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# EROS 2 proper motion survey: a field brown dwarf, and an L dwarf companion to LHS 102 ⋆

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**Abstract.** We report the discovery of two L dwarfs (the new spectral class defined for dwarfs cooler than the M type) in a two-epoch CCD proper motion survey of 413 square degrees, complemented by infrared photometry from DENIS. One of them has a strong lithium line, which for very cool dwarfs is a proof of brown dwarf status. The other is a common proper motion companion to the mid-M dwarf LHS 102 (GJ 1001), which has a well determined trigonometric parallax. LHS 102B is thus one of the coolest L dwarfs of known distance and luminosity.

**Key words:** : Galaxy: kinematics and dynamics — dark matter — stars: low-mass, brown dwarfs

## 1. Introduction

Two years ago, several very cold dwarfs were identified by DENIS (Delfosse et al. 1997) and Kelu 1 was found through its high proper motion (Ruiz et al. 1997). Follow-up observations immediately showed that their optical spectra bear little resemblance to those of the slightly hotter M dwarfs and resemble the previously atypical spectrum of GD 165B (Becklin & Zuckerman 1988; Kirkpatrick et al. 1993). Martín et al. (1997) suggested a new class for these objects, the L spectral class. Kirkpatrick et al. (1999) and Martín et al. (1999) take first steps towards a definition of this class. The main characteristic of L dwarf visible spectra, compared with those of M dwarfs, is the gradual disappearance of the VO and TiO molecular bands, now understood as due to depletion of titanium and vanadium into dust. This class contains both very low mass stars with masses just above the hydrogen burning limit and brown dwarfs, like DENIS-P J1228.2-1547 (Delfosse et al. 1997) and Kelu 1 (Ruiz et al. 1997).

High proper motions have historically been the first tool used to systematically search the solar neighbourhood for very low mass stars (Luyten 1925), and the discovery of Kelu 1 shows that this remains a powerful technique. In this letter we report the detection of two new L dwarfs in a proper motion survey using the EROS 2 instrument, and their confirmation by infrared photometry from DENIS. The EROS 2 proper motion survey primarily aims at halo white dwarfs, but a preliminary two-epochs analysis already has useful sensitivity to very cool disk objects. One of the new detections is a confirmed brown dwarf and the

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other is a borderline object, which may be either a star or a brown dwarf. The latter is a common proper motion companion of the parallax star LHS 102 (d=9.6 pc, M3.5V), and significantly improves the determination of the colour-luminosity relation for low luminosities L dwarfs. We first detail the observational setup and the selection process, and then discuss the two objects in some detail.

## 2. The EROS 2 proper motion survey

### *2.1. Instrument and data characteristics*

The EROS 2 two colour CCD wide-field imager (Bauer et al. 1997) is mounted at the Cassegrain focus of the 1-m Marly telescope at La Silla (Chile). The pixel size is 0".6 and the field of view is $1\,^{\circ 2}$. It contains two $8k \times 4k$ CCD mosaics, illuminated through a dichroic beam splitter which defines the bandpasses. The *visible* and *red* bands are respectively centered close to the Johnson $V$ and Cousins $I$ filters, but considerably broader. Calibration is based on V-I=[0–1] mag stars and magnitudes of redder stars are indicative only.

Proper motion observations are performed one to two hours per dark night, within 90 minutes of the meridian to minimize atmospheric refraction. For the present analysis we used $183\,^{\circ 2}$ observed close to the South Galactic Pole, and $230\,^{\circ 2}$ in the Northern Hemisphere, which had been been observed twice or more, down to $V \simeq 21.5$ and $I \simeq 20.5$. The experiment is expected to last until 2002, and 4 or 5 epochs will eventually be available.

### *2.2. Proper motion determination*

The reduction software for source detection, classification and catalogue matching was written in the framework of the EROS PEIDA++ package (Ansari 1996), and processes data in $(11\ \mathrm{arcmin})^2$ chunks. As photon noise dominates the astrometric errors for most of the available volume, we use a simple two-dimensional gaussian PSF fitting to determine stellar positions. A rough star/galaxy classification is performed to limit galaxy contamination, with such cuts that few stars are misclassified. The catalogues for the two epochs are geometrically aligned using a linear transformation adjusted to the 40 brightest stars, and matched within a search radius of 9 arcsec. The average distance between matched stars (Fig.1) provides an upper limit to the total astrometric error, which for bright objects is 25 mas ($1\sigma$). For a 25 km/s disk star and a 1-year baseline this corresponds to a $5\sigma$ detection at 40pc.

### *2.3. Candidate selection*

Since our main goal is to identify dark matter contributors, we select all objects satisfying a magnitude-dependent proper motion cut, set to retain stars faster than $V_t$=25 km/s and fainter than $M_V = 19.7^m$ and $M_I = 16.9^m$, down to our detection limit (Fig.1). This selection in a proper motion-magnitude diagram is mostly sensitive to two object classes: halo white dwarfs and disk very low mass stars and brown dwarfs. As the current analysis is based on two epochs, we presently have to require a selection in both photometric channels to avoid excessive contamination by spurious faint candidates. Even though this procedure reduces the searched volume very significantly for L dwarfs, the one candidate it does select, LHS 102B, has a very red EROS colour, confirmed by DENIS photometry. Following this early success, we looked for all red objects with EROS colour similar to LHS 102B's, regardless of their proper motion, obtaining 25 additional candidates with $(V-I)_{EROS} > 2.9$.

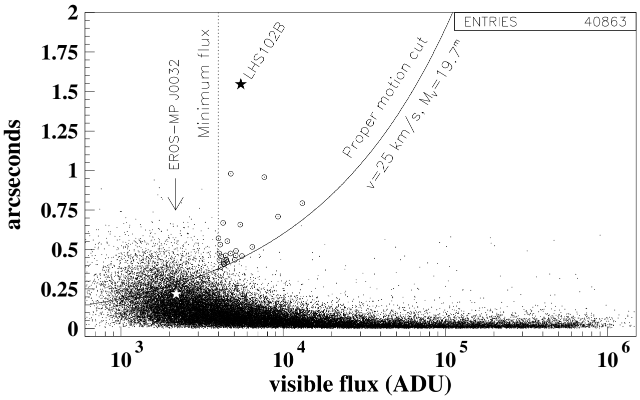


**Fig. 1.** Matching distance versus EROS flux in the visible band. For clarity only 5% of the sample is displayed. The dotted vertical line shows the minimum accepted flux, and the solid curve the minimum proper motion cut. The larger dots show the stars selected in the visible band only; only LHS 102B is selected in both bands.

**Table 1.** Basic parameters of the objects. LHS102A is satured in the EROS images, so its $\mu$ and $\theta_\mu$ are from van Altena et al. 1995. $\alpha$ and $\delta$ are for epoch J2000.0.

| | LHS102A | **LHS102B** | **EROS-MP J0032** |
|---|---|---|---|
| I | $10.2 \pm 0.05$ | $17.0 \pm 0.05$ | $18.6 \pm 0.2$ |
| I-J | $1.4 \pm 0.07$ | $3.70 \pm 0.07$ | $3.7 \pm 0.2$ |
| J-$K_s$ | $1.0 \pm 0.07$ | $1.90 \pm 0.07$ | $1.25 \pm 0.25$ |
| $\mu$ ($''.\mathrm{yr}^{-1}$) | 1.618 | $1.55 \pm 0.06$ | $0.17 \pm 0.04$ |
| $\theta_\mu$ (°) | 154 | $158 \pm 7$ | $137 \pm 2$ |
| $\alpha$ (J2000) | 00:04:36.5 | 00:04:33.9 | 00:32:55 |
| $\delta$ (J2000) | -40:44:02 | -40:44:06 | -44:05:05 |

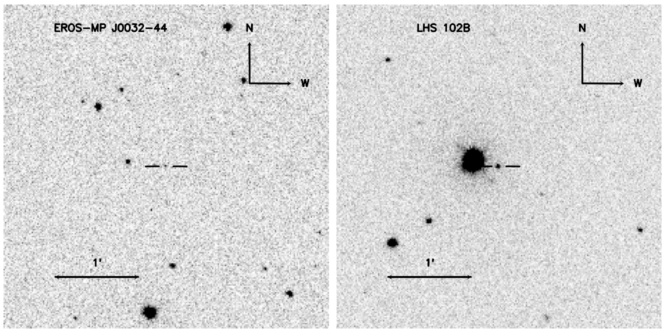


**Fig. 2.** I band finding chart from the DENIS images. The chart size is $\sim 3.5' \times 3.5$, with North up and East left.

## 3. DENIS photometry

We obtained I, J and $K_s$ photometry for 12 of the 25 candidates in the course of the DENIS survey. DENIS observations are carried out on the ESO 1m telescope at La Silla, with a three-channel infrared camera (Copet et al. 1999). Dichroic beam splitters separate the three channels, and focal reducing optics provides image scales of $3''$ per pixel on the $256{\times}256$ NICMOS3 arrays used for the two infrared channels and $1''$ on the $1024{\times}1024$ Tektronix CCD detector of the I channel. DENIS photometry is an efficient estimator of spectral type or approximate effective temperature for M and L dwarfs (Delfosse et al. 1999). Two of the 12 objects clearly have colours typical of L dwarfs, with I–J larger than 3.5 (see Table 1). Fig.2 gives finding charts for these new L dwarfs. High and medium resolution optical spectra obtained at the Keck telescope confirm their L dwarf status, and are discussed in two separate papers (Basri et al. 1999, Martín et al. 1999).

## 4. Discussion

### *4.1. LHS 102B: an L dwarf companion to an M dwarf*

One of the two L dwarfs is within 20 arcsec of a previously known high proper motion star, LHS 102 (M3.5V). It shares its proper motion of $1\farcs62 \mathrm{yr}^{-1}$ towards PA=155°, and the two objects are thus physical companions. The trigonometric parallax of LHS 102 (van Altena et al. 1995) provides a distance for the system of $9.6 \pm 1.2$ pc, and LHS 102B is thus a rare case of an L dwarf of known distance and luminosity. Just a few months ago only two other L dwarfs had known distances: GD 165B (Becklin & Zuckerman 1988) through its association with GD 165A, and Roque 25 which Martín et al. (1998b) established to lie (at 94 % C.L.) in the Pleiades, whose distance $131 \pm 3$ pc is known through main-sequence fitting (Pinsonneault et al. 1998, Soderblom et al. 1998) and whose radius is $\sigma_d = 4 \pm 2$ pc (Narayanan & Gould 1999). Kirkpatrick et al. (1999) have since presented preliminary parallaxes for another three L dwarfs. They are also shown in Fig. 3, though Martín et al. (1999) suggest that they might perhaps have problems, as the stars would be very young for field objects ($\simeq 0.1$ Gyr) and would have preserved lithium contrary to model expectations and observations in the Pleiades (see Martín et al. 1998a). It is difficult to assess their reliability from the limited information in Kirkpatrick et al. (1999), but possible sources of trouble include a relatively short timespan, and strong differential colour refraction from the extreme colours difference between the L dwarfs and their reference frames (as the USNO uses a very broad filter). Alternatively those sources could be binaries, though it seems unlikely that all three are.

Fig. 3 shows M dwarfs of known distance and the six L dwarfs in an $M_I$ vs I–K HR diagram, together with two sets of theoretical tracks, NextGen and NG–DUSTY. Dust condenses in the atmospheres of very cool dwarfs, with two main consequences: depletion from the atmosphere of the refractory elements; such as Ti and V; decreases line opacities; and dust continuum opacity changes the atmospheric structure through a greenhouse effect. The NextGen models (Hauschildt et al. 1999) ignore dust condensation altogether, while the NG–DUSTY models (Leggett et al. 1998, Allard & Hauschildt 1999) account for its effect on both the chemical equilibrium and the continuous opacity. As can be seen in Fig. 3, the NextGen models provide an excellent fit to near-IR colours and luminosities of M dwarfs, but fail to reproduce the J–K reddening of the late M and L dwarf sequence. The NG–DUSTY models in contrast provide an impressive fit of the near IR colours and luminosities of L dwarf, especially when one considers the still preliminary nature of these complex models. Clearly dust condensation plays a dominant role in the atmospheric physics at these temperatures.

Comparison with the NG–DUSTY models gives an effective temperature of $1700 \pm 50$ K for LHS 102B, consistent with that derived from the optical spectrum (Basri et al. 1999). The best fit is obtained for the 5 Gyr isochrone and a mass of $0.072\,\mathrm{M}_\odot$ (just at the stellar/substellar mass limit for models using NG–DUSTY atmospheres (Allard & Hauschildt 1999)), but the data are also consistent with a 1 Gyr age and a (substellar) mass just above $0.06\,\mathrm{M}_\odot$. Since LHS 102B has depleted its lithium (Basri et al. 1999), its mass must be larger than $0.06\,\mathrm{M}_\odot$ and its age therefore cannot be less than $\sim$1 Gyr. The optical spectrum indicates shows weak $\mathrm{H}_\alpha$ emission, and this low level chromospheric activity may indicate that LHS 102B is not very much older than that minimum age. It can be either a star or a brown dwarf and we cannot presently say on which side of the border it stands.

### *4.2. EROS-MP J0032-4405: a field brown dwarf*

The second object, EROS-MP J0032-4405, has I–J= $3.7 \pm 0.2$ and J–K= $1.2 \pm 0.14$. From comparison with NG–DUSTY atmospheric models, we obtain an effective tem-

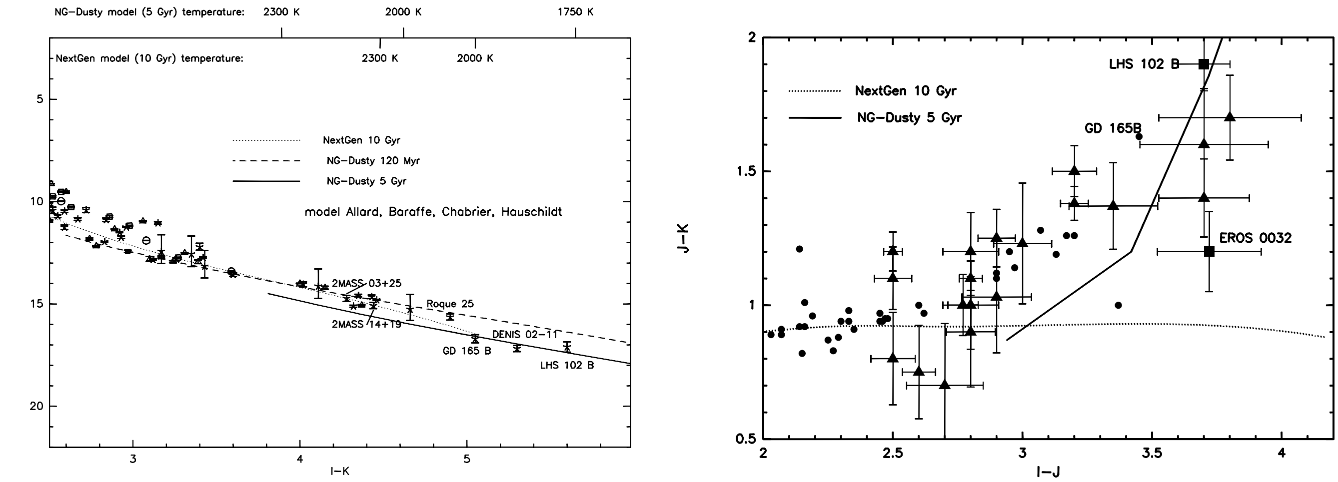


**Fig. 3.** a) $M_I$:I–K HR diagram for our objects, along with M and L dwarfs with known distances (from Leggett 1992, Tinney et al. 1993 and Kirkpatrick et al. 1999). Models are overlaid for both dust-free and NG–DUSTY atmospheres and for ages of 5 Gyr (~appropriate for field objects) and 120 Myr (appropriate for the Pleiades brown dwarf Roque 25). b) Colour-colour diagram of M and L dwarfs (Fig. 6 of Delfosse et al. 1999) with the two new L dwarfs (square symbols).

perature of $T_{eff} = 1850 \pm 150$ K. This is only marginally consistent with the effective temperature of 2200+-100 K, which corresponds to the L0 spectral type derived by Martín et al. 1999, with 1-$\sigma$ error bars extending to M9.5–L0.5 classes. The 670.8 nm lithium line absorption in the optical spectrum (see Fig.4 and Martín et al. 1999) indicates that this fully convective very cool dwarf has not depleted its lithium. Since lithium is destroyed by proton capture at lower temperature than needed for hydrogen fusion (Rebolo et al. 1992), EROS-MP J0032-4405 has to be a brown dwarf, less massive than 0.06 $M_\odot$. Since models show that 0.06 $M_\odot$ brown dwarfs cool down to effective temperatures of ~ 1800 K at an age of ~1Gyr (and less massive ones cool faster), it must also be younger than ~1 Gyr.

## 5. Conclusions

Coming after the recent discoveries of DENIS-P J1228.2-1547 (Delfosse et al. 1997), Kelu 1 (Ruiz et al. 1997), LP 944-20 (Tinney 1998) and of field brown dwarfs found by 2MASS (Kirkpatrick et al. 1999), the identification of EROS-MP J0032-4405 in a small surveyed volume again indicates that brown dwarfs are quite common in the solar neighbourhood. This should not come as a surprise, since the mass function of the Pleiades cluster (Bouvier et al. 1998; Zapatero Osorio et al. 1999) rises mildly into the brown dwarf domain.

EROS 2 combined with DENIS has proved their capabilities to find L dwarfs in the solar neighbourhood. We are currently analysing a larger area with three epochs and a longer time baseline. This will allow us to relax the requirement of a detection in the two colour channels, and provide more accurate proper motions. We therefore hope to find new, cooler objects, and to further characterize the brown dwarf population of the solar neighbourhood.

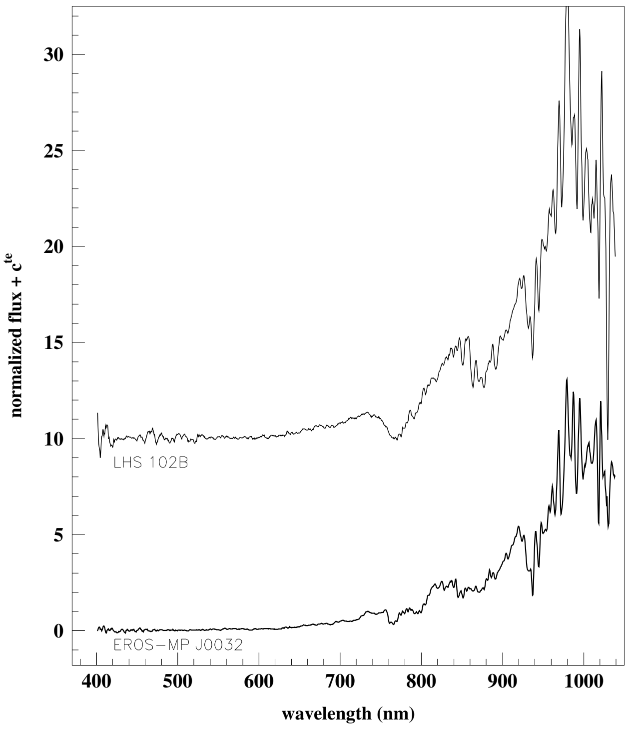


**Fig. 4.** Spectrum of EROS J0032-4405 and LHS 102B (shifted by 10 units), as in Martín et al. 1999. The flux has been normalized to the counts in the region 738–742 nm. See Martín et al. 1999 for details.

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