Microlensing towards the Magellanic Clouds and M31: is the quest for MACHOs still open?

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Abstract. Microlensing is the tool of choice for the search and the analysis of compact halo objects (“MACHOs”), a still viable class of dark matter candidates at the galactic scale. Different analyses point towards an agreement in excluding dark matter MACHOs of less than about $10^{-1}$ $M_\odot$; it remains however an ongoing debate for values in the mass range $(0.1 - 1)$ $M_\odot$. The more robust constraints, though not all in agreement, come from the observational campaigns towards the Magellanic Clouds (the LMC and the SMC). The analyses towards the nearby galaxy of M31, in the so called “pixel lensing” regime, have expanded the perspectives in this field of research. In this contribution first we draw a critical view on recent results and then we focus on the pixel lensing analysis towards M31 of the PLAN collaboration.

1. Introduction
The original suggestion of Paczyński (1986) of using microlensing as a tool to probe compact halo objects as a dark matter candidate at the galactic scale has given rise, in the meantime, to a much larger range of applications of microlensing which has become an efficient tool of research for many different relevant astrophysical issues. (The observational driving reason being the relatively large rate of events expected, and by now routinely observed, towards the Galactic bulge.) A partial list includes the study of the inner Galactic structure (Moniez, 2010 for a review), many aspects of stellar astrophysics (Gould, 2001) with in particular analyses on the mass function towards the Bulge (Gould, 2000; Calchi Novati et al, 2008) and the recent exciting result on an unbound or distant planetary mass population (Sumi et al, 2011). Currently, however, the main field of application of microlensing has become the search of exoplanets thanks to its ability to explore different part of the planetary parameter space with respect to other techniques (Gaudi, 2010; Dominik, 2010 for recent reviews). Within this framework first results on the frequency of exoplanets have also been reported (Sumi et al, 2010; Gould et al, 2010). Microlensing is indeed well suited to infer the statistical properties of the underlying exoplanet population, still, an adequate strategy to this purpose must be adopted (Dominik et al, 2010).

The search of MACHOs remains however an active field of research, with observational campaigns being carried out to this purpose both towards the Magellanic Clouds and M31. As more thoroughly discussed in the following sections, the debate is currently centered on an hypothetical MACHO population in the mass range $(0.1 - 1)$ $M_\odot$. This is however the very same range of mass for normal stars acting as lenses (we broadly refer to this case as “self lensing”,...
as opposed to MACHO lensing), the lens mass being the driving physical parameter of the observed characteristics of microlensing light curves. This coincidence may therefore be taken as an hint of some bias in the analyses. If not the case, however, the reported sizeable fraction of MACHOs in this mass range (up to about \( f = 20\% \) in mass of the halo) would represent a real astrophysical challenge certainly worth more detailed analyses.

2. The results towards the Magellanic Clouds

The main results along this line of sight have been reported by the MACHO, the EROS and the OGLE collaborations. We refer to Moniez (2010) for a detailed discussion on the subject and a full list of references. The relevant and definite result of all these observational campaigns is that compact halo object are not a major component of the Galactic halo. However, some disagreement remains to be clarified in some of the considered mass ranges. There is a full consensus to exclude, for a fraction in mass well below 10%, MACHOs as viable dark matter candidates from about \( 10^{-7} \, M_\odot \) up to a mass below about 0.1 \( M_\odot \). This agreement then breaks down in the mass range (0.1 \(-\) 1) \( M_\odot \). For larger values of the MACHO mass the smaller number of expected candidates makes the constraints less tight (although, in a re-analysis of the OGLE-II and OGLE-III data, Calchi Novati and Mancini (2011) obtained the stronger bounds to date by microlensing in this mass range). More in particular, the MACHO collaboration (Alcock et al, 2000a) reported an evidence of a signal, \( f \sim 20\% \) (in the hypothesis of a “standard” pseudo-isothermal spherical density distribution for the halo\(^1\)) for about 0.5 \( M_\odot \) MACHOs out of observations towards the LMC. Two critical aspects of this analysis are worth being recalled: MACHO monitored mainly the central LMC region, where one can expect a larger contamination by the LMC self-lensing signal; MACHO considered as viable sources also rather faint stars and this complicates the analysis of the detection efficiency and therefore the related aspect of the estimate of the expected signal. The results of the MACHO collaboration, substantially confirmed in a more recent analysis by Bennett (2005), have then been challenged by the EROS collaboration (Tisserand et al, 2007) and more recently by the analyses of the OGLE collaboration whose OGLE-II and OGLE-III campaigns towards both the LMC and the SMC have been discussed in a recent series of papers by Wyrzykowski et al (2009, 2010, 2011a,b). Taken at face value, all these last analyses indicate that self lensing alone is able to explain the observed rate of events, clearly at odds with the result of the MACHO collaboration.

The results of the MACHO collaboration have been the object of several investigations trying to explain the observed rate without introducing a dark matter component. Additional (stellar) lens populations contributing to the self-lensing signal (in his more broad exception) may come from local structures along the line of sight (Zaritsky and Lin, 1997; Zhao et al, 2003). Such populations, even if not very massive, may enhance a large enough lensing signal with respect to LMC self lensing because of the larger source-lens distance would imply an increase in the microlensing cross section. For the same reason an enhancement in self lensing would also come from a more complicate LMC density distribution (Zhao and Evans 2000), or from a source population lying behind the LMC (Alcock et al, 2001).

Comparing to the case of M31, to be discussed in the next Section, it is worth recalling a few points specific to the observations towards the Magellanic Clouds (in addition to the different microlensing regime one enters when looking at the more distant sources in M31). First, an intrinsic bias in the results may be introduced by the implicit underlying, though not probed, assumption that the single line of sight probed in this case through the Galactic halo is representative of this full component. This may not be the case for instance because of tidal

\(^1\) As it has been already observed, eg Bennett (2005), the fact that MACHOs, if any, are not the main component of dark matter haloes, also implies that they may not follow its spatial distribution. In turn, this implies that the actual mass fraction related to the observed events, if really to be attributed to MACHO lensing, may in fact be smaller than that evaluated for a standard halo model.
interactions with the Galaxy and/or local halo clumpiness. Second, the expected rate by “self lensing” is small (with a sizeable fraction of lenses to be expected from the Milky Way disc, as recently pointed out by Calchi Novati and Mancini, 2011), both in absolute number, at least for the reported observational campaigns, and in a relative sense with respect to MACHO lensing. In fact, the EROS collaboration discussed the MACHO fraction out of a single candidate event observed towards the SMC and none towards the LMC, and the observed rate of the recent OGLE-II and OGLE-III campaigns is of the order of a few events only. This is in fact a bonus as the small “background” signal of self-lensing events with respect to MACHO lensing facilitates the statistical interpretation of the results. However, the small statistics of events at disposal becomes a problem to the extent that it makes difficult an analysis of the event characteristics which may shed more light on the nature of the events beyond the “simple” statistics based essentially on the number of events alone (as outlined, eg, in the analyses of Mancini et al, 2004 and Calchi Novati et al, 2006 where the event duration and spatial distributions were used to this purpose). A larger self-lensing statistics would therefore definitively help as it would make self-lensing signal a robust test case so to finally better probe MACHO lensing. The relevance of carrying out more detailed analyses on the lens nature is made apparent also by the thorough analysis of OGLE-2005-SMC-001 (Dong et al, 2007), out of which the authors conclude that “halo lenses are strongly favored but SMC lenses are not definitively ruled out”. In fact, Dong et al (2007) conclusions are at odds also with respect to the results of the MACHO collaboration as they favor, to explain the lens, a Milky Way halo \( \sim 10 M_\odot \) black hole solution, namely in a mass range already excluded by Alcock et al (2000a). This composite picture strongly motivates the still ongoing observational effort towards the LMC and the SMC carried out by OGLE-IV (Udalski, 2011) and MOA-II (Sumi, 2011).

3. Pixel Lensing towards M31

Lying at about 770 kpc, the nearby giant spiral galaxy of M31 is more than one order of magnitude more distant than the LMC (with a difference in distance modulus between the LMC and M31 of about 6). This makes the potential sources of microlensing events along this line of sight unresolved for most ground-based telescope. This is the underlying reason for the different regime one enters in that case, the so-called “pixel lensing” (Gould, 1996). The source being unresolved, the source flux is usually more difficult, if not impossible, to be estimated from the light curve data alone. This complicates the analysis as it adds an additional degeneracy in the microlensing parameter space (M31 is however, fortunately, near enough so that light curve data, if sufficiently well sampled, especially along the wings of the microlensing flux variations, may allow one to break this degeneracy). On the other hand, with respect to the LMC, there is a much larger number of potential sources available within a comparatively much smaller cone of view. (In fact, the sensitivity of past and current observational campaigns allowed to detect only microlensing flux variations out of very bright sources lying at the bright end of the luminosity function, roughly stars brighter than \( M_I \sim 2 \). Since this is a magnitude range where the luminosity function is still undergoing an extremely steep rise, an increase in sensitivity may therefore bring to hugely extend the number of potential sources and accordingly of the expected signal.) M31 is therefore a target of choice for the search of MACHOs. A main bonus of this line of sight is the possibility to map all of the M31 dark matter halo, which is not possible for the Milky Way one. In fact, at parity of halo mass fraction and MACHO mass, one expects about one third of MACHO events from the Milky Way dark matter halo. This is because the (much) larger number of available lenses in M31 is (almost) exactly compensated by the (much) larger cross section of the Milky Way halo lenses.

The observational results towards M31 have been reviewed in Calchi Novati (2010). We recall the 4 years (1999-2002) observational campaign carried out at the 2.5m INT telescope, whose data have been analysed, in a completely independent way, by the POINT-AGAPE and
the MEGA collaborations. Interestingly, the conclusions reached by these two groups on the MACHO issue differ. For POINT-AGAPE, Calchi Novati et al (2005) reported an evidence of a MACHO signal along this line of sight, with in particular a lower limit for $f$ of about 20% in the mass range $(0.1-1)$ M$_\odot$. This result has been however challenged by MEGA (de Jong et al, 2006) who concluded that self lensing could explain the full observed rate and placed an upper limit on $f$ of about 30% in the same mass range. The small statistics is an issue for the POINT-AGAPE analysis which is based on 5 reported microlensing candidates and for which, in addition, the robustness of the conclusions on the MACHO issue rests mainly upon a single candidate, PA-99-N2, for which, according to the POINT-AGAPE analysis, the large distance from the M31 centre makes very unlikely the attribution to a self-lensing population. The analysis of the MEGA collaboration, based on a more than twice as much larger set of microlensing candidates, has been on the other hand challenged on the basis that the characteristics of the observed events are in fact at odds with a full self-lensing explanation (Ingrosso et al 2007).

Even beyond its importance within the POINT-AGAPE analysis, PA-99-N2 is a very peculiar event. The good coverage and tested achromaticity in three different bands make of it a very robust candidate in itself. A caveat is the rather large full width at half maximum duration, about 20 days (coupled to a very large flux deviation at maximum), at the very limit of the usually expected shorter values (a prediction confirmed by several other microlensing candidates). The genuine microlensing nature of this flux variation is on the other hand confirmed also by an anomaly along the light curve which turned out to be compatible with a binary lens model (An et al, 2004). Indeed, it was subsequently observed that the secondary lens could be due to a planetary system (Ingrosso et al 2009, 2011) although the large uncertainty on the model parameters does not allow sharp conclusions on this issue. (This would make of PA-99-N2 the second extra-galactic exoplanet candidate possibly ever observed after that of the microlensing event MACHO LMC-1, the very first event reported by the MACHO collaboration towards the LMC, Alcock et al 1993, which remarkably showed an anomaly that could even be explained by an exoplanet secondary lens Dominik & Hirshfeld 1994, 1996; Alcock et al, 2000b).

The disagreement of the MEGA and the POINT-AGAPE analyses may be traced back to two main lines of explanation, both turning around the problem of the estimate of the expected signal. First, the evaluation of the expected self lensing signal, due to the M31 luminous populations, still suffers from possibly inaccurate modeling of these components. Second, the correct evaluation of the efficiency of a given pipeline, the essential link to meaningfully compare the theoretical prediction with the observed rate is, even more for M31 than for the LMC case, highly non trivial.

To complicate the analysis one has to face the fact that the expected self lensing signal, at least in the central M31 region, is about of the same order of magnitude of an hypothetical MACHO population in the stellar mass range. This complication comes together with the additional degeneracy of the lensing parameter space peculiar to the pixel lensing regime which makes usually difficult reliable estimates on the physical time scale of the event and therefore even more difficult any investigation on the lens nature. In fact the statistics of choice to disentangle MACHO lensing from self lensing is the event spatial distribution, with self lensing expected to be, relatively, more clustered around the M31 centre (in fact, whatever the lens population, the signal gets larger towards the M31 centre following the spatial density distribution of the sources, at least as long it is not severely suppressed by the huge background noise of the underlying M31 surface brightness profile). As a second order effect, M31 MACHO lensing, because of the inclination of M31 along the line of sight, is expected to show an asymmetry in the spatial distribution which should help to characterize this signal (Crotts, 1992; Baillon et al 1993; Jetzer 1994). The (recurrent) caveat is the small statistics at disposal which has made difficult, at least up to now, to efficiently carry out this kind of analyses.

Parallel to the statistical analysis of full data set, as those of POINT-AGAPE and MEGA,
the importance of carrying out thorough analyses of single events has become in the meantime increasingly clear. Whenever they are possible, namely when the data are endowed with a sufficiently good sampling along the flux variation, these analyses are extremely useful as they allow one to extract additional and useful information on the lens nature. This has probed to be the case in particular for two events, both enjoying coverage by two different data set. (Incidentally, the routinely performed merging of several data set for events observed and followed up towards the Galactic bulge should not lead to underestimate the importance of having successfully carried out a similar analysis for M31 pixel lensing events.) The PA-S3/GL1 event, first reported by the POINT-AGAPE collaboration (Paulin-Henriksson et al, 2003) and then by the WeCAPP collaboration (Riffeser et al, 2003) has been subsequently analysed in more detail by Riffeser et al (2008). Based on the extremely large flux deviation at maximum amplification the authors of this last work conclude, even for an event lying in the very inner M31 region, strongly in favor of a MACHO hypothesis for the lens nature. A similar conclusion, even if with a lower statistical significance, was reached in the analysis of the OAB-N2 event carried out by the PLAN collaboration (Calchi Novati et al 2010). In this case the analysis was based on the study of the finite size source effect and the related study of the lens proper motion made possible by the excellent sampling along the full microlensing flux variation together with a careful analysis on the unlensed source flux based on archive HST data.

More recently, Lee et al (2011) presented the first results of a new challenging observational M31 pixel lensing project, PAndromeda, carried out at the 1.8m PS1 telescope with a huge field of view (7 deg²). In particular they report 6 new candidate events out of their first season of data, for an analysis restricted to a subfield of 40′ × 40′ around the M31 centre, showing in particular excellent flux stability. New data and analyses from this project are expected.

3.1. The PLAN campaign at OAB

As a PLAN (Pixel Lensing Andromeda) collaboration we have been carrying out a pixel lensing observational campaign towards M31 using the 152cm Cassini telescope located at “Osservatorio Astronomico di Bologna” in central Italy (at declination 44°.4, perfectly suitable to observe M31). Following a shorter pilot season in 2006, during the following 4 years PLAN has been allocated about 50 (almost) consecutive full nights/year.

| (1) | (2) | (3) |
|-----|-----|-----|
| 2006 | 8/11 (73%) | 4.2 |
| 2007 | 31/50 (62%) | 3.8 |
| 2008 | 38/65 (58%) | 4.6 |
| 2009 | 25/36 (69%) | 5.5 |
| 2010 | 20/41 (49%) | 4.6 |
| tot | 122/203 (60%) | 4.5 |

The observational strategy is set so to match the characteristics of the expected signal and maximise, at the same time, the expected rate. Microlensing variations in M31 are typically expected to last (in term of the full width at half maximum duration, $t_{1/2}$, which characterize

2 Results reported on behalf of the PLAN collaboration.
the observed signal) a few days only. A regular sampling with high time-resolution along the expected flux variations is therefore essential first to distinguish microlensing variations from other kind of intrinsic variable signals, second to properly characterize the lensing parameter space (as mentioned, a good enough sampling can even allow one to break the degeneracy and get reliable estimate of the physical duration, the Einstein time $t_E$). As a result, a long enough baseline (at least 2-3 weeks) of consecutive nights is essential to carry out such an observational programme. A longer baseline is then useful both to increase the statistics of expected events and to better constrain microlensing against other variable signals. Achromaticity is a further peculiar characteristic of microlensing useful to be exploited so that observations should preferentially be carried out in two bands (in particular, the expected sources being typically luminous red giants, we have used two broad-band filters similar to $R, I$ Cousin). To reach a large enough signal-to-noise level is also essential as we have to overcome the large background noise set by the M31 surface brightness profile. With a 1.5m class telescope we have therefore to get to a long enough equivalent integration time per night, at least of the order of 1-2 hours per filter. With a CCD field of view of $13' \times 13'$ (pixel scale of 0.58$''$), we have carried out observations towards 2 fields respectively North and South the M31 centre, leaving out the inner 2 arcmin. This way we cover the inner M31 part, in fact almost all of the M31 bulge region, still we reach far enough away from the M31 centre so to be able, at least in principle, to disentangle MACHO lensing from self lensing on the basis of the spatial distribution of the events. Overall our observational strategy, requiring about 8 hours per night (2 hours/field/filter), is set to match the number of potentially available hours per night with our target comfortably below an airmass of 1.5. Full details on the set up and observational strategy are further discussed in Calchi Novati et al (2007).

The statistics of the observations are reported in Table 1. Overall, the average weather conditions (humidity, cloud coverage) have not shown to be optimal to our purposes, introducing a lot of unwanted gaps in the sampling. The ratio of at least partially clear nights has indeed remained at about the 60% level, which is barely sufficient, with however in addition an average number of hours we could actually observe M31 during those nights below 5 hours, so that the overall fraction of hours useful to our purposes, with respect to those allocated and potentially usable, turned out to be in fact well below 40%.

The search for flux variations compatible with a microlensing signal is carried out with a fully automated selection pipeline. The result of this analysis are then compared to the expected signal evaluated through a full Monte Carlo simulation of the experiment, where the observational set up is reproduced together with the astrophysical and the microlensing amplification model (in particular, we duly include the finite size source effect). The events selected within the Monte Carlo are then simulated on the raw data upon which we apply from scratch the selection pipeline (we stress that in this last step the simulation is being carried out on the images). This way we get to an extremely reliable estimate of the efficiency of the selection pipeline which in turn allows us a correct estimate (for a given astrophysical model) of the number of expected events.

Full details of the selection process, the Monte Carlo simulation and the related efficiency simulation as well as the adopted astrophysical model are given in Calchi Novati et al (2009) where we have also reported the results of the 2007 season of data. In particular, two flux variations passed the full selection pipeline and accordingly have been classified as microlensing candidates: OAB-N1 and OAB-N2. Although primarily made to the purpose of maximising the efficiency (and the observed rate), the selection pipeline is also intended to leave the final sample of candidates completely free from contaminations of intrinsic variable sources (the only viable option so to draw some meaningful conclusion when dealing with a signal of a few expected events compared to thousands of detected flux variations). Still, with few exceptions, the fate of microlensing events is to keep their attribution of candidates if not for being altogether rejected.
In this specific case, both detected flux variations had some features that did not make them appealing. As a main problem, OAB-N1 is affected by noisy data, but this could in fact simply reflect the overall quality of our data set, and indeed we could not find any plausible alternative explanation to microlensing (and its estimated duration is well in agreement with the expected signal). OAB-N2 is a high signal-to-noise flux variation nicely following the microlensing shape. However, as presented in Calchi Novati et al (2009), it completely lacks data points along the descent. The genuine microlensing nature of OAB-N2 was to be strongly supported in a second moment when additional data, in particular useful to properly sample the descent, were kindly made available to us by the WeCAPP collaboration (Calchi Novati et al 2010).

The estimate of the expected signal resulted in about 1 self-lensing event, and about the same for full haloes (both M31 and the Milky Way) of 0.5 $M_\odot$ MACHOs (and about twice as much for $10^{-2} M_\odot$ MACHOs). Comparing to the two candidate microlensing events the observed rate looks therefore in agreement with the expected self-lensing rate, the expected MACHO signal on the other hand being too small to allow us to draw meaningful conclusions.

The perspective on this initial tentative result was to be modified by the already reported thorough analysis of OAB-N2 (once the sampling completed by the WeCAPP data) which allowed us to conclude that OAB-N2 should be, though not with very large significance, attributed to MACHO lensing rather than to self lensing (Calchi Novati et al 2010). We are currently completing the analysis of the remaining three years of data (Calchi Novati et al, 2012). Hopefully, the enlarged statistics is going to allow us to draw sharper conclusions on the candidates lens nature and the MACHO issue.

4. Conclusions

Nowadays the effort of the observational microlensing community is mainly driven by the search of exoplanets. The search of dark matter at the galactic scale in the form of compact halo objects remains however an important and challenging open issue. In fact, this second line of research is susceptible to benefit from the exoplanet effort and this opportunity should not be lost. The upgraded OGLE-IV and MOA-II systems, even with their main target being the Galactic bulge, will give the chance to proceed to new and more thorough researches of MACHOs towards the Magellanic Clouds. As for M31, a main challenge is to enlarge the observed rate up to a level for which first, the MACHO issue could be fully addressed on the basis of a large enough statistics. Second, a large enough rate would allow parallel lines of research to be addressed, as those carried out towards the Galactic bulge, first of all the search of exoplanets (lines of research for which microlensing would constitute one of the few, if not the only, available tool). A further challenge is to get, for M31 as already currently done for the Galactic bulge targets, to a survey alert system coupled to a follow up round-the-clock coverage of the ongoing events. To this purpose, however, one has to face the difficulty linked to acknowledge the microlensing nature of a pixel lensing variation already during its raising part, a difficulty enhanced by the usually rather short duration of the flux variations involved. This remains however a compelling step to fully address the issue of the correct understanding of the lens parameter space.

Microlensing observational campaigns have robustly established that compact halo objects do not constitute the main fraction of galactic dark matter haloes. The picture is still to be fully understood, however, in particular for MACHO in the mass range $(0.1–1) M_\odot$: a sizeable fraction of these objects, as that suggested by some results, would indeed in any case represent a relevant challenge to our understanding of galactic astrophysics. The larger statistics of events expected from the ongoing campaigns towards both the Magellanic Clouds and M31 promise to help to finally solve the puzzle.
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