OBSERVATIONS OF THE BINARy MICROlENS EVENT MACHO 98-SMC-1 BY THE MICROlENSING PLANET SEARCH COLLABORATION

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ABSTRACT

We present observations of the binary microlensing event MACHO 98-SMC-1 conducted at the Mount Stromlo 1.9 m telescope by the Microlensing Planet Search (MPS) collaboration. The MPS data constrain the first caustic crossing to have occurred after 1998 June 5.55 UT and thus directly rule out one of the two fits presented by the PLANET collaboration (model II). This substantially reduces the uncertainty in the relative proper-motion estimations of the lens object. We perform joint binary microlensing fits of the MPS data together with the publicly available data from the EROS, MACHO/GMAN, and OGLE collaborations. We also study the binary lens fit parameters previously published by the PLANET and MACHO/GMAN collaborations by using them as initial values for \( \chi^2 \)-minimization. Fits based on the PLANET model I appear to be in conflict with the GMAN-CTIO data. From our best fit, we find that the lens system has a proper motion of \( \mu = 1.5 \pm 0.3 \) km s\(^{-1}\) kpc\(^{-1}\) with respect to the source, which implies that the lens system is most likely to be located in the Small Magellanic Cloud, strengthening the conclusion of previous reports.

Subject heading: dark matter — gravitational lensing — stars: low-mass, brown dwarfs

1. INTRODUCTION

The Microlensing Planet Search (MPS) Project monitors microlensing events discovered in progress by the EROS (Afonso et al. 1998), MACHO (Alcock et al. 1997a), and OGLE (Udalski et al. 1994) experiments in search of a microlensing signature of planets orbiting faint lens stars or "nonstandard" microlensing light curves that can provide an additional constraint on the distance and mass of the "dark" lens systems. The MPS project primarily monitors microlensing events toward the central regions of the Galaxy, where the microlensing events are most numerous. However, "nonstandard" events detected toward the Magellanic Clouds present a unique opportunity to learn about the composition of the dark halo that dominates the mass of the Milky Way, and these events are observed at a high priority. The binary microlensing event MACHO 98-SMC-1 was one such case.

After its discovery and announcement by the MACHO/GMAN collaboration (Becker et al. 1998; Bennett et al. 1998) as a binary microlensing event that had crossed a caustic, this event was monitored by five different microlensing experiments. The results have been presented by the EROS collaboration (Afonso et al. 1998), the PLANET collaboration (Albrow et al. 1999a), the MACHO/GMAN collaboration (Alcock et al. 1999a), and the OGLE collaboration (Udalski et al. 1998).

The measurements of the microlensing optical depth toward the Large Magellanic Cloud (LMC) indicate that there is a previously unknown "dark lens population" toward the LMC (Alcock et al. 1997a). If the microlensing population is dominated by Galactic halo objects, the timescale of the microlensing events indicates their typical mass to be \( \sim 0.5 M_\odot \), which suggest that these objects may be low-mass stars, white dwarfs, or primordial black holes (Nakamura et al. 1997). A large population of low-mass stars or white dwarfs in the Galactic halo would likely have other observable effects, and it has been speculated that the LMC microlensing events are due to normal stars in the LMC itself (Sahu 1995). The possible confusion between LMC self-lensing and lensing by Galactic halo objects derives from the fact that the distance and the mass of the lensing objects cannot be directly measured for most of the microlensing events. For a "standard" microlensing event, the only constraint on the three unknowns of the distance, velocity, and mass of the lens system comes from a single observed quantity, the "Einstein ring radius crossing time" \( t_E \).

In a caustic-crossing binary lensing event, one can measure one more independent parameter, namely, the "source radius crossing time", \( t_s \), and thereby estimate the relative proper motion \( \mu \) of the lensing object with respect to the source by independently determining the angular size of the source star from its brightness and color. A measurement of the relative proper motion, \( \mu \), allows the determination of the angular Einstein ring radius, \( \theta_E = \mu t_E \). Once \( \theta_E \) is known, the mass of the lensing object is expressed as a simple monotonic function of the distance to the lens (if the distance to the source is known). If \( D_l \) and \( D_s \) are the distances to the lens and the source star, and \( \delta = D_l/D_s \), then

\[
\left( \frac{M}{M_\odot} \right) = \frac{\delta}{1 - \delta} \left( \frac{D_s}{60 \text{ kpc}} \right) \left( \frac{\theta_E}{0.369 \text{ mas}} \right)^2.
\]

\( D_l \) is not known, but it is strongly correlated with the proper motion, \( \mu \). For example, if we take our best-fit value of \( t_E = 70.5 \) days and assume \( D_s = 60 \) kpc and \( \mu = 1 \) km s\(^{-1}\) kpc\(^{-1}\), then the lensing object will be a binary in the

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SMC with the total mass $M \approx 0.36 \, M_\odot$ for $D_s - D_t = 2$ kpc. For a typical halo lens we expect $D_s \approx 10 \, \text{kpc}$ and a transverse velocity of $\approx 200 \, \text{km s}^{-1}$, assuming a standard isothermal sphere halo model (Binney & Tremaine 1987). This yields $\mu \approx 20 \, \text{km s}^{-1} \, \text{kpc}^{-1}$ for a typical halo lens (which would imply a lens mass of $M = 0.81 \, M_\odot$ from eq. [1]). Of course, in order to compare to our measurement of $\mu$, we should compare to the predicted $\mu$ distributions for halo and SMC lenses. This has been done for some simple SMC and halo models by Graff & Gardiner (1998), Albrow et al. (1999a), Alcock et al. (1999a), and Honma 1998, and their results indicate that for most values of $\mu$, either a halo or SMC lens is strongly preferred. However, depending on the halo and SMC models used, there is an overlap region at $\mu = 2-4 \, \text{km s}^{-1} \, \text{kpc}^{-1}$, which is marginally consistent with either a halo or SMC lens at the 2–3 $\sigma$ confidence level. (Honma [1998] also points out a selection effect that will tend to bias $\mu$ measurements toward smaller values.) In the case of MACHO 98-SMC-1, model II of the PLANET collaboration (Albrow et al. 1999a) yields $\mu = 2 \, \text{km s}^{-1} \, \text{kpc}^{-1}$, which does not allow a definite determination of the lens location in the in the halo or in the SMC (Honma 1998).

The main features of a binary lensing event are determined by the location of the caustic curve in the source plane. The number of images of a source star changes by two when the source star crosses a caustic curve. In binary lensing, the caustic curve is made of one, two, or three closed curves, and the number of images is five inside the closed curves and three outside. The caustic curves for MACHO 98-SMC-1 (according to the MPS fit) are shown in Figure 1. When the source moves inside one of these caustic curves, two new images are created, and the magnification of these new images is singular at the point of the caustic crossing. Because of this discontinuity (intrinsic width zero), the finite angular size of the source star is necessarily resolved during a caustic crossing. At the same time, this discontinuity makes it difficult to observe the first caustic crossing (going into the caustic). However, there is always the second opportunity to monitor a caustic crossing once the first caustic crossing has occurred because caustic curves are closed, and the second caustic-crossing time can be predicted through real-time data reduction and binary lens fitting as the source proceeds inside the caustic.

The timely pre–caustic-crossing announcements from the MACHO/GMAN group (Becker et al. 1998; Bennett et al. 1998) allowed intense monitoring of the second caustic crossing of the MACHO 98-SMC-1 by the microlensing community around the clock from all three (temperate) continents of the southern hemisphere (Afonso et al. 1998; Albrow et al. 1999a; Alcock et al. 1999a). As a result, the MACHO 98-SMC-1 has become the first binary microlensing event with complete coverage of the second caustic crossing.

According to our fit, the binary lensing event MACHO 98-SMC-1 was magnified by $\approx 70$ times at the maximum of the second caustic crossing. Such extreme magnification is also useful in studying the properties of the lensed star (Lennon et al. 1996; Alcock et al. 1997c). In order to obtain an accurate model of the lensing event, which is necessary to determine $\mu$, however, it is not enough to have only meticulous measurements of the second caustic crossing. The GMAN project routinely monitors MACHO microlensing events toward the Magellanic Clouds and provided a valuable “uniform” coverage of this event from Chile. The MPS collaboration turned out to be the only other follow-up group that monitored the event from early on, and MPS data (from Australia) add a crucial constraint on the time of the first caustic crossing, which was poorly sampled. As a result, the PLANET model II that raised the possibility that the lensing objects were in foreground debris of the SMC is directly ruled out.

2. MPS OBSERVATIONS AND A CONSTRAINT ON THE FIRST CAUSTIC CROSSING

The Microlensing Planet Search project has been allocated approximately 100 nights on the Mount Stromlo Observatory (MSO) 1.9 m telescope for the 1997 and 1998 Galactic bulge seasons. Ongoing microlensing events announced by the MACHO, OGLE, and EROS collaborations are monitored at intervals of 1–2 hr using the Monash Camera, which is a Cassegrain imager fitted with a SITE 15 $\mu$m 2048 $\times$ 4096 AR-coated thinned CCD. Each observation is reduced within a few minutes after it is taken, using automated Perl scripts written by one of us (A. C. B.) that call a version of the SoDOPHOT photometry routine (Bennett et al. 1999). This allows the immediate discovery of any unusual microlensing features that might be in progress.

MPS made its first observation of event MACHO 98-SMC-1 about 1 day after MACHO microlensing alert issued May 25.9 UT and continued its observations as a medium-priority target. One of these observations was obtained at June 5.549 UT, which turned out to be the last observation prior to the caustic crossing. After the caustic-crossing binary lensing alert issued June 8.99 UT, MACHO 98-SMC-1 was upgraded to a high-priority target. However, we were not scheduled on the MSO 1.9 m until June 18, so our coverage of the event while the source was

![Configuration of the caustic curves for the MPS light curve fitted to binary lensing event MACHO 98-SMC-1. The crosses indicate the locations of the lenses, and the straight line indicates the path of the source star with respect to the caustic curves. The red dots on the source-star path indicate the location of the source at various dates given in June, UT. The distance scale for the axes is the Einstein ring radius, $R_E$. Note that the actual size of the source star is only about 0.0015 $R_E$ that is much less than the thickness of the curves in the figure.](image-url)
inside the caustic curve was minimal. On June 18, the imager was available again, and the MSO staff kindly altered the telescope pointing limits to allow us to observe the SMC almost completely under the pole at an air mass of 3.2. We made the first observation at June 18.332 UT about 40 minutes after the trailing limb of the star cleared the caustic (according to our best fit, which indicates the second caustic-crossing endpoint at June 18.304 UT). Although we missed the second caustic crossing, we kept MACHO 98-SMC-1 at a high priority to cover the “cusp approach” light-curve feature. This was a rise to a gentle peak and subsequent decline that occurs as the source passes in front of one of the sharp “cusps” of the caustic curve (see Fig. 1). Good coverage of this feature is important if we hope to constrain the global parameters of the lensing event. Unfortunately, because of poor (la Niña) weather, our coverage of the cusp approach is not very good.

The intense worldwide monitoring of the event was concentrated around the second caustic crossing, making it the best-covered caustic crossing in microlensing history. However, a reasonable amount of data around the first caustic crossing is necessary to pin down the lens parameters. The OGLE observation June 6.40 UT and the MACHO/GMAN observation at June 6.45 UT (see Fig. 3) indicate that the first caustic crossing must have occurred by June 6.0 or so. A lower limit on the time of the first caustic crossing is set by the MPS observation at June 5.549 UT, which is the last observation before the first caustic crossing. The measured flux of this MPS observation is consistent with the slow variation of the light curve for a source approaching a binary caustic prior to the first contact of the caustic with the stellar limb. Thus, the first caustic crossing is constrained to have been completed within the window of ~20 hr between June 5.55 and 6.40 UT.

3. BINARY LENSING ANALYSIS

A binary lensing event involves seven parameters. These include three parameters that also exist for single lens events: the Einstein ring crossing time, $t_{E}$; the “impact distance,” $u_{\text{min}}$, from the origin of the coordinate system; and the time of the closest approach to the origin, $t_{0}$. We choose the lens system center of mass as the origin so that $t_{0}$ would be the most reasonable generalization of the time for the maximum amplification of a single lens. (The center of mass resides inside the caustic here. It always does when the lens separation $a \leq \sqrt{2}$.) This would also be the most convenient coordinate system if we were to consider the lens system orbital motion. There are three additional parameters intrinsic to a binary lens: the fractional mass, $\epsilon$, of the first lens, the lens separation $a$, and the intersection angle of the source trajectory with the lens axis, $\theta$. (The first lens is the one on the left in Fig. 1.) The final parameter is the source radius crossing time $t_{\ast}$, which is obviously critical for the lens proper-motion determination.

In addition to these microlensing parameters, we must have additional parameters, to describe the unlensed brightness of source star in each passband, from each observing site (since the instrumental passbands from different telescopes are never identical). Also, since the microlensing events are found in crowded stellar fields, it is usually the case that the lensed source is blended with other unlensed sources that happen to fall within the same seeing disk. Thus, we require an additional parameter for the brightness of any unlensed sources that are blended with the lensed source. These parameters need not be included for the non-linear $\chi^2$-minimization process, however, because the observed flux depends linearly on the brightness of lensed star and its unresolved companions. Our $\chi^2$ calculation routine automatically minimizes $\chi^2$ with respect to these linear parameters for every set of intrinsic microlensing parameters that is considered. This makes our fitting routine converge to the best fit much more quickly than it would if these were included as nonlinear fit parameters. However, it also complicates the interpretation of our error estimates because the error estimates for the blending parameters are calculated with the intrinsic lensing parameters held fixed.

When a source is inside a caustic curve, there are two extra images in addition to the three “normal” images, and when the caustic curve crosses the source star, the two extra images are only partial images joined together along the critical curve. The time it takes for the stellar diameter to cross the caustic, $2\Delta t$, can be measured using only observations near the time of the caustic crossing. However, $t_{\ast}$ can be determined from $\Delta t$ only if we know the angle, $\phi$, between the source trajectory and the caustic curve at the crossing: $t_{\ast} = \Delta t \ \sin \phi$. The angle $\phi$ can be determined only by a fit to the entire microlensing light curve, so measurements of the caustic crossing alone are not sufficient to determine $t_{\ast}$. It is possible to constrain $t_{\ast}$ without a determination of $\phi$ (Afonso et al. 1998), but this constraint may be very weak.

The modeling of a binary lensing event presents a number of difficulties. First, the caustic crossings mean that binary lensing light curves generically have very sharp features, and since the photometric measurements discretely sample the light curves, there can be large changes in $\chi^2$ caused by small changes in the parameters that happen to move a
caustic past the location of a data point. The singular nature of microlensing magnification also causes difficulties for the integrations necessary to calculate the microlensing magnification of a finite size source star and prevents the use of fast high-order methods (Bennett & Rhie 1999).

Yet another difficulty with binary lens fits is that the location of the caustic crossing in the light curve depends in a complicated way on the microlensing parameters. The time of the caustic crossings can generally be pinned down to reasonable accuracy simply by inspection of the microlensing light curves, but it is difficult to translate this into a constraint on the microlensing parameters: $\epsilon, a, \theta, u_{\min}, t_0$, and $ef$. However, since the times of the caustic crossings can readily be calculated for any set of parameters, it is possible to shift $t_0$ and rescale $ef$ to put two caustic crossings at specified locations in time. We use such a procedure to replace the parameters $t_0$ and $ef$ by the first and second caustic-crossing times, $t_{cc1}$ and $t_{cc2}$, for many of our binary lens fits.

The $\chi^2$-minimization for our microlensing fits is carried out with the aid of the MINUIT routine. The fitting proceeds in several stages. First, in order to find candidate global fits, we take the data sets and remove many of the data points from regions where the data highly oversample the light curve features in order to speed up the calculations in the early phases of the fitting process. We also remove all of the data points that resolve the caustic crossing so that the search for candidate global microlensing fit parameters can be done in the point-source limit, which typically speeds up the calculations by a factor of 10 or more. We then start a number of Monte Carlo parameter searches to find good starting points for the microlensing fits using MINUIT’s SEEK routine. During the Monte Carlo parameter searches, the values of $t_{cc1}$ and $t_{cc2}$ are constrained to small time intervals, which were determined by inspection of the individual light curves. This results in a number of candidate microlensing models which are passed to the second stage of the fitting procedure.

In the second stage of the fitting process, we include some of the data that resolve the caustic crossing and fit all of the candidate microlensing models again with a finite value for $t_s$. This procedure converges to the final fit much more quickly than if all the data were used at this stage. Once the finite source effects are included, it is necessary to take the limb darkening of the source into account. For our preliminary fits, we have used a standard “linear” limb-darkening model, but we have also used the “square-root” model advocated by Diaz-Cordoves & Gimenez (1992) at the stage of the final fits, which use the full data set. The limb-darkening coefficients were taken from Claret, Diaz-Cordoves, & Gimenez (1995) and Diaz-Cordoves, Claret, & Gimenez (1995).

If $h$ is the cosine of the angle between the line of sight and the star’s radial direction, the limb darkening is expressed as the luminosity profile of the star normalized by the luminosity at the center $I_0$.

$$I / I_0 = \sum_{n=0}^{\infty} a_n h^n \quad : \quad n = 0, 0.5, 1, 2, \quad \sum_{n=0}^{\infty} a_n = 1 \quad .$$

In a linear model, $a_{0.5} = a_2 = 0$, and the coefficient in Table 4 refers to the value of $a_1$. A square-root model is given by $a_2 = 0$, and in Table 4, $c = a_1$ and $d = a_{0.5}$.

In addition to this procedure used to find new fits, we have also tried fits using initial conditions based upon the fits reported by the PLANET and MACHO/GMAN collaborations.

### 3.1. Previous Observations, Analyses, and Fits

Observations of MACHO 98-SMC-1 have been previously presented by the EROS, PLANET, MACHO/GMAN, and OGLE collaborations (Afonso et al. 1998; Albrown et al. 1999a; Alcock et al. 1999a; Udalski et al. 1998). The EROS observations from La Silla covered a significant fraction of the falling curve of the second caustic crossing through the caustic-crossing “endpoint” and several hours beyond, and it was the first time that the linearity toward the endpoint was observed. At the endpoint, the source star completely exits the caustic, and the additional two bright partial images vanish, causing the slope of the overall light curve to change abruptly at the caustic endpoint. (The endpoint is a sharp feature if the source luminosity profile is discontinuous at the limb. The analytic models we consider here all have discontinuities as long as the coefficient $a_0$ does not vanish in equation (2). The EROS and CTIO data let us speculate that the limb of the star may not be sharp, but we cannot be conclusive owing to the fluctuations of the data.) The endpoint was estimated to have occurred June 18.297 UT (Afonso et al. 1998), but we have recently been informed that this is in error (A. Gould 1999, private communication) and that the correct caustic-crossing endpoint time for the EROS data is June 18.303 UT. From the linearity spanning 1.8 hr, the EROS collaboration suggested a constraint $\mu \sin \phi \leq 1.5 \text{ km s}^{-1} \text{ kpc}^{-1}$. Since they reported on data only from the night of the second caustic crossing, EROS was not able to determine the caustic-crossing angle $\phi$, so their constraint on the lens proper motion was weak.

However, the EROS data have the best coverage of the caustic-crossing endpoint, which proves very valuable when combined with other data sets.

The PLANET collaboration monitored the event since shortly after the binary lens alert and had excellent coverage of the second caustic-crossing peak turnover from the SAAO 1 m telescope. They also measured the spectrum at the light curve peak from the SAAO 1.9 m telescope. They presented two binary lens fits, which we will refer to as PLANET-I and PLANET-II, that resulted in $t_s = 0.122$ and 0.0896 days. The models PLANET-I and II differ by $\sim 58$ in $\chi^2$, which is formally a 7.6 $\sigma$ deviation. However, the $\chi^2$ per degree of freedom for each were fairly large (2.37 and 2.73, respectively), and they argued that both the fits should be considered to be viable fits (to account for unspecified systematic errors).

The MACHO/GMAN group reported their data from the Mount Stromlo 1.3 m and the CTIO 0.9 m telescopes (Alcock et al. 1999a) and presented a binary microlens fitted to the data combined with the EROS data. Their fit differed from both PLANET-I and PLANET-II, and MACHO/GMAN suggested that both the PLANET models might be inconsistent with pre-caustic-crossing MACHO/GMAN data. Their estimate of the source radius crossing time was $t_s = 0.116$ days. The CTIO 0.9 m observations registered the caustic-crossing endpoint at $\approx$ June 18.304 UT, which

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*See F. James 1994, the CERN Program Library Long Writeup D506, at http://wwwinfo.cern.ch/asdoc/WWW/minuit/minmain/minmain.html.*
agrees with the EROS data reduced with SoDOPHOT (see Fig. 4). The MACHO/GMAN fit indicates that the second caustic-crossing peak amplification was \(\approx 70\), while PLANET-I indicates that the maximum amplification was \(\approx 100\). The main difference here is that the PLANET-I indicates a fainter source star, with more of the baseline flux coming from unlensed stars.

The OGLE collaboration reported their data from Las Campanas (1.3 m Warsaw telescope), which includes the first observation after the first caustic crossing at June 6.40 UT. They did not perform any microlensing fits, but they suggested that model PLANET-I is more consistent with the OGLE data than PLANET-II. They also suggested that MACHO/GMAN fit may be off by 0.14 days for the first caustic crossing. In the MACHO/GMAN fit, the first caustic peak crossing occurred at \(\approx June 6.24\) UT, and hence, the suggestion by the OGLE team corresponds to the first caustic peak crossing at \(\approx June 6.10\) UT. In model PLANET-I, the peak crossing time was \(\approx June 6.08\) UT, and thus the OGLE team concluded that the OGLE data are probably most consistent with model PLANET-I.

### 3.2. MPS Fits, Analyses, and Comparison

In this section we present our binary microlensing fit results for the data set including the MPS data plus the publicly available MACHO/GMAN, EROS, and OGLE data, and we interpret the meaning of these results. We assume that the source star is a single lens star which was lensed by a binary lens with no significant orbital motion.

The most obvious result of the MPS observations is that it requires the first caustic crossing to occur after June 5.55 UT and rules out the PLANET-II model, which allowed the possibility that the lens system might reside in the foreground of the SMC. The MPS observation at June 5.55 UT indicates that the leading limb of the source star has not yet crossed the caustic. On the other hand, the PLANET-II model predicts the leading limb to cross the caustic at June 5.25 UT, the stellar center "caustic-crossing time" at June 5.36 UT, and the first caustic-crossing light-curve peak to occur at June 5.43 UT.

In order to put it into the statistical perspective, we normalize the MPS data to the PLANET-II fit using the 34 other observations (which do give an acceptable fit to the data), and the PLANET-II prediction for June 5.55 UT exceeds the observed brightness by 29 \(\sigma\). If we fit all 35 observations including the datum at June 5.55 UT to the PLANET-II model, using the normalization as the parameter, the observation at June 5.55 UT induces the other points to go off the fit curve, as can be seen in Figure 2. Note that in Figure 2 and in all subsequent plots, the MPS data have been binned into nightly bins for all nights with multiple observations except for the night of June 18, where 16 observations have been grouped into four bins.

The MPS observation on June 5.55 along with the OGLE observation at June 6.40 UT and the GMAN-CTIO observation at June 6.45 constrain the caustic crossing to have occurred close to June 6.0 UT. The MPS fit to the combined data set provides an acceptable fit to the data near the first caustic crossing and indicates that the first "caustic-crossing time" was June 5.83 UT, and PLANET-I and MACHO/GMAN also seem consistent with this data within the limit of the poor coverage. Therefore, we will focus on a comparison between the MPS, MACHO/GMAN, and PLANET-I fits as well as the light-curve details of the second caustic crossing, which we hope to reconstruct the "missing peak." (A future comparison with the PLANET data should test our ability to predict the features of the second caustic-crossing peak from the other data sets that do not sample the peak.)

Tables 1–4 shows the summary of the results of the microlensing fits we have performed on the combined

![Fig. 3.—MPS fit using the square-root and linear limb-darkening models. The EROS-rouge, MACHO-V, and CTIO-B data are not shown. The MPS fits with linear and square-root limb-darkening models are indistinguishable on this plot.](image1)

![Fig. 4.—Second caustic-crossing endpoint MPS fit using the square-root and linear limb-darkening models. The square-root model is the one that predicts a slightly lower magnification at June 18.20.](image2)
TABLE 1
BINARY LENSING PARAMETERS AND STATISTICS

| Parameter | PLANET I | PLANET I * | MACHO/GMAN * | MPS-linear | MPS-sqrt |
|-----------|----------|------------|--------------|------------|----------|
| \( t_{cc1} \) | ~6.0 | ~6.0 | ~6.2 | 5.828 | 5.848 |
| \( t_{cc2} \) | 18.12 | 18.12 | 18.2 | 18.144 | 18.155 |
| \( t_0 \) (Jun UT) | 14.130 | 14.228 | 13.931 (15) | 13.105 | 13.120 |
| \( t_0 \) (days) | 108.4 | 108.91 (29) | 73.76 (41) | 70.52 | 70.47 |
| \( a \) | 0.58685 | 0.58288 (75) | 0.66365 (84) | 0.64635 (22) | 0.6462 (20) |
| \( u_{\min} \) | 0.03164 | 0.03185 (8) | 0.04628 (12) | 0.04434 (16) | 0.04479 (19) |
| \( \theta \) (rad) | 0.2060 | 0.2019 (33) | 0.1803 (18) | 0.1603 (20) | 0.1611 (21) |
| \( v \) | 0.2221 | 0.2214 (42) | 0.2793 (57) | 0.3411 (27) | 0.3423 (23) |
| \( \chi^2 / \text{dof} \) | 1979.2/1617 | 1887.9/1617 | 1802.0/1617 | 1803.5/1617 |

EROS/GMAN/MACHO/MPS/OGLE data set. The MPS fit is the fit generated by our fit search procedure, as discussed above. The fits labeled "PLANET-I*" and "MACHO/GMAN*" are fits in which we started with the binary lens parameters reported by these groups as initial conditions. The columns labeled "PLANET-I" and "PLANET-II" report results for the fit parameters found by the PLANET collaboration; the only additional fitting was to find the best fit fluxes for the lensed star and its unresolved companions.

The blend fractions or "fractional lensed luminosity" values listed in Table 3 require some explanation. These blend fractions have large uncertainties for many of the passbands because there are few or no observations when the source is not magnified significantly for most of the passbands. The only tight constraint on the unlensed flux comes from the MACHO data, where there are more than 600 observations in both MACHO passbands when the source is unmagnified. The \( f_s \) values in Table 3 can also depend on the seeing of the best images from each of the data sets. With routines such as DOPHOT, SoDOPHOT, or ALLFRAME, the photometry is based upon the stars that can be individually identified in the best-seeing frames. Thus, two data sets using the nearly identical passbands can yield different \( f_s \) values if the seeing in the best-seeing frames differs between the two data sets.

Table 1 shows the summary of the lens parameters and statistics; \( t_{cc1} \) and \( t_{cc2} \) refer to the first and second caustic-crossing times, which are fit parameters for the MPS fits but not for the MACHO/GMAN or PLANET-I fits. The caustic-crossing times appear to agree well between the different fits. The MACHO/GMAN and MPS fit parameters agree in general except in the mass ratio, but these fits differ more substantially from the PLANET-I fit. Of course, this is not very surprising since the MACHO/GMAN and MPS fits are based on data sets that have a lot of overlap with each other but no overlap with the data that generated the original PLANET-I fit.

Much of the difference between the PLANET-I and MACHO/GMAN and MPS fits can be traced to the fact

TABLE 2
FIT \( \chi^2 \) VALUES FOR INDIVIDUAL PASSBANDS

| Passband | PLANET II | PLANET I | PLANET I * | MACHO * | MPS-linear | MPS-sqrt |
|----------|-----------|----------|------------|---------|------------|----------|
| MACHO Rm | 926.2/704 | 944.0/704 | 938.4/704 | 921.5/704 | 917.6/704 | 918.5/704 |
| MACHO Vm | 783.0/712 | 795.6/712 | 786.2/712 | 763.8/712 | 762.8/712 | 763.9/712 |
| CTIO R   | 88.0/84   | 103.8/84 | 59.6/84    | 44.4/84 | 30.2/84    | 30.7/84 |
| CTIO B   | 31.9/22   | 31.5/22   | 18.0/22    | 10.4/22 | 9.3/22     | 9.2/22 |
| EROS R   | 20.5/38   | 47.0/38   | 20.9/38    | 19.5/38 | 19.8/38    | 20.5/38 |
| EROS B   | 14.9/38   | 34.7/38   | 11.5/38    | 12.2/38 | 11.5/38    | 10.8/38 |
| MPS R    | 129.3/35  | 47.0/35   | 45.8/35    | 46.9/35 | 48.4/35    | 47.4/35 |
| OGLE I   | 5.4/7     | 2.2/7     | 7.5/7      | 4.6/7   | 2.3/7      | 2.1/7   |

TABLE 3
FRACTIONAL LENSED LUMINOSITY \( f_s \)

| Passband | PLANET II | PLANET I | PLANET I * | MACHO * | MPS-linear | MPS-sqrt |
|----------|-----------|----------|------------|---------|------------|----------|
| MACHO Rm | 0.409 (5)  | 0.301 (4) | 0.300 (4)  | 0.475 (6) | 0.494 (6)  | 0.494 (6) |
| MACHO Vm | 0.480 (5)  | 0.353 (4) | 0.352 (4)  | 0.557 (6) | 0.578 (6)  | 0.579 (6) |
| CTIO R   | 0.85 (7)   | 0.58 (4)  | 0.55 (4)   | 0.79 (5)  | 0.89 (6)   | 0.87 (6)  |
| CTIO B   | 0.90 (17)  | 0.67 (12) | 0.70 (13)  | 1.07 (20) | 1.01 (18)  | 1.01 (18) |
| EROS R   | 1.17 (76)  | 1.07 (82) | 1.35 (130) | 1.03 (36) | 0.82 (34)  | 0.89 (40) |
| EROS B   | 0.54 (7)   | 0.70 (15) | 0.63 (12)  | 0.40 (4)  | 0.40 (4)   | 0.42 (4)  |
| MPS R    | 0.07 (1)   | 0.42 (12) | 0.42 (12)  | 0.57 (16) | 0.55 (14)  | 0.55 (14) |
| OGLE I   | 1.5 (2.7)  | 1.2 (2.3) | 0.14 (4)   | 0.39 (17) | 1.17 (1.37) | 1.11 (1.22) |
that the PLANET-I fit indicates more blending. In other words, the lensed source implied by the PLANET-I model is fainter and has brighter unlensed neighbors than in the MACHO/GMAN and MPS models. This can be seen from the best-fit blend fractions listed in Table 3. The fraction of the lensed light is \( f_l(V) \approx 0.57 \) and \( f_l(R) \approx 0.49 \) for the MACHO/GMAN and MPS fits of the MACHO data, while for the PLANET-I fit the values are \( f_l(V) \approx 0.35 \) and \( f_l(R) \approx 0.30 \). So, the MACHO/GMAN and MPS fits imply that the lensed source is about half a magnitude brighter than implied by the PLANET-I fit. It is interesting to note that the \( \chi^2 \) difference between the MACHO/GMAN and MPS fits and the PLANET-I fit is seen only in the MACHO and CTIO data sets. These are the data sets with the best light-curve coverage and are the only data sets in which the unmagnified fit fluxes are the same for the different fits. For the EROS, MPS, and OGLE data sets, the unmagnified brightness of the lensed source is predicted to be substantially fainter for the PLANET-I fit than for the MACHO/GMAN and MPS fits. Thus, additional data from EROS, MPS, OGLE, and perhaps PLANET as well should help to distinguish between these fits.

The form of the fit curves near the caustic crossings depends on the assumed form for the limb darkening. Following the PLANET collaboration, the PLANET-I and PLANET-II \( \chi^2 \) results reported here assume no limb darkening. For most of the fits that we have done, we have assumed the common “linear” limb-darkening model, but the fit labeled MPS-sqrt was done using the square-root model of Diaz-Cordoves & Gimenez (1992), which is expected to be more accurate. The parameters used for each passband are listed in Table 4, and they are appropriate for a star with an effective temperature of \( T = 8000 \) K and a surface gravity of \( \log g = 4.5 \). (See § 3.3 for a discussion of the properties of the source star.)

The modeling of the light curve near the second caustic-crossing peak is subject to some systematic uncertainty owing to the features and limitations of the MACHO and EROS data, which bracket the peak. The MACHO/GMAN paper noted that there is an apparent light-curve deviation near June 17.7 that might be explained as a caustic crossing due to a faint companion to the source star. Another possible explanation might be systematic photometric errors. In either case, this deviation will add to the uncertainty in our prediction for the light curve during the missing peak of the caustic crossing.

The timing of the second caustic crossing is seen to be very close to the last pre-caustic-crossing prediction from MACHO/GMAN: \( t_{cc2} = \) June 18.18 UT versus the prediction of June 18.2 UT (issued via e-mail on June 17).

The peak magnification of the caustic crossing is predicted to have occurred at June 18.055 for the MPS-linear fit and June 18.045 for the MPS-sqrt fit. The light-curve peak assumed by PLANET seems to be earlier than this by \( \sim 0.03 \) days, which agrees with our prediction when we account for the systematic errors mentioned above. (After this paper was submitted, the PLANET collaboration submitted a new paper in which they claim \( t_{cc2} = June 18.124 \pm 0.0009 \) [Albrow et al. 1999b].)

As a way to judge the overall merit of the different light-curve fits, we compare the fitted \( \chi^2 \) values for each of the models. The MPS-linear and MPS-sqrt \( \chi^2 \) values differ by only 1.5, which is not statistically significant. The \( \chi^2 \) value for the MACHO/GMAN fit is larger than the MPS-linear value by 21.3, which is formally equivalent to a 4.6 \( \sigma \) deviation, while the \( \chi^2 \) value for the PLANET-I fit is larger by 85.9 or 9.3 \( \sigma \). Thus, the PLANET-I fit is clearly disfavored, but it is premature to dismiss it, as we have not yet included the PLANET data itself in our fits. The inclusion of the PLANET data plus additional data from the other groups in our fits should resolve this question, however.

### 3.3. Source-Star Characterization

In order to estimate the proper motion from the microlensing fits, we must estimate the angular radius of the source star. This can be accomplished with estimates of the stellar temperature, brightness, and the amount of extinction. The brightness estimate depends on the amount of blending as determined by the binary microlensing fit, but the temperature and extinction can be estimated from the broadband colors and a spectrum. The PLANET collaboration has spectrum from the SAAO 1.9 m telescope near peak magnification, which indicates that the source star is an A star with \( T \approx 8000 \) K. The color of the star has been estimated by PLANET to be \( V-I = 0.31 \pm 0.02 \), while MACHO estimates \( V-R = 0.03 \pm 0.03 \). These colors are somewhat difficult to reconcile, and we suspect that one or both color estimates may be subject to systematic errors larger than the estimates above.

The uncertainty in the calibration of the MACHO color estimate can be investigated by repeating the calibration calculation using the template air-mass formula given in Alves et al. (1998) and Alcock et al. (1999b) instead of the calculation using the template air-mass formula given in Alves et al. (1998) and Alcock et al. (1999b) instead of the calibration for MACHO SMC field 207. This yields \( V-R = 0.09 \), so we will use \( V-R = 0.09 \pm 0.06 \) for the MACHO color. Following PLANET, we'll assume an extinction of \( A_V = 0.22 \pm 0.1 \).

From the MACHO photometric calibrations and the MPS fit, we estimate the unlensed magnitude of the source at \( V = 21.98 \), and if we use the PLANET photometric zero point, we get \( V = 21.91 \). (Since the magnitude of the lensed star depends on the binary lens fit, we have made the comparison to the PLANET zero point using the total flux at the minimum between the two caustic crossings where the different fits predict the same total flux.) We adopt \( V = 21.95 \pm 0.15 \). The source star is expected to be a member of the SMC, but if the lens is in the SMC as well, then the source star is likely to be located on the far side of the SMC. Since it does appear that the lens is likely to be located in the SMC, we will assume a distance of 62.5 \pm 2.5 kpc to the source. (This distance estimate has only a minor effect on the measurement of \( \mu \) as it only affects the bolometric correction.) This yields an absolute magnitude of \( M_V = 2.75 \pm 0.2 \). From the Bertelli et al. (1994) isochrones,

### Table 4

| Passband | Linear | Square Root-c | Square Root-d |
|----------|--------|---------------|---------------|
| MACHO R  | 0.467  | 0.071         | 0.562         |
| MACHO V  | 0.600  | 0.119         | 0.682         |
| CTIO R   | 0.491  | 0.081         | 0.582         |
| CTIO V   | 0.662  | 0.116         | 0.775         |
| EROS R   | 0.446  | 0.071         | 0.562         |
| EROS V   | 0.545  | 0.1055        | 0.624         |
| MPS R    | 0.491  | 0.081         | 0.582         |
| OGLE I   | 0.401  | 0.043         | 0.510         |
we see that this is compatible with a metal-poor ([Fe/H] = −1 ± 0.3) A star with a bolometric correction of −0.03 ± 0.02 magnitudes. This yields a stellar radius of $\theta_s = 9.4 \pm 1.1 \times 10^{-8}$ arcseconds, or $R = 1.26 \pm 0.15 \, R_\odot$, assuming a distance of 62.5 ± 2.5 kpc. Our best-fit value for $t_\ast$ is 0.108 days (using the square-root limb-darkening model), but this value is sensitive to uncertainties in the blending for the EROS data. The publicly available EROS data consist of only data taken on the night of the caustic crossing, and it has essentially only two features: a linear decline followed by a period of constant brightness. This means that if we fit only the EROS data with an unknown amount of blending, there will be a fit degeneracy that will allow a change in the caustic-crossing timescale to be compensated by a blending change. This will be constrained by the shape of the fit curve in other passbands near the caustic-crossing peak, but the MACHO data seems to show an anomaly near the peak. Because of these uncertainties, we will add an additional 0.015 days as a systematic uncertainty to our measurement of $t_\ast$. This yields $\mu = 1.51 \pm 0.28 \, \text{km s}^{-1} \, \text{kpc}^{-1}$ and $v = 94 \pm 17 \, \text{km s}^{-1}$. These are consistent with the $\mu$ and $v$ estimates from the PLANET-I and MACHO/GMAN models, but it is substantially less than proper motion predicted from the PLANET-II model (Albrow et al. 1999a; Alcock et al. 1999a).

4. CONCLUSIONS

The MPS data add a constraint on the first caustic crossing and rule out PLANET-II model. Since the PLANET-II model was the only proposed model that indicated a relative proper motion significantly different from our value of $\mu = 1.51 \pm 0.28 \, \text{km s}^{-1} \, \text{kpc}^{-1}$, this result significantly decreases the uncertainty in $\mu$. As discussed previously (Afonso et al. 1998; Albrow et al. 1999a; Alcock et al. 1999a), this proper-motion value clearly favors a lens in the SMC, and it does not require that the SMC be tidally disrupted as seemed to be necessary for the PLANET-II model to make sense.

While our analysis clearly favors the MPS fit over the MACHO/GMAN and PLANET-I fits, it would be best to perform joint fits with all of the available data before making a final judgment. Particularly valuable would be the PLANET data and additional EROS data. One significant difference between the MPS and MACHO/GMAN fits and the PLANET-I fit is that the PLANET-I fit implies that the lensed source is more severely blended and is therefore significantly fainter. From Table 3 we see that PLANET-I fit predicts that only 35% of MACHO-$\gamma$ band flux is lensed while the MPS and MACHO/GMAN fits predict 58% and 56%, respectively. Future Hubble Space Telescope images of the lensed star should resolve the lensed star from its nearby unlensed companions and determine the correct blend fractions in the different passbands. If the lensing star is found to be the dominant source of the blending, our measurement of $\mu = 1.51 \pm 0.28 \, \text{km s}^{-1} \, \text{kpc}^{-1} = 0.32 \, \text{mas yr}^{-1}$ implies that the resolution of the lens from the source star will probably not be possible with the current generation of optical telescopes. (See Aubourg et al. 1998 for a preliminary "grand joint fit.")

While the observations of MACHO 98-SMC-1 have clearly established that the lens is in the SMC, the implications for the interpretation of the lensing excess seen by the MACHO Collaboration toward the LMC are not clear. The standard model of the LMC is that it is basically a disk galaxy that is inclined by about 27° from face onto the line of sight. Gould (1995) has shown that the microlensing optical depth of such a galaxy is constrained by its line-of-sight velocity dispersion. This suggests that the self-lensing optical depth of the LMC is quite small, but it is conceivable that the LMC disk is not the whole story. For example, Weinberg (1998) suggests that the tidal interactions of the LMC and the galactic disk might give the LMC a larger self-lensing optical depth, but it is not known if this suggestion is consistent with the observed line-of-sight velocity dispersion of the LMC of $\approx 20 \, \text{km s}^{-1}$ (Meatheringham et al. 1988).

Unlike the LMC, the SMC is thought to be extended along the line of sight, and some estimates of the self-lensing optical depth of the SMC (Afonso et al. 1998; Alcock et al. 1999a) are very similar to the measured microlensing optical depth of the LMC. However, a recent $n$-body model of the SMC predicts a somewhat smaller microlensing optical depth (Graff & Gardiner 1998), although this prediction, $\tau_{\text{SMC}} = 0.4 \times 10^{-7}$, is larger than most predictions for $\tau_{\text{LMC}}$. So far, there are two microlensing events detected toward the SMC: MACHO 98-SMC-1, discussed here, and MACHO 97-SMC-1 (Alcock et al. 1997b). It has been suggested, because of its long timescale, that MACHO 97-SMC-1 might also be due to an SMC lens (Palanque-Delabrouille et al. 1998). However, attempts to make this argument more quantitative have invoked the assumption that the lens is a main-sequence star, which cannot be considered a consistent assumption in the context of the dark matter problem. There has also been one caustic-crossing binary event seen toward the LMC (Bennett et al. 1996; Alcock et al. 1997a), but the light-curve sampling of this event was not sufficient to yield an unambiguous determination of the location of the lens system.

For MACHO 98-SMC-1, we have no such ambiguity because of the complete light-curve coverage. We can conclude with high confidence that the lens system resides in the SMC. Since this is the only Magellanic Cloud event with a reliable location, we cannot reach any conclusion about the location of the other Magellanic Cloud events. Furthermore, the rate of binary lensing events discovered toward the Magellanic Clouds is only about 0.3 yr$^{-1}$, so the current generation of microlensing surveys is not likely to solve this problem. Fortunately, there are plans for second-generation microlensing surveys (Stubbs 1999), which should increase the microlensing detection rate toward the Magellanic Clouds by more than an order of magnitude. This will generate a large enough sample of microlensing events with distance estimates to resolve the puzzle presented by the microlensing results toward the LMC. MPS will contribute to this effort by expanding to include observations from the Boyden Observatory near Bloemfontein, South Africa, in 1999.

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