NEW BROWN DWARFS IN THE PLEIADES CLUSTER

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ABSTRACT

We present intermediate- and low-resolution optical spectroscopy (650–915 nm) of seven faint, very red objects (20 > I ≥ 17.8, I – Z ≥ 0.5) discovered in a CCD-based IZ survey covering an area of 1 deg² in the central region of the Pleiades open cluster. The observed spectra show that these objects are very cool dwarfs having spectral types in the range M6–M9. Five out of the seven objects can be considered Pleiades members on the basis of their radial velocities, Hα emissions, and other gravity-sensitive atomic features like the Na i doublet at 818.3 and 819.5 nm. According to current evolutionary models, the masses of these new objects range from roughly 80 M_Jup for the hottest in the sample down to 45 M_Jup for Roque 4, the coolest and faintest confirmed member. These observations prove that the cloud fragmentation process extends well into the brown dwarf realm, suggesting a rise in the initial mass function below the substellar limit.

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

1. INTRODUCTION

In the last 2 years, with the discoveries of the first bona fide brown dwarfs (BDs; Rebolo, Zapatero Osorio, & Martín 1995; Nakajima et al. 1995), it has been proved that objects with masses between those of stars and planets can be formed in nature. Because of its youth and proximity, the Pleiades star cluster is an ideal hunting ground for substellar objects (see Hambly 1997 for a review). The discovery of BDs like Teide 1 and Calar 3 in a small survey of the Pleiades (Zapatero Osorio et al. 1997b) suggests that a large number of very low mass objects may populate this cluster. If this is the case, astronomers have a unique opportunity to establish the observational properties of these rather elusive objects and to characterize the initial mass function beyond the star-BD boundary.

With the aim of searching for new Pleiades BDs, Zapatero Osorio et al. (1997c) have performed a deep CCD IZ survey covering 1 deg² in the central region of the cluster. More than 40 faint (I ≥ 17.5), very red (I – Z ≥ 0.5) objects have been detected down to I ~ 22. Their location in the I-Z color diagram suggests cluster membership. According to the “NextGen” theoretical evolutionary models of Chabrier, Baraffe, & Plez (1996), they should have masses in the interval 80–30 M_Jup (1 M_Jup ~ 10⁻⁷ M☉). In this Letter, we present spectroscopic observations for seven of the candidates with magnitudes in the interval I = 17.8–20 mag. We have determined spectral types, radial velocities, and Hα emissions that allow us to assess their membership and, therefore, their substellar nature.

2. OBSERVATIONS AND RESULTS

We have collected intermediate- and low-resolution spectra in optical wavelengths for the objects listed in Table 1 (the full name of the objects is Roque Pleiades, hereafter “Roque”) using the William Herschel Telescope (WHT; Observatorio del Roque de los Muchachos, La Palma) and the Keck II telescope (Mauna Kea Observatory, Hawaii). Table 1 summarizes the log of the observations. Finding charts for these objects are provided in Zapatero Osorio et al. (1997c). Figure 1 depicts the color-magnitude diagram of our 1 deg² survey in which the locations of the new BD candidates are indicated. Our targets were chosen to be fainter than HHJ 3 (Hambly, Hawkins, & Jameson 1993) and with (I – Z) colors redder than those given by an extrapolation of the borderline denoting the separation between cluster members and field objects.

The instrumentation used was the ISIS double-arm spectrograph at the WHT (we used only the red arm) with the grating R158R and a TEK (1024 × 1024 pixel²) CCD detector and the LRIS spectrograph with the 830 and 1200 line mm⁻¹ gratings and the TEK (2048 × 2048 pixel²) CCD detector at the Keck II telescope. The nominal dispersions and the wavelength coverage provided by each instrumental setup are listed in Table 1. Slit width projections were typically 3 pixels, except for the observations of Roque 14 and 15, for which the seeing conditions forced us to have a slit width projecting onto 5 pixels. Exposure times ranged from 30 minutes to 1 hr for the faintest objects. Spectra were reduced by a standard procedure using IRAF, which included debiasing, flat-fielding, optimal extraction, and wavelength calibration using the sky lines appearing in each individual spectrum (Osterbrock et al. 1996). Finally,
TABLE 1

| Object       | Telescope  | Dispersion (Å pixel⁻¹) | Δλ (nm) | Date (1996) |
|--------------|------------|------------------------|---------|-------------|
| Roque 4 & 11; Calar 3 | Keck II 1.83 | 654–833               | Dec 3   |
| Roque 11     | Keck II 0.63 | 654–775               | Dec 4   |
| Roque 13, 14, 15, 16 & 17; PPI 15 | WHT 2.90 | 650–915               | Dec 8–9 |

The observed spectra clearly correspond to very late M-type dwarfs showing prominent VO and TiO molecular absorption bands and rather strong atomic lines of K i (766.5 and 769.9 nm) and Na i (818.3 and 819.5 nm). In Table 2, we give accurate spectral types derived by measurements of the pseudocontinuum PC 1–4 indices (Martín, Rebolo, & Zapatero Osorio 1996), as well as the derived radial velocities and the equivalent widths of some atomic lines (Hα and Na i) present in the spectra. The VO index (Kirkpatrick, Henry, & Simons 1995), also measured, was found to be consistent with late spectral types (M6–M9). Radial velocities were obtained by cross-correlating the spectra in the regions 654–700 nm, 730–750 nm, and 840–880 nm with templates observed using the same instrumental configuration. These templates were LHS 248 (M6.5V; Basri & Marcy 1995) and Calar 3 (M8; Rebolo et al. 1996). We have not measured radial velocities for Roque 14 and 15 because the resolution of their spectra is rather low (∼15 Å). We note that for Roque 11, spectra of two different resolutions (∼2 and 6 Å) are available, and the radial velocities agree well with each other.

There are several spectroscopic indicators that allow us to investigate the membership of our objects in the Pleiades. Cluster members are found with radial velocities in the range 0–14 km s⁻¹ (Stauffer et al. 1994). All our candidates with radial velocity measurements clearly meet this criterion within the estimated error bars. Further evidence for membership is given by the presence of Hα in emission. According to Stauffer et al. (1994) and to Hodgkin, Jameson, & Steele (1995), Hα equivalent widths among very cool cluster members seem to be greater than 3 Å. We find that all of our targets, except Roque 4, share this characteristic, which supports their membership. The lack of Hα in emission in Roque 4 (M9) should not be interpreted as inconsistency with membership because...
the behavior of this line for Pleiades later than M8 is unknown. It could be that beyond a certain temperature, activity decreases considerably in the atmospheres of such cool objects, and Hα may be no longer seen in emission. The sensitivity of the Na i doublet to gravity makes it, too, useful as a membership criterion (Steele & Jameson 1995; Martín et al. 1996). We find that the equivalent width of this doublet is lower in our objects than in field stars with similar spectral type and temperature, indicating lower gravity and hence, younger age. Finally, as expected for true Pleiades, our objects nicely fit and extend the sequence delineated by very low mass cluster members in the I magnitude versus spectral type diagram of Martín et al. (1996).

We conclude on the basis of all the above spectroscopic membership criteria that five of our objects (Roque 4, 11, 13, 16, and 17) are very likely members of the cluster. Additional support is provided by our K-band measurements that locate them in the Pleiades IR photometric sequence (Zapatero Osorio, Martín, & Rebolo 1997a). We remark that Roque 11 is a photometric and spectroscopic “twin” of Teide 1 and of Calar 3 and that Roque 4 could be the least luminous and coolest cluster member yet found, being very similar in appearance to PIZ 1 (Cossburn et al. 1997). These two Roque objects together with Roque 13 can be classified as genuine BDs, while Roque 16 and 17 might be transition objects lying in the region between stars and BDs. To reach a definitive conclusion on the membership status of Roque 14 and 15, we shall await radial velocity measurements and IR photometry.

We find higher VO indices and more intense TiO molecular bands in the M8 and M9 Pleiades than in field dwarfs with the same spectral types. This might be associated with the formation of dust in the atmospheres (Tsuji, Ohnaka, & Aoki 1996) and its dependence on gravity. The larger the gravity is, the larger the pressure, which favors the formation of grains at cool temperatures. Young BDs have lower gravities than field objects and, therefore, dust molecules (silicates and grains) may condense less efficiently. The effect of grain formation is to decrease the number of vanadium, titanium, and oxygen atoms in the gas phase and therefore the abundance of the molecular species of VO and TiO, resulting in a more transparent atmosphere in field dwarfs than in young BDs at optical wavelengths.

3. DISCUSSION AND FINAL REMARKS

In order to estimate the mass of our objects, we must first derive their luminosities. One can convert IK photometry and spectral type to bolometric luminosity by employing relationships derived for cool field dwarfs (Jones et al. 1994, and references therein) and averaging the results. Good agreement (+0.15 dex) has been found between luminosities derived from different calibrations. We have adopted a distance modulus of 5.53 to the Pleiades, an extinction of $A_V = 0.07$ mag and $M_\text{bol} = 4.76$ mag for the Sun. The resulting luminosities are given in Table 2. Masses have been inferred by comparing these luminosities with the theoretical evolutionary tracks for an isochrone of 120 Myr provided by Chabrier et al. (1996). We find that Roque 16 and 17 have masses in the range 80–60 $M_{\text{Jup}}$ similar to PPl 15 (Basri, Marcy, & Graham 1996), and thus may help to define the star-BD boundary in the Pleiades cluster. Roque 13 has a mass between those of PPl 15 and Teide 1. Roque 11 resembles Teide 1 and Calar 3, and hence we infer the same mass (55 ± 15 $M_{\text{Jup}}$; Rebolo et al. 1996). Since Roque 4 is 0.2 dex less luminous than Roque 11, its mass is 10 $M_{\text{Jup}}$ smaller according to the same models, and thus it is the least massive BD in our sample. An object with similar photometric and spectroscopic characteristics, PIZ 1, has been found by Cossburn et al. (1997), although it still lacks a radial velocity measurement. Recently, the Hipparcos satellite has provided new parallax measurements, deriving a Pleiades distance modulus of 5.32 mag (van Leeuwen & Hansen-Ruiz 1997). This would impose a reduction in our luminosities by 0.08 dex. Lower luminosities should lead to an older cluster age (up to about 130–150 Myr). However, a closer distance and an older age roughly compensate without introducing significant changes in the masses determined above.

We recall that lithium is preserved in BDs less massive than 65 $M_{\text{Jup}}$ during their whole lifetime, in marked contrast with low mass stars ($M \lesssim 0.3 M_{\odot}$), which significantly destroys this element at very young ages. The reappearance of lithium, although dependent on age and mass, should take place in a quite short luminosity range (see, e.g., D’Antona & Mazzitelli 1994). At the age of the Pleiades, the lithium- and hydrogen-burning mass limits coincide, which makes this cluster ideal for characterization of the substellar borderline. According to theoretical predictions, Roque 11 and 4 have fully preserved their initial lithium content and will never deplete it, while our remaining higher mass BDs are destroying or are about to destroy their lithium. Until now, only PPI 15 was considered to be on the borderline between BDs and stars in the Pleiades. Additional measurements of lithium in objects with similar characteristics are needed in order to provide a better location of this boundary as well as an improved age determination for

Table 2: Data for Our Pleiades BDs

| Name       | R.A. (J2000) | Decl. (J2000) | I  | I − K | Na i (Å) | Hα (Å) | $v_{\text{rad}}$ (km s$^{-1}$) | log $L/L_\odot$ |
|------------|--------------|--------------|----|-------|---------|-------|-------------------------------|----------------|
| Roque 16   | 3 47 39.0    | 24 36 22     | 17.79 | 3.18 | M6      | 4.7   | 5.0 −20 ± 15                  | −2.89           |
| Roque 15   | 3 45 41.2    | 23 54 11     | 17.82 | ...  | M6.5    | 6.0   | 4.0 ...                      | −2.86           |
| Roque 17   | 3 47 23.9    | 22 42 38     | 17.78 | 3.45 | M6.5    | 4.5   | 15.0 −14 ± 15                | −2.83           |
| Roque 14   | 3 46 42.9    | 24 24 50     | 18.21 | ...  | M7      | 5.0   | 17.0 ...                     | −3.00           |
| Roque 13   | 3 45 50.6    | 24 09 03     | 18.25 | 3.65 | M7.5    | 5.4   | 10.5 −1 ± 15                 | −3.00           |
| Roque 12   | 3 47 12.1    | 24 28 32     | 18.73 | 3.63 | M8      | 4.8   | 5.8 −6 ± 12                  | −3.15           |
| Roque 11   | 3 43 35.5    | 24 31 11     | 19.75 | 4.52 | M9      | 4.7   | <5 +4 ± 12                   | −3.35           |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Coordinates are accurate to ±3″. The uncertainty in the spectral type determination is ±0.5 subclasses. Typical error bars for the equivalent widths of the atomic lines are ±1 Å. Luminosities are given to a relative accuracy of ±0.02 dex owing to errors in the photometry. All error bars are given at 1σ.

* Radial velocity measured from the high-resolution spectrum obtained at the Keck II telescope.
the cluster (Basri et al. 1996). The observation of lithium in Roque 4, which is cooler than Teide 1, is also important as it would give key information on the formation of lithium lines in the atmospheres of very cool dwarfs. This is a subject of increasing importance given the detections of lithium in recently discovered extremely cool field dwarfs (Ruiz, Leggett, & Allard 1997; Martín et al. 1997a; Tinney, Delfosse, & Forveille 1997; Rebolo et al. 1997).

Only a small fraction (∼17%) of the BD candidates found in our Iz survey (see Fig. 1) have been investigated in this paper. We have collected follow-up low-resolution optical spectroscopy for seven of the brighter candidates (I < 20). These observations confirm cluster membership for five of them and indicate that the other two are likely members, although radial velocity measurements are still required. The number of remaining candidates in the explored area is large enough to ensure that follow-up spectroscopic and infrared observations will confirm many more BDs. Among the faintest ones, there could be BDs with masses as low as 30 MJup.

Our spectroscopic results show that a high percentage of the objects found in the Zapatero Osorio et al. (1997c) photometric survey in the Pleiades may indeed be true cluster members. The number of BD candidates identified indicates a continuing rise of the initial mass function (IMF; dN(m)/dM ∝ M−3+) across the stellar-substellar boundary. A preliminary estimate of the slope index can be found in Martín et al. (1997b), which gives α = 1 ± 0.5. A similar IMF slope was found by Meusinger, Schilbach, & Souchay (1996) for Pleiades members with masses in the range 1.0–0.4 MJ and by Hambly & Jameson (1991) for the range 0.5–0.1 MJ. Even though the IMF appears to rise up to about 45 MJup it is not steep enough for BDs in the mass range 75–45 MJup to make a significant contribution to the total mass of the cluster. However, their population is probably quite numerous, 200–300 in the whole cluster area. If the IMF is extrapolated toward very low masses, say 10 MJup (roughly the deuterium-burning limit), the total number of BDs in the cluster would be increased to the order of 1000 objects, and thus BDs may even double the number of known members in the Pleiades. Nevertheless, they would not contribute significantly to the mass of the cluster (providing less than 5% the mass contained in stars). Assuming that the sub-stellar Pleiades IMF is representative of field objects and normalizing to the local volume density of M0–M8 dwarfs identified within d = 5 pc (0.0726 stars pc−3; Lang 1992), we find that, in the solar neighborhood, BDs with masses 80–40 MJup could be as numerous as M-type dwarfs.

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