LATEST RESULTS FROM THE POINT-AGAPE PIXEL-LENSING SURVEY OF THE ANDROMEDA GALAXY

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I report on recent results from the POINT-AGAPE pixel-lensing experiment, which is engaged in a search towards the Andromeda galaxy (M31) for gravitational microlensing signatures from massive compact halo objects (Machos). An analysis of two years of data reveals over 360 light-curves compatible with microlensing. The third year of data, currently being analysed, will be crucial in determining how many of these candidates are long-period variables rather than microlensing. Within the dataset we have isolated a subset of four high signal-to-noise ratio, short duration events which are compelling microlensing candidates. The properties and possible origins of these events are discussed.

1. Microlensing and pixel lensing

For about a decade a number of microlensing surveys have focused on the Magellanic Clouds to look for evidence of dark matter in the form of massive compact halo objects (Machos) in our own Galaxy\textsuperscript{1}. They have monitored millions of resolved stars on a nightly basis in order to detect rare transient magnifications of starlight due to the passage of intervening objects. The two key microlensing observables are the Einstein radius crossing time, \( t_E \propto m^{1/2} \), where \( m \) is the Macho mass, and the microlensing rate, \( \Gamma \propto f m^{-1/2} \), where \( f \) is their fractional contribution to the dark matter density. Galactic microlensing surveys determine \( t_E \) directly from the light-curve of the event:

\[
F(t) = A(t)F_* = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}F_*; \quad u^2 = u_0^2 + \left( \frac{t - t_0}{t_E} \right)^2, \tag{1}
\]

where \( F \) is the flux observed at epoch \( t \), \( A \) is the microlensing magnification, \( F_* \) is the baseline flux of the source star, and \( u_0 \equiv u(t_0) \) is the impact
parameter in units of the Einstein radius.

More recently a new technique, pixel lensing, has allowed microlensing surveys to target more distant galaxies in which most of the sources are unresolved. For such galaxies microlensing is detected as a small enhancement in pixel flux within a seeing disk. A detection typically requires high magnification \( A \gtrsim 10 \), when the excess flux due to lensing is \( (A - 1)F_* \approx F_*/u \). Pixel-lensing light-curves therefore take on a degenerate form:

\[
F(t) = F_{\text{bg}} + (A - 1)F_* \approx F_{\text{bg}} + \frac{\Delta F_0}{\sqrt{1 + \left(\frac{t - t_0}{u_0t_E}\right)^2}},
\]

where \( F_{\text{bg}} \) is the contribution to the seeing disk flux from the local galactic surface brightness (unresolved stars) and sky background, and \( \Delta F_0 = F_*/u_0 \) is the excess flux from the lensed source at maximum magnification. Hence, instead of \( t_E \), the observed timescale is the full-width at half-maximum duration, \( t_{1/2} \approx 2\sqrt{3}u_0t_E \). Therefore, with the exception of very high signal-to-noise ratio (S/N) events, one cannot disentangle \( F_* \), \( u_0 \) and \( t_E \) in pixel lensing.

An additional complication is that seeing and sky background variations must be minimised to reveal real flux variations. Over the last six years methods have been developed to accomplish this and real variations at the level of \( \sim 1\% \) can now be detected reliably. The power of pixel lensing rests in the fact that large external galaxies can be probed, potentially providing large numbers of Macho events and allowing their distribution to be mapped across the target galaxy. The information this provides makes up for the the loss of timescale information.

2. The POINT-AGAPE survey

The POINT-AGAPE survey is an Anglo-French experiment which is targeting M31 using the wide-field camera (WFC) on the 2.5 m Isaac Newton Telescope (INT). POINT-AGAPE is the successor to the pilot AGAPE (Andromeda Galaxy Amplified Pixels Experiment) survey, where POINT is an acronym for “Pixel-lensing Observations with INT”. Since 1999 we have been observing a large region of the M31 disk (left-hand panel of Fig. 1) in the Sloan-like \( r' \) band, augmented by observations in either Sloan-like \( i' \) or \( g' \). Our exposures are typically 5-10 mins per night and we have been able to collect data on most nights, weather permitting, when the WFC is mounted during the M31 observing season (August to January). To date we have around 180 epochs of data spanning three seasons.
The principal goal of the survey is to measure or constrain the abundance of Machos from the Jupiter mass scale up to several Solar masses. M31 provides a powerful signature for Macho detection (right-hand panel of Fig. 1). Its high disk inclination ($i = 77^\circ$) should produce an asymmetry in the M31 Macho spatial distribution if they occupy a spheroidal dark halo. This permits M31 Machos to be discriminated statistically from Milky Way Machos, and from stellar microlenses or variable stars in the M31 disk. Combining this spatial information with the number of events and their $t_{1/2}$ duration allows the M31 Macho mass and density contribu-
tion to be measured\(^5\), though we expect that at least three seasons of data are required. Milky Way Machos can also be detected, though the lack of an obvious spatial signature makes their contribution more difficult to measure.

3. Current status

We have analysed the first two seasons of data, and are currently analysing our third season. We have defined a set of event selection criteria based upon the goodness of fit to a theoretical microlensing curve, and upon our sensitivity, sampling and observation baseline. These criteria have produced 362 candidate events\(^6\). With only two seasons of data we are not yet in a position to eliminate some classes of long-period variables, such as Miras, and we suspect many of our candidates are not microlensing events. A more accurate calibration of the number of microlenses must therefore await completion of the third-year analysis.

In the meantime we have isolated a small subset of four high S/N events, which are compelling microlensing candidates\(^6\). All have \(t_{1/2} < 25\) days and \(\Delta F_0\) corresponding to a \(R \leq 21\) mag star. The high S/N and short \(t_{1/2}\) together provide a very high level of discrimination against bright, long-period variable stars. The positions of the four events are indicated in the left panel of Fig. 1, and the multi-colour light-curves are shown in Fig. 2. Each candidate provides a very good fit to microlensing in all bands.

4. Interpretation of the candidate events

Remarkably, for three of the events we have been able to break the light-curve degeneracy of Eqn. (2) and measure, or strongly constrain, \(t_E\). In the case of PA-99-N1 this has been achieved because the source star has almost certainly been identified on archive Hubble Space Telescope (HST) images\(^7\). The position and colour of the event as measured from INT data provide a good match to a resolved giant star on the HST frames (see Fig. 3). Since \(t_E = \theta_E/\mu_{\text{rel}}\), where \(\theta_E \propto m^{1/2}\) is the angular size of the Einstein radius and \(\mu_{\text{rel}}\) is the relative proper motion of the lens across the line of sight, a measurement of \(t_E\) leads to a constraint on the lens mass. The small value of \(t_E = 9.7\) days for PA-99-N1 indicates that either \(m\) is small or else \(\mu_{\text{rel}}\) is large. The excellent fit of this event to a point-source light-curve indicates that \(\theta_E\) must be much larger than the angular size of the source star, and requires that \(\mu_{\text{rel}} > 0.3\) \(\mu\)as/day. If PA-99-N1 is a Macho then it is likely to be a brown dwarf, but if it is a star in M31 the strong proper motion
Figure 2. Light-curves in $g'$, $r'$ and $i'$ bands of the four high S/N, short-duration candidate events. Clockwise from top-left the durations ($t_{1/2}, t_E$) of the events in days are: (1.9, 9.7 ± 0.7), (25, 92 ± 4), (2.1, 129$^{+143}_{-72}$), and (2.3, 13$^{+5}_{-3}$).

constraint demands a lens mass in the restricted range $m = 0.27^{+0.21}_{-0.12}$ $M_\odot$, making it a typical M dwarf star.

For two other events, PA-99-N2 and PA-00-S3, their high S/N is sufficient to provide a measure of $t_E$. Microlensing events are expected to have a broad timescale distribution centred on $t_E \sim (50, 60, 30, 20) \times (m/M_\odot)^{1/2}$ days for (Macho, disk–disk, bulge–bulge, bulge–disk) lensing, respectively. PA-00-S3 is almost certainly due to a bulge star, however the other events may be due to either Machos or stellar lenses. Intriguingly, the proximity of PA-00-S4 to the satellite galaxy M32, together with the colour of the event, suggest that this system involves a stellar lens in M32 and an M31 source star$^8$. If it is not a Macho then PA-00-S4 is highly likely to be the
Figure 3. Superposition of the Hipparcos colour magnitude diagram (black points) and M31 stars resolved by HST (pixelated area). The Hipparcos stars have been moved to the distance modulus of M31. The colour and location of the source star for PA-99-N1 has been determined directly from our INT data. An object consistent with these measurements was found on HST archive data. The horizontal and vertical lines show the colour and magnitude of the HST object.

first detected intergalactic microlensing event.

These initial results mark an encouraging first step towards the goal of detecting or constraining the Macho population. High S/N events in particular constitute an important sub-sample because often their $t_E$ can be measured or strongly constrained, providing tight limits on the masses of individual lenses. More generally, the entire pixel-lensing dataset will allow us to probe statistically the contribution and mass scale of Machos. Pixel-lensing experiments are also demonstrating how galactic microlensing surveys need not be confined to our own Galaxy, and that microlensing is now becoming a powerful and unique tool for studying the global structure and stellar inventory of Local Group galaxies.
References

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