CANDIDATE MICROLENSING EVENTS FROM M31 OBSERVATIONS WITH THE LOIANO TELESCOPE

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ABSTRACT

Microlensing observations toward M31 are a powerful tool for the study of the dark matter population in the form of MACHOs both in the Galaxy and the M31 halos, a still unresolved issue, as well as for the analysis of the characteristics of the M31 luminous populations. In this work, we present the second-year results of our pixel lensing campaign carried out toward M31 using the 152 cm Cassini telescope in Loiano. We have established an automatic pipeline for the detection and the characterization of microlensing variations. We have carried out a complete simulation of the experiment and evaluated the expected signal, including an analysis of the efficiency of our pipeline. As a result, we select 1–2 candidate microlensing events (according to different selection criteria). This output is in agreement with the expected rate of M31 self-lensing events. However, the statistics are still too low to draw definitive conclusions on MACHO lensing.

Key words: dark matter – galaxies: halos – galaxies: individual (M31, NGC 224) – Galaxy: halo – gravitational lensing

Online-only material: color figures

1. INTRODUCTION

The search for microlensing events aimed at the characterization of the MACHO distribution in galactic halos, first discussed by Paczyński (1986), is by now an established technique. The results obtained up to now are, however, debated. Toward the LMC, the MACHO group have claimed the detection of a MACHO signal from objects of ~0.4 M⊙ that would constitute a halo mass fraction of about f ∼ 0.2 (Alcock et al. 2000; Bennett 2005), whereas the EROS group have found no candidate microlensing events and put a rather stringent upper limit on the same quantity, f < 0.1 in the MACHO mass range preferred by the MACHO results (Tisserand et al. 2007). The issue of the nature of the detected candidates still remains an open question (Sahu 1994; Wu 1994; Mancini et al. 2004; Calchi Novati et al. 2006; Evans & Belokurov 2007).

The contradictory results obtained toward the Magellanic Clouds challenge one to probe the MACHO distribution along different lines of sight. Beyond the Galaxy, M31 represents the next most suitable target for microlensing searches (Crotts 1992; Baillon et al. 1993; Jetzer 1994). Looking at it from outside, we can globally study the M31 halo; the line of sight toward M31 allows one to probe the Galactic halo along a different direction; the inclination of the M31 disk is expected to give a clear signature in the spatial distribution for microlensing events due to lenses in the M31 halo. Several observational campaigns have been carried out: AGAPE (Ansari et al. 1997), who presented the first convincing microlensing candidate along this line of sight (Ansari et al. 1999), Columbia-VATT (Crotts & Tomaney 1996), POINT-AGAPE (Aurière et al. 2001; Paulin-Henriksson et al. 2003), SLOTT-AGAPE (Calchi Novati et al. 2002, 2003), WeCAPP (Riffeser et al. 2003), MEGA (de Jong et al. 2004), and NainiTal (Joshi et al. 2005). The detection of a few microlensing candidates has been reported, as well as first, though contradictory, conclusions on the MACHO content along this line of sight. The POINT-AGAPE group have reported evidence of a MACHO signal (Calchi Novati et al. 2005), whereas the MEGA group have concluded that their detected signal is compatible with the expected M31 self-lensing rate (de Jong et al. 2006). Very recently, Riffeser et al. (2008) have presented a new analysis of a previously reported bright event observed toward the M31 central region. Taking into account the effects of the source’s finite size, they have concluded that the lens of this event should be attributed to the MACHO population. Finally, we recall that a few interesting attempts have also been proposed (Totani 2003), or already carried out (Baltz et al. 2004), toward targets located beyond the Local Group.

In 2006, we began a new observational microlensing campaign toward M31 using the Cassini 152 cm telescope at the “Osservatorio Astronomico di Bologna” (OAB) located in Loiano.8

The results of the first-year pilot season have been discussed in Calchi Novati et al. (2007). In this paper, we discuss the second-year campaign. As the main result, we have carried out a complete analysis of the microlensing flux variations, selected two microlensing candidates, and compared them with the expected microlensing signal. In Section 2, we present the observational setup and outline our data reduction and analysis technique. In Section 3, we present our pipeline for the search for microlensing-like flux variations. In Section 4, we present the simulation of the experiment with an evaluation of the expected signal. In Section 5, we discuss the main results of the present analysis. Finally, in the Appendix, we describe in some detail some of the steps of our selection pipeline and of our Monte Carlo scheme.

8 http://www.bo.astro.it/loiano/index.htm
2. DATA ANALYSIS

2.1. Observational Setup, Data Acquisition, and Reduction

The data have been collected at the 152 cm Cassini telescope located in Loiano (Bologna, Italy). We make use of a CCD EEV of $1340 \times 1300$ pixels of 0.58 for a total field of view of $13' \times 12/6$, with a gain of 1.0e$^-$/ADU (this value has changed with respect to that of the first season because of some electronics problems) and low readout noise (3.5e$^-$/pixel$^-1$). We have been monitoring two fields of view around the inner M31 region, centered respectively in R.A. = $0^h42^m50^s$, decl. = $41^\circ23'57''$ (North) and R.A. = $0^h42^m50^s$, decl. = $41^\circ08'23''$ (South; J2000), so to leave out the innermost ($\sim3'$) M31 bulge region, and with the CCD axes parallel to the south–north and east–west directions so to get the maximum field overlap with previous campaigns. This second-year campaign lasted 50 consecutive full nights, from 2007 November 11 to December 31, with a fraction of good weather of almost 60%. In order to test for achronaticity, data have been acquired in two bandpasses (similar to Cousins $R$ and $I$), with exposure times up to 6 minutes per frame. Overall we collected about 410 (280) exposures per field over 31 nights in the $R$ ($I$) band.$^9$

Typical seeing values are $2''$ (somewhat worse than during the first season). Sky flat frames were taken whenever possible so as to build a master flat image (per filter), and standard data reduction, including bias subtraction, was carried out using the IRAF package.$^{10}$ We corrected $I$ filter data for fringe effects. The analysis presented in this paper is based on the 2007 season data only.

2.2. Image Analysis

As for the preliminary image analysis, we closely follow the strategy (the “pixel-photometry”) adopted by the AGAPE group (Ansari et al. 1997; Calchi Novati et al. 2002), wherein each image is geometrically and photometrically aligned relative to a reference image. To account for seeing variations, we then substitute the flux of each pixel with that of the corresponding 5 pixel square “superpixel” centered on it (whose size is chosen so as to cover most of the average seeing disk) and then apply an empirical, linear, correction in the flux, again calibrating each image with respect to the reference image. The final expression for the flux error accounts both for the statistical error in the flux count and for the residual error linked to the seeing correction procedure. Finally, in order to increase the signal-to-noise ratio (S/N), we combine the images so to get one data point per night per filter.

We evaluate the calibration zero point for the instrumental magnitude versus standard ($R$) magnitudes by using a sample of secondary reference stars (Massey et al. 2006). We find for $R$ and $I$ bands data $C_R = 23.1$ and $C_I = 22.7$, respectively (the reported values corresponding to the standard magnitude for an object with an instrumental magnitude of 1 ADU s$^{-1}$).

3. MICROLENSING EVENT SEARCH PIPELINE

We have established a fully automated pipeline for the detection and characterization of microlensing-like flux variations. We work in the “pixel-lensing” regime (Gould 1996), in which one looks for flux variations whose sources are not resolved objects, so that one has to monitor flux variations of every element of the image, further characterized by the fact that the noise is dominated by the underlying background level (the varying M31 surface brightness). As for this specific analysis, our strategy starts from that described in Calchi Novati et al. (2005) with a few changes introduced to take into account the peculiarities of the present data set.

During the analysis, we have to face two main sources of contamination: “fake” signals, namely spurious variations to be attributed to cosmic rays, defects in the CCD, saturated pixels, and so on; background intrinsically variable objects, that can either mimic microlensing signals or, somewhat more dangerously, add non-Gaussian noise to the light curves.

Our pipeline can be schematically divided into four steps. First, detection of the potentially interesting flux variations. Second, characterization of the light-curve shape. Third, probe against the contamination by spurious detections. Fourth, probe against the contamination by variable signals.

3.1. Bump Detection

As for the first step, we closely follow the strategy outlined in Calchi Novati et al. (2003, 2005). To begin, we detect flux variations along light curves using the $L$ estimator (we ask $L > 50$ to get rid of too small S/N variations). Each given flux variation enhances a signal over a few pixels (a “cluster”) around the central one. We make use of the “$Q$” estimator to characterize the significance of the selected flux variations.$^{11}$ We fix a lower threshold $Q_{th} = 50$. At this stage, therefore, we have to shift from the light-curve analysis (the estimation of $L$ and $Q$) to an analysis based on the spatial information across the CCD in which we have to distinguish, separate, and pick up the flux variations associated with each different cluster. This search is somewhat biased in favor of light curves showing a single variation (in particular, all short-period variables are in principle excluded). This first step is carried out using the (more numerous and less noisy) $R$-band data only.

3.2. Light-Curve Shape

The aim of the second step is to single out the variations whose shape is compatible with that of a Paczyński light curve. To this end, we use a series of selection criteria. As a starting point, we perform a seven-parameter Paczyński fit in the two bands simultaneously.$^{12}$ As an output, we retain the following parameters: the baseline levels; the time of maximum magnification, $t_0$; the full width at half-maximum duration, $t_{1/2}$ (proportional to the Einstein time, $t_E$, multiplied by a function of the impact parameter $u_0$); the flux deviation at maximum (with respect to the baseline), which we convert to magnitude and denote $\Delta R$, together with the color of the variation, $R - I$ ($\Delta R$ is proportional to the source flux, $\phi^*$, multiplied by a function of the impact parameter); and the reduced $\chi^2$ of the fit. We make use of the full parametrization of the Paczyński fit, looking for the Einstein time, the magnification and the unlensed source flux values, even if the intrinsic parameter degeneracy (linked to the fact that the source is not resolved), in most cases, does not allow

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$^9$ We do not have exactly the same number of data points per night per filter for the two fields, so that the indicated value is actually an upper limit.

Furthermore, within the analysis, we exclude a small fraction of data points that show anomalously large relative error values, usually associated with poor seeing conditions or, more generally, poor image quality.

$^{10}$ http://iraf.noao.edu/

$^{11}$ It results $L > 0$ whenever there are at least three consecutive points at least $3\sigma$ above the background. The value of $Q$ is given by the ratio of the $\chi^2$ of a flat baseline fit over that of a Paczynski fit (Calchi Novati et al. 2003).

$^{12}$ We use the CERNLIB-MINUIT libraries, [link](http://cernlib.web.cern.ch/cernlib/).
one to accurately estimate the single parameters. As a selection
 criterion, we ask $\chi^2$/dof < 10. This rather high threshold is
 motivated by the necessity to handle light curves contaminated
 by low-level noise of non-Gaussian nature that can be attributed
 in particular to nearby blended intrinsic variables.

As a second test on the shape, we ask for the bump to be
suitably sampled by the observed data points. We split our
analysis on the basis of a more or a less demanding requirement,
so that we are going to refer to set “A” and set “B” of candidates,
respectively. The details are given in Appendix A.

As a final test on the shape, we look at the characteristics of
the detected flux variations. The two relevant parameters are the
event duration, $t_{1/2}$, and the flux deviation at maximum, $\Delta R$. In
order to appropriately delimit these parameter spaces, we have
to balance for the efficiency, the expected event characteristics
and the risk of contamination of the background of variable
stars. We introduce a cut to exclude too faint variations, too
noisy, and therefore difficult to distinguish against the variable
contamination. As a selection criterion, we ask for $\Delta R < 21.5$.
As for the duration, we do not expect microlensing events to
last more than 10–20 days (Section 4.1). Besides, we expect
long-duration variations to be heavily contaminated by intrinsic
variable signals. However, we prefer not to introduce any cut
for this parameter allowing for long-duration candidates. As
detailed below, all of these are rejected in the following steps of
the analysis anyway.

3.3. Point-Spread Function (PSF) Shape: Spurious Detection

Up to now the analysis is based on the light curve pixel-
photometry only (besides the initial “cluster” analysis), in
particular we do not make use of the PSF of the flux variations
we are looking for. In this respect, our approach is completely
different from that based on the difference image analysis.
As it is, however, this approach suffers from a high risk of
contamination by spurious variations. To reject them in an
automated way, as a third step we perform an extremely rough
difference image analysis. The underlying rationale is that,
whenever we detect a variation on a light curve, in order to retain
it we want to “see” a corresponding well-shaped PSF when we
look at the image difference of the maximum magnification
minus the baseline. Further details are given in Appendix B.

3.4. Variable Signals

As a fourth and final step, we probe the surviving variations
against the background of variable contamination. Our limited
baseline, 50 days, does not allow us by itself to carry out this
programme. For this reason, we make use of the three years
baseline, 50 days, does not allow us by itself to carry out this
against the background of variable contamination. Our limited

As has already been remarked (Ansari et al. 1997), it turns out
that only luminous sources (about $M_I < 2$) are expected to give
rise to detectable events. In the most crowded region, this may
sum up to hundreds of available source stars per pixel (this can
be considered as a completely blended situation with respect to,
for instance, studies toward the LMC). As for the luminosity
function that we use to characterize the sources, it is worth
mentioning that we are mostly interested in its bright end (even if we
need the information over the complete magnitude range for the
normalization), whereas, for the mass function that we need for
the luminous lenses, we are rather interested into the opposite
tail.

We have made use of the IAC-star software (Aparicio &
Gallart 2004) to build a synthetic luminosity function for the M31 bulge, following the procedure outlined in Bozza
et al. (2008), in particular as for the metallicity distribution
(Sarajedini & Jablonka 2005), with the difference that we have
now used, as a mass function, a power law $\xi(m) \propto m^{-\alpha}$
with index $\alpha = 1.33$ up to $1 M_\odot$ and $\alpha = 2$ above. For bulge lenses
we have for consistency used the same mass function with upper
bound fixed at one solar mass. For the disk luminosity function,
as in Calchi Novati et al. (2005), we make use of the local
neighborhood data obtained by Hipparcos corrected at the bright

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13 Data collected at the 2.5 m INT telescope during 1999–2001 (Aurière et al.
2001; Paulin-Henriksson et al. 2005).

14 The accuracy of the astrometric transformation is below 1 pixel, but we
must accept the limit given by the larger size of the OAB pixels, 0′′58, with
respect to the POINT-AGAPE ones, 0′′33.
end (Perryman et al. 1997; Jahreiß & Wielen 1997). For the disk lens mass function, we follow as well the local determination (Kroupa 2007) with upper bound fixed at 10 $M_\odot$. For MACHO masses, we try a set of single values ranging from $10^{-3}$ to 1 $M_\odot$.

We fix the total mass of the bulge to $4 \times 10^{10} M_\odot$ (Kent 1989; this can be considered a "safe" value for microlensing analyses, for the purpose of evaluating the expected self-lensing signal, as it is likely to be an upper limit, Riffeser et al. 2006, for this quantity), and that of the disk to $3 \times 10^{10} M_\odot$ (Kerins et al. 2001; Riffeser et al. 2006). Looking for microlensing effects, the value we are actually interested in is the stellar mass, and indeed our overall value for this quantity agrees well with the analysis of Tamm et al. (2007). We consider a uniform extinction across the field, both foreground, $E(B-V)=0.062$ (Schlegel et al. 1998), and intrinsic (for this second term, this hypothesis should of course be taken only as a first-order approximation), $\text{ext}_R=0.19$ for the bulge (Han 1996; Riffeser et al. 2006), and $E(B-V)=0.22$ for the disk (Stephens et al. 2003; Riffeser et al. 2006).

Together with the M31 color (not corrected for extinction) $B-r=1.3$ (Kent 1989), $B-V=1.0$, and $V-R=0.8$ (Walterbos & Kennicutt 1987), this translates into the values (corrected for extinction) $M/L_R=3.1$ and 1.1 for the bulge and disk, respectively.

The bulge velocity distribution is dominated by its dispersive component, with line-of-sight velocity dispersion of $\sigma=120\text{ km s}^{-1}$. For the disk, we take into account both the dispersive motion, $\sigma=60\text{ km s}^{-1}$ (a value that can be taken as an upper limit), and a circular bulk motion, with disk circular velocity $v=250\text{ km s}^{-1}$ (Carignan et al. 2006). M31 proper motion is set according to van der Marel & Guhathakurta (2008).

Given the values of the circular velocity, 220 km s$^{-1}$ and 250 km s$^{-1}$ for the Milky Way and M31 respectively, we fix accordingly the central densities and therefore the overall masses of the halos and the values of the one-dimensional velocity dispersions. As for the total dark matter halo mass value, within a truncation radius of 100 kpc and 130 kpc for the Milky Way and M31 (we estimate the ratio of these values from those of the circular velocities), we have, respectively, 1.0 $\times$ 10$^{12}$ $M_\odot$ (in good agreement with previous determination, e.g., Vallenari et al. 2006, but somewhat in excess with respect to the recent determination by Xue et al. 2008) and 1.8 $\times$ 10$^{12}$ $M_\odot$.

4.2. The Simulation

Within the Monte Carlo simulation, given the astrophysical model, we generate microlensing signals with Paczyński magnification corrected for finite size effects of the sources, build the corresponding light curves and carry out a first rough selection, paying attention not to reject any light curve that could be detected through our pipeline. In particular, for a variation to be selected, as a unique criterion we ask for at least three consecutive points (with one point per night and reproducing the observed sampling) 3$\sigma$ above the background level ($L>0$ according to the estimator introduced in Section 3). On the other hand, we are aware that we cannot reproduce within the Monte Carlo, where we only deal with light curves, all of the actual conditions of the pipeline we carry out in the real data set (where the analysis starts from the images). Amongst other effects, we most prominently cannot reproduce crowding effects, the underlying variable signals and the sources of non-Gaussian noise. Furthermore, we cannot run the first essential step of bump “cluster” detection. To account for these effects, we simulate those light curves that are selected within the Monte Carlo on the images (before the geometrical and all photometric corrections, namely, on the astronomical images just after the basic bias-flat fielding reductions) and then we run from scratch our pipeline. Conceptually, this is just a last step in the Monte Carlo that allows us to accurately evaluate the efficiency of our pipeline. The "efficiency," hereafter, should therefore be intended as that relative to the light curves selected within the Monte Carlo.

Within the Monte Carlo, each simulated event carries a (different) “weight,” $w_i$ (where $i$ is the index of the simulated events) that is linked in part to the drawing process and in part to the quantity we are evaluating (the microlensing rate), and is completely independent of the selection process. The expected number of events is therefore the sum of the weights, $n_{\text{exp}}=\sum_i w_i$, where the sum runs over the events selected within the Monte Carlo (correspondingly we can estimate the associated statistical error based on Poisson statistics). Accordingly, by “efficiency,” $\epsilon_{\text{eff}}$, we mean the ratio of selected over simulated events, where the number we refer to is always given by the sum of the weights. This is usually different (both numerically and from a logical point of view) from the actual ratio of selected over simulated events, a quantity that is not used even if in some cases it may be useful to be looked at. In particular, we do not expect, and in fact we do not find, these two values to be too different. Indeed, such a result should be taken as a hint of the presence of some bias in the way the event weights are distributed with respect to the selection process within the simulation.

For each lens population, we simulate up to a few thousands events per field, with 500 events per field per simulation in order to avoid overlap problems. Indeed, in particular in the inner M31 region, where we expect most of the events, simulated events may overlap (we draw at random from the Monte Carlo the events we simulate, with all their characteristics, including the line of sight) and thus lead us to bias the estimate of the efficiency of our pipeline. To test for this effect, for a fixed set of 500 events per field for which we had already evaluated the efficiency, we have carried out as many different simulations as needed, taking care to leave a minimum distance of at least 20 pixels among any couple of generated events, so to exclude overlap problems. As a result, we have found no significant differences in the two analyses. Overall, we have simulated 12,000 light curves to evaluate self-lensing efficiency, and 8000 for each value of the mass for MACHO lensing.

According to the selection pipeline, in which we require for the flux variations to be large enough, $\Delta R<21.5$, out of the Monte Carlo we extract, and then simulate on the images, selected events with flux deviation at maximum down to $\Delta R=21.8$. This limit is used accordingly when we evaluate the number of expected events. This way we allow for the observed

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15 For bulge sources we use the radius values from the IAC database, for disk sources we use a color temperature relation evaluated from the model of Robin et al. (2003), and we evaluate the radii from Stefan’s law using a table of bolometric corrections from Murdin (2001). For the microlensing amplification, we use the analytical expression derived in Witt & Mao (1994).

16 As for this technical aspect, our analysis therefore differs, for instance, from that discussed in Kerins et al. (2001), as we draw all the values of the random variable according to their actual distributions rather than according to the microlensing rate (further details are given in Appendix C). In addition, Kerins et al. (2001) propose to perform the Monte Carlo simulation only to evaluate the pipeline efficiency whereas we make use of this tool also to evaluate the number of expected events.

17 As a matter of fact, within the Monte Carlo, where we have only a statistical error, we find a much fainter “theoretical” lower bound for the flux deviation at maximum (Figure 1). The efficiency analysis, on the other hand, showed us that the chosen threshold value for $\Delta R$ is appropriate, because the efficiency dramatically decreases when we consider too faint flux variations.
rms of the evaluated flux deviations versus the input values. The exact value of this threshold is not, however, essential, as long as we keep the selection criterion on the flux deviation fixed at \( \Delta R < 21.5 \) coherently with the selection pipeline. A brighter threshold would translate into a larger value for the efficiency and, at the same time, a smaller number of expected events (not corrected for the efficiency), and vice versa. These two effects balance when we evaluate the number of expected events corrected for the efficiency.

As for the expected characteristics of the observed events, in Figure 1 we show the resulting distributions for the distance from the M31 center (both self-lensing and MACHO lensing), and, for self-lensing, the distribution for the durations (the full width at half-maximum, \( t_{1/2} \)) and the flux deviations at maximum (\( \Delta R \)).

Finally, it is worth stressing that we simulate microlensing events only. Therefore, the simulation is restricted to saying whether and how our pipeline is going to select microlensing signals but it can say nothing about whether it might select as a microlensing a variable signal of different origin.

5. RESULTS

In this section, we present and discuss the results of our analyses: the selection pipeline for microlensing flux variations and the evaluation of the expected microlensing signal.

5.1. The Selection Pipeline

In Table 1, we report the results of the selection pipeline analysis together with the results for the efficiency of the corresponding analysis carried out on self-lensing simulated events.

We start the analysis working over the complete set of pixels, namely \( 2 \times (1340 \times 1300) \) light curves. The initial sample of selected flux variations consists of \( \sim 4000 \) light curves. Within the shape analysis, the sampling cut severely reduces this initial set, and then the flux deviation cut leaves us with \( \sim 200 \) light curves, most of which, according to the PSF analysis, are to be attributed to spurious variations. Finally, we are left with

| Criterion          | Selection No. of Events | Simulation Efficiency \( \epsilon_w \) (%) |
|--------------------|-------------------------|------------------------------------------|
|                    | Set A | Set B | Set A | Set B |
| Bump detection     | 4200  |       | 41.2 ± 3.5 |       |
| \( L_1 > 50 \)     | 3033  |       | 35.5 ± 3.2 |       |
| Shape analysis     | 2901  |       | 32.7 ± 3.0 |       |
| \( \chi^2/dof < 10 \) | 174   | 241   | 18.3 ± 2.0  | 21.9 ± 2.4 |
| \( \Delta R < 21.5 \) | 75    | 108   | 13.0 ± 1.5  | 20.4 ± 2.3 |
| PSF                | 14    | 23    | 13.0 ± 1.5  | 15.7 ± 1.9 |
| Variable           | 1     | 2     | 11.9 ± 1.4  | 14.6 ± 1.8 |

Notes. The results of the selection pipeline for microlensing light curves: analysis and simulation. For each step we report the number of selected light curves and the efficiency of the pipeline (%) for the expected self-lensing signal. According to the choice of the sampling criterion, we have split our selection results in set A and set B (left and right columns, respectively).
do not show a few rejected events with solid lines delimit the excluded region (bottom panel, upper-left corner) in the flux difference δ. The squares indicate the two candidate microlensing events of our selection (according to the terminology introduced in Section 5.2). The solid lines delimit the excluded region (bottom panel, upper-left corner) in the last step of the analysis. The star symbol indicates the second event, beside N1, belonging to both set A and set B. Bottom panel: for visualization purposes we do not show a few rejected events with δ(Δf) < 0 and PR > 20.

(A color version of this figure is available in the online journal.)

Figure 2. Selection pipeline results: the sample shown here consists of the light curves selected after the PSF analysis. Scatter plot of the flux deviations vs. the event duration (top panel); scatter plot of the Lomb “power” PR vs. the relative flux difference δ(Δf) (filled and empty symbols for set A and B variations, respectively). The squares indicate the two candidate microlensing events of our selection (according to the terminology introduced in Section 5.2). The solid lines delimit the excluded region (bottom panel, upper-left corner) in the last step of the analysis. The star symbol indicates the second event, beside N1, belonging to both set A and set B. Bottom panel: for visualization purposes we do not show a few rejected events with δ(Δf) < 0 and PR > 20.

(A color version of this figure is available in the online journal.)

∼40 flux variations, divided into sets A and B (according to the sampling criterion), most of which we expect to be intrinsic variables whose single-bump appearance is to be attributed to our short (50 days) baseline. (As outlined in Appendix A, set A flux variations are not a subsample of set B: among those surviving the PSF cut, 14 and 23 respectively, only two flux variations are in common between the two data sets, out of which one also survives the last cut.) The results of the last cut analysis are shown in the bottom panel of Figure 2 in the parameter space PR = δ(Δf). We find, as expected, the flux deviation of most OAB variations to be compatible with the corresponding INT variations (small values of δ(Δf)), for which, at the same time, we find a clear sign of variability (large value of PR). As an example, in Figure 3, we show the INT extension of four OAB-selected light curves. Only for two selected OAB flux variations, instead, we find the corresponding INT extension to be flat. Therefore, the selection pipeline finally leaves us with two microlensing candidates (one belonging to set B only). The same sample of light curves is represented in the ΔRmax−t1/2 parameter space (top panel of Figure 2). We find most of the variations located in the upper part (corresponding to small flux deviations), with set B variations (empty symbols) biased toward short durations. In particular, we find the set A microlensing candidate (filled square symbol) located in a parameter space region where the contamination by the intrinsic variable signals is large. The only clear outlier is the bright and short set B microlensing candidate. We discuss the selected candidates in detail in Section 5.2.

Comparing with the efficiency simulation analysis, a few points are worth being mentioned. First, it may look as if the “bump detection” step alone severely reduces the overall efficiency. However, in fact, only a very small fraction of light curves that are not selected at this point would pass all the other criteria. According to the same principle, the single cut that excludes most of the simulated light curves is the sampling criterion. This is also the reason why we have split our selection pipeline at this level. As for the simulation, we stress that this simply reflects the choice we have made in the Monte Carlo to select light curves on the basis of the L > 0 criterion only. Next, the PSF analysis proves to be a rather efficient criterion. Indeed it results that almost 50% of the simulated light curves fulfill this criterion and that this fraction rises to about 80% if we consider the subset of light curves that have already passed the bump detection and the shape analysis cuts. A usual reason that may cause the PSF Gaussian fit to fail is the presence, near the simulated event, of some other resolved object. Often enough, however, in these cases also the pixel photometry we use may have problems. (For both of these related aspects, a proper difference image analysis approach would be of course expected to give better results.) Poorly sampled light curves, on the other hand, simply do not have enough points near maximum magnification, so that it turns out to be usually not possible to carry out a good enough PSF fit. Finally, as for the analysis on the POINT-AGAPE extension to check for variable signals, we have seen this cut to be essential to get rid of otherwise dangerous contaminating flux variations. At the same time, this shows to be an extremely efficient criterion. Out of the complete set of simulated light curves, only about 13% of the INT light curves are clearly variable (PR > 20) and this fraction falls to 7% when we add the demand for the INT flux deviation to be compatible with the OAB simulated one.

In Table 2, we report the results for the efficiency of the simulations for MACHO lenses. With respect to self-lensing events, there is a (rather small) effect linked to the different spatial distribution. The main effect is, however, due to the value of the mass, which is linked to the event duration, with smaller values of the efficiency corresponding to decreasing values of the MACHO lens mass.

In Tables 1 and 2, we have given the results for the efficiency as a single value for the overall set of simulated events. On the other hand, the efficiency does vary quite significantly for data binned, for instance, in the distance from the M31 center and/or in the flux deviation at maximum. We find the larger values for the efficiency, up to 30% or more, for bright events in the outer regions of M31. On the other hand, the expected number of events, not corrected for the efficiency, is larger near the M31 center for faint events (Figure 1), namely, right where the efficiency is smaller (down to below 5%, depending on the choice of the binning). Overall, however, we find the expected number of events corrected for the efficiency to be rather insensitive, within the statistical error of the simulation, to any binning scheme, and this motivates our choice for the way to present our results.

5.2. The Microlensing Candidate Events

The selection pipeline described in the previous section leaves us with two candidate microlensing events, which we name OAB-N1 and OAB-N2 (“N” indicates that they are both located in our “North” field). Their characteristics are summarized in Table 3, and their position within our field of view is shown in

18 The overall efficiency would jump to ∼20% taking into account all the criteria except the sampling criterion.
Figure 4. As for the sampling criterion, OAB-N1 fulfills both sets A and B demands, while OAB-N2 only the set B one.

OAB-N1. This is a relatively large flux variation, with significance bump estimators equal to $L = 183$ and $Q = 108$; quite short, $t_{1/2} = 7.1$ days, and not too bright, $\Delta R = 21.1$. The OAB-N1 light curve is shown in Figure 5, together with its INT extension and the image difference around the candidate position upon which is based our PSF analysis. The INT data extension of the OAB-N1 light curve appears to be flat (small Lomb periodogram power, $P_R = 6.3$, and significantly large value for the difference of flux deviation, $\delta(\Delta f) = 10.0$). However, the quality of the Paczyński fit is not good. A few points before the bump deviate significantly from the expected shape, and this is reflected in the rather poor value of $\chi^2$. This might be attributed to underlying nearby variables, but we cannot exclude it to be a sign of an intrinsic nonmicrolensing nature. Indeed, we have shown that OAB-N1 is located in a part of the $t_{1/2}-\Delta R$ parameter space where the background of variable stars is large (top panel, Figure 2). A possible contamination,

Table 2

| Mass ($M_\odot$) | Efficiency $\epsilon_w$ (%) |
|-----------------|-----------------------------|
| Set A           | Set B                        |
| 1               | 16.5 ± 1.2                  | 18.7 ± 0.9                  |
| 0.5             | 18.5 ± 1.1                  | 21.3 ± 1.2                  |
| 0.1             | 16.5 ± 1.2                  | 19.9 ± 1.4                  |
| $10^{-2}$       | 13.8 ± 1.2                  | 16.5 ± 1.3                  |
| $10^{-3}$       | 11.1 ± 1.3                  | 13.2 ± 1.4                  |

Table 3

| Characteristics of the Microlensing Candidates OAB-N1 and OAB-N2 |
|------------------------------------------------------------------|
| OAB Data | Source Flux Fixed |
|----------|-------------------|
| OAB-N1   | OAB-N2            |
| $\alpha$ (J2000) | $0^\circ42^\prime57^\prime$ | $0^\circ42^\prime50^\prime$ |
| $\delta$ (J2000) | $41^\circ22^\prime50^\prime$ | $41^\circ18^\prime40^\prime$ |
| $\sigma_{\phi_{mot}}$ (arcmin) | 7.1 | 2.8 |
| $t_0$ (JD-2450000.0) | 4433.3 ± 0.5 | 4467.3 ± 0.3 |
| $t_{1/2}$ (days) | 7.1 ±0.1 | 2.6 ±0.3 |
| $\Delta R$ | 21.1 ± 0.1 | 19.1 ± 2 |
| $R-I$ | 1.0 ± 0.1 | 1.1 ± 0.1 |
| $\chi^2$/dof | 3.9 | 1.4 |
| $f_0$ (days) | 3.9 ±2.7 | 4.18 ±0.5 |
| $u_0$ | 0.23 ±0.12 | 0.224 ±0.008 |
| $\phi^0_2$ (ADU s$^{-1}$) | 15 ±12 | 7.6 |
| $\phi^0_3$ (ADU s$^{-1}$) | 28 ±22 | 15.1 |
| $R^\ast$ | 20.2 ±14 | 20.9 |
| $I^\ast$ | 19.1 ±17 | 19.7 |

Notes. For OAB-N2, we show the results for the fit performed both with our data set alone (left column) and fixing the source flux from a possible identification with a source in the Massey et al. (2006) catalog. The error on the standard magnitude values and colors includes an extra ±0.1 mag term from the calibration equation.

19 The original M31 image has been taken from the CDS database, http://cdsweb.u-strasbg.fr/.
Figure 4. Projected on M31, we display the boundaries of the two $13' \times 12'.6$ monitored fields. The filled circle mark the position of the selected microlensing candidate events.

compatible with its “one bump” nature, besides a possible very long period variable, might come from some kind of eruptive variable (even if Novaecan be excluded because the flux variation is far too small). On the other hand, the descent is fairly well sampled and matches nicely enough the fitted Paczyński shape. In the top-right part of Figure 5, we show the “color” light curve, namely the ratio $R/I$ band of the difference of the light curve flux, along the bump, and the background level, that we expect to be constant for microlensing.

Through the pipeline, and in particular for OAB-N1, as an initial condition for the time of maximum magnification in the Paczyński fit we choose the value of the time corresponding to the data point with the maximum flux value, in this case $t = 4435.4$ (JD−2450000.0). During the fit procedure, it is difficult for this parameter to exit from the $\chi^2$ minimum well around this value (whose bounds are usually set by the sampling) and indeed as a result we find $t_0 = 4433.8 \pm 0.2$ (JD−2450000.0). Motivated by the OAB-N1 light curve appearance, irregular sampling, and noisy aspect, we have therefore carried out a search for other $\chi^2$ minima in different regions of the $t_0$ space. As a result, we have found a new, well isolated, minimum with a lower value of the reduced $\chi^2$ ($\chi^2$/dof = 3.5 to be compared with $\chi^2$/dof = 3.9 found in the previous case) for $t_0 = 4430.6 \pm 0.4$ (JD−2450000.0). Correspondingly, we find new values for the duration and the flux deviation at maximum, $t_{1/2} = 18$ days and $\Delta R = 21.5$ (this last value being at the limit of our threshold cut), namely, a rather different result from the previous one. Such a light curve would have still been selected as a microlensing candidate within our pipeline. However, the longer duration would have further weakened its microlensing interpretation (Section 5.4). The coexistence of these two minima might be suggestive, accepting the microlensing hypothesis, of a binary lens or binary source solution. The available data, however, do not allow us to robustly test this hypothesis.

OAB-N2. This looks (Figure 6) like an extremely bright and short flux variation ($t_{1/2} = 2.6$ days, $\Delta R = 19.1$), located near the M31 center (at a distance $d = 2.8'$), with a completely flat INT extension ($P_R = 8$, $\delta(\Delta f) = 25$). The sampling along the bump is, however, extremely poor (indeed, both the time of maximum amplification and the flux deviation at maximum are not strongly constrained; Table 3). In particular, the lack of data points in the descent prevents us from probing the expected microlensing symmetric shape, so that it is difficult to draw definitive conclusions about its nature. On the other hand, the rising part of OAB-N2 looks achromatic, and is rather well constrained, and this strengthens the microlensing hypothesis. Indeed, both the shape and the achromaticity are hardly compatible with the only possible kind of contamination for such a kind of flux variation, if not microlensing, namely some sort of contamination.

20 Through the selection pipeline we have only considered (single bump) Paczyński-like microlensing variations. The analysis of the possible binary lens solutions for OAB-N1, together with a systematic search for binarylike flux variations, will be presented in V. Bozza et al. (2009, in preparation).
eruptive-like object. Furthermore, though few, the points along the bump allow us to get to a reasonable fit for all the parameters of the microlensing event. At the 1σ level, the χ² analysis gives us best values and lower bounds for the impact parameter and the source flux and best value and upper bound for the Einstein time (with, however, a rather large relative 1σ error, even exceeding 50%; Table 3). Finally, the guess for the flux source value allows us to carry out a more constrained color analysis (as for OAB-N1, but subtracting the source flux from the baseline, bottom-left panel of Figure 6). As for the value of the source flux, the results of the Paczyński fit have been confirmed by the cross-identification of the possible source star in the catalog of Massey et al. (2006). Indeed, within 1 pixel of our evaluated position, we find a typical red giant with RC = 20.9 and R−I = 1.2 (values fully compatible with those evaluated from our data set alone). Knowledge of the source flux allows us to better constrain the fit parameters; in particular, the time of maximum amplification and the flux deviation at maximum (in fact t₀ shifts back to the position of the last observed data point so that, accordingly, ΔR gets fainter). Furthermore, we may now completely break the degeneracy among the amplification parameters. Indeed, we estimate t_E = 4.2^{+0.6}_{−0.4} days and μ₀ = 0.22^{+0.01}_{−0.03} (A_max = 4.5).

We have also searched for X-ray counterparts in the XMM-Newton archive \(^{21}\) and verified that neither of the microlensing candidates’ coordinates correspond to any of the identified sources in the EPIC images (Strüder et al. 2001; Turner et al. 2001; Shirey et al. 2001). In the case of OAB-N2 there is an X-ray counterpart, but only within ∼30′, so that we can safely rule out the identification.

5.3. The Expected Number of Events

The Monte Carlo simulation, completed by the efficiency analysis, allows us to estimate the expected number of microlensing events for our experimental setup. In Table 4, we report the resulting values, already corrected for the efficiency. The results we obtain using the set B criteria are larger by up to about 30% with respect to set A. This is a combined effect of the larger value of the efficiency and of the effective baseline length increase.

As for self-lensing events, it turns out that most of them, ∼50%, are due to bulge–bulge events (lens–source, respectively), with the remaining distributed almost equally between disk–bulge and bulge–disk events. The second configuration is enhanced in the South field because in this case we see the bulge in front of the disk. It is also worth noting that, according to our model, almost half of the overall bulge mass is located within our cone of view, but only about 1/7 of that of the M31 disk.

As for MACHO lensing, about 2/3 of the events are expected to belong to the M31 halo. Actually, the overall mass within our cone of view of the M31 halo is larger than the Galactic one by a factor of a few thousands, but Milky Way halo lensing is strongly enhanced by the much larger size of the Einstein radius.

\(^{21}\) http://xmm.esac.esa.int/xsa/

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**Figure 5.** Microlensing candidate event OAB-N1. Top-left panel: R- and I-band light curves (filled and empty symbols, respectively). The R-band data are normalized with respect to I-band data using the color of the flux variation. The solid and the dashed lines are the best-fitting Paczyński curves with t₀ = 4433.8 and t₀ = 4430.6 (JD−2450000.0), respectively (see Section 5.2 for details). Top-right panel: color light curve. Bottom panel (left): the extension along the INT data (the solid and dotted lines are as in Figure 3). The units on the x-axes are time in days (JD−2450000.0). The ordinate axes units are flux in ADU s⁻¹ per superpixel (left panels) and magnitude (top-right panel). Bottom panel (right): OAB R-band data surface plot image difference between the image at maximum magnification and the baseline level. The units on the space x-y-axes is pixels, the surface plot values are in ADU per pixel. (A color version of this figure is available in the online journal.)
Figure 6. Microlensing candidate event OAB-N2. Top panel: normalized $R$- and $I$-band light curves (filled and empty symbols, respectively). The $R$-band data are normalized with respect to $I$-band data using the color of the flux variation. The solid line is the best-fitting Paczyński curve. In the inset, we show the residual with respect to the Paczyński fit along the bump. Bottom panels (left): color light curve; right: extension along the INT data (the solid and dotted lines are as in Figure 3). The units on the x-axes are time in days (JD$-2450000.0$). The ordinate axes units are magnitude for the bottom-left panel, and flux in ADU s$^{-1}$ per superpixel for the remaining panels.

Table 4

The Expected Number of Microlensing Events

|                | Set A     | Set B     |
|----------------|-----------|-----------|
| Bulge–bulge    | 0.35 ± 0.07 | 0.44 ± 0.08 |
| Bulge–disk     | 0.18 ± 0.02 | 0.23 ± 0.03 |
| Disk–bulge     | 0.06 ± 0.01 | 0.07 ± 0.01 |
| Disk–disk      | 0.015 ± 0.002 | 0.019 ± 0.002 |
| SL             | 0.6 ± 0.1   | 0.8 ± 0.1   |
| Mass ($M_\odot$) |           |           |
| 1              | 0.7 ± 0.1   | 0.9 ± 0.2   |
| 0.5            | 1.1 ± 0.2   | 1.3 ± 0.2   |
| 0.1            | 1.6 ± 0.1   | 1.9 ± 0.1   |
| 10$^{-2}$      | 2.0 ± 0.2   | 2.3 ± 0.2   |
| 10$^{-3}$      | 1.3 ± 0.2   | 1.5 ± 0.2   |

Notes. The expected number of microlensing events, for M31 self-lensing (lenses belonging to either the M31 bulge or disk) and MACHO lensing (lenses belonging to either the M31 or the Milky Way halo), for a full halo with different values of the MACHO mass. For self-lensing events, we report also the number for each lens–source population we consider. We report the results of the Monte Carlo simulation corrected for the efficiency evaluated according to both set A and B criteria.

We expect the largest number of MACHO lensing events from 10$^{-1}$ to 10$^{-2}$ $M_\odot$ objects, as our efficiency dramatically drops for smaller MACHO masses.

Together with the expected event number we report the statistical error associated with the simulation on the basis of Poisson statistics. The uncertainties intrinsic in the model (whose detailed discussion is beyond the scope of the present paper) make, however, the corresponding systematic error in principle even larger.

5.4. Discussion

We have designed our (fully automated) pipeline so as to get rid of most forms of stellar variability, while preserving genuine microlensing. As a result, therefore, all survivors could in principle be variables but with varying (hopefully large) degrees of confidence that they are not. Coming to the present data set, we have selected two flux variations compatible with a microlensing signal. While discussing the possible physical meaning of this result, however, we have to keep in mind that, although with different degrees of confidence, we have no strong evidence in favor of the microlensing hypothesis for either candidate: OAB-N1 because of both the light curve appearance (reflected in the $\chi^2$ value) and its position in the duration/flux-deviation parameter space, and OAB-N2 because of its extremely poor sampling (that has not prevented us, however, from finding a convincing microlensing Paczyński fit further confirmed by the possible identification of the source). In conclusion, looking at the candidate light curves, we might be tempted to classify OAB-N1 as a very “poor” candidate, and OAB-N2 as a “good” one, keeping in mind, however, that this might simply reflect the bias induced by the observational sampling.

With the care suggested by the above discussion, we come now to the comparison of the observed events with the expected signal. As for the event characteristics, we may take as a
reference the distributions shown in Figure 1. Given the caveat that these distributions cannot be compared directly with the results of the analysis because of the correlation of the pipeline efficiency with the event characteristics, both candidates appear compatible with the expected signal with respect to the duration and the distance from the M31 center. The case for the present selection might allow a sufficient characterization of the light curves.

On the other hand, the expected number of MACHO lensing events is not large if compared to that of self-lensing. Even for a full MACHO halo we would expect about as many self-lensing events as MACHO lensing. It is clear, therefore, that on the basis of the number of events alone our statistics are still too small to draw conclusions on this contribution.

It may be asked, then, how we might disentangle the two signals: self-lensing from MACHO lensing. First, an improvement in the event statistics might help us to further exploit the expected differences in the spatial distributions (top panels, Figure 1). Second, a good enough sampling (such as was not the case for the present selection) might allow a sufficient characterization of the selected flux variations. In turn, this could give possible hints on the nature of the lens, as was the case for the detailed analysis linked to the finite source size effect for the PA-S3 event carried out by Riffeser et al. (2008). Both these reasons motivate the need for further observations.

In this perspective our campaign, as well as that carried out by the ANGSTROM Collaboration right toward the M31 center (Kerins et al. 2006), may help in shedding more light onto this important issue.

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APPENDIX A

THE MICROLENSING PIPELINE: THE SAMPLING CRITERION

The rationale of the present cut is to test whether the detected flux variation is sufficiently sampled. As a starting point we use the results of the Paczyński fit, and in particular the values of the time at maximum magnification, $t_0$, and of the bump duration, the full width at half-maximum $t_{1/2}$. Given these values we identify six intervals along the light curve, symmetric around $t_0$, namely, $[t < t_0 - 3t_{1/2}]$, $[t_0 - 3t_{1/2} < t < t_0 - t_{1/2}/2]$,

$$[t_{1/2}/2 < t < t_0], \ [t_0 < t < t_0 + t_{1/2}/2], \ [t_0 + t_{1/2}/2 < t < t_0 + 3t_{1/2}], \ [t > t_0 + 3t_{1/2}]$$

As a first set of criteria we ask for at least $n_{\text{min}}$ data points in at least three out of the four inner intervals, within $t_0 \pm 3t_{1/2}$,
and at least one data point in both the joined outer intervals \( t < t_0 - t_{1/2}/2 \) and \( t > t_0 + t_{1/2}/2 \), namely, we allow the same data point to be counted twice. The value of \( n_{\text{min}} \) is fixed according to the duration, with \( n_{\text{min}} = 1, 2, 3 \) for \( t_{1/2} < 5, <15, \) and \( >15 \) days, respectively.

As a second set of criteria we ask for at least one data point in at least two out of the four inner intervals and at least one data point in at least one of the two tail intervals \( (t < t_0 - 3t_{1/2} \) and \( t > t_0 + 3t_{1/2}/2) \).

We refer to the two set of criteria, and to the corresponding selected flux variations, as set "A" and set "B," respectively.

The set A criterion is more demanding as for the sampling along the inner part of the flux variation, whereas set B makes, in a way, a stronger demand on the coverage of the far tails, so that set A selected events are not a simple subsample of set B events. Furthermore, it results that the time of maximum magnification for set A events is constrained within the limits of the observational run whereas for set B it can also fall (slightly) outside. Set B flux variations therefore enjoy an effective longer baseline.

The sampling analysis is carried out along R-band data only.

APPENDIX B

THE MICROLENSING PIPELINE: THE PSF CRITERION

As outlined in Section 3, through this criterion we want to check whether the detected variation along the light curve can be attributed to a physically meaningful flux variation (a variable star or microlensing) or to some kind of spurious signal (cosmic rays, bad pixel, seeing effects, and so on). To this purpose, we have to turn to an analysis carried out on the images. As a criterion we test whether the spatial form of the detected bump has a well-enough-shaped PSF. As we are not carrying out difference image photometry, we can safely stop at the first-order approximation of a two-dimensional Gaussian, namely

\[
P(x, y) = \exp \left\{ -\frac{1}{2(1-\rho^2)} \left[ \frac{x-\mu_x}{\sigma_x} \right]^2 + \left[ \frac{y-\mu_y}{\sigma_y} \right]^2 - 2\rho \frac{x-\mu_x}{\sigma_x} \frac{y-\mu_y}{\sigma_y} \right\},
\]

(B1)

Equation (B1) is sometimes used, namely

\[
P_t(x, y) = \exp \left\{ \frac{(x \cos \phi + y \sin \phi)^2}{2\sigma_a^2} - \frac{(-x \sin \phi + y \cos \phi)^2}{2\sigma_b^2} \right\}.
\]

(B2)

In fact the two formulations are equivalent, one can easily evaluate the parameters \( \sigma_a, \sigma_b, \) and \( \phi \) as a function of \( \sigma_x, \sigma_y, \) and \( \rho, \) and vice versa (it must be noted, however, that the parameter \( \rho \) plays a double role, giving both an inclination and a distortion).

Within the parametrization of Equation (B2), we find our cuts to roughly correspond to \( 1 < \sigma_a < 3, 1 < \sigma_b < 3, \) and \( \phi \approx \text{arbitrary} \). Still, we prefer Equation (B1) as the fit procedure looks, in this case, more stable.

APPENDIX C

MONTE CARLO SIMULATION: THE DRAWING PROCESS

In this Appendix, we discuss some further details regarding the Monte Carlo simulation described in Section 4.

A microlensing event is fully specified by 10 parameters. The line of sight, specified by two angles, \( \theta, \rho \), out of which we determine the (angular) position within our fields as \( x = \rho \cos(\theta), y = \rho \sin(\theta) \); the lens distance \( D_l \) and mass \( \mu_l \); the source distance \( D_s \) and flux \( \phi_s \); the lens–source relative velocity, specified by a modulus \( v_r \) and a phase \( \psi_v \); finally, the microlensing amplification parameters, the impact parameter \( u_0 \), and the time of maximum amplification \( t_0 \). Each of these parameters has its own physical distribution function from which we draw a value for each event realization. Even if we simulate only \( R \) light curves, the available information within the luminosity functions used allows us to evaluate also the source radius, so to properly take into account the finite size source effect, as for the microlensing amplification.

A key aspect of our Monte Carlo scheme is the "weight," \( w_i \), that we associate with each event. This is linked in part to the drawing process and in part to the physical process we are studying. As for the first part, this follows from the fact that for a given distribution function we have two choices as for the drawing process. Either we may directly draw according to the distribution, and in this case the corresponding weight is \( w_i = 1 \), either we may draw with a uniform distribution and give the event a weight proportional to the distribution function. As for the second part, we take the weight to be proportional to the following:

\[
w_i \propto (2 R_E u_{\text{MAX}} v_r \Delta T_{\text{OBS}}) \times n_s,
\]

(C1)

where \( R_E \) is the Einstein radius, \( u_{\text{MAX}} \) is the maximum value for the impact parameter, \( \Delta T_{\text{OBS}} \) is the duration of the observational campaign, and \( n_s \) is the number surface density of available sources (for a fixed line of sight). In fact, according to our simulation scheme, first we fix the lens line of sight and specify all of the events characteristics. Then, as the purpose of the Monte Carlo is to evaluate the number of expected microlensing events, we have to evaluate how many sources (given the M31 surface brightness and luminosity function) are available within a surface delimited by the event characteristics and the experimental conditions. Indeed, the term \( 2 R_E u_{\text{MAX}} v_r \Delta T_{\text{OBS}} \) in Equation (C1) is the surface area on the lens plane (for a fixed event configuration) where it is possible to find a suitable source.

The last contribution to the weight comes from the need to evaluate the number of available lenses. For each lens
population, this is computed as the ratio of the total mass of the component within the observed field of view divided by the average lens mass. More specifically, the weight linked to the choice of the line of sight is normalized to the total mass.

As for the drawing of the line of sight we have the following: for lenses in the Milky Way halo, we assume the spatial distribution across the observed field of view to be uniform; for lenses in the M31 halo, because of the assumed spherical symmetry, the resulting distribution for the angle $\theta$ is uniform; for bulge and disk lenses, we make use of the Kent (1989) bulge–disk decomposition (whenever using the Kent 1989 profile, we use a uniform distribution and then attribute to the event a “weight” as described above).

Once the event configuration, and its weight, have been specified, we build the corresponding light curve and, given our observational setup, we evaluate whether the event is selected or not. This selection process is completely independent of the event weight. The selected events delimit the overall integration space, so that the expected number of events is given by the sum of the weights of these selected events only. (This same set of events is then taken, with all of their characteristics, as the input set for the simulation on the images described in Section 4.2.)

In Table C we report, for each parameter, the distribution function used and its range of variability.

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