Magellanic Cloud Gravitational Microlensing Results: What Do They Mean?

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Abstract

Recent results from gravitational microlensing surveys of the Large Magellanic Cloud are reviewed. The combined microlensing optical depth of the MACHO and EROS-1 surveys is \( \tau_{\text{LMC}} = 2.1^{+1.3}_{-0.8} \times 10^{-7} \) which is substantially larger than the background of \( \tau_{\text{back}} \leq 0.5 \times 10^{-7} \) from lensing by known stellar populations although it is below the expected microlensing optical depth of \( \tau = 4.7 \times 10^{-7} \) for a halo composed entirely of Machos. The simplest interpretation of these results is that nearly half of the dark halo is composed of Machos with a typical mass of order \( 0.5 \, M_\odot \). This could be explained if these Machos are old white dwarfs, but it is not obvious that the generation of stars that preceded these white dwarfs could have gone undetected. It is also possible that Machos are not made of baryons, but there is no compelling model for the formation of non-baryonic Machos. Therefore, a number of authors have been motivated to develop alternative models which attempt to explain the LMC microlensing results with non-halo populations. Many of these alternative models postulate previously unknown dark stellar populations which contribute significantly to the total mass of the Galaxy and are therefore simply variations of the dark matter solution. However, models which postulate a unknown dwarf galaxy along the line of sight to the LMC or a distortion of the LMC which significantly enhances the LMC self-lensing optical depth can potentially explain the LMC lensing results with only a small amount of mass, so these can be regarded as true non-dark matter solutions to the Macho puzzle. All such models that have been proposed so far have serious problems, so there is, as yet, no compelling alternative to the dark matter interpretation. However, the problem can be solved observationally with a second generation gravitational microlensing survey that is significantly more sensitive than current microlensing surveys.

1 Introduction

In the past few years, the question of the composition of the Galactic dark matter has changed from a topic of theoretical speculation to an experimen-
tal question. A number of different experiments have or will soon have the sensitivity to probe most of the leading dark matter candidates in realistic parameter regimes. The most exciting result to come from these experiments so far has been the apparent detection of dark matter in the form of Machos by the MACHO and EROS Collaborations [1,2]. (Macho stands for MAssive Compact Halo Objects and refers to dark matter candidates with masses in the planetary to stellar mass range.) The MACHO Project, in particular, has measured a gravitational microlensing optical depth that greatly exceeds the predicted background of lensing by ordinary stars. However, the timescales of the detected microlensing events indicate an average lens mass that is firmly in the range of Hydrogen burning stars or white dwarfs at \(~0.5M_{\odot}\). Both of these possibilities appear to have other observable consequences that are not easy to reconcile with other observations. This difficulty has led a number of authors to propose alternative scenarios. One possibility is that the Machos are not baryonic despite having similar masses to stars [3,4]. Another possibility is that there is some population of normal stars that contributes a much higher microlensing optical depth than predicted by standard Galactic models. In this scenario, the detected microlensing events are caused by ordinary stars and have little to due with the Galactic dark matter. This possibility is particularly appealing to those searching for other dark matter candidates.

In this paper, we will discuss the microlensing technique as a dark matter search tool, and we review the latest dark matter results from the MACHO and EROS collaborations. We will then explore the various models that have been proposed to explain these microlensing results, and we shall see that there is no compelling alternative to the dark matter interpretation. Then, we will show how observations of “exotic” microlensing events which do not conform to the standard microlensing lightcurve shape can be used help pin down the location of the lens objects along the line of sight. Finally, we’ll discuss the “Next Generation Microlensing Survey” which will have the sensitivity to discover a statistically significant sample of “exotic” microlensing events which should resolve the basic question of whether the lensing objects reside in the Galactic halo.

2 The Microlensing Technique

Gravitational microlensing was proposed as a tool to study dark matter in our galaxy by Paczyński in 1986 [5], and a few years later serious microlensing dark matter searches were initiated [6,7] These searches are sensitive to dark matter in the mass range \(10^{-7} - 1 M_{\odot}\), but region of greatest initial interest was the \(0.01 - 0.1 M_{\odot}\) brown dwarf mass range.
At present there are four gravitational microlensing surveys of the Magellanic Clouds currently in operation. The three original microlensing surveys, EROS, MACHO, and OGLE all discovered their first microlensing events in September, 1993, and all three are still in operation. MACHO was the first project to operate a dedicated microlensing survey telescope with large format CCD cameras. They have a 64 million pixel dual color imaging system on the 1.3m telescope at Mt. Stromlo which has been observing for the microlensing project almost exclusively since late 1992. To date, they’ve obtained over 70,000 images of the Magellanic Clouds and the Galactic bulge. Each image covers about half a square degree on the sky. Their most recently published dark matter results come from observations of 22 square degrees of the central regions of the LMC over a period of 2 years ending in late 1994.

The EROS group is currently operating the EROS-2 telescope at La Silla. This 1-m telescope is equipped with a 128 million pixel dual color camera which images 1 square degree-similar to the MACHO camera but with a field of view that is a factor of 2 larger. Their published work is based upon their earlier EROS-1 system which involved digitizing Schmidt Plates from the ESO Schmidt telescope to search for microlensing events lasting longer than a week as well as a CCD survey which imaged the central region of the LMC very frequently using a 0.4m telescope to search for short timescale microlensing events.

The microlensing survey teams have yet to publish Magellanic Cloud microlensing survey results. The OGLE group is now observing the clouds with the OGLE-2 system which consists of a 1.3m telescope with a single 2k×2k CCD camera operated in drift scan mode, but their published survey results are from the OGLE-1 survey which did not observe the Clouds. The other microlensing team observing the Magellanic Clouds is the MOA project which is a New Zealand/Japanese collaboration that observes the LMC from a site in New Zealand that is far enough South that it is able to observe the LMC at every hour of the night.

3 Microlensing Results from MACHO and EROS

The first LMC microlensing events were discovered in September, 1993, by the EROS and MACHO collaborations [8,9]. This was the first hint that Machos might comprise a significant fraction of the Galactic Dark matter, but the first quantitative measurement of a microlensing optical depth significantly above the background didn’t come until a few years later when MACHO released
Table 1
Microlensing by Stars

| Population       | \(\tau(10^{-7})\) | \(\langle \hat{t} \rangle\) (days) | \(\langle l \rangle\) (kpc) | \(N_{\text{exp}}\) |
|------------------|-------------------|-----------------------------------|---------------------------|-----------------|
| Thin disk        | 0.15              | 112                               | 0.96                      | 0.29            |
| Thick disk       | 0.036             | 105                               | 3.0                       | 0.075           |
| Spheroid         | 0.029             | 95                                | 8.2                       | 0.066           |
| LMC center       | 0.53              | 93                                | 49.8                      | 0.71            |
| LMC average      | 0.32              | 93                                | 49.8                      | 0.71            |
| Total            | 0.54              | 99                                | -                         | 1.14            |
| Observed         | \(2.9^{+1.4}_{-0.9}\) | 87                               | ?                         | 8               |
| 100% MACHO dark halo | 4.7               | ?                                | 14.4                      | ?               |

1 This table shows the predicted properties for microlensing by known populations of stars for the MACHO 2-year data set. A Scalo PDMF is assumed, and the density and velocity distributions given in [10]. \(\langle l \rangle\) is the mean lens distance. The expected number of events \(N_{\text{exp}}\) includes the MACHO detection efficiency averaged over the \(\hat{t}\) distribution. For the LMC, two rows are shown; firstly at the center, and secondly averaged over the location of our fields; only the averaged \(N_{\text{exp}}\) is relevant. For comparison, the observed values and those predicted for a halo composed entirely of MACHOs are shown.

The LMC results from their first two years of operation [1]. They found eight microlensing events which indicated an optical depth of \(\tau_{\text{LMC}} = 2.9^{+1.4}_{-0.9} \times 10^{-7}\) which significantly exceeds the expected microlensing optical depth of \(\tau_{\text{back}} \leq 0.54 \times 10^{-7}\) from known stellar populations in the Galaxy and the LMC. Formally, the odds of obtaining a measured optical depth as high as \(\tau_{\text{LMC}}\) in a Universe in which the true microlensing is \(\tau_{\text{back}} \leq 0.54 \times 10^{-7}\) are about 0.04%. A detailed comparison of the LMC microlensing results from the MACHO Collaboration and the various stellar lensing backgrounds is given in Table 1. The prediction for a standard halo composed of Machos is also shown.

The EROS-1 microlensing survey has also reported an optical depth for the LMC of \(\tau_{\text{LMC}} = 0.82^{+1.1}_{-0.5} \times 10^{-7}\) [2]. These error bars were not reported by the EROS collaboration, but they were computing assuming Poisson statistics for events of the same timescale. This value is substantially less than the MACHO 2-year result, but because of the substantial statistical uncertainties, these have been shown to be consistent with each other. Because there is little overlap between the time and spatial coverage of the MACHO 2-year and the EROS-1 experiments, the data sets are essentially independent and it makes sense to average them. The relative sensitivity of the two experiments can be determined by comparing the expected number of events for the standard halo models for an assumed Macho mass of \(0.4M_\odot\). According to [1,2], EROS-
1’s sensitivity is about 58% of that of the MACHO 2-year data set. With this weighting, we find a combined EROS-1 & MACHO-2-year microlensing optical depth of $\tau_{\text{LMC}} = 2.1^{+1.3}_{-0.8} \times 10^{-7}$.

### 3.1 The Dark Matter Interpretation

Since the MACHO and EROS experiments were designed as dark matter detection experiments, the simplest interpretation of a signal above background is that some of the dark matter halo has been detected. As shown in Table 1, the line of sight to the LMC passes through only one known Galactic component massive enough to provide a microlensing optical depth of $\tau_{\text{LMC}} = 2.1^{+1.3}_{-0.8} \times 10^{-7}$ and that is the Galactic halo. However, the typical mass of the lenses is estimated to be $\sim 0.5M_\odot$ which is well above the Hydrogen burning threshold. If these $\sim 0.5M_\odot$ lens objects are made of ordinary Hydrogen and Helium, then they would be bright main sequence stars which are far too bright to be the dark matter.

A more reasonable choice for Macho dark matter would be white dwarf stars which would be too faint to be easily seen. However, white dwarfs generally form at the end of a star’s life and only a fraction of the star’s initial mass ends up as a white dwarf. Thus, scenarios in which white dwarfs comprise a significant fraction of the dark matter can be constrained by limits on the brightness and heavy element production from the evolution of the stars which preceded the white dwarfs [11–15]. However, a population of white dwarfs which contributes substantially to the mass of the dark halo must have some unusual characteristics in order to avoid appearing as a normal old stellar population, so we must be wary of constraints which rely upon the empirically determined properties of white dwarfs as a hypothetical dark matter population would necessarily have some differences.

Another possibility is that the Machos do make up the dark matter, but they are not made of baryons. Non-baryonic Macho candidates include such things as black holes, strange stars, and neutrino balls [3,16]. These possibilities would behave as cold dark matter as far as galaxy formation scenarios are concerned, so the non-baryonic Macho option would allow Machos to comprise all of the dark matter in the Universe without posing any difficulties for the galaxy formation scenarios favored by cosmologists. It would seem to be a bit of a coincidence that the dark matter mass would end up nearly the same as the mass of stars. One scenario that might avoid this coincidence is the possibility of black hole formation at the QCD phase transition [3] because the horizon at the at the phase transition contains about a solar mass of radiation. It takes only one horizon size region in $10^8$ to collapse to form a black hole in order to have a critical density of black holes today. If the QCD transition is first
order, this might enhance horizon sized density perturbations somewhat, but this scenario probably requires a feature in the density perturbation spectrum at the mass scale of the observed Machos so it see that some sort of fine tuning is required in this scenario.

If the dark matter interpretation is correct, there is an additional puzzle of the composition of the remainder of the dark matter since the observed microlensing toward the LMC appears to be less than expected for a dark halo made of only Machos. It could be that the rest of the halo is made of particle dark matter such as WIMPs, axions, or massive neutrinos, but another possibility is more massive Machos such as $\sim 20M_\odot$ black holes which might form from the collapse of very massive stars. These events would be 40 times less common than the observed shorter timescale events, so current microlensing searches cannot put an interesting limit on them. One microlensing event thought to be caused by a $\sim 20M_\odot$ black hole has been seen towards the Galactic bulge, however.

4 LMC Microlensing Events as a Background

An alternative to the dark matter interpretation is the possibility that the lensing background from ordinary stars has been seriously underestimated. This requires a substantial increase above the estimates shown in Table 1 which would require a substantial revision of the standard Galactic or LMC model or else an entirely new component of the Galaxy. The different models that have been proposed are summarized in Table 2.

4.1 Stars in the Galactic Disk or Spheroid

The local Galactic disk is perhaps the best understood part of the Milky Way, so it is difficult to make a modification to the standard model of the disk of the magnitude required to account for much of the observed microlensing signal. The thin disk, in particular, is very well characterized. There are tight constraints on the observed density of all types of stars in the disk as well as constraints on the total column density of the disk within 1 kpc of the Galactic plane: $\Sigma_0 < 80M_\odot$ pc$^{-2}$. The observed density of stars and gas in the thin disk comprises about half of this limit [17], so there is some room for additional material in a massive thick disk. However, in order to explain the observed LMC microlensing events, the bulk of the matter in this massive thick disk must be more than 1 kpc from the Galactic plane. Furthermore, this thick disk is far more massive than the thick disk that has been observed in the stellar distribution, so it must be composed of objects that are much darker
than an ordinary stellar population.

The Galactic spheroid is a roughly spherical distribution of stars with a density that falls as $r^{-3.5}$ at large radii. This distribution has been determined by comparison to star counts. If a standard stellar mass function is assumed, then these data can be used to estimate the microlensing optical depth yielding the result shown in Table 1. In order to obtain a microlensing optical depth that can explain the observed signal, a dark spheroid population with 50-100 times the mass of the observed stellar population must be added.

Thus, both the spheroid and thick disk models are more properly considered to be variations of the dark matter interpretation rather than lensing by the background of ordinary stars. Because the thick disk and spheroid densities drop more rapidly at large radii than the canonical dark halo models, these model predict a lower total mass in Machos for a given microlensing optical depth than a standard halo model does [18]. This might ease some of the difficulties with the white dwarf lens option because these distributions would require fewer white dwarfs in the Galaxy.

4.2 Warped and Flared Disk: the Galactic Bagel

A recent paper by Evans et al. [19] has proposed that both the thin and thick disk might be both flared and warped in the direction of the LMC. This seems like a reasonable option because warping is observed in external galaxies and the gaseous component of our own Galactic disk does appear to be flared. Interactions with accreting dwarf galaxies like the recently discovered Sagittarius dwarf might plausibly give rise to both these effects.

Evans et al. [19] have investigated such models and found that they did not yield an interesting microlensing optical depth, so they turned to a more radical set of models. The class of models that Evans et al. propose has a disk column density that grows with Galactic radius beyond the solar circle. Their most extreme model is able to generate a microlensing optical depth of $\tau = 0.9 \times 10^{-7}$ which is below the MACHO Project’s 95% confidence level lower limit on $\tau_{\text{LMC}}$ even when the other backgrounds listed in Table 1 are included. However, some drastic assumptions are required in order to generate this relatively modest microlensing optical depth. This model has a total disk mass of $1.5 \times 10^{10} M_\odot$ inside of the solar circle ($R_0 = 8$ kpc), but it has $1.39 \times 10^{11} M_\odot$ between 8 and 24 kpc. The total mass within 50 kpc is $2.12 \times 10^{11} M_\odot$. Thus, the mass distribution resembles that of a bagel with most of the mass contained within a toroidal region outside of the solar circle.

It is instructive to compare this mass distribution to that of an isothermal sphere with a circular rotation speed of 200 km/sec. The isothermal sphere has
a mass of $7.4 \times 10^{10} M_\odot$ inside 8 kpc and $1.49 \times 10^{11} M_\odot$ between 8 and 24 kpc. (Note that a flattened distribution of matter supports a faster rotation speed than a spherical distribution.) Thus, Evans et al.’s Galactic bagel provides only a small fraction of the mass needed to support the rotation at the solar circle, but it provides virtually all of the mass needed between 8 and 24 kpc. Thus, if dark halo provides the additional mass needed to support the Galactic rotation curve, it must have a relatively high density inside the solar circle, but essentially no mass between 8 and 24 kpc. The halo density would grow once again to comprise most of the Galactic mass beyond 24 kpc. Such a halo is virtually impossible with cold dark matter, but it might be possible to make a halo that resembles this with massive neutrinos if most of the mass inside the solar circle in a baryonic component that is different from the Galactic disk/bagel. In short, the Evans et al. model is similar to the thick disk model discussed above in that the microlensing optical depth toward the LMC is raised by significantly increasing the total stellar mass of the Galaxy. It differs from the massive thick disk model in that the additional stars are added far from the solar circle so that they can be brighter without violating limits on the stellar content of the solar neighborhood.

4.3 Magellanic Cloud Stars

According to Table 1, lensing by ordinary stars in the LMC is the largest contribution to microlensing background, and because the SMC is thought to be elongated along the line of sight, the SMC self-lensing optical depth is thought to be substantially larger than this [20]. Furthermore, we don’t have as stringent constraints on star counts and the distance distribution of stars in the Magellanic Clouds. These facts led Sahu and Wu [21,22] to suggest that perhaps lensing by LMC stars could be responsible for most of the observed LMC microlensing events. However, Gould [23] showed that the self-lensing of self-gravitating disk galaxy, inclined by less than 45° like the LMC, is related to its line of sight velocity dispersion by the formula, $\tau < 4 \langle v^2 \rangle / c^2$ under the assumptions that the stellar disk is a relaxed virialized system. Since the velocity dispersion of the LMC is measured to be 20 km/sec, the implied self-lensing optical depth of the LMC is $\tau \lesssim 2 \times 10^{-8}$ which is far too low to explain the LMC microlensing events.

This constraint can be avoided only if the LMC has a higher velocity dispersion than current measurements indicate - perhaps in the central LMC where measurements are rather sparse and where the the microlensing search experiments have concentrated their observations. Such a model would then predict that the microlensing optical depth would be much lower in the outer LMC than in the central bar. This is contrary to the observed distribution of event locations which seems independent of distance from the LMC center,
Table 2
Models to Explain the LMC Microlensing Results

| Lens Population         | $\tau_{\text{pred}}/\tau_{\text{LMC}}$ | mass of pop.         | lens identity | problems                      |
|------------------------|----------------------------------------|----------------------|---------------|-------------------------------|
| halo Machos            | 1                                      | $2 \times 10^{11} M_\odot$ | WD or BH?     | Macho formation?              |
| dark thick disk        | 1                                      | $\sim 10^{11} M_\odot$  | WD or BH?     | Macho formation?              |
| & spheroid             |                                        |                      |               |                               |
| foreground gal.        | 1                                      | $10^9 - 10^{10} M_\odot$ | stars         | stars not seen;               |
| ZL foreground gal.     | $< 0.13$                               | $10^9 M_\odot$       | stars         | stars in LMC                  |
| warped flared disk     | $\lesssim 0.5$                         | $\sim 10^{11} M_\odot$ | stars         | contrived                     |
| LMC                    | $< 0.2$                                | $10^{10} M_\odot$     | stars         | $\tau$ too small              |

This table compares the various models that have been proposed to explain the LMC microlensing results.

but the current data sets are too small for a highly significant test of this effect. Another possible way to evade Gould’s limit on the LMC self-lensing optical depth would be if the LMC is not a virialized self-gravitating system.

4.4 Foreground Dwarf or Tidal Tail

Inspired by the recent discovery of the Sagittarius Dwarf Galaxy on the far side of the Galactic bulge, Zhao proposed that there might be another similar sized dwarf galaxy along the line of sight toward the LMC. This possibility could neatly explain the LMC microlensing events with a normal stellar system of very small mass, and so it involves no new population of Machos or faint stars in unexpected locations. Like the Sagittarius Dwarf, such a galaxy could possibly have evaded detection because its stars would generally be confused for LMC stars. The one obvious drawback of this model is that such dwarf galaxies are quite rare. The Sagittarius Dwarf is the only known dwarf galaxy with a mass large enough to have a significant gravitational lensing optical depth to explain the LMC microlensing results, and it only covers about one thousandth of the sky. So, the a priori probability of a chance foreground dwarf galaxy is only about 0.001. Zhao [24] also suggested that a more likely scenario might be to have a “tidal tail” of a Galaxy like the LMC or even the LMC itself be responsible for the lensing events.

These “foreground galaxy” models a significant boost when Zaritsky & Lin [25] (hereafter ZL) reported the detection of a feature in the LMC color-magnitude diagrams which they interpreted as evidence for a population of “red clump”
stars in the foreground of the LMC. However, neither Zhao’s models or ZL’s interpretation of their observations has stood up very well under scrutiny. The following counter arguments indicate that these foreground galaxy or tidal tail models are not likely to be correct:

- The MACHO Project [26] showed that there is no excess population of foreground RR Lyrae stars toward the LMC indicating that there is no foreground dwarf galaxy with a old, metal poor stars at a distance of less than 35kpc towards the LMC.
- Beaulieu & Sackett [27] argued that the CM diagram feature seen by ZL is a feature of the LMC’s giant branch rather than a foreground population.
- Bennett [28] showed that even if ZL’s interpretation of the LMC CM diagram is correct, the implied microlensing optical depth is only 3-13% of the microlensing optical depth seen by MACHO.
- Gould [29] showed that the outer surface brightness contours of the LMC do not allow for a foreground galaxy or tidal tail that extends beyond the edge of the LMC.
- Johnston [30] showed that tidal debris from the LMC or a similar galaxy would not be expected to remain in front of the LMC for any significant length of time.

5 Exotic Microlensing Events

Observations of exotic microlensing events such as caustic crossing events, parallax events, and binary source events can provide addition information that can pin down the location of the lens. For example, the recent observations of the binary caustic crossing for the event MACHO Alert 98-SMC-1 have measured the time it takes for the projected position of the lens center of mass to cross the diameter of the source star [31–33]. Since we can make a reasonable estimate of the source star size from multicolor photometry or spectra of the source star, a reasonable estimate of the angular velocity of the lens can be obtained. In the case, of MACHO 98-SMC-1, the angular velocity was low indicating that the lens resides in the SMC which is not a surprise because the self-lensing optical depth of the SMC is expected to be large[20]. Another type of exotic event that has only been definitively observed towards the galactic bulge is the microlensing parallax effect [34] which is a lightcurve deviation due to the motion of the Earth. This also yields information on the distance to the lens although accurate photometry is required to detect parallax effect for lenses in the halo. Also, the converse of the parallax effect (sometimes called the xallarap effect) can be observed if the source star is a binary and the effects of its orbital motion can be seen. This requires multiple follow-up spectra to characterize the binary source orbit [35].
It is generally the case that the characterization of these exotic microlensing events requires more frequent or higher accuracy photometry than can be obtained by the microlensing survey teams, but this is now routinely made possible by the routine discovery of microlensing events in real time [36–38]. However, the rate that these exotic microlensing events are detected in the LMC is only about 0.3 per year which is not enough to get a statistically significant sample in a reasonable amount of time. However, the next generation of microlensing surveys [39] should have a event detection rate that is more than an order of magnitude higher than this which should yield enough exotic events to resolve the Macho mystery.

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