Preliminary results on galactic dark matter from the complete EROS2 microlensing survey

P. TISSERAND and A. MILSZTAJN
Dapnia, Service de Physique des Particules, CEA-Saclay, F-91191 Gif-sur-Yvette, France
for the EROS2 collaboration

The EROS-2 collaboration has conducted a survey of the Magellanic Clouds between July 1996 and February 2003 (6.7 years), in order to search for microlensing phenomena due to putative machos (massive astronomical compact halo objects). About 55 million stars were monitored over 100 deg², typically with 400 to 500 measurements per star, simultaneously in two wide passbands. The full EROS-2 Magellanic Cloud data set was processed using the same program chain, and a photometric database was constructed. The lightcurves of the brightest 33 million stars were then searched for the characteristic signature of microlensing phenomena, in the wide timescale range of 1 to 1000 days (corresponding to macho masses ranging from about 0.01 solar mass to a few hundred solar masses). The sensitivity of this new analysis is better by a factor 4. The new EROS-2 microlensing candidates towards the LMC and the corresponding (preliminary) final limits from EROS-2 on the macho content of the halo are presented; they are by far not numerous enough to account for the galactic dark matter. We have also followed, whenever possible, the microlensing candidates that were previously published by the EROS and MACHO collaborations. 1 MACHO and 2 EROS LMC candidates have shown subsequent variability and cannot be considered to be serious candidates.

1 Introduction

Nowadays, the galactic dark matter problem is still not understood and has been confirmed from studies of many spiral galaxies. The rotation curves of their different components lead to a dynamical mass estimate 5-10 times higher that that of the visible components. Since 1986 and Paczyński’s proposal, gravitational microlensing has been proven to be a powerful probe of galactic halo dark matter under the form of machos. The signature of these objects is a transient amplification of the light from extragalactic stars by the gravitational lens effect when they are close to their line of sight. Events are extremely rare and millions of stars, towards the Large and Small Magellanic Clouds (LMC and SMC), have thus been monitored photometrically since
1990 by several experiments for a period of years in order to obtain a useful detection rate. Some
microlensing candidates have been observed towards the two targets 4, 2, 1: 9 by EROS (5 LMC, 4 SMC) and 18 by MACHO (16 LMC, 2 SMC), only 1 candidate is in common (97-SMC-1). As of 2003, both experiments have two different points of view: because of the unknown stellar variability background, EROS published an upper limit of the macho content of the halo, at 20% (95% C.L.) in the mass range $10^{-7}$ to 1 solar mass ($M_{\odot}$); and the MACHO collaboration suggest that their result can be understood as a signal of about 20% of the halo mass with a mass for the lenses in the range 0.15-0.9 $M_{\odot}$. Thus the two results were compatible.

2 The EROS experiment

The EROS experiment (Experience de Recherche d’Objets Sombres) has been divided in two phases. The first one (1990-1995) was dedicated to a low mass macho search (no candidate were found in the mass range $10^{-7}$ to $10^{-3}$ $M_{\odot}$), and a medium sensitivity search to higher mass objects ($10^{-4}$ to 1 $M_{\odot}$). Results can be found in Renault et al (1997) and references therein. The second phase started in Jun 1996 with the aim of improving the sensitivity by at least an order of magnitude for higher mass objects. It was conducted until Feb 2003, using a 1 meter dedicated telescope, the MARLY, situated at La Silla (Chile) and two wide field 32 million pixel CCD mosaics covering 1 deg$^2$. The total number of stars followed was 55 million (including 6 in the SMC), compared to 4 million LMC stars in the EROS-1 phase. The monitored solid angle was 88 (10) deg$^2$ in the LMC (SMC). (For comparison, the MACHO collaboration monitored 11 million stars over 15 deg$^2$, mostly in the central region of the LMC). We decided to restrict our analysis to the 33 million brightest stars in our sample (29 in the LMC, 4 in the SMC). In order to analyse a homogeneous sample, all Magellanic Clouds images were photometered anew, using better and slightly deeper template images than in our previous reports. The typical sampling of light curves is about twice per week in each of two passbands.

3 Analysis and results

The analysis conducted aimed at Einstein timescales shorter than two years. In this case, the
microlensing light curves display a visible baseline flux. After having applied a series of cuts to
select single excursion from the baseline with a minimum signal-to-noise ratio, we then selected
candidates by comparing the measurements with the best-fit point-source point-lens microlensing
light curve; the last set of cuts deals with physical backgrounds, mainly ”blue bumper” stars
and supernovae. The former are easy to reject because of their limited and chromatic variations
(larger in redder passbands), but the latter, which occur in galaxies behind the Magellanic Clouds
(between 500 and 1000 Mpc), represent the dominant population in our sample of microlensing
candidates at the end of the analysis: we found 28 such objects, a rate comparable to that found
by MACHO, preferentially in outer regions of the LMC. Supernovae are rejected by performing
a fit of a function that includes an asymmetry parameter $S$, and reduces to the usual symmetric
microlensing light curve when $S=0$, see Tisserand (2004). The function is obtained by replacing
in the usual microlensing formula the Einstein timescale $t_E$ with $t_E[1 + S \arctan((t - t_0)/t_E)]$.
We reject all candidates that have a large asymmetry parameter, $|S| > 0.3$, or that are situated
in the close neighbourhood of a visible galaxy (the probability of a chance alignment is very
low). 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). Combining our observation duration (6.7 years), the number of stars analysed and
our average detection efficiency, the sensitivity of this analysis is better by a factor 4 compared
to the last search published by EROS-2 in the LMC and by a factor 2 with the one published
by MACHO.
3.1 Follow-up of the published microlensing candidates

The first result came from the follow-up of the published microlensing candidates. The final EROS-2 data provides an additional 6.6, 3.7 and 5.1 years time base compared to the latest publications by EROS1, Aubourg et al. (1993), EROS2, Milsztajn & Lasserre (2001) and MACHO, Alcock et al. (2000a), useful to check for the stability of the baseline.

There were 5 surviving microlensing candidates from EROS towards the LMC, one from EROS-1 (number 1) and four from EROS-2 (numbered 3, 5, 6 and 7). Two of them (number 1 and 3) showed new variation incompatible with a microlensing effect. Candidate 1 displayed a new variation in 1998 (see figure 1), 6.3 years after the first one, of similar amplitude (a factor two) and timescale (28 days). This second variation is well fit by a microlensing light curve, but because variations are separated in time by more than 80 Einstein timescales, the probability that these two bumps correspond to the microlensing of a double source star is lower than half a percent. We also attempted to follow all 13 MACHO candidates selected by their analysis A (stricter cuts). We were able to identify unambiguously nine of them and one star, MACHO-A-LMC#23, displays a new variation in Dec 2001, very similar to that observed by the MACHO group in Feb 1995 (variation of 1 magnitude and timescale of 40 days) (see figure 1).

The second result came from the improved photometry and the refined cut to reject supernovae. The light curves of candidates 5, 6 and 7 show an asymmetry between the rise and fall times; they correspond to supernovae. Note that candidate 5 is identical to MACHO candidate 26, which was rejected by Alcock et al. (2000a) for the same reason.

The conclusion is that none of the former EROS microlensing candidates published towards the LMC are still considered valid.

3.2 LMC results

The present analysis of the LMC data has selected four new microlensing candidates. One, EROS2-LMC#8, is a high signal-to-noise microlensing event which shows a chromatic variation of a factor 12 (25) in the red (visible) band. Its position in the colour-magnitude diagram is abnormal, almost 1 mag redder than comparable LMC objects in the main sequence. When a possible blending is taken into account however, the microlensing fit becomes excellent, with agreement between the timescales in the two passbands. The baseline flux corresponding to the magnified object appears to be within the dimmer part of the observed LMC main sequence; this is compatible with the source being an LMC star. In contrast, the non-amplified component is now redder, and cannot correspond to an LMC star. A good solution is that the unmagnified flux corresponds to the lens, a 13.5 mag M dwarf (absolute mag) at a distance of 300 pc. The three other candidates, EROS2-LMC#9 to 11, have lower signal-to-noise. Their source stars have baseline flux at about 21st mag and the timescales range from 35 to 55 days.
Figure 2: The preliminary 95\% C.L. upper limit on the macho content of the halo obtained from the final EROS2 LMC data only (red curve between $10^{-4}$ and 100 $M_\odot$). The lower cross is the value of the optical depth towards the LMC corresponding to the three candidates. The dashed line that goes through this cross shows what the limit would be in the absence of microlensing candidates. This limit is compared to that presented in Lasserre et al. (2000) (green curve between $10^{-7}$ and 10 $M_\odot$). The smaller orange-shaded contour between 0.1 and 1 $M_\odot$ is the signal presented by Alcock et al. (2000a), with the lighter cross indicating their preferred solution. It must be recalled that the fields monitored by MACHO and EROS2 are not identical.

As the event EROS2-LMC#8 is most likely due to a galactic disk lens, the optical depth has been calculated with the remaining 3 candidates, if interpreted as machos. The value obtained is $1.5 \times 10^{-8}$, i.e. 3\% of the standard spherical halo. A preliminary version of a 95\% C.L. upper limit on the macho content of the halo is presented in Fig. 2. It uses only the EROS-2 LMC data set; combination with both the EROS1 and the EROS2 SMC results will be done later. The limit is better than 12\% of the halo for macho masses between $2.1 \times 10^{-4}$ and 1 $M_\odot$.

4 Conclusion

The first account of the analysis of the full EROS-2 data set towards the LMC was presented. This data set has presently the largest sensitivity to halo machos. The small number of microlensing candidates is lower than expected from the results of the MACHO group. From this, one derives strict limits on the abundance of machos. A few microlensing candidates have been shown to vary again, many years later; they should be removed from the candidates census.

References

1. C. Afonso et al., A&A 400, 951A (2003).
2. C. Alcock et al., ApJ 542, 281A (2000a).
3. E. Aubourg et al., Nat 414, 617 (1993).
4. T. Lasserre et al., A&A 355L, 39L (2000).
5. A. Milsztajn & T. Lasserre, Nucl. Phys. B Proc. Sup. 91, 413 (2001).
6. B. Paczyński, ApJ 304, 1P (1986).
7. N. Palanque-Delabrouille et al., A&A 332, 1 (1998).
8. C. Renault et al., A&A 324, L69 (1997).
9. P. Tisserand, PhD thesis (2004), University of Nice-Sophia Antipolis.