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*Letter to the Editor*

# Keck HIRES spectra of the brown dwarf DENIS-P J1228.2-1547*

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**Abstract.** We report Keck high-resolution echelle spectroscopic observations of two very cool field dwarfs discovered by the near-IR photometric survey DENIS. DENIS-P J1228.2-1547 shows a conspicuous LiI resonance line that confirms it as an incontrovertible brown dwarf (BD). From the presence of Li, and its low surface temperature, we estimate from theoretical models a mass and an age upper limit of $\sim$60 jupiters and $\sim 10^9$ years. The other DENIS object shows no detectable LiI line in our data, and thus we infer a mass $\geq$60 jupiters for it. It could be a high-mass BD or very low-mass star. Both objects have modest radial velocities that suggest they are kinematically young. They show the strongest and broadest resonance line profiles from low ionization species ever seen. The extreme breadth of the KI lines are good further indicators of the expected high gravity in very low-mass dwarfs. We suggest a new spectral class, "L", for objects cooler than M-type (as these are) that do not show TiO molecular bands. The confirmation of at least one field BD in only $\sim$1% of the final DENIS survey is a strong indication of the presence of a numerous population of these objects in the solar neighborhood.

**Key words:** stars: abundances, late-type, low-mass, brown dwarfs, luminosity function, mass function

## 1. Introduction

The first incontrovertible brown dwarfs (BDs) have recently been found using two different strategies: looking for faint members of the Pleiades open cluster (Teide 1; Rebolo et al. 1995), and for companions to nearby stars (Gl 229B; Nakajima et al. 1995). These discoveries provided a breakthrough in our understanding of substellar objects. However, the answer to one of the fundamental questions about BDs, their contribution to Galactic structure and evolution, requires a different approach. We have to look for these objects in wide field surveys, covering large volumes of space.

The main problem with identifying BDs in wide field searches is that they are hard to distinguish from the lowest mass stars. The difficulty arises because the age of a free-floating object cannot be measured with certainty, as it is well known that old very low-mass (VLM) stars and young BDs overlap in the H-R diagram. Until 1995, the coolest dwarf known had been GD 165B (Becklin & Zuckerman 1988) with a $T_{eff}$ of about 1800 K (Tsuji et al. 1996). Evolutionary models indicated that, for solar composition, the lowest mass stars (0.075 $M_\odot$, or equivalently 75 Jupiters) could cool down to $T_{eff}$ as low as 1800 K in about a Hubble time (cf. Burrows et al. 1993, Nelson et al. 1993). Thus, given the current observational and theoretical knowledge, the $T_{eff}$ of GD 165B does not guarantee that it is an ironclad BD.

A method to identify genuine BDs is to use Li as a probe of the central temperature (Rebolo et al. 1992), because this element is destroyed by proton capture at lower temperatures than needed for hydrogen fusion. Theoretical simulations showed that strong Li lines should be observable in BDs (Pavlenko et al. 1995), and Keck observations of Pleiades BDs (Rebolo et al. 1996) confirmed it. The Pleiades BDs, being quite young ($\sim 10^8$ years), have spectral types M7 or later (Martín et al. 1996), similar to VLM old stars. Early extensive searches in field M7–M9.5 dwarfs gave only LiI non detections (Martín et al. 1994, Basri & Marcy 1995). No LiI measurement has yet been reported for GD 165B, which is faint and affected by scattered light from the much brighter GD 165A. Recently, the first LiI detection in a very cool field dwarf was announced (Ruiz 1997). Dubbed Kelu 1, it was discovered in a proper motion survey. The presence of Li has since been confirmed by us (Basri et al. 1997) and Rebolo (1997).

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The discoveries of GD 165B and Gl 229B have prompted considerable advances in the modeling of very cool atmospheres, but they provide little information on the frequency of formation of BDs, and their role in the Galaxy. BDs as companions to other stars might be rare; those two examples were the only positive detections in surveys of hundreds of stars. The best prospects for studying the properties of BDs as a function of age, mass, rotation and metallicity are the searches in open clusters and the field. In both cases candidates are most effectively identified through broad-band photometry in several filters. In clusters the stellar-substellar boundary can be defined by Li observations of a few objects, and afterwards the problem is reduced to confirming membership, which usually does not require very large telescopes. Each field object, on the other hand, is isolated and the Li test has to be carried out for every candidate. There are thresholds in luminosity and temperature below which Li detection guarantees a substellar status (Basri 1997), though a non-detection does not preclude high mass BDs. The main aim of the spectroscopic observations reported in this paper is to apply the Li test to the coolest DENIS BD candidates.

## 2. Sample selection and observations

The first analysis of the DENIS Brown Dwarf mini-survey (DENIS-P) has provided a list of a dozen BD candidates (Delfosse et al. 1997a, hereafter D97), the most interesting of which are three objects with I-J colors similar to GD 165B. These DENIS objects are fortunately ~1.5 mag. brighter than GD 165B, presumably because they are closer (D97).

On 1997, June 2–4 UT, we obtained high-resolution spectra (R=31,000) of DENIS-P J1058.7-1548 and J1228.2-1547 using the HIRES echelle spectrometer mounted on the 10 m Keck I telescope at Mauna Kea, Hawaii. The names of these objects will be abbreviated hereafter to DENIS 10-15 and DENIS 12-15. Their coordinates and IJK magnitudes are given in D97. Details on the instrumental configuration and data reduction procedures are similar to those described in Marcy et al. (1994). We obtained 2 exposures of integration time 2700 s each, and 1 exposure of 1800 s for DENIS 12-15. Only 1 exposure of 2700 s was recorded for DENIS 10-15. We also observed Gl406 (300 s) and LHS2924 (1200 s), for use as reference M-type spectra.

TiO bandheads are quite strong in the mid-M dwarfs, but become weaker in the very late-M dwarfs. The DENIS objects follow the trend of losing TiO towards cooler temperatures, probably due to the depletion of Ti into dust grains of perovskite (Allard 1997). We concur with the suggestion of Kirkpatrick (1997) that a new spectral class is needed for these objects. The M spectral class is defined by the appearance of the TiO molecule, which is not present in these spectra. We float the suggestion that "L" would be an appropriate new class, suggestive of "Low-temperature". The advantage of L is that it is close to M, and there is the precedent that B-type stars designate earlier spectral type than A-type. It would then be possible to have a notation like "$L_{Li}$" and "$L_{CH_4}$" for cool BDs confirmed by Li or methane (along the lines of designations like dMe). The usual subclass numbering and its relation to $T_{eff}$ remain to be worked out. Then, DENIS 12-15 and Kelu 1 would be $L_{Li}$, while DENIS 10-15 and GD 165B would be simply L class. Gl 229B would be a $L_{CH_4}$ object, and PPl15, Teide 1 and Calar 3 could be bd$M_{Li}$. The prefix "bd" in the latter case would be necessary as there is an unfortunate tendency to only remember very cool objects as BDs, despite the fact that we are certain of "hot" BDs in the Pleiades, and almost certain of even younger BDs in star forming regions. It should now be emphasized that BDs can be either M or L spectral class, and that not all L class objects are necessarily BDs according to current theory of the bottom of the main sequence.

The Li spectra of the DENIS objects are displayed in Fig. 1a, together with M dwarfs for comparison. The LiI 670.8 nm line is detected in all three individual spectra of DENIS 12-15, despite the low S/N ratio of ~4 per pixel, because it is very broad (~60 pixels) and the spectrum is quite flat in this region. Our pseudo equivalent width (PEW, measured by direct integration of the line profile area with respect to the local pseudo-continuum) of the LiI resonance feature in DENIS 12-15 is 3.5 Å, much larger than the strongest PEW measured in the Pleiades BDs (1.8 Å, Rebolo et al. 1996). This difference is probably not due to a higher Li abundance in DENIS 12-15, but to the cooler $T_{eff}$, higher gravity, and the suppression of the TiO absorption background against which the LiI line is formed. The S/N ratio of our DENIS 10-15 spectrum is similar to the sum of the three DENIS 12-15 spectra (~6), but shows no hint of a LiI line. We place a 1 $\sigma$ upper limit on the LiI PEW of ~0.5 Å.

Although the DENIS colors of DENIS 10-15 and DENIS 12-15 are similar, their near-IR spectra show that the latter object is significantly cooler (D97). We confirm this in our spectra because we see stronger resonance lines of CsI and RbI. In Fig. 1b we show the CsI 852.1 nm line of the DENIS objects and the two M-dwarfs observed with the same instrumental configuration. The CsI feature becomes stronger with decreasing $T_{eff}$ (with PEWs of 0.24, 0.44, 2.1, and 4.3 Å), as expected from its low excitation potential of 3.9 eV. Model atmosphere fitting to this line should lead to a good $T_{eff}$ scale for the latest M-type and all L-type objects. We also see increasing pressure broadening towards cooler $T_{eff}$. Of particular note is the KI resonance doublet near 770.0 nm (Fig. 1c). Because this is a more abundant species than Cs, Li, or Rb, its profile becomes extremely strong. It produces a feature so broad that it resembles Balmer line profiles in white dwarfs. This enormous feature could be used to help define the L class even at very low dispersion. As in white dwarfs, it is due to the collisional broadening induced by high gravity, though log(g) is still below 6 and the mechanism is Van der Waals rather than Stark broadening (Schweizer et al. 1996). The KI lines of our two DENIS objects are similar, hence they must have similar gravities.

The molecular features near 870 nm are not visibly pressure-broadened, and we use them to determine radial and rotational velocities. This is done by crosscorrelation with Gl 406, whose heliocentric radial velocity is known (19.2±0.1 km $s^{-1}$, Delfosse et al. 1997b). We find 11 and 4 km $s^{-1}$ for DENIS 10-15 and DENIS 12-15, respectively (with an uncertainty of about 5 km $s^{-1}$). The radial velocity of DENIS 12-15 is character-

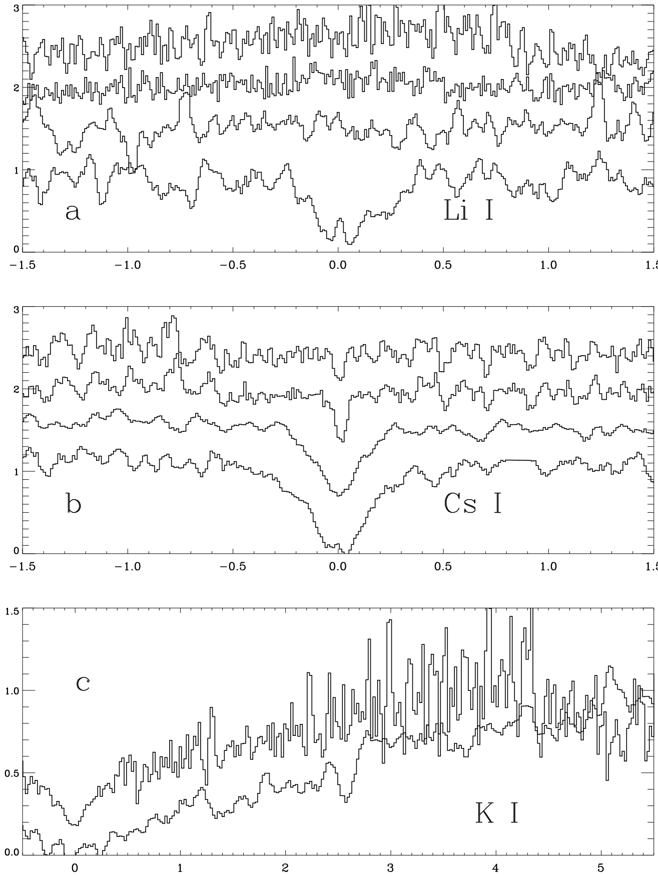


**Fig. 1. a** The resonance LiI line 670.8 nm region in (from top to bottom with offsets of 0.5) Gl 406 (dM6), LHS 2924 (dM9), DENIS 10-15 and DENIS 12-15 . Wavelengths are in nm from line center. The DENIS-P objects are boxcar smoothed by 5 pixels. **b** Same as above but for CsI 852.1 nm. Note the progression in the strength of the CsI feature towards cooler $T_{eff}$. **c** The KI 769.9 nm line of Gl 406 and DENIS 10-15 normalized at 770.5 nm (no offset). The width of this line is so large that it exceeds the coverage of the echelle order.

istic of young disk stars, consistent with other age indicators discussed below. We also estimate rotational $v$ sin$i$ of ≈30 and ≈20 km s$^{-1}$ for DENIS 10-15 and DENIS 12-15 (with an uncertainty of about 10 km s$^{-1}$), respectively, from the widths of the crosscorrelation functions. These continue the trend to find high $v$ sin$i$ in very low-mass dwarfs (Basri & Marcy 1995; Delfosse et al. 1997b).

During the preparation of this manuscript, we learned that the strong LiI feature of DENIS 12-15 was independently confirmed after us by two different groups (Tinney et al. 1997, Rebolo 1997). Interestingly, the LiI PEWs of DENIS 12-15 measured by Rebolo (7 Å) and Tinney et al. (2.3 Å) are quite different than ours. Both Tinney and Rebolo used a lower spectral resolution, so it is not possible to directly compare our results. In particular, Tinney et al. find a weaker LiI line but stronger CsI (using two different resolutions). However, the differences in PEWs seem large enough that they raise the question of whether the lines could be intrinsically variable. Some variability might be expected due to the influence of variable dust condensation

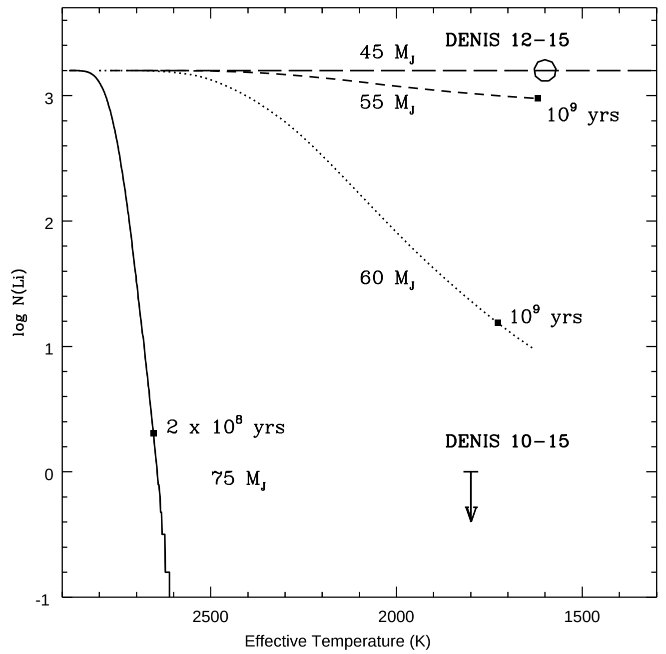


**Fig. 2.** The Lithium-$T_{eff}$ evolutionary relationship from models given by Baraffe (1996). Some relevant masses and ages are labelled. For placing our objects in this diagram, we have assumed that DENIS 12-15 has preserved its initial cosmic Li abundance and that DENIS 10-15 has depleted Li by more than a factor of $10^3$.

on the upper photosphere. Further observations are needed to test this possibility.

## 3. Discussion

The evolution of the Li surface abundance (in the usual scale of log N(H)=12) vs. $T_{eff}$ from recent models (Baraffe 1996) is plotted in Fig. 2. The location of the DENIS objects in this diagram has been estimated under crude $T_{eff}$ and abundance assumptions. For DENIS 10-15, we adopt the $T_{eff}$ of GD 165B (∼1800 K), as justified by their similar infrared colors and spectra, and for DENIS 12-15 we use a slightly cooler $T_{eff}$ of 1600 K. Different calibrations agree within ±300 K and we propagate this uncertainty to our age and mass estimates. We also assume that Li has been depleted by more than three orders of magnitude in DENIS 10-15, and essentially preserved in DENIS 12-15. Their large LiI strength differences justify this hypothesis, since they have similar $T_{eff}$ and gravity. It has been recently pointed out that in objects cooler than ∼2000 K the convection region may start well below the atmosphere and hence the photospheric Li may not be mixed with the interior (Allard 1997). But, as shown in Fig. 2, the depletion of Li in objects with masses ≥60 $M_J$ takes place at $T_{eff}$ ≥2000 K, where mixing should be efficient. Moreover, overshooting probably mixes material in cooler objects. Therefore, we conclude that the Li-test remains valid even for objects cooler than 2000 K.

The location of DENIS 12-15 in Fig. 2 agrees well with the evolutionary behavior for BDs less massive than about 55 $M_J$.

Taking into account the $T_{eff}$ and Li abundance uncertainty, 60 $M_J$ is a conservative upper limit to its mass. An upper limit to its age of $\sim 10^9$ years is also inferred because objects of 55 $M_J$ or less cool to $T_{eff}$ <1600 K for older ages. We obtain similar upper limits to the age and mass of DENIS 12-15 from models kindly given to us by both Baraffe (1996) and Burrows (1997). Our Li non-detection in DENIS 10-15 indicates that it is more massive than DENIS 12-15. Its BD status is ambiguous. The present data can equally well be explained with a (stellar) mass of 75 $M_J$ and an age of $\sim 3\times10^9$ years, or with a (substellar) mass of 65 $M_J$ BD that is $\sim 8\times10^8$ years old. The radial velocity suggests that the younger age, and hence BD mass, might be more appropriate.

It comes as no surprise that the first BD discovered by DENIS is relatively young, because these are more luminous and are favored in a flux-limited survey. In fact, the sensitivity of DENIS does not allow detection of BDs as faint as Gl 229B beyond 6.5 parsecs, implying that few will be found. DENIS will mostly reveal relatively young BDs, similar to or warmer than the objects studied in this work. We have demonstrated that the Li test remains valid for objects even cooler than GD 165B. Lithium observations of field BD candidates should be pursued to estimate individual masses, and pave the way for deriving the field substellar mass function. All field dwarfs later than about M6.5 should be considered as BD candidates because at the age of the Pleiades the substellar limit is located at such spectral type (Martín et al. 1996, Basri 1997).

The presence of one or more BDs in just $\sim$1% of the DENIS survey indicates that a numerous population of free-floating substellar objects lurks in the solar neighborhood. Recent deep photometric surveys of the Pleiades show a numerous BD population, and suggest a mildly rising initial mass function inside the substellar regime (Rebolo et al. 1995, Martín et al. 1997). The first DENIS results suggest that the mass function of the solar neighborhood might also be rising into the substellar domain. The all-sky near-IR surveys DENIS and 2MASS will soon reveal more of our closest substellar neighbors, enabling us to improve our knowledge of the local mass density.

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