EROS: a Galactic Microlensing Odyssey

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Abstract

The EROS microlensing survey has monitored nearly 100 million stars for seven years, to search for halo brown dwarfs and compact objects in the Galactic disk. In this paper, we review the various EROS observation programs and the corresponding microlensing search results. In particular, based on LMC and SMC observations, EROS excludes a major contribution from compact objects with masses in the range $2 \times 10^{-7} - 1 M_{\odot}$ to the Galactic halo. Less than 25% of the standard halo mass can be made of such objects, while the EROS measured optical depths toward the Galactic spiral arms ($< \tau_{SA} > \simeq 0.43 \times 10^{-6}$) and Galactic bulge ($< \tau_{GC} > \simeq 0.93 \times 10^{-6}$) are compatible with Galactic model predictions if the contribution from an elongated bar in the centre is taken into account.

1 Introduction

EROS (Expérience de Recherche d’Objets Sombres) odyssey started in 1990, when J. Rich and M. Spiro initiated one of the first microlensing surveys, following B. Paczynski suggestion, to search for compact dark halo objects.

The EROS project, a mostly French collaboration involving particle physicists and astrophysicists from DAPNIA, IN2P3 and INSU started LMC and SMC observations at the end of 1990, using photographic plates taken with the ESO Schmidt telescope at La Silla observatory (Chile). Nearly a year later, a dedicated wide field CCD camera mounted on a 40 cm telescope started operations at La Silla. The Schmidt photographic plates where used to search for long duration ($\sim$ days) microlensing events, while the CCD-T40 images provided sensitivity for short duration events.

In 1994, a more ambitious program was approved by the EROS team and the funding agencies in order to disentangle contributions from different Galactic components (disk, bar, halo) to the optical depths. The enlarged EROS collaboration, with Danish and Chilean participation started then the commissioning of EROS 2- MARLY dedicated wide field telescope and camera system. This instrument and EROS 2 observation programs are described in section 3. Section 2 presents the basics of microlensing and compact massive halo object (MACHO) search. In section 4, I describe the EROS 2 LMC and SMC observation programs and microlensing search results. The EROS observation programs toward the Galactic spiral arms and the bulge, as well as the observed optical depths in these directions are presented in section 5.

2 Microlensing basics

It is now rather well established that a large fraction of matter in the universe is in an unknown non luminous form, other than stars, gas and dust. The dynamics of galaxies, in particular
the rotation velocities of stars and gas in spiral galaxies, including the Milky way cannot be explained by the distribution of the visible matter and favours the presence of dark haloes, with masses up to ten times the visible mass. In addition, the baryonic matter density inferred from Big Bang Nucleosynthesis or recent CMB anisotropy measurements is much larger that the visible matter density, implying that dark haloes could be baryonic.

Brown dwarfs, sub stellar objects too light to burn hydrogen, are one of the plausible candidate for baryonic halo dark matter. The massive compact halo objects are very often called MACHOs (Massive Compact Halo Objects). The mass range extends from the evaporation limit \(10^{-7} M_\odot\) to the ignition limit \(0.08 M_\odot\) for brown dwarfs, and extends well above 1 \(M_\odot\) for stellar remnants and black holes. A detailed discussion of various candidates for MACHOs can be found in [Carr 94], [kerins 94] and [Carr 00].

Direct observation of MACHOs is nearly impossible. However, as pointed out by Paczynski in 1986 [Paczynski 86], their presence in the Galaxy may be revealed through their gravitational microlensing effect on background stars.

A massive object \(L\), passing close enough to the line of sight \(OS\) for a star, acts as a gravitational lens and induces a relativistic light deflection. Multiple images of the source are generally produced, well known in case of the lensing of distant galaxies by foreground galaxies or clusters. In the case of Galactic MACHOs, image separation is of the order of \(10^{-3}\) arcsec. The two images can not be resolved, and lensing leads then to an increase of the apparent brightness of the star. This light amplification is simply due to collection by the observer of light in a larger solid angle from the source in the presence of the deflector.

For a point like source \((S)\) and deflector \((L)\), and an observer at \(O\), the The light amplification \(A\) can be expressed as a function of the reduced impact parameter \(u\) :

\[
A = \frac{u^2 + 2}{u \sqrt{u^2 + 4}}, \quad u = \frac{D_{\perp}(OS, L)}{R_E}
\]

and the Einstein ring radius \(R_E\) in the deflector plane can be written as:

\[
R_E^2 = \frac{4GM_L D}{c^2}, \quad D = \frac{D_{OL} D_{LS}}{D_{OS}}
\]

Due to the deflector movement relative to the line of sight, the impact parameter \(u\) is time dependent, and hence is the observed light amplification. The lensing becomes then an observ-able phenomenon.

The amplification time scale is set by the time interval \(t_E = R_E/v_{\perp}\) taken by the deflector to cross the Einstein ring radius, where \(v_{\perp}\) is the projected transverse velocity of the deflector relative the line of sight \(OS\). The time varying reduced impact parameter \(u(t)\) can then be written as a function of \(u_0\), the reduced impact parameter at the time of closest approach \(t_0\):

\[
u^2(t) = u_0^2 + \frac{(t - t_0)^2}{t_E}
\]

For stars in the Large Magellanic Cloud, and deflectors in our Galaxy halo, with a maxwellian velocity distribution at 200 km/s, the average duration is \(\tau \simeq 70\) days \(\times \sqrt{M/M_\odot}\).

Measurable amplification occurs only for well aligned observer, deflector and source systems \((A_{\max} > 1.34\) for \(u_0 < 1\). The lensing probability for a given amplification The optical depth corresponds to the lensing probability with amplification \(A > 1.34\) and can be expressed as the fraction of the sky covered by MACHO’s Einstein disks. The Einstein disk surface is proportional to \(R_E^2\), which is proportional to \(M_L\), whereas the number of deflectors, for a given
total mass is proportional to $M^{-1}_L$. The optical depth $\tau$ is thus nearly independent of the mass of the MACHOs. Typically, $\tau = 0.5 \times 10^{-6}$ for stars in the LMC and for a “standard” halo made of MACHOs ($M_{tot} \approx 4.10^{11} M_\odot$ up to 50 kpc).

This very low lensing probability on one hand ($\sim 10^{-7}$), and the difficulty of distinguishing genuine microlensing events from the background of variable stars make the search for MACHOs a challenging task. The intrinsic properties of microlensing effect is used in background rejection, in particular the symmetry of the light curve, its specific shape and achromaticity. However, the light curve shape is altered when more subtle effect such as the finite size or the parallax effects are taken into account. A discussion of these effects can be found in [Derue 99] and [Rahvar 03]. In the case of binary lenses, the light curve present spectacular and characteristic features when caustic crossing occurs [Dominik 99].

3 EROS-2 instrument and observation program

3.1 EROS2-MARLY instrument

The MARLY telescope (D=1 m, f/5) has been specially refurbished and fully automated for the EROS-2 survey [Bauer 97]. The telescope optics allows simultaneous imaging in two wide passbands $V_{Eros} (\lambda_{peak} \simeq 600 \text{ nm}, \Delta \lambda \sim 80 \text{ nm}), R_{Eros} (\lambda_{peak} \simeq 760 \text{ nm}, \Delta \lambda \sim 80 \text{ nm})$ [Regnault 00] over a one-square-degree field of view. The two focal planes are equipped with CCD cameras, each made of a mosaic of $8 \times 4 \times 2048 \times 2048$ thick CCD’s, covering a total field of $0.7^\circ \times 1.4^\circ$ (right ascension) $\times 1.4^\circ$ (declination). The pixel size is 0.6 arcsec, with a typical global seeing of $<2$ arcsec FWHM. Each camera has more than 32 millions pixels, representing a total of 128 megabytes of image data for each frame.

The EROS2-MARLY telescope-camera system has been installed at La Silla observatory in Chile in spring 1996. Regular operations were started in July 1996, and has been carried out up to February 2003. During these seven years, EROS accumulated more than $\sim 2 \times 10^6 2K \times 2K$ image frames, representing $\sim 15$ terabytes of data. The cumulative image data distribution is shown in figure [1].

3.2 Scientific programs

EROS-2 was primarily designed and optimized to measure microlensing optical depths for different lines of sight through the Galactic disk and halo. Systematic photometric surveys were carried out in several directions, with typical sampling times of a few days. Around 80 fields are being monitored toward the Large Magellanic Cloud (LMC) and 10 fields toward the SMC. A large area in direction of the bulge is also included in our survey (CG, $\sim 150$ fields) as well as 29 fields in the Galactic plane, away from the bulge.

Type I supernovae are being used as standard candles to probe the Universe geometry. EROS has discovered around 60 supernovae in the period 1997-1999. 25 have been spectroscopically identified, of which 20 are of type Ia. The EROS automated SN search has been able to discover $\sim 1 \text{ SN} / 2 \text{ hours observing time, or } \sim 1 \text{ SN} / 10-20 \text{ deg}^2$ with an average redshift of $< z > \sim 0.1$ [Regnault 00].

A small fraction of the EROS telescope time has been used to search for red and white dwarves in the solar neighbourhood through proper motion measurements. The constraints from this survey can be found in [Goldman 02].
3.3 Data management and photometric pipeline

The EROS data is stored at the IN2P3 computing centre (CC-IN2P3) at Lyon (France) where a hierarchical storage system (HPSS) is used. Data files (Images, catalogs, lightcurves ...) management is done using the Oracle relational database, with the help of the ErosDb software written in Java and Tcl. Task scheduling and monitoring for the photometric and lightcurve processing pipeline is also handled by ErosDb. The PEIDA++ C++ class library is the basis for the different photometric, image processing and lightcurve analysis software modules. The standard EROS photometric pipeline [Ansari 96] performs PSF photometry for each of the images using a reference star catalog. This catalog contains star positions and reference flux obtained from a high signal to noise ratio reference image. The reference image is usually obtained by the coaddition of a set of 10 to 20 good quality images. The main steps of processing for a given image frame are: the geometric alignment, PSF photometry with fixed positions and PSF parameters, and photometric alignment. The light curve data base is then updated with the new flux measurement for each of the stars in the reference catalog.

4 Magellanic clouds observations

4.1 SMC

Ten fields, representing $8.6 \text{deg}^2$ over the Small Magellanic Cloud has been monitored by EROS, with exposure times ranging from 5 to 15 minutes. Figure 2 (left) shows the field positions on the sky. The latest published analysis correspond to five years SMC data (July 1996 - March 2001) and $5.2 \times 10^6$ light curves with $\sim 400 - 500$ images in each of the two EROS pass bands (B,R) [ErosSMC 03]. Four microlensing (SMC-1,2,3,4) candidates has been found in this anal-

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1More information available from the CC-IN2P3 web site [http://webcc.in2p3.fr/]
2PEIDA++ documentation is available from [http://www.lal.in2p3.fr/recherche/eros/PeidaDoc/index.html]
Their light curves are shown on figure 2 (right). The montecarlo estimated efficiencies for events with $u_0 < 1.5$ and normalised to the 5 years observation period reaches a maximum of $\sim 14\%$ for event time scales of $t_E \sim 100$ days, and drops to less than $3\%$ for time scales $t_E$ below 10 days or above 1300 days.

SMC-1 has a duration $t_E \sim 101$ days and corresponds probably to a deflector in SMC itself. The three other candidates (SMC-2,3,4) are long duration events with $t_E \sim 390, 612, 243$ days. These events are probably misidentified variable stars or due to self-lensing within the cloud. Indeed, deflectors in the halo would need to have supersolar masses to account for such durations.

4.2 LMC

EROS has monitored 89 fields covering the large magellanic cloud. The published analysis has been carried out on 39 $\text{deg}^2$ well sampled fields, using data from the three first years. A total of $25.5 \times 10^6$ light curves with 100-200 measurements have been analysed, with selection efficiencies ranging from $5\%$ ($t_E \sim 5$ days) to $20\%$ ($t_E \sim 100$ days). The characteristics of the four microlensing candidates are shown in table 1. Detailed description of the two years and three years analysis can be found in [ErosLMC 00] and [Milsztajn 00].

|     | $u_0$ | $t_E$ | $\chi^2$/dof | $V_J$ |
|-----|-------|-------|--------------|------|
| LMC-3 | 0.21  | 44    | 219/143      | 22.4 |
| LMC-5 | 0.58  | 24    | 658/176      | 19.2 |
| LMC-6 | 0.38  | 36    | 682/411      | 21.3 |
| LMC-7 | 0.23  | 33    | 722/356      | 22.7 |

Table 1: Characteristics of LMC microlensing candidates
4.3 halo constraints

The combined EROS constraints on the contribution of compact objects to the galactic halo is shown in figure 3. Massive compact objects with masses in the range $2 \times 10^{-7} M_\odot$ and $1 M_\odot$ cannot represent more than 25% of the halo mass, in the case of a standard spherical, isothermal Galactic halo, encompassing $4 \times 10^{11} M_\odot$ out to 50 kpc. These limits have been obtained in a conservative approach, where all the candidate microlensing events are attributed to deflectors in the halo, and taking into account the corresponding event durations.

However, it should be noted that SMC and LMC microlensing candidates have different event duration distribution and can hardly be due to the same lens population. In the case of a standard halo, the optical depth toward SMC would be slightly larger than toward LMC ($\tau_{SMC} \sim 1.4 \tau_{LMC}$). Based on MACHO optical depth and event duration distribution from MACHO, we would expect three short duration events ($t_E > 30$ days) where none is observed.

Figure 3: Exclusion diagram at 95% C.L. for the standard halo model ($4 \times 10^{11} M_\odot$ inside 50 kpc). The thick line is the combined limit from five different EROS data sets and analysis [ErosSMC 03]

5 Galactic plane observations

5.1 Spiral arms (GSA) microlensing search

The 29 Galactic plane fields (GSA) are grouped in four directions ($\beta_{Sct}, \gamma_{Sct}, \gamma_{Nor}, \theta_{Mus}$) and cover a wide range of longitude. The three year data set discussed here contains 9 million light curves: 2.1 towards $\beta_{Sct}, 1.8$ towards $\gamma_{Sct}, 3.0$ towards $\gamma_{Nor}$ and 2.1 towards $\theta_{Mus}$. The analysis corresponds to data taken from July 1996 to November 1998, except for $\theta_{Mus}$ which has been monitored since January 1997. Detailed description of the analysis can be found in [ErosBS 01]. Seven light curves satisfy all the selection criteria and are labelled GSA1 to 7. Five events have been found toward $\gamma_{Sct}$ with durations $t_E \sim 6, 24, 59$ and 72 days and two events with...
$t_E \sim 72$ and 98 days toward $\gamma$Nor. Two of the most interesting events (GSA-1 and GSA-5) are shown in figure 4.

We have computed the expected optical depths using a three component model (bar, disk, halo) to represent deflector distribution in the Galaxy. An average distance of $\sim 7$ kpc has been used in this analysis. Figure 5 shows the expected optical depth up to 7 kpc at galactic latitude $b = -2.5^\circ$ as a function of the Galactic longitude, for two sets of bar parameters. The corresponding values for the four targets are also indicated on figure 5.

We find an estimated optical depth averaged over the four directions

$$< \tau_{GSA} > = 0.43^{+0.24}_{-0.11} \times 10^{-6}$$
in agreement with expectations. However, as shown on figure 5, optical depths or limits computed for each direction indicates a small excess toward $\gamma_{Sct}$ direction (mainly due to short events), compared to other directions.

5.2 galactic bulge fields

2.3 million stars, observed on 15 best sampled Galactic bulge fields out of 82, have been analysed, using the first three years data. Each light curve has a total of 200 to 400 measurement points. Detailed description of the analysis can be found in [ErosBulge 03]. The search for microlensing events has been restricted to clump red giant stars, in order to minimize the blending effect and yielded a total of 16 candidates, two of which are long duration events. We find an optical depth

$$\tau_{CG} = (0.94 \pm 0.29) \times 10^{-6}$$

well in agreement with model predictions. Figure 6 shows one of the EROS bulge events, as well as optical depths measured by different microlensing surveys toward the Galactic bulge.

![Bulge Optical Depths](image)

Figure 6: Left: One of the EROS microlensing candidates toward the Galactic bulge. Right: Measured bulge optical depths, from various groups

6 Conclusion

The EROS2-MARLY instrument has been successfully operated in La Silla for seven years, from July 1996 to February 2003, producing a huge amount of photometric data for microlensing and variable stars studies toward Magellanic clouds and in the Milky Way. The microlensing searches performed on less than the total available data rules out significant contribution of MACHOs in mass to the standard halo, and constrains the mass distribution in the Galaxy. However, although the observations has been stopped, the analysis of complete EROS data set should improve significantly these constraints.
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