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LETTER

Letter to the Editor

Field brown dwarfs found by DENIS*

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Abstract. We present three candidate *field* brown dwarfs, identified by the DENIS survey. This on-going three colour survey of the southern sky has, as of July 1997, covered over 30% of the southern hemisphere in the I, J and K_{short} passbands. The enormous sampled volume makes DENIS ideal for detecting brown dwarfs. The present results are based on preliminary processing of about 230 square degrees of DENIS data – a small fraction of the existing sky coverage. This reveals a sizeable population of very cold dwarfs, three of which are at least as cool as GD 165B. Infrared spectra confirm their dwarf status, and provide effective temperature information: one object (DENIS-P J1058.7-1548) is comparable in temperature to GD 165B and a second (DENIS-P J1228.2-1547) is slightly cooler, while a third (DENIS-P J0205.4-1159) is significantly so – though not as cold as Gl 229B. The infrared spectrum of DENIS-P J0205.4-1159 shows evidence for a methane absorption band, which implies an effective temperature much below the stellar limit. Lastly, recent detections of lithium in DENIS-P J1228.2-1547 have proven it to have a substellar mass. This makes it (together with the recently discovered object Kelu-1) the first *bona-fide* isolated field brown dwarf.

Key words: stars: late-type – low-mass – brown dwarfs

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* Partly based on observations obtained at the European Southern Observatory

1. Introduction

The DEep Near-Infrared Survey (DENIS) is a southern sky survey (Copet et al. 1997), which will provide full coverage of the southern hemisphere in two near-infrared bands (J and K′) and one optical band (I). The approximate 3-σ limits of the survey are I=18.5, J=16.5, K=13.5. The major DENIS products will be databases of calibrated images, extended sources, and small objects. The survey started in January 1996 and is expected to be completed within five years. As of April 1997 some 30% of the sky has been observed. One area of research in which such a survey will clearly have a profound impact is the study of brown dwarfs. With a 50% completeness limit of I=18.5, and coverage of the whole southern sky, DENIS is uniquely sensitive to this class of object. Moreover, the optical-infrared I–J and I–K colours provided by DENIS are sensitive probes of effective temperature for very cool objects, so that they can be easily selected from the DENIS catalogues.

Over the last two years a brown dwarf has been found orbiting the nearby star Gl 229 (Gliese 229B, Nakajima et al. 1995), and a number of free floating ones have been identified in the Pleiades cluster (Rebolo et al. 1995; Basri et al. 1996). So brown dwarfs have moved from the realm of abstract theoretical construction, into observational astronomy. However, important issues remain to be addressed.

The two coolest known dwarfs, GD 165B (Becklin & Zuckerman 1988) and GL 229B, have been found as companions to brighter nearby stars. The technique of "looking for things around other things" has therefore been very successful, but unfortunately does not directly determine the local brown dwarf density. The relation between the mass distributions in binaries and in the field is a matter of lively debate (e.g. Kroupa 1995, and Reid & Gizis 1997). Low mass brown dwarfs have also been found in the Pleiades, where recent surveys (Zapaterio Osorio et al. 1997a; 1997b) suggest a rising mass function, $dN/dM{\sim}M^{-1}$ (Martín et al. 1997a). Brown dwarfs may be thus a numerous and dynamically important galactic disk population. However, the IMF in a particular young cluster may not be representative of the disk altogether. Moreover, their present mass function may also have been affected by cluster evaporation, which is a mass sensitive process. It is clearly essential to search for brown dwarfs in the field, which is precisely what DENIS will do.

We present here three objects discovered by DENIS, which are significantly cooler than the coolest known isolated field dwarf star – 2MASP J0345 – which was found with the 2 Micron All Sky Survey proto-type camera (Kirkpatrick et al. 1997a). Soon after the discovery of the three objects discussed in this paper was first announced (Delfosse et al. 1997b), Ruiz (1997) presented observations of Kelu 1, a similar field brown dwarf.

2. The DENIS brown dwarf mini-survey

DENIS observations are carried out on the ESO 1m telescope at La Silla (Chile), with a three channels infrared camera (Copet et al. 1997). Dichroic beam splitters separate the three channels, and focal reducing optics provides image scales of 3” on the 256×256 NICMOS3 arrays used for the two infrared channels and 1” on the 1024×1024 Tektronix CCD detector of the I channel. The instantaneous field of view is 12’ for all three channels, and a focal plane microscanning mirror is used to obtain 1” sampling for the two infrared channels. The sky is scanned in a step and stare mode, along 30 degrees strips at constant right ascension which contitute the basic DENIS observing units.

The sources discussed in this letter were identified during analysis of 230 square degrees of DENIS data at high galactic latitude, which constitutes the “DENIS Brown Dwarf Mini-survey”. The image data were obtained from the Paris processing center and had been processed with the standard pipeline software (Borsenberger 1997). The instrumental and sky background are derived from a local clipped mean along the strip. Flat-field corrections are derived from observation of the sunrise sky, which are analysed by a linear regression of the pixel values on the mean background level of each image. Source detection and photometry were performed in Grenoble, using the SExtractor package (Bertin & Arnouts 1996). The details of the selection process are described in Delfosse et al. (1997), who use the resulting sample to determine the luminosity function of extreme M dwarfs. In this letter we restrict discussion to the three reddest objects (DENIS-P J1228.2-1547, J1058.7-1548 and J0205.4-1159), whose parameters are summarised in Table 1. Figure 1 displays their positions in the I–J/J–K colour-colour diagram, along with some known very low mass stars. These three objects are clearly as red as (or redder than) GD165B, with I–J colours greater than 3.6.

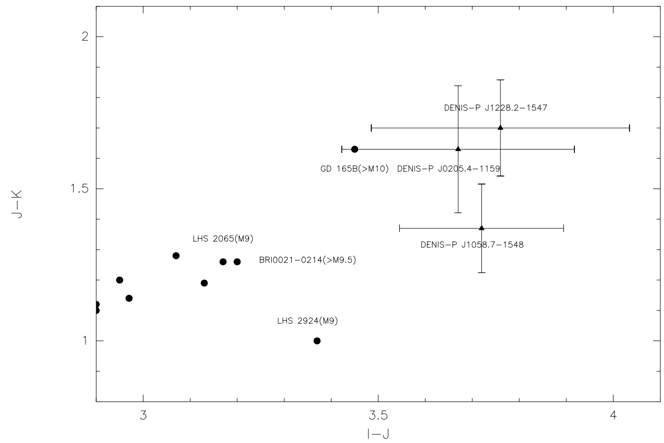

Fig. 1. The I–J/J–K diagram for the three redder DENIS objects. Symbols are: circle: previously known very low mass-stars, triangle: new DENIS objects

3. Infrared spectroscopy

With ± 0.3 magnitude photometric accuracy at its limits, the DENIS survey data by itself cannot provide unbiased samples. Near infrared spectroscopy was thus obtained at the 3.9-m Anglo-Australian Telescope, on the nights of 1996 April 9 and 10 (UT) and 1996 October 21 and 22 (UT). On both runs the Infra-Red Imaging Spectrograph (IRIS – Allen et al. 1993) was used in its cross-dispersed HK echelle mode. This provides complete wavelength coverage from 1.438 – 2.536 μm, at a resolution of $\lambda/\Delta\lambda$ = 440, and a dispersion of $\lambda/\Delta\lambda$ = 780. A slit of width $1.4''$ and length $13''$ was used.

Figure 2 shows the resulting spectra. Because the AAT is a low-altitude site, observations through the atmospheric water vapour bands were impossible. Outside these regions, the spectra show broad *stellar* H_2O absorption bands characteristic of low temperature atmospheres. Other typical cool atmosphere features include: CO bandheads at 2.3-2.4μm; and numerous spectral lines of neutral metals – in particular Na I $\lambda\,2.20\mu$m and Ca I $\lambda\,1.627\mu$m.

The appearance of the spectrum of DENIS-P J1058.7-1548 is similar to that of GD165B, while both DENIS-P J1228.2-1547 and J0205.4-1159 are later. DENIS-P J0205.4-1159 is the coolest of the three, and only Gl 229B has a later spectral type. It is by a significant margin the coldest isolated object identified to date. Its spectrum shows evidence for the onset of absorption by methane at 2.22μm. This feature is present in *both* of the independent spectra which were averaged to produce Figure 2 – leaving us confident of the feature’s reality. Given the presence of methane in the even colder atmosphere of Gl 229B (Allard et al. 1996), its association with this feature in DENIS-P J0205.4-1159 seems reasonable. This would imply a photospheric temperature of $T_{eff} \lesssim 1500$K (cf. Tsuji et al. 1994, Figure 3), which is definitely substellar.

Jones et al. (1994) have shown that L and/or T_{eff} information can be obtained for late-type dwarfs using features in their infrared spectra. In particular, the strength of H_2O (as measured

Table 1. DENIS photometry and positions for the reddest Mini-survey objects. Positions are for epochs that range between 1995.9 – 1996.7 and for equinox J2000.0. They are based on the encoder readings of the ESO 1m telescope and only good to ∼10-20".

name	α	δ (2000)	I	J	K	I–J	J–K	I–K
DENIS-P J1228.2-1547	12:28:13.8	-15:47:11	18.19±0.27	14.43±0.05	12.73±0. 15	3.76±0.27	1.70±0.16	5.46±0.31
DENIS-P J1058.7-1548	10:58:46.5	-15:48:00	17.80±0.17	14.08±0.04	12.71±0. 14	3.72±0.17	1.37±0.15	5.09±0.22
DENIS-P 0205.4-1159	02:05:29.0	-11:59:25	18.30±0.24	14.63±0.06	13.00±0. 20	3.67±0.25	1.63±0.21	5.30±0.31

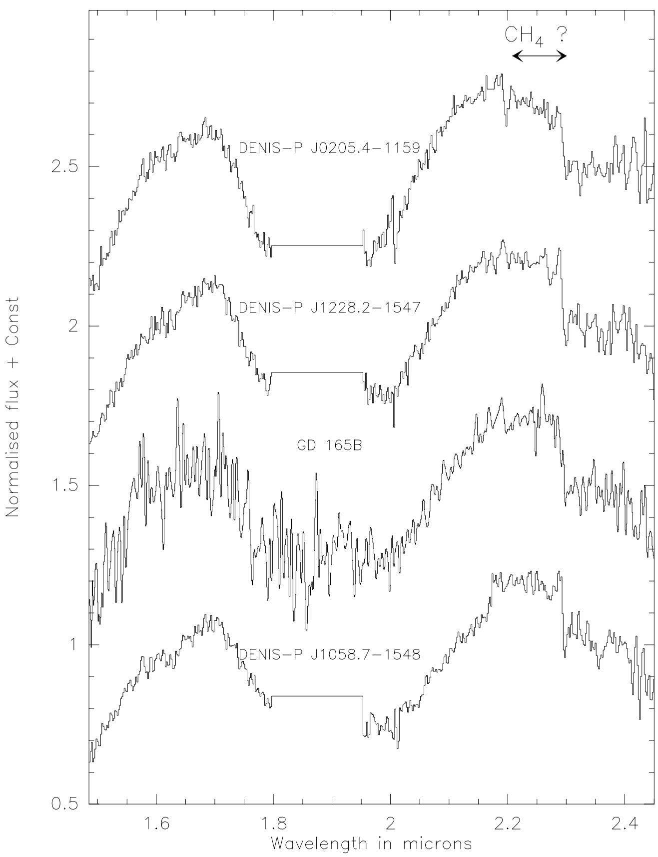

Fig. 2. Near infrared AAT spectra of the three DENIS BD candidates, as well as a comparison spectrum of GD165B (Jones et al. 1994). The 2.18μm break in the spectrum of DENIS-P J1058.7-1548 corresponds to a location where the join between echelle spectrograph orders is not perfect, causing an apparent spectral feature which is not physical.

by the slope of the pseudo-continuum in regions of stellar H_2O absorption) is a sensitive measure. We have used both literature data and our own observations of known late dwarfs to calibrate an empirical relation between these slopes and Mk. In essence, we use the H2O absorption strength, much like a broad band colour, as an estimator of Teff. Moreover, brown dwarfs, as they age, slide *along* an extension of the main sequence in the H-R diagram (D'Antona & Mazzitelli 1985) – the luminosity spread in this main sequence "extension" due to mass differences is ~ 1 magnitude, which is similar to that seen due to metallicity for stars on the main sequence (eg. Tinney et al 1995, fig 3). So in the absence of parallaxes or atmospheric models, infrared spectra can provide luminosity information in the same way that colours do for stars on the main sequence. In particular, we derive the following luminosity estimates (Delfosse et al 1997); DENIS-P J1228.2-1547: M_K = 12.1 ± 0.4, DENIS-P J1058.7-1548: M_K = 11.4 ± 0.4, DENIS-P J0205.4-1159: M_K = 12.3 ± 0.4. These compare with M_K = 11.7±0.2 for GD 165B (Dahn private communication). So, DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159 are of lower luminosity than GD 165B, and only Gl 229B (M_K = 15.5, Matthews et al. 1996) has a lower luminosity.

4. Masses

Recently, Martín et al. (1997b, hereafter MBDF) and Tinney et al. (1997, hereafter TDF) have independently obtained high resolution optical spectra of DENIS-P J1228.2-1547 and J1058.7-1548 – TDF using the Anglo-Australian Telescope; MBDF using Keck I. They both find a very strong 670.8 nm lithium line in the DENIS-P J1228.2-1547 spectrum, and set an upper limit for DENIS-P J1058.7-1548.

Since these very cool dwarfs have been fully convective for extended periods, the lithium detection proves beyond reasonable doubt that the mass of DENIS-P J1228.2-1547 is lower than the lithium burning threshold of ∼0.06 solar masses (Nelson, Rappaport, Chiang 1993), and *a fortiori* that it is a brown dwarf.

The status of DENIS-P J1058.7-1548 and DENIS-P J0205.4-1159 is less clear cut, as one has to rely on model and age-dependent effective temperature arguments. For an age of a few Gyr current models place the transition between stars and brown dwarfs at $T_{eff}{\sim}2000K$ and a spectral type later than M10 (Baraffe & Chabrier 1996, Chabrier et al. 1996), though the recent inclusion of dust formation in atmospheric models (Jones & Tsuji, 1997, Allard 1997a) may change this limit. All three DENIS objects clearly have infrared spectral types later than M10V, as also found in TDF from optical spectra. Dusty atmospheric models provide a best estimate of 1800K for the effective temperature of GD 165B (Allard 1997b, Kirkpatrick et al. 1997b). Given the similarity of its infrared spectrum with that of GD 165B, the effective temperature of DENIS-P J1058.7-1548 is close to 1800 K. The effective temperatures of DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159 are clearly lower than 1800 K. The 2.2μm feature in DENIS-P J0205.4-1159, if indeed due to methane, implies $T_{eff} \lesssim$ 1500K.

Taken together, the data and the available models imply that DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159 are brown dwarfs. DENIS-P J1228.2-1547 *certainly* is, given its Li detection. Given its later spectral type and probable CH_4 detection, DENIS-P J0205.4-1159 must be even cooler, and most likely of lower mass. It will be searched for lithium as soon as it becomes observable later in 1997. DENIS-P J1058.7-1548 is probably

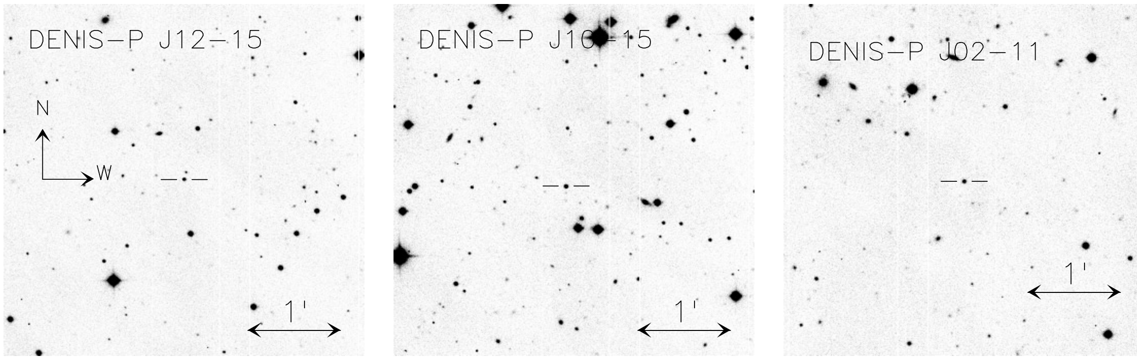

Fig. 3. Finding charts for the DENIS brown dwarf candidates, obtained with a Gunn *i* filter at the Danish 1.54m telescope at ESO (La Silla).

also a brown dwarf, but given the uncertainties in theoretical models, we consider its status – like GD 165B – more uncertain.

Scaling the detection of these three objects to the full survey, DENIS will detect a few hundred brown dwarfs. Once their distances are measured, they will unambiguously establish the luminosities appropriate to brown dwarfs and will define the brown dwarf sequence in the HR diagram. We are measuring the parallaxes of the three objects discussed here, and a parallax follow-up of the brown dwarfs in the full survey is planned. This will provide much needed contraints for brown dwarf interior and atmospheric models. Exciting times are ahead for brown dwarf research.

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