SEARCH FOR MICROLENSING OF STARS BY LOW MASS OBJECTS IN THE GALACTIC HALO

Christophe Magneville*
DAPNIA/SSP, CE-Saclay
91191 Gif-Sur-Yvette CEDEX, France

Representing the EROS Collaboration†

ABSTRACT

I report results from a search of unseen compact objects in the Galactic Halo by the EROS Collaboration at the European Southern Observatory at La Silla, Chile. Both photographic plates and CCD techniques are discussed. A full lesson in this School was devoted to microlensing phenomena, so I focus on the handling and analysis of the data. Two microlensing candidates are presented.

*Funded by Commissariat á l'Energie Atomique, CEA/DSM.
†Experience de Recherche D'Objets Sombres.

1 Introduction

Experimental evidence, like the observation of flat rotation curves of spiral galaxies, and of the anomalous velocity dispersion of objects in galaxy clusters, supports the hypothesis that, at least locally, a large amount of matter is invisible.[1]

Candidates for this dark matter are nonbaryonic matter, such as axions, massive neutrinos, WIMPs, and baryonic matter, such as gas and massive compact objects.

During the last few years, an intense activity has developed in order to investigate these two possibilities. The most natural candidates for baryonic dark matter are aborted stars (MACHOs) with masses above $10^{-8}\ M_\odot$ (the evaporation limit[2]) and below $0.08\ M_\odot$ (the ignition threshold).

2 Microlensing

As suggested by Paczyński,[3] dark massive compact objects (MACHOs) could be detected in the halo of our galaxy by monitoring the brightness of the individual stars in the Large Magellanic Cloud (LMC) using the gravitational microlensing effect. Gravitational lensing leads to an apparent temporary brightening of stars outside our galaxy as the unseen object passes near the line of sight. The amplification is given by $A = (u^2+2)/[u(u^2+4)^{1/2}]$, where u is the undeflected "impact parameter" of the light ray with respect to the unseen object in units of the "Einstein Radius," $R_E = (4\ GM_d Lx(1-x)/c^2)^{1/2}$. Here, M_d is the deflector mass, L is the observer-source distance, and Lx is the observer-deflector distance. EROS monitors stars in the LMC with $L = 55$ kpc, yielding typical values $R_E \sim 2 \cdot 10^3\ R_\odot \sqrt{M_d/M_\odot}$. For the "standard" isothermal halo model,[4] the rate per monitored star for microlensing events with amplifications greater than a threshold amplification A_T corresponding to an impact parameter u_T, has been calculated[5] to be $1.66 \cdot 10^{-6} u_T (M_\odot/M_d)^{1/2}\ \mathrm{yr}^{-1}$. The model assumes a total galactic mass of $4.0 \cdot 10^{11}\ M_\odot$ within 50 kpc of the galactic center, which yields a flat rotation curve out to the position of the LMC. The time scale for amplification is the time for a halo object to move through an angle corresponding to its Einstein radius, and its average is $\tau \sim 75\ \sqrt{M_d/M_\odot}$ days. The resulting achromatic light curve has a characteristic shape, and, given the small rate for microlensing and the preponderance of intrinsically stable stars, the event should be the only significant variation on the curve. Because of geometry, the events are uniformly distributed in the impact parameter at maximum amplification, yielding a distribution of maximum amplifications that falls rather slowly with increasing amplification ($dN/dA \propto 1/A^2$ for $A \gg 1$).

3 Experimental Technique

The shape of the light amplification curve due to microlensing and the number of expected events, depend upon the MACHOs' masses, and may vary over a large range. For an ideal experiment observing 10^6 stars in the LMC during 10^7 seconds, with 100% efficiency to detect an amplification greater than 1.34, the mean amplification time and the number of expected events for various masses of the MACHOs are summarized in Table 1.

M ($M_\odot$)	Mean amplification time scale	Typical number of events
1	3 months	1
10^{-2}	1 week	5
10^{-4}	0.7 day	50
10^{-6}	2 hours	500

Table 1: The characteristics of microlensing events as a function of MACHO mass M (in units of $M_\odot$). The computations are performed for a standard galactic halo of $4 \cdot 10^{11}\ M_\odot$ within 50 kpc and for 10^6 observed stars in LMC; all MACHOs are considered to have the same mass.

This shows that microlensing searches for MACHOs should be conducted in two regimes. At high mass (above $10^{-3}\ M_\odot$), we expect a small number of events each having a long amplification time, i.e., we need to observe many stars, but do not need a short sampling time. In contrast, for low mass MACHOs (below $10^{-3}\ M_\odot$), the number of expected events is larger, but the amplification time is small, i.e., we need to observe fewer stars, but with a good sampling time.

The EROS Collaboration decided to design two experiments at the same time to be able to cover the total mass range. Both experiments take place in the European Southern Observatory in Chile and are observing the LMC.

The long period experiment uses photographic plates on the wide-field Schmidt 1 m telescope. A plate covers about $5^\circ \times 5^\circ$ in the LMC, and we monitor $8 \cdot 10^6$ stars. We take one plate with a red filter and one with a blue filter every few days, during five months of the year. The program is, therefore, sensitive to microlensing events with time scales larger than a few days.

The short period experiment uses a CCD camera,[6] built for this purpose, which consists of 16 buttable 579×400 pixel Thomson THX 31157 CCDs. Eleven CCDs were active in 1991-92, and 15 in 1992-93. The camera is mounted on a 40 cm reflector (F/10) refurbished by us and the Observatoire de Haute-Provence. The angular area covered is $1.1^\circ \times 0.4^\circ$. The exposure time was typically ten minutes, with up to 46 alternating red and blue images taken per night. The program is, therefore, sensitive to microlensing events with time scales larger than 30 minutes.

Plates have been digitized at the Observatoire de Paris. Both sets of experimental data are processed with a homemade photometric program. The first step in the analysis procedure is to construct one reference image for each color by combining images taken under good atmospheric conditions. From the reference images, a star-finding algorithm then establishes a star catalog. Then for each image, the magnitude of each star is computed from a chi-squared fit by imposing the star position from the catalog. Matching of stars in the two colors is then required. We end with light curves as shown in Fig. 1.

4 The Photographic Plate Experiment

The plate experiment consists of 304 plates taken at the Schmidt telescope. This represents three years of data taking: 56 plates in 1990-91, 198 plates in 1991-92, and 50 plates in 1992-93; 80 more plates from 1993-94 have not yet been analyzed.

We begin with $8.5 \cdot 10^6$ stars in our reference catalog. After the elimination of images of poor quality, of stars too bright or too faint, and of stars in a difficult or crowded environment, there remain $3.8 \cdot 10^6$ stars detected with sufficient accuracy in both colors. Each light curve is then subjected to a series of selection criteria chosen to isolate microlensing-like events. The efficiency of these criteria to accept real microlensing events is determined by applying the same cuts to Monte Carlo microlensing events that are constructed by amplifying points on randomly selected experimental light curves.

The analysis of microlensing events first uses the uniqueness of the microlensing on one star. For this, we first reconstruct the largest variations and compute their significance for the red (P_R^1) and for the blue (P_B^1) curves. Then we reconstruct the second largest variation and compute its significance (P_R^2 and P_B^2).

We first require that the largest variation be significant. The great majority of stars exhibit only random fluctuations due to measurement errors. These stars are eliminated mostly by a loose requirement that the most significant variation in the blue be compatible in time with the most significant variation in the red. After these cuts, 9100 stars remain. Intrinsically variable stars with a very significant second variation are eliminated by requiring that $(P_R^2 + P_B^2)$ for the second variation be small in each color; 900 stars survive. At this point, we ask that the size of the second variation be small relative to the size of the first variation $\left(\frac{P_R^2}{P_R^1} + \frac{P_B^2}{P_B^1}\right)$, and are left with 60 stars. Each of the three years is studied separately, and we do not allow a microlensing amplification to be over two years of data. We then ask that the dispersion in the studied year be greater than the dispersion over two years. This selects light curves with a large dispersion where the microlensing is supposed to be, and we are left with only four stars. We require that the amplification be achromatic, and only keep two stars. Figure 2 shows the achromaticity distribution of our last four events, together with the results of a Monte Carlo simulation. Figure 3 shows the chromatic variation light curves for one of the rejected events. The amplification is about 1.5 magnitude greater on the red curve than on the blue one. We end up with two microlensing candidates.[7]

The first candidate (EROS 1) is shown in Fig. 4. The amplification has been fitted to be 2.5 and the time scale 26 days. The amplified star has been studied through absolute photometry and spectroscopy. It was found to be a Be star with a visible magnitude $M_V = 19.11$, a color index $B - V = 0.35$, and an emission line in $H_\propto$. It is located at the right edge of the main sequence in the HR diagram (see Fig. 6). The fit of a theoretical microlensing amplification gave a chi-squared value of 0.8 per degree of freedom.

The second candidate (EROS 2) is shown in Fig. 5. The amplification has been fitted to be 3.3, and the time scale 30 days. It was found to be a $A0 - 2$ main sequence star (see Fig. 6) with a visible magnitude $M_V = 19.38$, and a color index $B - V = 0.04$. The fit of a theoretical microlensing amplification gave a chi-squared value of 1.2 per degree of freedom.

Using the time of amplification distribution, a 10^{-1} $M_\odot$ MACHO mass has been computed using the formula quoted in the first section. This is a very rough estimate, but it suggests a halo made of large mass MACHOs, or even possibly dim main sequence M stars (because of the wide distribution in time scales, the mass could be 0.02–0.9 $M_\odot$ at 95% confidence level).

5 The CCD Experiment

During two years of data taking, 8000 CCD frames were exposed. About 45,000 useful stars were monitored between December 18, 1991 and March 31, 1992, while about 82,000 stars were monitored between August 21, 1992 and March 31, 1993.

The CCD analysis is performed in the same spirit as the plate analysis.[8] We simply tune the algorithms to take into account the different time structure of the data. For example, when studying the 1992-93 data, we begin with 82,000 stars; the criteria using the significance of the main variation and the second variation, together with the time compatibility of the main variation in the blue and red filters, remove 85% of the stars, and 12,000 remain. After selecting on the relative significance of the second and main variations (see Fig. 7), 88 stars survive. Their light curves are then examined in detail, and are fitted with the theoretical microlensing light curve. Most of the 88 stars show an "unphysical" discontinuous flux variation, generally due to inaccurate photometry as a result of bad atmospheric conditions or inaccurate telescope guiding. These stars are eliminated by requiring good agreement between the time of maximum variation in the red and in the blue. After this cut, 11 stars remain. Figure 8 shows the location of these stars in the HR diagram. All of them are located in the upper part of the plot, in a region containing only 5% of our total sample. This is not compatible with microlensing amplification, which should not depend on the physical properties of the amplified stars. Six of the remaining stars have variations on long time scales ($\tau >$ seven days), and are concentrated in regions of the color-magnitude diagram known to contain many variable stars. For the purposes of short time-scale microlensing, we require $\tau <$ seven days, leaving us with five stars. This significantly reduces our efficiency for microlensing events only if the lensing objects have $M_d > 10^{-3} M_\odot$.

The five remaining stars show very small flux variations of an amplitude comparable with the photometric resolution. All events have reconstructed amplifications less than 1.16 which, if they were indeed microlensing events, would correspond to impact parameters, $u > 1.4$. Figure 9 shows the distribution of fitted impact parameters, u, for Monte Carlo events and for the five observed events. In contrast to the observed events, the expected distribution for microlensing events is concentrated at small impact parameters. We therefore make a final cut requiring impact parameters $u < 1.3$, leaving no candidates.

6 Conclusions

Using our Monte Carlo technique, we compute the number of events expected for our experiments as a function of MACHO mass. This is shown in Fig. 10. For example, in the CCD experiment we would expect around ten events if the total mass of the halo were made of $10^{-6}\ M_\odot$ MACHOs. It can be clearly seen that the lower mass region is covered by the CCD experiment, and the higher mass region by the plate experiment.

6.1 CCD Experiment

In this experiment, we do not see any microlensing event. Figure 10 shows the expected number of events as a function of the deflector mass for a standard isothermal halo comprised only of objects of that mass. The expected number of events is greater than 2.3 for $5 \cdot 10^{-8} < M_d/M_\odot < 7 \cdot 10^{-4}$, so we exclude this mass range at the 90% C.L. under the assumption that all objects in the Halo have the same mass. The expected number of events is greater than 6.9 for $3 \cdot 10^{-7} < M_d/M_\odot < 1.5 \cdot 10^{-5}$, so in this mass range, we exclude the possibility that such objects could account for as much as one-third of the halo. The excluded range applies to any distribution of mass that is sufficiently concentrated in the above range. For example, we consider a deflector mass distribution (see Fig. 11) of the form

$$\frac{dN}{dM} \propto M^{-\alpha} \qquad (M_{min} < M < 0.08\ M_\odot) \quad ,$$

and $dN/dM = 0$ otherwise. Figure 12 shows the excluded zone of the parameter space (α, M_{min}). For $\alpha > 2$, the halo mass is dominated by objects of mass near M_{min}, and we rule out, for $\alpha > 3$, the range $5 \cdot 10^{-8} < M_{min}/M_\odot < 5 \cdot 10^{-4}$. Near $\alpha = 2$, where each decade of mass contains the same total mass, the region $10^{-12} < M_{min}/M_\odot < 10^{-5}$ is ruled out. For $\alpha < 2$, the halo mass is dominated by high-mass objects, and we derive no interesting limits.[9] In the near future of the CCD experiment, we will increase our sensitivity by a factor of two just by analyzing the 1993-94 and 1994-95 data (see dashed line in Fig. 10).

6.2 Plate Experiment

The plate experiment shows two candidates. From the time of amplification, we crudely compute a MACHO mass of the order of 10^{-1} solar mass (with a formal one standard deviation error of a factor of three). At this mass, we expect around eight events. The microlensed stars are from different spectral classes; one is a Be star, and the other is an $A0-2$ main sequence star, while the gold-plated candidate from the MACHO experiment[10] is a red giant. This variety of lensed stars is in agreement with what is expected for microlensing amplification. At this point, we may say that our two candidates are compatible with microlensing, but are not incompatible with pre- or post-nova bursts, or with a new type of cataclysmic variable star. At present, we are doing high resolution photometry on our two candidates to compare the stability of the stars. Clearly, we need more data to check the time and amplification distributions against what is expected from microlensing. We are now designing a second generation experiment (EROS 2) using a larger telescope and a larger camera. This experiment will increase our sensitivity by a factor of three for each year of data taking, and will probably begin in the summer of 1995.

References

[1] General reviews of dark matter are given by V. Trimble, Ann. Rev. Astron. Astrophys. 1987, and by J. R. Primack, D. Seckel, and B. Sadoulet, Ann. Rev. Nucl. Sci. 1988.

[2] A. de Rùjula, P. Jetzer, and E. Massò, Astron. Astrophys. **254**, 99 (1992).

[3] B. Paczyǹski, Astrophys. J. **304**, 1-5 (1986).

[4] J. R. Primack, D. Seckel, and B. Sadoulet, Ann. Rev. Nucl. Sci. **26** (1988).

[5] K. Griest, Astrophys. J. **366**, 412 (1991).

[6] M. Arnaud *et al.,* Exp. Astron. **4**, 265-278; *ibid.* 279-296 (1994).

[7] E. Aubourg *et al.,* Nature **365**, 623-625 (1993).

[8] F. Queinnec, Ph.D. thesis, Saclay report DAPNIA/SPP 94-21 (1994).

[9] E. Aubourg *et al.,* submitted to Astron. Astrophys.

[10] C. Alcock *et al.,* Nature **365**, 621-623 (1993).