Probing MACHOs Toward the Galactic Bulge

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ABSTRACT

If the massive compact halo object (MACHO) fraction of the Galactic dark halo is \( f \sim 20\% \) as suggested by some microlensing experiments, then about 1.2\% of lensing events toward the Galactic bulge are due to MACHOs. For the 40\% of these that lie nearby (\( D_l < 4\) kpc), measurement of their distance \( D_l \) would distinguish them from bulge lenses, while measurement of their transverse velocity \( v_l \) would distinguish them from disk lenses. Hence, it would be possible to identify about 0.5\%(\( f/20\% \)) of all events as due to MACHOs. I show that a planned experiment using the Space Interferometry Mission (SIM PlanetQuest) could thereby detect 1 or 2 such events. This is at the margin of what is required because of a small, but non-negligible background from spheroid stars.

Subject headings: dark matter – galaxies: stellar content – gravitational lensing – instrumentation: interferometers

1. Introduction

Following the suggestion of Paczyński (1986), the MACHO (Alcock et al. 1993) and EROS (Aubourg et al. 1993) collaborations began searching for dark matter in the form of massive compact halo objects (MACHOs) by microlensing observations toward the Large Magellanic Cloud (LMC). This target seemed ideal because of the small column of known populations of stars compared to the huge volume of space that would be home to the putative MACHOs. The microlensing optical depth due to known stars was estimated to be \( \tau_{\text{MW}}^{\text{LMC}} = 8 \times 10^{-9} \) for the Milky Way disk (Gould et al. 1997) and \( \tau_{\text{LMC}}^{\text{LMC}} = 1 \times 10^{-8} \) for the LMC itself (Gould 1995b). By contrast, if the dark halo were completely composed of MACHOs, their optical depth would be of order,

\[
\tau_{\text{halo}}^{\text{LMC}} \sim \frac{v_{\text{rot}}^2}{c^2} = 5 \times 10^{-7},
\]
roughly 25 times higher. Here, \( v_{\text{rot}} = 220 \text{ km s}^{-1} \) is the Milky Way rotation speed. Hence, when the experiments began, it seemed as though even a crude measurement of \( \tau \) would unambiguously determine whether the halo was composed of MACHOs.

A decade later, the situation is far less clear than was anticipated. MACHO (Alcock et al. 2000) found \( \tau \sim 1 \times 10^{-7} \), roughly the root-mean-square of the results expected from MACHOs and stars. They interpreted this to mean that the halo was 20% composed of MACHOs and estimated the typical mass to be \( M \sim 0.4 \, M_\odot \). On the other hand, the EROS collaboration (Afonso et al. 2003a; Tisserand & Milsztajn 2005) found an upper limit for the optical depth due to MACHOs of 5% of the full-halo value.

One option for resolving this conflict is to explore other lines of sight. Crotts (1992) and Baillon et al. (1993) advocated M31, and several collaborations, including AGAPE (Ansari et al. 1999), Columbia-VATT (Uglesich et al. 2004), MEGA (de Jong et al. 2004), NainiTal (Joshi et al. 2005) POINT-AGAPE (Aurière et al. 2001), SLOTT-AGAPE (Calchi Novati 2003), and WeCAPP (Riffeser 2003), have pursued this suggestion. In many ways this is substantially more challenging than the observations toward the LMC, simply because M31 is 15 times farther away and hence the sources are substantially fainter. Events are now being reported from these experiments, and their implications for dark matter should be available soon.

The microlensing target field that has been monitored the most intensively is the Galactic bulge. Originally proposed by Paczyński (1991) and Griest et al. (1991), major surveys have been carried out by the OGLE (Udalski et al. 1993; Udalski 2003), DUO (Alard et al. 1995), MACHO (Popowski 2005), EROS (Afonso et al. 2003b), and MOA (Abe et al. 2004) collaborations. The primary motivation of both proposals was to probe for disk dark matter and other exotic objects such as a large population of Jupiters. Griest et al. (1991) does mention that if the halo is composed of MACHOs, then these will give rise to an optical depth \( \tau_{\text{halo}} = 1.3 \times 10^{-7} \), but since this is 4 times smaller than the predicted optical depth due to disk stars \( \tau_{\text{disk}} = 5.1 \times 10^{-7} \), there did not appear to be any way to isolate the MACHO events.

Bulge microlensing observations have been enormously fruitful. Kiraga & Paczyński (1994) showed that the optical depth due to bulge self-lensing was even greater than that due to disk stars. The high event rate encouraged searches for lensing anomalies due to planetary companions of the lenses (Mao & Paczyński 1991; Gould & Loeb 1992; Rhie et al. 2000; Albrow et al. 2001b; Gaudi et al. 2002; Abe et al. 2004), which has now yielded the first firm microlensing planet detection (Bond 2004). Bulge microlensing has enabled the first microlens mass measurement (An et al. 2003) and the probing of bulge-star atmospheres with \( \mu \)as resolution both photometrically (Alcock et al. 1997; Albrow et al. 1999, 2000; Fields et
al. 2003) and spectroscopically (Castro et al. 2001; Albrow et al. 2001a; Cassan et al. 2004).

Here I show that bulge microlensing can also be used to probe for halo dark matter (MACHOs) in the inner Galaxy. This seems absurd at first sight because the observed optical depth, $\tau_{\text{bulge}}^{\text{obs}} \sim 2 \times 10^{-6}$, is about 15 times higher than the rate predicted by Griest et al. (1991), $\tau_{\text{halo}}^{\text{obs}} \sim 1.3 \times 10^{-7}$, even assuming that the dark halo were completely composed of MACHOs. However, the microlensing experiments toward the LMC seem to imply that this fraction is no larger than 20%, which means that only about 1% of Galactic bulge microlensing would be due to halo objects. How would one identify these halo microlensing events within the barrage of microlensing by ordinary bulge and disk stars?

2. Needle in Haystack

Halo lenses are distinguished from disk lenses by the their transverse velocity $v_l$ relative to the Sun, and from bulge lenses by their distance from the Sun, $D_l$ (or equivalently, their absolute parallax $\pi_l$). Hence, to reliably identify the nearby, fast MACHOs, one must reliably measure $v_l$ and $\pi_l$. Since the MACHOs are by definition “dark” matter, direct observations of the lens cannot be employed in making these determinations, as they were for example for MACHO-LMC-5 (Alcock et al. 2001; Drake et al. 2004; Gould 2004a; Gould et al. 2004). Instead, these quantities must be derived entirely from observations of the source during and after the microlensing events.

2.1. Observables

These two quantities can be expressed in terms of microlensing observables by (e.g., Gould 2000),

$$\pi_l = \pi_{\text{rel}} + \pi_s,$$

$$\pi_{\text{rel}} = \pi_E \theta_E$$

and

$$v_l = \frac{\mu_{\text{rel}} + \mu_s}{\pi_{\text{rel}} + \pi_s} \text{AU},$$

$$\mu_{\text{rel}} = \frac{\theta_E}{t_E}.$$  

Here, $\pi_l$, $\pi_s$, $\mu_l$, $\mu_s$ are the absolute parallaxes and proper motions of the lens and source, $\pi_{\text{rel}} = \pi_l - \pi_s$ and $\mu_{\text{rel}} = \mu_l - \mu_s$ are the lens-source relative parallax and proper motion, $\theta_E$ is the angular Einstein radius, $t_E$ is the Einstein timescale, and $\pi_E$ is the microlens parallax (i.e., the inverse of the projected Einstein radius, $\pi_E = \text{AU}/\tilde{r}_E$). The direction of $\theta_E$ is that of the lens-source relative proper motion.

In brief, to determine $\pi_l$ and $v_l$, one must measure five observables, two 2-vectors ($\mu_s$
and $\theta_E$) and three scalars ($\pi_s$, $\pi_E$, and $t_E$).

2.2. Parameter Measurement

Two of these five parameters ($\pi_s$ and $\mu_s$) are related solely to the source, while the remaining three ($\pi_E$, $t_E$, and $\theta_E$) are microlensing-event parameters. Of these three, only one ($t_E$) is routinely measured during microlensing events. The other two are higher order parameters. While there are a variety of methods to measure $\pi_E$ and $\theta_E$ (see Gould 2001), these generally apply to only a small fraction of events. There are only two events (out of almost 3000 discovered) for which both parameters have been measured from microlensing data alone (An et al. 2003; Kubas et al. 2005), and both of these were binary lenses.

The only known way to routinely determine $\theta_E$ is by high-precision astrometric measurements of the microlensing event (Høg et al. 1995; Miyamoto & Yoshii 1995; Walker 1995; Paczyński 1998; Boden et al. 1998). The centroid of the microlensed images deviates from the source position by an amount and direction that yields both components of $\theta_E$.

The only known way to routinely determine $\pi_E$ is to make photometric measurements of the event from two locations separated by of order $\tilde{r}_E$ (Refsdal 1966; Gould 1994). The difference in the event parameters then yields both the size of $\tilde{r}_E$ and the direction of motion (the latter potentially confirming the direction extracted from $\theta_E$). Since $\tilde{r}_E \sim O(AU)$, in practice this means placing a satellite in solar orbit. Although there is a four-fold ambiguity in the determination of $\pi_E$, this can be resolved by higher-order effects (Gould 1995a). Moreover, measurement of the direction of $\theta_E$ also helps resolve this degeneracy.

2.3. SIM PlanetQuest Measurements

Gould & Salim (1999) showed that the Space Interferometry Mission (SIM PlanetQuest) combined with ground-based photometry, could determine both of these parameters with good $\sim 3\%$ precision with about 5 hours total observation time for bright ($I \sim 15$) events having typical lens parameters. Moreover, they showed that the same observations would also yield good measurements of $\pi_s$ and $\mu_s$. Hence, SIM (combined with ground-based photometry) could measure all the required quantities for about 200 events with about 1000 hours of observing time. Indeed, a SIM Key Project has been awarded 1200 hours of observation time to carry out such observations. The main objective of this project is to measure the bulge mass function but the same observations could cull out the handful of halo events that could be present in the same sample.
SIM has been descoped since Gould & Salim (1999) made their analysis. The new performance is not precisely known but it is likely that the precision will degrade to something like $\sim 5\%$ for $\pi_E$ and $\sim 10\%$ for $\theta_E$ for the canonical events considered by Gould & Salim (1999). Moreover, it is unlikely that 200 $I = 15$ events will be found during the 5-year primary SIM mission, and using fainter sources (e.g., $I = 16.5$) would further degrade the precision by a factor 2. Nevertheless, as I show below, this precision would be quite adequate for distinguishing halo lenses.

3. Background from Spheroid/Bulge Stars

Halo lenses could produce events anywhere along the line of sight from the Sun to the bulge and, assuming an isothermal halo model with core radius $a = 5$ kpc, the density

$$\rho_{\text{halo}} = \frac{v_c^2}{4\pi G (R^2 + a^2)}$$

rises all the way to the Galactic center. Here $R$ is Galactocentric distance. The optical depth per unit path length along a line of sight toward the Galactic center therefore also rises almost all the way in,

$$\frac{d\tau_{\text{halo}}}{dD_l} = \rho_{\text{halo}} \pi r_E^2 = \frac{v_c^2}{c^2} \frac{f (1 - x)}{R_0} \left( \frac{a}{R_0} \right)^2 + (1 - x)^2.$$  

Here, $r_E = (4GMD_l D_s/c^2 D_{os})^{1/2}$ is the Einstein radius, $D_l$ and $D_s$ are the source and lens distances, $D_{ts} = D_s - D_l$, $f$ is the fraction of the halo in the form of MACHOs, $R_0 = 8$ kpc is the Solar Galactocentric distance, $x \equiv D_l/R_0$, and $M$ (which cancels out) is the mass of the lens.

However, in the inner Galaxy, these halo lenses are completely submerged in the background of bulge lenses, and since they have similar kinematics, there is no way to reliably distinguish them. It is only out closer to the Sun, where the spheroidal population (here usually called “spheroid” or “stellar halo”), thins out that one may hope to separate the two populations. Even here, there is some possibility of contamination. The local spheroid density is only about 1% of the dark halo, but if $f \sim 20\%$ as Alcock et al. (2000) suggest, then MACHOs are only 20 times more common than spheroid stars locally. Moreover, as one approaches the Galactic center, the spheroid density grows substantially more rapidly than does the dark halo. To make a quantitative comparison, I adopt

$$\rho_{\text{spheroid}} = 1 \times 10^{-4} \frac{M_\odot}{\text{pc}^3} \left( \frac{R}{R_0} \right)^{-3.2}.$$  

(6)
After accounting for observed stars and extrapolating down to brown dwarfs and up to the progenitors of remnants, Gould et al. (1998) estimate $6.4 \times 10^{-5} M_\odot \text{pc}^{-3}$. However, both Dahn et al. (1995) and Gould (2003) find substantially more low-luminosity ($M_V > 8$) stars than did Gould et al. (1998) in their more local sample (see Fig. 2 from Gould 2004b), so I have adjusted their estimate upward. The power-law slope is measured by several techniques (Gould et al. 1998 and references therein).

Figure 1 shows the optical depth per unit distance due to spheroids and to putative MACHOs under the assumption that $f = 20\%$. It shows that even with a MACHO fraction of 20%, the halo dominates the spheroid from $R = R_0$ to $R = 4 \text{kpc}$, which latter is about the limit to which the local spheroid density profile can be reliably extrapolated. However, this domination is not overwhelming: at $R = 4 \text{kpc}$ it is only a factor of 5 and even at $R = 7 \text{kpc}$ (where the halo optical depth has fallen by a factor 5) the halo only dominates by a factor 10. This means that 2 or 3 halo lenses would have to be identified to constitute a reliable “MACHO detection”. Otherwise, there would be a significant possibility that spheroid lenses were responsible.

Since one must restrict attention to $D_1 < 4 \text{kpc}$, the total available halo optical depth is reduced by a factor 0.4 relative to the $1.3 \times 10^{-7}$ calculated by Griest et al. (1991). If we further assume $f = 20\%$, the available halo optical depth is further reduced to $10^{-8}$, about 0.5% of the observed optical depth of $\tau \sim 2 \times 10^{-6}$ (Afonso et al. 2003b; Popowski 2005; Sumi et al. 2005). Hence, assuming for the moment that the event rates are in proportion to the optical depths, roughly 200 measurements would be required to identify a single halo lens. Thus, if the SIM mission were extended from 5 to 10 years (as is currently envisioned) then one might expect to find about 2 halo lenses. As noted above this is just at the margin of a viable detection.

4. Practical Considerations

4.1. Event Timescales

The Einstein timescales of these halo events are given by,

$$t_E = 15 \text{day} \left[ \frac{M}{0.4 M_\odot} \frac{x(1-x)}{0.25} \right]^{1/2} \left[ \frac{v_\perp}{300 \text{km s}^{-1}} \right]^{-1},$$

where $v_\perp$ is the transverse lens velocity relative to the observer-source line of sight. Thus, for the mass range advocated by Alcock et al. (2000), the typical event timescales will be fairly short. This is important because the event must be identified and alerted to the satellite
well before peak in order to measure $\pi_E$ (Gould & Salim 1999). Hence, a fairly aggressive posture is required to keep the halo events in the sample.

However, the fact that these halo events are somewhat shorter than typical bulge events means that they are also more frequent than would be indicated by their optical depth alone. That is, the event rate $\Gamma \propto \tau/t_E$, so the rate is inversely proportional to the timescale. Hence, the shorter timescales enhances the viability of a given experiment relative to what was discussed in § 3, provided that not too many halo events are lost because they are too short.

### 4.2. Signal-to-Noise Ratios

The two microlensing parameters being measured are related to the underlying physical parameters by,

$$
\pi_E = \sqrt{\frac{\pi_{rel}}{\kappa M}}, \quad \theta_E = \sqrt{\kappa M \pi_{rel}},
$$

(8)

where $\kappa = 4G/AUc^2 \sim 8.1\text{ mas } M_\odot^{-1}$. Hence, for fixed $M$, both $\pi_E$ and $\theta_E$ are proportional to $\pi_{rel}^{1/2}$. Since the absolute errors in these two quantities are approximately independent of their size, this means that the fractional errors decline as $\pi_{rel}^{-1/2}$. The basic experiment is designed for typical bulge-bulge lensing, in which the lenses are of order $M \sim 0.5 M_\odot$ and the relative parallaxes are $\pi_{rel} \sim AU/7\text{ kpc} - AU/9\text{ kpc} = 31\mu\text{as}$. By contrast, since $D_l \leq 4\text{kpc}$, the halo-lens relative parallaxes are $\pi_{rel} > 125\mu\text{as}$. Hence, if a halo event is successfully monitored, both $\pi_E$ and $\theta_E$ will be measured substantially more accurately than for typical events.

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Fig. 1.— Optical Depth per unit path length $d\tau/dD_l$ as a function of distance from the Galactic center for a source near the Galactic center. The halo (assuming a $f = 20\%$ MACHO fraction) and the spheroid are shown by solid and dashed curves, respectively. For $f = 20\%$, spheroid stars are a 20% background at $R = 4$ kpc and a 10% background at $R = 7$ kpc, which implies that 2 or 3 halo lenses must be identified at $R > 4$ kpc for a reliable halo “detection”. Inside $R < 4$ kpc the spheroid continues to grow (and also transforms into the bulge), making the identification of halo lenses less secure. Hence, the experiment should be restricted to $R > 4$ kpc, where the total optical depth is $\tau = 5 \times 10^{-8} f$. 

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\caption{Optical Depth per unit path length $d\tau/dD_l$ as a function of distance from the Galactic center for a source near the Galactic center. The halo (assuming a $f = 20\%$ MACHO fraction) and the spheroid are shown by solid and dashed curves, respectively. For $f = 20\%$, spheroid stars are a 20% background at $R = 4$ kpc and a 10% background at $R = 7$ kpc, which implies that 2 or 3 halo lenses must be identified at $R > 4$ kpc for a reliable halo “detection”. Inside $R < 4$ kpc the spheroid continues to grow (and also transforms into the bulge), making the identification of halo lenses less secure. Hence, the experiment should be restricted to $R > 4$ kpc, where the total optical depth is $\tau = 5 \times 10^{-8} f$.}
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