The EROS Search for Dark Halo Objects

E. AUBOURG, P. BAREYRE, S. BRÉHIN, M. GROS, M. LACHIÈZE-REY, B. LAURENT, E. LESQUOY, C. MAGNEVILLE, A. MILSZTAJN, L. MOSCOSO, F. QUEINNEC, J. RICH, M. SPIRO, L. VIGROUX and S. ZYLBERAJCH, DAPNIA, CE Saclay, Gif-sur-Yvette, France

R. ANSARI, F. CAVALIER and M. MONIEZ, Laboratoire de l'Accélérateur Linéaire, Centre d'Orsay, France

J.-P. BEAULIEU, R. FERLET, PH. GRISON and A. VIDAL-MADJAR, Institut d'Astrophysique de Paris, France

J. GUIBERT, O. MOREAU and F. TAJAHMADY, Observatoire de Paris, France

E. MAURICE and L. PRÉVÔT, Observatoire de Marseille, France

C. GRY, Laboratoire d'Astronomie Spatiale de Marseille, France

1. Introduction

It is widely believed that the flat rotation curves observed for spiral galaxies like our own indicate that such galaxies are contained in a "halo" of dark matter [1]. While the mass of the dark halos should be as much as ten times that of the visible parts of galaxies, the composition of the halos is not known. Candidates range from hypothetical weakly interacting elementary particles to dark astronomical objects like brown dwarfs or black holes. The identification of the halo constituents would have profound implications for cosmology and theories of galaxy formation.

Paczyński [2] suggested that dark astronomical objects in our Halo could be detected by monitoring the brightness of individual stars in the Large Magellanic Cloud (LMC). Because of the gravitational deflection of light, if a massive Halo object passes near the line-of-sight to an LMC star, the amount of light received from this star by the observer will be increased. The amplification is a function of the "impact parameter" r_0, i.e. the minimum distance between the undeflected line-of-sight and the massive deflector. In terms of the normalized impact parameter *u*, the amplification is

$$A(u = r_0 / R_E) = \frac{u^2 + 2}{u\sqrt{u^2+4}}$$

where R_E, the "Einstein radius", is a function of the deflector's mass M, the observer-deflector distance D_d and observer-star distance D_S:

$$R_E^2 = \frac{4GM}{c^2} D_d \ (1 - D_d/D_s).$$

The size of the amplification is greater than 0.3 magnitude if the impact parameter is less than the Einstein radius of the deflector ($u < 1$). The probability of such an amplification, for a given star and at any given time, is simply the probability that this star lies behind a circle of area πR_E^2 centred on any deflector between us and the star. Since R_E^2 is proportional to the deflector mass while the number of deflectors in the Halo is inversely proportional to their mass, this probability depends only on the total dark matter mass along the line-of-sight and not on the individual deflector masses. This probability turns out to be of the order of the square of the galactic rotation velocity devided by the speed of light, or about 10^{-6}. A more precise estimate gives a probability of about 0.5 $\times 10^{-6}$ for amplifications greater than 0.3 magnitude. This figure was calculated assuming a spherical "isothermal" halo of total mass 4×10^{11} $M_\odot$ at distances from the Galactic centre less than the distance to the LMC. This mass would produce a flat rotation curve at the observed Galactic circular speed of 220 km s^{-1}.

Since the observer, star and deflector are in relative motion, a sizeable amplification lasts for a time of order R_E/v_T where v_T is the relative transverse velocity of the deflector. For the lensing of stars in the LMC by objects in our Halo, these relative speeds are of order 200 km s^{-1} and the most probable lensing time is roughly:

$$r = 70 \text{ days} \sqrt{\frac{M}{M_\odot}} \ . \qquad (1)$$

(We have taken the "lensing time" to be the time during which the amplification is greater than 0.3 magnitude.) The characteristic light curve is shown in Figure 1. The distribution of lensing times for a given deflector mass is expected to resemble that shown in Figure 2.

Since τ is proportional to $\sqrt{M}$, the number of microlensing events expected for a fixed observation time is inversely proportional to $\sqrt{M}$. To observe one event with characteristic time τ, the product of the number of stars monitored and the effective observing time must be of order $10^6\tau$. This can be achieved if the Halo consists of unseen objects in the mass range one to 10^{-7} solar masses, corresponding to characteristic times of a few months to a few hours. This range of masses covers hydrogenous objects that are both too light to burn hydrogen ($M < 0.07$ $M_\odot$) and too big to have evaporated since their formation in the early Universe ($M > 10^{-7}$ $M_\odot$) [3].

To be sensitive to amplifications of order 0.3 magnitude, the photometric precision per measurement should be of order or better than 0.1 magnitude. Rejection of intrinsically variable stars can be achieved, in principle, by requiring that light curves be symmetric, achromatic and exhibit a single extremum (the amplification events should not be repeated).

Following discussions in 1989 led by Charles Alcock of Livermore, two groups have initiated observation programmes to reach the required sensitivity. One group is a Livermore-Berkeley (Center for Particle Astrophysics)-Mount Stromlo-San Diego-Santa Barbara collaboration and is observing the LMC from Mount Stromlo, Australia [4]. The other group, called EROS (Expérience de Recherche d'Objets Sombres), is our own collaboration of particle physicists and astronomers, started in January 1990. We are observing the LMC from the ESO observatory in La Silla, Chile [5].

EROS consists of two programmes. The first is designed to be sensitive primarily to deflector masses in the range $10^{-4}M_\odot < M < 10^{-1}M_\odot$ corresponding to mean lensing durations in the range 1 day $< \tau <$ 30 days. It uses Schmidt plates of the LMC and permits us to monitor about ten million stars over a period of several years. (About

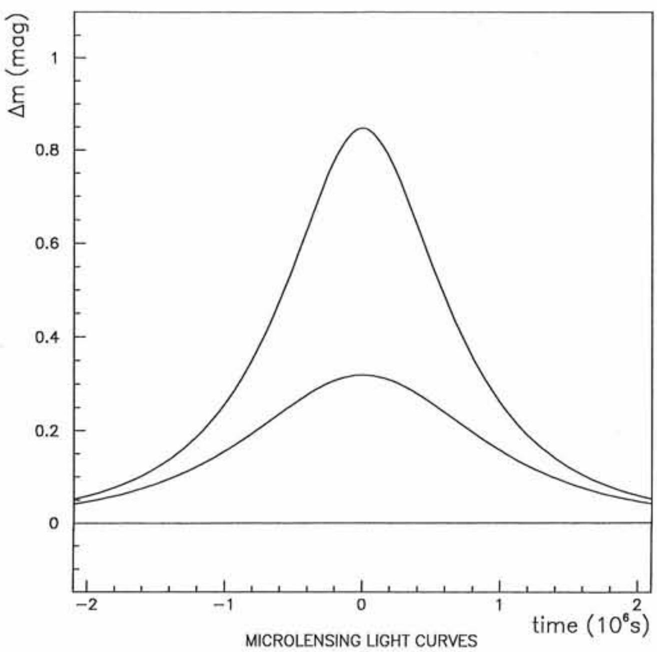

Figure 1: *The theoretical light curves for impact parameters of 0.5 R_E (upper curve) and 1.0 R_E (lower curve). The time dependence was calculated assuming a deflector of mass 10^{-2} $M_\odot$, 10 kpc from the Sun, moving with a relative transverse speed of 160 km/s.*

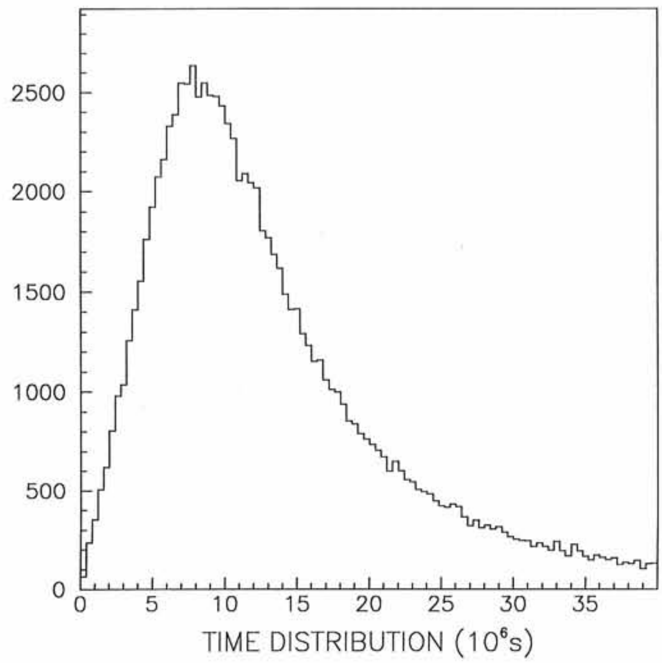

Figure 2: *Distribution of lensing times for an "isothermal" Halo composed of 1 $M_\odot$ deflectors, in units of 10^6 seconds. The lensing time is taken to be the interval during which the amplification is greater than 0.3 magnitude. For other masses, it scales with the square root of the deflector mass.*

half of these stars are bright enough to be monitored sufficiently accurately to observe variations at the 0.3 magnitude level.) The second programme is designed to be sensitive primarily to deflector masses in the range $10^{-7} M_\odot < M < 10^{-3} M_\odot$ corresponding to event durations in the range 1 hour $< \tau <$ 3 days. It uses a large CCD mosaic on a dedicated telescope to monitor about 150,000 stars every 20 minutes.

This report describes the present status of EROS and gives some preliminary results. Prospects for the future are also discussed.

2. The CCD Programme

The CCD programme started at La Silla in December 1990 with a one-month feasibility study during which we observed the LMC bar with the 40-cm GPO refracting telescope. We used a camera consisting of one 576 × 405 pixels Thomson CCD chip giving a field of 11 × 8 arcmin. A total of 63 images of one dense field of the LMC bar was taken. The strategy of using alternating blue and red filters was established.

Following this short study, we decided to replace the refracting telescope with a 40-cm reflector (f/10) mounted on the back of the GPO as shown in Figure 3. This allowed us to use wide band filters (centred at 480 nm and 670 nm) with the consequent reduction of exposure times. We also constructed a wide field CCD camera [6] with sixteen buttable 576 × 405 pixels Thomson THX 31157 CCDs (Fig. 4). The total field of this camera is about 1° × 0.5° and is oriented so as to follow the LMC bar.

Data acquisition and camera control are performed with a VME system based on a 68030 processor. The data taken during one night are stored on a

Figure 3: *The 40-cm reflector mounted on the GPO at La Silla.*

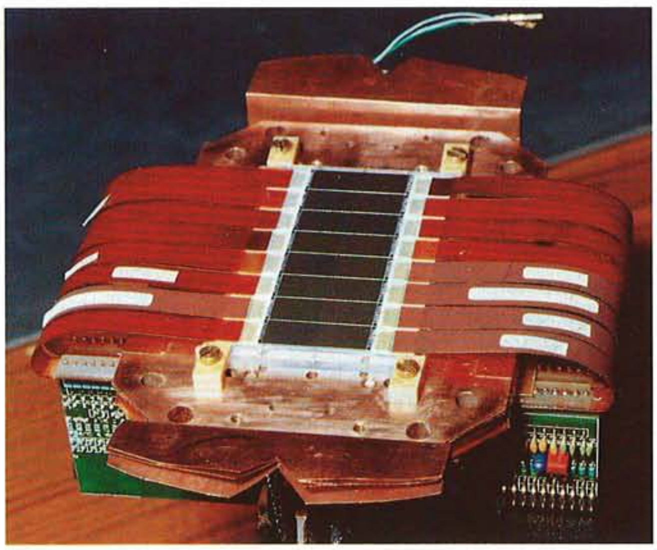

Figure 4: *The CCD mosaic.*