PROCEEDINGS OF SCIENCE

Final results from the EROS microlensing search for massive compact objects

M. Moniez[*†]
Laboratoire de l'Accélérateur Linéaire, IN2P3 CNRS, Université Paris-Sud, 91405 Orsay Cedex, France
E-mail: moniez@lal.in2p3.fr

We present the results of the EROS2 search for the hidden galactic matter of the halo through the gravitational microlensing of stars in the Magellanic clouds. Microlensing was also searched for and found in the Milky-Way plane, where foreground faint stars are expected to lens background stars. A total of 67 million of stars were monitored over a period of about 7 years. Hundreds of microlensing candidates have been found in the galactic plane, but only one was found towards the subsample of bright –well measured– Magellanic stars. This result implies that massive compact halo objects (machos) in the mass range $10^{-7}M_{\odot} < M < 5M_{\odot}$ are ruled out as a major component of the Milky Way Halo.

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[*]Speaker.
[†]on behalf of the EROS collaboration.

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1. Introduction

From 1990 to 2003, EROS team has performed a large program of microlensing survey towards the Magellanic Clouds (LMC and SMC), the Galactic center (CG) and the Galactic spiral arms (GSA), as far as 55° longitude away from the galactic center. Gravitational microlensing [12] occurs if a massive compact object passes close enough to the line of sight of a star, temporarily magnifying its light. In the approximation of a single point-like object moving with a relative constant speed in front of a single point-like source, the visible result is an achromatic and symmetric variation of the apparent source luminosity as a function of time. The "lensing time scale" t_E, given by the ratio between the Einstein radius of the deflector and its transverse speed V_T, is the only measurable parameter bringing useful information on the lens configuration:

$$t_E(days) = 78 \times \left[\frac{V_T}{100km/s}\right]^{-1} \times \left[\frac{M}{M_\odot}\right]^{\frac{1}{2}} \times \left[\frac{L}{10\,Kpc}\right]^{\frac{1}{2}} \times \frac{[x(1-x)]^{\frac{1}{2}}}{0.5} \ ,$$

where L is the distance to the source, xL is the distance to the deflector and M its mass. The optical depth τ towards a target is defined as the average probability for the line of sight of a target star to intercept the Einstein ring of a deflector (producing a magnification > 1.34).

2. Observations and data reduction

EROS2 uses a ~ 1 deg^2 CCD mosaic mounted on the MARLY 1 meter diameter telescope installed at the La Silla ESO observatory (see [6] and references therein). We monitored 98 deg^2 in the Magellanic Clouds, 60 deg^2 in the CG, and 29 deg^2 in the GSA. Images were taken simultaneously in two wide passbands. Each field has been measured a few hundred times in each passband. The production of light curves proceeded in three steps : template images construction, star catalog production from the templates, and photometry of individual images to obtain the light curves. Our catalogues contain about 29.2×10^6 objects from the LMC, 4.2×10^6 from the SMC, $20. \times 10^7$ from the CG and 12.9×10^7 from the GSA. After alignment with the catalogue, photometry is performed on each image with software specifically designed for crowded fields, PEIDA (Photométrie et Étude d'Images Destinées à l'Astrophysique) [4].

3. Using the brightest stars to escape the blending problems

Using sophisticated simulations, we found that the optical depth underestimate due to the microlensing magnification underestimate induced by source confusion (blending) is compensated by extra events due to faint stars within the seeing disk of resolved objects. Nevertheless, considering the size of the effects, we decided to consider only the subsample of the brightest stars, that do much less suffer from blending complications, to obtain reliable microlensing optical depth estimates towards the Magellanic clouds and the Galactic center. We then concentrated on the clump red-giant stars towards the CG, and on the stars with $R_{eros} < 18.2$ to 19.7 (depending on the field density) towards the LMC. Another advantage to use these brightest stars is that they also benefit from the best photometric resolution. The philosophy is somewhat different towards the Galactic

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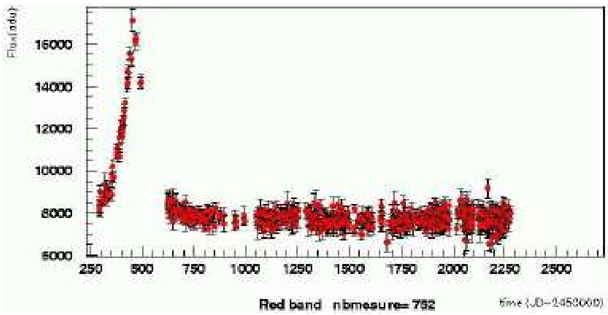


Figure 1: *Light-curve of the SMC microlensing event in the EROS red-passband.*

spiral arms, because of, contrary to the other targets, the distance of the sources is widely distributed and poorly known. We therefore decided to use all the stars for the optical depth estimates, and to define the concept of "catalogue optical depth", that is relative to our specific catalogue of monitored stars. The interpretation of this optical depth requires a careful modelling of the galaxy plane as it results from an average of optical depth on a continuum of source distances. The final sample of light-curves on which we have searched for microlensing then contains respectively 6.05×10^6 and 0.9×10^6 bright stars towards LMC and SMC, 5.6×10^7 clump-giant stars towards the CG and 12.9×10^7 stars towards the GSA.

4. The search for lensed stars

The general philosophy for the event selection is common to all the targets. Details on the analysis of CG, LMC and GSA can be found in [9], [13] and [11].

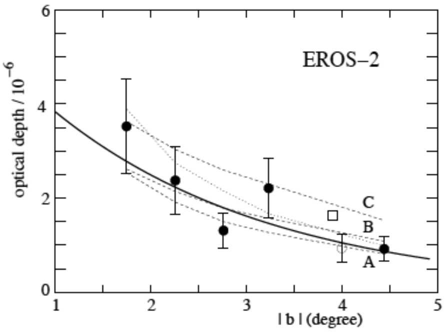
We first searched for bumps in the light curves, that we characterized by their probability to be due to accidental occurrence on a stable star light curve. We select the light curves that have a significant positive fluctuation in both colors with a sufficient time overlap. To reject most of the periodic or irregular variable stars, we remove the light curves that have significant other bumps (*positive or negative*). After this filtering, the remaining light curves can be fitted for the microlensing hypothesis, and the final selection is based on variables using the fitted parameters. We apply criteria devised so as to select microlensing events, keeping in mind that such analysis should also detect events with second order effects such as parallax, binary lens... Specific rejection criteria against background supernovae have also been applied towards the Magellanic clouds. We estimate our detection efficiency using the technique of the superposition of simulated events on experimental light curves from an unbiased sub-sample of our catalogues.

5. Candidate sample

We found 120 events towards the sample of clump-giants of the CG [9], 26 events towards the GSA [11], and only one event [1] (see Fig. 1) towards the bright stellar population of SMC/LMC. With respect to previous EROS publications [3, 10], the number of events towards LMC/SMC has changed. Amongst the reasons are the fact that we now concentrate on the bright stars, and the fact that candidates died because they exhibited another significant bump years after their selection.

6. Discussion. Limits on the abundance of machos

We find that the optical depths towards the CG and the 4 targets in the GSA are in good agreement with the predictions from the galactic models [9, 7] (Fig. 2).



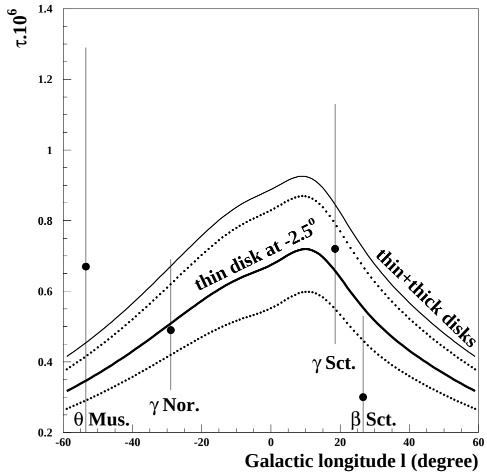


Figure 2: *Measured and expected optical depth as a function of the galactic latitude (up) and of the galactic longitude (right).*

In contrast, we have found only one event towards the Magellanic clouds, whereas ~ 50 events would have been expected if the halo were entirely populated by objects of mass $0.2M_\odot < M < 0.8M_\odot$. We then deduce an upper limit on the contribution of the compact objects to the so-called standard spherical halo (see Fig. 3). This limit can also be expressed in optical depth. In the t_E range favored by the MACHO collaboration, we find $\tau_{lmc} < 0.3 \times 10^{-7}$ *at* 95% *CL*, in clear conflict with the value of the MACHO collaboration, $\tau_{lmc} = 1.2^{+0.4}_{-0.3} \times 10^{-7}$, based on the observation of 17 events [2], but in excellent agreement with the recently published results from the OGLE collaboration [14]. For the SMC, the one observed event corresponds to an optical depth of 1.7×10^{-7}. Taking into account only Poisson statistics on one event, this gives $.085 \times 10^{-7} < \tau_{smc} < 8.7 \times 10^{-7}$ *at* 95% *CL*. This is consistent with the expectations of lensing by objects in the SMC itself [8], $\tau_{smc-smc} \sim 0.4 \times 10^{-7}$. The value of $t_E = 120$ *days* is also consistent with expectations for self-lensing as $\langle t_E \rangle \sim 100$ *days* for a mean lens mass of $0.35M_\odot$. We also note that the self-lensing interpretation is favored from the absence of an indication of parallax in the light curve [5].

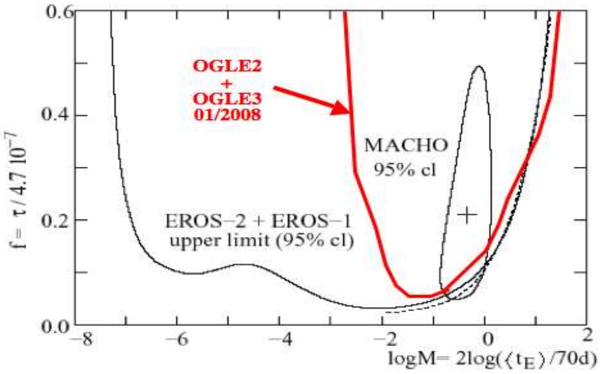


Figure 3: *The solid line shows the* EROS *upper limit on the contribution of compact objects to a standard spherical Galactic halo, as a function of their mass, based on zero observed* LMC *events and assuming that the one observed* SMC *event is not due to halo lensing.*

There are considerable differences between the EROS and MACHO data sets that may explain the conflict. Generally speaking, MACHO uses faint stars in dense fields (1.2×10^7 stars over 14 deg^2) while EROS2 uses bright stars in sparse fields (0.7×10^7 stars over 90 deg^2). As a consequence of the use of faint stars, only two of the 17 MACHO candidates are sufficiently bright to be compared to our bright sample (and the corresponding events occurred before EROS data taking). The use of dense fields by the MACHO group also suggests that the higher MACHO optical depth may be due, in part, to self lensing in the inner parts of the LMC. The contamination of irregular variable objects faking microlensing in low photometric resolution events should also be stronger in the faint sample of stars used by MACHO. As already mentioned, another problem with the use of faint source stars is the large blending effects that must be understood. The experience with the use of faint stars in the Galactic Bulge suggest that the uncertainty induced by the blending effects in such a sample may be underestimated.

7. Conclusions

The EROS and MACHO programs were primarily motivated by the search for halo brown dwarfs of $M \sim 0.07 M_\odot$. EROS has demonstrated its sensitivity to microlensing events, finding microlensing rates compatible with the predictions of the galactic models in the Galactic plane. The lack of events towards the Magellanic clouds clearly indicates that the Galactic hidden matter is not made of compact objects in the mass range $10^{-7} M_\odot < M < 5 M_\odot$. Whatever the source of the disagreement between EROS and MACHO on this subject, we can hope that new data from the OGLE3 , MOA and SUPER-MACHO collaborations will settle the matter.

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