

*Letter to the Editor***Not enough stellar mass Machos in the Galactic halo [★]**

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Abstract. We combine new results from the search for microlensing towards the Large Magellanic Cloud (LMC) by EROS2 (Expérience de Recherche d'Objets Sombres) with limits previously reported by EROS1 and EROS2 towards both Magellanic Clouds. The derived upper limit on the abundance of stellar mass MACHOS rules out such objects as an important component of the Galactic halo if their mass is smaller than $1M_{\odot}$.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content – galaxies: Magellanic Clouds – cosmology: dark matter – cosmology: gravitational lensing

1. Research context

The search for gravitational microlensing in our Galaxy has been going on for a decade, following the proposal to use this effect as a tool to probe the dark matter content of the Galactic halo (Paczynski 1986). The first microlensing candidates were reported in 1993, towards the LMC (Aubourg et al. 1993; Alcock et al. 1993) and the Galactic Centre (Udalski et al. 1993) by the EROS, MACHO and OGLE collaborations.

Because they observed no microlensing candidate with a duration shorter than 10 days, the EROS1 and MACHO groups were able to exclude the possibility that a substantial frac-

tion of the Galactic dark matter resides in planet-sized objects (Aubourg et al. 1995; Alcock et al. 1996; Renault et al. 1997; Renault et al. 1998; Alcock et al. 1998).

However a few events were detected with longer timescales. From 6-8 candidate events towards the LMC, the MACHO group estimated an optical depth of order half that required to account for the dynamical mass of the standard spherical dark halo; the typical Einstein radius crossing time of the events, t_E , implied an average mass of about $0.5 M_{\odot}$ for the lenses (Alcock et al. 1997a). Based on two candidates, EROS1 set an upper limit on the halo mass fraction in objects of similar masses (Ansari et al. 1996), that is below that required to explain the rotation curve of our Galaxy¹.

The second phase of the EROS programme was started in 1996, with a ten-fold increase in the number of monitored stars in the Magellanic Clouds. The analysis of the first two years of data towards the Small Magellanic Cloud (SMC) allowed the detection of one microlensing event (Palanque-Delabrouille et al. 1998; see also Alcock et al., 1997b). This single event, out of 5.3 million stars, allowed EROS2 to further constrain the halo composition, excluding in particular that more than 50% of the standard dark halo is made up of $0.01 - 0.5 M_{\odot}$ objects (Afonso et al. 1999). In contrast, an optical detection of a halo white dwarf population was reported (Ibata et al. 1999).

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[★] Based on observations made at the European Southern Observatory, La Silla, Chile.^{**} Alfred P. Sloan Foundation Fellow¹ Assuming the EROS1 candidates are microlensing events, they would correspond to an optical depth six times lower than that expected from a halo fully comprised of MACHOS.

Table 1. Results of microlensing fits to the two new LMC candidates; t_E is the Einstein radius crossing time in days, u_0 the impact parameter, and $c_{\text{bl}}^{R(V)}$ the $R(V)$ blending coefficients.

	u_0	t_E	c_{bl}^R	c_{bl}^V	χ^2/dof	V_J	R_C
LMC-3	0.23	41	0.76	1	208/145	22.4	21.8
LMC-4	0.20	106	1	1	406/150	19.7	19.4

In this letter, we describe the analysis of the two-year light curves from 17.5 million LMC stars. We then combine these results with our previous limits, and derive the strongest limit obtained thus far on the amount of stellar mass objects in the Galactic halo.

2. Experimental setup and LMC observations

The telescope, camera, telescope operation and data reduction are as described in Bauer et al. (1997) and Palanque-Delabrouille et al. (1998). Since August 1996, we have been monitoring 66 one square-degree fields in the LMC, simultaneously in two wide passbands. Of these, data prior to May 1998 from 25 square-degrees spread over 43 fields have been analysed. In this period, about 70-110 images of each field were taken, with exposure times ranging from 3 min in the LMC center to 12 min on the periphery; the average sampling is once every 6 days.

3. LMC data analysis

The analysis of the LMC data set was done using a program independent from that used in the SMC study, with largely different selection criteria. The aim is to cross-validate both programs (as was already done in the analysis of EROS1 Schmidt photographic plates, Ansari et al. 1996) and avoid losing rare microlensing events. Preliminary results of the present analysis were reported in Lasserre (1999). We only give here a list of the various steps, as well as a short description of the principal new features; details will be provided in Lasserre et al. (2000).

We first select the 8% “most variable” light curves, a sample much larger than the number of detectable variable stars. Working from this “enriched” subset, we apply a first set of cuts to select, in each colour separately, the light curves that exhibit significant variations. We first identify the baseline flux in the light curve - basically the most probable flux. We then search for *runs* along the light curve, *i.e.* groups of consecutive measurements that are all on the same side of the baseline flux. We select light curves that either have an abnormally low number of runs over the whole light curve, or show one long run (at least 5 valid measurements) that is very unlikely to be a statistical fluctuation. We then ask for a minimum signal-to-noise ratio by requiring that the group of 5 most luminous consecutive measurements be significantly further from the baseline than the average spread of the measurements. We also check that the measurements inside the most significant run show a smooth time variation.

Table 2. Detection efficiency in% as a function of the Einstein radius crossing time t_E in days, normalised to events generated with $u_0 < 1$, and to $T_{\text{obs}} = 2$ yrs.

t_E	5	11	18	28	45	71	112	180	225	280
ϵ	2	5	11	15	19	23	26	25	18	2.5

The second set of cuts compares the measurements with the best fit point-lens point-source constant speed microlensing light curve (hereafter “simple microlensing”). They allow us to reject variable stars whose light curve differs too much from simple microlensing, and are sufficiently loose not to reject light curves affected by blending, parallax or the finite size of the source, and most cases of multiple lenses or sources.

After this second set of cuts, stars selected in at least one passband represent about 0.01% of the initial sample; almost all of them are found in two thinly populated zones of the colour-magnitude diagram. The third set of cuts deals with this physical background. The first zone contains stars brighter and much redder than those of the red clump; variable stars in this zone are rejected if they vary by less than a factor two or have a very poor fit to simple microlensing. The second zone is the top of the main sequence. Here we find that selected stars, known as blue bumpers (Alcock et al. 1997a), display variations that are always smaller than 60% and lower in the visible passband than in the red one. These cannot correspond to simple microlensing, which is achromatic; they cannot correspond to microlensing plus blending with another unmagnified star either, as it would imply blending by even bluer stars, which is very unlikely. We thus reject all candidates from the second zone exhibiting these two features.

The fourth set of cuts tests for compatibility between the light curves in both passbands. We retain candidates selected in only one passband if they have no conflicting data in the other passband. For candidates selected independently in the two passbands, we require that their largest variations coincide in time.

The tuning of each cut and the calculation of the microlensing detection efficiency are done with simulated simple microlensing light curves, as described in Palanque-Delabrouille et al. (1998). For the efficiency calculation, microlensing parameters are drawn uniformly in the following intervals: time of maximum magnification t_0 within the observing period ± 150 days, impact parameter normalised to the Einstein radius $u_0 \in [0, 2]$ and timescale $t_E \in [5, 300]$ days. All cuts on the data were also applied to the simulated light curves.

Only two candidates remain after all cuts. Their light curves are shown in Fig. 1; microlensing fit parameters are given in Table 1. Although the candidates pass all cuts, agreement with simple microlensing is not excellent.

The efficiency of the analysis, normalised to events with an impact parameter $u_0 < 1$ and to an observing period T_{obs} of two years, is summarised in Table 2. The main source of systematic error is the uncertainty in the influence of blending. Blending lowers the observed magnifications and timescales. While this

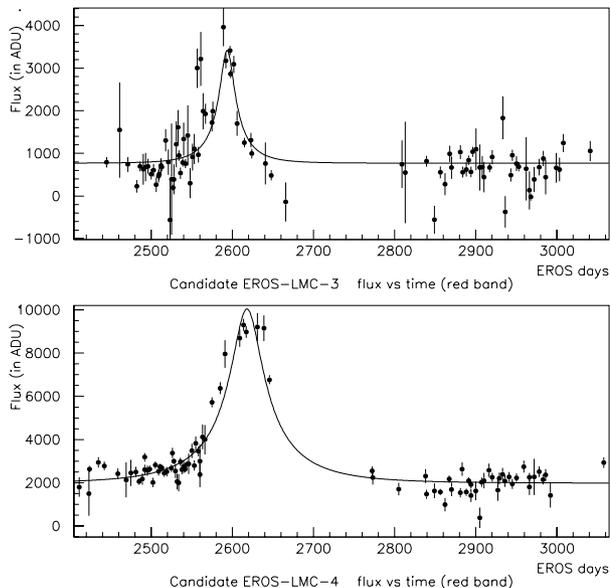


Fig. 1. Light curves of candidates EROS-LMC-3 and 4. The plain curves show the best point-lens point-source fits; time is in days since Jan. 1, 1990 (JD 2,447,892.5).

decreases the efficiency for a given star, the effective number of monitored stars is increased so that there is partial compensation. This effect was studied with synthetic images using measured magnitude distributions (Palanque-Delabrouille 1997). Our final efficiency is within 10% of the naive efficiency.

4. EROS1 results revisited

The two EROS1 microlensing candidates have been monitored by EROS2. The source star in event EROS-LMC-2 had been found to be variable (Ansari et al. 1995), but microlensing fits taking into account the observed periodicity gave a good description of the measurements. Its follow-up by EROS2 revealed a new bump in March 1999, eight years after the first one². This new variation, of about a factor two, was not well sampled but is significant. Therefore, EROS-LMC-2 is no longer a candidate and we do not include it in the limit computation.

5. Limits on Galactic halo Machos

EROS has observed four microlensing candidates towards the Magellanic Clouds, one from EROS1 and two from EROS2 towards the LMC, and one towards the SMC. As discussed in Palanque-Delabrouille et al. (1998), we consider that the long duration of the SMC candidate together with the absence of any detectable parallax, in our data as well as in that of the MACHO group (Alcock et al. 1997b), indicates that it is most likely due to a lens in the SMC. For that reason, the limit derived below

² We thank the MACHO group for communication about their data on this star.

uses the three LMC candidates; for completeness, we also give the limit corresponding to all four candidates.

The limits on the contribution of dark compact objects to the Galactic halo are obtained by comparing the number and durations of microlensing candidates with those expected from Galactic halo models. We use here the so-called “standard” halo model described in Palanque-Delabrouille et al. (1998) as model 1. The model predictions are computed for each EROS data set in turn, taking into account the corresponding detection efficiencies (Ansari et al. 1996; Renault et al. 1998; Afonso et al. 1999; Table 2 above), and the four predictions are then summed. In this model, all dark objects have the same mass M ; we have computed the model predictions for many trial masses M in turn, in the range $[10^{-8} M_{\odot}, 10^2 M_{\odot}]$.

The method used to compute the limit is as in Ansari et al. (1996). We consider two ranges of timescale t_E , smaller or larger than $t_E^{\text{lim}} = 10$ days. (All candidates have $t_E > t_E^{\text{lim}}$.) We can then compute, for each mass M and any halo fraction f , the combined Poisson probability for obtaining, in the four different EROS data sets taken as a whole, zero candidate with $t_E < t_E^{\text{lim}}$ and three or less (alt. four or less) with $t_E > t_E^{\text{lim}}$. For any value of M , the limit f_{max} is the value of f for which this probability is 5%. Whereas the actual limit depends somewhat on the precise choice of t_E^{lim} , the difference ($\lesssim 5\%$) is noticeable only for masses around $0.02 M_{\odot}$. Furthermore, we consider 10 days to be a conservative choice.

Fig. 2 shows the 95% C.L. exclusion limit derived from this analysis on the halo mass fraction, f , for any given dark object mass, M . The solid line corresponds to the three LMC candidates; it is the main result of this letter. (The dashed line includes the SMC candidate in addition.) This limit rules out a standard spherical halo model fully comprised of objects with any mass function inside the range $[10^{-7} - 4] M_{\odot}$. In the region of stellar mass objects, where this result improves most on previous ones, the new LMC data contribute about 60% to our total sensitivity (the SMC and EROS1 LMC data contribute 15% and 25% respectively). The total sensitivity, that is proportional to the sum of $N_* T_{\text{obs}} \epsilon(t_E)$ over the four EROS data sets, is 2.4 times larger than that of Alcock et al. (1997a). We observe that a large fraction of the domain previously allowed by Alcock et al. (1997a) is excluded by the limit in Fig. 2.

6. Discussion and conclusion

After eight years of monitoring the Magellanic Clouds, EROS has a meager crop of three microlensing candidates towards the LMC and one towards the SMC, whereas 27 events are expected for a spherical halo fully comprised of $0.5 M_{\odot}$ objects. These were obtained from four different data sets analysed by four independent, cross-validated programs. So, the small number of observed events is unlikely to be due to bad detection efficiencies.

This allows us to put strong constraints on the fraction of the halo made of objects in the range $[10^{-7} M_{\odot}, 4 M_{\odot}]$, excluding in particular at the 95% C.L. that more than 40% of the standard halo be made of objects with up to $1 M_{\odot}$. The preferred

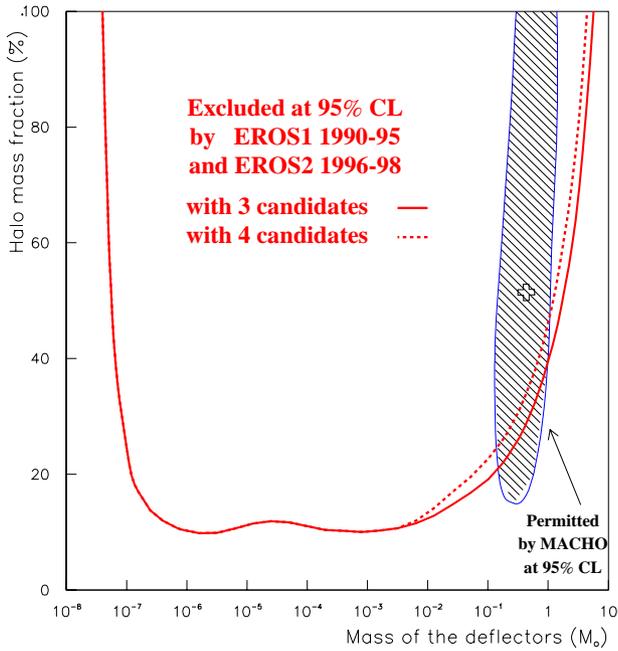


Fig. 2. 95% C.L. exclusion diagram on the halo mass fraction in the form of compact objects of mass M , for the standard halo model ($4 \times 10^{11} M_{\odot}$ inside 50 kpc), from all LMC and SMC EROS data 1990-98. The solid line is the limit inferred from the three LMC microlensing candidates; the dashed line includes in addition the SMC candidate. The MACHO 95% C.L. accepted region is the hatched area, with the preferred value indicated by the cross (Alcock et al. 1997a).

value quoted in Alcock et al. (1997a), $f = 0.5$ and $0.5 M_{\odot}$, is incompatible with the limits in Fig. 2 at the 99.7% C.L. (but see the note added below).

What are possible reasons for such a difference? Apart from a potential bias in the detection efficiencies, several differences should be kept in mind while comparing the two experiments. First, EROS uses less crowded fields than MACHO with the result that blending is relatively unimportant for EROS. Second, EROS covers a larger solid angle (43 deg^2 in the LMC and 10 deg^2 in the SMC) than MACHO, which monitors primarily the central 11 deg^2 of the LMC. The EROS rate should thus be less contaminated by self-lensing that is more common in the central regions - the importance of self-lensing was first stressed by Wu (1994) and Sahu (1994). Third, the MACHO data have a more frequent time sampling. Finally, while the EROS limit uses both Clouds, the MACHO result is based only on the LMC. For halo lensing, the timescales towards the two Clouds should be nearly identical and the optical depths comparable. In this regard, we remark that the SMC event is longer than all LMC candidates from MACHO and EROS.

Finally, given the scarcity of our candidates and the possibility that some observed microlenses actually lie in the Magellanic Clouds, EROS is not willing to quote at present a non zero *lower* limit on the fraction of the Galactic halo comprised of dark compact objects with masses up to a few solar masses.

Note added. While the writing of this letter was being finalised, the analysis of 5.7 yrs of LMC observations by the MACHO group was made public (Alcock et al. 2000). The new favoured estimate of the halo mass fraction in the form of compact objects, $f = 0.20$, is 2.5 times lower than that of Alcock et al. (1997a) and is compatible with the limit presented here. None of the conclusions in this article have to be reconsidered. A detailed comparison of our results with those of Alcock et al. (2000) will be available in our forthcoming publication (Lasserre et al. 2000).

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