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Evidence for Halo Microlensing from a Survey of M31

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Abstract. We report on the final microlensing result from one survey (VATT/Columbia) monitoring stars in M31, and the initial results of a larger study (MEGA), which together seem to indicate the presence of a microlensing halo component comprising a significant fraction of the dark matter in M31.

1. Survey Rationale and Description

The composition of dark matter in disk galaxies remains a mystery. The MACHO survey revealed a microlensing rate that was unanticipated in the context of the visible stellar population alone, but may compose a significant part of the dark matter halo (Alcock et al. 2000), consistent with only upper limits from EROS (Afonso et al. 2003). A decade ago we proposed that M31 offers a favourable alternative for probing the halo dark matter in disk galaxies, applying microlensing techniques to stars in M31 itself, for lenses primarily in M31. Such a signal could be easily distinguished in terms of an asymmetry in microlensing rate across the face of M31, and could be monitored effectively using image subtraction to suppress the severe crowding of M31's stars (Crotts 1992). This required developing techniques for the application of image subtraction to a time series of images (Tomaney & Crotts 1996), which led to the first candidate microlensing events in M31 (Crotts & Tomaney 1996). Several years of such observations were required to both amass sufficient lensing events for a statistically meaningful sample and to cull out variable stars by extending the baseline. M31 microlensing surveys have also been conducted by the AGAPE groups (Calchi Novati et al. 2002), and the survey reported here has been extended (Crotts et al. 2001, deJong et al. 2003), the first results of which we mention in conjunction with these in reaching our conclusion. Together our two surveys hint that a significant portion of the dark halo might be composed of stellar-mass lensing objects.

The positions of our two fields were chosen to maximize the number of stars being monitored and to provide optimal leverage for measuring the near

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to far-side optical depth asymmetry: along the minor axis, on opposite sides of the nucleus and at equal galactocentric radius, largely just beyond the bulge, and rotated to nearly match M31's principle axes. The filters (close to R and I) chosen maximize sensitivity to red giants which constitute the dominant stellar population in our fields and provide colour separation in order to test for achromaticity of microlensing candidates. Since our primary sieves for microlensing events involved the R-band data, some priority was given to R over I. Furthermore, data was sometimes completed in the farside field at the expense of coverage in the nearside field. The observations made for this survey were obtained at three telescopes: 1) The 1.8-meter Vatican Advanced Technology Telescope (VATT) on Mt. Graham, Arizona provided median $1''.09$ seeing over the survey. The imaging camera ("the Columbia SSCCD") featured a SITe 2048×2048 (24 μm) pixel^2, thinned CCD covering $11'.3 \times 11'.3$. We installed a doublet biconvex achromat corrector lens that allows for relatively straightforward image subtraction to be performed; 2) The MDM 1.3-meter (McGraw-Hill) telescope on the southwest ridge of Kitt Peak, Arizona utilized a CCD nearly identical to the VATT's, covering a field of view of $17'.0 \times 17'.0$. The median seeing, August 1997 - December 1999, was $1''.65$; 3) Additional data was obtained at the Isaac Newton Telescope (INT 2.5-meter), La Palma, Canary Islands, with the Wide Field Camera (WFC), as detailed elsewhere (de Jong et al. 2003). For this telescope the fields are configured in a north-south pair, but almost all of the VATT fields are covered.

The image analysis pipeline is detailed in Uglesich et al. (2003). We reduce images using IRAF, then perform image subtraction using the fourier quotient kernel package we developed (DIFIMPHOT: Tomaney & Crotts 1996) for imaging time series. Additional points from the INT/WFC sample were added to lightcurves after events were identified from the R-band lightcurves from the VATT and MDM samples.

2. Lightcurve Analysis and Conclusions

The analyses above are sufficient to isolate a variable source from the huge density of stellar sources in ground-based images of M31. We still need techniques to discriminate microlensing events from the usual, more numerous (or more rare) ways in which stars vary intrinsically. We use a series of criteria to isolate microlensing events from variable stars, remembering that by use of our image subtraction analysis we can no longer access the baseline flux of the stars in our images. In M31, however, we have the added benefit of easily extending our search over large portions of the galaxy, and therefore have the potential of distinguishing microlensing events from false backgrounds on the basis of spatial distribution, including: a) the strong farside/nearside asymmetry (Crotts 1992), due to the higher density of lenses and more favourable lensing geometry for stars on the more distant side of M31's disk, and b) the expectation of a diminished gradient in microlensing events versus stellar populations as one moves away from the center of the galaxy (Baltz, Gyuk & Crotts 2003), since the distance from the lens to the source D_{ls} grows roughly linearly with the projected distance from the center of M31. Consequently, optical depth grows, as

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D_{ls}, like the microlensing cross-section $\sigma_{lens} = \pi R_e^2 = 4\pi D_{ls} D_{ol}/GmD_{os}$, where $D_{ol} \approx D_{os}$ in the case of M31.

In Uglesich et al. (2003) we justify in detail our microlensing event acceptance filters. Our seven criteria include: I) Minimum number of detections: for a lightcurve to be catalogued, detections of at least 4σ in 2 nightly stacks must occur at the same point (to within 1.0 arcsec). This produces a sample of 8162 lightcurves; II) Good fit to Gould filter function: Gould (1996) proposed an alternative function to describe microlensing lightcurves for point sources and masses in the unresolved regime as in M31. Microlensing events are well represented by this Gould function and we retain only those lightcurves fit by it below a $\chi^2/\nu < 20$ threshold. Additionally, we require that the fit maximum be contained in the range of lightcurve points in R found within a FWHM of the peak. These requirements retain exactly 100 lightcurves; III) Adequate sampling of event maxima: We retain only candidates which have at least 4 points during the event with flux difference greater than 4-σ above the baseline and which lie on both sides of the peak, based on 1.3-meter R-band data only. After this requirement 45 lightcurves remain; IV) MDM 1.3-meter, R-band Paczynski curve fit must be less than $\chi^2/\nu = 2$. This threshold in reduced $\chi^2/\nu = 2$ will rule out less than one in 10^4 of true lensing events for lightcurves with the number of points as ours. This criterion actually reduces the surviving candidates to 26; V) Joint R and I χ^2/ν threshold: We set a threshold in reduced $\chi^2/\nu = 1.5$ (including INT lightcurve points), which will rule out less than 1% of true lensing events for lightcurves with the number of points as ours, much less than one event for the sample surviving criteria I - IV. This criterion actually reduces the surviving candidates to 17. VI) No secondary peak in R and/or I: Any contiguous peak (or drop) relative to the baseline in contiguous epochs resulting in an increase in χ^2 of more than 100 will cause the candidate event to be eliminated. The probability of a true microlensing event showing this behavior is minimal. This reduces the surviving candidates to 16; VII) The amplified flux from the event must have $0.3 < R - I < 1.4$ (corresponding to $0.6 < V - I < 2.8$) to avoid regions of the colour-magnitude diagram in which variability detectable with our survey would dominate the source star population. Four candidates survive this test, landing in regions of the H-R diagram which are likely to be free of detectable variabilty, and are consistent with red giant stars, which should represent the preponderance of source for microlensing events. We have no better hypothesis than to elevate these 4 events to the category of true microlensing events.

Our criteria on sampling (I and III) are sufficiently explicit that we can compute their effects on our microlensing event detection efficiency given our knowledge of the sampling time series for our survey, and the other criteria are sufficiently inclusive of microlensing events as to have negligible impact on this efficiency. This calculation relies on the lensing models of Baltz et al. (2003), as is detailed in Uglesich et al. (2003). The model for microlensing rates tells us the distribution of events both as a function of event FWHM in time t_{fwhm} and as a function of position across the face of M31. A maximum likelihood calculation yields contours in halo fraction f_b and component mass m. If we marginalize over f_b and m in turn, we determine a measurement for each parameter separately to be microlensing halo mass fraction of $f_b = 0.29^{+0.30}_{-0.13}$ of the total dark matter, and a lensing component mass m between 0.02 and 1.5 $M_\odot$ (1σ limits,

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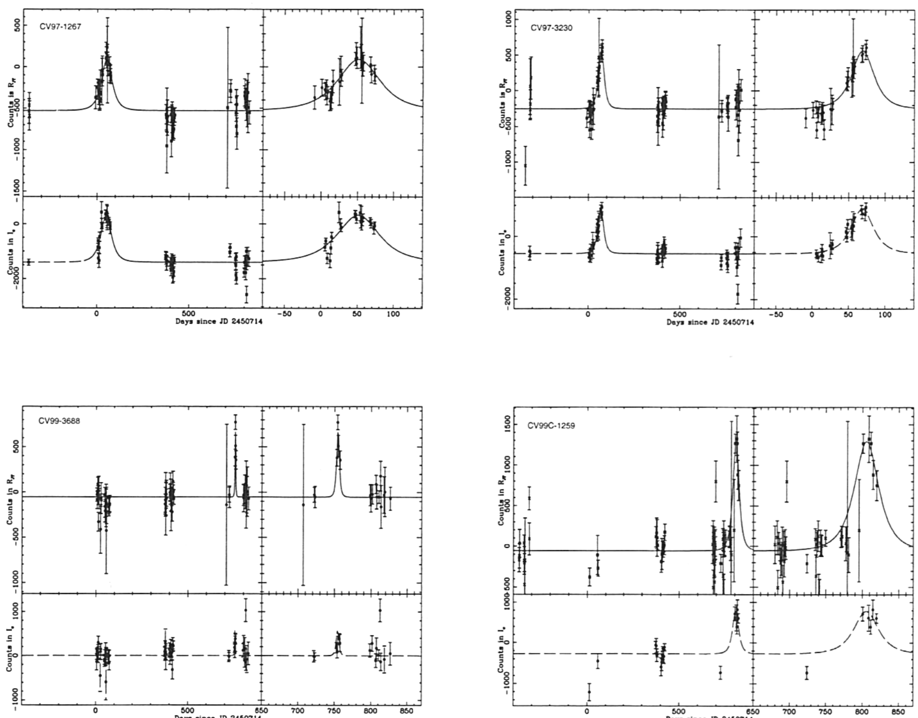

Figure 1. Candidate lightcurves from VATT/Columbia survey, plotted in ADU counts in the R and I bands as a function of Julian date. Points used in the Paczynski fits (from the MDM 1.3-meter) are indicated by the solid symbols; data from the VATT (first season) and INT (last season) are indicated by small diagonal crosses.

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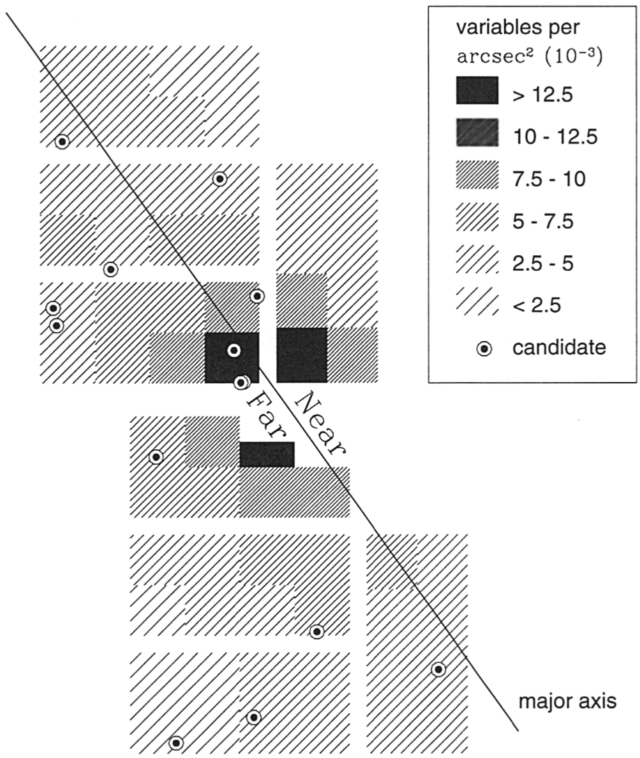

Figure 2. Surface density map of long period variable stars in the MEGA field surveyed by INT/WFC: Each chip was subdivided into 2×4 rectangles (300×324 arcsec^2), in which the number of variables with periods longer between 150 and 600 days was counted. Only stars with accurately determined periods were used and the edges of the chips were avoided to ensure only well sampled lightcurves were used, leaving 32,841 variables. The positions of the microlensing candidates are indicated, as well as the major axis of M31. The microlensing candidates prefer the far side (lower left) at roughly the 2σ level over the long period variables. Note that only about 15% of the MEGA survey data are represented here.

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with a most favoured value of 0.53 $M_\odot$). This component mass constraint is very weak, especially considering that we adopted a prior of $10^{-3}\ M_\odot < m < 10\ M_\odot$ in constructing our maximum likelihood estimate. This compares with the MACHO survey (Alcock et al. 2000), that detects 13-17 events towards the LMC when only ~2-4 events would have been expected due to known stellar populations. The maximum likelihood halo fraction is $f_b = 20\%$ (8% - 50%, 95% confidence interval). The M31 halo microlensing fraction f_b we find is consistent with that seen by MACHO towards the LMC. Any disagreement is highly dependent on the assumed singular, isothermal sphere model, which might easily exaggerate the inconsistency. Our result is nearly as consistent with no halo as that reported by MACHO, however. On the basis of further M31 microlensing evidence, we tend to accept the positive halo indication. The VATT/Columbia survey serves as the pilot study for a larger survey, MEGA ("Microlensing Exploration of the Galaxy and Andromeda:"), and the first results from this effort (de Jong et al. 2003) also shows a marginally significant farside surplus asymmetry. While this other work does not estimate f_b, such an asymmetry is a nearly unique marker of a dark matter halo of microlensing objects (or a stellar spheroidal distribution of extreme mass and mass/light ratio, which approaches the same thing). Later data from this survey will encompass almost an order of magnitude more observations, so indicates that the result will become more clear in the near future. We look forward to additional progress in using M31 to generalize and extend the insight which has been won from microlensing searches in nearby galaxies.

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