EROS and MACHO Combined Limits on Planetary Mass Dark Matter in the Galactic Halo

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ABSTRACT

The EROS and MACHO collaborations have each published upper limits on the amount of planetary mass dark matter in the Galactic Halo obtained from gravitational microlensing searches. In this paper the two limits are combined to give a much stronger constraint on the abundance of low mass MACHOs. Specifically, objects with masses $10^{-7} M_\odot < m < 10^{-3} M_\odot$ make up less than 25% of the halo dark matter for most models considered, and less than 10% of a standard spherical halo is made of MACHOs in the $3.5 \times 10^{-7} M_\odot < m < 4.5 \times 10^{-5} M_\odot$ mass range.

Subject headings: dark matter - gravitational lensing - Stars: low-mass, brown dwarfs
If a significant fraction of the dark matter in the Galactic Halo is in the form of MACHOs (objects of masses \( m \gtrsim 10^{-8} \, M_\odot \)), then these objects can be detected via gravitational microlensing (\( \sim \)), which is the temporary brightening of a background star as the unseen object passes close to the line of sight. The EROS and MACHO collaborations have been monitoring the brightnesses of millions of stars in the Magellanic Clouds for several years to search for these gravitational microlensing events, and several candidate events have been detected \( (?; ?) \), with Einstein ring diameters crossing times 33 days \(< t < 266 \, \text{days} \). For a MACHO of mass \( m \), the average timescale of a microlensing event (assuming a standard spherical halo) is given by \( (? \sim t) \)

\[
\langle t \rangle \sim 130 \sqrt{m/M_\odot} \, \text{days} ,
\]

so these events correspond to lens masses \( m \gtrsim 0.1 \, M_\odot \). For planetary mass objects \( (10^{-8} \, M_\odot \lesssim m \lesssim 10^{-3} \, M_\odot) \), the event durations become quite short, from a fraction of an hour to a few days. Both groups have reported upper limits on the abundance of planetary mass dark matter \( (?; ?) \), but because there is only a small overlap in exposure between the projects, it is possible to produce stronger limits by combining the largely independent results of the two groups.

The EROS search for low mass MACHOs (a part of the first phase of the EROS experiment) is described in detail in \( (?) \) and \( (?) \). The EROS program (Expérience de Recherche d’Objets Sombres) used a CCD camera at the European Southern Observatory at La Silla, Chile, devoted to the detection of events with small durations occurring between 1991 and 1995. One field of about half a square degree was observed about 20 times per night in two colors and contains about 150,000 stars. The first three years were devoted to the observation of one field in the bar of the LMC, the last year to one field in the center of the SMC. Each year of data was analyzed separately. The search is sensitive to microlensing durations ranging from 15 minutes to a few days on stars brighter than about 19.5 magnitude in V band. More than 19,000 images have been processed using custom designed fast photometric reconstruction software to produce light curves. None of the 350,000 good light curves exhibits a form which is consistent with a microlensing event. Using the detection efficiency, largely affected by blending effects and the finite size of the source at the lowest durations, objects in the range \( 2 \times 10^{-7} \, M_\odot < m < 2 \times 10^{-3} \, M_\odot \) can be excluded as a major constituent of the dark halo for different models of the Galaxy.

The MACHO collaboration search for low mass MACHOs (is described in detail in \( \) and \( \)). In summary, because the initial observing strategy of the MACHO collaboration was designed to maximise the detection rate for lenses in the brown-dwarf range \( 10^{-3} \) to 0.1 \( M_\odot \) (corresponding to event durations of a few days or longer), images of a given field were taken at most once or twice per clear night. For planetary mass lenses whose event durations are typically less than one day, there would be at most one or two (if any) magnified points on the lightcurve. If such an event were found it could not be classified as microlensing, but strong limits can be placed on the amount of dark matter in the form of low mass MACHOs if few of these events are found. Analysis of two years of data (from 20 July 1992 through 26 October 1994) on 8.6 million stars in 22 LMC fields found none of these “spike” events, and it was reported that MACHOs in the mass range \( 2.5 \times 10^{-7} \, M_\odot < m < 5.2 \times 10^{-4} \, M_\odot \) can not make up the entire mass of a standard spherical halo.

Even though the two experiments use very different analysis techniques, they produce fairly similar results. This is because the MACHO analysis has a very low efficiency (\( \sim 1\% \) for magnifications greater than 1.042) but a very large number of stars, and the EROS analysis gives a fairly high efficiency (up to 40% for a magnification greater than 1.08) on a small number of stars. Therefore there is little overlap in exposure for the two projects, and the two limits can be combined after taking this into account.

The 22 MACHO LMC fields used in this analysis are shown in Figure 1, along with the field used by the EROS experiment. The redundant measurements were eliminated by removing those
stars in the MACHO database which lie in the EROS field on nights when those stars were imaged by both collaborations. (The MACHO data were removed because the efficiency is much lower so less sensitivity was lost.) This reduced the MACHO effective exposure by about 10%. The MACHO limits were then recalculated, and the number of expected events were simply added to the number of expected events from the EROS analysis.

Each collaboration has used different halo models when reporting their results, but once the detection efficiency is known it is fairly simple to calculate the combined limits for both sets of models, which are summarized in Table 1. Models 1 - 5 are used by the EROS collaboration, and models S - G are used by the MACHO collaboration. Models 1 - 4 and A - G are the power-law models of (?) and models 5 and S are simple spherical models as described in (?) and (?). With these 13 models, we cover a fairly large range of reasonable Galactic Halo mass and velocity distributions. (Model E has the bulk of the Galactic mass in the disk. This is very likely an unreasonable assumption, but we include this model anyway for comparison to previous publications.)

The number of expected events as a function of lens mass (assuming a δ-function mass distribution) can be found in Figure 2 for the five EROS models and the eight MACHO models. Also, Figure 3 shows the 95% confidence level upper limit on the fraction of the halo dark matter which can consist of MACHOs of mass m. Here it can be seen that for most models, objects with masses $10^{-7} M_\odot \lesssim m \lesssim 10^{-3} M_\odot$ comprise less than 25% of the halo dark matter, and less than 10% of a standard spherical halo (model 5) is made of MACHOs in the mass range $3.5 \times 10^{-7} M_\odot < m < 4.5 \times 10^{-5} M_\odot$. Because we are using δ-function mass distributions, any mass function consisting entirely of masses in the excluded intervals is also eliminated (?). Figure 4 shows the amount of halo mass that can be comprised of MACHOs of mass m, which is a more model-independent limit (?). Here it is shown that for all models considered, a canonical halo mass of $4.1 \times 10^{11} M_\odot$ can not be comprised entirely of MACHOs in the mass range $10^{-7} M_\odot \lesssim m \lesssim 10^{-3} M_\odot$, and MACHOs with masses $10^{-7} M_\odot \lesssim m \lesssim 10^{-4} M_\odot$ account for less than $1 \times 10^{11} M_\odot$ of the total halo mass. These are the strongest limits published on dark matter in this mass range, and the limits will get stronger in time as more data are collected and analyzed.

The MACHO collaboration is currently analyzing two more years of LMC data, and is also continuing to collect data. However, the EROS short duration microlensing search was discontinued in April 1995, and because of the temporal sampling of the new data now being collected (?), a spike analysis will not be performed.

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Fig. 1.— The locations (J2000) of the MACHO fields used in this analysis and the location of the EROS field (thick line).

Fig. 2.— Total number of expected events versus lens mass for the combined MACHO and EROS results. The five EROS models are shown on the top plot and the eight MACHO models are shown on the bottom. Also shown in the top plot is the contribution to the results for model 1 from the EROS results (thin dotted line) and the MACHO results (dot-dash line). The relative contributions are roughly the same for all models.
Fig. 3.— Halo fraction upper limit (95% c.l.) versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.

Fig. 4.— Upper limit (95% c.l.) on total halo mass in MACHOs versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.
Table 1. Halo Model Parameters.

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<th>$q^b$</th>
<th>$v_0$ (km/sec)$^c$</th>
<th>$R_c$ (kpc)$^d$</th>
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$^a$ $\beta$ gives the shape of the rotational velocity curve ($v_{\text{circ}} \propto R^{-\beta}$).

$^b$ $q$ is the halo flattening parameter. ($q = 1$ gives spherical halo, $q = 0.7$ represents ellipticity of E6).

$^c$ $v_0$ is a normalization velocity (which corresponds to $v_{\text{circ}}$ if $\beta = 0$).

$^d$ $R_c$ is the Galactic core radius.

$^e$ $R_0$ is the radius of the solar orbit.

$^f$ $M_{50}$ is the total mass of halo dark matter interior to 50 kpc from the Galactic center.