THE FIRST L-TYPE BROWN DWARF IN THE PLEIADES

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ABSTRACT

We have obtained low-resolution optical spectra of three faint brown dwarf candidates in the Pleiades open cluster. The objects observed are Roque 12 (Ic = 18.5), Roque 5 (Ic = 19.7), and Roque 25 (Ic = 21.2). The spectrum of Roque 25 does not show the strong TiO band heads that characterize the optical spectra of M-type stars, but molecular bands of CaH, CrH, and VO are clearly present. We classify Roque 25 as an early L-type brown dwarf. Using current theoretical evolutionary tracks we estimate that the transition from M type to L type in the Pleiades (age ~120 Myr) takes place at T eff ~2200 K or M ~0.04 M⊙. Roque 25 is a benchmark brown dwarf in the Pleiades because it is the first known one that belongs to the L-type class. It provides evidence that the initial mass function (IMF) extends down to about 0.035 M⊙ and serves as a guide for future deep searches for even less massive young brown dwarfs.

Subject headings: open clusters and associations: individual (Pleiades) — stars: evolution — stars: fundamental parameters — stars: low-mass, brown dwarfs

1. INTRODUCTION

Until recently there were no convincing observations of brown dwarfs (BDs), but this situation has dramatically changed in only a few years. Currently, observations of several dozen BDs have been reported. These formerly elusive objects have been unambiguously identified in the Pleiades (Rebolo, Zapatero Osorio, & Martín 1995; Basri, Marcy, & Graham 1996; Rebolo et al. 1996; Zapatero-Osorio et al. 1997; Stauffer, Schultz, & Kirkpatrick 1998), ρ Oph (Luhman, Liebert, & Rieke 1997), as well as in the field (Ruiz, Leggett, & Allard 1997; Delfosse et al. 1997; Tinney 1998; Liebert et al. 1998), and as companions to stars (Nakajima et al. 1995; Rebolo et al. 1998). Optical spectra of the coolest BD candidates have shown that they have properties different to those that characterize M-type stars, in particular they do not show prominent TiO bands (Kirkpatrick et al. 1998; Tinney et al. 1998). Thus, it has been proposed to use the term “L type” for stars and BDs that are too cool to be classified as M type (Martín et al. 1997).

Searches for BDs in the Pleiades open cluster have been particularly fruitful because this cluster offers an ideal combination of young age, nearby distance, high metallicity, low reddening, richness (over 800 proper motion members), and compactness. Three recent deep CCD surveys have provided over 50 photometric Pleiades BD candidates. The International Time Project (ITP) CCD survey has covered 1 deg² in the cluster core using IZ filters and reaching a completeness limit of Ic ~ 21.2 (Zapatero Osorio et al. 1997, 1998). The other two new surveys have been presented by Bouvier et al. (1998) and Festin (1998). The luminosity and mass functions inferred from these deep searches suggest that the number of BDs in the Pleiades could be of order of a few hundred (Zapatero Osorio et al. 1997; Martín, Zapatero Osorio, & Rebolo 1998b; Bouvier et al. 1998). The number density of BDs could be similar to that of stars, but they probably do not contribute a significant amount of mass to the cluster. One of the most important open questions about the initial mass function (IMF) is whether there is a minimum mass for fragmentation of molecular clouds. It is important to characterize the properties of the faintest BD candidates discovered by the deep surveys in the Pleiades in order to guide the search for even lower mass objects. L-type objects in young open clusters are especially interesting because they represent very low mass brown dwarfs.

The most secure Pleiades BDs are those with kinematic information that supports cluster membership and lithium detections that confirm their substellar status. The faintest of these BDs are Teide 1 and Calar 3 (Ic = 18.8), which have spectral types of M8 (Martín, Rebolo, & Zapatero Osorio 1996) and masses of 0.055 ± 0.015 M⊙ (Rebolo et al. 1996). Fainter Pleiades BD candidates have been reported by the different surveys cited above. The coolest and faintest BD candidates with published spectra are PIZ 1 (Ic = 19.64; M9; 0.048 ± 0.015 M⊙; Cosssburn et al. 1997) and Roque 4 (Ic = 19.75; M9; 0.045 ± 0.015 M⊙; Zapatero Osorio et al. 1997). We expect that fainter Pleiades BD candidates should be cooler, and thus they should extend the substellar spectral sequence into the new L spectral class. In this Letter we report low-resolution spectroscopic observations of three BD candidates identified by the ITP team (Zapatero Osorio et al. 1998). Two of them have very late M spectral types, and the faintest of the three is indeed the first L-type object identified in the Pleiades cluster.

2. SPECTROSCOPY

The “Roque” BD candidates were discovered in the ITP survey of the Pleiades carried out using the 2.5 m Isaac Newton telescope (Zapatero Osorio et al. 1997, 1998). In Table 1 we list the names and photometry of our program objects. Coordinates, additional photometric data, and finding charts for these and other new Roque objects are provided in Zapatero Osorio et al. (1998).

We observed Roque 25 on 1997 November 3, using the low-resolution imaging spectrograph (LRIS) attached to the Cassegrain focus of the Keck II telescope. The 600/7500 grating
with a slit width of 1.5′ and a binning of 2 × 2 pixels provided a resolution of FWHM ∼ 6.1 Å and a spectral range 634.3–891.2 nm. The total integration time was 6600 s. We also obtained one 1600 s exposure of Roque 12 in the same night. The images were bias subtracted, flat-fielded, sky subtracted, and variance extracted using routines within IRAF. We calibrated in wavelength using the emission spectrum of NeAr lamps. The 1′ dispersion of the third-order polynomial fit was 0.12 Å. The data of Roque 25 were somewhat affected by passing clouds. The telluric water bands are stronger than in the spectra of other targets. No flux standard was observed in this run because we had to close the telescope due to bad weather.

Additional observations of Roque 25 were obtained in service time on 1997 December 17, with LRIS at the Keck II telescope. The instrumental configuration was slightly different than in the November observations. The 600/5000 grating and a 1.0 slit were used. The spectral range was 639.2–896.5 nm, and the resolution was FWHM ∼ 5.4 Å. Two exposures of 1800 s were obtained under photometric conditions. The flux standard star HZ 4 was observed immediately after Roque 25. Using IRAF routines, we reduced the spectra as described above and we corrected for instrumental response. The final spectra of Roque 12 and Roque 25 are shown in Figure 1. In the same figure we also show a low-resolution spectrum of Roque 5, which we obtained at the 4.2 m William Herschel telescope (WHT) on 1997 December 27. The red arm of the ISIS spectrograph was used, with the R158 grating, a slit width of 25′ and a TEK 1024 pix2 detector. The resolution was FWHM ∼ 16 Å, and the wavelength range 629.3–925.6 nm. The integration time was 3000 s. It was corrected for instrumental response using the flux standard G161–B2B observed in the same run. In Figure 1 we have also plotted the spectrum of BRI 0021–0214 obtained by Martín et al. (1996) and a spectrum of Kelu 1 that we obtained at the WHT on 1997 June 16, using ISIS with the R158 grating, a slit width of 1′, and a TEK 1024 pix2 detector. The resolution was FWHM ∼ 6 Å, and the wavelength range 633.1–929.0 nm. The integration time was 2400 s. We used BD +26°2606 as flux standard.

The spectral types of Roque 12 and Roque 5 were measured using the pseudocontinuum indices defined by Martín et al. (1996). They should be accurate to ±0.5 spectral subclasses. Hα emission was detected in Roque 12 and Kelu 1. We give the pseudo-equivalent widths (PEW) (measured with respect to the local pseudocontinuum) in Table 1. For the other objects we provide upper limits. Li i 670.8 nm was detected in Kelu 1, confirming the detection of Ruiz et al. (1997). The spectra of the Pleiades objects were quite noisy in the lithium region. Consequently, the upper limits to the PEW of Li i are very high. The PEW of Li i among Pleiades BDs are observed to range between 0.5 and 2.5 Å (Basri et al. 1996; Rebolo et al. 1996; Martín et al. 1998a; Stauffer et al. 1998). Our Li i PEW upper limits are higher than the expected PEW for Pleiades BDs because of the low-resolution and poor signal-to-noise (S/N) ratio of our data in the lithium region. Hence, our non-detections do not imply that these objects have depleted any lithium. The detection of Li i in Roque 12, Roque 5, and Roque 25 should be pursued because it would be a final confirmation of their substellar status.

### Table 1

| Parameter                      | Roque 12 | Roque 5 | Roque 25 | BRI 0021–0214 | Kelu 1 |
|-------------------------------|----------|---------|----------|----------------|--------|
| \( I_c \)                     | 18.47    | 19.71   | 21.17    | 15.1           | 16.8   |
| \( I_c - K_0 \)               | 3.37     | 4.31    | 4.90     | 4.43           | 4.98   |
| Spectral type                 | M7.5 V   | M9 V    | Early L  | M9.5 V         | Early L|
| Pseudo-equivalent width (Hα) (Å) | 19.7 ± 0.3 | ≤8      | ≤5       | ≤1             | 0.9 ± 0.6 |
| Pseudo-equivalent width (Li i) (Å) | ≤1.5     | ≤8      | ≤5       | ≤0.4           | 4.3 ± 0.6 |
| Pseudo-equivalent width (K i) (Å) | 26 ± 3   | 35 ± 10 | 48 ± 5   | 63 ± 6         | 94 ± 8  |

Note.—The PEW of Hα refers to line emission with respect to the local pseudocontinuum, whereas PEW (Li i) and PEW (K i) refer to line absorption.

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![Fig. 1.—Low-resolution spectra of program objects. All of them have been normalized around 750 nm and are offset in steps of 2. A boxcar smoothing of 3 points has been applied to all the spectra. Note that the spectrum of Roque 5 has lower spectral resolution than the other three spectra (see text for details). Identification of the main spectral features is given in the top. The telluric absorption bands are marked with dashed lines.](image-url)
the number density of early-L objects (like Kelu 1 and GD 165B) found in the DENIS minisurvey (Delfosse et al. 1997). The number density of these objects is 0.01–0.005 pc⁻³ in the solar vicinity. The number density of M₈–M₉ dwarfs is about 4 times lower (~0.0024 pc⁻³; Kirkpatrick et al. 1994). An object like Kelu 1 would appear to lie on the BD Pleiades sequence shown in Figure 2 if it were at a distance of ~90 pc. Since the completeness limit of the 1 deg² ITP survey was $I \sim 21$, the probability to find one field object like Kelu 1 at a distance of 90 ± 5 pc is in the range 25%–10%. Moreover, there were four objects occupying the same region as Roque 25 in the $(I, I-Z)$ diagram of Zapatero Osorio et al. (1998). Hence, the probability that Roque 25 is a field object rather than a Pleiades member is less than 6%. We argue below that our spectroscopic observations support indeed that Roque 25 belongs to the cluster.

For Roque 12, we obtain a heliocentric radial velocity of $+9 \pm 12$ km s⁻¹ in the reference frame of the star VB10 ($v_{rad} = +35$ km s⁻¹), consistent with cluster membership (Martín et al. 1998a; Stauffer et al. 1998). Our spectra of Roque 5 and 25 do not allow us to obtain precise radial velocities because of their low S/N ratio. Another membership criterion is to consider gravity-sensitive spectral indicators. Pleiades BDs should be typically younger than field VLM stars and BDs, and consequently they should have larger radii and lower gravities. Martín et al. (1996) found that Teide 1 and Calar 3 have slightly weaker Na i doublet (818.3 nm, 819.5 nm) and stronger VO bands than field stars of similar spectral type. Luhman et al. (1997) reported that the Na i lines are much weaker in an extremely young M₈.5 BD belonging to the ρ Oph star-forming association than in field M₈–M₉ stars. In L-type objects the Na i IR doublet becomes very weak because it is not a resonance line. In Roque 25 the Na i lines are not detected. The absorption feature at ~820 nm is probably due to a telluric H₂O band (Fig. 1). On the other hand, L-type objects develop extremely broad K i resonance doublets (766.5 nm, 766.9 nm; Martín et al. 1997; Tinney et al. 1998). Spectral synthesis calculations (Ya. Pavlenko 1997, private communication; P. H. Hauschildt 1998, private communication) show that the breadth and strength of the K i doublet is very sensitive to gravity and temperature. The K i lines become narrower and weaker for lower gravity and/or higher temperature. We have found that the K i doublet in Roque 25 is indeed weaker and narrower than in the field VLM star BRI 0021–0214. The PEWs measured with respect to the pseudocontinuum at ~780 nm are given in Table 1. Owing to the large breadth of the two K i lines, their wings are blended and hence we measured the PEW of the whole doublet. The spectrum of Roque 25 is quite similar to that of the BD Kelu 1 (Ruiz et al. 1997), as might be expected from their similar I – K colors (Table 1). However, some differences are clear (Fig. 1). Roque 25 has weaker K i doublet and stronger VO bands. We conclude that Roque 25 must have lower gravity than BRI 0021–0214 and Kelu 1 and hence it is a younger, lower mass object. Thus, the gravity-sensitive features in the spectrum of Roque 25 strongly support its membership to the young Pleiades cluster.

The optical spectrum of Roque 25 is characterized by the following features: (1) the lack of strong molecular absorption band heads in the range 640–760 nm—in particular, the strong TiO bands starting at 705.0 nm that are conspicuous in Roque 12 and can still be seen in Roque 5 are absent or extremely weak in Roque 25; (2) the molecular systems of CaH, CrH, and FeH become as strong or stronger than the systems of TiO and VO; (3) the atomic lines of K i and Cs i that are very
strong in L-type objects (Ruiz et al. 1997; Martín et al. 1997; Tinney, Delfosse, & Forveille 1997; Tinney et al. 1998) are weaker in Roque 25. Using the models of Baraffe et al. (1998) and the photometry of Zapatero Osorio et al. (1998), we infer $T_{\text{eff}} \sim 2350$ K and 2050 K for Roque 5 and Roque 25, respectively.

The transition from M to L has to take place at a temperature slightly below that of Roque 5. Pleiades BDs with $T_{\text{eff}}$ intermediate between Roque 5 and 25 should exist (the ITT, Nordic Optical Telescope [NOT], and Canada-France-Hawaii Telescope [CFHT] surveys have revealed a few candidates), and we expect that they will have a spectral type around L0 and $T_{\text{eff}} \sim 2200$ K. The temperature of Roque 25 estimated from the evolutionary models is warmer than the $T_{\text{eff}}$ of 1900 K obtained by Ruiz et al. (1997) for Kelu 1, consistent with the bluer $I - K$ color of Roque 25 (Table 1). Consequently, Roque 25 should be assigned a slightly earlier L-type subclass than Kelu 1. The calibration of the L-type temperature scale will have to await systematic observations of a large number of L-type objects and a good understanding of their atmospheres. We emphasize that the Pleiades BDs are very useful for calibrating the L-type class because the differences along the cluster spectral sequence should depend on mass and $T_{\text{eff}}$, with age and metallicity being approximately constant (this is by no means the case for field objects).

The chromospheric activity diminishes with decreasing mass along the Pleiades sequence. Roque 5 and 25 do not show strong Hα emission, consistent with the trend of decreasing chromospheric activity for decreasing temperature observed among Pleiades VLM members (Zapatero Osorio et al. 1997). The same tendency is also present among field very late M dwarfs (Basri & Marcy 1995). L-type field dwarfs do not usually have strong Hα emission (Martín et al. 1997; Tinney et al. 1998), although some exceptions do exist (Liebert et al. 1998). The lack of strong Hα emission in Roque 25 indicates that L-type objects are not very active even when they are quite young.

In this work the Pleiades spectral sequence has been extended from the coolest M types (Roque 4, Roque 5, PIZ 1) to the beginning of the L-type class (Roque 25). We have found that Roque 25 has photometric and spectroscopic properties supporting that it is a Pleiades L-type brown dwarf. The discovery of Roque 25 indicates that the cluster IMF extends to masses as low as $\sim 0.035 M_\odot$. Very deep surveys should address the problem of whether there is a lower mass cutoff of the IMF. The minimum mass for BD formation could be close to the deuterium burning mass limit ($\sim 0.012 M_\odot$; cf. Burrows et al. 1997), as suggested by estimates of the minimum fragmentation scale of molecular clouds. The large $I - K$ color of Roque 25 indicates that near-IR large format cameras or mosaics would be advantageous to extend the Pleiades BD sequence to extremely low-mass objects. Future surveys should be sensitive to late L-type objects like those found in the field (Delfosse et al. 1997; Liebert et al. 1998; Kirkpatrick et al. 1998). L-type objects in the Pleiades would generally be less massive than their field counterparts because they are younger.

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