IS THE LARGE MAGELLANIC CLOUD A LARGE MICROLENSING CLOUD?

N. WYN EVANS AND EAMONN KERINS
Theoretical Physics, Department of Physics, 1 Keble Road, Oxford, OX1 3NP, England, UK

ABSTRACT

An expression is provided for the self-lensing optical depth of the thin Large Magellanic Cloud (LMC) disk surrounded by a shroud of stars at larger scale heights. The formula is written in terms of the vertical velocity dispersion of the thin-disk population. If tidal forcing causes $\sim 1\%$–5% of the disk mass to have a height larger than 6 kpc and $\sim 10\%$–15% to have a height above 3 kpc, then the self-lensing optical depth of the LMC is $\sim(0.7$–$1.9) \times 10^{-7}$, which is within the observational uncertainties. The shroud may be composed of bright stars provided they are not in stellar hydrodynamical equilibrium. Alternatively, the shroud may be built from low-mass stars or compact objects, although then the self-lensing optical depths are overestimates of the true optical depth by a factor of ~ 1.5.

The distributions of timescales of the events and their spatial variation across the face of the LMC disk offer possibilities of identifying the dominant lens population. We use Monte Carlo simulations to show that, in propitious circumstances, an experiment lifetime of $\lesssim 5$ years is sufficient to decide between the competing claims of Milky Way halos and LMC lenses. However, LMC disks can sometimes mimic the microlensing properties of Galactic halos for many years, and then decades of survey work are needed for discrimination. In this case observations of parallax or binary caustic events offer the best hope for current experiments to deduce the dominant lens population. The difficult models to distinguish are Milky Way halos in which the lens fraction is low ($\lesssim 10\%$) and fattened LMC disks composed of lenses with a typical mass of low-luminosity stars or greater. A next-generation wide-area microlensing survey, such as the proposed "SuperMACHO" experiment, will be able to distinguish even these difficult models with just a year or two of data.

Subject headings: dark matter — gravitational lensing — Magellanic Clouds — Galaxy: halo

1. INTRODUCTION

The location of the microlensing events toward the Large Magellanic Cloud (LMC) is a matter of controversy. Alcock et al. (1997a) assert that the lensing population lies in the Galactic halo and comprises perhaps $\sim 50\%$ of its total mass. Early suggestions that the LMC may provide the bulk of the lenses were made by Sahu (1994) and Wu (1994), and this location is favored by the data on the binary caustic crossing events (Kerins & Evans 1999). One of the main obstacles to general acceptance of this idea has been the sheer number of observed lensing events, which appear to be too great to be accommodated by the LMC alone. The experimental estimate of the microlensing optical depth τ toward the LMC is $2.1^{+1.3}_{-0.8} \times 10^{-7}$ (e.g., Bennett 1998). This is substantially greater than the optical depth of simple tilted-disk models of the LMC. For example, Gould's (1995) ingenious calculation involving the virial theorem sets the self-lensing optical depth of the LMC disk as $\sim 1 \times 10^{-8}$. Section 2 of this paper generalizes Gould's analysis to provide upper limits on the self-lensing optical depth of thick models of the LMC disk. These values are smaller than, but of comparable magnitude to, the observations. So, it is reasonable to suggest that the microlensing signal may come either from a fattened LMC disk or from a Milky Way halo only partly composed of lensing objects. The timescale distributions and the geometric pattern of events across the face of the LMC disk will of course be different in these two cases. The timescales of events for the same mass functions will be longer for lenses in the LMC as compared to those in the Milky Way halo as the lower velocity dispersion of the LMC outweighs the effects of the smaller Einstein radii. However, the use of the timescales as a dis-

criminant is spoiled by the fact that there is no reason why the Milky Way halo and the LMC should have the same mass function. A more hopeful indicator may be the distribution of events across the face of the LMC disk. If the lenses lie in the Milky Way halo, the events will trace the surface density of the LMC, whereas if the lenses lie in the Clouds, the events will be more concentrated toward the dense bar and central regions, scaling like the surface density squared. How long will it take to distinguish between the two possibilities? Section 3 develops a maximum likelihood estimator that incorporates all the timescale and positional information to provide the answer to this question, both for the existing surveys like MACHO and for the next-generation experiments such as Super-MACHO (Stubbs 1998). Finally, § 4 evaluates the strategies by which the riddle of the location of the lenses may be solved.

2. OBESE MAGELLANIC DISKS

Gould's (1995) limit relates the self-lensing optical depth of any thin disk to its vertical velocity dispersion σ_z via

$$\tau = 2 \frac{\sigma_z^2}{c^2} \sec^2 i , \qquad (1)$$

where c is the velocity of light and i is the inclination angle. Taking the observed velocity dispersion of CH stars as ~ 20 km s^{-1} (Cowley & Hartwick 1991) and the inclination angle $i = 27°$ (de Vaucouleurs & Freeman 1972), Gould argued that the self-lensing optical depth of the LMC disk is likely to be $\sim 1 \times 10^{-8}$, which is some 20 times smaller than the observations. As Gould's derivation depends only on the Poisson and Jeans equations for highly flattened geome-

tries, the formula is clearly irreproachable. How could it be yielding misleading results as to the self-lensing optical depth? Consider a thought experiment in which a very thin disk is gradually surrounded by a flattened shell of matter, bounded by two similar concentric ellipsoids (a homoeoid). By Newton's theorem, the attraction at any internal point of a homoeoid vanishes. So, the introduction of the homoeoid leaves the velocity dispersion in the thin disk quite unchanged. But, the self-lensing optical depth is strongly enhanced. In applying Gould's formula, we must be *very* careful not to use the velocity dispersion of the thin disk, but rather the mass-weighted velocity dispersion of the entire configuration—otherwise we will obtain a misleadingly small answer. It is clearly worthwhile extending the calculations to more sophisticated, structure-rich models of the LMC, in which the self-lensing optical depth is written in terms of the velocity dispersion of the thin-disk population (which is directly accessible to observations) instead of the mass-weighted velocity dispersion.

Let us now derive formulae for the self-lensing optical depth of an ensemble of n exponential disks, each with a different scale height h_i, midplane density ρ_i, and column density $\Sigma_i = 2\rho_i h_i$. Clearly, this is a very idealized representation of the LMC, although similar models of the Milky Way disk have already proved useful (cf. Gould 1989). The vertical density law for the disk is

$$\rho(z) = \sum_{i=1}^{n} \rho_i \exp\left(-\frac{|z|}{h_i}\right). \tag{2}$$

The relationship between height z and potential ϕ is given by solving Poisson's equation in the form appropriate for a flattened geometry (see Binney & Tremaine 1987, p. 48). Gould (1995) shows that the self-lensing optical depth of any thin disk with total column density Σ is

$$\tau = \frac{2\pi G \Sigma \sec^2 i}{c^2} \int_0^\infty dz\{1 - [G(z)]^2\},$$

$$G(z) = \frac{2}{\Sigma} \int_0^z dy\rho(y). \tag{3}$$

For our ensemble of exponential disks we have

$$G(z) = 1 - \sum_{i=1}^{n} F_i \exp\left(-\frac{|z|}{h_i}\right), \tag{4}$$

where F_i is the mass fraction in each population. The self-lensing optical depth is now entirely analytic and given by

$$\tau = 2\frac{\sigma_1^2}{c^2} \sec^2 i \frac{1}{F_1 h_1} \left(\frac{4}{3}\sum_{i=1}^{n} F_i h_i - \frac{2}{3}\sum_{i,\,j=1}^{n} \frac{F_i F_j h_i h_j}{h_i + h_j}\right). \tag{5}$$

The formula has been written in terms of σ_1, which is the vertical velocity dispersion of the thinnest disk population only. It is the line-of-sight velocity dispersion of the youngest, thinnest populations in the LMC that are observationally reasonably well determined. The Jeans equation has been solved under the assumption that the thinnest disk dominates the gravitational potential near the midplane. Our formula only assumes that the thinnest population is in equilibrium. It makes no assumptions as to the relationship between velocity dispersion and height for the thicker populations. It is therefore the appropriate formula for an equilibrium thin disk surrounded by dispersed and patchy

populations of stars. Let us note that equation (5) really estimates the value of the optical depth near the LMC center (as the radial structure of the disk is ignored). The assumption that the disks are exponential rather than completely isothermal (that is, sech^2) causes our estimates to be on the low side. The assumption that the line-of-sight velocity dispersion σ_{los} is roughly equal to the vertical velocity dispersion σ_z causes our estimates to be on the high side. This correction factor depends on the uncertain shape of the velocity dispersion tensor in the LMC thin disk. If the velocity dispersions in the disk are well approximated by epicyclic theory, then $\sigma_\phi^2 \sim \sigma_z^2 \sim 0.45\sigma_R^2$ (Binney & Tremaine 1987, p. 199). In this case, σ_{los}^2 overestimates σ_z^2 by $\sim (1 + 0.6 \sin^2 i)$. Finally, in the limit of a single, thin disk ($n = 1$), our result (eq. [5]) reduces to Gould's original formula, as it should.

Weinberg (2000) has described self-consistent simulations of the tidal forcing of the Magellanic Clouds by the Milky Way galaxy. He shows that the effect of this tidal heating is to fatten the structure of the LMC. He reports that $\sim 1\%$ of the disk mass has a height larger than 6 kpc (which we will call "the veil") and $\sim 10\%$ above 3 kpc ("the shroud"). Let us devise a three-component model of the LMC, composed of a massive thin disk surrounded by an intermediate shroud and an extended veil. To model the LMC, let us take the scale height of the thin disk as $h_d \sim 300$ pc (Bessell, Freeman, & Wood 1986). The vertical velocity dispersion of the stars in this disk is ~ 30 km s^{-1}. The scale heights of the shroud h_s and the veil h_v are 3 and 6 kpc, respectively. As suggested by Weinberg's (2000) calculation, we put 10% of the mass in the shroud and 1% in the veil. De Vaucouleurs & Freeman (1972) estimated the inclination angle of the LMC to be 27° by assuming that the optical and 21 cm H I isophotes should be circular. This is not likely to be a good approximation for such an irregular structure like the LMC, and so this widely used value of the inclination angle is at least open to some doubt. More recently, evidence from detailed fitting of the surface photometry (excluding the star-forming regions) and from the low-frequency radio observations (which are less sensitive to local effects) suggest a higher value of the inclination angle of the main disk of $i \sim 45°$ (see, e.g., Alvarez, Aparici, & May 1987; Bothun & Thomson 1988). Westerlund (1997) reviews all the evidence and argues that this higher value of the inclination is most likely. We will consider both possibilities. When 10% of the mass is in the shroud and 1% in the veil, the self-lensing optical depth is 0.7×10^{-7} if $i = 27°$ and 1.1×10^{-7} if $i = 45°$. Figure 1 shows how the self-lensing optical depth varies as the mass fractions in the shroud and the veil are changed. Marked on Figure 1 are the contours corresponding to the best observational estimate of 2.1×10^{-7}, together with the $1\,\sigma$ and $2\,\sigma$ lower limits. If the mass fractions are increased to 15% and 5%, respectively, then the optical depth is 1.2×10^{-7} if $i = 27°$ and 1.9×10^{-7} if $i = 45°$. These values are comparable to the observed optical depth of $2.1^{+1.3}_{-0.8} \times 10^{-7}$ (Bennett 1998). On moving to the larger inclination, the assumption that the line-of-sight dispersion is roughly equal to the vertical velocity dispersion becomes less valid. Using our earlier correction based on epicyclic theory, we find that some $\sim 15\%$ of the increase in the optical depth on moving to the larger inclination of 45° is spurious. However, the important conclusion to draw from these calculations is that it requires comparatively little luminous material at higher
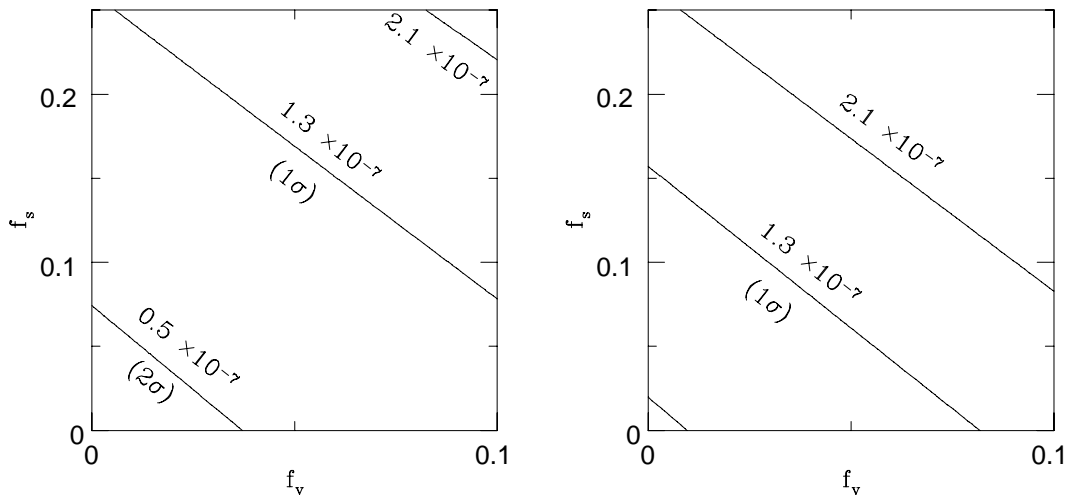
FIG. 1.—Contours of the self-lensing optical depth of the LMC are shown. Both panels show the effect of variation of the mass fractions in the shroud f_s and veil f_v, assuming $h_s/h_d = 10$ and $h_v/h_d = 20$ with $h_d = 300$ pc. The left panel assumes an inclination angle of $27°$, the right panel an inclination of $45°$. The observational estimate of the optical depth of 2.1×10^{-7} is shown, together with the $1\,\sigma$ and $2\,\sigma$ contours.

scale heights above the LMC thin disk to give a substantial boost to the optical depth.

There is one obvious difficulty with this suggestion. There are no visible tracers in the LMC with a velocity dispersion greater than 33 km s^{-1} (Hughes, Wood, & Reid 1991; Westerlund 1997). If in equilibrium, any luminous material belonging to disks with scale heights of 3 or 6 kpc must have a larger velocity dispersion than observed. For example, the tidal heating mechanism advocated by Weinberg (2000) must produce some visible hot tracers. The stars that are heated are expected to have the same luminosity function as those that remain in the thin disk. There are two possible loopholes in this line of argument. First, it might be possible for a metal-rich, old population with a large velocity dispersion to have eluded detection. Second, the relationship between scale height and velocity dispersion applies only to steady state equilibrium models. If this is not the case, then it may be possible for populations to be dispersed at larger heights above the LMC thin disk than suggested by their vertical velocity dispersion. It is worth cautioning that equilibrium models of the LMC may be a poor guide to interpreting the kinematics. In particular, no equilibrium models of galaxies with off-centered bars are presently known, either analytically or as the endpoints of N-body experiments. If both these loopholes are closed, then the last possibility is that any lenses in the larger scale height populations must be dark or at very least dim— perhaps low-mass stars or compact objects. This is difficult to rule out, although there are no obvious natural mechanisms to produce such components. In this case, our self-lensing formula (eq. [5]) will overestimate the microlensing optical depth, as the population of lenses and sources do not coincide. It should be replaced by

$$\tau = \frac{4}{3}\frac{\sigma_1^2}{c^2}\sec^2 i \times \frac{1}{F_1 h_1}\sum_{i=1}^{n} F_i h_i . \qquad (6)$$

For the same mass fractions F_i, the optical depths (eq. [6]) are reduced by a typical factor of ~1.5 from our earlier self-lensing estimates (eq. [5]). Aubourg et al. (1999) and Salati et al. (1999) have recently advanced models of the LMC surrounded by swathes of low-mass stars and sug-

gested that they could provide most of the observed microlensing optical depth, although others have contested this (e.g., Gyuk, Dalal, & Griest 1999).

3. THE LOCATION OF THE LENSES

Can the positions and timescales of the microlensing events be used to determine whether the dominant lens population lies in the LMC or in the Milky Way halo? The Bayesian likelihood estimator employed by Alcock et al. (1997a) can be extended to consider lenses from multiple galactic components distributed over a finite solid angle. For an experiment of lifetime T in which $N(T)$ events are observed with Einstein diameter crossing durations $\hat{t}_i$ and Galactic coordinates l_i, b_i ($i = 1, \ldots, N$), one can ascribe a likelihood L, where

$$\ln L(f_1, \ldots, {}_n, \phi_1, \ldots, {}_n) = -\sum_{j=1}^{n} f_j \mathcal{N}(\phi_j, T)$$
$$+ \sum_{i=1}^{N(T)} \ln\left[\sigma(l_i, b_i)\mathscr{E}(\hat{t}_i, l_i, b_i, T)\sum_{j=1}^{n} f_j \frac{d\Gamma(\phi_j, l_i, b_i)}{d\hat{t}_i}\right], \qquad (7)$$

to a galactic model comprising $j = 1, \ldots, n$ components, each component being characterized by a lens fraction f_j and mass function ϕ_j. In the above formula, Γ is the theoretical event rate, $\mathscr{E}$ is the detection efficiency, σ is the number of sources per unit solid angle, and

$$\mathcal{N}(\phi_j, T) = T\iiint \sigma(l, b)\mathscr{E}(\hat{t}, l, b, T)$$
$$\times \frac{d\Gamma(\phi_j, l, b)}{d\hat{t}}\, d\hat{t}\, dl\, d(\sin b) \qquad (8)$$

is the number of events predicted for component j when $f_j = 1$. The spatial variation of microlensing events has been studied before by Gyuk (1999), although using the optical depth and rate rather than the timescales (and with the emphasis on the inner Galaxy).

Let us set up two competing models. In the first, the Milky Way halo provides the dominant lens population, although there is some residual contribution from the stars in the LMC disk and bar. In the second, there is no Milky Way halo and the LMC disk and bar are augmented by the

existence of an enveloping shroud and veil, so that all the lenses reside close to or in the LMC. The density laws describing the components are summarized in Table 1. The LMC disk has an inclination of $45°$. The disk and bar together provide the estimated central column density of $363\ M_\odot\ \mathrm{pc}^{-2}$ (Alcock et al. 1996) and are populated with lens masses m drawn from the ordinary stellar disk population. The broken power law

$$\phi_{\mathrm{LMC}} \propto m^\gamma \quad (m_L = 0.08\ M_\odot \le m \le m_U = 10\ M_\odot),$$

$$\gamma = \begin{cases} -0.75 & (m_L \le m < 0.5\ M_\odot) \\ -2.2 & (0.5\ M_\odot \le m \le m_U), \end{cases} \quad (9)$$

describes the LMC stellar mass function (cf. Hill, Madore, & Freedman 1994; Gould, Bahcall, & Flynn 1997). For our Milky Way halo, we adopt a δ-function

$$\phi_h \propto \frac{1}{m}\, \delta(m - m_{\mathrm{dark}}) \quad (10)$$

as characterizing the lens mass. For the competing LMC-only model, there is an extended shroud and veil (hereafter collectively referred to simply as the shroud) enveloping the LMC stellar disk and bar. For simplicity, let us investigate the case in which the shroud consists primarily of dark lenses (either remnants or low-mass stars). Since the Milky Way halo and LMC shroud populations are both dark, we always make comparisons assuming the same lens mass m_{dark}. For this calculation, we make the simplifying assumption that the LMC is virialized, so that any decrease in the mass of the shroud implies a corresponding decrease in its velocity dispersion. This is important because changes in the velocity dispersion affect the derived lens timescale distribution. Suppose the ratio of the disk to shroud masses is originally r. Then if the mass of our shroud is decreased by a factor f_s, the virial theorem indicates that the velocity dispersion decreases by a factor $f_\sigma = [(f_s + r)/(1 + r)]^{1/2}$. We must also make the corresponding transformations: $\hat{t} \to f_\sigma^{-1} \hat{t}$ and $d\Gamma/d\hat{t} \to f_\sigma^2 f_s\, d\Gamma/d\hat{t}$.

Let us proceed by simulating microlensing experiments over a range of lifetimes T. We approximate the current generation of microlensing surveys by an ideal experiment which monitors the central $3° \times 3°$ of the LMC. We assume the Milky Way halo is an isothermal spherical halo with rotation curve of amplitude $v_0 = 220\ \mathrm{km\ s^{-1}}$. A fraction f_h of the halo comprises lenses of mass m_{dark}. This provides us with our input model with which to generate "observed" events. The expected number of events for an experiment of lifetime T is simply $\mathcal{N}(T) = \mathcal{N}(\phi_{\mathrm{LMC}}, T) + f_h \mathcal{N}(\phi_h, T)$, where $\mathcal{N}(\phi_{\mathrm{LMC}}, T)$ and $\mathcal{N}(\phi_h, T)$ are obtained from equation (8). We then generate a Poisson realization

$N(T)$ for the number of observed events. For each event a location is generated from within this region using the distribution

$$P(l, b\,|\,T) \propto \sigma(l, b) \int \mathscr{E}(\hat{t}, l, b, T)$$
$$\times \left[\frac{d\Gamma(\phi_{\mathrm{LMC}}, l, b)}{d\hat{t}} + f_h \frac{d\Gamma(\phi_h, l, b)}{d\hat{t}} \right] d\hat{t}, \quad (11)$$

which traces the event number density as a function of position. The Einstein diameter crossing time $\hat{t}$ is generated from the distribution

$$P(\hat{t}\,|\,l, b, T) \propto \mathscr{E}(\hat{t}, l, b, T)$$
$$\times \left[\frac{d\Gamma(\phi_{\mathrm{LMC}}, l, b)}{d\hat{t}} + f_h \frac{d\Gamma(\phi_h, l, b)}{d\hat{t}} \right]. \quad (12)$$

The detection efficiency $\mathscr{E}$ is not just a function of $\hat{t}$ and T, but also Galactic coordinates l and b. The spatial dependency of $\mathscr{E}$ has not yet been assessed by any of the current experiments and is inevitably experiment-specific. In the following analysis we consider an idealized microlensing survey in which the spatial dependency is sufficiently weak to be neglected. This is not a good assumption for the current LMC microlensing surveys which do not observe all regions with the same frequency, but the method we present is general and can be used to take account of spatial variations in efficiencies when these become available. As microlensing experiments continue, they become more sensitive to longer duration events. However, the efficiency $\mathscr{E}$ does not approach unity because of photometric limits imposed by the observing conditions. Instead one might anticipate, say, a limiting efficiency $\mathscr{E}_{\mathrm{max}} \approx 0.5$. We propose the following model for the time evolution of the efficiency for our ideal experiment:

$$\mathscr{E} = \begin{cases} \max\,[0, \mathscr{E}_{\mathrm{short}}(\hat{t})] & (\hat{t} < \hat{t}_{\mathrm{peak}}) \\ \max\,[0, \mathscr{E}_{\mathrm{short}}(\hat{t}_{\mathrm{peak}})]\, \exp\{-[\log\,(\hat{t}_{\mathrm{peak}}/\hat{t})/0.5]^2\} & \\ & (\hat{t} \ge \hat{t}_{\mathrm{peak}}), \end{cases} \quad (13)$$

where

$$\hat{t}_{\mathrm{peak}} = 0.12T$$
$$\mathscr{E}_{\mathrm{short}} = \min\,\{\mathscr{E}_{\mathrm{max}}, 0.2[\log\,(\hat{t}/\mathrm{days}) - 0.38]\}$$
$$\mathscr{E}_{\mathrm{max}} = 0.5. \quad (14)$$

Here $\hat{t}_{\mathrm{peak}}$ is the Einstein diameter crossing time at which the efficiency peaks, which of course depends on the experiment lifetime T. As Figure 2 shows, the model (dashed lines) provides an excellent approximation of the Alcock et al.

TABLE 1

DESCRIPTION OF THE MODELS USED TO REPRESENT THE LMC IN THE MONTE CARLO SIMULATION

Component	Model	Scale Length (kpc)	Scale Height (kpc)	Mass ($10^9\ M_\odot$)
LMC disk	Double exponential	1.6	0.3	4.0
LMC shroud	Double exponential	1.6	3.0	2.0
LMC veil	Double exponential	1.6	6.0	0.2
LMC bar	Exponential spheroid	1.6	0.3	0.4

NOTE.—The position angle of the bar is offset from the position angle of the LMC disk by $50°$. The overall mass in the shroud and veil can be adjusted by f_s. In the Monte Carlo simulations, f_s is chosen so that the two competing models have similar total numbers of events. Just the timescale and geometry information are used to distinguish between them.
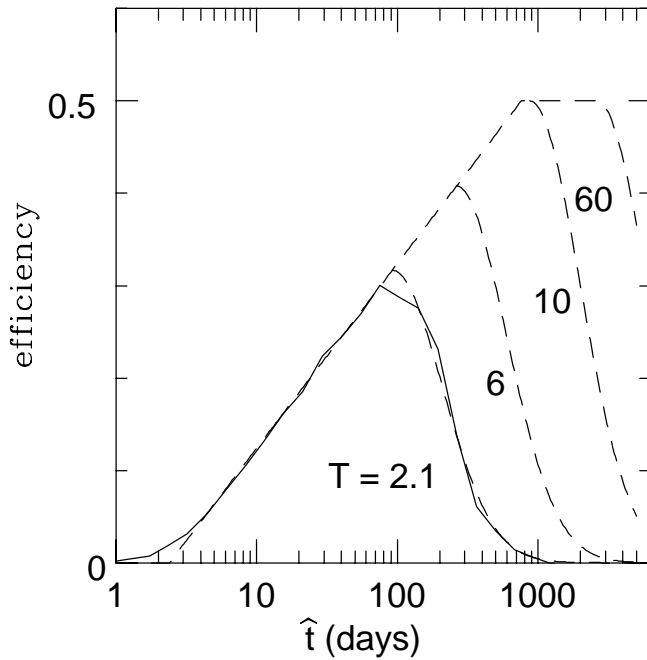
FIG. 2.—Assumed evolution of detection efficiency toward the LMC with experiment lifetime T for $T = 2.1$, 6, 20, and 60 years (*dashed lines*). The efficiency is assumed to increase with T for longer Einstein diameter crossing times $\hat{t}$ up to a maximum efficiency level of 0.5. The actual detection efficiency of Alcock et al. (1997a) after 2.1 years observation is shown by the solid line.

(1997a) 2.1 year efficiencies (*solid line*). It is also broadly consistent with provisional 4 year MACHO efficiency estimates (Sutherland 1999). Note from Figure 2 that the limiting efficiency $\mathscr{E}_{\max}$ is not reached until $T \simeq 20$ years, much longer than the nominal lifetime of the MACHO experiment. Let us emphasize that this model is only a plausible representation of how the efficiencies for the current generation of microlensing experiments might evolve.

We can now use simulated data sets to compute likelihoods for any desired theoretical model via equation (7). For the data set, we calculate the likelihood L_h for the input (true) halo and LMC disk and bar parameters. Let the likelihood of the competing model of a shrouded LMC disk and bar be L_s. The ratio L_s/L_h then provides a direct measure of the preference of the data set for the (true) halo model or (false) shroud model. Given just these two alterna-

tives, we can define a discrimination measure

$$D = \frac{L_h}{L_s + L_h}, \tag{15}$$

which is the probability, given the data, that the halo rather than the shroud, represents the underlying model. Individual data sets can be misleading, so we generate a large ensemble of data sets for every experiment lifetime T. (Specifically, we use either 10^5 data sets or a cumulative total of 3×10^6 events, whichever is reached first.) From the resulting distribution of D-values, it is possible to assess not just the degree of discrimination for a particular data set between the input and comparison model, but also the likelihood of obtaining a data set with at least that level of discrimination.

In Figure 3, we plot D_{95} (that is, the 95% lower limit on D) computed from the ensemble of simulated data sets, for a variety of input and comparison models (all assuming $f_s = 1$) for experiments with a lifespan of up to 20 years. The figure clearly illustrates how much longer it takes to distinguish between the competing models for smaller halo fractions and larger lens masses. For halo fractions $f_h \gtrsim 0.3$, we expect our experiment to clearly distinguish between the two models after about 5 years if $m_{\mathrm{dark}} \lesssim 0.5 \; M_\odot$. The amount of time T required to decisively reject the shroud model is about twice as long for lens masses $m_{\mathrm{dark}} = 0.5 \; M_\odot$ than for $m_{\mathrm{dark}} = 0.1 \; M_\odot$, and this is due to the larger number of events typically observed for the lower mass lenses. If our ideal experiment is indicative of the progress of the MACHO survey, it seems that even after 10 years the experiment may still be unable to clearly distinguish between the halo and shrouded LMC models if $f_h \sim 0.1$ and $m_{\mathrm{dark}} \gtrsim 0.1 \; M_\odot$.

Table 2 shows the experimental lifetime T, in years, required to constrain $D_{95} > 0.95$, at which point 95% of data sets clearly reject the shroud model. The limits displayed in Figure 3 are summarized in columns (2)–(4) of Table 2. Columns (5)–(7) show the equivalent limits if one employs a likelihood statistic that does not take into account the spatial distribution of the events. Columns (8)–(10) are for a shroud mass factor half as large as assumed in Figure 3. For columns (5)–(7), we have assumed that the timescale distribution at all locations is the same as the distribution for the line of sight through the LMC center. We see that the spatial distribution of events becomes an increasingly important discriminant for halos of lower lens

TABLE 2

EXPERIMENT LIFETIME T (IN YEARS) REQUIRED BEFORE D_{95} EXCEEDS 0.95 FOR VARIOUS HALO FRACTIONS, f_h, LMC SHROUD MASS FACTORS, f_s, AND HALO/SHROUD LENS MASSES, m_{dark}

	f_s								
	1			1 (No Angular Distribution)			0.5		
	f_h			f_h			f_h		
m_{dark} (1)	0.1 (2)	0.3 (3)	0.5 (4)	0.1 (5)	0.3 (6)	0.5 (7)	0.1 (8)	0.3 (9)	0.5 (10)
$0.1 \; M_\odot$	9.5	2	1	14	2	1	6.5	1.5	1
$0.5 \; M_\odot$	20.5	3.5	2	35	4.5	2	14.5	3	2

NOTE.—For cols. (5)–(7), the lifetimes are based on likelihood comparisons which ignore the angular distribution of events.
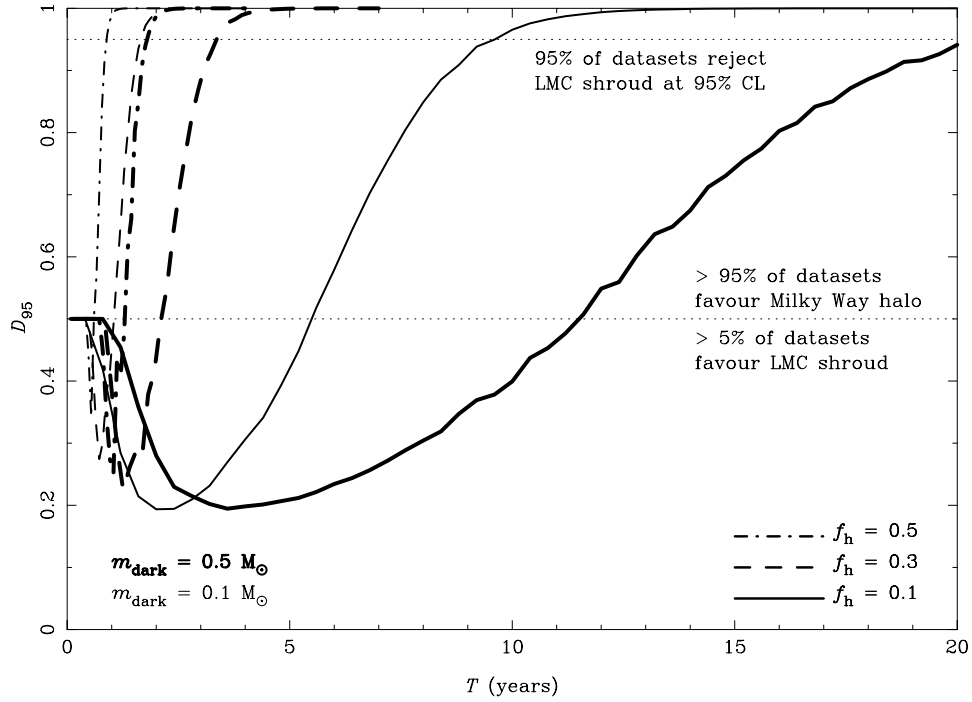
FIG. 3.—Discriminatory power of our idealized LMC microlensing experiment as a function of its lifetime T. The input (true) lens model comprises an LMC disk and bar, together with a Milky Way halo comprising MACHOs of mass $m_{\mathrm{dark}} = 0.1\ M_{\odot}$ (*thin lines*) and 0.5 $M_{\odot}$ (*thick lines*), and fractional contribution $f_h = 0.1$ (*solid lines*), 0.3 (*dashed lines*), and 0.5 (*dot-dashed lines*). The comparison model consists of the same LMC disk and bar, but in place of a Milky Way halo is a diffuse LMC shroud comprising lenses of the same mass m_{dark} but with a mass factor $f_s = 1$. The discrimination measure D represents the confidence with which the data favor the input model (halo) over the comparison model (shroud) after time T, and D_{95} is its 95% lower limit value derived from a large ensemble of data sets. Lines dipping below the dotted line at $D_{95} = 0.5$ indicate configurations in which more than 5% of simulated data sets misleadingly implicate the shroud model over the halo model. Lines rising above the $D_{95} = 0.95$ dotted line indicate that in 95% of simulations sufficient data have been accumulated to reject the shroud model with greater than 95% confidence.
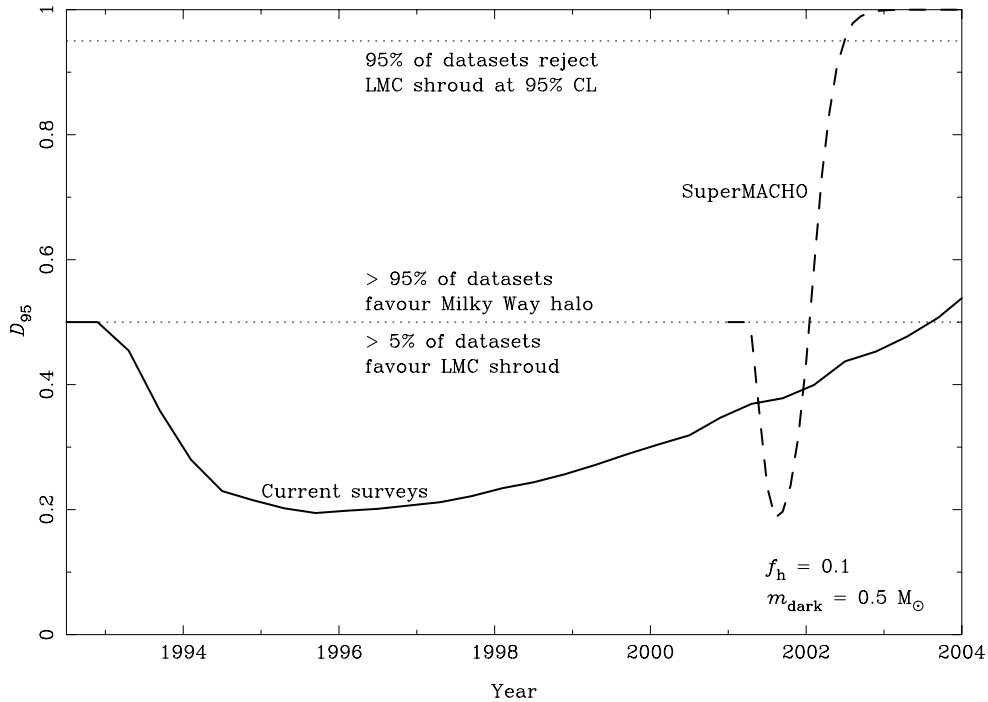

FIG. 4.—The 95% lower limit on the discriminatory power, D_{95}, of current surveys (*solid line*) and the proposed next-generation survey, "SuperMACHO," of Stubbs (1998) as a function of observation epoch. We assume a starting date of 1992.5 for the current surveys and 2001 for SuperMACHO. The limits shown are for the halo model with $f_h = 0.1$ and $m_{\mathrm{dark}} = 0.5\ M_{\odot}$.

fraction and lenses of larger mass. In the case where $f_h = 0.1$, the incorporation of the angular distribution of events into the likelihood statistic greatly enhances the sensitivity of the analysis to the lens population. In this case the number of generated events is similar for the competing halo and shroud models, and so the spatial distribution becomes an important discriminatory factor. Comparing columns (2)–(4) with columns (8)–(10), where a shroud mass factor $f_s = 0.5$ is assumed, we see that less massive LMC disks are easier to distinguish. The overall constraints for $f_s = 0.5$ are stronger for a given T than those for $f_s = 1$ because the halo events always outnumber LMC events. The relative constraints for different f_h and m_{dark} are similar for both values of f_s; LMC and halo models with $m_{dark} = 0.5\ M_\odot$ are about twice as difficult to differentiate as those with $m_{dark} = 0.1\ M_\odot$.

Stubbs (1998) has proposed a next-generation microlensing survey (provisionally dubbed "SuperMACHO") capable of detecting events at a rate at least an order of magnitude greater than current experiments. Gould (1999) finds that coverage of the whole LMC disk is the key to maximizing the returns of such a survey. In Figure 4 we compare the discrimination capability of SuperMACHO with that of current surveys, assuming that SuperMACHO commences 9 years after the current surveys and that the current experiments are continued through the next decade (in reality, the current surveys are scheduled to terminate in the next few years). Let us assume that the SuperMACHO angular coverage will be as suggested by Gould (1999), namely, $11° \times 11°$ centered on the LMC bar, that the number of detected events will be 10 times greater than current yields, and that the detection efficiency evolves according to equations (13) and (14). In reality the SuperMACHO detection efficiency is likely to be qualitatively different than for the current experiments because many of the central fields will be strongly blended.

In Figure 4 we have replotted the 95% limit on the discriminatory power (D_{95}) of current surveys for the case $f_h = 0.1$, $m_{dark} = 0.5\ M_\odot$ (solid line). This time we plot D_{95} against epoch rather than experiment lifetime. We adopt 1992.5 as the start of the current surveys (it actually corresponds to the start of the MACHO survey), with the SuperMACHO survey, shown by the dashed line, assumed to start in 2001. Whilst current surveys would take 20 years to distinguish clearly between LMC and halo populations for this model, SuperMACHO takes only 18 months to reach the same level of discrimination. SuperMACHO will surpass the sensitivity of current surveys within a year of starting (if it indeed starts on the assumed date). A survey along the lines of SuperMACHO represents one of the best ways to discriminate statistically between halo and LMC lens populations in the next few years.

4. CONCLUSIONS

It is possible to build models of the Large Magellanic Cloud with microlensing optical depths that are comparable to, although lower than, the observations. Such models are fatter than is conventional, with material extending to scale heights of ~ 6 kpc above the plane of the LMC disk, as is suggested by Weinberg's (2000) numerical simulations of the evolution of the LMC in the tidal field of the Milky Way. In this paper we have derived the formula for the self-lensing optical depth of an equilibrium thin disk surrounded by stars dispersed at greater scale heights. As a

shorthand, we call such material the shroud, even though its distribution may be quite patchy. When $\sim 10\%$ of the total column density is in the shroud, the self-lensing optical depth is typically between 0.7×10^{-7} and 1.1×10^{-7}. The self-lensing optical depth rises to between 1.2×10^{-7} and 1.9×10^{-7} when $\sim 20\%$ of the column density is in the shroud. These figures should be compared to the observational estimate of $2.1^{+1.3}_{-0.8} \times 10^{-7}$. Provisional estimates using the 4 year data set suggest that the optical depth may be lower (Sutherland 1999). Additionally, the difficulty of reproducing the high optical depths reported by both Udalski et al. (1994) and Alcock et al. (1997b) toward the Galactic center using barred models of the inner Galaxy (e.g., Häfner et al. 2000) hints at a possible systematic overestimate afflicting the experimental values. Clearly, the suggestion that almost all the microlensing events emanate at or close to the LMC cannot be dismissed lightly.

The difficulty with fattening the LMC disk is that there are no known LMC populations with a line-of-sight velocity dispersion exceeding 33 km s^{-1} (Hughes et al. 1991). Stars in equilibrium in a thick disk with a scale height of 3 kpc typically possess a larger velocity dispersion than this. One possibility is that the shroud stars belong to an old, metal-rich population that could have evaded detection. More likely, perhaps, is that the material in the shroud is not in a steady state at all. Its spatial distribution may be quite patchy, making it difficult to pick out against the bright central bar. A final option is that the shroud is composed of dark or dim material, such as low-mass stars or compact objects (cf. Aubourg et al. 1999). Self-lensing optical depths then overestimate the true optical depth by a factor of ~ 1.5, although this may be partly compensated by increasing the mass fraction in the shroud. The idea is tantamount to enveloping the LMC in its own dark halo. So, a shrouded LMC may not dispense with the need for compact dark matter. It merely relocates it from the Milky Way halo to the LMC, although of course a much lower total mass budget in compact objects is implied. A dark shroud is difficult to rule out, although there is no obvious way to arrange the low-mass stars or compact objects around the LMC thin disk.

It is natural to hope that the spatial distribution of events across the face of the LMC disk and the timescale information can be used to identify the main location of the lenses. In some circumstances, an experiment lifetime of $\lesssim 5$ years is sufficient to decide between the competing claims of Milky Way halo lenses and LMC lenses. However, there is an awkward régime in which fattened LMC disks can mimic anorexic halos, and several decades of survey work are needed for discrimination. The difficult models to distinguish are Milky Way halos in which the lens fraction is very low ($f_h \lesssim 0.1$) and obese LMC disks composed of lenses with a typical mass of low-luminosity stars or greater, $m_{dark} \gtrsim 0.1\ M_\odot$. This suggests that the timescales and the geometric distribution of the microlensing events may not be sufficient for an unambiguous resolution of the puzzle of the origin of the lenses within the lifetime of the current surveys.

One suggested approach to this problem is to employ a much more sensitive microlensing survey covering the whole LMC disk, not just the regions around the bar. The proposed "SuperMACHO" survey (Stubbs 1998) should be able to discriminate between even anorexic halos and fattened LMC disks within 18 months of starting. So, the com-

mencement of a program such as SuperMACHO represents one of the most promising ways to answer this question in the next few years. In the meantime, we may still hope to differentiate between the lens locations using data from binary caustic crossing events and from the presence or absence of parallax events. As Kerins & Evans (1999) have already argued, the former are a particularly powerful diagnostic. If the next binary caustic crossing event has a high projected velocity, then this securely establishes a lensing component in the Milky Way Galaxy. If the next binary caustic crossing event has a low projected velocity, then—given the existing data set—it becomes overwhelmingly likely that most of the lenses lie in a fattened LMC. This method, though, does suffer from a possible bias if the Milky Way halo is underendowed with binaries. Another possible diagnostic is a radial velocity survey of the microlensed sources. This could determine whether the sources occur preferentially at the back of the LMC disk, as is expected for self-lensing (Zhao 1999).

In the longer term, a definitive test is to measure simultaneously the photometric and astrometric microlensing signals of a few events with the *Space Interferometry Mission* (*SIM*), which is currently scheduled for launch in mid-2005. This suggestion has been advanced by Boden, Shao, & van Buren (1998) and Gould & Salim (1999). It enables the unambiguous identification of the lens location at the cost of about 20 hours exposure time per event with *SIM*. Since this method is able to discern the location of the lenses on an event-by-event basis, rather than by ensemble likelihood statistics, *SIM* and SuperMACHO should provide useful and complementary data sets. One way or another, the location of the lenses will be known within 5 years or so.

REFERENCES

Alcock, C., et al. 1996, ApJ, 461, 84
———. 1997a, ApJ, 486, 697
———. 1997b, ApJ, 479, 119
Alvarez, H., Aparici, J., & May, J. 1987, A&A, 176, 25
Aubourg, E., Palanque-Delabrouille, N., Salati, P., Spiro, M., & Taillet, R. 1999, A&A, 347, 850
Bennett, D. 1998, Phys. Rep., 307, 97
Bessell, M. S., Freeman, K. C., & Wood, P. R. 1986, ApJ, 310, 710
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Boden, A., Shao, M., & van Buren, D. 1998, ApJ, 502, 538
Bothun, G. D., & Thomson, I. B. 1988, AJ, 96, 877
Cowley, A. P., & Hartwick, F. D. A. 1991, ApJ, 373, 80
de Vaucouleurs, G., & Freeman, K. 1972, Vistas Astron., 14, 163
Gould, A. 1989, ApJ, 341, 748
———. 1995, ApJ, 441, 77
———. 1999, ApJ, 517, 719
Gould, A., Bahcall, J., & Flynn, C. 1997, ApJ, 482, 913
Gould, A., & Salim, A. 1999, ApJ, 524, 794
Gyuk, G. 1999, ApJ, 510, 205

Gyuk, G., Dalal, N., & Griest, K. 1999, ApJ, submitted (astro-ph/9907338)
Häfner, R., Evans, N. W., Dehnen, W., & Binney, J. J. 2000, MNRAS, in press (astro-ph/9905086)
Hill, R. J., Madore, B. F., & Freedman, W. L. 1994, ApJ, 429, 204
Hughes, S. M. G., Wood, P. R., & Reid, N. 1991, AJ, 101, 1304
Kerins, E. J., & Evans, N. W. 1999, ApJ, 517, 734
Sahu, K. 1994, Nature, 370, 275
Salati, P., Taillet, R., Aubourg, E., Palanque-Delabrouille, & Spiro, M. 1999, A&A, 350, L57
Stubbs, C. 1998, in ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman (San Francisco: ASP), 503
Sutherland, W. 1999, paper presented at Royal Astronomical Society Meeting, London, 1999 March 12
Udalski, A., et al. 1994, Acta Astron., 44, 165
Weinberg, M. D. 2000, AJ, submitted (astro-ph/9905305)
Westerlund, B. 1997, The Magellanic Clouds (Cambridge: Cambridge Univ. Press)
Wu, X.-P. 1994, ApJ, 435, 66
Zhao, H. S. 1999, ApJ, 526, 141