# EROS and MACHO combined limits on planetary-mass dark matter in the galactic halo

Alcock, C; Allsman, RA; Alves, D; Ansari, R; Aubourg, E; Axelrod, TS; Bareyre, P; Beaulieu, J P; Becker, AC; Bennett, DP

*Published in:*
Astrophysical Journal

*DOI:*
10.1086/311355

THE ASTROPHYSICAL JOURNAL, 499:L9–L12, 1998 May 20


# EROS AND MACHO COMBINED LIMITS ON PLANETARY-MASS DARK MATTER IN THE GALACTIC HALO

C. ALCOCK,[1,2] R. A. ALLSMAN,[3] D. ALVES,[1,4] R. ANSARI,[5] É. AUBOURG,[6] T. S. AXELROD,[7] P. BAREYRE,[6,8] J.-PH. BEAULIEU,[9,10] A. C. BECKER,[2,11] D. P. BENNETT,[1,2,12] S. BREHIN,[6] F. CAVALIER,[5] S. CHAR,[13] K. H. COOK,[1,2] R. FERLET,[9] J. FERNANDEZ,[13] K. C. FREEMAN,[7] K. GRIEST,[2,14] PH. GRISON,[9] M. GROS,[6] C. GRY,[15] J. GUIBERT,[16] M. LACHIÈZE-REY,[6] B. LAURENT,[6] M. J. LEHNER,[17] É. LESQUOY,[6] C. MAGNEVILLE,[6] S. L. MARSHALL,[1,2] É. MAURICE,[18] A. MILSZTAJN,[6] D. MINNITI,[1] M. MONIEZ,[5] O. MOREAU,[16] L. MOSCOSO,[6] N. PALANQUE-DELABROUILLE,[6] B. A. PETERSON,[7] M. R. PRATT,[19] L. PRÉVÔT,[18] F. QUEINNEC,[6] P. J. QUINN,[20] C. RENAULT,[6,21] J. RICH,[6] M. SPIRO,[6] C. W. STUBBS,[2,7,11] W. SUTHERLAND,[22] A. TOMANEY,[2,11] T. VANDEHEI,[2,14] A. VIDAL-MADJAR,[9] L. VIGROUX,[6] AND S. ZYLBERAJCH[6]
*Received 1998 March 9; accepted 1998 March 19; published 1998 May 4*

## 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 Letter, the two limits are combined to give a much stronger constraint on the abundance of low-mass MACHOs. Specifically, objects with masses $10^{-7}\ M_\odot \lesssim m \lesssim 10^{-3}\ M_\odot$ 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 (Paczyński 1986), which is the temporary brightening of a background star as the unseen object passes close to the line of sight. The EROS (Expérience de Recherche d'Objets Sombres) and MACHO collaborations have been monitoring the brightnesses of millions of stars in the Magellanic Clouds for several years in order to search for these gravitational microlensing events, and several candidate events have been detected (Alcock et al. 1997; Ansari et al. 1996), with Einstein ring diameter crossing times 33 days $< \hat{t} <$ 266 days. For a MACHO of mass $m$, the average timescale of a microlensing event (assuming a standard spherical halo) is given by (Griest 1991)

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

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 (Alcock et al. 1996; Renault et al. 1998), 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 Renault et al. (1997, 1998). The EROS program 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 3 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 mag in the $V$ band. More than 19,000 images have been processed by using custom-designed fast photometric reconstruction software to produce light curves. None of the 350,000 good light curves exhibit a form that is

[1] Lawrence Livermore National Laboratory, Livermore, CA 94550.
[2] Center for Particle Astrophysics, University of California, Berkeley, CA 94720.
[3] Supercomputing Facility, Australian National University, Canberra, ACT 0200, Australia.
[4] Department of Physics, University of California, Davis, CA 95616.
[5] Laboratoire de l'Accélérateur Linéaire, IN2P3 CNRS, Université Paris-Sud, F-91405 Orsay Cedex, France.
[6] CEA, DSM, DAPNIA, Centre d'Études de Saclay, F-91191 Gif-sur-Yvette Cedex, France.
[7] Mt. Stromlo and Siding Spring Observatories, Australian National University, Weston, ACT 2611, Australia.
[8] Laboratoire de Physique Corpusculaire, Collège de France, Laboratorie Associé au CNRS-IN2P3 (LA 41), F-75231 Paris Cedex 05, France.
[9] Institut d'Astrophysique de Paris, INSU CNRS, 98 bis Boulevard Arago, F-75014 Paris, France.
[10] Kapleyn Astronomical Institute, N-9700 AV Groningen, The Netherlands.
[11] Departments of Astronomy and Physics, University of Washington, Seattle, WA 98195.
[12] Physics Department, University of Notre Dame, Notre Dame, IN 46556.
[13] Universidad de la Serena, Faculdad de Ciencias, Departemento de Fisica, Casilla 554, La Serena, Chile.
[14] Department of Physics, University of California, San Diego, CA 92093.
[15] Laboratoire d'Astronomie Spatiale de Marseille, Traverse du Siphon, Les Trois Lucs, F-13120, Marseille, France.
[16] Centre d'Analyse des Images de l'INSU, Observatoire de Paris, 61 avenue de l'Observatoire, F-75014, France.
[17] Department of Physics, University of Sheffield, Sheffield S3 7RH, England, UK.
[18] Observatoire de Marseille, 2 place Le Verrier, F-13248 Marseille Cedex 04, France.
[19] Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.
[20] European Southern Observatory, Karl Schwarzschild Strasse 2, D-85748 Gärching bei München, Germany.
[21] Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany.
[22] Department of Physics, University of Oxford, Oxford OX1 3RH, England, UK.

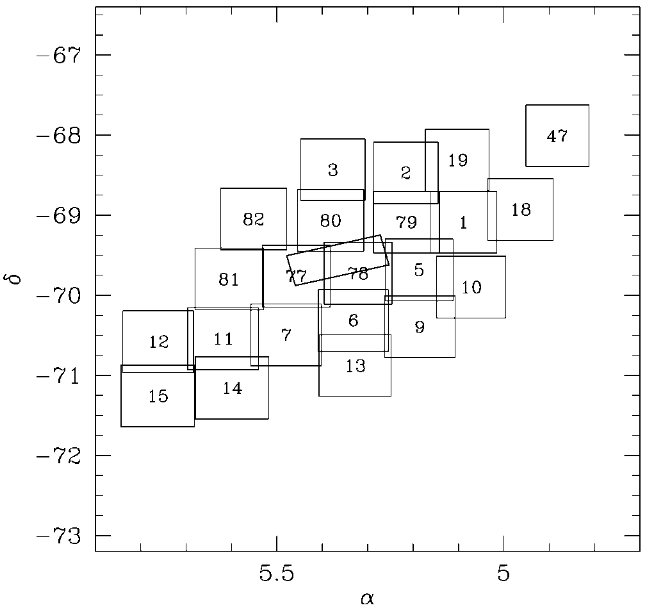


FIG. 1.—The locations (J2000) of the MACHO fields used in this analysis and the location of the EROS field (*unnumbered rectangle*).

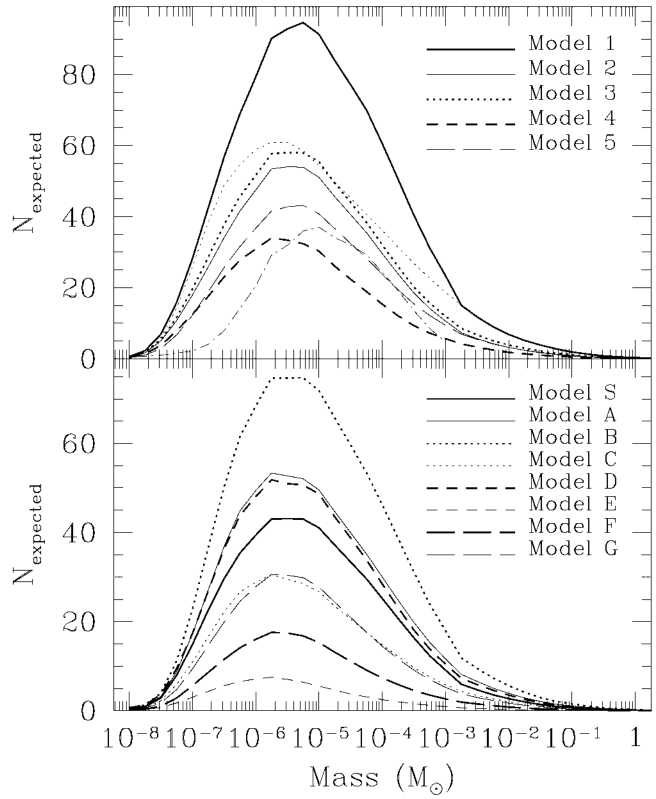


FIG. 2.—Total number of expected events vs. lens mass for the combined MACHO and EROS results. *Top*: the five EROS models. *Bottom*: the eight MACHO models. Also shown in the top plot is the contribution to the results for model 1 from the EROS results (*thin dotted line*) and the MACHO results (*dot-dashed line*). The relative contributions are roughly the same for all models.

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 Alcock et al. (1996) and Lehner et al. (1996). In summary, because the initial observing strategy of the MACHO collaboration was designed to maximize the detection rate for lenses in the brown-dwarf range, $10^{-3}$–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 1 day, there would be at most one or two (if any) magnified points on the light curve. 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 2 years of data (from 1992 July 20 through 1994 October 26) 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 $2.5 \times 10^{-7}\ M_\odot < m < 5.2 \times 10^{-4}\ M_\odot$ cannot 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 true of the following reasons: the MACHO analysis has a very low efficiency (~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 magnifications 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 that 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 Evans (1994), and models 5 and S are simple spherical models, as described in Griest (1991) and Ansari et al. (1996). 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 with 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 (c.l.) upper limit on the fraction of the halo dark matter that 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

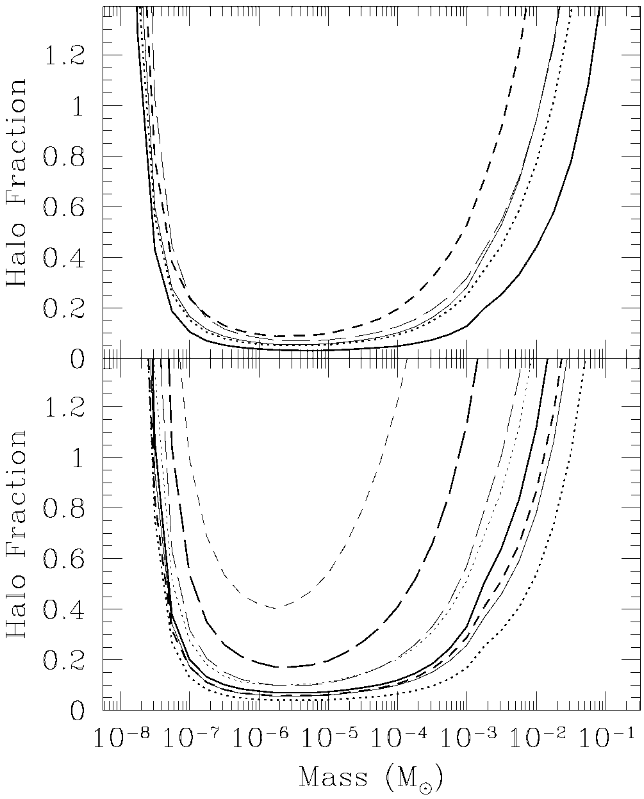


FIG. 3.—Halo fraction upper limit (95% c.l.) vs. lens mass for the five EROS models (*top*) and the eight MACHO models (*bottom*). The line coding is the same as in Fig. 2.

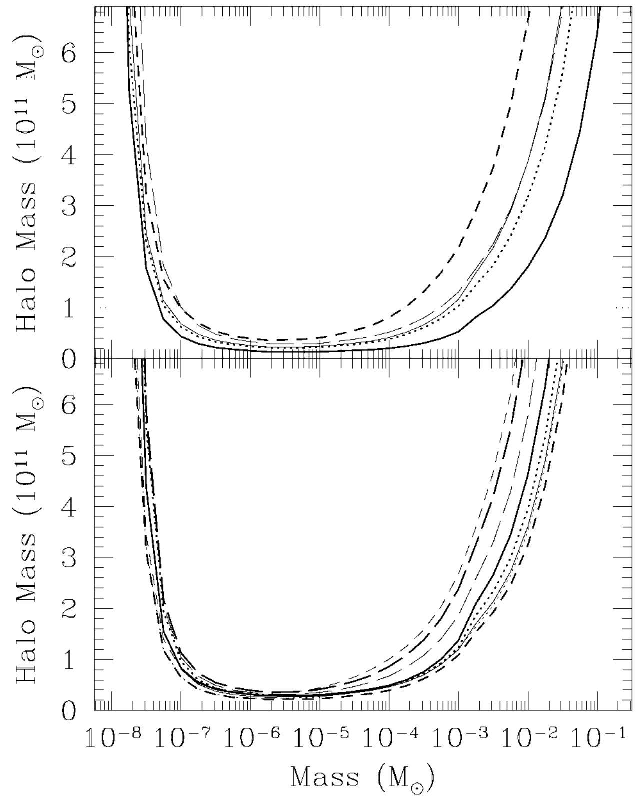


FIG. 4.—Upper limit (95% c.l.) on total halo mass in MACHOs vs. lens mass for the five EROS models (*top*) and the eight MACHO models (*bottom*). The line coding is the same as in Fig. 2.

in the $3.5 \times 10^{-7}\ M_\odot < m < 4.5 \times 10^{-5}\ M_\odot$ mass range. Because we are using δ-function mass distributions, any mass function consisting entirely of masses in the excluded intervals is also eliminated (Griest 1991). Figure 4 shows the amount of halo mass that can be composed of MACHOs of mass *m*, which is a more model-independent limit (Alcock et al. 1996).

TABLE 1
HALO MODEL PARAMETERS

| Model | $\beta$[a] | $q$[b] | $v_0$[c] (km s$^{-1}$) | $R_c$[d] (kpc) | $R_0$[e] (kpc) | $M_{50}$[f] ($10^{11}\ M_\odot$) |
|---|---|---|---|---|---|---|
| 1 …….. | 0.0 | 1.00 | 269 | 5.6 | 7.9 | 4.10 |
| 2 …….. | 0.0 | 1.00 | 203 | 5.6 | 7.9 | 4.10 |
| 3 …….. | 0.0 | 0.75 | 204 | 5.6 | 7.9 | 4.10 |
| 4 …….. | 0.0 | 0.75 | 154 | 5.6 | 7.9 | 4.10 |
| 5 …….. | … | … | 185 | 7.8 | 7.9 | 4.10 |
| S …….. | … | … | 220 | 5.0 | 8.5 | 4.13 |
| A ……. | 0.0 | 1.00 | 200 | 5.0 | 8.5 | 4.62 |
| B ……. | −0.2 | 1.00 | 200 | 5.0 | 8.5 | 7.34 |
| C ……. | 0.2 | 1.00 | 180 | 5.0 | 8.5 | 2.36 |
| D ……. | 0.0 | 0.71 | 200 | 5.0 | 8.5 | 3.74 |
| E …….. | 0.0 | 1.00 | 90 | 20.0 | 7.0 | 0.82 |
| F …….. | 0.0 | 1.00 | 150 | 25.0 | 7.9 | 2.10 |
| G ……. | 0.0 | 1.00 | 180 | 20.0 | 7.9 | 3.26 |

[a] $\beta$ gives the shape of the rotational velocity curve ($v_{\rm circ} \propto R^{-\beta}$).
[b] $q$ is the halo flattening parameter ($q = 1$ represents a spherical halo, $q = 0.7$ represents an ellipticity of E6).
[c] $v_0$ is a normalization velocity (which corresponds to $v_{\rm circ}$ 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.

Here it is shown that for all models considered, a canonical halo mass of $4.1 \times 10^{11}\ M_\odot$ cannot be composed 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 2 more years of LMC data and is also continuing to collect data. However, the EROS short-duration microlensing search was discontinued in 1995 April, and because of the temporal sampling of the new data now being collected (Palanque-Delabrouille et al. 1998), a spike analysis will not be performed.

The EROS collaboration is grateful for the support given to the project by the technical staff at ESO La Silla. The MACHO collaboration is grateful for the support given the project by the technical staff at the Mt. Stromlo Observatory. Work performed at LLNL is supported by the DOE under contract W-7405-ENG-48. Work performed by the Center for Particle Astrophysics personnel is supported by the NSF through AST 9120005. The work at MSSSO is supported by the Australian Department of Industry, Science, and Technology. K. G. acknowledges support from DOE, Alfred P. Sloan, and Cotrell Scholar awards. C. S. acknowledges the generous support of the Packard and Sloan Foundations. W. S. is supported by a PPARC Advanced fellowship. M. J. L. acknowledges support from an IGPP minigrant.

REFERENCES


Alcock, C., et al. 1996, ApJ, 471, 774
———. 1997, ApJ, 486, 697
Ansari, R., et al. 1996, A&A, 314, 94
Evans, N. W. 1994, MNRAS, 267, 333
Griest, K. 1991, ApJ, 366, 412
Lehner, M. J., et al. 1996, in Dark Matter in the Universe, ed. D. B. Cline (Amsterdam: North-Holland), 145
Paczyński, B. 1986, ApJ, 304, 1
Palanque-Delabrrouille, N., et al. 1998, A&A, in press
Renault, C., et al. 1997, A&A, 324, 69L
———. 1998, A&A, 329, 522