Binary Microlensing Event MACHO-98-SMC-1

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The recent binary microlensing event toward the Small Magellanic Cloud MACHO-98-SMC-1 was alerted by the MACHO collaboration and monitored by many microlensing experiments for its complete coverage of the second caustic crossing. The purpose of this global monitoring campaign was to determine the relative proper motion \( |\vec{\mu}| \) of the lensing object with respect to the source star that may be indicative of the location of the lensing object. (“Is it a Galactic halo object or not, that is the question.”) The estimated value \( |\vec{\mu}| \approx 1.3 \text{ km s}^{-1} \text{ kpc}^{-1} \) indicates that the binary lensing object belongs to the stellar population of the SMC. We discuss the implication of this binary event for the halo dark matter.

1 Introduction

Two and half years ago in the Santa Monica meeting, DM96, we advocated that a microlensing planet search network can be used for high time resolution observations of microlensing events toward the Magellanic Clouds during the off-season of the Galactic Bulge to help out dark matter search efforts. MACHO-98-SMC-1 showed up as a microlensing event (alerted by the MACHO collaboration May 25, 1998) in the middle of the Bulge season, and the Microlensing Planet Search collaboration (MPS) immediately started monitoring the target star. Microlensing events toward the Clouds are relatively rare (currently, \( \sim 4 \) events per year) and the necessity not to miss the possible chance to learn better about the lensing object is so much urgent. On June 8, the event was announced to have crossed a caustic (first caustic crossing) by the MACHO/GMAN collaboration based on the data from CTIO 0.9m. One of the MPS observations at June 5.55 UT would turn out to be crucial for the reconstruction of the binary lens and determining the relative proper motion \( \mu \) of the lensing object.

The estimation of the microlensing optical depth towards the Large Magellanic Cloud (LMC) by the MACHO collaboration\(^{1}\), \( \tau = 2.9^{+1.4}_{-0.9} \times 10^{-7} \), indicates that there are previously unknown “dark lens populations” toward the LMC. If one assumes that the eight microlensing events toward the LMC are due to lensing objects that constitute a fair sample of the halo mass density as described by the “standard isothermal model” of the Galaxy, the distribution of the Einstein ring crossing time of the observed microlensing events, \( 20 < t_E < 70 \) days (\( < t_E > \sim 40 \) days), indicates that the typical mass of the
lensing objects is $\sim 0.5 \text{M}_\odot$, which may be white dwarfs, or something more imaginative such as primordial black holes (PBH) whose existence may be testable through the detection of gravitational waves generated by coalescing binary PBH’s or boson stars that can exist in scalar-gravity field theories.

Or, the lensing objects may be normal stars in the Clouds as has been claimed by Sahu. His estimation of the LMC self-lensing optical depth, $\tau \sim 5 \times 10^{-8}$, is “far” short of the observed optical depth toward the LMC, however. Gould also showed that the LMC-LMC self-lensing optical depth is constrained by the line of sight velocity dispersion and estimated the upper bound $\tau < 1 \times 10^{-8}$. More recently, Weinberg suggested a tidally flared LMC and a larger self-lensing optical depth. Since the hotter, the larger the velocity dispersion, it will be interesting to see if the model is consistent with the observed velocity dispersion of the LMC ($\sim 20 \text{km s}^{-1}$). It will be more encouraging if the 2MASS studies reveal that the LMC disk is indeed extended as Weinberg predicts. (Figure 6 in Weinberg’s shows that the “observed tidal radius” of the LMC $r_t \sim 10.8 \text{kpc}$ is “saturated” by $t = 0.5 \text{Gyr}$, and it is not clear if the rather stable evolution in the later epoch is an artifact of the tidal boundary condition. Without the boundary condition, the numerical satellite galaxy may evaporate more freely.)

There also have been suggestions that the “dark lens population” be an intervening galaxy, tidal debris, a thick or warp component of the Galactic disk, etc.

It is the unsettling status of microlensing dark matter search experiments that the interpretation of their measurements is subject to a variety of unknowns instead of setting global constraints on the intricate dynamics of matter. It is especially acute because in principle, one must be able to determine the mass and the location of the lensing object for each microlensing event within the microlensing measurements. That is, if each microlensing event is fully measured. Lacking parallax satellites or astrometric measurements, however, one can only determine a single quantity, namely, the Einstein ring radius crossing time $t_E$, out of three unknowns of distance, velocity and mass of the lensing object for most of the microlensing events – the “standard” or symmetric photometric microlensing events. Thus, the mass or the location of each individual microlensing object has never been directly measured, and the identity of the lensing objects remains to be statistical which depends on the models of the Galaxy and the Clouds. Furthermore, the handful of microlensing events toward the Clouds (projected to be $\approx 20$ events by the end of 1999) are far too small a statistic to sort out the characteristics of the lensing populations and determine whether there is the Galactic halo component. The next generation microlensing experiments may just come to the rescue with
hundreds of microlensing events toward the Clouds. Different lines of sight such as M31 and Fornax dwarf spheroid will have to be actively investigated as well.

In a caustic crossing binary lensing event, one can measure one more independent parameter, namely, the “source radius crossing time”, $t_\ast$, and thereby estimate the relative proper motion $\mu$ of the lensing object with respect to the source star by independently determining the angular size of the source star from its brightness and color. The logic is that if $\mu$ is very small, the binary lensing must be due to a self-lensing of the SMC. So far, no one has come up with a halo model that allows $\mu$ as small as $\mu \sim 1 \text{ km s}^{-1}\text{ kpc}^{-1}$ with non-negligible probability. For a typical halo lens we expect $\mu \approx 20 \text{ km s}^{-1}\text{ kpc}^{-1}$. So, the semi-open global monitoring campaign was conducted involving most of the microlensing experiment teams. $\mu \sim 1.3 \text{ km s}^{-1}\text{ kpc}^{-1}$ was small, and as a consequence, the monitoring continued more than 24 hours in high time resolution and with high level of adrenaline. One of the conference attendee commented after the talk, “It seems very interesting even though chaotic.”

The result was the first complete coverage of the second caustic crossing of the binary microlensing event MACHO-98-SMC-1. The details can be found in the reports issued by various collaborations: the EROS collaboration, the PLANET collaboration, the MACHO/GMAN collaboration, the OGLE collaboration, and the MPS collaboration.

2 Observations and Reconstructions of the Binary Microlensing Event MACHO-98-SMC-1

The lensed star is located in the SMC at $(\alpha, \delta) = (00:45:35.2, 72:52:34.1)$ (J2000). The mass ratio of the binary lensing stars is $\approx 2 : 1$, and their projected distance is $\approx 2/3$ in units of the Einstein ring radius of the total mass. (See table 1 of the MPS paper for more details.) Figure shows the trajectory of the source across the caustic curve where the traverse took about 12 days.

The world-wide monitoring campaign was mostly focused on the coverage of the second caustic crossing where the lensed star exited the caustic curve. The peak turn-over occurred around June 18.0 UT over South Africa, and it was observed from SAAO 1m by the PLANET collaboration. Also, the spectrum was taken at the peak, and the star was determined to be a A star with $T \approx 8000K$. See figure for the PLANET data and their binary lens fit light curves. The high resolution peak turn-over data from South Africa can be seen in the inset. The curvature change of the light curve around $t \approx 982.43$ is where the limb of the lensed star ”touches” the caustic curve from
inside. Here, the apparent curvature change looks more prominent because of the homogeneous luminosity profile (constant surface luminosity over the disk of the star) used for the fit curve. The two fit curves disagree notably near the first caustic crossing and earlier where the PLANET data coverage is null. The binary lens model with earlier first caustic crossing resulted in $\mu \sim 2 \text{ km s}^{-1} \text{kpc}^{-1}$ offering the possibility that the lensing binary belongs to a foreground tidal debris or the Galactic halo. MACHO/GMAN found this fit to be inconsistent with their baseline data prior to the caustic crossings. Now it is ruled out by the MPS observation at June 5.55 UT that is consistent with a slowly rising amplification of a source star that approaches a binary caustic. The first caustic crossing occurred around June 6.0 UT over the South Africa.

In a binary lensing, the number of images are three or five: three “normal” images when the source is outside the caustic loops and two extra images inside. The “normal” images are always full images. The two extra images are partial and are connected across the critical curve, however, when the source star crosses the caustic curve. The critical curve is where the magnification of a point source diverges. Thus, the two extra images are very bright. As the source exits the caustic, the two partial conjoined images completely disappear (“into the critical curve”), and the star dims rapidly. This rapid change was observed by the EROS. This was the first time the linear characteristic of the falling light curve of a caustic crossing was actually measured.

Figure 3 shows the photometric data from EROS, MACHO/GMAN, MPS and OGLE collaborations and the MPS lightcurve fit to the data. While the PLANET data were unavailable, it was an opportune case to test if we could find the correct binary lens parameters and reconstruct the “missing peak” from the joint data shown in figure 3. The MPS analysis team found that the fitting process was arduously slow without the MPS data constraining the first caustic crossing in time. According to the MPS fit, the maximum amplification of the second caustic crossing was $\sim 70$. The PLANET fit with later first caustic crossing produced the maximum amplification $\sim 100$, for which the blending level was “preassigned” perhaps due to the lack of baseline data. Thus, the work of the PLANET collaboration amounted to a “complementary test” whether the correct binary lens can be reconstructed from the high resolution data for the second caustic crossing (plus the MACHO/GMAN data that were made available with the MPS real time fitting during the monitoring campaign: http://darkstar.astro.washington.edu/ and http://bustard.phys.nd.edu/MPS/).

Caustic crossing binary lensing event is an exciting object all by itself. To the eyes of beholders, the spectacular increase of the light flux during the
caustic crossing can be as cathartic as witnessing the resonance of the charm-anti-charm bound state. However, the real motivation had derived from the relatively rare opportunity to measure the relative proper motion of the lensing object and throw a clean verdict whether the lensing object is in the Galactic halo or not. A Galactic halo object will have a high proper motion, while the proper motion of an SMC object will be small. The “long duration” brilliance of the caustic crossing that was watched from all three continents in the Southern hemisphere turned out to mean a slow progression of the star across the caustic and the conclusion that the lensing object is not in the Galactic halo. The size of the star was determined to be $\approx 1.1$ solar radius, and $\mu \approx 1.3 \, \text{km} \, \text{s}^{-1} \, \text{kpc}^{-1}$.

There have been claims that binary microlensing events can not be reconstructed uniquely. These claims were made without any analysis of the correlation with the quality of the data as if it were a generic feature of binary lensing. The case MACHO-98-SMC-1 restores the common sense: in a plagiarism of James Carville, “Coverage, stupid!” Obviously, if we have one datum on the light curve, there will be infinitely many other light curves that fit the datum. There is a need for systematic analysis for “smart coverages”.

In fact, the coverage of the MACHO-98-SMC-1 is judged to be good enough to test the limb darkening profile of the lensed star. This is planned for the “grand joint fit” where all the data will be combined and analysed. Figure 4 shows the (unnormalized) second caustic crossing light curves of the extra two images of stars with different luminosity profiles.

3 What can we conclude?

MACHO-98-SMC-1 is the second microlensing event discovered toward the SMC, is a binary lensing event, and is an SMC-SMC event. What does it tell us? It is a peculiar reminder that the first LMC event discovered by the MACHO collaboration was most likely a binary lensing event and the LMC microlensing statistic is dominated by single lens events. Binary objects are known for stellar populations. Black hole Machos are also expected to in binaries at a less level of $\approx 8\%$ even though an accurate estimation will need more sophisticated calculations. Boson star binary statistics are not available in literature. SMC has been expected to have a high self-lensing probability because of the elongated feature toward us. So, what can we conclude? Much more statistics and active monitoring of microlensing events for extra information besides the Einstein ring crossing time!!!
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Figure 1: This figure shows the configuration of the caustic curves for the MPS lightcurve fit 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.
Figure 2: This figure shows the photometric data and fit curves of the binary microlensing event MACHO-98-SMC-1 from the article by the PLANET collaboration. The inset shows the peak turn-over data from South Africa. The curvature change of the light curve around $t \approx 982.43$ is where the limb of the lensed star “touches” the caustic curve from inside. Here the apparent curvature change looks more prominent because of guiding fitting curve for which the homogeneous luminosity profile of the lensed star was used. The two fit curves presented by the PLANET collaboration illustrate the kind of uncertainties in the reconstruction of binary lensing light curves from “incomplete data.” The one with the earlier first caustic crossing will be ruled out by the MPS observation at June 5.55 UT.
Figure 3: This figure shows the MPS lightcurve fit to binary lensing event MACHO-98-SMC-1 as represented by the data from the EROS, MACHO/GMAN, MPS and OGLE collaborations.

$\chi^2 = 1802.1$ for 1617 d.o.f.
Figure 4: As the caustic line scans across the surface of the star, the integrated surface luminosity profile is “read out” in time. This figure shows the behavior of the analytic terms: homogeneous ($f_0$), square root ($f_{0.5}$), linear ($f_1$) and quadratic ($f_2$). The star “touchles” the caustic line at $a = -1$ and exits the caustic at $a = 1$ in this plot.

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\begin{align*}
    f_0(x) &= (1-x^2)^{1/2} \\
    f_{0.5}(x) &= (1-x^2)^{3/4} \\
    f_1(x) &= 1-x^2 \\
    f_2(x) &= (1-x^2)^{3/2}
\end{align*}
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