The Case for a Next Generation LMC Microlensing Survey

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Abstract. Microlensing surveys search for the transient brightening of a background star that is the signature of gravitational lensing by a foreground compact object. This technique is an elegant way to search for astrophysical candidates that might comprise the dark matter halo of the Milky Way. While the current projects have successfully detected the phenomenon of microlensing and have reported many important results, the relatively large event rate reported towards the LMC remains a puzzle. The first step in resolving this mystery is determining the location of the excess lensing population. This will require a microlensing survey with an order of magnitude increase in sensitivity over current projects. I summarize the present status of microlensing surveys, and present (and advocate!) a next-generation program that should be capable of unambiguously determining whether the dark halo of the Galaxy is indeed made up of MACHOs, or whether the observed events are due to previously unappreciated ordinary stellar populations.

1. Introduction

A convergence of progress in both computing and detector technology in the late 1980′s led a number of groups to undertake searches for gravitational microlensing. A primary motivation for much of this work was the elegant idea (Paczynski 1986) of searching for Galactic dark matter in the form of MAssive Compact Halo Objects (MACHOs) by looking directly for their gravitational effects. This has the advantage of using the one thing we know about dark matter; it exerts a gravitational influence on its surroundings. Comprehensive reviews of the technique and initial results have been presented by Paczynski (1996) and Roulet and Mollerach (1997).

Although the microlensing surveys are frequently characterized as searches for Baryonic dark matter, we should bear in mind that these projects are sensitive to any object that gravitates like a point mass. MACHOs need not necessarily be made of Baryonic matter.

The basic idea in a microlensing dark matter hunt is to monitor a population of background stars and search for the signature of gravitational lensing due to foreground compact objects. If the foreground object passes close to the line of sight to a background star, gravitational lensing produces multiple images of the

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source star. Due to the relatively short (Galactic-scale!) distances in the case of microlensing, the multiple images are not individually resolvable, as opposed to lensed quasars which can have image separations of order arc seconds. Since the source, lensing object and detector are in relative motion the observable effect is a transient brightening of the background star, with an apparent amplification $A(u)$ given by

$$A(u) = \frac{u^2 + 2}{u \sqrt{u^2 + 4}},$$  \hspace{1cm} (1)

$$u = \frac{b}{R_E},$$  \hspace{1cm} (2)

$$R_E = \sqrt{\frac{4GM_D}{c^2(D_1 + D_2)}}$$  \hspace{1cm} (3)

where $b$ is the separation of the lens from the undeflected line of sight, $R_E$ is the Einstein radius (in the lens plane), $D_1, D_2$ are the distances from the lens to the source and detector, respectively, and $m$ is the lens mass.

The fraction of background stars that lie within one Einstein radius of a foreground lens is a dimensionless number: the optical depth $\tau$. For an isothermal halo with a typical velocity $\beta = v/c \sim 10^{-3}$, we expect $\tau \sim 10^{-6}$. This means that a microlensing survey must monitor many millions of stars in order to have a reasonable event detection rate.

The duration $\hat{t}$ of a microlensing event is determined by the lens’ position, its mass, and its transverse velocity. It is difficult to disentangle these for any single event. Real-time detection and follow-up observations of exotic events are helping to lift this degeneracy in certain cases, however, as described below. For a fixed total mass of lensing objects in the Galactic halo, a population of low mass lenses produces short events, while if the MACHOs were more massive there would be fewer, but longer, events.

Microlensing surveys are being carried out towards stars in the Galactic center, and towards our near-neighbor galaxies the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC). More speculative work is being carried out towards M31 (Andromeda) and other targets.

Using wide-field CCD arrays and 1 meter class telescopes, three groups made essentially simultaneous announcements (Udalski et al. 1993, Alcock et al. 1993, Aubourg et al. 1993) of the detection of microlensing. At the time of this writing (Fall 1998) the total number of reported microlensing events exceeds 300. The overwhelming majority of these are seen towards the Galactic center, presumably due to lensing by ordinary objects in the disk or bulge of the Galaxy. The ratio of the number of microlensing events reported thus far towards the Galactic center to the number seen towards the LMC and SMC is very roughly given by $(N_{\text{center}} : N_{\text{LMC}} : N_{\text{SMC}}) \sim (100 : 10 : 1)$. The event rates towards the LMC and SMC probe directly the amount of lensing material along those lines of sight, which may be dominated by dark matter. The microlensing rate towards the Galactic Center also has a bearing on the Galactic dark matter, as it can be used to map out the mass distribution in the disk. This can help determine the extent to which the Galactic rotation curve is supported by disk matter.
Figure 1. Light Curve of MACHO event 95-30, an exotic “Finite Source” event. The amplification as a function of time (in days) is shown. Also shown to scale are the size of the source star and the Einstein radius of the lensing object, which traversed the face of the star. Intense monitoring of exotic events can be used to lift the degeneracy between lens mass, position, and transverse velocity.

1.1. Lifting Degeneracies with Exotic Events

The formulation for $A(u)$ given above assumes a point lens, a point source, and a detector that are in relative inertial motion. If any one of these assumptions breaks down, the observed light curve can depart from the form given by Eq 1. These perturbations, sometimes very dramatic, can convey additional information about the lens mass, location or velocity. One of the pleasantly surprising aspects of the microlensing field has been the speed with which the rich phenomenology of exotic microlensing was observationally established.

Examples of exotic microlensing that have been seen include:

1) Finite source effects, where the lens passes very close to (or even across the face of) the background star. In this case the peak amplification is attenuated since the source of light is distributed across an extended region. An example of such an event is shown in Figure 1, taken from Alcock et al., 1997b. Finite
source effects provide a way to determine $\theta = \phi_e / \phi_{\text{source}}$, the angular size of the Einstein radius, $R_E$, in units of the source star's angular extent. The projected transverse velocity of the lens can also be determined.

2) Parallax effects, due to the acceleration of the line of sight as the earth orbits the sun. This can be used to establish a relationship between the lens' mass and its position along the line of sight.

3) Xallarap effects, the complement of parallax effects, where the source star is orbiting a companion object. (Xallarap is “parallax” backwards).

4) Binary lenses, where a compound system acts as a lens. In this case, dramatic structures can be seen in the light curve, as the caustic lines of the asymmetrical lens pass across the source star. By measuring the time it takes for a caustic line to pass across a star of known diameter, the projected velocity of the lens can be measured. An example of a binary lensing event is shown in Figure 2.

Much of the data shown in Figure 2 were obtained after the real-time detection of the anomaly in the light curve (Alcock et al., 1998b, Afonso et al., 1998). Currently, not only are the majority of microlensing events detected in real time (meaning within a few hours of the image being taken), but anomalies in the light curves of ongoing events are also sought, giving rise to “Level 2” Alerts. See [http://www.darkstar.astro.washington.edu](http://www.darkstar.astro.washington.edu) and [http://www.astrouw.edu.pl/~ftp/ogle/ogle2/ews/ews.html](http://www.astrouw.edu.pl/~ftp/ogle/ogle2/ews/ews.html) for descriptions of ongoing events.

The observed frequency and characteristics of these various exotic events will play an important role in the next-generation survey described below.

2. Current and Future Results from Existing Microlensing Surveys

The extensive monitoring programs carried out by the microlensing surveys have generated a prodigious amount of raw image data. The MACHO project, for example, has generated over 6 Terabytes of CCD image data. The frames are subjected to photometric analysis, and the resulting light curves are scanned for evidence of microlensing. Approximately one object per thousand in the MACHO database exhibits significant variability. While intrinsic stellar variability is a nuisance when searching for microlensing, this data set is an unprecedented resource for the study of variable stars. This paper, however, will focus on dark matter.

The microlensing projects have collectively produced two results of significance regarding the Galactic dark matter. In order of significance they are:

1. The lack of short events in the joint MACHO + EROS data set excludes any compact objects in the mass range $10^{-7} < M/M_\odot < 10^{-3}$ from comprising a significant fraction of the Galactic dark matter (Alcock et al., 1998).

2. The MACHO team has reported (Alcock et al.1997a) an excess of events towards the LMC, relative to the number expected from known stellar pop-
Figure 2. Example light curve from a binary lens, in this case MACHO SMC-98-1. The dramatic changes in the light curve occur when caustic lines cross in front of the source star, and the transit time can be used to measure the angular transverse velocity of the lens, given the size of the source star.

Simulations. Cast in terms of an optical depth, $\tau_2^{200} = 2.9^{+1.4}_{-0.9} \times 10^{-7}$ vs. the $\sim 0.5 \times 10^{-7}$ expected from microlensing due to known stellar populations.

2.1. The Null Result- No Short Events

The exclusion plot from the joint EROS + MACHO search (Alcock et al. 1998) for events with durations less than 20 days is shown in Figure 3. This null result is very important progress in the ongoing search for dark matter, as it excludes much of the previously “favored” astrophysical mass regime, particularly the notoriously elusive brown dwarf population below the 0.08 $M_\odot$ nuclear ignition threshold.

This exclusion plot, which spans over five decades in mass at interesting confidence levels, is a triumph of the microlensing surveys. On the basis of this null result alone, the microlensing projects have been a great success!
Figure 3. Exclusion plot from the joint MACHO + EROS search for short microlensing events. The curves in the two panels show constraints for a variety of halo models. The regions above the lines are excluded at greater than 95% confidence. Note for comparison that a mass (within 50 kpc) of $\sim 4.5 \times 10^{11}$ is typically predicted for models of the Galactic halo.

2.2. The LMC Events: The Detection of Dark Matter, Or Is It Just Stars?

The MACHO project has published (Alcock et al., 1997a) a determination of the optical depth $\tau_{200}$ towards the LMC, for events with durations between 2 and 200 days. Interestingly, the observed optical depth and the event rate towards the LMC exceed the values expected from known stellar populations.
In this context “known” refers to populations that were used for optical depth predictions made before the results were presented.

Since the distribution of durations for halo microlensing events depends on the velocity, mass and spatial distributions of the lensing population, one must in general make assumptions about two of these in order to constrain the third. If we assume an isothermal halo population of lensing objects, and a rotation curve that is flat at the solar circle, taken at face value the MACHO result corresponds to having detected roughly half of the halo dark matter, in objects with masses of about half a solar mass.

The alternative to the dark matter interpretation, of course, is lensing by some stellar population. There are a number of possibilities for producing a rate of lensing events towards the LMC that exceeds the predictions of double-exponential axisymmetric models of the Galaxy. Any one or some combination of them might well be responsible for the observed lensing events. The proposed populations include:

1) Stars in the LMC,
2) An intervening dwarf galaxy,
3) The spheroidal component of our Galaxy,
4) A wisp of tidal debris from the interaction between the LMC and the Galaxy,
5) A severe warp in the disk of the Galaxy, and
6) A thick disk component of our Galaxy.

All dark matter searches face the challenge of discriminating between background processes and the signal from dark matter. Microlensing is no exception. The survey teams have successfully learned how to discriminate microlensing events from intrinsic stellar variability, and the challenge now is to distinguish between microlensing due to dark matter objects and microlensing due to stars.

In my opinion there are two logically distinct stepping stones on the path forward. First, we need to determine with high confidence whether the microlensing events are due to Galactic dark matter. If so, and only then, we will need to establish how much of the halo is in the form of MACHOs, and ascertain the nature of these lensing objects (white dwarfs, primordial black holes, MACHinos...).

3. Distinguishing Between Lensing Populations

The main point of this paper is that the various proposed lensing populations have observable differences which, given enough events, will allow us to determine what is responsible for the LMC events. Most importantly, we should be able to discriminate halo MACHOs from the various stellar alternatives, using a variety of distinguishing characteristics.
3.1. Luminosity

If ordinary stars are responsible for the microlensing events, then these stars should be visible in careful studies of color-magnitude diagrams, proper motions, and star counts. Some of this work is already under way, and is an important complement to the microlensing surveys.

3.2. Spatial Distribution

The spatial distributions of the proposed stellar lensing populations differ from the $\rho_{DM}(r) \sim 1/r^2$ scaling expected in typical dark matter halo models. Both along the line of sight and across the sky there will be observable differences between the various alternatives. Over the $\sim 120$ square degrees of the LMC we would expect a fairly uniform (after correcting for detection efficiency) distribution of halo lensing events, whereas tidal tails and foreground stellar associations would likely show spatial structure on this scale. This of course assumes there is no substructure in the phase space distribution of the dark matter.

The location of the lenses along the line of sight is also measurably different for the various populations. For example, a nearby population of thick disk lenses will show more parallax effects than would a more remote class of objects. Conversely, lenses in the LMC would exhibit more sensitivity to the xallarap effect. High accuracy followup photometry would help determine the relative incidence of these light curve fine structure effects.

3.3. LMC stellar density

The various stellar populations will also have lensing rates that have different scalings with LMC stellar density. For example, the case of LMC-LMC lensing should (after correcting for event detection efficiency) have a very different dependence on LMC stellar density, $\rho_\star$, than lensing by foreground populations. Roughly, we would expect LMC-LMC lensing to show an event rate that scales as $\epsilon \rho_\star^2$, where $\epsilon$ is a density-dependent detection efficiency factor. Events from halo MACHOs, on the other hand, would likely scale as $\epsilon \rho_\star$, a linear rather than quadratic dependence on background stellar density.

3.4. Kinematics

Finally, there are big differences in the projected velocity of the lens, as seen in the plane of the source. The relevant observable quantity is $v_{\text{proj}}$, the projected transverse velocity with which the lens sweeps across the source star, as seen in the frame of the source. For a lens at a dimensionless distance $x = D_s / (D_1 + D_2)$ along the line of sight, $v_{\text{proj}} = v_\perp / x$, where $v_\perp$ is the lens’ velocity component transverse to the line of sight. Nearby lenses have large projected velocities, compared to a more distant lens moving at the same transverse velocity.

This is a powerful discrimination tool, as shown in the recent case of event MACHO 98-SMC-1, where the location of the binary lens was inferred from a measurement of the caustic crossing time.

3.5. How to Tell Where the Lenses Are

Table 1 summarizes the distinguishing characteristics of the different populations. Given enough events, particularly ones detected in real time with adequate
followup photometry, we should be able to discriminate between the alternative lensing populations.

Table 1. Distinguishing Characteristics for Various Lensing Populations

|                        | Thick Disk | Foreground Stars | LMC Stars | Dark Matter |
|------------------------|------------|------------------|-----------|-------------|
| Parallax               | few %      | Minimal          | No        | ~ 1 %       |
| Xallarap               | No         | Minimal          | Yes       | Minimal     |
| $\epsilon_\rho_*$     | Linear     | Linear           | Quadratic | Linear      |
| Spatial                | Uniform    | Non-Uniform      | Non-Uniform| Uniform    |
| $v_{proj}$(km/sec)     | 5000       | 300/x            | 80        | 1000        |
| Luminous?              | Yes        | Yes              | Yes       | No          |

How many events will be needed? We certainly need to be out of the present regime where the Poisson statistics of a few events preclude our investigating dependences on stellar-density and spatial distributions. Also, roughly 10% of the Galactic center events seen to date exhibit some sort of exotic structure in their light curves, and we hope to exploit this towards the LMC as well. Both of these considerations argue in favor of event totals in the hundreds, an order of magnitude increase from the present sample. Will the present surveys provide this? I think not.

### 3.6. A Look Ahead: Microlensing in Y2K

Current plans call for the MACHO project to terminate operation at the end of 1999, and the EROS team also intends to shut down in a similar time frame. By the year 2000, the existing microlensing projects will likely have detected tens of LMC events, a handful towards the SMC, and many hundreds of events towards the Galactic center. We should have by then contour maps of $\tau(\ell, b)$, the optical depth towards the Galactic center as a function of Galactic latitude and longitude. These will provide important new information on the structure of the Galaxy, and will impact our interpretation of the Galactic rotation curve. In addition, the lensing events of Galactic bulge and disk stars will provide unprecedented opportunities for high resolution spectroscopy and (by searching for perturbations of the light curves) opportunities to search for relatively low mass planetary companions to the lensing stars.

The optical depth towards the LMC will likely have been measured at the 20% level, and that towards the SMC at something like the 100 % level. The nature of the lensing populations will, in my opinion, remain a mystery.

This is because, based on existing detection rates, the current projects will simply not have generated enough events by the year 2000 to meet the criteria given above. A new project, with at least an order of magnitude increase in sensitivity, is needed, and can be carried with existing technology (Stubbs 1997). Rather than achieving the required event total by operating the existing surveys for another decade, a next-generation project would detect a comparable number in the first year of operation.
4. A Next Generation Microlensing Survey

An appropriate figure of merit for a microlensing survey is simply the number of stars that can be monitored in a given amount of time. This is obtained from the expression that gives the Signal-to-Noise ratio for the measurement of the flux \( \Phi_{\text{star}} \) from a single star, \( SNR = \frac{\Phi_{\text{star}} D^2(QE) t}{\sqrt{\sigma^2 \Phi_{\text{sky}} D^2(QE) t}} \), where \( D^2 \) is the telescope effective aperture, \( QE \) is the detector efficiency, \( t \) is the measurement time, \( \Phi_{\text{sky}} \) is the sky background flux, and \( \sigma \) is the seeing. (The approximation of objects fainter than sky is appropriate, as shown below). This expression can be rearranged to determine the time needed to obtain a given Signal-to-Noise ratio, so that the overall figure of merit, including now a term \( \text{FOV} \) that gives the field of view of the camera system, for a microlensing survey is \( FOM = \frac{D^2(QE)\text{FOV}}{\sigma^2 \Phi_{\text{sky}}} \).

No big surprise here. A survey benefits from a dark site with good seeing, and a high throughput wide field camera. This expression does allow us to make a quantitative comparison between existing and potential future projects, however.

4.1. A Concrete Proposal

The MACHO project uses a pair of 4K x 4K pixel front-illuminated cameras on a 1.3 meter telescope on the outskirts of Australia's capital city. By comparison the proposed new survey will be carried out at one of the world’s premier astronomical sites, on a much larger aperture telescope than any used by an existing survey, with a state-of-the-art wide field camera system. We are working to establish a next-generation project using the DuPont 2.5 meter telescope at Las Campanas, equipped with a state-of-the-art mosaic of 2K x 4K thin CCDs. Table 2 lists a comparison of the relevant specifications of the two systems, for the elements that enter into the Figure of Merit given above.

|                  | MACHO | Next Gen Survey | FOM Gain |
|------------------|-------|-----------------|----------|
| Seeing           | 2"    | <1"             | >4       |
| CCD QE           | thick | thin            | 2        |
| Aperture         | 1.3m  | 2.5m            | 3.5      |
| Field            | 0.5 sq deg | 1 sq deg | 2        |
| Sky              |       |                 | >2       |
| Nominal Figure of Merit Gain |       |                 | >100     |

While it is often overly optimistic to count on a performance improvement given by a simple figure of merit, it is clear from Table 2 that an order of magnitude increase in system throughput is readily achievable. This implies that the next-generation survey described here should be able to monitor at least ten times as many stars as the MACHO project does, in an equal amount of time. Reality is slightly more complicated. There are a finite number of stars in the LMC bright enough to usefully monitor with the system described here,
and their luminosity distribution will determine whether there are in fact ten times as many detectable events to be seen.

Gould (1998) has calculated these effects in some detail, and comes to the reassuring conclusion that in fact an order of magnitude increase in event tally is achievable with the system parameters summarized in Table 2. Attaining this will require monitoring all regions in the LMC with a surface brightness that exceeds 24.5 mag/arcsec\(^2\).

A tight coupling between the survey’s detections and followup telescopes will be an important ingredient in extracting the maximum information from exotic microlensing events. A network of 1m class followup telescopes would complement the next-generation survey system. Selected events would ideally also be monitored with adaptive or space-based imaging systems, to achieve high angular resolution and thereby minimize the effects of blended unlensed light.

5. Conclusion

The microlensing technique is the only dark matter search that presently shows a persistent signal. It is imperative that we determine whether the observed event excess is due to a halo population of lenses. This is achievable, with an appropriate commitment of existing telescope resources augmented with state-of-the-art CCDs and appropriate computing power.

If the outcome of this next-generation project shows that ordinary stars are responsible for the lensing excess, this will be strong evidence in favor of particle physics dark matter, simply because the astrophysical mass regime will have been effectively eliminated.

On the other hand, if the lensing events are shown to be due to a halo population we will be confronting a new era in dark matter research. The Galactic dark matter in the form of MACHOs will be a main focus of our attention.

While we can engage in an extended debate about the source of the events seen to date, this issue will not likely be resolved with existing surveys. This is an experimental question and we should conduct the obvious next experiment.

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