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LETTER

Letter to the Editor

EROS 2 intensive observation of the caustic crossing of microlensing event MACHO SMC-98-1*

The EROS collaboration

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Abstract. We report on intensive photometric monitoring on 18 June 1998 of MACHO SMC-98-1, a binary-lens microlensing event seen toward the Small Magellanic Cloud (SMC). The observations cover 5.3 hours (UT 5:17–10:37), and show a sharp drop of 1.8 mag during the first 1.8 hours, followed by an abrupt flattening at UT $7{:}08 \pm 0{:}02$. We interpret the kink at 7:08 as the end of the second caustic crossing (when the source first moved completely outside the caustic).

These results indicate that $\mu \sin\phi \lesssim 1.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ at the 2σ level, where μ is the proper motion of the lens (relative to the line of sight to the source), and ϕ is the unknown (and so random) angle of the caustic crossing. Hence, the lens probably does not lie in either the Galactic halo or disk and so is most likely in the SMC itself. Our data can be combined with those of other groups to give more precise constraints on the proper motion (and hence the nature) of the lens.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content – Magellanic Clouds – dark matter – gravitational lensing

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1. Introduction

The EROS collaboration is engaged in long term microlensing observations toward the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) in order to determine the fraction of the Milky Way halo in the form of massive compact halo objects, as first proposed by Paczyński (1986). Ten candidate events have been detected toward the LMC, eight by MACHO (Alcock et al. 1997a) and two by EROS (Ansari et al. 1996b). The typical Einstein radius crossing time measured for these events is $t_E \equiv r_E/v \sim 45$ days, with r_E the Einstein radius and v the transverse speed of the lens relative to the observer-source line of sight. The optical depth implied is of order half that required to account for the dynamical mass of the dark halo. This time scale is more than twice the value expected for a halo of brown dwarfs, (*i.e.*, where the mass of the objects is $M < 0.08\,M_\odot$). Since $r_E \propto M^{1/2}$, this would seem to imply that the lenses have masses $M \sim 0.4\,M_\odot$. However, they cannot be main-sequence stars since their density would then be almost two orders of magnitude more than is observed. Sahu (1994) and Wu (1994) have suggested that the lenses might be in the bar/disk of the LMC itself. Dynamical arguments seem to rule out this possibility (Gould 1995). Numerous other suggestions as to the nature of the lenses (Zhao 1998; Zaritsky & Lin 1998; Evans et al. 1998) have brought forth equally numerous counter-arguments (Alcock et al. 1998b, Gould 1998a; Bennett 1998; Beaulieu & Sackett 1998).

SMC microlensing searches provide a powerful test of the halo-lens hypothesis. If the lenses observed toward the LMC are indeed in the halo, then both the optical depth and the typical duration should be similar toward the SMC (but see Sackett & Gould 1993). To date, two events have been observed toward the SMC, MACHO-97-SMC-1/EROS-SMC-1 (Alcock et al. 1997c; Palanque-Delabrouille et al. 1998) with $t_E \sim 123$ days and MACHO-98-SMC-1 which is still in progress. Both of these events are substantially longer than the average for LMC events, but since the durations lie in the general range of the LMC time scales, and since there are only two events, no definite conclusion can be drawn from this comparison.

2. Observations and data reduction

The telescope, camera, and telescope operations are as described in Palanque-Delabrouille et al. (1998) and references therein. However the observational strategy and data reduction differed substantially from our previous practice.

The event itself was electronically alerted by the MACHO collaboration[1] on 25 May 1998, just before we began a planned maintenance shutdown (26 May–17 June). On 8 June, MACHO issued a secondary alert following a dramatic increase in magnification to $A \sim 13$, indicating that the source had crossed a binary caustic. On 15 June, MACHO predicted a second crossing on 19.3 ± 1.5 June. On 17 June, the PLANET collaboration[2] posted photometric data which allowed us to predict a crossing at 18.21 ± 0.08 June, i.e., the first night of our resumed operations. (PLANET independently predicted 18.0 June based on the same data.) In view of the importance of caustic crossings for understanding the nature and location of the lens (see § 4 and Mao & Paczyński 1991), we elected to temporarily abandon our normal monitoring strategy and to observe only this field. In addition, we changed our pointing so that the lensed source would fall on a better quality CCD than during normal monitoring. We conducted a continuous series of 5 min. exposures from 18.23 June (when the SMC first rose above our telescope limits) until 18.35 June, then a continuous series of 10 min. exposures (because the magnification of the star had dropped significantly) until dawn at 18.45 June.

Photometry was carried out by means of image subtraction, using the method of (Alard & Lupton, 1998) which we have modified, automated, and adapted to our system. This method differs markedly from the point spread function (PSF) fitting program (PEIDA, Ansari 1996a) that lies at the heart of our microlensing search. Image subtraction is more accurate for crowded field photometry: we are now using PEIDA to find events but use image subtraction to measure their light curves.

1 http://darkstar.astro.washington.edu

2 http://thales.astro.rug.nl/˜planet/

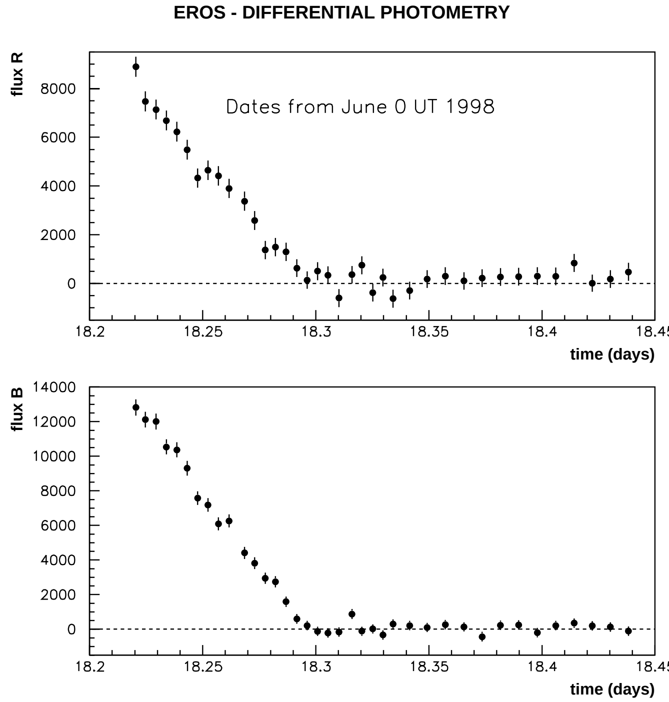

Fig. 1. Differential photometry of EROS data taken on 18 June 1998. R data on top, B data on bottom, in ADU.

3. Results

Fig. 1 shows the flux in the EROS red and blue filters in ADU, relative to a template constructed from 4 images from the flat part of the curve. Image subtraction does not yield a direct measurement of the total flux, but no such measurement is required for any of the analysis of this *Letter*.

However, to make contact with other work, we show in Fig. 2 the position of the source on a color-magnitude diagram at the beginning and end of the falling part of the curve, as determined from PEIDA photometry. The fact that the source changes color as the magnification falls shows that it is heavily blended, although since the seeing deteriorated rapidly during the night, it is possible that blending was a worse problem when the fainter images were taken. (We have done photometry sequences on non-varying stars in the field to verify that the seeing changes do not significantly affect the image-subtraction photometry.)

The blue and red curves show very similar behavior: they begin with an almost perfectly linear decline of 1.8 mag, and then abruptly flatten at UT 18.2970 ± 0.0012 June and 18.2980 ± 0.0021 June respectively. We interpret this break in the slope as the end of the caustic crossing, measured accurately to within 2 min. The ratio of the slopes of the curves (7900 ADU/hr in blue, 5700 ADU/hr in red) gives our best (i.e., blending-free) estimate of the color of the source, $B_{\rm EROS} - R_{\rm EROS} = -0.35^{+0.03}_{-0.04}$. Comparison of this color with the value at the peak ($B_{\rm EROS} - R_{\rm EROS} = -0.41$) displayed in Fig. 2 shows that the color at the brightest PEIDA point is not significantly affected by blending.

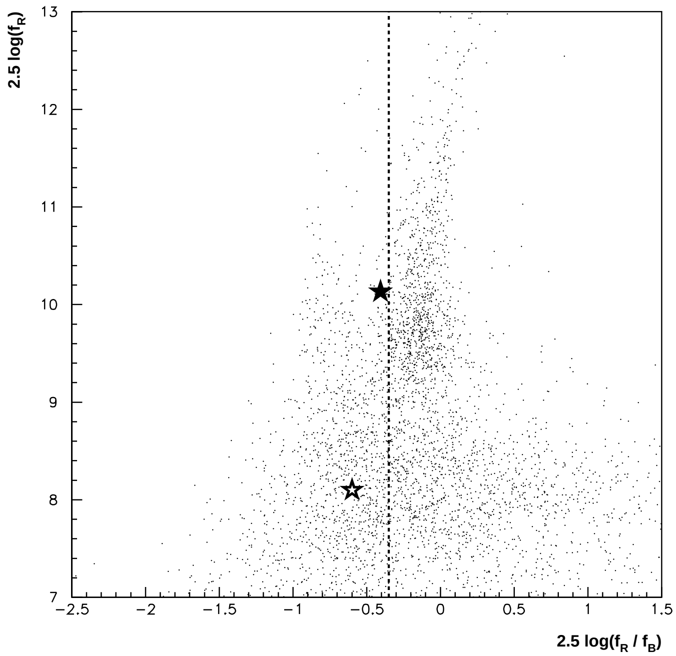

Fig. 2. HR diagram of the field of the microlensing event, PEIDA photometry. Stars indicate the position of the source at the beginning (filled star) and end (empty star) of the falling curve. Dashed line indicates color as given by the ratio of slopes in B and R. Colors are given in the EROS non standard filters.

4. Analysis

As we discuss below, by analyzing the complete light curve, one can measure the proper motion of the lens relative to the observer-source line of sight. Since the expected proper motion of halo lenses is $\mu_{\rm halo} \sim 220\,{\rm km\,s^{-1}}/15\,{\rm kpc} \sim 15\,{\rm km\,s^{-1}\,kpc^{-1}}$, while that of SMC lenses is $\mu_{\rm SMC} \sim 30\,{\rm km\,s^{-1}}/65\,{\rm kpc} \sim 0.5\,{\rm km\,s^{-1}\,kpc^{-1}}$ (Hatzidimitriou et al. 1997), one should be able to clearly distinguish between these two possibilities.

Unfortunately, the EROS data cover only a small portion of the light curve. Nevertheless, these data are sufficient to derive important constraints. Let Δt be half of the total amount of time that some part of the source is over the caustic. The curvature of the caustic is small compared to the source radius and so the caustic can be approximated as a straight line. Let ϕ be the angle between this line and the source trajectory. Then,

$$\mu = \frac{\theta_* \csc\phi}{\Delta t}, \qquad (1)$$

where θ_* is the angular radius of the source. In principle one can estimate θ_* from the color and flux of the source using the Planck law and the (quite reasonable) assumption that the source is a black body. The instrumental color is well determined from the ratio of slopes (see above). In practice, however, the photometry is not sufficiently well calibrated to accurately determine the temperature from the measured color, and our pre-event data are not of sufficiently high quality to accurately measure the unlensed flux. We therefore adopt a pre-event magnitude of $V = 21.8$ from the original MACHO alert. We assume an extinction of $A_V = 0.22$ and an SMC distance of 65 kpc ($A_V = 0.12$ foreground, from Schlegel, Finkbeiner, & Davis (1998) and 0.1 ± 0.1 estimated internal extinction). We then find $M_V = 2.5$, corresponding to an A8 or F0 star with radius $R_* \sim 1.5 R_\odot$ (Lang 1991), and so $\theta_* = R_*/D_{\rm SMC} \sim 0.106\mu$as.

Clearly, $(2\Delta t) > 1.8$ hours, since the light curve falls for at least this length of time. However, we can use the smallness of the curvature of the falling blue light curve in Fig. 1 to place still stronger constraints on Δt. A binary lens gives rise to 5 images when the source is inside a caustic and 3 when it is outside. As a point source approaches a caustic from the inside, 3 of the images change only very slowly, while the remaining two diverge as $\sim (t_0 - t)^{-1/2}$, where t_0 is the time of the caustic crossing (Schneider & Weiss 1986). At $t = t_0$, these two suddenly disappear. Hence, one can model the light curve of a point source as

$$g_p(t; t_0, A, B, C) = A(t_0 - t)^{-1/2}\Theta(t_0 - t) + Bt + C \qquad (2)$$

where Θ is a Heaviside step function. For a finite source of uniform surface brightness and with crossing time $2\Delta t$, the light curve is given by

$$g(t; \Delta t, t_0, A, B, C) = \frac{1}{\pi(\Delta t)^2}\int_{-\Delta t}^{\Delta t} ds \sqrt{(\Delta t)^2 - s^2} \times g_p(t + s; t_0, A, B, C). \qquad (3)$$

We fit the blue data (more accurate than the red data) to this form, with errors estimated from fluctuations on the baseline and rescaled according to photon statistics – this method is corroborated by the value of the χ^2/dof on the fit before the kink $(14.4/15)$. We find that fits with $\Delta t < 3$ hours are unacceptable at the $2\,\sigma$ level ($\Delta\chi^2 > 4$) because they have too much curvature. This implies

$$\mu \sin\phi = \frac{\theta_*}{\Delta t} \lesssim 1.5\,{\rm km\,s^{-1}\,kpc^{-1}}. \qquad (4)$$

The angle ϕ could be estimated from the full light curve, but is difficult to extract from the EROS data alone. Better constraints could be obtained, particularly on the angle ϕ, if the EROS data were combined with those of MACHO, GMAN, and PLANET. If the overall lensing geometry were well determined from a joint fit to all available data, the detailed EROS light curve of the end of the caustic crossing would also enable us to measure the limb darkening of the source.

5. Discussion

Fig. 3 shows the distribution of expected values of $\mu \sin\phi$ for halo lenses together with the upper limit from Eq. 4. If the lens is in the halo, it sits in the extreme (7.3%) lower end of the distribution. The proper-motion limit is larger than typical expected SMC proper motions, $\mu \sim 0.5\,{\rm km\,s^{-1}\,kpc^{-1}}$. However, this may be partially due to the fact that Eq. 4 gives an upper limit rather than an estimate. If the SMC is tidally disrupted, the lens motion could also be substantially larger than virial estimates.

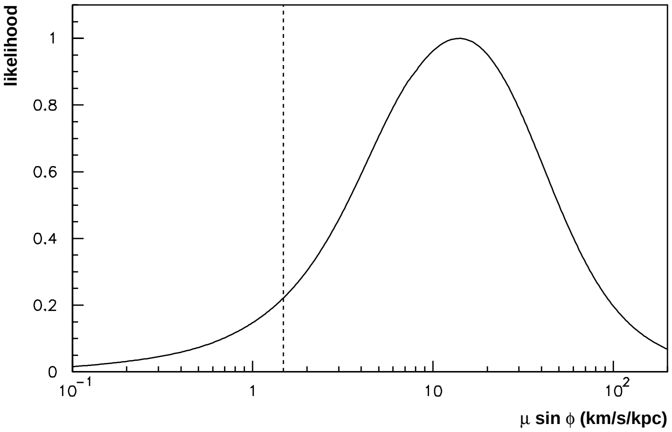

Fig. 3. Distribution of expected values of $\mu \sin \phi$ for halo objects, where μ is the proper motion and ϕ is the caustic-crossing angle. Dashed line is the upper limit derived from our data.

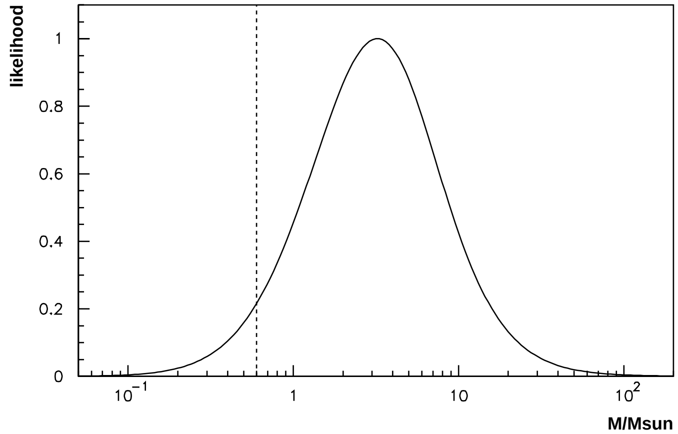

Fig. 4. Mass likelihood for EROS-SMC-1 event, taking into account our parallax limit. 95% of the distribution has $M > 0.6\,M_\odot$ (dashed line).

At present, the most plausible interpretation is that the lens lies in the SMC.

Regarding the other SMC event, EROS-SMC-1, we placed constraints in Palanque-Delabrouille et al. (1998) on the size of the parallax effect, which can be expressed as $R_E/(1-x) = 0 \pm \sigma_{\delta u}\mathrm{AU}$ where $\sigma_{\delta u} = 0.027$. Assuming a halo characterized by a fixed rotation speed $v_c = 220\,\mathrm{km\,s^{-1}}$ and a $\rho(\mathbf{r}) \propto r^{-2}$ density distribution, one can estimate the likelihood of the event as a function of its mass

$$L(M) \;=\; M^{1/2}\int_0^1 dx[x(1-x)]^{3/2}\rho(x)\exp\left[-\frac{R_E^2(x,M)}{(v_c t_E)^2}\right] \times \exp\left\{-\frac{1}{2}\left[\frac{(1-x)\mathrm{AU}}{R_E(x,M)\sigma_{\delta u}}\right]^2\right\}, \qquad (5)$$

where $\rho(x) \propto [1+(xQ)^2 - 0.8(xQ)]^{-1}$, $Q \sim 8.1$ is the ratio of D_{SMC} to the Galactocentric distance, $R_E^2(x,M) = 4GMD_{\mathrm{SMC}}x(1-x)/c^2$, and $t_E = 123$ days is the Einstein radius crossing time of the event. This distribution is shown in Fig. 4. Note that the peak is near $M \sim 3.2\,M_\odot$ and that 95% of the distribution lies at $M > 0.6\,M_\odot$. This is highly implausible for a halo lens unless it is a new type of object like a primordial black hole. On the other hand, as we showed in Palanque-Delabrouille et al. (1998), if the lens is in the SMC, then it is consistent with being a low mass star.

Thus, both of the lenses discovered toward the SMC show significant evidence of being in the SMC itself. The LMC binary event (Bennett et al. 1996) also indicates that the lens is very likely in the LMC. We therefore believe that Sahu's (1994) suggestion that the LMC events are due to self-lensing should be given very serious consideration notwithstanding the "proof" (Gould 1995) that this idea is impossible.

Continued (and intensified) monitoring of the SMC will be important for testing this hypothesis. In addition, if possible, all LMC and SMC events should be intensively monitored for parallax effects. If the lenses lie in the LMC or SMC, then like EROS-SMC-1, they will show no sign of parallax. If they are in the halo, some will show such signs (Gould 1998b).

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