The first spectroscopically identified L dwarf in Praesepe

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ABSTRACT

We have obtained a low-resolution optical spectrum for one of the faintest cluster member candidates in Praesepe with the Optical System for Imaging and low Resolution Integrated Spectroscopy mounted on the 10.4 m Gran Telescopio de Canarias. We confirm spectroscopically the first L dwarf member in Praesepe, UGCS J084510.66+214817.1. We derived an optical spectral type of L0.3±0.4 and estimated its effective temperature to $T_{\text{eff}}=2279\pm371$ K and a mass of $71.1\pm23.0\,M_J$, according to state-of-the-art models, placing it at the hydrogen-burning boundary. We measured the equivalent width of the gravity-sensitive sodium doublet at 8182/8194Å, which adds credit to the membership of this new L dwarf to Praesepe. We also derived a probability of $\sim20.5\%$ that our candidate would be a field L0 dwarf. We conclude that this object is likely to be a true member of Praesepe, with evidence of being a binary system.

Key words: open clusters and associations: individual: Praesepe — stars: low-mass, brown dwarfs — stars: fundamental parameters — techniques: spectroscopic.

1 INTRODUCTION

More than 900 L dwarfs have been confirmed spectroscopically so far, most of them nearby and old (i.e. $\geq 1$ Gyr). Nonetheless, some of them have been observed in young (i.e. $\leq 10$ Myr) star-forming regions and confirmed spectroscopically, e.g. in Upper Scorpius (Lodieu et al. 2008), Taurus (Luhman et al. 2008), σ Ori (McGovern et al. 2004; Zapatero Osorio et al. 2000), Trumpler 14 (Barrado y Navascués et al. 2001; Martin et al. 2001), Chamaeleon I (Luhman et al. 2008), Trapezium (Lucas et al. 2006), ρ Oph (Alves de Oliveira et al. 2012), NGC 1333 (Scholz et al. 2012). To the contrary, very few L dwarf candidates have been confirmed spectroscopically as L dwarf members of older clusters with ages greater than 10 Myr. Except in the case of the Pleiades where near-infrared spectroscopic follow-up of L dwarf candidates has been conducted (Bihain et al. 2010), no other spectroscopic L dwarf has been announced in regions like IC 2391 (50 Myr; Barrado y Navascués et al. 2004), α Per (85 Myr; Barrado y Navascués et al. 2004), Blanco 1 (132 Myr; Cargile et al. 2010), or the Hyades (625 Myr; Perryman et al. 1998), to cite only a few examples. L dwarfs contract and cool with time, becoming fainter with age (Dantona & Mazzei 1985; Burrows et al. 2001), making spectroscopic follow-up in these old clusters challenging with current instrumentation. However, such spectroscopic observations are of prime importance to define spectral type vs effective temperature as a function of age for L dwarfs (Kirkpatrick 2003; Cruz et al. 2009) and to trace the early evolution of brown dwarfs (Luhman 2012).

Praesepe is an important open cluster that can contribute to this goal considering its age ($590^{\pm150}_{-120}$ Myr; Fossati et al. 2008), as this would help to fill the gap between L dwarfs known in young populations (i.e. $\leq 10$ Myr) and the old L dwarfs in the field (i.e. $\geq 1$ Gyr). Praesepe is also in interesting target to search for L dwarfs, considering its distance ($181.97^{+150}_{-120}$ pc; van Leeuwen 2009), significant proper motion ($\mu_\alpha \cos \delta = -35.81^{\pm0.29}$ mas/yr and $\mu_\delta = -12.85^{\pm0.24}$ mas/yr; van Leeuwen 2009), and the low extinction towards the cluster ($E(B-V)=0.027^{\pm0.004}$ mag; Taylor 2006). In Boudreault et al. (2012) we presented 1,116 candidate cluster members from an analysis of a near-infrared (ZYJHK) wide-field survey of 36 square degrees in Praesepe carried out by the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) Galactic Clusters Survey (GCS) and released in the Ninth Data Release (DR9).

We have initiated a spectroscopic follow-up of the homogeneous samples of low-mass member candidates extracted from the UKIDSS GCS in Praesepe. The objectives are two-fold (1) obtain well-defined spectroscopic samples of late-M and early-L dwarfs with known ages and distances, and (2) confirm spectroscopically the discrepancy observed between the lower-end of the Praesepe and Hyades mass functions.
namely, a decrease in the Praesepe mass function of only \(\sim 0.2\) dex from 0.6 down to 0.1\(M_\odot\), compared to \(\sim 1\) dex for the Hyades (Boudreault et al. 2012).

Among our Praesepe candidates, one object has the colours of field L dwarfs (\(Z – J = 2.36\) mag and \(J – K = 1.39\) mag; Hewett et al. 2006; Schmidt et al. 2010). This object, UGCS J084510.66+214817.1 (hereafter GCS0845), is plotted in a vector-point diagram and a colour-magnitude diagram in Fig. 1.

In this letter, we confirm spectroscopically the first L dwarf selected from our sample of photometric and astrometric cluster member candidates in Praesepe (Boudreault et al. 2012). In Section 2 we describe the spectroscopy and the data reduction. We derive the spectral type in Section 3, determine the effective temperature (\(T_{\text{eff}}\)) and mass of GCS0845 in Section 4, and discuss its membership likelihood in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

The observations of GCS0845 were carried out in service mode on the night of 16 January 2013 with the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS) mounted on the 10.4 m Gran Telescopio Canarias (GTC) in the Roque de Los Muchachos Observatory in La Palma (Canary Islands). We used the R300R grism and a 1.0 arcsec slit with a \(2\times2\) binning, yielding a spectral resolution of \(R = 348\) at 6865 \(\AA\). This configuration shows contamination from the second order light redwards of 9000 \(\AA\). Therefore, we restrain the range of analysis of our spectra to the 6000–9000 \(\AA\) wavelength range. We observed our target with six on-source integrations of 700 sec on the same night with a dither pattern of 10 arcsec along the slit, giving a total exposure of 1h10m.

We also observed three field dwarfs with known optical spectral types with the same instrumental setup: 2M0251+2521 (M9), 2M0345+2540 (L0), and 2M0030+3139 (L2; Kirkpatrick et al. 1999). They are over-plotted on the spectrum of our target as red lines in Fig. 2. We observed field L dwarfs with spectral types bracketing our target to derive a spectral type. Also we can compare the EW of the gravity-sensitive Na I doublet in our cluster candidate with the ones of field dwarfs to better constrain the membership of GCS0845. Log of the observations are provided in Table 1.

The spectra were reduced using standard IRAF packages (Tody 1986, 1993). First, the standard CCD reduction steps (overscan subtraction, trimming, and flat-fielding) were performed on a nightly basis using the ccdrred package. After extraction of the spectra, we performed the wavelength calibration using a combination of HgAr, Ne and Xe lamps. We calibrate our targets in flux with the spectrophotometric standard star G191–B2B (Oke 1990) and Ross 640 (Oke 1974).

3 OPTICAL SPECTRAL TYPE

We derived the spectral type of GCS0845 in three ways. First, we directly compared the optical spectrum of our target with field dwarfs with known spectral types (Fig. 2 and 3). Second, we computed the root-mean-square (RMS or residuals) between the spectrum of GCS0845 and those of field dwarfs with known spectral types, normalising
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Table 1. Dates of observations, number of exposures (nbr.), exposure times, and signal-to-noise ratio (SNR) of the spectra at $\lambda 8600\,\AA$.

| Object     | Date of observations | Exp. time | SNR |
|------------|----------------------|-----------|-----|
|            | dd/mm/yyyy           | nbr. x sec|     |
| GCS0845    | 16/01/2013           | 6 x 700 sec | 34  |
| G191–B2B   | 16/01/2013           | 1 x 7.5 sec | >120|
| 2M0251+2521 (M9) | 22/08/2012      | 1 x 60 sec | 41  |
| 2M0345+2540 (L0) | 22/08/2012     | 1 x 60 sec | 36  |
| 2M0030+3139 (L2) | 22/08/2012     | 1 x 60 sec | 63  |
| Ross 640   | 22/08/2012           | 1 x 60 sec | >120|

Figure 2. GTC/OSIRIS optical spectrum of GCS0845 (black thick line), classified as a L dwarf and a cluster member candidate of Praesepe, based on proper motion and photometry. Overplotted are the spectra of field dwarfs (Kirkpatrick et al. 1999) observed with the same instrumental configuration: 2M0251+2521 (M9; red dotted line), 2M0345+2540 (L0; dash-dotted line), and 2M0030+3139 (L2; red dash line). All spectra are normalised at 7500Å with offset of +1 between each spectra for clarity.

In Fig. 2 we present the spectrum of GCS0845 and the spectra of the field dwarfs (Kirkpatrick et al. 1999) observed with OSIRIS: 2M0251+2521 (M9), 2M0345+2540 (L0), and 2M0030+3139 (L2). Visually, the best agreement is obtained for the L0 dwarf rather than for the M9 or L2 dwarfs. We also compared GCS0845 with other field dwarfs of known spectral types from the literature (see below for references).

We computed the residuals between the spectrum of our target and those of the field dwarfs observed with OSIRIS. We used a normalisation in six different wavelength regions with a width of 25Å and centered at 6500 Å, 7000Å, 7500Å, 7900Å and 8250Å. This allows us to (1) know which reference star gives the best agreement at different normalised regions, and (2) to confirm, quantitatively, that the spectral type determination is not influenced by the normalisation point. The RMS values are presented in Table 2 both for the field dwarfs observed with the same instrumental configuration and field dwarfs from the literature. We observe that the best agreement with our optical spectrum is for the L0 dwarf 2M0345+2540 normalised at 6500Å, 7900Å and at 8250Å. On the other hand, the best agreement with the spectra taken from the literature is with the L1 dwarf 2M1439+1929.

Figure 3. Same as Fig. 2 but the spectrum of GCS0845 is compared to those of other field dwarfs with known spectral types taken from the literature not observed with GTC/OSIRIS: the 2M0251+2521 (M9.0; Kirkpatrick et al. 1999), 2M1733+4634 (M9.5; Gizis et al. 2000), 2M0058–0651 (L0.0; Kirkpatrick et al. 2000), 2MJ0147–3453 (L0.5; Kirkpatrick et al. 1999), and 2M1439+1929 (L1.0; Kirkpatrick et al. 1999) from bottom to top. All spectra are normalised at 7500Å with offset of +1 between each spectra for clarity.
normalised at 7500Å. However, considering the other similar RMS values for the L0 dwarf 2M0058−0651 with normalisation at 7500Å and for the L0.5 dwarf 2M0147+3453 with normalisation at 8250Å, we consider that the agreement taken with spectra from the literature span from L0 to L1, hence assuming an L0.5.

Finally, we used three spectral indices (CrH−a, Rb−b/TiO−b, and Cs−a/VO−d) from Kirkpatrick et al. (1999) defined in their Table 7 and also the PC3 spectral index from Martin et al. (1999). We report the values of the spectral indices and their associated spectral types in Table 5. The spectral indices CrH−a and Rb−b/TiO−b are consistent with the ones of a L0 and a L2 dwarf respectively, while the spectral index Cs−a/VO−b suggests a later type closer to L1. The PC3 spectral index suggests a spectral type of L0.1 or L1.4.

We took the average of all the spectral type determinations (2×L0 from the optical visualisation, L0 and L0.5 from the residuals, and L0.9 from the spectral indices) and used the standard deviation to estimation of the error. We derive a spectral type of L0.3 with a standard deviation of 0.4 subclass for GCS0845.

4 EFFECTIVE TEMPERATURE AND MASS

We used the average and standard deviation of our spectral type (L0.3±0.4) to derive the spectroscopic \( T_{\text{eff}} \) of GCS0845. We used three \( T_{\text{eff}} \) vs spectral type relations to derive the effective temperature: from Stephens et al. (2001), Burgasser (2001), and Dahn et al. (2002). The \( T_{\text{eff}} \) vs spectral type relation of field L dwarfs from Stephens et al. (2001) gives 2190±40 K, while the \( T_{\text{eff}} \) vs spectral type relation from Burgasser (2001) gives us 2338±98 K. No equations of \( T_{\text{eff}} \) vs spectral type are provided by Dahn et al. (2002). Therefore, we apply a linear regression between the \( T_{\text{eff}} \) and spectral type values of the M and L dwarfs with known parallaxes from Dahn et al. (2002; their Table 5). With this we obtain \( T_{\text{eff}} = 2310±35 \) K. Taking the average of these estimates and adding the errors in quadrature, we derive \( T_{\text{eff}} = 2279±371 \) K for GCS0845.

With the derived \( T_{\text{eff}} \) and using an evolutionary track for objects with dusty atmospheres (DUSTY; Chabrier et al. 2000), at the age of Praesepe (590+120−100 Myr; Fossati et al. 2008) following Boudreault et al. (2012), we inferred a spectroscopic mass of 71.6±15.0 M\(_{\text{Jup}}\) for GCS0845. If we repeat the same procedure with the recent BT-Settl models (Allard et al. 2012), we obtain a mass of 70.5±17.5 M\(_{\text{Jup}}\). The errors on the masses take into account the uncertainties on the age of the cluster. Taking the average of these values, we derive a mass of 71.1±23.0 M\(_{\text{Jup}}\), which places GCS0845 at the stellar/substellar boundary at \( \approx 70 \) M\(_{\text{Jup}}\) (assuming a solar composition; Chabrier & Baraffe 2000). The lithium feature at 6708Å would address its substellarity. However, the low signal-to-noise ratio at the location of LiI at \( \lambda 6708 \) Å does not allow us to draw conclusions about its presence. This, and considering the error on the mass determination of GCS0845, it not possible to contain its stellar or substellar nature.

5 DISCUSSION ON MEMBERSHIP

As mentioned previously, the low signal-to-noise ratio at the location of the Hα at \( \lambda 6563 \) Å does not allow us to draw conclusions about its presence or to measure its equivalent width (EW). Because of our low spectral resolution, we do not resolve the gravity-sensitive NaI doublet at 8182/8194Å because of the low spectral resolution of our spectra. We measured an EW of 6.0±2.5Å for the unresolved NaI doublet of GCS0845 whereas we obtained 11.4±0.5Å, 8.4±1.2Å, and 18.4±1.8Å for the field dwarfs 2M0251+2521, 2M0345+2540 and 2M0030+3139. The EW of the gravity-sensitive feature of GCS0845 is 1σ lower than the field L0 dwarf 2M0345+2540, more than 2σ lower than the field M9 dwarf 2M0251+2521, and more than 4σ lower than field L2 dwarf 2M0030+3139. We advocate cautiousness with these measurements, considering that the NaI doublet is not resolved but only its merged feature at 8188Å. However, our measurements point towards an object with a lower surface gravity than the field objects. This is consistent with the age of Praesepe (590+120−100 Myr) being younger than those of the field dwarfs (i.e. > 1 Gyr).

In order to establish a membership probability for GCS0845, we used the local density of field L0 dwarfs around the Sun from Caballero et al. (2008), which is \( \approx 7 \times 10^{-4} \) pc\(^{-3}\). We defined a total volume of \( \approx 23,450 \) pc\(^3\) for our survey of Praesepe, considering its coverage (\( \approx 36 \) square degrees; Boudreault et al. 2012) and that the cluster candidates span \( \approx 1 \) mag at around the Z−J colours of GCS0845 (Fig. 1). We find \( \approx 16.4 \) L0 field dwarfs at the location of Praesepe, which would have been mistakenly considered as cluster members with photometry only. On the other hand, a field L0 dwarf at the location of Praesepe could have a random proper motion as high as 67 mas/yr (corresponding to a tangential velocity of \( \approx 100 \) km/s, which is observed for some late-type dwarfs in the field; Faherty et al. 2012), giving a total coverage of \( \approx 14,000 \) mas/yr\(^2\) in the vector point diagram, while our target is within 1.5σ around the mean motion of Praesepe, yielding 175 mas/yr\(^2\) (i.e. 1.25%). Hence, we estimate a total of \( \approx 0.205 \) L0 field dwarf with photometry and astrometry consistent with Praesepe, equivalent to a probability of \( \approx 20.5\% \) that our target is a field dwarf. This number is consistent with the upper limit of contamination in the astrometric and photometric selection of cluster candidate members from Boudreault et al. (2012): 23.8% for masses below 0.15 M\(_{\odot}\).

We used the calibrated absolute magnitude \( M_J\) vs spectral type relations from Hawley et al. (2002) and Dahn et al. (2002) to derive the observed magnitude of GCS0845 at the distance of Praesepe (m−M = 6.3 mag), obtaining \( J = 18.15±0.15 \) mag and \( J = 18.23±0.17 \) mag, respectively. The errors on the \( J \) magnitudes reflect the uncertainty on our spectral type determination. These values are

\[ 3 \] The error on this value of \( T_{\text{eff}} \) is higher because, in addition to the error on the spectral type, we include the error on our linear regression of the values from Dahn et al. (2002).
not consistent with the observed magnitude of GCS0845 in UKIDSS GCS ($J = 17.42 \pm 0.03$ mag). However, these numbers would match with the observed magnitude of GCS0845 if this object is a binary system. The later would be consistent with the location of GCS0845 in the ($Z - J, Z$) colour-magnitude diagram in Fig. [1] the cluster sequence is observed from ($Z - J, Z$) ~ $1.3, 17.0$ to $(2.3, 20.5)$ with the binary sequence ~$0.75$ mag above it, where GCS0845 lies.

Considering that GCS0845 was originally selected as a photometric and astrometric member (Baudreault et al. 2012), has a spectral type consistent with the colours of a L dwarf, has a gravity-sensitive feature suggesting an age younger than ~1 Gyr, and has a ~79.5% probability of belonging to Praesepe, we conclude that GCS0845 is most likely a member of Praesepe. However, absolute magnitude $M_J$ vs spectral type relations do not support this conclusion, unless GCS0845 is a binary system, an argument also suggested by its location in the ($Z - J, Z$) diagram.

GCS0845 represents a new L dwarf with a known age and distance that is amenable to further investigation. This object will also guide current and future deep pencil-beam surveys to look for bona-fide brown dwarf members in Praesepe.

Table 2. RMS values for various regions of normalisation (column 1) between GCS0845 and the field dwarf presented in Fig. 2. We also give the RMS values for the field dwarfs presented in Fig. 3.

| Object                  | CrH–a | Rb–b/TiO–b | Cs–a/VO–b | PC3 | Avg |
|-------------------------|-------|------------|-----------|-----|-----|
| GCS0845                 | 0.015 | 0.984 | 0.840 | 10.144 | L0.9 |
| 2M0251+2521 (M9)        | 0.010 | 0.590 | 0.711 | 8.328 | M8.3 |
| 2M0345+2540 (L0)        | 1.118 | 0.656 | 0.708 | 9.935 | L1.0 |
| 2M0030+3139 (L2)        | 1.402 | 0.916 | 0.970 | 10.26 | L1.4 |

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