Probing Galactic structure using micro-lensing with EROS-2

R. Ansari
EROS collaboration

Laboratoire de l’Accélérateur Linéaire
IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex

Abstract

EROS has been monitoring few million stars in the Magellanic clouds, as well as toward the Galactic bulge and spiral arms since 1996, to search for microlensing events. In this paper, we present briefly the EROS setup and scientific program and discuss the results obtained from our observations in four directions in the Galactic plane, away from the bulge. Seven light curves, out of 9.1 million stars observed in these directions show luminosity variations interpreted as due to microlensing. The averaged estimated optical depth \( \bar{\tau} = 0.45^{+0.24}_{-0.11} \) is compatible with expectations from simple Galactic models. Nonetheless a small excess of short time-scale events may be present in the direction closest to the Galactic center.

1 Introduction

Following Paczynski’s 1986 proposal, several groups (EROS, MACHO, OGLE) started systematic photometric surveys in the beginning of the ’90s to search for microlensing events due compact objects (stars, brown dwarfs) present in the Galactic disk, and possibly in the halo. Since the first discoveries [1, 2, 3], hundreds of events have been detected in the Galactic bulge direction, while only a few events (\( \simeq 10–20 \)) have been observed toward the Magellanic clouds.

The event rates observed toward the Magellanic clouds (LMC, SMC) are significantly smaller than the expected rate from a standard halo, made of brown dwarves (MACHO’s). On the contrary, the large number of events seen in the direction of the bulge [4, 5] have led to the hypothesis of a barred structure for the Galaxy. This possibility, suggested by de Vaucouleurs in 1964, is now supported by different observations: bulge micro-lensing rate, photometric measurements [6], gas and star kinematics [7, 8] and star counting [9].

In order to disentangle contributions from different Galactic components (disk, bar, halo), EROS decided to design and build a second generation apparatus in 1994. We briefly describe this setup and our scientific program in the next section.
2 EROS-2 experimental setup and observation program

The MARLY telescope (D=1 m, f/5) has been specially refurbished and fully automated for the EROS-2 survey (Bauer et al. 1997). The telescope optics allows simultaneous imaging in two wide pass-bands $V_{Eros}$ ($\lambda_{peak} \simeq 560$ nm), $R_{Eros}$ ($\lambda_{peak} \simeq 760$ nm) over a one-square-degree field of view. The two focal planes are equipped with CCD cameras, each made of a mosaic of 8 ($2 \times 4$) Loral $2048 \times 2048$ thick CCD's, covering a total field of $0.7^\circ$ (right ascension) $\times 1.4^\circ$ (declination). The pixel size is 0.6 arcsec, with a typical global seeing of 2 arcsec FWHM.

This telescope-camera system has been in operation at the European Southern Observatory in La Silla, Chile, since June 1996. The observations are carried out for three main scientific programs. Type I supernovae are being used as standard candles to probe the Universe geometry. EROS participate in this effort through a powerful automated supernovae search ($z \sim 0.1$). Around 60 SN have been discovered in the period 1997-1999. We were able to determine the type for $\sim 25$ SN, of which 20 have been identified as type Ia supernovae. The mean discovery rate is around 1 SN / 2 hours observing time ($\sim 1$ SN$/10 - 20$ deg$^2$).

A small fraction of the EROS telescope time is used to search for Red dwarves through proper motion detection, while most of the telescope time is devoted to photometric surveys for microlensing searches. Systematic photometric surveys are being 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.

3 EROS-2 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 observation period for these fields span July 1996 - November 1998, except for $\theta_{Mus}$ which has been monitored since January 1997.

The first steps of the event selection criteria require the presence of a single bump, simultaneous in two colors. To reject variable stars, We require stability of the light curve outside the bump and compatibility with the expected microlensing shape (cuts on $\chi^2$ from microlensing fit).

Detailed description of EROS GSA data set and event selection can be found in [10, 11].

Seven light curves satisfy all the selection criteria and are labeled GSA1 to 7. The characteristics for these seven (7) microlensing events can be found in table 1.

GSA1 is a large magnification event, while GSA2 exhibit periodic luminosity modulation during amplification. Figure 1a shows the GSA2 light curve which is interpreted as a microlensing effect on a binary source system.

The efficiency of the selection process has been computed using montecarlo generated light curves, where randomly generated microlensing effect where superimposed on a representative sample of observed light curves.

We have computed the expected optical depths using a three component model (bar, disk, halo) to represent deflector distribution in the Galaxy. The distance distribution of the source stars is poorly known. Different studies indicate distances in the range 5-10 kpc [12, 13]. An average distance of $\sim 7$ kpc has been used in this paper. Figure 1b shows the expected optical depth as a function of the Galactic longitude, for two sets of bar parameters at $b = 2^\circ.5$. For a
Table 1: Characteristics of the 7 microlensing candidates and contribution to the optical depth.

| Candidate | GSA1 | GSA2 | GSA3 | GSA4 |
|-----------|------|------|------|------|
| field     | $\gamma$ Sct | $\gamma$ Nor | $\gamma$ Nor | $\gamma$ Sct |
| $\alpha$ (h:m:s) | 18:29:09.0 | 16:11:50.2 | 16:16:26.7 | 18:32:26.0 |
| $\delta$ (d:m:s) | -14:15:09 | -52:56:49 | -54:37:49 | -12:56:04 |
| $R_{EROS}$ - $V_{EROS}$ | 17.7 - 20.7 | 17.8 - 19.4 | 17.5 - 18.6 | 17.1 - 17.9 |
| $\Delta t = R_{E}/V_{T}$ (days) | 73.5 ± 1.4 | 98.3 ± 0.9 | 70.0 ± 2.0 | 23.9 ± 1.1 |
| Max. magnification | 26.5 ± 0.6 | 3.05 ± 0.02 | 1.89 ± 0.01 | 1.72 ± 0.02 |
| $\chi^2$ of best fit | 185.7/163 | 551/425 | 445/427 | 337/195 |
| contribution to $\tau$ $(\times 10^6)$ | 0.51 | 0.15 | 0.12 | 0.30 |

| Candidate | GSA5 | GSA6 | GSA7 |
|-----------|------|------|------|
| field     | $\gamma$ Sct | $\gamma$ Sct | $\gamma$ Sct |
| $\alpha$ (h:m:s) | 18:32:12.0 | 18:33:56.7 | 18:34:10.0 |
| $\delta$ (d:m:s) | -12:55:16 | -14:33:52 | -14:03:40 |
| $R_{EROS}$ - $V_{EROS}$ | 17.9 - 19.9 | 17.2 - 18.5 | 17.5 - 18.7 |
| $\Delta t = R_{E}/V_{T}$ (days) | 59.0 ± 5.5 | 37.9 ± 5.0 | 6.20 ± 0.50 |
| Max. magnification | 1.71 ± 0.03 | 1.35 ± 0.02 | 2.70 ± 0.30 |
| $\chi^2$ of best fit | 122/186 | 104/170 | 87 / 181 |
| contribution to $\tau$ $(\times 10^6)$ | 0.44 | 0.35 | 0.22 |

given target an estimation of the optical depth (or a limit) can be computed using the expression:

$$\tau = \pi/2 \times 1/(N_{obs} T_{obs}) \sum_{events} \Delta t/\epsilon(\Delta t)$$

where $N_{obs}$ is the number of monitored stars and $T_{obs}$ the duration of the search period. The corresponding values for the four targets are also indicated on figure 1.

4 Conclusion

We find an estimated optical depth averaged over the four directions

$$\bar{\tau} = 0.45^{+0.24}_{-0.11} \times 10^{-6}$$
in agreement with expectations. However, as shown on figure 1, optical depths or limits computed for each direction indicates a small excess of events toward $\gamma_{Sct}$ direction, compared to other directions.

Provided that this is not due to a statistical fluctuation, the shorter event time scale toward $\gamma_{Sct}$ favors an explanation based on an increased contribution from the bar. A significant difference in the source stars distance between different targets is another plausible explanation for the observed excess, $\gamma_{Sct}$ stars may be located at a larger distance, compared to other directions.

A larger number of events, with independent source stars distance determination will help in providing a more reliable explanation.
Figure 1: a: Light curve for candidate GSA2 ($V_{Eros}$), b: Expected optical depth ($\times 10^6$) up to 7 kpc for different components of the Milky Way. Estimated optical depths (or upper limits) for the four monitored directions are also shown.
References

[1] Aubourg, E. et al. (EROS Coll.) 1993, Nature, 365, 623
[2] Alcock, C. et al. (MACHO Coll.) 1993, Nature, 365, 621
[3] Udalski, A. et al. (OGLE Coll.) 1993, Acta Astronomica, 43, 289
[4] Udalski, A. et al. (OGLE Coll.) 1994, Acta Astronomica, 44, 165
[5] Alcock, C. et al. (MACHO Coll.) 1997, ApJ, 479, 119
[6] Dwek, E. et al. 1995, ApJ, 445, 716
[7] Weiner B.J. and Sellwood J.A., in astro-ph/9904130, 1999
[8] Zhao, H. Spergel D.N., Rich R., 1996, MNRAS, 282, 175
[9] Stanek, K.A. et al. (OGLE Coll.) 1994, ApJ, 429, L73
[10] Derue, F. Ph.D. Thesis, F. 1999, LAL
[11] Derue, F. et al. (EROS Coll.) 1999, A&A, in press
[12] Mansoux, Ph.D. Thesis, F. 1997, LAL