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HST Imaging of MEGA Microlensing Candidates in M31[1]

Patrick Cseresnjes[2], Arlin P.S. Crotts,[2] Jelte T.A. de Jong[3], Alex Bergier,[2] Edward A. Baltz[4], Geza Gyuk[5], Konrad Kuijken,[6,3] Lawrence M. Widrow[7]

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 supernova are possible for two). If these lenses arise in M31's halo, they are due to masses $0.08 < m/M_\odot < 0.85$ (95% certainty, for a δ-function mass distribution), brown dwarfs for disk/disk, and stellar masses for disk/bulge "self-lensing".

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

1. Introduction

Galaxian dark matter has been recognized for almost 70 years (Zwicky 1937), and tied in part to the halo for over 30 (Rubin & Ford 1970). Halo dark matter's nature is still a mystery. Gravitational microlensing can reveal individual dark matter objects of roughly stellar mass (Paczyński 1986). To test this, MACHO observed the Magellanic Clouds for 5.7 years, (Alcock et al. 2000) and EROS (Afonso et al. 2003) did so for 5. The former report microlensing events more common than the known, purely stellar expectation, with lensing fraction $f \approx 20\%$ of the dark matter halo mass (8-50%, with 95% confidence) of $\sim$0.4 $M_\odot$ masses. EROS found f consistent with zero (but marginally consistent with $f \approx 20\%$).

M31 microlensing could potentially settle this quandary definitively (Crotts 1992). For reasonable halo and stellar populations, there should be significant asymmetry in the microlensing rate across M31, given $f = 20\%$. Several surveys of M31 microlensing (Riffeser et al. 2003, Joshi et al. 2004, 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 have a tendency to confirm the MACHO result.

With its crowded target stars, M31 microlensing relies on image subtraction to reveal event lightcurves, which removes the baseline flux. Using *HST* to recover the source flux, we can compute event amplification, hence einstein parameters, constraining physical parameters e.g., lens mass. MEGA and VATT-Columbia also use source star color to distinguish microlensing from variable stars, since very red variables (miras and semiregulars) produce outbursts that, with their baselines subtracted, mimic point-source, point-lens ("paczyński") light curves (Uglesich

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[2]Columbia Astrophysics Laboratory, Columbia University, 550 W. 120th St., New York, NY 10027

[3]Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV, Groningen, The Netherlands

[4]Kavli Inst. for Particle Astrophysics & Cosmology, Stanford U., PO Box 20450, MS 29, Stanford, CA 94309

[5]Department of Astronomy and Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637

[6]Sterrewacht Leiden, University of Leiden, PO Box 9513,2300 RA, Leiden, The Netherlands

[7]Department of Physics, Queens University, Kingston, ON K7L 3N6, Canada

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Table 1
Event source photometry and Microlensing parameters

id	R_{hst}	I_{hst}	$(R-I)\|_{hst}, \|_{lc}$	A	t_E	χ^2/N	m_d	m_b	comment
ML-8	24.94 ± 0.14	24.34 ± 0.08	0.60, 0.59	8.49	60.6 ± 4.2	0.89	$0.31^{+0.48}_{-0.21}$	$0.20^{+0.79}_{-0.13}$	red clump or SN
ML-10	23.36 ± 0.09	22.31 ± 0.07	1.05, 1.05	4.00	64.7 ± 1.9	1.26	$0.33^{+1.04}_{-0.23}$	$0.24^{+0.75}_{-0.14}$	giant branch
ML-11 (S4)	24.86 ± 0.30	24.71 ± 0.26	0.15, 0.21	41.93	26.1 ± 1.1	1.01	$0.05^{+0.16}_{-0.03}$	$0.04^{+0.14}_{-0.03}$	very blue
ML-16 (N1)	>23.86	>23.32	– , –	>16.01	>6.9	1.29	> 0.00	> 0.00	undetected
ML-18	>25.09	>24.59	– , 0.51	>11.42	>86.6	1.04	> 0.62	> 0.45	in cluster or galaxy

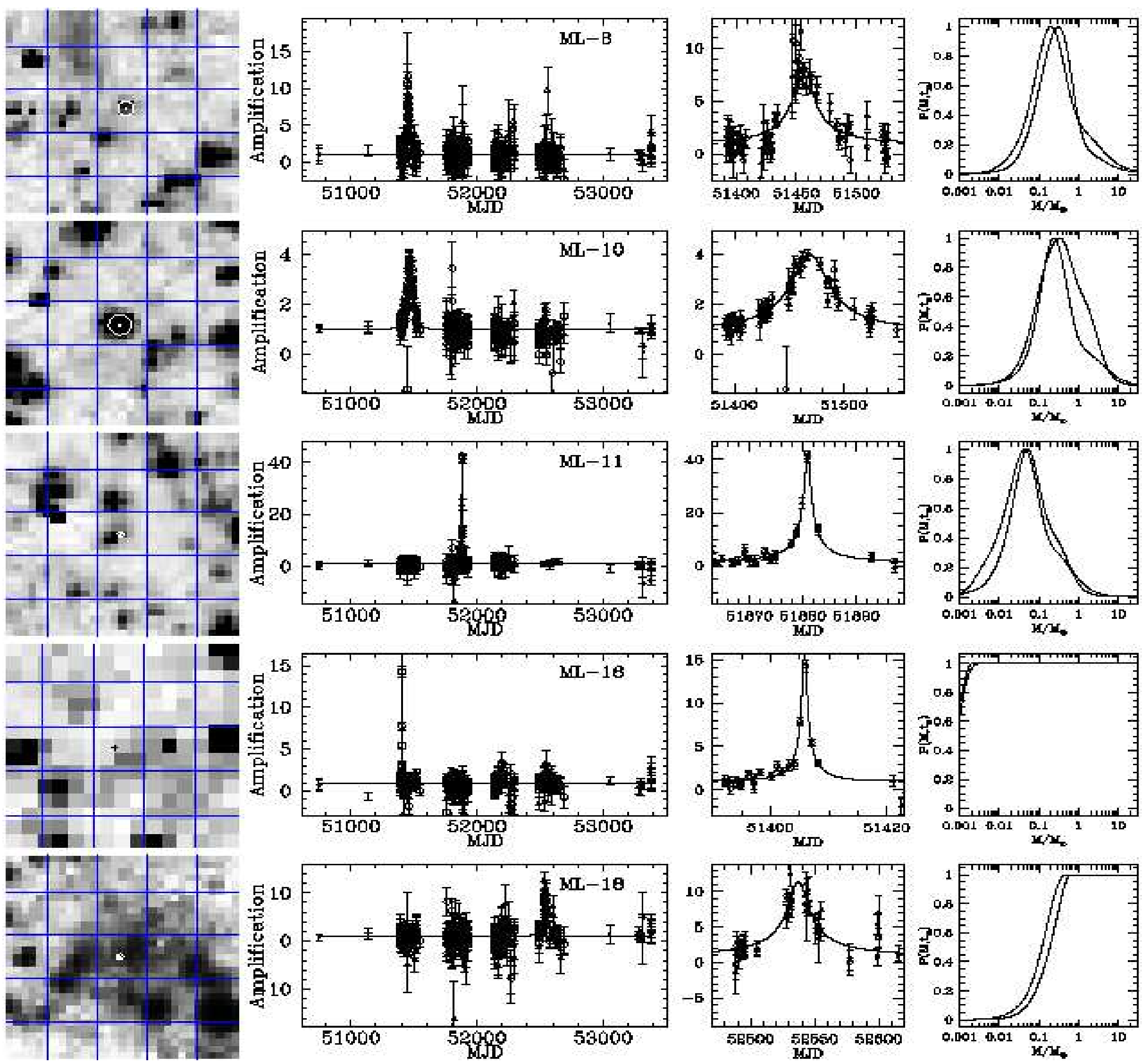

Fig. 1.— Left to right: 1) $(1''.5)^2$ *HST* image around microlensing candidates. The circles correspond to 1σ position errors. The grid represents the INT pixel sampling; 2) full combined light curve (Filled squares: KP-R, asterisks: KP-I, open circles: INT-r', open triangles: INT-i'); 3) Zoom on the event peak; 4) Lens-mass probability distribution for an isothermal halo; thick (thin) lines are for sources in the disk (bulge).

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.

2. Observations and analysis

To study candidate events we appeal to superior *HST* angular resolution: 160 ACS and WFPC2 images, taken in F555W and F814W filters in 16 orbits, cover 0.17 deg^2, ∼30% of the MEGA field. Here we study the largest sample of candidate microlensing events, the INT/WFC subsample of MEGA (de Jong et al. 2005), in order to understand and improve ground-based selection criteria.

The analysis used is detailed by Cseresnjes et al. (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 versus INT, r'/i' and KPNO 4m, R/I), providing up to 8 different position estimates (excepting one found by WFPC2 for ML-16). For a given ground-based position, the 2 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 are 0.02 to $0''.08$. Of 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 Fig. 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_E) to the combined light curve (Fig. 1). For the two undetected events, the resulting t_E corresponds to a lower limit. Only the einstein time-scale (t_E) constrains lens characteristics, particularly its mass m. In order to estimate m (or its lower-limit), we consider the simple case where the lens is part of a spherical isothermal halo composed of single mass objects. For a given time-scale t_E, the lens-mass probability distribution is $P(M, t_E) = (\mathrm{d}\Gamma/\mathrm{d}t_E)/\Gamma$, where Γ is the event rate (Griest 1991). We consider alternatively a source located in the disk and in the bulge. The lens mass probability function for each event is shown in Fig. 1, with 68% confidence limits in Table 1. Below we detail individual events:

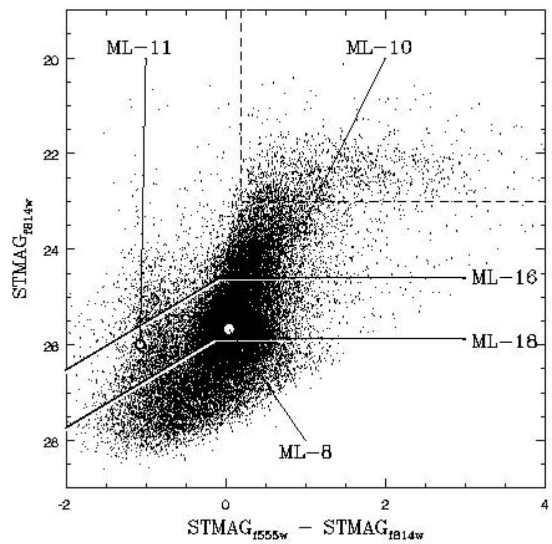

Fig. 2.— Color-magnitude plot of 5 candidate sources, with upper flux limits as thick lines. The dashed lines enclose the area where LPVs and semi-regulars are expected (Brown et al. 2004).

ML-8: this event's position lands within the FWHM of a red clump star, 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 paczynski fit yields amplification $A = 8.49$, an Einstein time-scale $t_E = 60.6 \pm 4.2$ days, and a disk source/halo lens mass $m = 0.31^{+0.48}_{-0.21} M_\odot$. However, this event lands $\sim 0''.9$ from the center of a background galaxy (subtending $\sim 1''.5 \times 0''.3$). Its color, flux and decline rate are consistent with a Type Ia supernova at $z \approx 0.5$, with $\lesssim 1$ mag extinction (see Johnson & Crotts 2005). One must balance the chance coincidence of a microlensing event this close to a $R \lesssim 23$ galaxy (probability $P \approx 3 \times 10^{-3}$) versus a supernova landing on a detected star of consistent color, $R - I = 0.6 \pm 0.3$ ($P \approx 10^{-2}$) or a star of consistent color at least this bright ($P \approx 3 \times 10^{-3}$).

ML-10: this lands within the FWHM disk of a giant branch star of color $\mathrm{R} - \mathrm{I} = 1.05$, in perfect agreement with the microlensing data. This source has $A = 4.00$ and $t_{_E} = 64.7 \pm 1.9$ days, corresponding to $m = 0.33^{+1.04}_{-0.23} M_\odot$. It lands suspiciously close to a region of the CMD common to variables. Still, the achromaticity of the variation, the well-fit and well-sampled peak ($\chi^2/N = 1.26$), and the stability of the baseline over 7 seasons strongly indicate a real microlensing event.

ML-11: this lands on a faint blue star ($\mathrm{R}-\mathrm{I} = 0.15\pm0.40$) severely blended with a red clump star. The light curves fit yields a similar $\mathrm{R}-\mathrm{I} = 0.21$. 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, $m = 0.05^{+0.16}_{-0.03} M_\odot$.

ML-16: this event (also seen by POINT-AGAPE) lands in a WFPC2 field. We find no detected source at this position, the nearest detected star landing $\sim 0''.1$ away. Since only INT-r' data are available during the event peak, and given the larger WFPC2 pixels, we cannot rule out this star as the source. Using this flux as an upper limit, we find $A > 16.01$, $t_{_E} > 6.9$ days, and $m > 0.003 M_\odot$ being poorly constrained.

ML-18: this event lands in a bright region, perhaps a cluster or background galaxy. We isolate no source here, providing only an upper limit baseline flux, estimated by taking the brightest pixel within $0''.05$ and considering that it contains <15% of the source flux. With this flux limit, $A > 11.42$, $t_{_E} > 86.6$ days, and $m \gtrsim 0.62\ M_\odot$.

3. Conclusions

Of 5 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 events from the asymtotic 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.

Taken together, these lenses in a halo model (Baltz, Gyuk & Crotts 2003) of a single component mass are constrained to $0.08 < m/M_\odot < 0.85$ at the 95% level for disk sources ($0.07 < m/M_\odot < 0.80$ if bulge sources). M31 microlensing rates may be consistent with pure self-lensing (de Jong et al. 2005), so we consider disk/bulge events ($0.35 < m/M_\odot < 2.5$), or disk/disk events which correspond to probably unrealistic brown dwarf masses ($0.008 < m/M_\odot < 0.08$).

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