The intermediate-age brown dwarf LP 944-20

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1 INTRODUCTION

LP 944-20 may possibly rank as one of the most overlooked objects in the astronomical literature. It was first catalogued by Luyten & Kowal in 1975, and remained unobserved for a further 15 years until it was independently re-discovered as a possible very late star by the Automated Plate Measuring machine (APM) colour QSO survey of Irwin, McMahon & Hazard (1991a). This survey, alongside its main aim of finding high-redshift quasars, turned up a number of extremely red objects, which were subsequently determined to be M dwarfs (Kirkpatrick, Henry & Irwin 1997; Irwin, McMahon & Reid 1991b). The re-discovery of LP 944-20 lead to it being given the new name of BRI0337-3535, by which it was referred to in the literature for several years before its original identification was pointed out by Kirkpatrick et al. (1997). Photometry of LP 944-20 has been published by Kirkpatrick et al. (1997) and Tinney (1996) – the latter work also presenting a trigonometric parallax. The data presented here were obtained in 1994 February as part of a study of the velocities of the lowest mass stars (Tinney & Reid, 1998).

2 OBSERVATIONS AND ANALYSIS

High-resolution spectra of a sample of very low-mass (VLM) stars were obtained using the Cassegrain Echelle Spectrograph (CASPEC) on the ESO 3.6-m telescope on the night of 1994 February 8 (UT). The resolution obtained was 16 km s$^{-1}$ at 6708 Å, at a dispersion of 9 km s$^{-1}$ pixel$^{-1}$. The wavelength range covered was 6400 to 9100 Å, although redwards of 8040 Å the wavelength coverage is not complete and suffers inter-order gaps. The data were reduced using the FIGARO data reduction system (Shortridge 1993) in a standard manner; the steps included bias subtraction, flat-fielding, cosmic ray cleaning, echelle order straightening, object extraction, wavelength calibration, blaze function correction and flux calibration. The data processing and analysis will be described in more detail by Tinney & Reid (1998).

Fig. 1 shows the region around the Li $\lambda$ 6708 line in three of the objects observed; LP 944-20, and the canonical late M-dwarfs LHS 2065 and LHS 2397a. Table 1 shows the observational details relating to these three objects, together with estimates of their spectral type from Kirkpatrick et al. (1995, 1997), and absolute magnitudes based on trigonometric parallaxes. Also shown in Table 1 are the heliocentric radial velocities derived for these objects by cross-correlation with the spectrum of VB8, which is assumed to have a radial velocity of +14.5 ± 1 km s$^{-1}$ (Tinney & Reid, 1998).

The obvious feature in Fig. 1 is the presence of an absorption near the wavelength of Li $\lambda$ 6708 line in LP 944-20 – and the absence of such a feature in LHS 2065 and LHS 2397a. Both of the latter are known to have depleted their Li, with Martin, Rebolo & Magazzù (1994) placing 1.65σ upper limits on their Li $\lambda$ 6708 equivalent widths (EWs) of 0.15 and 0.7 Å (respectively). Because of the strength of molecular absorption in the spectra of VLM stars, it is almost impossible to fit a true continuum for the purpose of estimating absorption EWs. Therefore, the spectrum of LHS 2065 was used as a template continuum. Its spectral type of M9V (Kirkpatrick, Henry & Simons 1995) makes it a close match in type to the ≥M9V of LP 944-20. The LHS 2065 spectrum was smoothed with a 1.5-pixel Gaussian (to decrease its shot noise), redshifted to the apparent radial velocity of the LP 944-20, and suitably normalized. The resulting EW = 0.53 ± 0.05 Å, where the uncertainty is determined by the photon counting errors shown in Fig 1. A fit to the position of the Li $\lambda$ 6708 absorption indicates an apparent radial velocity of +30.4 ± 4 km s$^{-1}$, or a heliocentric radial velocity of +12.6 ± 4 km s$^{-1}$ – consistent with the radial velocity obtained by cross-correlation on the entire spectrum (cf. Table 1). In

ABSTRACT

Observations are presented which show that Li $\lambda$ 6708 is detected with an equivalent width of 0.53 ± 0.05 Å in the proper-motion object LP 944-20 (which is also known as BRI0337-3535). HeI is detected in emission at an equivalent width of 1.2 ± 0.5 Å. The detection of Li implies a mass less than 0.065 M$_\odot$, making this object a brown dwarf. Moreover, the relative weakness of this Li detection (compared to the equivalent widths of 1–2 Å seen in objects of similar spectral type in the Pleiades) implies that Li has been somewhat depleted. This, together with the precisely determined luminosity of LP 944-20, implies a mass between 0.056 and 0.064 M$_\odot$, and age between 475 and 650 Myr. This makes it the first brown dwarf to have a well-constrained mass and age determined.

Key words: stars: individual: LP 944-20 – stars: low-mass, brown dwarfs.
the observing configuration Li I falls in two orders of the echellogram – the line was clearly detected in both orders, although with lower significance than seen in Fig. 1, which shows the merged orders.

H α is detected in emission – but only weakly, with an emission EW = 1.2 ± 0.5 Å, a full width at half maximum of < 50 km s⁻¹ and at a heliocentric velocity of 0 ± 10 km s⁻¹.

3 DISCUSSION

Kirkpatrick et al. (1997) have assigned a spectral type of ≥ M9V to LP 944-20, making it similar to, or slightly cooler than, LHS2924 (M9V), and giving an approximate effective temperature of 2200 K (Jones et al. 1994). The coldest available Li models are those of Pavlenko et al. (1995) at $T_{\text{eff}}$ = 2500 and 2000 K. They show that for EW = 0.53 Å the curve of growth is insensitive to temperature, and implies a Li abundance of $n$(Li) ≈ 0.0 ± 0.5 [where $n$(H) = 12]. Further confidence in this low Li abundance can be obtained by comparing the 0.53 Å observed in LP 944-20, with the 1.8 ± 0.4 and 1.0 ± 0.2 Å seen in M8V Pleaides members Calar 3 and Teide 1 by Rebolo et al. (1996). Based on these detections both Rebolo et al. (1996) and Pavlenko (1997) estimate $n$(Li), 3 for these objects. The lower equivalent width seen in LP 944-20 gives confidence that the $n$(Li) ≈ 0.0 ± 0.5 we estimate is reasonable. Further, given the likely initial abundance of $n$(Li), 2–3, this means that although Li is certainly present, it has been depleted by 1.5–3.5 dex.

Table 1. CASPEC Observations – 1994 February.

| Name             | Date (UT) | Time (s) | $I$  | $I-K$ | $M_K$  | $M_{\text{bol}}$ | Spectral Type | $V_{\text{hel}}$ (km s⁻¹) |
|------------------|-----------|----------|------|-------|--------|------------------|---------------|-------------------|
| LP 944-20 (BRI 0337-3535) | 1994 Feb 8 | 3600     | 14.16 | 4.58  | 11.10±0.06$^d$ | 14.32±0.07 | M9V             | 10.0±2.0          |
| LHS2065 (LP 666-9) | 1994 Feb 7 | 5400     | 14.44 | 4.46  | 10.33±0.05$^d$ | 13.53±0.05 | M9V             | 9.2±2.0           |
| LHS2397a (LP 732-94) | 1994 Feb 7 | 5400     | 15.05 | 4.26  | 10.02±0.06$^d$ | 13.22±0.07 | MBV             | 34.1±2.0          |

$^a$ – $M_{\text{bol}}$ derived using BC$^a$ of Tinney, Mould & Reid 1993. $^b$ – Kirkpatrick et al. 1997, 1995. $^c$ – Tinney 1996. $^d$ – Monet et al. 1992; Tinney et al. 1993. $^e$ – Monet et al. 1992; Tinney 1996.

Figure 2. Lithium depletion versus luminosity models in the brown dwarf regime, owing to Nelson et al. (dashed lines) and Chabrier et al. (solid lines). The masses of each model sequence is indicated, as sample logarithmic ages. The shaded region shows the location of the LP944-20 error box in this plane.
The known luminosity of LP944-20 and its Li depletion enable us to constrain its mass and age. Assuming $M_{\odot} = 4.72$, the $M_{\odot}$ of LP944-20 implies $\log(L/L_\odot) = -3.84 \pm 0.03$. Interiors models including the effects of Li depletion have been constructed by Chabrier, Baraffe & Plez (1996), Ushomirsky et al., (1997), Nelson, Rappaport & Chiang (1994), and D’Antona & Mazzitelli (1994). The models of Ushomirsky et al., however, cannot be directly compared with our data, because they present results in terms of $T_{\text{eff}}$ instead of luminosity. In Fig 2, we plot the relevant models in $\log(n$(Li)/$n$(Li)) versus luminosity from Chabrier et al. and Nelson et al. The shaded region represents the error box imposed by our luminosity and lithium depletion results. Chabrier & Baraffe (1997) state that the Li destruction produced by the older generation of Nelson et al. (1994) models is less efficient than that in the newer models owing to ‘the grey approximation, which yields larger $L$ and $T_{\text{eff}}$ and thus central densities, favouring the onset of degeneracy’ ... and also smaller Graboske et al. screening factors’. We therefore consider the Chabrier et al. (1996) models to be the best currently available, but also show the Nelson et al. models to give some idea of the sort of model-dependent uncertainties, which may be present in our derived mass and age for LP944-20, and because they lie on a denser mass grid.

Bearing this in mind we conservatively estimate by interpolating between the Chabrier et al. models that the age of LP944-20 lies somewhere in the range 475–650 Myr and that its mass lies in the range 0.056–0.064 $M_\odot$. This makes it considerably older than the brown dwarfs known in the Pleiades (Basri, Marcy & Graham 1996; Rebolo et al. 1996), but considerably younger than a typical old disc star. This is by far the most precise mass and age estimate yet derived for a brown dwarf. This is because of (1) the precise luminosity determination and (2) the location of LP944-20 in a part of the $n$(Li)/$L$ diagram, where there is little degeneracy between age and mass.

The Hα emission detected is at a very low level. It is, for example, significantly lower than the EW = 3–10 À seen in similar mass Pleiades-age objects (Zapatero-Osorio et al. 1997; Hodgkin, Jameson & Steele 1995; Stauffer et al. 1994) implying an age $\approx 150$ Myr. In fact the level of emission is more like that seen in the brown dwarf DENIS-P J11228.2-1547, which has age $\approx 1$ Gyr (Tinney, Delfosse & Forveille 1997). The level of chromospheric activity therefore argues for an age in the 200–1000 Myr range.

4 CONCLUSION

The discovery of a $\approx 500$ Myr brown dwarf which (other than having Li in its spectrum) looks just like a M9V very low-mass star, adds considerable support to the interpretation of the object 296A (Thackrah, Jones & Hawkins 1997) as a brown dwarf. In spite of a clear Li detection, the brown dwarf nature of this object has been questioned because of its very early M6V spectral type. The discovery of the brown dwarf nature of LP944-20, however, suggests a sequence of $\sim 0.06 M_\odot$ objects can be constructed from very faint and probably old ($\sim 1$ Gyr) brown dwarfs like DENIS-P J11228.2-1547 and Kelu-1 (Tinney et al. 1997; Ruiz, Leggett & Allard 1997); through somewhat younger (500–1000 Myr) brown dwarfs like LP944-20; to roughly Pleiades age brown dwarfs like 296A.

LP944-20 is the first brown dwarf for which tight (i.e. $\pm 10$ per cent) constraints can be placed on mass and age – largely owing to the knowledge of a precise luminosity, and despite being only able to guess at the initial Li abundance (which means that even with better data and modelling it is unlikely that the error bars on the Li depletion will fall much below 0.5 dex). It is clear that parallax programs targeted at objects like Kelu-1, DENIS-P J1228.2-1547 and 296A are essential to a more complete understanding of the mass and age of field brown dwarfs.

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