{\parallel \perp}) d^2\mathbf{v}_{\parallel \perp} \cos \theta
\]

where \( \theta \in (-\pi/2, \pi/2) \) is the angle between \( \mathbf{n} \) and \( \mathbf{v}_{\parallel \perp} \).

We assume that the velocity distributions of lenses and sources are isotropic around their streaming velocities (if present) due to the rotation of the considered population with respect to the M31 or MW center (we neglect

\[1\] Here we follow with some modifications the derivation in our previous paper [Ingrosso et al. 2006].
any transverse drift velocity of the M31 center with respect to the Galaxy). Accordingly, the lens (source) velocity is split into a random component - which follows a Maxwellian distribution with one-dimensional velocity dispersion \( \sigma \) and a streaming component, namely \( \mathbf{v}_l = \mathbf{v}_{l,\text{ran}} + \mathbf{v}_{l,\text{rot}} \) and \( \mathbf{v}_s = \mathbf{v}_{s,\text{ran}} + \mathbf{v}_{s,\text{rot}} \). When the lens and source velocities are projected onto the lens plane (transverse to the microlensing tube), the respective random velocity distributions are again described by Maxwellian functions, with the same one-dimensional velocity random velocity distributions are again described by the lens and source velocities are projected in the lens plane.

The resulting distribution function \( f(v_{\perp l}) \) of the relative, transverse velocity between the lenses and the microlensing tube is now given by the Maxwellian function \( f(v_{\perp s,\text{ran}}) \) shifted by the vector \( \mathbf{A}_{\perp} \), that we write in polar coordinates on the lens plane as

\[
f(v_{\perp l}) d^2v_{\perp l} = \frac{1}{2\pi \sigma_{\perp l}^2} e^{-\frac{(v_{\perp l} - A_{\perp})^2}{2\sigma_{\perp l}^2}} v_{\perp l} dv_{\perp l} \, d\theta .
\]  

(9)

Taking \( \alpha \) to be the angle between \( \mathbf{A}_{\perp} \) and the normal \( \mathbf{n} \) to the microlensing tube, it results that \( \varphi = \alpha + \theta \), where \( \varphi \) is the angle between \( \mathbf{v}_{\perp l} \) and \( \mathbf{A}_{\perp} \).

We recall that in the pixel lensing regime the effective radius of the microlensing tube is a function of the source star magnitude, namely \( u_{\text{th}}(M) \). Moreover in the following we evaluate the differential rate taking into account an efficiency function that depends on the impact parameter, \( \epsilon = \epsilon(u_{\text{th}}) \). Therefore, we are going to replace in eq. \ref{eq:neff} \( dN_e \) by \( \int dN_e/du_{\text{th}} \times \epsilon(u_{\text{th}})du_{\text{th}} \), with upper limit \( u_{\text{T}}(M) \).

Eventually, after integration on the angular variables \( \theta \) and \( \alpha \), one obtains the expected event number rate (events sr\(^{-1}\)) during the observation time \( T_{\text{obs}} \)

\[
\frac{dN_{\text{ev}}}{d\Omega} = T_{\text{obs}} 4\sqrt{2}\sigma_{\perp l} \sqrt{\frac{4GM_{\odot}}{c^2}} \int_0^{u_{\text{T}}(M)} du_{\text{th}} \int_{M_{\text{min}}}^{M_{\text{up}}} \phi_s(M) dM \int_{\mu_{\text{min}}}^{\mu_{\text{up}}} d\mu \frac{1}{2} \int_0^{\infty} D_{\text{cos}}^2 dD_{\text{os}} \int_0^{D_{\text{cos}}} dD_{\text{ol}} \sqrt{\frac{D_{\text{ol}}(D_{\text{os}} - D_{\text{ol}})}{D_{\text{os}}}} \left( \frac{\rho(D_{\text{ol}})}{\rho(0)} \right) \left( \frac{L_s(D_{\text{os}})}{L_s(0)} \right) \int_0^{\infty} z^2 e^{-\frac{z^2}{2}} I_0(2\beta z) \epsilon(t_{1/2}, \Delta f) \, dz .
\]  

(10)

where \( z = v_{\perp l}/(\sqrt{2}\sigma_{\perp l}) \), \( \beta = |A_{\perp}|/(\sqrt{2}\sigma_{\perp l}) \) and \( I_0(2\beta z) \) is the zero-order modified Bessel function \(^2\).

In the previous equation we explicitly take into account an experimental event detection efficiency \( \epsilon(t_{1/2}, \Delta f) \), given as a function of the full-width half-maximum event duration \( t_{1/2} \)

\[
t_{1/2} = t_E f(a) , \quad a = A_{\text{max}} - 1
\]

\[
f(a) = 2\sqrt{2} \left( \frac{a + 2}{\sqrt{a^2 + 4a}} - \frac{a + 1}{\sqrt{a^2 + 2a}} \right)^{1/2}
\]

(11)

and of the maximum flux difference during a microlensing event

\[
\Delta f = f_0(A_{\text{max}} - 1) .
\]

(12)

Here \( t_E \) is the Einstein time, \( A_{\text{max}} = A_{\text{th}}(u_{\text{th}}) \) the amplification at maximum and \( f_0 \) the unlensed source flux.

It is well known that self-lensing and dark-lensing events may have different time durations, depending on the MACHO mass value. On the other hand, in pixel-lensing observations experimental results are usually given in terms of the \( t_{1/2} \) time scale. Thus, it is important to evaluate the expected event rate as a function of \( t_{1/2} \).

From eq. \ref{eq:neff} and the relation \( t_E = R_E/v_{\perp l} \) it follows

\[
t_{1/2} = \frac{R_E f(a)}{z\sqrt{2}\sigma_{\perp l}} ,
\]

(13)

and it is straightforward to derive the differential event rate

\[
\frac{d^2N_{\text{ev}}}{dT dt_{1/2}} = T_{\text{obs}} 8\sigma_{\perp l}^2 \int_0^{u_{\text{T}}(M)} du_{\text{th}} \int_{M_{\text{min}}}^{M_{\text{up}}} \phi_s(M) dM \int_{\mu_{\text{min}}}^{\mu_{\text{up}}} d\mu \int_0^{\infty} D_{\text{cos}}^2 dD_{\text{os}} \int_0^{D_{\text{cos}}} dD_{\text{ol}} \sqrt{\frac{D_{\text{ol}}(D_{\text{os}} - D_{\text{ol}})}{D_{\text{os}}}} \left( \frac{\rho(D_{\text{ol}})}{\rho(0)} \right) \left( \frac{L_s(D_{\text{os}})}{L_s(0)} \right) \int_0^{\infty} z^2 e^{-\frac{z^2}{2}} I_0(2\beta z) \frac{1}{f(a)} \epsilon(t_{1/2}, \Delta f) \, dz .
\]

where \( z \) is now given in terms of \( t_{1/2} \) and \( A_{\text{max}} \) through eq. \ref{eq:neff}.

The model parameters that need to be specified are the luminosity \( \phi_s(M) \) and mass \( \psi_0(\mu) \) functions, the stellar mass distributions in M31 and MW, the mass-to-luminosity ratios for the stellar populations in M31, and the velocity dispersion \( \sigma_s \) and \( \sigma_l \) for the source and lens populations. Further model parameters derive from the consideration of the existence of dark matter in both M31 and MW halos.

\(^2\) By comparing eq. \ref{eq:neff} with eqs. \ref{eq:neff} and \ref{eq:neff} in Ingrosso et al. (2006) one can see that the composition of the two Maxwellian (projected) velocity distributions for lenses and sources permits now to evaluate analytically the two-dimensional integration on the source velocity in eq. \ref{eq:neff}.

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3. Models

3.1. Source luminosity function

In pixel-lensing experiments only bright and sufficiently magnified sources can give rise to detectable microlensing events. Monte Carlo simulations (e.g. Ingrosso et al. 2006) allow to determine the useful range of source magnitude $M_{\min} \simeq -6$ and $M_{\max} \simeq 3$, and the threshold value for the impact parameter $u_p(M)$. 

As regards the source luminosity function $\phi_s(M)$, in the lack of precise information about the luminosity functions in M31, we adopt the luminosity function derived for local stars in the Galaxy and assume that it also holds for M31, irrespectively on the position. In particular, following Mamon and Soucira (1982), the stellar luminosity function in the magnitude range $-6 \leq M \leq 16$ is given by

$$\phi_s(M) = H \frac{10^{\beta(M-M)}}{[1 + 10^{(\alpha-\beta)\delta(M-M^*)}]^{1/\delta}},$$

where, in the $R$-band (the observational band of the MEGA collaboration) $M^* = 1.4$, $\alpha \simeq 0.74$, $\beta = 0.045$ and $\delta = 1/3$. The constant $H$ in eq. (15) is determined via the normalization condition in eq. (16), namely

$$\int_{-6}^{16} \phi_s(M) L(M) dM = \rho_s(0) \left( \frac{M}{L_R} \right)^{-1},$$

where $(M/L_R)$ is the mass-to-luminosity ratio for the source star population in the $R$-band. Note that the normalization for the source density distribution, eq. (20), implies that the event rate does not depend on $(M/L_R)$.

3.2. Lens mass function

As far as the lens mass function is concerned, for lenses belonging to the bulge and disk star populations, the lens mass is assumed to follow a broken power law (Gould et al. 1997)

$$\psi_0(\mu) = K_1 \mu^{-0.56} \text{ for } \mu_{\min} \leq \mu \leq 0.59$$

$$= K_2 \mu^{-2.20} \text{ for } 0.59 \leq \mu \leq \mu_{\up}$$

where the lower limit $\mu_{\min} = 0.1$ and the upper limit $\mu_{\up}$ is 1 for M31 bulge stars and 1.7 for M31 and MW disk stars. The constants $K_1$ and $K_2$ are fixed according to the normalization condition given by eq. (2). The resulting mean mass for lenses in the bulges and disks are $\langle m_b \rangle \sim 0.41 M_\odot$ and $\langle m_d \rangle \sim 0.51 M_\odot$, respectively.

We also consider steeper mass function as proposed by Zoccari et al. (2001) and we find that our estimate of the self-lensing event number turns out to be rather insensitive to the mass function choice.

For the lens mass in the M31 and MW halos we assume the $\delta$-function approximation

$$\psi_0(\mu) = \delta(\mu - \mu_h)$$

and the MACHO mass, in solar units, $\mu_h = 10^{-1}$, 0.5, 1.

3.3. Mass distributions in M31 and MW

The visible mass distributions for the M31 bulge and disk are derived by fitting the observed brightness profiles given by Kent (1989) and by further assuming mass-to-light ratios for bulge and disk stellar populations. Moreover, the consideration of the M31 rotation curve data allows us to derive the distribution of the dark matter in the M31 halo.

Here, we use a coordinate system $(x, y, z)$ centered in M31, with $x$ axis along the disk major axis. We also assume that the disk is inclined by the angle $i = 77^0$ and that the disk azimuthal angle relative to the near minor axis is $\phi = 38.6^0$. The position angle of the bulge is $50^0$.

We neglect the MW disk since we have verified that the expected number of events due to lenses belonging to this mass component is only about 1% of the total number of M31 self-lensing events.

3.3.1. M31 bulge

The M31 bulge model is derived from Tab. I in Kent (1989) containing the bulge 3-d brightness density in the Gunn $r$-band and the ellipticity $e(x)$ as a function of the major-axis distance $a$ to the M31 center.

We fit the 3-d brightness profile with a single de Vaucouleurs $a^{1/4}$ law (reference model)

$$j_r(a) = j_r(0) \left( \frac{a}{a_{\min}} \right)^{-0.4(7.598a^{1/4})} \text{ a } a_{\min},$$

with central 3-d brightness density $j_r(0) = 9.57 \times 10^{-7} L_\odot$ arcsec$^{-3}$ (shifting to magnitudes, eq. (19) may be written in the form $m_r(a) = 15.048 + 7.598a^{1/4}$ mag arcsec$^{-3}$).
This model accurately fits Kent data for \( a_{\min} \simeq 1 \) arcmin, namely in the region usually explored by pixel lensing observations.

\[ \rho(0) = \left( \frac{M}{L_R} \right) 10^{-(0.4|15.048-(r-R) - \text{ext}_R - M_{\odot}/R - \text{d}_{\text{mod}}|}, \quad (20) \]

where \( (M/L_R) \) is the mass-to-light ratio in the \( R \)-band, \( (r-R) \) the color of the bulge stellar population, \( M_{\odot}/R = 4.42 \) the absolute brightness of the Sun in the \( R \)-band, \( \text{ext}_R \) the extinction in the same filter and distance modulus \( \text{d}_{\text{mod}} = 24.43 \) (for an M31 distance of 770 kpc). By using the values \( (M/L_R) = 2.96, (r-R) = 0.59 \) and \( \text{ext}_R = 0.36 \) quoted by Riffeser et al. (2000), we obtain \( \rho(0) = 4.53 \times 10^4 M_{\odot}/\text{pc}^3 \), corresponding to a total bulge mass \( M_{\text{bulge}} \simeq 3.85 \times 10^{10} M_{\odot} \), in agreement with the value given by Kent (1989).

Note that the observed 2-d brightness profile is also compatible with more concentrated mass distributions for the bulge (Beaton et al., 2006). For instance, we have tried a (boxy) model with 99% of the total mass inside 17.86 arcmin (4 kpc). The mass density is now given by

\[ \rho(a) = 4.40 \times 10^4 \times 10^{-(0.4|15.048-0.24|)} \quad a \leq 17.86' \]
\[ = 1.81 \times 10^{39} \times 10^{-(0.4|15.048-0.9|)} \quad a > 17.86'. \quad (21) \]

In Fig. 4 the projected 2-d brightness profile (in units of mag arcsec\(^{-2}\)) is shown for both models together with Kent data. In deriving these profiles, we assumed that the bulge isophote are triaxial ellipsoids with semi-major axes

\[ a^2(\epsilon) = x^2 + y^2 + \frac{z^2}{(1-\epsilon)^2} \]

and ellipticity varying on the semi-major axis according to the Kent data \(^{3}\). From Fig. 4 one can see that beyond 0.03 arcmin both reference and boxy models accurately reproduce Kent data. The only difference is the behaviour of the bulge contribution at large distance where in any case the disk contribution is dominant.

For comparison we also discuss the results obtained by using the bulge model adopted by the WeCapp collaboration (Riffeser et al., 2000).

### 3.3.2. M31 Disk

As in Kerins et al. (2001), the disk 3-d brightness density in the \( r \)-band is modeled by the law

\[ j_r(x, y, z) = j_r(0) \exp(-\sqrt{x^2 + y^2}/h) \text{sech}^2(z/H), \quad (24) \]

and a best fit procedure to the Kent data (for \( a \gtrsim 6 \) arcmin) allows to obtain the central brightness density \( j_r(0) = 4.2 \times 10^{-13} L_{\odot} \text{arcsec}^{-3} \) (corresponding to a central magnitude \( m_r(0) = 20.5 \)), the radial scale length

\[ \left( \frac{1}{1-\epsilon(a)} \right)^2 = 0.254 \frac{a}{\text{arcmin}} + 1.11. \quad (23) \]

\(^{3}\) The existing relation between \( \epsilon \) and \( a \) may be approximated by Riffeser et al. (2000)

\[ \left( \frac{0.254 a}{\text{arcmin}} + 1.11 \right)^2 = \frac{1}{1-\epsilon(a)} \]
h = 27.95 arcmin and the vertical scale length $H = 1.34$ arcmin (corresponding to $h = 6.4$ kpc and $H = 0.3$ kpc, respectively).

As for the bulge, the corresponding disk mass density profile follows the same behaviour as the brightness profile. Accordingly, the disk central mass density is derived by assuming the following parameter values $(M/L)_R = 0.88, (r - R) = 0.54$ and $\text{ext}_R = 0.68$ for the disk (Riffeser et al. [2006]), implying $\rho(0) = 0.2 M_\odot \text{pc}^{-2}$ and a total disk mass $M \simeq 3.09 \times 10^{10} M_\odot$. The 2-d disk brightness profile is also shown in Fig. 4 (dashed line).

### 3.3.3. M31 and MW halos

Both M31 and MW halo mass distributions are modeled as isothermal spheres

$$\rho(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_0}\right)^2}.$$  \hspace{1cm} (25)

For M31 a fit to the M31 rotational curve by using the three (bulge, disk and halo) component model allows to get the best fit parameter values $r_0 = 2$ kpc and $\rho(0) = 0.23 M_\odot \text{pc}^{-2}$ (see also Kerins et al. [2001] and Riffeser et al. [2006]). The overall M31 rotational curve and the contributions of the three components is shown in Fig. 2. In comparison with the recent determination of the mass distribution in M31 Carignan et al. [2006], we find that at $R = 35$ kpc the dark matter mass is $M_\text{h} = 3.7 \times 10^{11} M_\odot$ and the stellar mass $M_{\text{vis}} = 6.6 \times 10^{10} M_\odot$. This translates in a total dynamical mass of $\simeq 4.4 \times 10^{11} M_\odot$ and in a rotational velocity of $233 \text{ km s}^{-1}$ at $R = 35$ kpc, in agreement with the recent observations. The M31 halo is truncated at $R = 150$ kpc.

For the MW we use a core radius $a \simeq 5.6$ kpc and a local $(R_0 = 8.5$ kpc) dark matter density $\rho(R_0) \simeq 1.09 \times 10^{7} M_\odot \text{pc}^{-3}$. The corresponding asymptotic rotational velocity is $v_{\text{rot}} \simeq 220 \text{ km s}^{-1}$. The MW halo is truncated at $R \simeq 100$ kpc.

### Table 3. The MEGA event detection efficiency $\epsilon(t_{1/2}, \Delta f)$ is given as a function of $1/\Delta f$ (first row) for different values of $t_{1/2}$ (first column) in days. The numerical values are derived from Fig. 12 in de Jong et al. [2006].

| $t_{1/2}$ | 0.02 | 0.04 | 0.08 | 0.12 | 0.16 | 0.20 | 0.24 | 0.28 |
|----------|------|------|------|------|------|------|------|------|
| 1        | 0.09 | 0.08 | 0.02 | 0.01 |      |      |      |      |
| 3        | 0.22 | 0.20 | 0.12 | 0.09 | 0.04 | 0.02 |      |      |
| 5        | 0.24 | 0.21 | 0.14 | 0.08 | 0.04 | 0.02 | 0.01 |      |
| 10       | 0.29 | 0.30 | 0.30 | 0.19 | 0.12 | 0.06 | 0.02 | 0.01 |
| 20       | 0.25 | 0.25 | 0.24 | 0.20 | 0.14 | 0.09 | 0.05 | 0.02 |
| 50       | 0.14 | 0.16 | 0.22 | 0.21 | 0.19 | 0.15 | 0.12 | 0.08 |

### Fig. 3. The map $dN_{\text{ev}}/d\Omega$ of the expected (total) event rate towards M31 is shown, assuming the reference model, a MACHO mass value $\mu_h = 0.5$ and a MACHO halo dark matter fraction $f_h = 0.2$. Here and in the following figures and tables we adopt the observational parameters of the MEGA collaboration. Accordingly, we consider $T_{\text{obs}} = 2$ yr and we account for the detection efficiency $\epsilon(t_{1/2}, \Delta f)$ and maximum impact parameter $u_T(M)$ as given by de Jong et al. [2006]. From the outer to the inner M31 region, contour levels correspond to the values $5 \times 10^{-3}, 1 \times 10^{-2}, 2 \times 10^{-2}, 3 \times 10^{-2}, 1 \times 10^{-1}$ event arcmin$^{-2}$, respectively.

### Fig. 4. The same as in Fig. 3 but for the dark-to-total event number ratio. From the inner to outer region, contour levels correspond to the values 0.4, 0.5, 0.6, 0.7 and 0.8, respectively.

### 3.4. Velocity dispersions

The random velocities of stars and MACHOs are assumed to follow Maxwellian distributions, with one-dimensional velocity dispersion $\sigma = 140$ and 166 km s$^{-1}$ for the
Table 4. The integrated number of expected events inside each iso-rate contour of Fig. 3 is given for self-lensing and dark-lensing, assuming the reference model with $\mu_h = 0.5$ and $f_b = 0.2$. In the last column we show the corresponding number of events detected by the MEGA collaboration.

| Events inside the 8 MEGA fields | iso-rate contour (event arcm$^{-2}$) | self | dark | MEGA |
|---------------------------------|------------------------------------|------|------|------|
|                                 | $1 \times 10^{-5}$                 | 3.80 | 0.90 | 1    |
|                                 | $3 \times 10^{-2}$                 | 6.49 | 2.61 | 4    |
|                                 | $2 \times 10^{-2}$                 | 7.45 | 3.79 | 5    |
|                                 | $1 \times 10^{-2}$                 | 8.60 | 6.77 | 6    |
|                                 | $5 \times 10^{-3}$                 | 9.20 | 9.68 | 12   |
| overall                         |                                    | 9.68 | 11.76| 14   |

M31 bulge and MACHOs, and $\sigma = 156$ km s$^{-1}$ for the MACHOs in the MW halo. Moreover, following (Widrow and Dubinski, 2003), the M31 disk stars are assumed to have one dimensional dispersion velocity decreasing towards the outer part from the central value $\sigma(r = 0) \approx 110$ km s$^{-1}$ to $\sigma(r = 30$ kpc) $\approx 5$ km s$^{-1}$. In addition, a rigid rotational velocity of 40 km s$^{-1}$ has been taken into account for the M31 bulge (Kerins et al., 2001; An et al., 2004). For the M31 disk component the full rotational velocity as shown in Fig. 2 (solid line) is also considered.

4. Results and concluding remarks

The main purpose of the present analysis is to compare the predictions of our model with the observational results obtained by the MEGA collaboration (de Jong et al., 2006). Therefore, to evaluate the microlensing rate we reproduce the MEGA observational set up and we make use of the event detection efficiency $\epsilon(t_{1/2}, \Delta f)$, as a function of the time duration and amplification at maximum and the maximum impact parameter $u_T(M)$ values as given by de Jong et al. (2006). In Tab. 3 we give typical detection efficiency values derived from Fig. 12 in de Jong et al. (2006). In order to take into account the spatial variation of the detection efficiency we use two different evaluations of $\epsilon$ at distances smaller and larger than 11 arcmin from the M31 center. It results that on average $\epsilon$ is respectively smaller and larger by about 30% of the values quoted in Tab. 3.

In the following tables and figures, we assume for both M31 and MW halos a MACHO halo dark matter fraction $f_b = 0.2$ as suggested by microlensing observations towards the Magellanic Clouds (Alcock et al., 2000) and pixel-lensing observations towards M31 (Calchi Novati et al., 2005). However, most of our results can be easily rescaled to other values of $f_b$. In Tab. 4 we consider different values for the MACHO mass: $\mu_h = 0.1, 0.5$ and $1$ (in solar units). Figures 3 - 6 and Tabs. 4, 7 and 8 are given for $\mu_h = 0.5$.

Assuming the reference model for the M31 mass distribution, the spatial distribution of the expected events is shown in Figs. 3 and 4. Here we give maps in the sky plane of the (total) event rate and dark-to-total event number ratio, respectively. In Tab. 4 we give our estimate of the integrated number of expected events inside each iso-rate contour of Fig. 3. Here and in the following we consider events inside the 8 fields selected by the MEGA collaboration (as reported in Fig. 15 in de Jong et al. (2006) the innermost M31 region is excluded). From Fig. 3 and Tab. 4 one can see that dark-lensing gives an important contribution to pixel-lensing beyond the second (from the inner) iso-rate contour, namely beyond $\approx 10$ arcmin from the M31 center.

The expected number of self-lensing events inside the 8 MEGA fields is given in Tab. 5 for different source and lens populations. Here with the symbols b, d and h we indicate sources and/or lenses in the M31 bulge, disk and halo, respectively. Capital symbol H is used to indicate lenses in the MW halo. In any case, the first (second) symbol refers to the source (lens). From Tab. 5 one can see that for all the considered models (reference, boxy and WeCapp) the total number of self-lensing events is roughly the same (within 15%).

As far as the reference and boxy models are concerned, we note an increase of bulge-bulge events to compensate a decrease of disk-bulge ones. This is expected to be due to the different concentration of bulge mass for the two distributions. We also note the increase of the disk-bulge events in the WeCapp model due to the more extended bulge mass distribution.

Table 5. Number of self-lensing events expected given the set up of the MEGA campaign, for the different models discussed in the text. We consider different source and lens populations.

| Events inside the 8 MEGA fields | bb | bd | db | dd | self |
|---------------------------------|----|----|----|----|------|
| reference                       | 4.25 | 1.17 | 3.30 | 0.96 | 9.68 |
| boxy                           | 5.14 | 1.10 | 2.76 | 0.95 | 9.95 |
| WeCapp                         | 4.98 | 1.34 | 4.08 | 0.96 | 11.37 |

Assuming the reference model and $f_b = 0.2$, in Tab. 6 we give our estimate of the expected number of dark-lensing events for several MACHO mass value. We find that the total number of dark-lensing and self-lensing events turns out to be roughly the same. As regards the total (self+dark+background) number of expected events, $\sim 23$ including $\sim 1$ event due to SN contamination (see next), it is consistent at $2\sigma$ confidence level with the 14
Table 6. For the reference model, the expected number of dark-lensing events is given for $\mu_h = 0.1$, 0.5, 1 and $f_h = 0.2$.

| Events inside the 8 MEGA fields | $\mu_h$ | $bH$ | $dH$ | $H$ | dark |
|-------------------------------|--------|------|------|-----|------|
| reference                     | 0.1    | 2.55 | 1.04 | 8.81| 3.10 | 14.49|
|                              | 0.5    | 1.96 | 0.72 | 6.85| 2.23 | 11.76|
|                              | 1      | 1.68 | 0.58 | 5.80| 1.82 | 9.88 |

Table 7. The number of self-lensing and dark M31-lensing (due to MACHOs in the M31 halo) events is given for our two models (here labelled reference A and boxy A) assuming $M_b = 4.4$ and $M_d = 5.5$ (in units of $10^{10} \, M_\odot$) and $\mu_h = 0.5$, $f_h = 0.2$. To have the same luminosity for the M31 bulge and disk here we take $(M/L)_h = 3.38$ and $(M/L)_d = 1.56$. We refer to models with $M_d = 5.5$ and $H = 1$ kpc as maximal disk models. In the last row we report some results from Tab. 5 in de Jong et al. (2006), for the MEGA models in the case of high (MEGA A2) and low (MEGA A1) extinction and for a 20% M31 MACHO halo.

| Events inside the 8 MEGA fields | self | dark M31 | self | dark M31 |
|--------------------------------|------|----------|------|----------|
| reference A                    | $H = 0.3$ (kpc) | $H = 0.3$ (kpc) | $H = 1$ (kpc) | $H = 1$ (kpc) |
| boxy A                         | 12.4 | 8.8      | 15.5 | 8.6      |
| MEGA A2                        | 12.7 | 8.5      | 15.5 | 8.7      |
| MEGA A1                        | –    | –        | 12.4 | 5.7      |
|                                | –    | –        | 14.2 | 6.2      |

Table 8. Distribution of the number of self-lensing events with the distance from the M31 center for several models. In the last column, the same quantity is given for dark-lensing assuming the reference model, $\mu = 0.5$ and $f_h = 0.2$.

| Events inside the 8 MEGA fields | ref. | box. | Wec. | ref. |
|--------------------------------|------|------|------|------|
|                               | $d$(arcmin) | self | self | self | dark |
| 2 - 5                         | 3.81  | 4.55 | 3.92 | 0.93  |
| 5 - 10                        | 2.80  | 3.22 | 3.43 | 1.97  |
| 10 - 15                       | 1.32  | 1.06 | 1.73 | 2.46  |
| 15 - 20                       | 0.66  | 0.27 | 0.88 | 2.20  |
| 20 - 25                       | 0.42  | 0.17 | 0.55 | 1.78  |
| 25 - 30                       | 0.22  | 0.11 | 0.28 | 1.23  |
| 30 - 35                       | 0.09  | 0.06 | 0.12 | 0.78  |
| 35 - 40                       | 0.04  | 0.03 | 0.05 | 0.33  |

candidate MEGA events assumed to follow a Poisson distribution.

A comparison of our results with the corresponding values reported in Tab. 5 of de Jong et al. (2006) for low and high internal extinction shows that there is a fairly good agreement. Indeed, to get a more meaningful comparison for the self-lensing contribution we normalize the values for the mass of the luminous components to those of the MEGA models (e.g. for their models A, $M_b = 4.4 \times 10^{10} \, M_\odot$ and $M_d = 5.5 \times 10^{10} \, M_\odot$) and use a more broadened disk ($H = 1$ kpc). In Tab. 7 we report the obtained results for our models (reference and boxy, now labelled A) with the same bulge and disk mass as in MEGA models A, for two values of the disk scale height $H = 0.3$ kpc and $H = 1$ kpc. From Tab. 7 we can see that our estimate for the total number of the self-lensing events is in agreement with the de Jong et al. (2006) prediction only when considering more extreme (maximal) parameters for the disk component.

Nevertheless, at variance with de Jong et al. (2006) we do not conclude that all the 14 events detected by the MEGA collaboration can be explained by self-lensing only. Indeed, the spatial distribution of the events occurring inside the 8 MEGA fields, given in Tab. 8 for several models (reference, boxy and WeCapp) and shown (normalized to unity) in Fig. 5 for both self-lensing (reference and boxy) and total (self+dark) lensing (reference), clearly shows that the distribution with the distance from the M31 center of the self-lensing events hardly can be reconciled with the MEGA data. Indeed, as seen in Fig. 5 an excess of events with respect to expectations from self-lensing remains at large distance. This conclusion is enhanced assuming the boxy model for the M31 bulge.

A better agreement with MEGA data can be obtained if one considers also a dark-lensing (with $\mu_h = 0.5$ and $f_h = 0.2$) contribution. The compatibility between the observed MEGA event distribution as a function of distance from M31 center and the expected one has been evaluated for both self-lensing and self+dark lensing hypotheses. By using the Kolmogorov-Smirnov test (Press et al. 1986) we find a K-S probability $\simeq 0.51$ for self+dark lensing and $\simeq 0.18$ for self-lensing only, thus implying that a dark matter contribution to microlensing seems to be favored.

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5 Note that we are considering a total extinction in the r-band of 0.36 mag (0.68 mag) for the bulge (disk), irrespective of the line of sight.

6 As concerns our estimate in Tab. 4 of dark-lensing events due to M31 halo, we obtain a larger number of events with respect to MEGA expectations ($\simeq 9$ events instead of $\simeq 6$ events for $m_b = 0.5$ and $f_h = 0.2$). However, to describe the M31 dark matter halo we are adopting a different density law (an isothermal profile truncated at $R = 150$ kpc), which is in any case consistent with the full M31 rotation curve.

7 The comparison has been done excluding one event from the MEGA candidate list (in the exterior region) since we expect that at least one of them is due to the contamination of background supernovae (see next for more details.)
the volume within $z_{\text{max}} \simeq 0.4$ (the maximum distance at which the SN signal-to-noise ratio is at least $3\sigma$ above the typical baseline of 22 mag arcsec$^{-2}$) we expect about one detectable SN in the outer M31 regions during the observational MEGA campaign.

The distribution of the expected number of events with the time scale $t_{1/2}$ is shown in Fig. 6 for the reference model and $\mu_h = 0.5$. From this figure, one can see that self-lensing and dark-lensing events have almost the same $t_{1/2}$ distribution. Therefore, the $t_{1/2}$ event distribution is not particularly useful to discriminate the nature of the 14 MEGA events, at least for a MACHO mass value near $0.5\ M_\odot$ (see also discussion on this point in Ingrosso et al. (2006)). The excess of long duration events in the MEGA data suggests also a contamination by other variable objects.

We emphasize that our analysis shows that hardly all 14 MEGA events can be due to self-lensing events by M31 stars. On the other hand, given the few events detected up to now, it seems also premature to derive an estimate of the halo dark matter fraction in form of MACHOs.

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