

# MACHO Project Limits on Black Hole Dark Matter in the 1-30 Solar Mass Range.

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## ABSTRACT

We report on a search for long duration microlensing events towards the Large Magellanic Cloud. We find none, and therefore put limits on the contribution of high mass objects to the Galactic dark matter. At 95% confidence level we exclude objects in the mass range  $0.3 M_{\odot}$  to  $30.0 M_{\odot}$  from contributing more than  $4 \times 10^{11} M_{\odot}$  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:* dark matter — Galaxy: structure, halo — gravitational lensing — Stars: high mass — black holes

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## 1. Introduction

Recent results from the MACHO and EROS collaborations have ruled out Massive Compact Halo Objects (MACHOs) as the bulk the Galactic dark matter in the mass range  $10^{-7} M_{\odot}$  to a few solar masses (Alcock et al. 2000a; Lasserre et al. 2000; Alcock et al. 1998), 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 one thousand solar masses (Moore 1993), where black holes or other MACHOs, could make up the dark matter of the Milky Way. It was shown by Carr and 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 focussed 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 critical density,  $\Omega$ , 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), limits determined by line-to-continuum microlensing effects in quasars (Dalcanton et al. 1997). These limits 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  $4 - 200 M_{\odot}$  (Carr, Bond, & Arnett 1984). However, there are no strong limits on black holes or non-topological soliton states arising from the early Universe or on relics from a non-standard very early generation of stars.

More recently, the microlensing surveys are setting the best limits on the fraction of dark objects in our own dark halo over a wide range of masses. The above collaborations search for MACHOs using the fact that 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 (Paczynski 1986). 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 uniquely determined 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 in the Large Magellanic Cloud (LMC) have durations ranging from about 30 days to about 130 days (Alcock et al. 2000a), indicating lens masses in the  $0.1 M_{\odot}$  to  $1 M_{\odot}$  range. However, the number of events found, while larger than the expected background of 2–4 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 a most likely MACHO halo fraction of 20% was found, and a 100% MACHO halo was ruled out at 95% c.l. Earlier EROS (Aubourg et al. 1995; Alcock et al. 1998) and MACHO (Alcock et al. 1996; Alcock et al. 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  $10^{-7} M_{\odot}$  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% c.l. limit that objects in the  $10^{-7} M_{\odot}$  to  $4 M_{\odot}$  range do not constitute 100% of the dark halo, and 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 is precisely the data used in Alcock et al. (2000a; hereafter A2000a), to which we refer the reader for details. In brief, this dataset includes 5.7 years of data on 11.9 million stars in the LMC. These comprise 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 lightcurves and searched for microlensing using the analysis and statistics described in A2000a. Event selection was performed using those statistics, and in this paper we consider selection criteria similar to the 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 this set of selection criteria gives 13 microlensing events, with fit durations between 34 days and 103 days. This corresponds to physical durations between 42 days and 126 days when a statistical correction for blending is made. We note that one event (event 22) was considered marginal in A2000a and 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 AGN in a galaxy at redshift  $z = 0.23$  and, therefore, is very unlikely to be microlensing. Our redshift is based upon spectra with wavelength coverage 4340-9017 angstrom obtained with the DBS spectrograph on the 2.3m telescope at Siding Springs Observatory. The exclusion of event 22 is relevant for this paper 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 spirit of the current analysis is similar to that used in the Alcock et al. (1996) search for planetary mass dark matter, but 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 selection criteria set A, but tailored to find only events with durations longer than 150 days. No such events are found, so any Galactic dark matter model that predicts more than 3 microlensing events is ruled out at 95% c.l. 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 choose simply selection criteria A from A2000a with the additional constraint “ $\hat{t} > 150$  days”. Thus the complete set of selection criteria we use is described in Table 3 of A2000a. This set of cuts gives no candidate microlensing events. Using this set of cuts, 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 Van dehei (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 photome-

tered 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 A from A2000a. This efficiency is then convolved with the predicted distribution of microlensing durations from a halo model 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

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

where  $\rho_H$  is the halo density,  $\rho_0 = 0.0079 M_\odot \text{ pc}^{-3}$  is the local dark matter density,  $r$  is Galactocentric radius,  $R_0 = 8.5 \text{ kpc}$  is the Galactocentric radius of the Sun, and  $a = 5 \text{ kpc}$  is the halo core radius. With the standard thin disk, this model has a total rotation speed at 50 kpc of 200 km/s, with 190 km/s 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 1-D rms velocity of 155 km/s, and assume a  $\delta$ -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  $\alpha$ , the probability of detecting 0 events is  $\exp(-\alpha)$ . For  $\alpha = 3$ , one has  $P(0\text{events}) = \exp(-3) = 0.05$ . Thus any model that predicts more than 3 events is ruled out at 95% c.l. 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 95% c.l. We see that objects with masses between  $0.3 M_\odot$  and  $30.0 M_\odot$  cannot make up 100% of the dark halo in this model. Combining these limits with earlier limits (Alcock et al. 1998), that are stronger at lower masses where the microlensing surveys have their peak sensitivity, we see that objects with masses under  $10 M_\odot$  cannot make up more than 40% of the Galactic dark matter in this model. Note that since the microlensing experiments can only detect MACHO dark matter, the fractional limit on the dark halo mass is strongly dependent on the total amount of dark matter assumed to exist in the dark

halo. Since this is quite uncertain, a more model independent way to state these results is that at 95% c.l., less than  $4 \times 10^{11} M_{\odot}$  in compact objects with masses less than  $30 M_{\odot}$  can be present in the Milky Way dark halo, and less than  $1.6 \times 10^{11} M_{\odot}$  can be present in compact objects with masses less than  $10 M_{\odot}$ . Limits on 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  $30 M_{\odot}$ .

#### 4. Discussion

The limits given in this paper 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 which must be removed, and our main signal-to-noise 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 fit 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-year data set will go some way towards 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 dataset has been analyzed.

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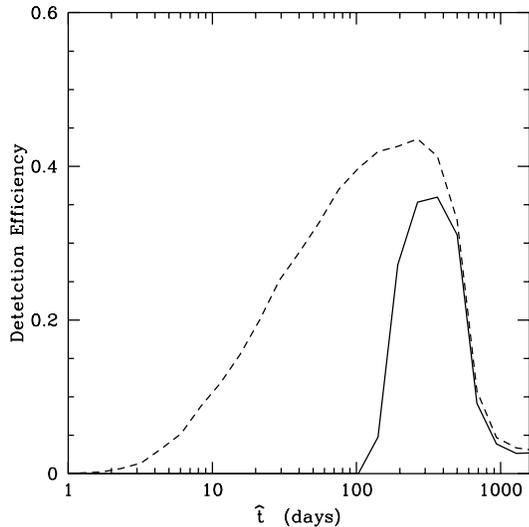


Fig. 1.— Microlensing detection efficiency for the 5.7-year MACHO data, as a function of event timescale  $\hat{t}$ . The *solid line* shows the photometric efficiency computed for cut set A, with the additional constraint that  $\hat{t} > 150$  days. The *dashed line* (from A2000a) is the same but without the additional constraint.

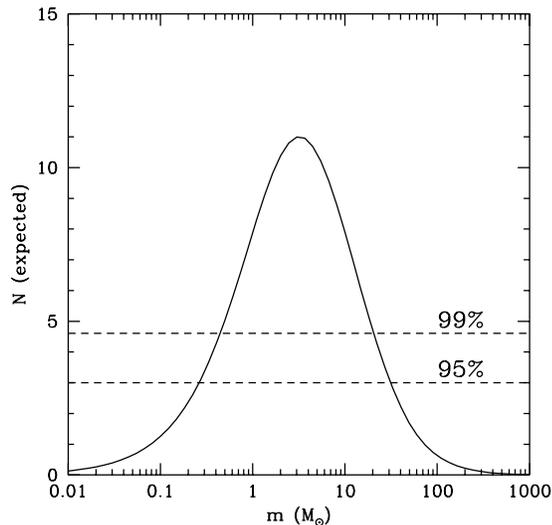


Fig. 2.— Number of long duration events expected vs. lens mass for halo model S. The dashed lines drawn at  $N = 3$  and  $N = 4.6$  indicate the 95% c.l. and the 99% c.l. limit respectively. Masses above these lines are ruled out at their respective confidence limits.

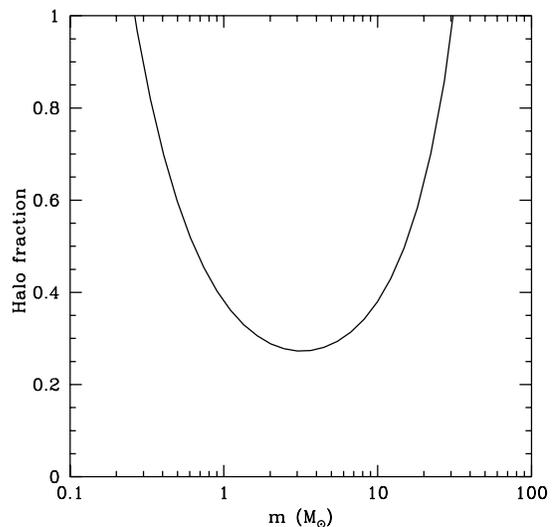


Fig. 3.— Halo fraction upper limit as a function of lens mass for model S. The region above the line is ruled out at 95% c.l. This model contains  $4 \times 10^{11} M_{\odot}$  within 50 kpc, so a less model dependent result can be found by reading the ordinate as “Halo mass in MACHOs/ $(4 \times 10^{11} M_{\odot})$ ”.