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MACHO PROJECT LIMITS ON BLACK HOLE DARK MATTER IN THE 1–30 $M_\odot$ RANGE

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ABSTRACT

We report on a search for long-duration microlensing events toward the Large Magellanic Cloud. We find none and therefore put limits on the contribution of high-mass objects to the Galactic dark matter. At a 95% confidence level, we exclude objects in the mass range of 0.3–30.0 $M_\odot$ from contributing more than 4×10^{11} $M_\odot$ to the Galactic halo. Combined with earlier results, this means that objects with masses under 30 $M_\odot$ cannot make up the entire dark matter halo if the halo is of typical size. For a typical dark halo, objects with masses under 10 $M_\odot$ contribute less than 40% of the dark matter.

Subject headings: black hole physics — dark matter — Galaxy: halo — Galaxy: structure — gravitational lensing

1. INTRODUCTION

Recent results from the MACHO and EROS collaborations have ruled out MAssive Compact Halo Objects (MACHOs) as the bulk of the Galactic dark matter in the mass range from 10^{-7} $M_\odot$ to a few solar masses (Alcock et al. 1998, 2000a; Lasserre et al. 2000), thus eliminating the main candidate for baryonic dark matter in the Milky Way. However, there still remains a window between several solar masses and around 1000 $M_\odot$ (Moore 1993), where black holes or other MACHOs could make up the dark matter of the Milky Way. It was shown by Carr & Hawking (1974) that primordial black holes could have formed at very early stages in the universe as a result of initial inhomogeneities, and recent work has focused on the spike in the primordial black hole mass spectrum that could arise during the quark-hadron phase transition in the early universe (e.g., Jedamzik 1997). As reviewed by Carr (1994), the density relative to the critical density Ω in compact dark objects with masses of 0.01–20 $M_\odot$ must be less than 0.1 (increasing, however, to $\lesssim 1$ for 60–300 $M_\odot$ objects). These limits are determined by the line-to-continuum microlensing effects in quasars (Dalcanton et al. 1994), and they still allow the Milky Way halo to consist largely of such objects. For comparison, Galactic chemical-enrichment arguments, assuming a standard initial stellar mass function and standard stellar evolution, limit the remnants of Population III stars to $\Omega \leq 0.001$ for remnants in the range of 4–200 $M_\odot$ (Carr, Bond, & Arnett 1984). However, there are no strong limits on black holes or nontopological soliton states arising from the early universe or on relics from a nonstandard, very early generation of stars.

More recently, the microlensing surveys have set the best limits on the fraction of dark objects in our own dark halo over a wide range of masses. When a compact dark object passes in front of a source star in a nearby dwarf galaxy, the source star suffers a temporary magnification due to gravitational microlensing (Paczyński 1986), and this is used by the above collaborations to search for MACHOs. The duration of this magnification is determined by a combination of the lens distance, velocity, and mass, and this degeneracy means that the lens mass cannot be determined uniquely for an individual lensing event unless other information is available. However, for a given halo model, an average over the lens density and velocity distributions can be made, and an average duration can be estimated (Griest 1991):

$$\hat{t} \approx 130 \sqrt{m/M_\odot} \text{ days}, \quad (1)$$

where $\hat{t}$ is the time for the source to cross the Einstein ring diameter.

The 13–17 events discovered by the MACHO collaboration

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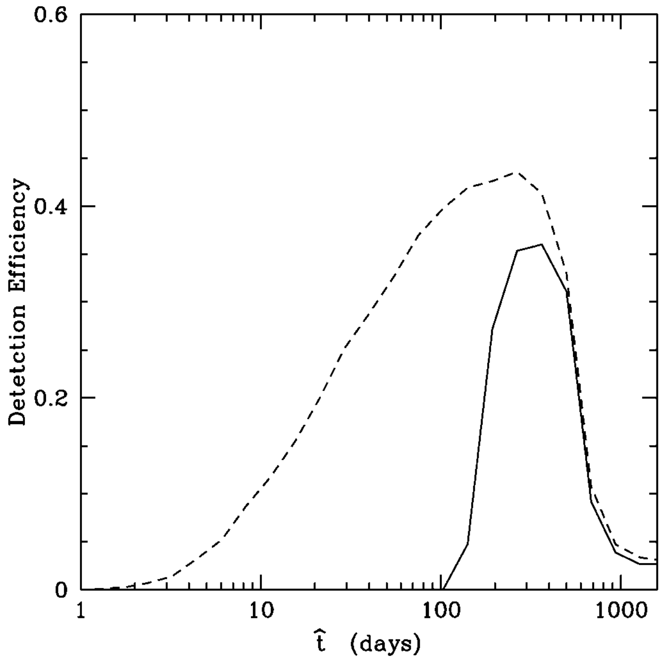

FIG. 1.—Microlensing detection efficiency for the 5.7 yr MACHO data as a function of event timescale $\hat{t}$. The dashed line (from A2000a) shows criteria set A efficiency. The solid line shows set A′, used in this Letter, which is criteria set A plus the additional constraint of $\hat{t} > 150$ days.

in the Large Magellanic Cloud (LMC) have durations ranging from about 30 to 130 days (Alcock et al. 2000a, hereafter A2000a), indicating lens masses in the 0.1–1 $M_\odot$ range. However, the number of events found, while larger than the expected background of two to four events from known stellar populations, is significantly less than the 60–80 events expected if the dark matter consisted entirely of objects in this mass range. Thus, the most likely MACHO halo fraction of 20% was found, and a 100% MACHO halo was ruled out at the 95% confidence level (CL). Earlier, EROS (Aubourg et al. 1995; Alcock et al. 1998) and MACHO (Alcock et al. 1996, 1998) searched for events with durations of less than 10 days and found none, limiting the MACHO fraction of dark matter to less than 25% in the range from 10^{-7} to 10^{-4} $M_\odot$. Finally, and most powerfully for the high-mass end, the EROS collaboration (Lasserre et al. 2000) did a combined analysis of all their microlensing surveys of the Magellanic Clouds and set a 95% CL limit that objects in the 10^{-7} to 4 $M_\odot$ range do not constitute 100% of the dark halo and that objects less than 1 $M_\odot$ contribute less than 40% of the dark halo.

In this Letter, we improve on these limits in the high-mass region by performing a search for events with durations longer than 150 days. We did not find any such events and therefore can improve the upper limit to around 30 $M_\odot$.

2. DATA

The data used in this analysis are precisely the data used in A2000a, to which we refer the reader for details. In brief, the data set included 5.7 yr of data on 11.9 million stars in the LMC. These comprised 21,570 images taken over 30 $42' \times 42'$ fields in two filter bands, with the number of exposures per field ranging from 180 to 1338. The photometry of these objects was arranged in light curves and was searched for microlensing by using the analysis and statistics described in A2000a. Event selection was performed using those statistics, and in this Letter we use a superset of set A selection criteria described in A2000a, which was the more conservative of the two sets of selection criteria used there. After removal of variable stars and background supernovae selection, criterion A gave 13 microlensing events, with fitted durations between 34 and 103 days. This corresponds to physical durations between 42 and 126 days after a statistical correction for blending was made. We note that one event (event 22) was considered marginal in A2000a and was excluded by hand from event set A for reasons described in A2000a. Further study of this event shows that the source is extended and contains emission lines that are not characteristic of stellar objects. Event 22 seems likely to be a supernova of exceptionally long duration or an active galactic nucleus in a galaxy at redshift $z = 0.23$ and is therefore very unlikely to be microlensing. Our redshift is based on spectra with wavelength coverage of 4340–9017 Å obtained with the double-beam spectrograph on the 2.3 m telescope at the Siding Springs Observatory. The exclusion of event 22 is relevant for this Letter since this event is the longest duration candidate microlensing event with $\hat{t} = 230$ days. See A2000a and Alcock et al. (2000b, hereafter A2000b) for details of data taking, analysis, and event selection.

3. NEW ANALYSIS

The current analysis is similar to that used in the Alcock et al. (1996) search for planetary mass dark matter but is applied to the long-duration end of our data rather than the short-duration end. We create a simple set of selection criteria similar to the set A selection criteria but tailored to find only events with durations longer than 150 days. Many sets of selection criteria were explored, but since our final result at the high-mass end depends very little on which set of cuts we use, we simply choose set A selection criteria from A2000a with the additional constraint of "$\hat{t} > 150$ days," hereafter referred to as selection criteria set A′. A complete description of selection criteria set A can be found in Table 3 of A2000a. Selection criteria set A′ gives no candidate microlensing events. Using selection criteria A′, we then calculate the complete photometric efficiency as a function of input $\hat{t}$ with the method described briefly in A2000a and in detail in A2000b and Vandehei (2000). This efficiency calculation takes into account inefficiencies caused by bad weather, seeing, telescope slips, etc., and includes a careful treatment of blending. Blending occurs when a single photometered object actually consists of several underlying stars, only one of which is microlensed (see A2000b for a detailed discussion). The resulting efficiency is shown in Figure 1, along with the efficiency for criteria set A from A2000a. Note that there is nonzero efficiency even beyond the explicit set A cut of $\hat{t} < 600$ days since events that are blended can appear to be of shorter duration than the actual input $\hat{t}$. The efficiency is then convolved with the predicted distribution of microlensing durations from a halo model in order to find an expected number of microlensing detections if the Galactic halo consisted 100% of MACHOs.

For simplicity, we use model S from Alcock et al. (1997), which is given by

$$\rho_H(r) = \rho_0 \frac{R_0^2 + a^2}{r^2 + a^2}, \qquad (2)$$

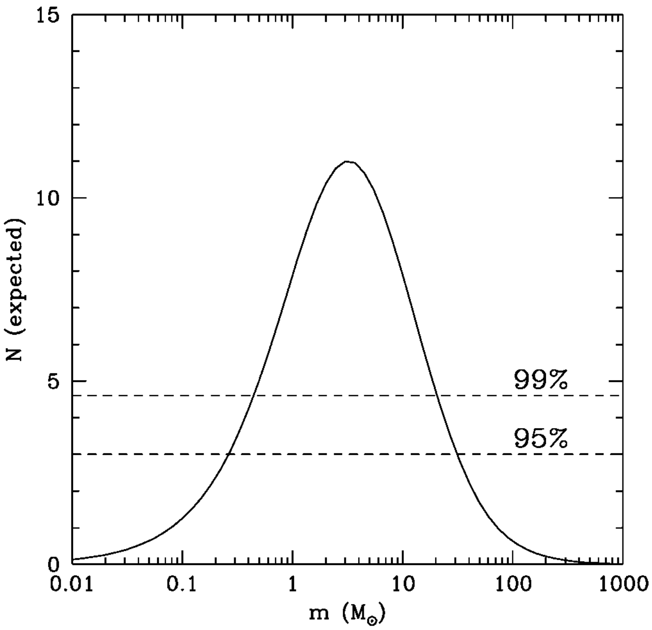

FIG. 2.—Number of long-duration events expected vs. lens mass for halo model S. The dashed lines drawn at $N = 3$ and $N = 4.6$ indicate the 95% CL limit and the 99% CL limit, respectively. Masses above these lines are ruled out at their respective confidence limits.

where ρ_H is the halo density, $\rho_0 = 0.0079\ M_\odot\ \mathrm{pc}^{-3}$ is the local dark matter density, r is the Galactocentric radius, $R_0 = 8.5$ kpc is the Galactocentric radius of the Sun, and $a = 5$ kpc is the halo core radius. With the standard thin disk, this model has a total rotation speed of 200 km s^{-1} at 50 kpc, with 190 km s^{-1} coming from the halo, giving a total halo mass of $4 \times 10^{11}\ M_\odot$ out to 50 kpc. We assume an isotropic Maxwellian distribution of velocities with a one-dimensional rms velocity of 155 km s^{-1} and assume a δ-function MACHO mass function of arbitrary mass m.

In Figure 2, we plot the resulting expected number of events as a function of MACHO mass. The number of events is Poisson-distributed. Therefore, when the number of expected events is α, the probability of detecting 0 events is $\exp(-\alpha)$. For $\alpha = 3$, one has $P(\text{zero events}) = \exp(-3) = 0.05$. Thus, any model that predicts more than three events is ruled out at a 95% CL. We note that if a continuous range of masses is ruled out, then any mass function containing only masses in the ruled-out range is also ruled out (Griest 1991).

Using the number of expected events from Figure 2, we easily derive Figure 3, the exclusion plot for the new analysis, with the area above the solid line being ruled out at a 95% CL. We see that objects with masses between 0.3 and 30.0 $M_\odot$ cannot make up 100% of the dark halo in this model. Since this model contains $4 \times 10^{11}\ M_\odot$ within 50 kpc, this means that at a 95% CL, objects with masses between 0.3 and 30 $M_\odot$ cannot contribute more than $4 \times 10^{11}\ M_\odot$ to the Milky Way dark halo inside 50 kpc. In A2000a, it was shown that limits on the mass of the halo in MACHOs are fairly independent of the halo model.

Combining these limits with earlier limits (Alcock et al. 1998), which are stronger at lower masses where the microlensing surveys have their peak sensitivity, we see that objects with masses under 10 $M_\odot$ cannot contribute more than $1.6 \times 10^{11}\ M_\odot$ to (or make up more than 40% of) the Galactic

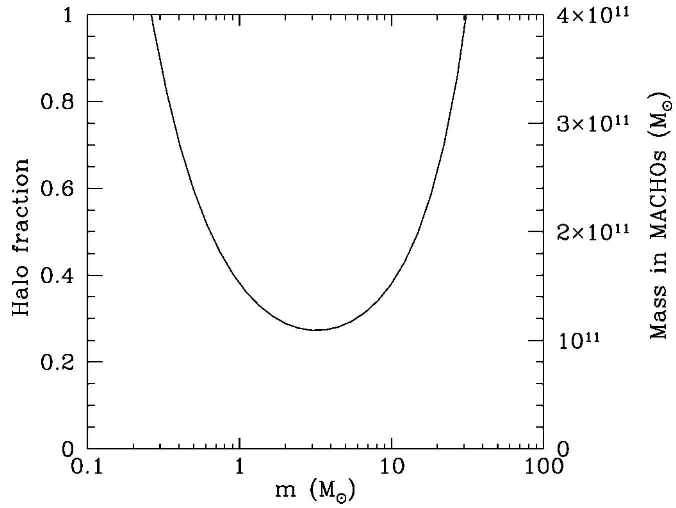

FIG. 3.—Limit on MACHO contribution to the Galactic halo as a function of lens mass for model S. The region above the line is ruled out at a 95% CL. The left axis shows the MACHO halo fraction, while the right axis shows the more model-independent constraint on total mass in MACHOs within 50 kpc.

dark matter in this model. Note that since the microlensing experiments can only detect MACHO dark matter, fractional limits on the dark halo mass are strongly dependent on the total amount of dark matter assumed to exist in the dark halo. Limits on the total mass in MACHOs also depend on the halo model but are more model-independent. Limits on the halo fraction will scale roughly with the total mass out to 50 kpc in a given halo model; that is, a model with twice as much dark matter will have a limit of around 50% rather than 100% at 30 $M_\odot$.

Finally, one may ask how we have been able to extend the mass range considered in A2000a using the same data and a subset of the same events. The answer is that criteria set A′ is specifically focused on long-duration events and that no microlensing events were found with criteria set A′. So compared with criteria set A that found 13 events, all of which would have had to be considered background, stronger limits can be set using criteria set A′. The basic idea is that if high-mass MACHOs existed in large numbers, then some long-duration events should have been detected. In A2000a, we did not attempt to answer the question of how many high-mass MACHOs would be required for the data to become inconsistent with a given halo model.

4. DISCUSSION

The limits given in this Letter are the strongest to date on compact halo objects with masses above 1 $M_\odot$. In particular, black holes or other dark compact objects with masses less than 30 $M_\odot$ cannot make up the bulk of the dark matter.

We do note, however, that the present survey/analysis does not have much sensitivity to objects with masses greater 30 $M_\odot$. There is a large background of slowly varying variable stars that must be removed, and our main signal-to-noise ratio cuts are not very good at distinguishing these from microlensing. Thus, we rely primarily on a long, flat baseline and on a direct cut on the fitted event duration ($\hat{t} < 600$ days) to remove this background. Unfortunately, these cuts also limit our ability to detect long-duration events coming from high-mass lenses. We expect that analysis of the complete 8 yr data set will go some way toward solving this problem, and we expect to be able to push the current limit to higher masses or to present long-duration microlensing events when that data set has been analyzed.

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