Microlensing in M31 - The MEGA Survey’s Prospects and Initial Results

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Abstract. January 2000 completes the first season of intensive, wide-field observations of microlensing and stellar variability in M31 by MEGA (“Microlensing Exploration of the Galaxy and Andromeda”) at the Isaac Newton 2.5m Telescope, the KPNO 4m, and the 1.3m and 2.5m telescopes of MDM Observatory. In preliminary analysis, we detect \(~50000\) variable objects, including some consistent with microlensing events. We present the level of sensitivity to be reached in our planned three-year program to test for the presence of a significant halo microlensing population in M31, as well as its spatial distribution and mass-function. We also discuss our application of image subtraction to these wide fields and HST WFPC2 Snapshot followup observations to confirm candidates identified from previous years' surveys.

We present intermediate results from our smaller-field survey, on the MDM 1.3m and Vatican Advanced Technology 1.8m Telescope, from 1994-1998, wherein we have discovered 8 additional probable microlensing events, over about one-half the time base of the project, in addition to confirming three of our original 6 microlensing candidates from 1995.
1. Introduction

Microlensing has become an interesting probe of dark matter in our Galaxy. Recent microlensing surveys have indicated that a large fraction of the matter in the Galactic halo may be dark objects with masses comparable to those of stars, but have not revealed what these objects might be. We have detailed how microlensing internal to M31 (Crotts 1992, Gyuk and Crotts 2000) might be used to test such results and show better how the microlensing matter is distributed in space and as a function of mass. A survey of small fields in M31 has revealed several such candidate events, at roughly the predicted rate (Crotts & Tomaney 1996). We discuss below what efforts have been required to further verify the microlensing nature of these events.

Many papers predict microlensing optical depths $\tau$ in M31, which should approach $\tau \approx 10^{-5}$, over ten times greater than towards the LMC, but previously none of these works studied variations in halo microlensing optical depth over the face of M31. Since M31 differs from the Galaxy in that many sightlines for microlensing are seen by an observer at Earth, the variation of $\tau$ depending on the spatial distribution of microlensing objects should be explored.

2. Testing Candidate Microlensing Events

Originally, Crotts & Tomaney (1996) identified six events from the 1995 observing season in M31 (using the Vatican Advanced Technology 1.8-meter telescope on Mt. Graham, Arizona) over $\sim 60$d covering a 125 arcmin$^2$ field. These events were characterized by full-width half-maximum timescales of $10d < t_{\text{fwhm}} < 50d$. The longer end of this range is troublesome, coinciding with pulsewidths seen in miras and other longterm red variables. In fact, a mira light curve, resembling a symmetric sawtooth in magnitude, with peak-to-valley amplitudes of about 5 magnitudes in the $R$ band, appears similar to the lightcurve of a simple (point-mass, point-source) microlensing event during its maximum amplification. Furthermore, if the period of a mira is about $\frac{2}{3}$ yr, one must monitor for two M31 seasons beyond (or preceding) the peak in the light curve in order to detect another peak, since proximate peaks occur when M31 is not easily observable. The peak of such a mira has $t_{\text{fwhm}} \approx 40d$, which would corresponds to lensing masses $m \approx 0.5M_\odot - 1M_\odot$ for typical lensing geometries in our survey region. Hence mira-like variables are troublesome contributors to a potential false event rate, and require multiple seasons of observations in order to be eliminated.

We have performed two tests of these six original candidates: 1) constructing well-sampled lightcurves over the M31 seasons of the three subsequent years (through 1998), and 2) obtaining HST WFPC2 snapshot observations of these sources in order to determine if their colors are consistent with mira-like variables. (The latter test is impossible from the ground, since crowding does not allow one to resolve typical sources in average seeing conditions. Variable sources are made to appear isolated from one another by virtue of image subtraction e.g. Tomaney & Crotts [1996]). The result of these two event filters is to eliminate three of the six events, with the remainder firmly inconsistent with mira-like variables. For the remaining events, now that we have measured their baseline magnitudes from WFPC2 images, we can calculate a more accurate peak am-
Figure 1. An $80 \times 40$ arcmin$^2$ plot of M31’s center (major axis of M31 is horizontal, minor axis vertical) showing contours of the predicted event rate for bulge and halo microlensing in M31. The highest contour is for 50 events yr$^{-1}$ arcmin$^{-1}$ (near the center), with lower contours at 20, 10, 5, 2, 1, 0.5, 0.2 (dotted), 0.1 and 0.05 events yr$^{-1}$ arcmin$^{-1}$.

This reasonable model, for an unflattened halo with a 5 kpc core radius, predicts over 100 detections during an M31 observing season.

plification (assuming that the lensing mass rests as close as possible along the sightline to the core of M31). These persist with estimates for the lensing masses in the range $0.3 M_\odot \lesssim m \lesssim 2 M_\odot$, with two events possible arising from stars in M31’s bulge, but one almost certainly not a bulge lens, given its source position 2.5 kpc out into the disk.

3. Possible Results from a Larger Survey

Given the robust nature of some of the candidate microlensing events from the small area survey discussed above, it is worth considering possible results of a larger, wide-angle survey, especially since the advent of CCD imagers covering large fractions of a square degree. We present here representative results simulating a survey in which roughly 0.5 square degree is imaged for two hours every night on a two-meter telescope, in 1-arcsec seeing, requiring each event to be sampled at the 4σ level over at least 3 day timescales. The event rate predicted for such a survey is large e.g. Figure 1, which shows the predicted distribution of events over the field containing our survey area, for a typical model with 50% of the halo dark matter composed of $0.5 M_\odot$ microlensing masses.

The halo fraction, halo flattening ($q$) and core radius ($r_c$) are allowed to vary between models, and then a maximum likelihood calculation is performed to yield resulting values for these parameters. These parameters can result in large changes in the distribution of microlensing optical depth across the face of M31 (see Figure 2), which significantly affects the distribution of microlensing event detections.
Figure 2. The same region as in Fig. 1, but for contours of lensing optical depth (halo only) for two models of the spatial distribution of halo microlensing masses. The top panel corresponds to an unflattened model with 1.5 kpc core radius, and, on the bottom, a 3.3-to-1 flattening and a 10 kpc core radius. The dotted contours (just below center in each panel) correspond to $2 \times 10^{-6}$, increasing towards the top (far side of disk) to over $6 \times 10^{-6}$ in the top panel and $3.5 \times 10^{-6}$ in the bottom. In addition to the halo contribution shown, the central 10 arcmin diameter contains a $\tau \lesssim 5 \times 10^{-6}$ bulge signal (represented in Fig. 1); a uniform $\tau \lesssim 10^{-6}$ due to the Galaxy and a much smaller contribution from M31 disk-disk lensing (Gould 1994) are spread throughout.
Our calculations show that this larger survey might easily observe \( \sim 100 \) such events per M31 observing season, which would allow the shape of a strong microlensing halo of M31 to be mapped. Since most masses reside near where the sightline passes the center of the galaxy, at a known source-lens distance, this survey would also allow a more exact determination of the masses doing the lensing. Selected fields in M31 might also serve as independent sightlines through the halo of our Galaxy. The preliminary epochs for a large survey in M31, over one-half square degree, have already been obtained, initiating the project MEGA: Microlensing Exploration of the Galaxy and Andromeda.

Our ability to measure \( r_c \) and \( q \) depend on the true value of \( r_c \), with small values providing greater \( \tau \) in the galaxy’s center, where more sources exist. All models produce \( \geq 100 \) events per season, with small \( r_c \) models producing more. After three seasons, \( r_c \) can be measured to within \( \sim 1.5 \) kpc \((1\sigma)\), and \( q \) to \( \sim 0.1 \) (for \( r_c < 5 \) kpc), or \( \sim 2.5 \) kpc and \( \sim 0.2 \), respectively for \( r_c > 10 \) kpc. With \( q \) and \( r_c \) well-constrained, the data allow a superior estimate of lens mass distribution. This many events can result from a campaign using existing wide-field CCD arrays on two-meter+ class telescopes. Figure 3 shows the fields being covered.
by MEGA on some of the telescopes being used, compared to the fields for the earlier VATT/Columbia survey (described below). We have initiated this effort (MEGA) by establishing long baselines eliminating long-period variables, having obtained several epochs of such data in 1997 and 1998, and having begun more intensive observations in 1999 to detect microlensing events across much of M31 over the course of several seasons. At the time of the meeting, we have found approximately 40000 variables in the INT WFC data (some consistent with microlensing), which implies a sample of some 50000 when KPNO and MDM fields are included. (INT data are being collected in cooperation with AGAPE - see Kerins, this volume.)

Considerable improvements can be made in estimating halo shape parameters, as well as the microlens mass, if Einstein crossing times \( t_{\text{ein}} \) can be measured for events. Since the densest portion of the halo should sit over the bulge of M31, the lens-source distance is constrained by noting the impact parameter of the line of sight to the source relative to M31’s center. Hence, \( t_{\text{ein}} \) can be converted, roughly, to a mass, at a much greater accuracy than in the LMC sightline situation. Furthermore, events that are due to halo lenses have preferentially longer \( t_{\text{ein}} \) than confusing bulge events, hence measurements of \( t_{\text{ein}} \) can lead to better determination of halo shape parameters beyond those accuracies quoted above.

The Einstein crossing time can be measured in two ways, the \( \sigma_n \) method of Baltz and Silk (2000), and by using HST imaging to determine baseline magnitudes by resolving the source star. As we showed at the meeting, neither of these is sufficiently reliable by itself to determine \( t_{\text{ein}} \) without a large fraction of outlying measurements, either due to misidentification of source stars in HST images, or poor \( S/N \) in the wings of microlensing lightcurves, where \( \sigma_n \) is determined. However, if a large field (\( \sim 0.2 \text{ deg}^2 \)) is imaged with HST/ACS, requiring \( \sim 15 \) orbits, both methods will be available (\( \sigma_n \) from ground-based data), leading to \( t_{\text{ein}} \) for \( \sim 100 \) events, constraining the average microlensing mass to \( \sim 0.1 M_\odot \) or better, and significantly improving halo shape parameter determinations.

4. Intermediate Results from the VATT/Columbia Survey

Uglesich, Crotts and Tomaney conducted a preliminary survey of two 125 arcmin\(^2\) fields using the VATT 1.8m and MDM 1.3m. Data are reduced using the difference image photometry method of Tomaney and Crotts (1996), and example of which is shown in Figure 4 for typical MDM 1.3m images. The \( S/N \) ratio in these difference images is limited by photon shot noise, not seeing fluctuations, as evidenced in several studies e.g. Uglesich et al. 1999. Quantities of data sufficient to find microlensing events for masses in the 0.1-1\( M_\odot \) range where obtained in late 1995 through early 1999, with the best temporal coverage in the 1998-1999 season. Most of these data are now reduced, with the final season now having been searched for possible microlensing events. There are still \( \sim 20 \) epochs to be added from additional observatories, but already 11 potential events have been found, with 8 sampled over the peak of the best-fit microlensing curve, and points on either side. These 8 candidate events are shown in Figure 5. (At the time of the meeting, we had only fit these with the high-amplification microlensing curve fit of Gould [1997], rather than the full parameter range implicit in
general point-mass, point-lens microlensing curves of Paczynski [1986].) These sources have also been monitored in previous years’ data, and have maintained a stable baseline, inconsistent with longterm variables e.g. miras. We expect a large number of events to be found in this season’s and other season’s data. The VATT/Columbia survey has the potential for sensing the asymmetry in microlensing events across the face of M31, as seen in Figure 2, if a halo microlensing population actually exists as a significant fraction of the dark matter in spiral galaxy halos.

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Figure 5. Eight new microlensing candidate lightcurves (ADUs vs. JD) from 1998 R-band MDM 1.3m data. Data from other observatories (and MDM) show that these do not vary on extended baselines, and will fill in points during each event. Curves fit to the data are from Gould (1997) high-amplification fits, not full Paczynski (1986) fits.