Microlensing towards the Large Magellanic Cloud: self-lensing for OGLE-II and OGLE-III

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Accepted 2011 May 24. Received 2011 May 23; in original form 2011 April 1

ABSTRACT

We present an analysis of the results of the OGLE-III microlensing campaign towards the Large Magellanic Cloud (LMC). We evaluate for all the possible lens populations along the line of sight the expected microlensing quantities, number of events and duration. In particular, we consider lensing by massive compact halo objects (MACHOs) in the dark matter haloes of both the Milky Way (MW) and the LMC, and ‘self-lensing’ by stars in the LMC bar and disc, in the MW disc and in the stellar haloes of both the LMC and the MW. As a result, we find that the self-lensing signal is able to explain the two OGLE-III microlensing candidates. In particular, we estimate the expected MW disc signal to be almost as large as that from LMC stars and are able, by itself, to explain the observed rate. We evaluate a 95 per cent confidence level (CL) upper limit for $f$, the halo mass fraction in the form of MACHOs, in the range $10^{-2}$ to $0.5 M_\odot$, and $f = 24$ per cent for $1 M_\odot$ (below 10 per cent in this full range and in particular below 5 per cent for $10^{-2}$ to $0.1 M_\odot$) for the Bright (All) samples of source stars. Furthermore, we find that these limits do not rise much even if we assume that the observed events are MACHOs. For the All sample, we also evaluate a rather significant constraint on $f$ for larger values of the MACHO mass, in particular $f \sim 50$ per cent (95 per cent CL) for $100 M_\odot$, to date the stronger bound coming from microlensing analyses in this mass range. Finally, we discuss these results in the framework of the previous observational campaigns towards the LMC, that of the MACHO and the Expérience pour la Recherche d’Objets (EROS) collaborations, and we present a joint analysis of the OGLE-II and the OGLE-III campaigns.

Key words: Gravitational lensing: micro – Galaxy: halo – Galaxy: structure – dark matter.

1 INTRODUCTION

Microlensing has been originally proposed by Paczyński (1986) as a tool to detect dark matter in the form of (faint) massive compact halo objects (MACHOs) in the galactic haloes. Because of the small optical depth (we refer to Mao 2008 and references therein for an introduction to microlensing), the dense stellar field has to be monitored to increase the rate of events. The more nearby available targets to look for MACHOs within the Galactic halo are the Magellanic Clouds [the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC)], which have been therefore the objects of the first microlensing campaigns by the MACHO (Alcock et al. 1993), the EROS (Aubourg et al. 1993) and the Optical Gravitational Lensing Experiment (OGLE) (Udalski et al. 1993) collaborations and for which several results have been reported so far (for a recent review we refer to Moniez 2010). Meanwhile microlensing has moved on and currently is an established tool of investigation over a broad range of astrophysical issues, with one of the main focuses being currently the search and the characterization of extra solar planets (Bozza et al. 2011).

As for microlensing searches towards the Magellanic Clouds, previous analyses are in agreement to exclude MACHOS as a viable dark matter candidate for masses below $\approx (10^{-1}–10^{-2}) M_\odot$. However, a relevant discrepancy still exists as for a possible population of compact halo objects in the mass range $(0.1–1) M_\odot$. The MACHO collaboration claimed for a halo mass fraction in the form of MACHOs of about $20\%$ to $25\%$ per cent out of the observations of 13–17 microlensing candidate events towards the LMC (Alcock et al. 2000), a result more recently confirmed by Bennett (2005), who in particular confirmed the microlensing nature of 10–12 out of the original set of 13 candidate events. On the other hand, the EROS (Tisserand et al. 2007) and OGLE-II (Wyrzykowski et al. 2009; 2010), out of the observations towards both the LMC and...
SMC, concluded by putting extremely severe upper limits on the MACHO contribution also in this mass range (in particular, the EROS collaboration reported an upper limit $f = 8$ per cent for $0.4 M_{\odot}$ MACHOs). Finally, we recall that results on MACHOs through microlensing searches have also been reported from observational campaigns towards M31 (Calchi Novati 2010).

A source of debate for these results is the intrinsic nature of the reported microlensing events. Indeed, in order to draw meaningful insights into the contribution of compact halo dark matter objects it is essential first to estimate accurately all the possible contributions due to (luminous) lenses belonging to the known populations located along the line of sight. We refer to this possibility (first addressed by Sahu 1994 and thereby the objects of several investigations, among which Gyuk, Dalal & Griest 2000; Jetzer, Mancini & Scarpetta 2002) as, broadly speaking, 'self-lensing', to indicate any lens population that is not composed by MACHOs. A possibly non-exhaustive list includes lenses belonging to the luminous components of the LMC which act also as sources (the disc and the bar), the disc of the Milky Way (MW) and the somewhat more elusive stellar haloes for both the MW and the LMC.

Hints on the nature of single specific events require additional information necessary to break the intrinsic degeneracies within the lensing parameter space. These may come from observed features along the microlensing light curves, as in binary systems, or by new independent measurements. This issue has been addressed for a few Magellanic Cloud events, and in particular for two SMC events both found to be attributed more likely to self-lensing: the caustic crossing binary event MACHO 98-SMC-1 (analysed for instance by Alcock et al. 1999 and Rhie et al. 1999) and MACHO 97-SMC-1, a long-duration event for which a spectroscopic analysis of the source has been carried out by Sahu & Sahu (1998). On the other hand, the halo lensing solution is strongly favoured for OGLE-2005-SMC-001, thanks to a space-based parallax measurement (Dong et al. 2007). The SMC is in any case somewhat peculiar with respect to the LMC, both for its intrinsic density distribution and orientation, and a global analysis for the events detected along this line of sight is still missing. We also recall the LMC event MACHO-LMC-5, whose lens has been directly observed by means of the Hubble Space Telescope (HST; Alcock et al. 2001c) and finally acknowledged to be an MW disc M-dwarf lying at a distance of about 580 pc (Drake, Cook & Keller 2004; Gould 2004; Gould, Bennett & Alves 2004), more likely to be attributed to the thick-disc component also because of its proper motion.

A different approach to the same problem is that based on a statistical analysis of a full set of events. Within this framework, in previous analyses, we considered the set of events reported by the MACHO collaboration and showed that, on the basis of both their number and their characteristics (duration and spatial distribution), they cannot all be attributed to self-lensing (Mancini et al. 2004). In Calchi Novati et al. (2006), we considered the possible role played by the LMC dark matter halo, and in particular we challenged the current view that the halo fractions in the form of MACHOs for the MW and the LMC are equal. In Calchi Novati et al. (2009), we discussed the results of the OGLE-II campaign towards the LMC, confirming in particular the outcomes of Wyrzykowski et al. (2009) in that the observed rate was consistent with the expected self-lensing signal. Finally, Mancini (2009) reconsidered microlensing towards the LMC by adopting a non-Gaussian velocity distribution for the sources.

Here, we report on a detailed analysis of the recent results of the OGLE-III campaign towards the LMC (Wyrzykowski et al. 2011). In particular, we estimate the number of the expected events for all the possible lens population with the purpose to derive an accurate limit on the halo fraction in the form of MACHOs. As a result, overall, we find the observed rate to be compatible with the expected self-lensing signal. The plan of the paper is as follows. In Section 2, we resume the main outcomes of the OGLE analysis, with, in particular, a discussion on the issue of blending (and a comparison with the MACHO and the EROS strategies). In Section 3, we present our analysis. After introducing, in Section 3.1, our main tool of investigation, the microlensing rate and the assumed astrophysical model (Section 3.2), in Section 3.3 we derive the expected microlensing quantities, number of events and duration. On the basis of this result, in Section 3.4 we discuss the possible nature of the reported observed events and in particular we evaluate the limits on dark matter in the form of compact halo objects. Finally, in Section 4 we present our conclusions.

2 MICROLENSING OBSERVATIONS TOWARDS THE LMC: THE OGLE CAMPAIGNS

OGLE has continuously upgraded its setup moving on successively to OGLE-II and OGLE-III for finally recently entering in its OGLE-IV phase of evolution. In Fig. 1, we show the contours of the monitored fields of view towards the LMC for the OGLE-II and the OGLE-III campaigns (with overall 21 and 116 fields, respectively). Besides the observed fields, the relevant statistics that characterize an observational campaign are the overall duration, $T_{\text{obs}}$, and the number of monitored stars that act as potential sources for microlensing events, $N_{\text{obs}}$ (sometimes the product of these two terms is indicated as the overall ‘exposure’, $E$). Finally, a selection

![Figure 1](https://academic.oup.com/mnras/article-abstract/416/2/1292/1060563/1293)
pipeline is further specified by the maximum allowed value for the impact parameter, $u_{\text{MAX}}$, and the efficiency, usually expressed as a function of the event duration, the Einstein time, $E = E(t_E)$.

In Table 1, we report the main statistics for the OGLE-II and OGLE-III experimental setup and selection pipeline (in both cases, $u_{\text{MAX}} = 1$). We further discuss the underlying rationale for the two sets of sources, All and Bright samples, below. In particular, the improvement of the available statistics given by OGLE-III with respect to OGLE-II both in terms of the experiment duration and number of potential sources is apparent. In Fig. 2 (top), we show $E(t_E)$ for the inner OGLE-III field 163 and the partly overlapping OGLE-II field 4. As apparent, there is a significant decrease in the OGLE-III efficiency, in particular in the range of $t_E$ values corresponding to those of the observed candidate events (Table 2). This explains, as detailed in the next sections, the reason of the relatively small increase in the expected number of events for the OGLE-III campaign compared to OGLE-II.

Wyrzykowski et al. (2011) for their OGLE-III analysis have reported the evaluation of the efficiency for only the two fields of view (rather, for one CCD out of eight for each of these two fields) where the events have been observed: field 163 and 122 located, respectively, in the central and in the outer LMC regions. In particular, moving towards the outer LMC region the fields gradually become less dense, with fewer observed objects. A reliable measure of the crowedness of the fields is given by the number of estimated sources per field. In Fig. 2 (bottom), we show the histogram of these values as reported by Wyrzykowski et al. (2011). Wyrzykowski et al. (2011) remarked that the efficiency is larger in less crowded fields, and this turns out to be by about a factor between 2 and 3 for field 122 with respect to field 163 (both for the All and the Bright samples of stars, at least for $t_E > 10$ days; see the discussion below).

Accordingly, for our analysis, we evaluate the efficiency in each field, given the number of sources, making use of a linear interpolation$^1$ for each value of $t_E$. In the innermost and outer LMC regions, to avoid extrapolation, we use the value of the efficiency for fields 163 and 122, respectively. (Extrapolation would in fact quickly lead to unreasonable small values for the efficiency in the inner LMC region, whereas in the outer region whatever choice is almost irrelevant as the expected rate, following the decrease in the number of sources, quickly drops to very small values.)

For small values of the duration $t_E$, below about 5–10 d, the efficiency drops quickly below 10 per cent down to 0. This makes OGLE-III, as well as OGLE-II, rather insensitive to MACHOs with masses below about $10^{-3} M_\odot$, for which in particular the expected durations, not corrected for the efficiency, are below 2 d. Furthermore, the statistics of the simulated light curves used to evaluate $E(t_E)$ is increasingly poor moving towards smaller values of $t_E$, so that all the results there should be taken with some care. In particular, contrary to the average result also reported above, the efficiency turns out to be larger in the inner, more crowded, field 163 with respect to the outer field 122 for $t_E < 5$ d.

The overall large field of view monitored by OGLE-III towards the LMC, going from the more crowded inner region to the outer sparse field, can be exploited to carry out analyses based on the spatial distribution. In the following we are going to make use of this chance; in particular, we identify three bins based on the number of estimated sources per field: the inner 14 fields with $N_{\text{obs}} > 400 \times 10^3$, corresponding roughly to the region monitored by OGLE-II, the 22 ‘intermediate’ fields with $200 < N_{\text{obs}} < 400 \times 10^3$ and the

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Table 1. Characteristics of the OGLE-II and OGLE-III observational campaigns towards the LMC: the overall duration of the experiment, number of monitored (estimated) sources, both Bright and All samples (see text for details) and overall field of view.

|              | Duration (d) | $N_{\text{obs}}$ ($\times 10^6$) | FOV (deg$^2$) |
|--------------|--------------|----------------------------------|---------------|
| All          | 1428         | 11.8                             | 4.5           |
| Bright       | 1428         | 3.6                              |               |
| OGLE-II      | 2850         | 22.7                             | 40            |
| OGLE-III     |              | 6.3                              |               |

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Table 2. Microlensing candidate events for the OGLE-II and OGLE-III observational campaigns towards the LMC.

| Event         | RA (J2000.0) | Dec. (J2000.0) | $t_E$ (d) | Field no. |
|---------------|--------------|---------------|-----------|-----------|
| OGLE-LMC-01   | 5:16:53:26   | −69:16:30:1   | 57.2      | 8         |
| OGLE-LMC-02   | 5:30:48:00   | −69:54:33:6   | 24.2      | 2         |
| OGLE-LMC-03   | 5:07:03:63   | −71:17:06:3   | 35.0      | 122       |
| OGLE-LMC-04   | 5:25:39:58   | −70:19:49:7   | 32.8      | 163       |

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$^1$ The reliability of this approximation scheme is supported by the fact that the OGLE-III observational sampling, besides the field crowedness a driving element of the observational setup for the determination of the efficiency, was relatively uniform over all the LMC fields (Ł. Wyrzykowski, private communication).
outer 80 fields with $N_{\text{obs}}^\text{bulge} < 200 \times 10^5$ (to which we refer to also as bins 1, 2 and 3, respectively, Figs 1 and 2).

In Table 2, we report on the information on the microlensing candidate events for the OGLE-II (Wyrzykowski et al. 2009) and OGLE-III (Wyrzykowski et al. 2011) campaigns towards the LMC. Comparing to our mentioned choice for the bin in the spatial distribution, we see that one event is located within the inner bin (OGLE-LMC-04), while the second event (OGLE-LMC-03) is located within the outer bin at the very boundary of the overall monitored fields (Fig. 1).

The choice for the two sets of source stars (and the two parallel corresponding microlensing search pipelines), to which OGLE refers to as the All and the Bright samples, is related to the issue of blending. The term blending indicates that usually more than one star is enclosed within the seeing disc of a given resolved object whose light curve is searched for microlensing variations (this is opposed to the pixel lensing regime, Gould 1996, where one looks for flux variations of unresolved sources, as for instance towards M31). Blending complicates the analysis because, first, the real number of sources is larger than the number of observed objects; secondly, it can make unreliable the estimate of the microlensing parameters, in particular the duration $t_\text{E}$. These effects somewhat tend to compensate for each other for the evaluation of the optical depth; none the less, blending remains a main issue of concern for the interpretation of microlensing results. Indeed, only the acknowledgement and then a deeper understanding of this problem lead finally to reconcile theory and observations for the optical depth evaluations towards the Galactic bulge, (Popowski et al. 2005; Hamadache et al. 2006; Sumi et al. 2006) for the final analyses of the MACHO, OGLE and EROS collaborations, respectively (we also recall the previous analysis of the Microlensing Observation in Astrophysics (MOA) group Sumi et al. 2003 who used a Monte Carlo simulation to address the issue of blending and we refer to Calchi Novati et al. 2008 for a discussion on the microlensing rate for Galactic bulge observations).

The strategy adopted to minimize blending was to take as potential sources only a subset of the brighter observed objects. In particular, for these Galactic bulge searches, the sources were selected in a well-defined region of the colour–magnitude diagram (CMD) in order to select, as best as possible, only bulge (red) clump giants. In fact, Sumi et al. (2006), as opposed to the MACHO and EROS analyses, already stressed the extent to which blending was relevant also for these bright objects, an issue further analysed in Smith et al. (2007), to which we refer for a more through discussion. Following the underlying rationale of these Galactic bulge analyses, a similar strategy was then adopted also by EROS for its final LMC analysis (Tisserand et al. 2007), with however a somewhat looser cut within the CMD specified only with the request for the source objects to be brighter than a given threshold, with a value varying with the field. In the inner region the threshold magnitude was fixed at $I_{\text{eros}} \sim I_{\text{OGLE}} = 18.2$, whereas fainter threshold values, by more than about 1 mag, were allowed for in the outer LMC region. This allowed us to include as viable sources, besides the clump giant region, also, in particular, both redder giants and very bright main-sequence stars. This way EROS reduced the number of sources down to about 20 per cent of the original set, with $N_{\text{obs}}^\text{All} = 5.5 \times 10^6$ spread over its (huge) LMC field of view of about 84 deg$^2$. On the other hand, the MACHO collaboration for its final analysis of 5.7 years of data (Alcock et al. 2000) had chosen a different strategy allowing also for faint sources. Furthermore, MACHO looked mostly at the inner, and denser, LMC region with for an overall field of view of 13.4 deg$^2$. The MACHO’s detection efficiency (Alcock et al. 2001a) was then specifically designed to hold for a total exposure of $E \equiv N_{\text{obs}}^\text{bulge}$.

| Bin number | All sample | Bright sample |
|------------|------------|---------------|
| Bin 1      | 1.27 ± 0.08 | 1.14 ± 0.04   |
| Bin 2      | 1.13 ± 0.03 | 1.07 ± 0.02   |
| Bin 3      | 1.06 ± 0.02 | 1.02 ± 0.01   |

$T_{\text{obs}} = 6.12 \times 10^7$ object years (rather than for stars), for $11.9 \times 10^6$ observed objects, with an estimated mean value stars (brighter than $V = 24$) per object of 10.84 ± 2.4. In particular, the reported efficiency was found to vanish for unresolved stars fainter than $V \sim 24$ (while observing objects down to $V \sim 22$). We recall that the difference in their respective strategies, looking down to faint viable sources in the inner LMC region (MACHO), rather than for bright sources only across a much more extended field of view (EROS), has already been considered as a possible way out to explain the discrepancy already mentioned above in their results as for the compact halo objects fraction in the mass range (0.1–1) $M_\odot$ (Moniez 2010, and references therein). For this reason the mentioned choice of OGLE, which we now discuss in more detail, looks promising to better address this issue.

The strategy adopted by OGLE for its final LMC analyses, similar for both OGLE-II and OGLE-III, has been to carry out two parallel microlensing search pipelines on two distinct sets of sources: the All sample, for objects down to a limit threshold magnitude of $I_{\text{C}} = 20.4$ and a Bright sample composed by a ~30 per cent subset of the brighter sources with a threshold magnitude fixed at 1 mag fainter than the centre of the CMD red clump ($I_{\text{C}} = 18.8$ for their reference field LMC_SC1, located in the innermost LMC region). Through an analysis of the underlying luminosity function, OGLE estimated the number of source stars per observed object down to a magnitude $I = 23.9$ (23.4) for OGLE-II (OGLE-III) respectively. As a measure for the impact of blending, we report (Table 3) the ratio of the number of stars per object for the three bins in the spatial distribution already introduced. As to be expected, blending is more relevant in the crowded inner LMC region (bin 1), with 1.27 (1.14) stars per object for the All (Bright) sample, respectively (we recall that for OGLE-II the corresponding reported values were 2.1 and 2.9$^2$). In particular, we find worth pointing out the extent to which blending is reported to be significant also for the Bright sample, in fact almost at the same level of the All sample (with a relative difference of only about 10 per cent, both for OGLE-II and OGLE-III). A possible reason behind this outcome is the strategy of OGLE, its choice for the threshold magnitude values for the All and Bright

$^2$ The reason behind the smaller values reported for OGLE-III should be looked into a combination of effects: first and more important the better image quality of OGLE-III, then the 0.5 mag difference for the threshold value and finally the refined OGLE-III analysis used to determine the underlying luminosity function (Wyrzykowski, private communication).
samples, which appears somewhat intermediate comparing to the MACHO and EROS strategies. In particular, the OGLE threshold magnitude for the All sample is brighter than that of MACHO (to compare with V-band values of the MACHO analysis we recall that the colour for the red clump centre, where most sources are located, is $V - I \sim 1.0$), while the OGLE threshold magnitude for the Bright sample is fainter than that of EROS. Next observational campaigns, in particular the ongoing OGLE-IV, might hopefully further address this issue.

3 ANALYSIS

3.1 The microlensing rate

Microlensing observations offer two main tools of investigation to compare observations with the expected signal and accordingly draw conclusions on the astrophysical issues of interest: the optical depth, $\tau$, and the microlensing rate, $\Gamma$ (Mao 2008). The first is the instantaneous probability of observing a microlensing event, and therefore a static quantity. In particular, $\tau$ is directly related to the overall lens population density distribution, but it turns out to be independent from the lens mass, one of the more crucial parameters one is usually interested in. This is at the same time a bonus, as it makes $\tau$ less model dependent, and a limit, as it does not allow one to actually characterize the observed events. To this purpose the microlensing rate is therefore the quantity of choice, being a dynamic quantity, which allows one to compute the number of microlensing events per unit time for a given number of monitored stars. In particular, through the analysis of $\Gamma$, one can estimate the number of the expected events, $N_{\text{exp}}$, and their characteristics, more notably their duration and spatial position:

$$N_{\text{exp}} = N_{\text{obs}} T_{\text{obs}} \int \frac{d\tau}{d\Omega} \mathcal{E}(\tau),$$

where we have explicitly taken into account the experiment detection efficiency and written the rate in a differential form (which also provides the expected duration distribution for the events).

Microlensing observations, at least for the more usual lensing configuration of single point source and point lens with uniform relative motion, allow one to estimate a single physically relevant quantity, the event duration $\tau_E$, which is a function of the lens and source distances, the lens mass and the modulus of the lens–source relative transverse velocity which relates the Einstein radius, the microlensing event cross-section, to the Einstein time, $\tau_E = R_E/\dot{v}_E$. As distances, velocities and lens mass are not directly observable, one has to assume a model for all these quantities to integrate them out. The details of the models we use, as well as details on the evaluation of the microlensing rate, are discussed in our previous works, and in particular we refer to Calchi Novati et al. (2009) for a discussion on all the possible source and lens population we consider: for the sources, disc and bar LMC stars; for the lenses, disc and bar LMC stars (a case to which we refer in particular as ‘LMC self-lensing’), Galactic disc stars and finally stars of both the LMC and the Galaxy stellar haloes, all of these lens populations contributing to ‘self-lensing’ and finally, for MACHO lensing, compact halo objects for both the MW and the LMC dark matter haloes.

3.2 The astrophysical model

The modelling of the LMC, in particular of its luminous components, is an extremely live subject of research. Our model, as described in detail in Mancini et al. (2004), is mainly based on the work of van der Marel and collaborators (van der Marel et al. 2002, and references therein), whose conclusions have been challenged by several authors (see for instance the recent analyses of Subramanian & Subramaniam 2010 and Bekki 2011, and references therein). It is beyond the purpose of the present analysis to further address this issue. This is because, as we detail in the following, our main results with respect to compact halo objects are almost insensitive to the exact amount of the LMC self-lensing contribution. The same argument applies also with respect to the stellar haloes, with the additional caveat that their modelling is even more problematic. In particular, for the LMC stellar halo (that giving the larger contribution of the two), here we use our Calchi Novati et al. (2009) ‘fiducial’ model based on the analysis of Alves (2004). As also discussed in Calchi Novati et al. (2009), the more recent analysis of Pejcha & Stanek (2009) suggests a different spatial distribution for this component that may indeed significantly enhance the microlensing signal.

A fully detailed knowledge of the stellar structure of the MW is still lacking. To our purposes, the relevant quantities are the local stellar density and the vertical distribution. An accurate modelling becomes particularly important for a survey as OGLE-III where the MW’s disc lensing can be expected, besides LMC self-lensing, to give a relevant contribution to the rate. As we further address in the following sections, this is because of the broader spatial distribution of the expected MW disc signal, beyond the inner LMC region, with respect to that expected from LMC lenses. For this reason, we update the model used in Calchi Novati et al. (2009). We assume a standard double exponential disc model (Dehnen & Binney 1998) with scalelength $R_d$ and scaleheight $h_d$, summing a thin-disc and a thick-disc component. Following the detailed stellar mass budget of Kroupa (2007), we fix the thin-disc stellar central density to $\rho_{\text{thin},c} = 0.044 M_\odot {\text{pc}}^{-2}$, to be compared for instance with $0.038 M_\odot {\text{pc}}^{-2}$ in Flynn et al. (2006). For a scaleheight $h_{\text{thin}} = 250$ pc, this gives a local disc column density $\Sigma_{\text{thin}} = 22 M_\odot {\text{pc}}^{-2}$ (we do not consider the luminous gas component that does not lens). To complete our fiducial thin-disc model we fix $R_{\text{th}} = 2.75$ kpc. Larger values of $h_d$ are also reported. For instance, $h_{\text{th}} = 300$ pc (Juric et al. 2008) would lead to $\Sigma_{\text{th}} = 26.4 M_\odot {\text{pc}}^{-2}$. The details of the model for the thick disc are less well constrained. This is important for microlensing as the larger scaleheight of this component is expected to significantly enhance the signal (Gould 1994; Gould, Miralda-Escude & Bahcall 1994). Here, we follow the recent analysis of de Jong et al. (2010) and take as our fiducial model $\rho_{\text{thick},c} = 0.005 M_\odot {\text{pc}}^{-3}$, $h_{\text{thick}} = 750$ pc, summing up to $\Sigma_{\text{thick}} = 7.5 M_\odot {\text{pc}}^{-2}$, and $R_{\text{d,thick}} = 4.1$ kpc. These values, also compatible with the analysis of Juric et al. (2008), indicate a quite substantial thick disc over thin-disc local density fraction, $f_{\text{thick}}$, here $f_{\text{thick}} = 11$ per cent (together with a relatively small scaleheight) compared to previous analyses where values in the range $f_{\text{thick}} = 1–10$ per cent were reported (we refer to the discussion in Juric et al. 2008 and de Jong et al. 2010, and references therein). As an extreme case of a ‘light’ thick disc we will report also the results for $f_{\text{thick}} = 1$ per cent. For the thin (thick) disc component, we assume a line-of-sight velocity dispersion of $30 \text{ km s}^{-1}$ ($40 \text{ km s}^{-1}$), respectively.

3.3 Expected events number and duration

The starting point of our analysis is the evaluation of the differential microlensing rate, which enters in equation (1), towards (the centre of) all the 116 OGLE-III fields. This allows us to characterize the expected microlensing signal, in particular the events duration and number, that we now discuss in turn.

© 2011 The Authors, MNRAS 416, 1292–1301
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Useful insights can in fact be gained already by an analysis of the optical depth. We have addressed this issue in our previous papers (Mancini et al. 2004; Calchi Novati et al. 2009). Here we recall that a main difference for the optical depth maps for MW and LMC lens populations is that the contour levels of those for MW lenses are almost constant across the LMC field of view. This is explained by the geometry of the configuration, with the lenses being so close to the observer (a few kpc or even less, so that the spatial lens density distribution remains approximately constant across the full monitored field of view) and the distance of the lens being so small compared to distance of the source. Coming to the microlensing rate, this outcome translates, in particular, into the very small variations for the expected event duration across the LMC’s field of view (Calchi Novati et al. 2009). (This does not apply, however, when moving to the expected number of events where the source density spatial distribution, strongly peaked at the LMC’s centre, comes into play.) On the other hand, the differential rate and the expected duration vary quite significantly for the LMC lens populations, and this holds in particular for the LMC self-lensing, with the shorter duration expected in the inner LMC region. This is made apparent in Fig. 3 (top panel), where we report the efficiency-corrected and normalized differential LMC self-lensing rate calculated along the direction towards the two observed events (located one in the inner and one in the outer LMC regions), together with the MW disc rate. The plot also makes clear the rather large variance of these distributions. A more global picture is given in Fig. 3 (bottom panel), where we report, always for LMC self-lensing, the expected median duration as a function of the optical depth (providing a stronger correlation than the distance from the LMC’s centre). As a median value for the expected duration (corrected for the OGLE efficiency), we find, for LMC self-lensing, values in the range 45–80 d, with the shorter duration expected in the central region; for MW disc lenses (both thin and thick components), about 40 d; for compact halo objects, the duration varies with the assumed mass. For 0.1, 0.5 and 1.0 $M_\odot$ MW MACHOs, we evaluate the expected median durations of 21, 41 and 56 d, respectively. Furthermore, as already pointed out in Calchi Novati et al. (2006), LMC dark matter halo lenses are expected to give, for a given MACHO mass, a shorter duration than Galactic MACHOs, with in particular 0.2 $M_\odot$ LMC MACHOs expected to have a similar duration than 0.5 $M_\odot$ MW MACHOs.

Moving with our analysis to the expected number of events, in Table 4 we report the number of expected events for the luminous populations considered, for both the All and the Bright samples of stars. Taking into account the detection efficiency, in Fig. 4 we show

| Lenses    | OGLE-III Bright | OGLE-III All | OGLE-II Bright | OGLE-II All |
|-----------|-----------------|--------------|----------------|-------------|
| LMC SL    | 0.63            | 1.60         | 0.46           | 1.10        |
| MW disc   | 0.45            | 1.14         | 0.06           | 0.12        |
| LMC SH    | 0.20            | 0.51         | 0.09           | 0.20        |
| MW SH     | 0.09            | 0.24         | 0.03           | 0.07        |
| Total     | 1.37            | 3.49         | 0.64           | 1.49        |

Figure 3. Top: the differential rate, $d^2N/dt_\| dt_\|$, corrected for the efficiency and normalized, for LMC self-lensing evaluated along the line of sight towards the OGLE-III observed events (solid bold and thin line for OGLE-LMC-03 and OGLE-LMC-04, respectively) and for MW disc lenses (dashed line). The vertical solid lines indicate the values of the duration for the two OGLE-III observed events. Bottom: the expected median duration (corrected for the efficiency) for the LMC self-lensing events for the 116 OGLE-III fields as a function of the corresponding value of the LMC self-lensing optical depth. The vertical lines correspond to the optical depth values towards the observed events, the solid horizontal lines indicate the values of the duration for the two OGLE-III observed events. The dotted horizontal lines indicate the expected values for MW disc lenses.

Figure 4. Expected number of MACHO lensing events for OGLE-III (OGLE-II) campaigns (solid and dashed lines, respectively), for both the MW (top) and the LMC dark matter haloes, for the Bright (bold) and the All samples of stars.
the expected number of events for MACHO lensing, both MW and LMC, for a set of delta mass function.

In Table 4 and Fig. 4, we also report the expected number of events of the OGLE-II LMC campaign as evaluated in our previous analysis (Calchi Novati et al. 2009) (for MW disc lenses, using the same model as in Calchi Novati et al. 2009 we would have found, for OGLE-III, an expected signal of 0.17 and 0.43 events, for the Bright and the All sample, respectively). At first glance, a somewhat striking result is a relatively overall small increase in the expected number of events moving from OGLE-II to OGLE-III, when taking into account the overall longer duration and larger number of sources, almost a factor of 2 each (Table 1), both entering linearly into the expression for evaluating the expected number of events (equation 1). As discussed in Section 2, the first and essential reason behind this result should be looked into the smaller detection efficiency reported for OGLE-III.

The expected numbers of MW disc lensing are 0.45 and 1.14 for the Bright and All sample, respectively (about 70 per cent of the expected LMC self-lensing signal), to which the thick-disc component contributes to about 50 per cent. With reference to the discussion on the model in Section 3.2, we note that this fraction would drop below 10 per cent for \( f_{\text{thick}} = 1 \) per cent (and overall the MW disc over the LMC self-lensing signal to 40 per cent). On the other hand, for a thin-disc scaleheight of 300 pc, we would get an expected number of events for the Bright and All samples of 0.54 and 1.38, respectively, almost 90 per cent of the LMC self-lensing signal. In any case, among the contributions to self-lensing, these values make apparent the relevance of the MW disc signal with respect to the LMC self-lensing signal.

Systematic uncertainties related to the assumed astrophysical model, besides those detailed for that of the MW disc, are to be expected in particular for the other prominent luminous lens population, the LMC stars. We have addressed this issue in a previous analysis (Mancini et al. 2004). For somewhat extreme models of LMC, both structure and kinematic, we found variations in the expected number of events up to 30–50 per cent.

The expected number of events is related, besides the lens population under exam, to the underlying source density distribution. Together, these elements determine the expected spatial distribution of the microlensing events. For a large enough set of events, the spatial distribution becomes an extremely powerful tool of analysis to better address an essential problem of this analysis, namely the understanding on the nature of the observed events (as we did in our previous analyses of the MACHO events in Mancini et al. 2004 and Calchi Novati et al. 2006). For the present analysis of the OGLE-III results, with only two observed events, we cannot expect this analysis to give unambiguous outcomes. We may however take advantage of the rather large overall field of view of the OGLE-III fields across the LMC to at least address this issue and gain some insight into the problem. As introduced in Section 2, based on the number of the sources, which traces the underlying LMC populations, we address this issue by identifying three bins within the monitored OGLE-III region. Moving towards the outer LMC region, each bin is composed by 14, 22 and 80 OGLE-III fields, with a total fraction of sources per bin of 42, 27 and 31 per cent, respectively. The rationale behind this choice is that the innermost bin roughly corresponds to the innermost LMC region, in particular, the OGLE-II fields were distributed), whereas the two outer bins are chosen so to have, overall, roughly the same number of sources. The strong variation into the number of sources per field, moving from the crowded inner region to the more sparse LMC outskirts, is clearly reflected in the increasing number of fields per bin. The expected spatial distribution according to this bin choice is given in Table 5 where we report the fractions of the expected number of events per bin for each lens population considered. The outcome is driven by two competitive effects: the larger number of sources towards the LMC centre against the corresponding decrease in the detection efficiency. The other aspect is related to the spatial distribution of the lens, with LMC lenses being more concentrated in the innermost region and MW lenses almost uniformly distributed across the monitored field of view. As a result, the LMC self-lensing signal is, as expected, more concentrated in the inner bin, where we find about 50 per cent of the expected signal. For the other lens populations, in particular for MW disc lenses, we find a more smooth distribution, with roughly 30 per cent, 30 and 40 per cent of the expected events moving from the inner to the outer bin (the mean number of events per field, however, is as expected strongly peaked in the central LMC region).

| Lenses          | Fraction of \( N_{\text{exp}} \) |
|-----------------|---------------------------------|
|                 | Bin 1  | Bin 2  | Bin 3  |
| LMC SL          | 0.484  | 0.273  | 0.244  |
| MW disc         | 0.262  | 0.311  | 0.426  |
| LMC SH          | 0.340  | 0.363  | 0.297  |
| MW SH           | 0.261  | 0.314  | 0.425  |
| MW halo         | 0.260  | 0.315  | 0.426  |
| LMC halo        | 0.282  | 0.340  | 0.378  |

This bin-based analysis also offers a second key of understanding on the relatively small increase of the number of events in OGLE-III with respect to OGLE-II. In particular, we find the MW disc signal to increase for a much larger factor (about 3) with respect to LMC self-lensing (with a relative increase of only a factor about 1.5). The reason behind this lies into the already discussed much stronger concentration of LMC self-lensing in our innermost LMC bin (corresponding also roughly to the OGLE-II fields) with respect to the more smoothly distributed MW’s disc signal.

### 3.4 The nature of the observed events

On the basis of the analyses carried out in the previous section, we can attemptively draw some conclusions on the nature of the observed signal. Both OGLE-II and OGLE-III events, with a duration of about 30 days, fall at the inferior limit of the expected duration distribution for the LMC self-lensing events (Fig. 3). This holds, in particular [because of the correlation of the expected duration with the distance from the LMC’s centre, Fig. 3 (top panel)], for the outer event OGLE-LMC-03, for which we find only 13 per cent of the expected events with expected shorter duration. This fraction rises to 19 per cent for the inner event, OGLE-LMC-04. The observed durations nicely match, on the other hand, the expected values for Galactic disc events (median value about 40 d). The observed event durations are also in agreement with expected Galactic MACHOs, in the mass range 0.1–1\( M_\odot \) (median value from 21 up to 56 d). Furthermore, as already remarked, for the Galactic lens...
populations, the expected duration has a rather uniform distribution across the entire LMC field of view, which is also in agreement with the observed values.

The analysis on the number of expected events on the other hand, Table 4, indicates that LMC self-lensing alone can explain the two reported microlensing candidates. This holds for the All sample ($N_{\text{exp}} = 1.60$), but also, even if this case is somewhat more contrived, for the Bright sample (for $N_{\text{exp}} = 0.63$ we evaluate, according to a Poisson distribution, a 13 per cent probability of finding more than two events). These conclusions are supported by the analysis of the spatial distribution. In fact, the strong decrease of the LMC self-lensing rate in the outer LMC region is at least partially compensated by the extremely large number of observed fields. In particular, even if almost half of the events are expected in the central 14 LMC fields, corresponding to the inner bin in our division (Table 5), still 0.40 (0.15) events are expected in the outer bin, giving a probability of 32 per cent (14 per cent), for the All (Bright) sample, respectively, to observe more than 1 event into the outer bin.

The analysis on the expected number of events from MW disc lenses, on the other hand, supports the hint coming from the analysis on the duration. In fact, with $N_{\text{exp}} = 1.14$ and 0.45 for the All and Bright samples, respectively, MW disc lenses by themselves could explain both reported events almost at the same level of confidence than LMC star lenses. This explanation would be, however, even more contrived for the Bright sample (with an 8 per cent probability of observing more than two events, a value that would drop below 3 per cent assuming the ‘light’ thick-disc model). As for the spatial distribution, the situation is inverse with respect to the LMC self-lensing case, with now the reported candidate in the inner bin more difficult to be explained. Still, we evaluate a probability of 26 per cent (12 per cent), for the All (Bright) sample, respectively, to observe more than 1 MW disc event into the inner bin.

All the above considerations can be made more quantitative taking furthermore into account simultaneously all the possible lens populations and the characteristics of the reported candidate events through a likelihood analysis. In particular, by Bayesian inversion, this allows us to evaluate, for a given MACHO mass, the probability distribution for the halo mass fraction in the form of MACHOs, $P(f)$ (we consider a constant prior for $f$ different from zero in the interval (0,1)).

$$L(f, m) = \exp(-N_{\text{exp}}(f, m)) \prod_{j=1}^{N_{\text{obs}}} \left. \frac{d\Gamma_E}{dT_E} \right|_{t_{\text{ei}}},$$

where $\Gamma_E$ is the microlensing rate corrected by the detection efficiency $d\Gamma_E/dT_E = d\Gamma(t_E)/dT_E \cdot E(t_E)$. The expression reported in equation (2) for the likelihood allows one to take explicitly into account the observed duration as well as the event position as the differential rate is evaluated along the direction towards the events. Here, both $N_{\text{exp}}$ and the differential rate $d\Gamma_E/dT_E$ are to be intended as given by the sum over all the possible lens populations, with the MACHO lensing contributions multiplied by the factor $f$. In principle, it is possible to rewrite equation (2) by taking directly into account bins in distance from the LMC’s centre (similarly for instance to the pixel lensing M31 analysis discussed in Calchi Novati et al. 2005). Following the bin choice of the previous section, we have found that this analysis does not lead to any substantial change in the results.

The results of the likelihood analysis are reported in Fig. 5 where, for a given MACHO mass, we show the limits for the halo mass fraction in the form of MACHOs, $f$. In particular, for the Bright star sample we evaluate a 95 per cent confidence level (CL) upper limit well below 20 per cent in the mass range $(10^{-2}$ to $2 \times 10^{-1})M_\odot$ and below 10 per cent up to 1 $M_\odot$ for the All star sample.

Self-lensing, as discussed, can account for both observed events, however, to the purpose of the evaluation of the limits on $f$; it must be acknowledged that it does not have a leading role. In fact, it is the number of expected MACHO lensing (Fig. 4), at least in the MACHO mass range $(10^{-2}$ to $1)M_\odot$, as compared to the number of reported microlensing candidate, which leads to firmly exclude a significant contribution of this population. This is apparent by inspection of Fig. 5 (dashed lines) where we show the results of the likelihood analysis assuming both the observed events are MACHOs: the increase with respect to the case where we include also self-lensing is of a few per cent only. In that case it makes sense, in principle, to also evaluate a lower limit for $f$, which we find to vary in the range $f \sim (2–4)$ per cent in the MACHO mass range $(10^{-2}$ to $1)M_\odot$ (for the Bright star sample).

Finally, we perform a joint likelihood analysis for the OGLE-II and OGLE-III campaigns (Fig. 5, bottom panel). As a result we find the upper limits on $f$ almost unchanged (with in particular a marginal decrease for the All sample of stars). Comparing to the results discussed in Calchi Novati et al. (2009) this reflects the larger statistics achieved during the OGLE-III campaign compared to the OGLE-II one.
Our results compare well, both qualitatively and quantitatively, with those reported in the OGLE-III Wyrzykowski et al. (2011) r-based analysis. They rule out subsolar MACHOs, and in particular they report an upper limit $f < 7$ per cent at 95 per cent CL for 0.4 $M_\odot$ for the All sample, a result which is almost identical with that we reach in our analysis.

An exception to this agreement is found, on the other hand, in the mass range above 1 $M_\odot$, in particular for the All star sample, where we estimate a relatively strong upper limit for the halo mass fraction, (8, 14 and 51 per cent for 1, 10 and 100 $M_\odot$, respectively, at 95 per cent CL). The driving motivation for the difference with Wyrzykowski et al. (2011) can be traced back to our larger estimate of the expected self-lensing signal, 3.49 events, to be compared with the value 2 assumed by Wyrzykowski et al. (2011) on the basis of the number of reported candidates. The longer expected self-lensing signal derives within the framework of a CL, an estimate for a Poisson distribution with a background (Feldman & Cousins 1998) to smaller values for the upper limit on the signal (the background signal for MACHO lensing being that of self-lensing). A second reason is the likelihood analysis we carry out where, in particular, besides the number of the reported candidates one also takes into account the duration for the candidate event. Given the observed values, about 30 d, this becomes more and more important moving towards large values for the MACHO mass for which the expected durations are extremely large. (For 100 $M_\odot$, we evaluate a median duration of almost 500 d.)

4 DISCUSSION

In this paper, we have analysed the results presented in Wyrzykowski et al. (2011) for the OGLE-III microlensing campaign towards the LMC. In particular, going beyond the optical depth-based analysis of Wyrzykowski et al. (2011), but still in agreement with their conclusions, we have presented an analysis focused on the estimate of the expected number and duration of events through the evaluation of the microlensing rate for all the possible lens populations. In particular, for MACHO lensing both the MW and the LMC dark matter halo, and for self-lensing, the LMC disc and bar, MW disc and MW and LMC stellar haloes. As a main result, we find that compact halo objects might contribute only to a negligible fraction of the dark matter haloes. In particular, we evaluate a 95 per cent CL upper limit for $f$, the halo mass fraction in the form of MACHOs, in the range $10^{-2}$–20 per cent for values of the mass $(10^{-2}$ to 0.5) $M_\odot$, and $f = 24$ per cent for 1 $M_\odot$ (below 10 per cent in this full range, and in particular below 5 per cent for $(10^{-2}$ to 0.1) $M_\odot$) for the Bright (All) samples of source stars. Indeed, the expected self-lensing turns out to be sufficient to explain the observed signal, $N_{\text{obs}} = 2$ (both for the Bright and the All samples), with 1.37 (3.49) expected events for the Bright (All) sample, respectively. However, the number of the reported candidate microlensing events is so small compared to the number of expected MACHO lensing events, about 40 (90) for 0.1 $M_\odot$ MACHOs for the Bright (All) sample of stars, respectively, that the limits on the halo fraction would not change much even assuming the events are MACHOs. An interesting outcome of the present analysis is the relatively significant upper limit on the halo mass fraction we obtain in the mass range above 1 $M_\odot$, at least for the All sample (8, 14 and 51 per cent for 1, 10 and 100 $M_\odot$, respectively). This is a stronger constraint with respect to those reported in previous microlensing analyses (Alcock et al. 2001b; Tisserand et al. 2007) and also in the OGLE-III analysis of Wyrzykowski et al. (2011), and fills the gap, from the microlensing side, with the upper limit from the analysis of halo wide binaries (Yoo, Chanamé & Gould 2004). Stressing the caveat that this outcome holds for the All sample only, we also recall the event reported towards the SMC, OGLE-2005-SMC-001, for which there is evidence in favour for the lens being a heavy mass (about 10 $M_\odot$) compact halo object (Dong et al. 2007). Finally, we have also evaluated the limits for the joint OGLE-II and OGLE-III analyses; in particular, for the Bright sample of stars they remain almost unchanged.

A further relevant result of the present analysis is the role played by the MW disc population, for which we find the expected lensing signal to be almost as large as that of LMC self-lensing, with a 50 per cent contribution from the thick-disc component. In particular, we evaluate 0.45 and 1.14 expected events, for the Bright and the All samples, respectively (against 0.63 and 1.60 for LMC self-lensing). Comparing to the two reported candidate events, both the LMC and the MW disc stars might explain the observed signal. In fact, for the All sample, the observed rate is smaller, though still fully compatible, than the overall expected self-lensing signal (3.49 events including the stellar halo components).

These results, although they look quite conclusive on the MACHOs contribution, at least for the mass range (0.1–1) $M_\odot$, still leave a few open issues. First, the statistics of the observed events is still too small to carry out a meaningful analysis on their observed characteristics, as duration and spatial distribution, so to draw stringent conclusions on the exact nature of the lenses. The observed durations, around 30 d, are shorter than the averaged expected durations for LMC self-lensing, which could still however, based on their expected number, explain both the observed events. At least one event, however, both for its position, in the outer LMC region, and duration, looks more easily explained by the Galactic disc population. Durations and positions are, on the other hand, also compatible with MACHO lensing, especially in the mass range (0.1–1) $M_\odot$; furthermore, the spatial distribution might be suggestive of an asymmetry compatible with that expected by the LMC dark matter halo (Calchi Novati et al. 2006). Again, however, the overall statistics of events is too small to further address this issue.

The number of reported candidates is the final outcome of the selection pipeline. It is beyond the purpose of this paper to address this issue; still we stress the potential difficulty within the evaluation of the detection efficiency to correctly take into account the risk of excluding bona fide microlensing candidates (as with the $\chi^2$ cut which severely reduces the number of viable candidates in the OGLE analyses). To better address this issue, whose importance is strongly enhanced by the very small number of candidate events reported, we believe that a full achromatic-based two-band analysis (even though complicated by the blending effect) would greatly help to more easily distinguish microlensing from intrinsic variables, and hopefully to lead more easily to a larger set of reliable candidate events. After the OGLE-II and OGLE-III campaigns, for which essentially the pipeline was carried out with $I$-band data only, we hope the ongoing OGLE-IV may therefore adopt this strategy.

For both its OGLE-II and OGLE-III LMC campaigns, OGLE chose to present its results for both a, smaller, ‘Bright’ and a ‘All’ sample of source stars. The underlying reason for this choice is linked to the central issue of blending. OGLE-II reported zero and two events out of the Bright and All sample selection pipelines, respectively, whereas OGLE-III reported two events for both samples. The expected self-lensing rate is 0.64 (1.49) for OGLE-II and 1.37 (3.49) for OGLE-III, for the Bright (All) sample, respectively. Once again, the overall small statistics is too small; however, it is clear that this two-sample strategy might be taken as an opportunity for a strong internal self-consistency check of the full analysis (selection
pipeline, efficiency and evaluation of the number of sources). Here again, the ongoing OGLE-IV campaign has a chance of going beyond these previous analyses. The obvious strategy for enhancing the microlensing rate is to allow for fainter sources, in particular within the All sample, even at the risk of complicating the blending analysis.

Finally, we have discussed the strategy of the OGLE-II and OGLE-III campaigns as compared to the previous ones carried out by the MACHO and the EROS collaborations. Given the caveats discussed above, it is clear that the results obtained by OGLE, in agreement with those of EROS (Tisserand et al. 2007), do not leave much place to a significant compact halo objects population. It remains increasingly difficult therefore to explain, within this framework, the results of MACHO (Alcock et al. 2000; Bennett 2005). A possible way out is, once more, that of a significant increase in the expected statistics for self-lensing events, so to allow one to use them as a strong test case to be compared with the expected MACHO lensing signal in this respect, the ongoing OGLE-IV campaign (Udalski 2011), with its still increased overall field of view, the MOA campaign (Sumi 2011), as well as SuperMACHO (Rest et al. 2005), might hopefully help to definitively address at least the issue of the contribution of faint compact objects and fill the gap between the MACHO and the EROS strategies and results.

ACKNOWLEDGMENTS

We are grateful to the referee for interesting suggestions and remarks that helped us to improve the manuscript. We warmly thank Ł. Wyrzykowski for carefully reading the manuscript, useful discussions and comments as well as for making available to us some unpublished data of its analysis. We acknowledge support by MIUR through PRIN 2008 prot. 2008NR3EBK.

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Self lensing for OGLE towards the LMC

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