HST Imaging of MEGA Microlensing Candidates in M31\textsuperscript{1,2}

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ABSTRACT

We investigate HST/ACS and WFPC2 images at the positions of five candidate microlensing events from a large survey of variability in M31 (MEGA). Three closely match unresolved sources, and two produce only flux upper limits. All are confined to regions of the color-magnitude diagram where stellar variability is unlikely to be easily confused with microlensing. Red variable stars cannot explain these events (although background supernovae are possible for two). If these lenses arise in M31’s halo, they are due to masses 0.15 < \(m/M_\odot\) < 0.49 (95% certainty, for a \(\delta\)-function mass distribution), with brown dwarfs for disk lenses and stellar masses for bulge lenses.

Subject headings: dark matter — galaxies: halos — galaxies: individual (M31) — gravitational lensing

Online material: color figure

1. INTRODUCTION

Galaxian dark matter has been recognized for over 70 years (Zwicky 1933) and has been tied in part to the halo for over 30 years (Rubin & Ford 1970). The nature of halo dark matter is still a mystery. Gravitational microlensing can reveal individual dark matter objects of roughly stellar mass (Paczynski 1986).

To test this, MACHO observed the Magellanic Clouds for 5.7 yr (Alcock et al. 2000), and EROS (Afonso et al. 2003) did so for 5 years. The former report microlensing events more common than the known, purely stellar expectation, with a lensing fraction of the dark matter halo mass (8%–50%, with 95% confidence) of \(0.4 \text{M}_\odot\). EROS found \(f\) to be consistent with zero (but marginally consistent with \(f \approx 20\%\)).

M31 microlensing could potentially settle this quandary definitively (Crotts 1992). Since we can explore microlensing across the face of M31, we can use this distribution to distinguish where in the galaxy the lenses arise. Several surveys of M31 microlensing (Riffeser et al. 2003; Joshi et al. 2005; Calchi Novati et al. 2005; including MEGA [de Jong et al. 2004] and its predecessor VATT/Columbia [Uglesich et al. 2004]) together report \(\sim 20\) probable microlensing events, and they have a tendency to confirm the MACHO result.

With its crowded target stars, M31 microlensing relies on image subtraction to reveal event light curves, which removes the baseline flux. Using HST to recover the source flux (e.g., Ansari et al. 1999; Aurière et al. 2001), one can compute the event amplification, hence the Einstein parameters, by constraining the physical parameters (e.g., the lens mass). MEGA and VATT/Columbia also use source star color to distinguish microlensing from variable stars, since very red variables (Mira and semiregular variables) produce outbursts that, with their baselines subtracted, mimic point-source, point-lens (“Paczynski”) light curves (Uglesich et al. 2004). Residual flux from these events, however, is redder than almost all potential microlensing source stars. MEGA will soon publish its microlensing sample, and now is an excellent opportunity to check these event selection criteria.

The analysis used is detailed by P. Cseresnjes et al. (2005, in preparation). We carefully align the HST and ground-based images by matching catalogs of ground-based versus Gaussian-convolved HST sources for each filter combination (HST, F555W/F814W vs. INT, \(r\)′/′ and KPNO 4 m, \(R\)/\(I\)), providing up to eight different position estimates. For a given ground-based position, the two independent HST positions (via F555W and F814W) always agree to \(\leq 0.03\) (typically \(0.01\)), so positional accuracy depends mainly on ground-based data. The adopted position is a weighted average of individual estimates (Fig. 1). The spread of different estimates for each event is \(0.02−0.07\). Of the five microlensing candidates analyzed, we identify three sources and find flux upper limits for two.

HST data were photometered with DAOPHOT (Stetson 1987), as prescribed in Sirianni et al. (2005). The locations of the candidate microlensing sources on a color-magnitude diagram are shown in Figure 2. For each candidate event, we normalized the differential light curves to \(R\)-fluxes, using color-magnitude diagrams and HST baseline fluxes (for the two undetected events, using the baseline flux upper limit), then performed a Paczynski fit in \((u_0, t_0, t_b)\) to the combined light curve.
Fig. 1.—Left to right, first column of panels: (1.5') HST image (F814W band) around microlensing candidates. The circles correspond to a 1σ spread of the individual position estimates. The grid represents the INT pixel sampling; for ML-16, the cross point corresponds to an independent estimate as described in the text. Second column: Full combined light curve (filled squares, KPNO R band; asterisks, KPNO I band; open circles, INT r' band; open triangles, INT i' band). Third column: Zoom on the event peak. Fourth column: Lens-mass probability distribution for a lens in an isothermal halo (solid line), in the disk (dashed line), and in the bulge (dotted line). [See the electronic edition of the Journal for a color version of this figure.]

(Fig. 1). For the two undetected events, the resulting \( t_E \) corresponds to a lower limit.

Only the Einstein timescale \( (t_E) \) constrains the lens characteristics, particularly its mass \( m \). For a given timescale \( t_E \), the lens-mass probability distribution is \( P(M, t_E) = (dV/dt_E)/\Gamma \), where \( \Gamma \) is the event rate (Griest 1991). Alternatively, we consider a lens located in the halo of M31, in the disk or in the bulge. For halo lensing, we consider the simple case in which the lens is part of a spherical isothermal halo composed of single mass objects, with a density distribution defined as

\[
\rho_s \propto \frac{1}{R^2 + r_c^2},
\]

where \( R \) is the radial distance to the center of M31 and \( r_c \) is a core radius of 5 kpc. The one-dimensional velocity dispersion of the lenses is set to 170 km s\(^{-1}\), consistent with a rotation curve of 240 km s\(^{-1}\). The disk is modeled by a double exponential with a radial scale length of 6 kpc and a vertical scale length of 400 pc. The bulge corresponds to the “small” bulge model of Kent (1989), with a velocity dispersion of 150 km s\(^{-1}\). More details about the model can be found in Baltz et al. (2003).

### 3. Individual Events

**ML-8.**—This event’s position lands within the FWHM of a red clump star’s image, with \( R - I \) in excellent agreement with the peak flux’s color in differential light curves (0.60 ± 0.16 vs. 0.59 mag). With the baseline set to this star’s flux, a Paczyński fit yields an amplification \( A = 8.49 \) and an Einstein timescale \( t_E = 60.6 \pm 4.2 \) days. The corresponding lens masses are \( m = 0.31^{+0.08}_{-0.03} M_\odot \) for a halo lens, \( m = 0.05^{+0.06}_{-0.01} M_\odot \) for a disk lens, and \( m = 2.85^{+0.03}_{-2.31} M_\odot \) for a bulge lens.

However, this event lands ∼0.9 from the center of a background galaxy (subtending ∼1.5' × 0.3'). Its color, flux, and decline rate are consistent with a Type Ia supernova (SN) at \( z \approx 0.5 \), with ≤1 mag extinction (see Johnson & Crotts 2005). One must balance the number of SNe (∼100 yr\(^{-1}\) deg\(^{-2}\); e.g.,
Woods & Loeb 1998) landing within the FWHM disk of a source star of consistent color that we would detect (1.2 arcsec$^{-2}$) versus the number of microlensing events (evidently approximately five) landing so close to an $R < 23$ galaxy (100 arcmin$^{-2}$; Huang et al. 2001). The expected number of both kinds of events are of the order of a few tenths, with perhaps microlensing being slightly more likely.

ML-10.—This event lands within the FWHM disk of a giant branch star of color $R - I = 1.05$, in perfect agreement with the microlensing data. This source has $A = 4.00$ and $t_e = 64.7 \pm 1.9$ days, corresponding to a halo lens mass $m = 0.33^{+0.04}_{-0.03} M_\odot$, a disk lens mass $m = 0.05^{+0.09}_{-0.04} M_\odot$, or a bulge lens mass $m = 2.0^{+1.66}_{-1.55} M_\odot$. It lands suspiciously close to a region of the color-magnitude diagram common to variables. Still, the achromaticity of the variation, the well-fit and well-sampled peak ($x^2/N = 1.26$), and the stability of the baseline over seven seasons strongly indicate a real microlensing event.

ML-11.—This event lands on a faint blue star ($R - I = 0.15 \pm 0.40$) severely blended with a red clump star. The light-curve fit yields a similar $R - I = 0.21$. Its baseline flux implies $A = 41.93$ and $t_e = 26.1 \pm 1.1$ days. This event, from Paulin-Henriksson et al. (2002), is near M32, suggesting that the lens resides there. If not, the most likely lens mass is $m = 0.05^{+0.03}_{-0.02} M_\odot$ in the halo, $m = 0.01^{+0.01}_{-0.01} M_\odot$ in the disk, and $m = 0.36^{+0.23}_{-0.28} M_\odot$ in the bulge.

ML-16.—This event lands in a WFPC2 field and was also seen by POINT-AGAPE (Aurière et al. 2001). They publish a color for the event peak based on INT $g'$ and $r'$ (no $i'$ data are available), corresponding to $V - I \approx 2.1$. We find no detected source at this position, the nearest detected star landing ~0.1 away (1 WFPC2 pixel) with $V - I \approx 1.1$. Using the flux of this star as an upper limit, we find $A > 16.01$, $t_e > 6.9$ days, and $m > 0.003 M_\odot$ being poorly constrained for a halo lens.

Aurière et al. (2001) seem to have isolated a different source star. Their celestial coordinates disagree with ours by 3" but cannot be checked from published data since no image of the source field is provided. In order to check our astrometry, we repeated the procedure that we applied to $r'$ data to $g'$ data retrieved from the INT archive. We also repeated the same procedure (for both $r'$ and $g'$ data) using the WFPC2 images taken by Aurière et al. from the archive. Finally, one of us (A. P. S. C.) made an independent check by choosing eight bright unsaturated, isolated stars as coordinate inputs to IRAF geomap to construct the coordinate transform. These various estimates agree to better than 0.5 pixels in the INT data, whereas the nearest star (two of them actually) with consistent colors and magnitudes to that claimed by Aurière et al. are 0"6 (or almost 1 INT pixels) away. Our position is marginally consistent with the faint source cited above and in Table 1, but inconsistent with that of Aurière et al.

ML-18.—This event lands in a bright region, perhaps a cluster or background galaxy. We isolate no source here, so we provide only an upper limit baseline flux, estimated by taking the brightest pixel within 0'05 and considering that it contains at most 15% of the source flux, as constrained by the point-spread function for ACS. With this flux limit, $A > 11.42$, $t_e > 86.6$ days, and $m > 0.62 M_\odot$ for a halo lens, $m > 0.09 M_\odot$ for a disk lens, and $m > 3.73 M_\odot$ for a bulge lens.

4. CONCLUSIONS

Of five events in our fields, we find three likely matches and baseline flux upper limits on the other two. Colors of the three identified sources agree with those obtained from their differential light curves alone. The two upper limits displace these

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**TABLE 1**

| Event Source Photometry and Microlensing Parameters |
|-----------------------------------------------|
| ID | ML-8 | ML-10 | ML-11 (S4) | ML-16 (N1) | ML-18 |
|-----------------------------------------------|
| R.A. (J2000) | 00 43 24.53 | 00 43 54.87 | 00 42 29.90 | 00 42 51.22 | 00 43 17.27 |
| Decl. (J2000) | 41 37 50.4 | 41 10 33.3 | 40 53 45.6 | 40 23 55.3 | 41 02 13.7 |
| $R_\text{int}$ | 24.94 ± 0.14 | 23.36 ± 0.09 | 24.86 ± 0.30 | >23.86 | >25.09 |
| $I_\text{int}$ | 24.34 ± 0.08 | 22.31 ± 0.07 | 24.71 ± 0.26 | >23.32 | >24.59 |
| $(R - I)_\text{int}$ | 0.60 | 1.05 | 0.15 | ... | ... |
| $(r - I)_\text{int}$ | 0.59 | 1.05 | 0.21 | ... | ... |
| $A_\text{max}$ | 8.49 | 4.00 | 41.93 | >16.01 | >11.42 |
| $t_e$ (day) | 60.6 ± 4.2 | 64.7 ± 1.9 | 26.1 ± 1.1 | >6.9 | >86.6 |
| $x^2/N$ | 0.89 | 1.26 | 1.01 | 1.29 | 1.04 |
| $m_{\text{halo}}$($M_\odot$) | 0.31^{+0.18}_{-0.21} | 0.33^{+0.04}_{-0.23} | 0.05^{+0.06}_{-0.05} | >0.00 | >0.62 |
| $m_{\text{halo}}$($M_\odot$) | 0.05^{+0.09}_{-0.05} | 0.05^{+0.09}_{-0.05} | 0.01^{+0.01}_{-0.01} | >0.03 | >0.09 |
| $m_{\text{halo}}$($M_\odot$) | 2.85^{+0.38}_{-0.24} | 2.00^{+1.26}_{-0.24} | 0.36^{+0.11}_{-0.26} | >0.05 | >3.73 |
| Comment | Red clump or SN Giant branch | Very blue | Undetected | In cluster or galaxy |

**Note:**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Most likely lens mass (with 1 σ confidence intervals).
events from the asymptotic giant branch, where confusing Mira and semiregular variables can occur. No candidate is a bright red variable. One might interpret ML-8 as a supernova, but a microlensing event is just as probable. We also cannot rule out a supernova as the source for ML-18, which might also coincide with a background galaxy. In a future paper, the complete MEGA data set will fill out ML-18’s light curve; unfortunately, we have no additional data on ML-8.

Taking the product of the individual mass probability distributions obtained for each event, these lenses in a halo model (Baltz et al. 2003) of a single component mass are constrained to $0.15 < m/M_\odot < 0.49$ at the 95% level. M31 microlensing rates may be consistent with pure self-lensing (de Jong et al. 2005), so we consider bulge lenses ($0.64 < m/M_\odot < 2.02$), or disk lenses that correspond to probably unrealistic brown dwarf masses ($0.02 < m/M_\odot < 0.06$).

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