Dark Matter Results from Microlensing

Kim Griest
Physics Department
University of California, San Diego
La Jolla, CA 92093
kgriest@ucsd.edu

Gravitational microlensing is well established as an important method of discovering dark objects. However, the dark matter contribution of the objects thus discovered is still uncertain. We discuss the data, the problems, and some possible ways to resolve the issues.

I. INTRODUCTION

Gravitational microlensing is established as a powerful method of discovering and characterizing populations of dark objects. Our collaboration, the MACHO collaboration, has discovered the bulk of the over 300 microlensing events that have been found. Most of these have been found towards the Galactic bulge, but for the dark matter question, which is the subject of this talk, only the dozen or so events towards the Large (LMC) and Small (SMC) Magellanic Clouds are relevant.

The microlensing surveys set out in the early 1990's to use gravitational lensing to search for dark matter in the form of Massive Compact Halo Objects (Machos). Since we discovered the signal we were looking for, the first and simplest interpretation of these events was that they represent a substantial fraction of the dark halo of the Milky Way Galaxy. A likelihood analysis gives a most likely contribution of around $2 \times 10^{11} M_{\odot}$, almost independent of the halo model used [1]. Since this is several times the total mass in known material such as stars, dust, and gas, if this interpretation is correct, then the LMC microlensing events represent the discovery of the dominant detected component of our Galaxy. However, this interpretation has some problems, and as I will discuss, the meaning of these dozen or events is still not settled. The main problem comes about because we usually cannot tell where along the line-of-sight the dark objects reside. If the lenses are not in the Galactic halo, then the above estimate of the mass in lenses is probably irrelevant for the dark matter problem. However, a non-halo stellar population has been searched for unsuccessfully, so if the lenses are not in the halo, it is not clear what these objects are. On the other hand, if the lenses are in the halo, then the mass of these lenses seems to be in the 0.1 to 1 $M_{\odot}$ range, and there are no compelling candidates for such a numerous dark population. This confusing situation is the subject of this talk.

II. MICROLENSING BASICS

The large surveys teams, MACHO [2,1], EROS [3,4], and OGLE [5,6] monitor millions of stars in the LMC and SMC, two of the nearest galaxies to the Milky Way. LMC and SMC distances of 50 kpc and 60 kpc respectively, place them inside the large dark halo of the Milky Way, and yet far enough away that substantial dark matter exists in the space between them and us. The dark halo is needed to explain the observed flat rotation curve of the Milky Way, and implies that the halo objects, whatever they may be, move with a mean speed of approximately 270 km/s.

When a compact object passes directly in front of a more distant star, the compact objects acts a gravitational lens and magnifies the source star. Perfect alignment results in a circular image called the Einstein ring, of radius

$$r_E = 610 R_{\odot} [\frac{m}{M_{\odot}} \frac{L}{\mathrm{kpc}} x(1-x)]^{1/2},$$

where L is the distance to the source star, $x = D_L/L$, D_L is the distance to the lens, m is the mass of the lens, and $R_{\odot}$ is the solar radius. The ring image gives theoretically infinite magnification, but perfect rings are expected to be extremely rare and other effects such as the finite size of the source star limit the magnification. Imperfect alignment gives two images instead of a ring but also can magnify the source substantially. Since the observer (on Earth), the lens, and the source are all in relative motion, these stellar magnifications are transient events, lasting for a duration $\widehat{t} = 2r_E/v_\perp$, where $v_\perp$ is the transverse speed of the lens relative to the line-of-sight.

The main problem of microlensing interpretation can be understood from these formulas. During a typical event, there is only one measurable observable, the duration $\widehat{t}$, but there are four physical parameters, L, m, $v_\perp$, and x that determine it. L can usually be estimated since the source is visible, but there is degeneracy between the m, $v_\perp$, and x parameters. Thus, on an event-by-event basis, one cannot determine either the lens distance or the lens mass. By assuming a mass and velocity distribution, one can determine the typical lens mass in a statistical way. Using 6 events from the 2-year LMC data, such an analysis was performed and a Macho halo fraction of $\sim 50\%$ with a typical Macho mass of $0.5 M_\odot$ was found [1]. These conclusions depend upon the assumption that the events come from objects in the dark halo, since a model is needed to statistically average over possible lens distances and velocities. An assumption of a non-halo population for these lenses can give quite a different determination of the amount of material that the dozen or so LMC events represent.

III. INTERPRETATION OF RESULTS

Before discussing alternative interpretations of the dozen or so LMC/SMC events, one should point out a very robust dark matter result from the microlensing surveys. Both the MACHO and EROS collaborations did intensive searches for short duration microlensing events and found none. Short duration events would be caused by low mass Machos, which smaller have Einstein rings. The non-observation of such events allows one to rule out a dark halo consisting of low mass compact objects. Our most sensitive analysis to date [7] implies that objects with masses between $10^{-7} M_\odot$ and $10^{-3} M_\odot$ (Mars to Jupiter mass) make up less than 25% of the dark halo, and objects with mass m in the range $3.5 \times 10^{-7} M_\odot \leq m \leq 4.5 \times 10^{-5} M_\odot$ make up less than 10% of the dark matter. These results are not very sensitive to the halo model used and do not suffer from the interpretation problems discussed below. These are the strongest limits to date on baryonic dark matter in the Milky Way.

However, more interesting than limits on low mass dark matter is the interpretation the dozen or so microlensing events actually discovered. The main problem with the dark matter interpretation of the LMC/SMC microlensing events is that the most likely lens mass is found to be around $0.5 M_\odot$. Objects with masses above $0.08 M_\odot$ should be main sequence stars, which would be easily visible and therefore ruled out as dark matter candidates. Regular main sequence stars is one thing we know the dark matter is not! If the mass determined from the microlensing likelyhood analysis had been in the brown dwarf range (below $0.08 M_\odot$), then most people probably would have accepted the dark matter interpretation, but now the question becomes, “What could these objects be?”

Many possible answers to this question have been given, but none of them are particularly satisfactory. For example, old white dwarf stars have masses of around $0.6 M_\odot$, and are probably too dim to be seen in any current experiment. So a reasonable candidate might be the white dwarf remants from a very numerous early generation of stars. But a star loses more than 50% of its mass on route to becoming a white dwarf, so one must ask where all that material went. Some ideas, such as the fact that much of it might be blown out of the galaxy by the strong stellar winds and supernova that are expected to have occurred, have been given, but it still seems problematic to hide so much material. Neutron stars and regular black hole remnants of an early generation of stars have similar problems. Primordial black holes formed in the early Universe would avoid these problems, but so far no mechanism that could create large numbers of these objects without substantial fine-tuning of the model parameters has been suggested. Thus no compelling candidate for dark halo Machos of $\sim 0.5 M_\odot$ has appeared.

So some workers have turned to non-dark matter alternatives. However, each of these alternatives is also problematic, so at present there is no compelling explanation for the LMC microlensing events. For example, suppose there is a small dwarf galaxy in front of the LMC that contains the lenses. Our survey monitors only about 20 square degrees on the sky, and we derive the large dark matter mass by assuming that the LMC line-of-sight is typical. A small galaxy could give 6 or so events [8], in which case we have only discovered a small neighboring galaxy and not the dark matter. One group [9], claims to detect stars from just such a galaxy, but several other groups dispute both the

the claim of an intervening galaxy [10,11] and its ability to produce enough microlensing [12,13]. At this time the bulk of the evidence makes it quite unlikely that an intervening dwarf galaxy is the explanation for the LMC events.

Another non-dark matter possibility is that the LMC is lensing stars in the LMC itself [14]. This is possible, but explicit calculations of the size of this effect using standard models of the LMC suggest that only one of the dozen or so LMC events is likely to have come from LMC self-lensing [1,15]. Of course, the LMC may be more extended and more complicated than the simple disk models used, and in my opinion, this possibility is still one of the more likely explanations. However, I should note that recent much improved neutral hydrogen maps of the LMC show it to be a very symmetrical disk, with spiral features, just as the standard LMC model would predict [16]. Thus again, using the best available data, there is no detected source for these lenses. In summary, both the dark matter and non-dark matter interpretations have problems, and no clear answer is just now at hand.

IV. HOW TO SETTLE THE QUESTION

One way to prove that LMC self lensing, or an intervening dwarf galaxy between the LMC and the Milky Way is not the cause of the events, is to find lensing towards another line-of-sight, for example, the SMC. This has been done by two collaborations [17–19]. Unfortunately, the SMC is known to be extended along the line-of-sight, and so, in contrast to the LMC case, one expects SMC self-lensing to contribute to, or even dominate, the dark matter halo signal towards the SMC. Thus the two SMC events found do not resolve the question.

Clearly we need to discover where along the line-of-sight the lenses lie, that is, we need to make a determination of the distances to some LMC lenses. As discussed above, with standard point-source-point-lens (pspl) microlensing this is not possible on an event by event basis. However, there are several types of unusual microlensing cases where deviations from the pspl form occur and where it is possible to eliminate at least one of the three $(m, v_\perp, x)$ variables from the equations.

For example, if the event has a long duration, the Earth's motion around the Sun will most likely affect the lightcurve. Since the Earth's motion is well known, the projected transverse speed can be determined, resulting in a unique relationship between the lens mass and distance. This effect is called microlensing parallax, and we have detected it in events towards the bulge [20], but unfortunately not yet towards the LMC.

Similar information is obtained for non-pspl events where the finite size of the source star is resolved. This happens for the rare events where the lens comes very close to the observer-source line-of-sight, and therefore causes very high magnification. This effect has also been seen only in the bulge [21].

Finally, if the source is is a binary star [22], or the lens is a binary system [23], much more complicated lightcurves can result and additional information can be obtained. The most interesting case occurs when the lens is actually a binary system. General relativity predicts a complicated caustic structure in this case – caustics being positions on the sky (roughly behind the lens) where the magnification is theoretically infinite. The finite size of the source star prevents infinite magnification from occurring, but magnifications of more than 100 can occur for the brief time it takes the caustic to pass over the source star's limb. The time for which the source is highly magnified thus allows determination of the caustic sweep speed. The sweep speed depends strongly on the distance of the lens. For relatively nearby lenses in the halo, sweep speeds of ~ 1000 km/s are expected, while for lenses in the LMC or SMC, speeds of ~ 100 km/s are more typical.

Recently the MACHO collaboration detected such an event towards the SMC [18]. Three follow-up programs (MACHO GMAN, EROS, and PLANET) were enlisted and helped detect the caustic crossing described above [18,19,24]. The duration of this crossing was such that a sweep velocity of ~ 90 km/s was found – strong evidence that the lens in this case is in the SMC itself and not in the dark matter halo. Since self lensing is expected to be large for the SMC, this does not resolve the dark matter question, but a few events like this towards the LMC should help in straightening out the interpretation of LMC microlensing.

V. CONCLUSIONS AND DISCUSSION

In conclusion, with current data, the dark matter interpretation of the microlensing events is still up-in-the-air. What is most needed are determinations of the distances to some lenses causing LMC events. Even one determination of a lens distance of around 10 kpc, typical of a halo lens, would show that some of the microlensing was due to halo objects and would therefore imply a substantial Macho contribution to the Milky Way dark matter. Alternately several lens distances of around 50 kpc, would show that LMC/LMC lensing is the dominate effect and lead to the conclusion that Machos are probably not a main contributor to the dark matter.

Fortunately, the possibility of getting these distances is improving. Several new microlensing experiments such as EROS2 [19] and OGLE2 [6], are in operation and a next generation microlensing project (NGMP) has been proposed [25]. In addition, the search for extra-solar planets using follow-up on microlensing events towards the bulge is rapidly expanding, and these experiments get the detailed photometry needed to determine the lens distances in some cases. Also needed for the future are better models of the LMC, SMC, and Milky Way, and if Macho dark matter is confirmed, ideas of what Machos are and how they could have formed will also be needed.

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[1] C. Alcock, *et al.*, ApJ 486, 697, 1997.
[2] C.Alcock, *et al.*, ApJ 479, 119, 1997.
[3] Renault, C., *et al.*, A&A, 324, 69 (1997).
[4] Palanque-Delabrouille, N., *et al.*, A&A, 332, 1 (1998).
[5] Udalski, A., *et al.*, Acta Astronomica, 44, 165 (1994).
[6] Udalski, A., *et al.*, Acta Astronomica, 47, 319 (1997).
[7] C. Alcock, *et al.*(MACHO + EROS collaboration), ApJ Lett. 499, L9 (1998).
[8] Zhao, H., MNRAS, 294, 139 (1998).
[9] Zaritsky, D., and Lin, D.N.C., AJ, 114, 2545 (1997).
[10] Beaulieu, J.P. & Sackett, P.D. ApJ, 116, 209 (1998).
[11] C.Alcock, *et al.*, ApJ Lett. 490, L59, 1997.
[12] Gould, A. ApJ 499, 728 (1998).
[13] Bennett, D.P., ApJ Lett, 493, L79 (1998)
[14] Sahu, K., Nature, 370, 275 (1994)
[15] Gould, A., ApJ, 404, 451 (1993)
[16] Kim, S., *et al.*, ApJ, 503, 674 (1998)
[17] C. Alcock, *et al.*, ApJ Lett. 491, L11, 1997
[18] C.Alcock, *et al.*, astroph/9807163, submitted to ApJ, 1998.
[19] Afonso, C, *et al.*, A&A 337, L17 (1998).
[20] C.Alcock, *et al.*, ApJ Lett. 454, L125 1995.
[21] C. Alcock, *et al.*, ApJ 491, 436, 1997.
[22] K. Griest and W. Hu, *Astrophysical Journal,* **397,** 362 (1992).
[23] Mao, S. & Paczynski, B., ApJL 374, L37 (1991).
[24] Albrow, M. D., *et al.*, astro-ph/9807086, submitted to ApJ Lett (1998).
[25] Stubbs, C. private communication, 1998.