MICROLENSING TOWARDS M31:
CANDIDATES AND PERSPECTIVES

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Recent results of the SLOTT-AGAPE and POINT-AGAPE collaborations on a
search for microlensing events in direction of the Andromeda galaxy, by using the
pixel method, are reported. The detection of 4 microlensing events, some likely to
be due to self-lensing, is discussed. One microlensing light curve is shown to be
compatible with a binary lens. The present analysis still does not allow us to draw
conclusions on the MACHO content of the M31 galaxy.

1. Introduction

Since Paczyński’s original proposal1 gravitational microlensing has been proben
to be a powerful tool for the detection of the dark matter component in galactic haloes
in the form of MACHOs. Searches in our Galaxy towards LMC2,3 show that up
to 20% of the halo could be formed by objects of around \( M \sim 0.4 M_\odot \), but these
results are still debated.4

Searches towards M31, nearby and similar to our Galaxy, have also been
proposed5,6,7. This allows to probe a different line of sight in our Galaxy, to
globally test M31 halo and, furthermore, the high inclination of the M31 disk is
expected to provide a strong signature (spatial distribution) for halo microlensing
signals.

Along a different direction, results of a microlensing survey towards M87, where
one can probe both the M87 and the Virgo cluster haloes, have also been presented.8

For extragalactic targets, due to the distance, the sources for microlensing sig-
als are not resolved. This claims for an original technique, the pixel method, the
detection of flux variations of unresolved sources.9,10,11

I review here the results from two different survey of M31 aimed at the detection
of microlensing events, carried out by the SLOTT-AGAPE12,13 and by the POINT-
AGAPE collaborations14,15. The WeCapp16,17 and the MEGA18 collaborations

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have also presented a handful of microlensing events.

2. Pixel lensing with MDM data

The SLOTT-AGAPE collaboration has been using data collected on the 1.3m McGraw-Hill Telescope at the MDM observatory, Kitt Peak (USA). Two fields, 17′ × 17′ wide each, on the opposite side (and including) the bulge are observed (centered in α = 00h 43m 24s, δ = 41°12′10″ (J2000) “Target”, on the far side of M31, and α = 00h 42m 14s, δ = 41°24′20″ (J2000) “Control”). Two filters, similar to standard $R$ and $I$ Cousins, have been used in order to test achromaticity. Furthermore, this particular colour information gives the chance of having a better check on red variable stars, which can contaminate the search for microlensing events. Observations have been carried out in a two years campaign, from October 1998 to the end of December 1999. Around 40 (20) nights of observations are available in the Target and Control field respectively.

To cope with photometric and seeing variations we follow the “superpixel photometry” approach, where one statistically calibrate the flux of each image with respect of a chosen reference image. In particular, the seeing correction is based on an empirical linear correction of the flux, and we do not need to evaluate the PSF of the image.

The search for microlensing events is carried out in two steps. Through a statistical analysis on the light curve significant flux variations above the baseline are detected, then we perform a shape analysis on the selected light curve, $\sim 10^3$, to distinguish between microlensing and other variable stars.

The background of variable sources is a main problem for pixel lensing searches of microlensing signals. First, the class of stars to which we are in principle most sensitive are the red giants, for which a large fraction are variable stars (regular or irregular). Second, as looking for pixel flux variations, it is always possible to collect (in the same pixel) light from more than one source whose flux is varying. Thus, in the analysis, one is faced with two problems: large-amplitude variable sources whose signal can mimic a microlensing signal, and variable sources of smaller amplitude whose signal can give rise to non-gaussian fluctuations superimposed on the background or on other physical variations.

In a first analysis we followed a conservative approach to reduce the impact of these problems. Severe criteria in the shape analysis with respect to the Paczyński fit were adopted (with a stringent cut for the $\chi^2$) and, furthermore, candidates with both a long timescale ($t_{1/2} > 40$ days) and a red colour ($(R - I)_C > 1$) were excluded, since these most likely originate from variable stars.

In this way 10 variations compatible with a microlensing (time width in the range 15-70 days, and flux deviation at maximum all above $\Delta R \sim 21.5$) were selected. However, due to the rather poor sampling and the short baseline, the uniqueness bump requirement could not be probed efficiently. A successive analysis on the INT extension of these light curves then shows that all these variations are indeed
due to variable sources and rejected as microlensing candidates. Indeed, in the same position, a variation with compatible time width and flux deviation is always found on INT data. In Fig. 1 (left) we show one MDM flux variation (T5) from this selection, nicely fitting a Paczyński light curve, then its extension on the INT data where it is clearly seen that the bump does repeat with the same shape, showing that this is actually a variable source.

A second analysis is then carried out where we relax the criteria introduced to characterize the shape, as this has proven not to efficiently reject variable stars and indeed could introduce a bias against real microlensing events whose light curve might be disturbed by some non-gaussian noise, and, on the other hand, we restrict the allowed space of physical parameters, in particular we consider only relatively short (time width less than 20 days) flux variations (this range of parameter space being consistent with what expected on the basis on Monte Carlo simulations\(^\text{12}\)).

As an outcome, out of further 8 detected flux variations, INT vetting allows to firmly exclude 5 as microlensing, leaving 2 light curves for which this test is considered inconclusive and 1 lying in a region of space not covered by the INT field (with \(t_{1/2} \in (13,20)\) days and \(\Delta R_{max} \in (21.0,21.8)\)).

By “inconclusive” it is meant that a flux variation is detected at the same position on INT data, but where the comparison of the time width and the flux deviation added to the rather poor sampling along the bump do not allow to conclude sharply
on the uniqueness test, leaving open the possibility of the detection of a microlensing light curve superimposed on (the light curve of) a variable star (Fig. I right).

3. Microlensing events with INT data

The POINT-AGAPE collaboration\textsuperscript{14} is carrying out a survey of M31 by using the Wide Field Camera (WFC) on the 2.5 m INT telescope. Two fields, each of $\sim 0.3$ deg$^2$ are observed. The observations are made in three bands close to Sloan $g', r', i'$. We report here on the results from the analysis of 143 nights collected in two years between August 1999 and January 2001. As described for MDM data, superpixel photometry is performed to bring all the images to the same reference one, then a similar analysis for the search of microlensing candidates is carried out.

A first analysis\textsuperscript{15} is made with the aim to detect short ($t_{1/2} < 25$ days) and bright variations ($\Delta R < 21$ at maximum amplification), compatible with a Paczyński signal. The first requirement is suggested by the results on the predicted characteristics of microlensing events of a Monte Carlo simulation of the experiment. As an outcome, four light curves are detected, whose characteristics are summarised in Table I and whose light curve are shown in Fig. 2 (with a third year data added). We stress that their signal is incompatible with any known variable star, therefore it is safe to consider these as viable microlensing events.

|           | PA-99-N1 | PA-99-N2 | PA-00-S3 | PA-00-S4 |
|-----------|----------|----------|----------|----------|
| $\alpha$ (J2000) | 00h42m51.4s | 00h44m20.8s | 00h42m30.5s | 00h42m30.0s |
| $\delta$ (J2000) | 41° 23' 54'' | 41° 28' 45'' | 41° 13' 05'' | 40° 53' 47'' |
| $d$ | 7' 52'' | 22' 03'' | 4' 00'' | 22' 31'' |
| $t_{1/2}$ (days) | 1.8 ± 0.2 | 21.8 ± 0.2 | 2.2 ± 0.1 | 2.1 ± 0.1 |
| $\Delta R_{max}$ | 20.8 ± 0.1 | 19.0 ± 0.2 | 18.8 ± 0.2 | 20.7 ± 0.2 |

Once a microlensing event is detected it is important, given the aim to probe the halo content in form of MACHO, to find out its origin, namely, whether it is due to self-lensing within M31 or to a MACHO. This is not straightforward. The spatial distribution of the events is an important tool, but still unusable given the small statistic. The observed characteristics of the variations to some extent can give a hint on the nature of the lens, but again, the small number of detected events so far makes this approach rather unviable. However, we stress that the detection of some self-lensing event, as they are expected to be found (their existence being predicted only on the basis of the rather well known luminous component of M31), is essential to assess the efficiency of the analysis. In the following, starting from their spatial position, we briefly comment on each of the detected events.
PA-99-N1: For this event it has been possible to identify the source on HST archival images. The knowledge of the flux of the unamplified source allows to break the degeneracy between the Einstein crossing time and the impact parameter for which one obtains the values $t_E = 9.7 \pm 0.7$ and $u_0 = 0.057 \pm 0.004$. The baseline shows two secondary bumps: they are due to a variable star lying some 3 pixels away from the microlensing variation. The position of this event, $7'52''$ from the center of M31, makes unlikely the hypothesis of bulge-bulge self-lensing. The lens can be either a MACHO (with equal chance in the M31 or the Milky Way halo) or a low mass ($\sim 0.2 M_\odot$) disk star with the source lying in the bulge. The first case is more likely assuming a halo fraction in form of MACHOs above 20%.

PA-99-N2: This variation lies at some $22''$ away from the center of M31, therefore is an excellent microlensing MACHO candidate. However, this variation turns out to be almost equally likely to be due to disk–disk self-lensing. This light curve is particularly interesting because it shows clear deviations from a Paczyński shape, while remaining achromatic (and unique) as expected for a microlensing event. We recall that this shape is characteristic for variations where the point-like (source and lens) and uniform motion hypothesis hold. After exploring 19 different explanations, it is found that the observations are consistent with an unresolved RGB or AGB star in M31 being microlensed by a binary lens, with a mass ratio of $\sim 1.2 \times 10^{-2}$. An analysis of the relative optical depth shows that a halo lens (whose mass is estimated to lie in the range 0.009-32 $M_\odot$) is more likely than a stellar lens (with mass in this case expected in the range 0.02-3.6 $M_\odot$) provided that the halo mass fraction in form of compact objects is at least around 15%.

PA-00-S3: This event is the nearest found so far from the center of M31 ($d = 4'00''$). Its extension past in time on MDM data shows no variations. The good sampling along the bump allows to get a rather robust estimation of the Einstein time, $t_E = 13 \pm 4$ days. This value, together with its position, makes the bulge-bulge self-lensing hypothesis the most likely for this event.

PA-00-S4: This event is found far away from the M31 center, but only at $2'54''$ from the center of the dwarf galaxy M32. A detailed analysis shows that the source is likely to be a M31 disk A star, the main evidence being the observed rather blue colour ($R - I = 0.0 \pm 0.1$). Given that M32 lies $\sim 20$ kpc in front of M31, the study of the relative optical depth allows to conclude that the most likely position for the lens is M32.

4. Conclusions

As a general outcome of the results presented, we stress that the detection of microlensing events towards M31 is now established. The open issue to be still explored is the study of the M31 halo fraction in form of MACHOs. With respect to this analysis, the events detected so far are all compatible with stellar lenses, but the MACHO hypothesis is still open, and we recall that the analysis for the INT data is still not concluded (besides a third year data, variations with $\Delta R_{max} > 21$ have
still to be studied). Once this analysis completed, it is the necessary to “weight” it with an efficiency study of the pipeline of detection before meaningfully comparing its results with the prediction of a Monte Carlo simulation. This should eventually allow us to draw firm conclusions on the halo content in form of MACHO of M31.

Figure 2. Three years data light curves for the 4 POINT-AGAPE microlensing events.

References
1. B. Paczyński, ApJ 304, 1 (1986).
2. C. Alcock et al. 2000, ApJ 542, 281.
3. T. Lasserre et al., A&A 355, L39 (2000).
4. Ph. Jetzer, L. Mancini & G. Scarpetta, A&A 393, 129 (2002).
5. A. P. Crotts, ApJ 399, L43 (1992).
6. P. Baillon, A. Bouquet, Y. Giraud-Héraud, Y., & Kaplan, J., A&A 277, 1 (1993).
7. Ph. Jetzer, A&A 286, 426 (1994).
8. E. Baltz et al., astro-ph/0310845.
9. R. Ansari et al., A&A 324, 843 (1997).
10. R. Ansari et al., A&A 344, L49 (1999).
11. A. Tomaney & A. Crotts, AJ 112, 2872 (1996).
12. S. Calchi Novati et al., A&A 381, 848 (2002).
13. S. Calchi Novati et al., A&A 405, 851 (2003).
14. M. Aurière et al., *ApJ* **553**, L137 (2001).
15. S. Paulin-Henriksson et al. *A& A* **405**, 15 (2003).
16. A. Riffeser et al., *A& A* **379**, 362 (2001).
17. A. Riffeser et al., *ApJ in press* (astro-ph/0311135).
18. J. de Jong et al., *Astrophysics* (astro-ph/0307072).
19. J. An et al., *ApJ in press* (astro-ph/0310457).
20. S. Paulin-Henriksson et al, *ApJ* **576**, L121 (2002).