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# The EROS 2 proper motion search for halo white dwarfs

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**Abstract.** In 1996 EROS 2 started a survey of 350 square degrees down to the limiting magnitudes of I$\sim$20.5 and V$\sim$21.5 to look for nearby white dwarfs and brown dwarfs by proper motion, using its two-colour wide-field imager. We report the preliminary analysis of the first 140 $^{\circ 2}$ for which we possess two epochs in both colours. We expected around ten $M_V$=16.5–17 halo objects for a halo full of such objects, and found none. One brown dwarf was discovered, which probably belongs to the disk.

## 1. Introduction

The dark halo is one of the two most common solutions to the Galactic dark matter problem, with the so called maximum disk solution. For both, if baryonic, dark matter would likely be formed by stellar remnants or sub-stellar objects, but as of today it remains unseen.

Many programs tried to detect or constrain the shape and nature of the Galactic dark matter. Microlensing experiments (see Renault *et al* 1997, Alcock *et al* 1997) have provided around 15 microlensing candidates towards the Magellanic Clouds, the standard interpretation of which being that they belong to the Galactic halo, with a favoured mean mass between 0.1 and 1 $M_\odot$, forming around 50% of a *standard* $4.10^{11} M_\odot$ halo within a sphere of radius 50 kpc. However, this mass measurement is strongly model dependent, and a few events might be attributed to Magellanic Clouds lenses (Afonso *et al* 1998b, Alcock *et al* 1998, Udalski *et al* 1998). Substellar object mass contribution has been limited to 10 % of many halo models by Afonso *et al* (1998a) for objects with mass between $2.10^{-6}$ to $2.10^{-2}$ $M_\odot$ (95% C.L.). Deep searches using pencil beam WFPC images have also put strong limits to the contribution of brown and of white dwarfs redder than V-I = 1.7 mag (see Flynn *et al* 1996).

The direct search for faint, nearby white and brown dwarfs is an important step for the further understanding of the mass contribution of faint baryonic compact objects to the rotation curve. Here we present the preliminary results of a search for nearby white and brown dwarfs by proper motion. The use of the EROS 2 wide-field imager provides the necessary solide angle, in two bands, with time sampling optimized for fast, halo stars; we shall present the reduction procedure and conclude with the current preliminary results corresponding to the first two years of data (two epochs with a one year baseline).

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## 2. The EROS 2 proper motion survey

### 2.1. Instrument characteristics

The EROS 2 two colour wide-field imager is made of two identical $8k \times 4k$ CCD mosaics. It is mounted at the Cassegrain focus of the 1-m Ritchey-Chretien Marly telescope. The passbands are large, as defined by the dichroic beam splitter used to divide the flux. The *visible* band is centred on the Johnson V filter, while the *red* one is centred on the Cousins I filter, with sensitivity up to 1 micron. Calibrationis based on V-I=[0–1] mag stars and standard magnitudes of redder starsare indicative. The present analysis used seven CCDs ($0.81\,^{\circ 2}$) in the red passband and eight CCDs ($0.87\,^{\circ 2}$, due to cosmetic defects) in the visible band. The pixel size is 0".6.

### 2.2. Observing Strategy

EROS 2 operates its dedicated telescope on a full-time basis. Observations are conducted one to two hours per dark night, within 90 minutes from the meridian to minimize atmospheric refraction. Images are shared with the EROS Supernovae detection program (Hardin 1998), so that fields were selected within those of the Las Campanas redshift survey, at declination $-40\,^{\circ}, -45\,^{\circ}$ near the South Galactic Pole ($144\,^{\circ 2}$), and at $\delta = 0\,^{\circ}, -6\,^{\circ}, -12\,^{\circ}$ in the Northern Hemisphere ($219\,^{\circ 2}$). I$\sim$20–20.5 and V$\sim$21.5–22 limiting magnitudes are obtained with five to ten minute exposures. Each year every field is observed twice if possible (50% of all fields) or more. To date $296\,^{\circ 2}$ have been surveyed twice in 1996, 1997 or 1998. Observations for a third epoch started in August 1998, but are not included in the present analysis. The experiment is expected to last until 2002, so that eventually 3 to 5 epochs will be available.

### 2.3. Creation of the proper motion catalogue

The reduction software for source detection, classification and catalogue matching was written in the framework of the EROS PEIDA package. The data are processed by chunks of $(11\,\mathrm{arcmin})^2$, by fitting the image with a two-dimensional Gaussian PSF model. The astrometric precision for the larger fluxes could be improved by fitting a more sophisticaded PSF model, //rather than the Gaussian function we used, but as errors are dominated by the photon noise for low fluxes, as can be seen on Figure 1, that would not improve the astrometry for most of the volume. A rough star/galaxy classification is performed to limit galaxy contamination, with such cuts that few stars are misclassified.

The catalogues of the two epochs are then geometrically aligned using a linear transformation between the 40 brightest stars. Then the whole catalogues are matched, requiring that the matched stars have a compatible brightness, within a search radius of 9 arcsec, to be compared with the mean distance between two stars, 1 arcmin.

From the displacement between the star positions, we derive the total astrometric error. This includes the fitting error, the optical aberration due to the differences of light path between the two epochs, the transformation errors and the photon noise. It appears that the precision saturates at 0.04 pixel or 25 mas for the larger fluxes, corresponding to a $20\sigma$ detection of a 250 km/s halo star at 100pc from the Sun.

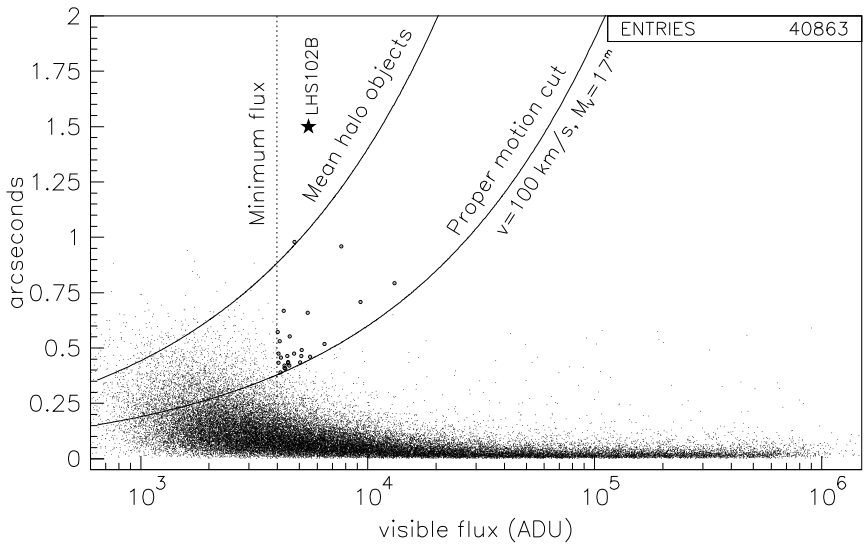


Figure 1. Matching distance versus the visible flux for $7\,^{\circ 2}$ (5% of all associated stars). The dotted vertical line is the flux cut; solid oblique lines are the proper motion cut and (above) the mean position of a typical 250 km/s, $M_V$=17 halo object.

## 3. Current expectations and results

### 3.1. Selection of the candidates

In the current analysis we try to select any candidate that could constitute a significant part of the dark matter, hence we impose a minimum proper motion according to the star relative magnitude, so that we get all stars faster than 100 km/s and fainter than $M_V = 16.7^m$, $M_I = 15.9^m$, down to the magnitude limits. If we do that using either the visible or the red images, many spurious candidates are selected close to the detection limit. They should be eliminated by the third epoch.

As we now possess only two epochs, we eliminate the spurious candidates by requiring the selection in both bands. This reduces the searched volume for brown dwarfs, hardly detected in the visible band, but not much for the coolest white dwarfs, which are expected to be bluer (Hansen 1998, Bergeron *et al* 1997).

### 3.2. Efficiency and sensitivity of the survey to halo white dwarfs

The efficiency calculation is of prime importance for such a survey, and it can be relatively safely determined for this CCD reduction procedure, by Monte–Carlo techniques. Inefficiency is due to the non–detection of objects on one of the images, poor astrometry, wrong classification or mismatching. Effects of the pointing errors and failure of the geometric alignement can be measured directly and are included in the value of the surveyed area. We then measured the matching and selection efficiency, calculated by simulated displacement of a random real star on every quarter of CCD, for different displacement radius and

Table 1. Number of expected objects in the present survey for a *standard* halo of $0.01 M_\odot/pc^3$ local density.

| Type of objects | V-I∼1 white dwarfs | | Brown dwarfs | |
|---|---|---|---|---|
| | $M_V$=16.7 | $M_V$=17.7 | $M_I$=15.9 | $M_I$=16.4 |
| Number of objects | 10 | 3 | 5 | 3 |

magnitude. Efficiency for any halo-type proper motion up to 8"/yr is around 80–85 % for large fluxes down to $10\sigma$ above background and then drops.

In the present analysis, the usable area for which we possess correct images for both epochs and both colours is 1,200 (20 min)$^2$ CCDs, or 140 $^{\circ 2}$. Taking into account the efficiencies indicated above, we calculate the number of expected stars, in the hypothesis that the halo is filled with white/brown dwarfs of a given magnitude and colour. The results are presented in Table 1.

### 3.3. Present detections

Among a thousand stars selected in either colour, six remained after requiring detection in both colours: four had incompatible visible and red proper motions; one was rejected by eye examination (apparent binary). The remaining, very red candidate (see Figure 2) was confirmed with a third epoch image in May 1998. Its DENIS infrared colours (Simon *et al* 1998) proved very interesting: I=17, I-K=5.6, I-J=4.7. It turned out to be the previously undetected companion to

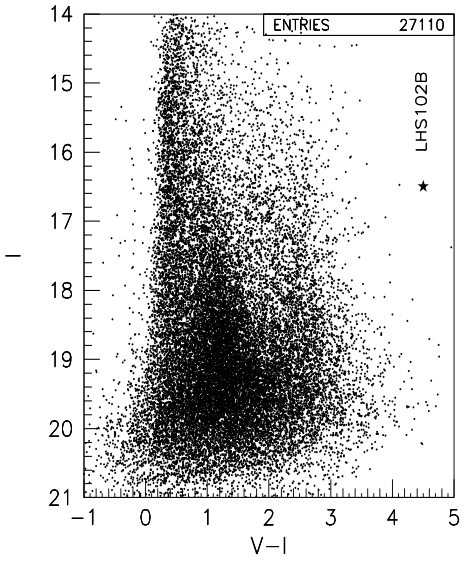


Figure 2. Standard V-I,I colour–magnitude diagram for 5 $^{\circ 2}$ close to the South Galactic Pole. Calibration according to (Bauer et al 1997).

LHS102, whose proper motion ($82 \pm 6$ km/s) and distance ($9.6 \pm 1.2$ pc) are known (van Altena *et al* 1995). It was later observed at Keck and confirmed by spectroscopy as a L–class, lithium depleted brown dwarf. Further information on this star can be found in Goldman *et al* (1998) and Martin *et al* (1998).

## 4. Conclusion

The EROS 2 proper motion program is now in its productive stage with data from two epochs reduced, and a third epoch being imaged. The present analysis restricted to fast and faint stars expects about ten $M_V$=17.2 halo white dwarfs to be detected for a halo filled with such those objects. With no halo object detected, we confirm the results of recent different detection programs (Lidman 1998), according to which hydrogen white dwarfs younger than ∼14 Gyr cannot form the full halo.

Within a few months, using third epoch images and relaxed cuts, the program should be sensitive to tens of halo white or brown dwarfs, putting definitive constraints on these types of objects in the local Dark matter budget. It will also be sensitive to faint disk objects, similar to the brown dwarf already detected, and help define the luminosity function of faint stars in the solar neighbourhood as well as their intrinsic characteristics.

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