Discovery and Characterization of a Caustic Crossing Microlensing Event in the SMC

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ABSTRACT

We present photometric observations and analysis of the second microlensing event detected towards the Small Magellanic Cloud (SMC), MACHO Alert 98-SMC-1. This event was detected early enough to allow intensive observation of the lightcurve. These observations revealed 98-SMC-1 to be the first caustic crossing, binary microlensing event towards the Magellanic Clouds to be discovered in progress.

Frequent coverage of the evolving lightcurve allowed an accurate prediction for the date of the source crossing out of the lens caustic structure. The caustic crossing temporal width, along with the angular size of the source star, measures the proper motion of the lens with respect to the source, and thus allows an estimate of the location of the lens. Lenses located in the Galactic halo would have a velocity projected to the SMC of $\hat{v} \sim 1500 \text{ km s}^{-1}$, while an SMC lens would typically have $\hat{v} \sim 60 \text{ km s}^{-1}$. The event lightcurve allows us to obtain a unique fit to the parameters of the binary lens, and to estimate the proper motion of the lensing system.

We have performed a joint fit to the MACHO/GMAN data presented here, including recent EROS data of this event (Afonso et al. 1998). These joint data are sufficient to constrain the time $t_*$ for the lens to move an angle equal to the source angular radius; $t_* = 0.116 \pm 0.010$ days. We estimate a radius for the lensed source of

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$R_\ast = 1.4 \pm 0.1 R_\odot$ from its unblended color and magnitude. This yields a projected velocity of $\hat{v} = 84 \pm 9 \, \text{km} \, \text{s}^{-1}$. Only $0.15\%$ of halo lenses would be expected to have a $\hat{v}$ value at least as small as this, while $31\%$ of SMC lenses would be expected to have $\hat{v}$ as large as this. This implies that the lensing system is more likely to reside in the SMC than in the Galactic halo. Similar observations of future Magellanic Cloud microlensing events will help to determine the contribution of Machos to the Galaxy’s dark halo.

*Subject headings:* dark matter - gravitational lensing - Stars: low-mass, brown dwarfs
1. Introduction

The MACHO project is monitoring stars in the Large Magellanic Cloud (LMC), in the Small Magellanic Cloud (SMC) and in the Galactic center, searching for the transient brightening that is characteristic of gravitational microlensing (e.g., Paczyński 1986). Our survey has detected over 250 likely lensing events to date. The majority of these are seen towards the Galactic center, presumably arising from lensing due to stars in the disk and bulge of the Galaxy. The event rates towards the LMC and SMC can be used to ascertain whether astrophysical objects comprise the dark matter halo of the Milky Way (Roulet & Mollerach 1997; Paczyński 1996). The rate of microlensing seen towards the LMC exceeds that predicted from known Galactic sources (Alcock et al. 1997b). The nature of this lensing population is unknown.

Are the excess LMC microlensing events due to Galactic dark matter in the form of Machos? The key to resolving this issue lies in determining the location of the lensing objects. If the excess microlensing optical depth seen towards the Magellanic Clouds is due to lensing by objects in the Magellanic Clouds, then the microlensing surveys will have ruled out Machos in the mass range $10^{-7} - 1 M_\odot$ as significant contributors to the mass of the Galaxy’s dark halo (Alcock et al. 1998; Alcock et al. 1997b; Renault et al. 1997).

An important development in the microlensing field has been the community’s ability to detect microlensing events in real time, allowing concentrated photometric and spectroscopic follow–up observations (Alcock et al. 1997a; Albrow et al. 1995; Udalski et al. 1994; Stubbs et al. 1994). The survey projects alert the community to ongoing microlensing events, and maintain web sites with pertinent information.

Occasionally a microlensing event’s light curve is seen to deviate from the characteristic shape expected for a point–like lens in inertial motion relative to the line of sight from us to a point–like source star. These “exotic” lensing events can break the degeneracy between the lens’ mass, location, and transverse velocity inherent in the standard gravitational microlensing model. In particular, if the foreground lens is a binary system, it is likely that the source will cross a lens “caustic” where two new images are created with a magnification which is singular for an instant, in the point source limit (Dominik 1998; Rhie 1997; Mao & Paczyński 1991). Once a caustic crossing has occurred, it is certain that a second caustic crossing will also occur because the extra images must disappear before the source departs the lens region.

Caustic crossing events, if adequately monitored, provide an opportunity to measure how long it takes for the caustic line to transit the face of the source star. Given the angular size of the source star, this provides a measurement of the transverse angular speed of the binary lens

1 EROS http://www-dapnia.cea.fr/Spp/Experiences/EROS/alertes.html
MACHO http://darkstar.astro.washington.edu
OGLE http://www.astrouw.edu.pl/~ftp/ogle/ogle2/ews/ews.html
with respect to the source, which constrains the lens’ transverse linear speed as a function of its distance along the line of sight. Such measurements are also possible for single lens events such as MACHO 95-BLG-30 (Alcock et al. 1997a), but finite source effects from single lenses will be extremely rare for sources of small angular size like those in the Magellanic Clouds.

2. 98-SMC-1: Discovery and Observations

Our ongoing survey program uses the 1.3m Great Melbourne telescope at Mt. Stromlo to produce dual-color photometry (Hart et al. 1996; Marshall et al. 1994; Stubbs et al. 1993). In addition, we have been granted the use of roughly one hour per night on the CTIO 0.9m telescope as service observing. We also make use of the 0.8m Reynolds telescope at Mt. Stromlo for following ongoing lensing events.

The source star in MACHO Alert 98-SMC-1 is located at \( \alpha = 00:45:35.2, \delta = -72:52:34.1 \) (J2000). A finding chart is available from the authors. MACHO Alert 98-SMC-1 was announced May 25.9 UT after the source had apparently brightened by \( \sim 0.9 \) mag. The baseline magnitude and color of the MACHO object had been constant over 5 years of observations, at \( V = 21.37 \pm 0.10, V - R = 0.14 \pm 0.05 \). Our binary microlens fit presented in Section 3 indicates that the lensed source has a brightness of \( V = 22.05 \pm 0.15, V - R = 0.03 \pm 0.10 \), with the additional unlensed flux provided by other sources within the seeing disk (as quite commonly occurs in these crowded fields).

Follow-up observations were scheduled nightly on the CTIO 0.9m telescope, which showed a gradual rise in the lightcurve until June 6.5 UT, when it was noticed the source had brightened suddenly by 1.5 mag. Photometry from the subsequent night confirmed that this was a likely caustic crossing event, and an IAU Circular was submitted alerting the astronomical community to the first real-time detection of a binary lensing event towards the Magellanic Clouds (Becker et al. 1998).

Continued observations allowed an estimate on the date of the second caustic crossing of June 19.3 \( \pm 1.5 \) UT (Bennett et al. 1998) to be issued June 15.3. This error bar was estimated based upon prior experience predicting caustic crossings (see Bennett et al. 1996a), and also because the path of the source was expected to cross the caustic at a small angle, so that a small error in the source trajectory translated into a large error in the time of the caustic crossing. Data from June 15 caused a revision of the caustic crossing time to June 19.2 \( \pm 1.5 \) UT, and June 17 data forced a revised prediction of June 18.2.

Figure 2 shows the joint MACHO/GMAN/EROS light curve for 98-SMC-1: dual color lightcurves from the MACHO Project’s Mt. Stromlo 1.3m telescope, the CTIO 0.9m telescope,
and the EROS Project’s 1.0m Marly telescope at La Silla (Palanque-Delabrouille 1997). The CTIO lightcurves are for the standard R and B bands, while the MACHO and EROS lightcurves are for their respective non-standard passbands. The MACHO and EROS data were reduced with the SoDOPHOT photometry package used for routine reduction of MACHO data, while the CTIO data were reduced with ALLFRAME (Stetson 1994). In each case, the photometric error estimates reported by the photometry code are used, with minimum errors of 0.014, 0.01, and 0.005 added in quadrature for the MACHO, EROS, and CTIO data, respectively. The CTIO error estimates are also multiplied by 1.5, although this appears to overestimate the errors for this event. Each lightcurve is normalized to the best fit unlensed flux of the source, so that the brightness of any unlensed (blended) sources has been subtracted out. The overall structure is consistent with a caustic crossing binary lens event.

Figure 2 shows a close-up of the latter part of the lightcurve for the MACHO-R, CTIO-R, and EROS-B data. The CTIO-R band data were generally taken over a period of less than 1.5 hours, and have been binned nightly for every night except for June 18.

3. Analysis

Once it was realized that 98-SMC-1 was a likely binary microlensing event, it was modeled using the binary lens fitting code developed by two of us (Rhie & Bennett 1998; Bennett & Rhie 1996). Starting with the data available on June 8, we began a series of Monte Carlo searches that initially resulted in several possible binary microlensing fits. By June 14, only one good fit remained, and an accurate caustic crossing prediction was announced (Bennett et al. 1998). This preliminary lightcurve and fit parameters were posted on the WWW.

A caustic crossing binary lens lightcurve can be described by 7 parameters if the orbital motion of the lensing objects is neglected. These parameters include the 3 parameters for a single lens fit which are \( \hat{t} \), the Einstein diameter crossing time; \( u_{\text{min}} \), the distance of closest approach between the lens center of mass and the source; and \( t_0 \), the time of the closest approach. The 3 intrinsic binary parameters are the binary source separation, \( a \), the mass fraction of the mass \# 1, \( \epsilon_1 \), and the angle between the lens axis and the source trajectory, \( \theta \). The final parameter is the stellar radius crossing time \( t_\star \), which is the time for the lens to move relative to the source by an angle equal to the source angular radius. Thus the caustic crossing duration is \( 2t_\star / \sin \phi \), where \( \phi \) is the angle between the relative motion vector and the caustic line. This parameter is sensitive to the assumed limb darkening model. We use a simple linear limb darkening model (Claret, Diaz-Cordoves, & Gimenez 1995) with coefficients 0.482, 0.620, 0.506, 0.697, 0.460, and 0.561 for the MACHO-R, MACHO-V, CTIO-R, CTIO-B, EROS-R, and EROS-B passbands, respectively.

\[^1\text{see http://darkstar.astro.washington.edu/98-SMC-1lev2.htm and http://bustard.phys.nd.edu/MPS/98-SMC-1/}\]
Table 1 shows the June 15 pre-caustic crossing fit parameter estimates (as the first line) and the current best fit parameters with errors in the second line. Note that the parameters have changed only slightly between the pre-caustic crossing fit and the current fit. The fit lightcurves are shown in Figures 1 and 2, and the parameters of the fit are shown in Tables 1 and 2. Fit statistics are shown in Table 3. Note that the $\chi^2$ per degree of freedom is less than 1 for every passband, except for the MACHO passbands where it is somewhat larger than 1. The excess fit $\chi^2$ in the MACHO data is partially due to excess scatter in the baseline, and from very high airmass observations on June 18. However, there is a significant “bump” in the MACHO lightcurves near June 17.7 which is not easily explained away as photometric error. This might be consistent with a caustic crossing of a binary companion 3-4 magnitudes fainter than the primary lensed star.

However, assuming a single source, the uniqueness of this fit seems sound. The MACHO data characterize the full lightcurve. Each night of CTIO observations, begun soon after MACHO’s initial alert, constrains the overall lightcurve at the $\lesssim 3\%$ level. Especially important constraints are the flux preceding the first caustic crossing, the minimum flux between caustics, and the magnitude of the cusp passage after the second caustic crossing, which strongly constrains $\theta$ and avoids fit uncertainties present in other analyses of this event (Albrow et al. 1998; Alonso et al. 1998). The two fits presented by the PLANET collaboration (Albrow et al. 1998), for example, both appear inconsistent with the pre-caustic crossing MACHO and CTIO data. However, PLANET was able to densely sample the peak of the caustic crossing, measuring to high precision the time taken by the caustic to transit the source. The EROS data used in this analysis strongly constrain the falling slope and end-point of the caustic crossing, which leads to our estimate of the lens velocity projected to the SMC.

3.1. Projected Lens Velocity ($\hat{v}$)

In order to convert the fit parameter $t_\ast$ to a projected velocity $\hat{v}$, we need to estimate the radius of the source star. The color of the lensed star is $V - R = 0.03$, which may be determined from the microlensing fit or simply from the mean color of the MACHO observations on June 17, when the entire star was highly magnified. Assuming $E(V - R) = 0.03$ and $T_{\text{eff}} = 8000K$ (Albrow et al. 1998), we obtain $R_\ast = 1.4 \pm 0.1 R_\odot$ and $M_V = 2.8 \pm 0.3$ (Bertelli et al. 1994; Lang 1991). For an assumed source distance of 60 kpc, this yields $m_V = 21.8 \pm 0.3$, which is consistent with the value $m_V = 22.05 \pm 0.15$ determined from the microlensing fit and the MACHO photometric zero point determination.

If we divide the stellar radius of $R_\ast = 1.4 \pm 0.1 R_\odot$ by the stellar radius crossing time $t_\ast = 0.116 \pm 0.010$ days, we obtain a projected velocity of $\hat{v} = 84 \pm 9$ km s$^{-1}$, which can be used to estimate the location of the lens.

By definition, $\hat{v} \equiv v_\perp / x$, where $v_\perp$ is the tangential velocity of the lens relative to the observer-source line, and $x$ is the ratio of the observer-source to observer-lens distances (cf. Han 

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For a given lens mass, the rate of microlensing is proportional to
\[
d\Gamma \propto \sqrt{x(1-x)} \rho_L(x) v_\perp f_S(v_S) f_L(v_L) \, dx \, dv_S \, dv_L.
\] (1)

where \( \rho_L \) is the density of lenses at distance \( x \), \( f_L(v_L) \) and \( f_S(v_S) \) are the 2-D lens and source velocity distribution functions (normalized to unity) in the plane perpendicular to the line of sight. The source and lens velocities \( v_S, v_L \) are related to \( \hat{v} \) by \( v_L = (1-x)v_\odot + x(v_S + \hat{v}) \), where \( \hat{v} = (\hat{v}\cos\alpha, \hat{v}\sin\alpha) \) and \( \alpha \) is the (unknown) direction on the sky of the relative proper motion.

Given a model for \( \rho_L, f_S, f_L \), we may integrate eq. (1) and thus obtain joint probability distributions for any of the variables. We need to consider the joint probability distribution of events in the \((x, \hat{v})\) plane, and then integrate over \( x \) to get a probability distribution of \( \hat{v} \) for each lens population. This gives
\[
L(\hat{v}) = \left. \frac{d\Gamma}{d\hat{v}} \right|_{\hat{v}} \propto \int dx \sqrt{x(1-x)} \rho_L(x) \hat{v}^2 x^3 \int dv_S \, dv_L \, f_S(v_S) f_L((1-x)v_\odot + x(v_S + \hat{v}))
\] (2)

We evaluate eq. (2) over \( \hat{v} \) separately for lenses either in the dark halo or the SMC. We assume that the source is in the SMC, thus \( f_S \) is a Gaussian with velocity dispersion of 30 km s\(^{-1}\) in each component, centered on the SMC mean velocity which is taken as the projection of \((U, V, W) = (40, -185, 171)\) km s\(^{-1}\) (Gardiner & Noguchi 1996) onto the plane normal to the line of sight. For halo lenses we assume \( \rho_L \) is a ‘standard’ isothermal sphere with core radius 5 kpc. We take \( f_L \) to be a Gaussian with zero mean and velocity dispersion 155 km s\(^{-1}\) in each component.

Figure 3 shows the predicted \( \hat{v} \) distributions as calculated from eq. (2) with the measured \( \hat{v} \) value indicated. The distributions peak at \( \sim 60 \) km s\(^{-1}\) for SMC lenses and 1500 km s\(^{-1}\) for halo lenses. (Note that since Figure 3 has a logarithmic \( x \)-axis, what is actually plotted is \( \hat{v}L(\hat{v}) = d\Gamma/d\log \hat{v} \), so areas under these curves represent relative probabilities.) The peak for SMC lenses occurs at a value larger than 30 km s\(^{-1}\) for several reasons: \( \hat{v} \) has two components, it is the relative source-lens motion, and there is the factor of \( v_\perp \) in the event rate per lens. Integrating these curves we find that only 0.15% of halo lenses would have a \( \hat{v} \leq 84 \) km s\(^{-1}\), while \( \sim 31\% \) of SMC lenses would have a \( \hat{v} \) larger than this value. Thus it is highly probable that this binary lens is located in the SMC.

4. Conclusions

The MACHO Alert system has detected the first on-going exotic microlensing event towards the Magellanic Clouds. The combination of real-time event detection and GMAN follow-up observations provided early recognition of 98-SMC-1 as a caustic crossing binary lens, and allowed an accurate prediction of the second caustic crossing time. MACHO/GMAN instituted intense photometric coverage of the event leading up to and during the second caustic crossing, allowing a unique binary lens solution for 98-SMC-1. Including data taken by the EROS collaboration during the caustic crossing (Afonso et al. 1998) allows a measurement of the lens proper motion.
Assuming a lensed source with $R_* = 1.4 \pm 0.1 R_\odot$ located at 60 kpc, the measured crossing time of $t_* = 0.116 \pm 0.010$ days gives an estimate of the lens velocity projected to the SMC of $\hat{v} = 84 \pm 9$ km s$^{-1}$. This relatively slow crossing indicates the source and lens are likely members of the same population in the SMC. The probability for a Galactic halo lens to produce a $\hat{v}$ value this small is of order 0.2%. This conclusion is substantially stronger than that of the EROS collaboration (Afonso et al. 1998) who concluded that $\sim 7\%$ of Galactic halo lenses were consistent with their caustic crossing data: this is because they were only able to constrain one component of $\hat{v}$ without a fit to the full microlensing lightcurve. The PLANET collaboration (Albrow et al. 1998) did fit the entire microlensing lightcurve, but neither of the two fits they present appears to be consistent with the MACHO and CTIO pre-caustic crossing data. However, our conclusions are qualitatively consistent with both EROS and PLANET analyses of this event.

Since this event is likely due to a lens in the SMC, and the previously discovered SMC event also may be due to an SMC lens (Palanque-Delabrouille et al. 1998; Alcock et al. 1997c), it is interesting to discuss the measured vs. expected optical depth for SMC self-lensing. We have not yet performed a careful efficiency calculation for the SMC, but with about 2.2 million stars monitored over about 5.1 years, and using SMC sampling efficiencies of about 30%, we estimate an observed optical depth $\tau_{\text{est}} = 2 - 3 \times 10^{-7}$ for the two known SMC events. For SMC self-lensing, Palanque-Delabrouille et al. (1998) use a prolate ellipsoid model aligned along the line-of-sight to predict optical depths between $1 \times 10^{-7}$ and $1.8 \times 10^{-7}$, depending upon the extent of the SMC along the line-of-sight. Given the small number of events, this estimate is quite consistent with the observed optical depth. For completeness, we note that the predicted optical depth for halo lensing towards the SMC is about $6 \times 10^{-7}$ for a 100% Macho halo.

There has been one previous caustic crossing binary lensing event detected towards the Magellanic Clouds, MACHO LMC-9, reported in Bennett et al. (1996b). This event occurred before the MACHO Alert system was fully functional, and was not discovered while in progress. However, there were two observations apparently taken during the first caustic crossing. These yield an estimate of $\hat{v} \sim 20$ km s$^{-1}$ which is rather slow, but is still consistent with a lens residing in the LMC if the LMC has a low velocity dispersion. If the LMC had self-lensing optical depth large enough to explain the bulk of the LMC microlensing events, then a high LMC velocity dispersion would also be expected (Gould 1995). This would be difficult to reconcile with the $\hat{v}$ estimate for LMC-9, suggesting that more complicated caustic crossing models (such as a binary source model) should be considered. The real–time discovery of MACHO 98-SMC-1 has resulted in the collection of enough data to avoid such ambiguities for this event.

Similar follow–up observations of future Magellanic Cloud microlensing events may also yield estimates of the lens distance through the observation of caustic crossings or other exotic microlensing phenomena, such as the parallax effect and binary source effects. A statistically

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4 PLANET maintains information on this microlensing event at [http://www.astro.rug.nl/~planet/MS9801.html](http://www.astro.rug.nl/~planet/MS9801.html)
significant sample of such events may help resolve the mystery posed by the microlensing results towards the Large Magellanic Cloud.

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Table 1. 98-SMC-1 binary microlensing event parameters

| $t_0$ a | $\tilde{t}$ (days) | $u_{\text{min}}$ | $a$ | $\theta$ (rad) | $\epsilon_1$ | $t_*$ (days) |
|---------|-------------------|-----------------|-----|----------------|-------------|--------------|
| 14.5    | 149               | 0.043           | 0.678 | -0.205         | 0.276       | ?            |
| 14.931 (15) | 147.58 (41) | 0.04628 (12) | 0.66365 (84) | -0.1803 (18) | 0.27929 (57) | 0.116 (10) |

a Date in June UT.

Line 1 presents the preliminary binary lens fit parameters announced on June 15, before the second caustic crossing. The second line shows the current best fit binary lens parameters used in the analysis.

Table 2. 98-SMC-1 binary microlensing blending parameters

| CTIO R | CTIO B | EROS R | EROS B | MACHO R | MACHO V |
|--------|--------|--------|--------|---------|---------|
| 0.79   | 1.00   | 0.83   | 0.40   | 0.47    | 0.56    |

Blend fractions are in the sense of $\text{flux}_{\text{lensed}}/\text{flux}_{\text{total}}$. 
Table 3. 98-SMC-1 fit statistics

| Passband | # Observations | $\bar{d} \delta m$ a | $\bar{d} \delta m$ b | Binary Lens Fit $\chi^2$ c |
|----------|----------------|----------------------|----------------------|-----------------------------|
| CTIO R   | 84             | —                    | 0.041                | 44.4                        |
| CTIO B   | 22             | —                    | 0.045                | 10.4                        |
| EROS R   | 38             | —                    | 0.20                 | 19.5                        |
| EROS B   | 38             | —                    | 0.077                | 12.2                        |
| MACHO R  | 704            | 0.55                 | 0.10                 | 921.5                       |
| MACHO V  | 712            | 0.49                 | 0.093                | 763.9                       |
| TOTAL    | 1598           |                      |                      | 1771.9                      |

a Average photometric error, in magnitudes, before alert.

b Average photometric error, in magnitudes, after alert.

c The binary lens fit contains 7 global constraints, plus 2 additional baseline constraints per passband.
Fig. 1.— The light curve of event 98-SMC-1. The panels show magnification as a function of time, with passbands and sites as indicated. The times of the initial alert and the confirmation of the caustic crossing are shown with arrows. The best fit binary microlensing curve is shown as a solid line.
Fig. 2.— A close-up view of the last half of the light curve of event 98-SMC-1. Included are the date of the original second caustic crossing prediction, and the prediction with error bars of 1.5 days. Only the MACHO-R (green triangles), CTIO-R (red circles) and EROS-B (blue squares) data are plotted.
Fig. 3.— Predicted $\hat{v}$ distributions for halo and SMC lenses. The measured value of $\hat{v}$ and error bars are indicated with vertical lines.