First results from the EROS-II microlensing experiment

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Abstract.

EROS-II is a second generation microlensing experiment. The experimental setup, in operation at the European Southern Observatory (ESO) at La Silla (Chile) since mid-1996 is briefly described together with its scientific objectives. The first results from our microlensing searches towards the Small Magellanic Cloud (SMC) and the Galactic Plane are presented. We also give some results from a dedicated campaign which took place in 96-97, and aimed at studying magellanic Cepheids systematically. We conclude by an overview of the semi-automated supernovæ search.

1. Introduction

The microlensing effect was proposed ten years ago (Paczynski 1986) as a unique experimental signature of MACHOs. Dark compact baryonic objects (MACHOs) are plausible components of the galactic dark matter. The flux of an observed star is gravitationally deflected if one of these objects passes close to the line of sight. Because the image distortion is undetectable, one is left with a transient magnification of the total flux. Under the simplifying assumption of a point-like deflector in uniform motion and static point-like source and observer, the time variation of the apparent source luminosity has a universal, time-symmetric and achromatic shape. Its time scale $\Delta t$, defined as the ratio between the deflector’s transverse speed ($v_T$) and a characteristic length of the phenomenon, the Einstein radius, is the only observable carrying physical information. It may be expressed as

$$\Delta t (\text{days}) = 39 \left( \frac{v_T}{100 \text{km.s}^{-1}} \right)^{-1} \sqrt{\frac{M}{M_\odot}} \sqrt{\frac{L}{10 \text{kpc}}} \sqrt{x(1-x)}$$

where $L$ is the distance to the source, $xL$ the distance to the deflector and $M$ its mass. The observable characterizing the event rate is the optical depth, denoted $\tau$, defined as the probability for observing a star being amplified by a factor greater than or equal to 1.34.

1on behalf of the EROS-II Collaboration
This approximation may be violated in several ways, most of them being useful in breaking (some of) the degeneracy on the inferred physical or geometrical parameters extracted from the events. Among these, the deflector may be binary, leading to singularities in the amplification known as caustic crossing. The Earth is rotating around the Sun; the source or the deflector may be orbiting as well. These orbital motions may distort the light curve, leading to observable effects known as parallax and “xallarap” in the first 2 cases. These are discussed in more details in D. Bennett 1999.

Few years after B. Paczynski’s proposal, few microlensing amplification of stars were observed in two different directions, the LMC (Alcock 1993, Aubourg 1993) and the Galactic Bulge (Udalski 1993). This field has now entered a more quantitative era. EROS-I has isolated 2 candidates over 3 years of running (Ansari 1996). The Macho collaboration has taken data from 1993 until now and has a handful microlensing candidates towards LMC, and several hundreds towards the Bulge (Alcock 1999). An upgraded version of OGLE is now running, and gave about 40 alerts towards the Bulge (Udalski 1997).

The observed optical depth towards LMC indicate a total halo MACHO mass fraction within a factor of two from the total required to explain the Galactic rotation curve. The combined null result from the search for short duration...
events by EROS-I and Macho exclude a significant contribution of objects in the mass interval $[10^{-7}, 10^{-3}]M_\odot$, as shown on figure (Alcock 1998). In addition the rather long time scales associated with the observed events indicate large lens masses, which is difficult to accommodate with known stellar populations.

To address these questions, EROS started as early as 1993 to build a new apparatus, which started observations in June 1996. We present our new instrument and first results of some of its programs in this contribution.

2. The experiment

The EROS-II instrument is a 1m diameter f/5 Ritchey-Chretien telescope, the MarLy, previously used in the French Alps until the mid-80s. It has been specially refurbished and automated in view of a microlensing survey. It is in operation at the European Southern Observatory at La Silla (Chile) since July 1996. EROS-II should be running until 2002.

The optics includes a dichroic beam splitter allowing simultaneous observations in two wide pass-bands (a blue one, $V_{EROS}$ and a red one, $R_{EROS}$). The field of the instrument is observed in each band by a mosaic of $2 \times 4$ Loral $2k \times 2k$ pixels thick CCDs. The mosaics cover $0.7^\circ(\alpha) \times 1.4^\circ(\delta)$ (0.6 arcsec per pixel). The median seeing (FWHM) is about 2. arcsec. CCDs from each mosaic are readout in parallel by DSPs. The total readout time is 50s. The data acquisition is controlled by two VME crates (one per camera) which transfer images to Alpha stations where flat-fielding, quality check and archiving onto DLTs are performed. Images are finally sent for analysis to the CCIN2P3 in Lyons. We are also developing an alert capability by monitoring on site, the day following the observation, a sample of stable stars from the microlensing fields. This effort is presently limited by the building of the stable stars database; up to now 5 alerts have been announced.

EROS-II is primarily aimed at the search for microlensing events. We do this in several directions: the Magellanic Clouds (60 fields for the Large, 10 for the Small), the Galactic Center (67 fields) and 4 areas within the Galactic Plane (≈ 6 fields each). We are currently giving the highest priority to the microlensing search in new lines of sight (the Small Magellanic Cloud and the Galactic Plane), from which we present some preliminary results. We also address other cosmologically important programs, such as a systematic study of Cepheids, a search for high proper motion stars and a semi-automated supernovae search. These programs use images from different regions in the sky; each night the schedule optimizes the observational conditions for each program.

3. Microlensing towards SMC

3.1. The 1st year analysis

The analysis of the SMC data from our first running year is published in Palanque-Delabrouille 1998. The SMC was observed from July 1996 to February

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1997 and then after July 1997 (our analysis includes data up to August 1997). A hundred images of each field are usable for subsequent analysis. In total more than \(5 \times 10^6\) light-curves could be analyzed. They were searched for microlensing events. This selection is described in Palanque-Delabrouille 1998. The cuts are designed to select light curves with a unique and achromatic magnification, a sufficient S/N ratio and no known variable star contamination. The global selection efficiency is about 15%. In our data 10 light-curves passed all cuts and where checked visually, one being finally selected: it is shown on figure 2. This event has also been seen by the Macho Collaboration (Alcock 1997). The amplified star is a blend of two stars with flux ratios of 70% and 30%, only the brightest of these two stars is amplified. EROS also reported a periodic modulation of the combined flux with a period of 5.128 days and an amplitude of about 3% of the brightest flux.

Using a simulation to compute our efficiency we also reported a first measurement of the Galactic halo optical depth \(\tau\) towards SMC: \(\tau \simeq 3.3 \times 10^{-7}\). Comparisons with several halo models show that this sole event contributes by about 40% of the optical depth due to the halo of our Galaxy. The event duration implies a most probable halo deflector mass of \(2.6^{+0.3}_{-0.2} M_\odot\), which would make it improbable as a brown dwarf. The absence of parallax effect in this long duration event tends to imply either a heavy halo lens (a few \(M_\odot\)) or a light (\(\leq 1 M_\odot\)) deflector near the source. In the latter case, we have derived \(\tau_{SMC-SMC} \simeq 1.3 \times 10^{-7}\) with basic assumptions on the SMC structure (Palanque-Delabrouille 1998).
3.2. The SMC-98-1 Binary event

On 25 May 1998, the Macho collaboration sent an alert towards SMC. At that time, EROS-II was shutting down for a planned technical maintenance (May 26th - June 17th). After their observation on June 8th of a dramatic increase in luminosity, interpreted as caused by a caustic crossing, it became clear that this event was induced by a binary lens. A second caustic crossing was predicted to occur around Jun 18th by several groups, including ourselves (using public data from the PLANET group). Due to the importance of this event, a high fraction of our observing time was immediately dedicated to observe this event during the first days after we restarted. As shown on figure 3, we were lucky to observe in great details the end of the 2nd caustic crossing. Using this data alone, we could extract a limit on the caustic crossing time, which together with public data from MACHO enabled us to already put interesting constraints on the lens location, indicating only a 10% likelihood for the deflector being a halo object (Afonso 1998). This was soon confirmed by other groups with much more confidence (see e.g. Bennett 1999 and references therein).

3.3. Perspectives

EROS-II has up to now observed two microlensing events towards SMC. We have obtained firm indications that the deflector causing them are both lying inside the SMC. The possibility for self microlensing inside the Magellanic Clouds receives therefore a strong support, in the case of the SMC. We are still continuing.
Figure 4. Map of our Galactic fields (galactic coordinates, latitude is in degree and longitude in hour). The shaded area represents the shape of the Galaxy. We have indicated our Galactic Center fields (CG) and the 4 zones searched for microlensing outside the Center (GS & BS - \( \gamma \) and \( \beta \) Scuti, GN - \( \gamma \) Normæ and TM - \( \theta \) Muscæ).

the data taking towards both Clouds. The analysis of data from our 2nd year towards SMC is near completion, and of course we are pushing hard the analysis of our LMC data (more than 5 times more data than SMC). Within the next year, we should be able to do a direct comparison between the LMC and SMC optical depths, which is important both for constraining Galactic halo models and elucidating the nature of the lenses.

4. Microlensing towards the Galactic Plane

Measuring optical depths in various directions in the Galactic Plane would help constraining the different Galactic components to the Bulge and LMC or SMC optical depths. We chose several directions to look at, grouped respectively near galactic longitudes of 25° (5 fields), 30° (6 fields), 310° (6 fields) and 320° (12 fields). They are indicated in figure 4. Exposures lie between 2 and 3 min, and are optimized to maximize the number of fields in a given observing time, while not reducing the precision of each measurement (see Mansoux 1997). The first images taken in these directions showed that we were able to monitor about 10 million stars in these directions, 50% of these with a photometric precision better than 10%. The color-magnitudes from our fields were analyzed qualitatively with the help of a simulation of the evolution of a star population. They are found in rough agreement with what is expected from 10^8 year old stars located at 6 to 8 kpc (within 10% ) and a reasonable reddening (Mansoux 1997). Sources lying
in such a rather small distance range is essential for understanding microlensing events.

We have analyzed our data towards each 4 directions, up to the beginning of 1998, which correspond to an average of 90 measurements per star. The light curves were searched for microlensing using a similar selection than that used in the SMC analysis. This analysis, summarized on table 1, produced 3 candidates (Derue 1999). Their duration is on average longer than those of the detected

Table 1. Summary of the microlensing search in the Galactic Plane

| Direction Zones | Scutum | Norma | Musca |
|-----------------|--------|-------|-------|
|                 | BS     | GS    | GN    | TM    |
| Fields          | 6      | 5     | 12    | 6     |
| Measurements    | 80     | 80    | 100   | 90    |
| # stars         | 1.7 $10^6$ | 1.5 $10^6$ | 2.3 $10^6$ | 1.6 $10^6$ |
| Distance (kpc)  | 6.5 ± 0.8(?) | 6.5 ± 0.8 | 8.0 ± 0.6(?) | ? |
| Candidates      | 1      | 0     | 2     | 0     |
| Durations (days)| 73     | -     | 98& 72 | -     |
| Optical depth   | 0.5 $10^{-6}$ | 0.56 $10^{-6}$ | -     |

Bulge events (80 and 30 days respectively). This may be explained as follows. For the directions examined here, the lenses are located in the disk and have therefore a slow transverse motion (≈ 40 $kms^{-1}$ - smaller than the disk/bulge relative transverse velocity). The light curves of our candidates are shown on
Figure 6. GSA-2 light curve. Superimposed onto the data point is a fitted curve for a binary source (50 days orbital period). In the zoom around the peak one may compare with the best fit for a static source.

Figure 7. GSA-3 light curve. Superimposed onto the data point is a fitted standard microlensing curve.
figure 5 to 7. These two events are peculiar. GSA-1 is a high amplification event, but neither blending nor parallax effects are seen. GSA-2 presents non-standard features, which are most probably explained by assuming that the source star lies in an orbiting binary system. This orbital motion modulates the line-of-sight (the “xallarap” effect). We have two satisfactory fits to the data, one with a period of $53 \pm 5$ days and one with $95 \pm 10$ days. We have computed the observed optical depths using preliminary efficiency calculation, uncorrected for blending (for which a better knowledge of the stellar population is required). These roughly agree with our expectations from simple Galactic models (Mansoux 1997). After these promising results, these directions are still monitored, in order to increase our statistics. We did also some observations in order to improve our knowledge of the source stars (nature, distance). We hope within the duration of the experiment to be able to extract from these directions valuable informations which would help understanding Galactic dynamics as well as microlensing results towards the other directions (the Bulge and the Clouds).

5. Magellanic cepheids

EROS-I reported a possible metallicity effect on the period-luminosity-color relation for SMC and LMC cepheids (Sasselov 1997). We pursued in 1996-7 a specific program in order to study this effect more accurately. Two fields in the center of LMC and two in that of SMC were imaged each night. These fields partially overlap those covered by the EROS-I CCD experiment. At the end, 110-160 images per field entered the analysis. The photometric reduction followed the same path as our microlensing images. The resulting light curves were searched for periodic variations. Cepheids were subsequently isolated using cuts in the C-M and Period-Luminosity diagrams, and finally a visual selection. Our new sample contains about 300 cepheids in LMC and 600 in SMC (Bauer 1997) to be compared with 80 and 400 respectively in the EROS-I database. Being observed with the same instrument and in similar atmospheric conditions also reduces systematics. This large catalog will soon be published.

Some systematic studies using this large catalog have been performed. When building the Period-Luminosity diagrams, for short period cepheids, typically $T \geq 2.5$ days, a non-linearity exists in both colors (Bauer 1998). We did systematic checks of this effect, seen significantly for the first time. Among them, we checked that it was already present in the EROS-I data although not statistically significant. This rules out much of the possible observational biases. This effect is in fact accounted for by the evolutionary models developed by Baraffe 1998. One should also remark cepheids used in the measurement of extragalactic distances have periods above this non-linearity.

This study will of course be extended to the sample of cepheids isolated within our microlensing data. We are also analyzing the sources of the observed dispersion in the P-L diagrams, searching for effects like a spread in distance of the cepheids (Graff 1998).
6. The supernovæ search

EROS-II has also started a semi-automated supernovæ search. It is aimed at discovering in a programmed way batches of supernovæ. Spectrography and photometry observations may thus be planned in order to classify and study them accurately. Supernovæ are rare phenomena (≈ 1 per century and per galaxy) and study a large (≈ 100) number of them offers interesting cosmological perspectives, for example measuring their rate, or study type Ia SN. Systematic surveys for nearby SNe have tackled to their usability as distance indicators (with ≈ 20 SNe, Hamuy 1996). This could be well studied in an intermediate redshift search such as that of EROS. Our detection threshold is estimated to be about the 22nd magnitude in V (10 mn exposures), corresponding to a redshift of 0.2. Such systematic studies are also essential in extracting cosmological informations from the distant SNe searches (Kim 1997, Leibundgut 1997).

Our program goes as follows. Using the EROS-II instrument, we take images near two new moons. The more recent (current) image is compared to the older one (reference) during daytime to search for SN, as shown on figure 9. This program was tested in spring 1997. Three supernovæ were discovered, in good agreement with our estimated discovery rate of \(1 \, SN, \text{deg}^{-2}\). More intensive campaigns followed in the end of 1997 and in 1998. We obtained photometric follow-up time on the ESO 1.5m Danish telescope, and have also few spectroscopic nights on the ARC 3.5m telescope (New-Mexico, USA), on the WHT telescope (Canaries) and on the 3.6m ESO telescope. 28 SNe were
Results from EROS-II

Figure 9. Pictorial view of the discovery of SN1997bl. The image (a) is our reference image, taken on 03/02/97, (b) is the discovery image taken on 07/03/97, showing the SN superimposed onto the host galaxy. (c) is the difference between (b) and (a), on which the supernova was detected.

...discovered during this period, at rate of about 4-5/new moon (we search for about 50deg^2 each new moon, when weather permits). Ten of them have been identified through a spectrum.

During this first intensive campaign, we were able to measure the SN explosion rate (Hardin 1998). We plan to intensify our follow-up efforts (contributions are welcome). We should also participate to a “joint nearby search” coordinated by the SN Cosmology Project in February-March 1999.

7. Conclusion

EROS-II started taking data more than two years ago. The instrument has been running quite well. We present a measurement of the galactic halo microlensing optical depth towards SMC based on one event found in the 1996-7 data. This event could however as well be interpreted as due to a lens lying within SMC, and presents some intriguing properties. A second event was triggered in 1998, which was a binary event with caustic crossings. Our follow-up data indicates that the lens is also probably within the SMC. The results from the analysis of our 2nd year towards SMC and from our LMC data should therefore bring some light on the nature of the lenses. We also conducted a microlensing search towards directions in the galactic plane, and isolated the first 3 candidates in these directions. Precise measurements of the optical depths should constraint Galactic models. We are also analyzing a large LMC and SMC cepheids database to check for systematic effects on the distance scale deduced from them. We have found a new feature in the P-L diagram which is non-linear for short period($T \leq 2.5$days) SMC F-Cepheids. Our SNe search has been quite intense between fall 1997 and the summer of 1998, leading to the discovery of $\approx 30$ SNe that have been scarcely followed-up with our instrument and others. These subjects are only a subsample of the rich physics outcome that is to be expected soon from EROS-II.
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