A Binary Lensing Event Toward the LMC: Observations and Dark Matter Implications

D.P.Bennett[a,b,c,d], C.Alcock[a,b], R.A.Allsman[e], D.Alves[b,c], T.S.Axelrod[b,f], A.Becker[g], K.H.Cook[b], K.C.Freeman[f], K.Griest[a,h], J.Guern[a,h], M.J.Lehner[a,h], S.L.Marshall[a,b], D.Minniti[b], B.A.Peterson[f], M.R.Pratt[b,g], P.J.Quinn[i], S.H.Rhie[a,b], A.W.Rodgers[f], C.W.Stubbs[a,h], W.Sutherland[j], and D.Welch[k]
*

[a]Center for Particle Astrophysics, University of California, Berkeley, CA 94720

[b]Lawrence Livermore National Laboratory, Livermore, CA 94550

[c]Department of Physics, University of California, Davis, CA 95616

[d]Department of Physics, University of Notre Dame, Notre Dame, IN 46556

[e]Supercomputing Facility, Australian National Univ., Canberra, ACT 0200, Australia

[f]Mount Stromlo and Siding Springs Obs., Australian National Univ., Weston, ACT 2611, Australia

[g]Departments of Physics and Astronomy, University of Washington, Seattle, WA 98195

[h]Department of Physics, University of California San Diego, La Jolla, CA 92093-0350

[i]European Southern Observatory, Garching, Germany

[j]Department of Physics, University of Oxford, Oxford OX1 3RH, U.K.

[k]Departments of Physics and Astronomy, McMaster Univ., Hamilton, Ont., Canada L8S 4M1

The MACHO collaboration has recently analyzed 2.1 years of photometric data for about 8.5 million stars in the Large Magellanic Cloud (LMC). This analysis has revealed 8 candidate microlensing events and a total microlensing optical depth of $\tau_{\rm meas} = 2.9\,^{+1.4}_{-0.9} \times 10^{-7}$. This significantly exceeds the number of events (1.1) and the microlensing optical depth predicted from known stellar populations: $\tau_{\rm back} = 5.4 \times 10^{-8}$, but it is consistent with models in which about half of the standard dark halo mass is composed of Machos of mass $\sim 0.5{\rm M}_\odot$. One of these 8 events appears to be a binary lensing event with a caustic crossing that is partially resolved, and the measured caustic crossing time allows us to estimate the distance to the lenses. Under the assumption that the source star is a single star and not a short period binary, we show that the lensing objects are very likely to reside in the LMC. However, if we assume that the optical depth for LMC-LMC lensing is large enough to account for our entire lensing signal, then the binary event does not appear to be consistent with lensing of a single LMC source star by a binary residing in the LMC. Thus, while the binary lens may indeed reside in the LMC, there is no indication that most of the lenses reside in the LMC.

1. INTRODUCTION

The MACHO project is a dedicated search for Galactic dark matter in the form of MAssive Compact Halo Objects (or Machos) using a grav-

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itational microlensing technique [1,2]. By photometrically monitoring millions of stars in the LMC, we are able to detect rare instances of gravitational microlensing. Microlensing occurs when a dark object, such as a faint star or a Macho, comes close enough to the line of sight to one of our target stars in the LMC so that the gravitational field of the dark object magnifies the star by a significant amount (typically a factor of 2 or more).

The MACHO team has recently completed analysis of data for 8.5 million stars spanning 2.1 years of observations [5,4]. The analysis of this data has revealed 8 candidate microlensing events with timescales in the range 34 days $< \hat{t} <$ 145 days. The probability that a single target star will be magnified by more than a factor of 1.34 is commonly referred to as the microlensing optical depth, τ. τ is a particularly useful measure of the "amount" of microlensing because it is proportional to the total mass in lensing objects and independent of the masses and velocities of the lenses. (It does depend on the spacial distribution of the lenses, however.) The MACHO data gives a microlensing optical depth in events with an Einstein diameter crossing time $\hat{t} < 200$ days of $\tau_{\rm meas} = 2.9^{+1.4}_{-0.9} \times 10^{-7}$. This can be compared to the predicted microlensing background due to lensing by known stellar populations of $\tau_{\rm back} = 5.4 \times 10^{-8}$ and the microlensing optical depth of a standard halo model consisting entirely of Machos: $\tau_{\rm halo} = 4.7 \times 10^{-7}$. This suggests that perhaps half of the mass of the "standard" dark halo of our Galaxy is composed of Machos which give rise to lensing events with $\hat{t} \lesssim 200$ days. The observed timescales imply a typical Macho mass of $\sim 0.5 M_{\odot}$, but this is somewhat model dependent. The simplest explanation of these microlensing results is that a significant fraction of the Galactic halo is composed of white dwarfs. The remainder of the dark halo could be in more massive Machos which give rise to longer events, or it could be in some form other than Machos. For some "non-standard" halo models it is even possible that the halo is composed entirely of Machos of mass $< 1 M_{\odot}$.

One difficulty with the microlensing dark matter search technique is that the distance and mass of the lens cannot generally be determined on on an event-by-event basis. For most events, all information on the distance, velocity, and mass of the lens is folded into a single measurable parameter, the event timescale $\hat{t}$. This is why the lensing by known populations of stars in the Galactic disk and the LMC cannot usually be distinguished from lensing by halo objects on an event-by-event basis. Thus, the main argument indicating that there is a previously undiscovered population of Machos in the halo is the excess observed number of events and optical depth over the predicted lensing background.

For certain types of exotic microlensing events additional parameters can be measured that can help lift the degeneracy. One example is a parallax event in which the lightcurve shows an asymmetry due to the orbital motion of the Earth [6]. A parallax event lightcurve fit provides an estimate of the transverse velocity of the lens projected to the position of the solar system. We can then use our knowledge of the velocity distributions in our Galaxy to make a lens distance estimate good to about 30%. Single [7] or binary [8,9] lensing events in which a caustic crossing occurs can also be used to estimate the distance to the lens. The intrinsic lightcurve shape at a caustic crossing is so highly peaked that the actual width of the caustic crossing lightcurve is determined by the angular size of the source star. The observed caustic crossing time can be compared to the known angular size of the source star to obtain a projected transverse velocity, and this can be used to make a distance estimate.

2. LMC Binary Event

Figure 1 shows the lightcurve of the LMC binary event as well as a closeup of the lightcurve along with the best fit binary lens lightcurve. There are many more data points in our blue band than in our red band for two reasons. First, the Mt. Stromlo 50" telescope has a equatorial German mount that allows us to observe from both sides of the Pier. For east of pier observations, this star falls on a non-functional region of one of our CCD's in the red focal plane. In addition, for the west of pier observations this

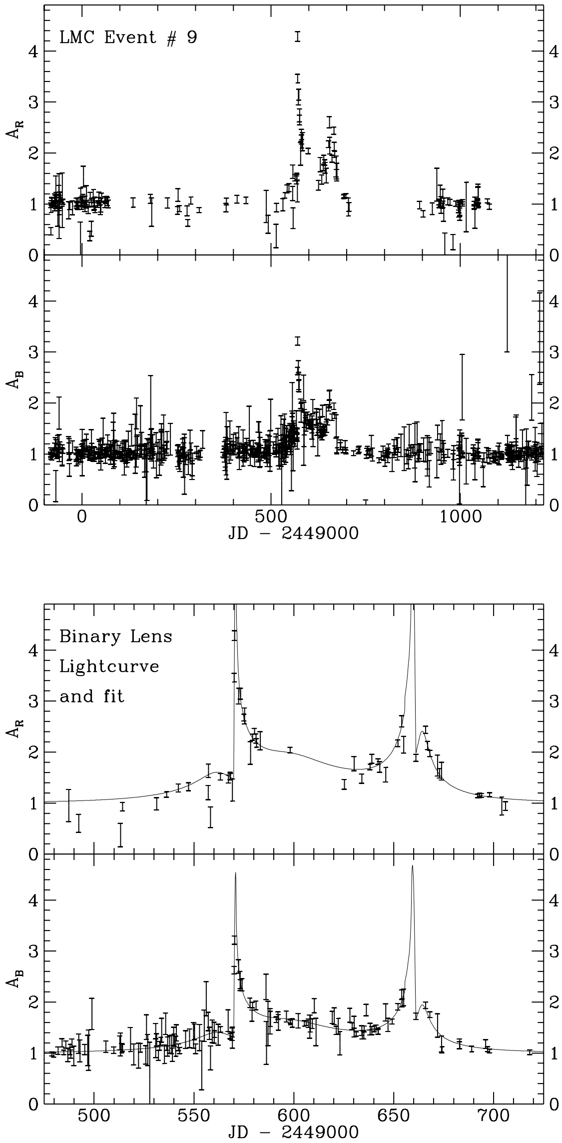

Figure 1. The full dual color lightcurve of the LMC binary lensing event is plotted in the upper panel while the lower panel shows a closeup of the lightcurve along with the fit lightcurve described in the text. Many of the measurements in the red band have been contaminated by a previously undetected CCD trap. A cut has been applied to remove the measurements in which this contamination is expected to be severe.

star often falls on or near a previously undetected CCD trap which smears the flux along a CCD column. We have removed all red data in which this bad column comes within 6 pixels and 1.5 times the PSF FWHM of the source star from the plot shown in Figure 1. Due to the extreme crowding of stellar images in this field, however, it is possible that this procedure does not remove all the red observations which might be contaminated.

A dual color binary microlensing lightcurve is described by 11 parameters. Two parameters, f_{0R} and f_{0B}, describe the unlensed brightness of the lensed star in each color band, and in the crowded fields in which we work, we also need two parameters (f_{uR} and f_{uB}) to describe the flux of unlensed stars that may be superimposed on the same resolving element as the lensed star. Three of the intrinsic microlensing parameters are the same as the parameters for a single lens. These are: the Einstein diameter crossing time for the total mass, $\hat{t}$, the time of closest approach, t_0, between the angular positions of the lens center of mass and the source star, and the distance of closest approach, $u_{\rm min}$, which is measured in units of the Einstein radius. There are three other intrinsic microlensing parameters which are unique to the binary lens: a, the separation of the two lens masses in units of the Einstein radius, the angle, θ, between the lens axis and the apparent motion of the source in the lens plane, and ϵ_1, the mass fraction of mass #1. ($\epsilon_2 \equiv 1 - \epsilon_1$.) Finally, the parameter which can allow us to learn more about the location of the lens is the time, $t_{\rm star}$, it takes for the source star to move by one stellar radius with respect to the angular position of the lens center of mass.

The formula for the lightcurve in terms of these parameters is well known [10,11] but is rather complicated. We obtain the following fit parameters: $f_{0R} = 0.259 \pm 0.002$, $f_{0B} = 0.174 \pm 0.001$, $f_{uR} = 0.741 \pm 0.004$, $f_{uB} = 0.826 \pm 0.002$, $\hat{t} = 143.4 \pm 0.2\,$days, $t_0 = 603.04 \pm 0.02\,$days, $u_{\rm min} = -0.055 \pm 0.001$, $a = 1.6545 \pm 0.0008$, $\theta = 0.086 \pm 0.001$, $\epsilon_1 = 0.620 \pm 0.002$, and $t_{\rm star} = 0.65 \pm 0.18\,$days. The binary lens fit gives $\chi^2 = 1489$ for 848 degrees of freedom or a reduced χ^2 of 1.76. (The best single lens fit gives a reduced χ^2 of 6.03.) The flux parameters have been normalized to give a total unlensed flux of 1 in each color band, and the unmagnified magnitudes of the lensed component are $V = 21.10$ and $R = 20.76$. Note that we must *assume* that the source star is a single star and not a close binary because we have only two observations on the caustic crossing feature. We have recently demonstrated the capability to predict caustic crossing events [9], so future caustic crossings can be observed much more frequently.

3. Implications

It is the parameter $t_{\rm star}$ that can potentially teach us more about the lensing event because it depends on the finite size of the source star. Using the magnitudes of the lensed star, and assuming between 0.2 and 0.6 magnitudes of extinction in V and an LMC distance modulus of 18.5, we estimate $M_V = 2.2 \pm 0.2$. This implies that the star is an A7-8 main sequence star with a radius of $R_{\rm star} = 1.5 \pm 0.2\, R_\odot$. Combining this with the observed $t_{\rm star}$ value yields

$$v_{\rm proj} = \frac{R_{\rm star}}{t_{\rm star}} = 19 \pm 6\,{\rm km/s} \qquad v_{\rm proj} \equiv \frac{v_\perp}{x}, \quad (1)$$

where $v_\perp$ is the transverse velocity of the lens with respect to the line of sight and x is the ratio of the lens and source distances.

Figure 1 shows the predicted $v_{\rm proj}$ distribution for lenses in the LMC disk and Milky Way halo with the measured $v_{\rm proj}$ also indicated. Clearly, a lens in the LMC disk is prefered over a halo lens. In fact, the $v_{\rm proj}$ value seems to be somewhat smaller than expected for a lens in the LMC disk. This is, in fact, what one would expect if the source was a short period binary rather than a single star. Roughly speaking, we can expect binaries with periods of less than a few hundred days to be separated by a distance much smaller than the Einstein ring radius. From reference [12], we see that about 20% of late A star binaries have periods of less than 100 days. Of these, about half will have a companion that is at least 25% as bright as the primary. Thus, a reasonable a priori estimate of the fraction of caustic crossing events that will have a detectable binary source character is about 10%. If the source star is a single star, then the measured $v_{\rm proj}$ value is only marginally consistent with lensing by an LMC object. For a binary source, however, we would expect abnormally low values of $v_{\rm proj}$ for lenses in the LMC, the Milky Way halo, or even the Milky Way disk. Thus, we need to determine if the source star is actually a binary in order to determine the location of the lens. It may be possible to accomplish this by obtaining a single spectrum of the source star because late A stars appear to have spectral peculiarities when they are in short period binary systems [12]. This will be complicated by the fact that the source star is superimposed on a brighter unlensed source, but analysis of the image centroid motion during the lensing event indicates that the brighter companion is actually 0.3" away from the lensed star. Thus, is possible to get a spectrum with HST that can determine whether the source star is likely to be a binary.

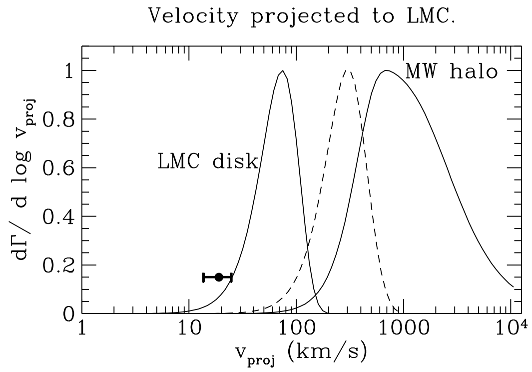

Figure 2. The probability distributions of the $v_{\rm proj}$ are plotted for lenses residing in the LMC disk and Milky Way halo. The dashed curve represents the $v_{\rm proj}$ distribution for a super-massive LMC disk with $\langle v^2 \rangle = 60\,{\rm km/s}$. The $v_{\rm proj}$ value for the LMC binary event is indicated with a horizontal error bar.

Now, let us assume that the source star is not a binary and consider the implications if the lens is actually in the LMC. It might be tempting to conclude that since the one lens that we can estimate the distance for appears to be in the LMC, perhaps LMC-LMC lensing might explain most

Table 1
LMC Velocity Dispersion and Self-Lensing Optical Depth

$v_{\rm rms}$	$P(v_{\rm prop} = 19\,{\rm km/s})$	τ(LMC-LMC)
20	13%	1.1×10^{-8}
25	7%	1.8×10^{-8}
30	4%	2.5×10^{-8}
40	1.8%	4.5×10^{-8}
50	0.9%	7.0×10^{-8}
60	0.5%	1.0×10^{-7}
75	0.3%	1.6×10^{-7}

The probability of obtaining the observed value of $v_{\rm prop}$ and the LMC self-lensing optical depth are listed as a function of the RMS line of sight velocity dispersion, $v_{\rm rms}$.

or even all of the lensing events. This would require that the microlensing optical depth for LMC-LMC lensing be substantially in excess of the value we have used in our microlensing background calculations. As Gould [13] has shown, the self-lensing optical depth of a self-gravitating system is related to its velocity dispersion. For a nearly face on disk like the LMC, the relationship is

$$\tau = 2\frac{\langle v^2 \rangle}{c^2}\sec^2 i = 2.52\frac{\langle v^2 \rangle}{c^2}, \qquad (2)$$

where we have used $i = 27°$ as the inclination angle of the LMC disk.

The $v_{\rm prop}$ distribution also depends on $v_{\rm rms}$. The solid curve in Figure 2 indicates the $v_{\rm prop}$ distribution for $v_{\rm rms} = 25\,{\rm km/s}$ which is the measured value for CH stars [14]. The dashed curve indicates the $v_{\rm prop}$ distribution for $v_{\rm rms} = 60\,{\rm km/s}$. Clearly, $v_{\rm prop} = 19\,{\rm km/s}$ is an unlikely value for such a high line of sight velocity dispersion. Yet, the self-lensing optical depth for $v_{\rm rms} = 60\,{\rm km/s}$ is still outside the 2-σ confidence interval of the measured microlensing optical depth. The relationship between $v_{\rm rms}$, the self-lensing optical depth and the likelyhood of $v_{\rm prop} = 19\,{\rm km/s}$ is summarized in Table 1. $P(v_{\rm prop} = 19\,{\rm km/s})$ is just the relative likelyhood of $v_{\rm prop} = 19\,{\rm km/s}$ compared to the most likely value for $v_{\rm prop}$. Only for $v_{\rm rms} = 75\,{\rm km/s}$ is the self-lensing optical depth consistent with the 2-σ confidence interval on $\tau_{\rm meas}$, but this gives a very small probability for the measured $v_{\rm prop}$ value. In this case, the most reasonable explanation for the small $v_{\rm prop}$ value is the possibility of a binary source as discussed above. However, if the source is a binary, then the argument favoring a lens in the LMC disappears. Thus, if the LMC self-lensing optical depth is significantly smaller than $\tau_{\rm meas}$, then there is some reason to suspect that the binary lens may reside in the LMC, but if LMC self-lensing is responsible for most of the total microlensing optical depth observed toward the LMC, then location of the LMC binary event cannot be determined from the caustic crossing fit parameter. Clearly, the LMC binary event lends no weight to the hypothesis that the LMC self-lensing optical depth is substantially larger than 3×10^{-8} (the value used for our lensing background calculations).

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