Primeval very low-mass stars and brown dwarfs – II. The most metal-poor substellar object

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ABSTRACT
SDSS J010448.46+153501.8 has previously been classified as an sdM9.5 subdwarf. However, its very blue $J - K$ colour ($-0.15 \pm 0.17$) suggests a much lower metallicity compared to normal sdM9.5 subdwarfs. Here, we re-classify this object as a usdLL1.5 subdwarf based on a new optical and near-infrared spectrum obtained with X-shooter on the Very Large Telescope. Spectral fitting with BT-Settl models leads to $T_{\text{eff}} = 2450 \pm 150$ K, [Fe/H] = $-2.4 \pm 0.2$ and log $g = 5.5 \pm 0.25$. We estimate a mass for SDSS J010448.46+153501.8 of 0.086 $\pm$ 0.0015 M$_{\odot}$ which is just below the hydrogen-burning minimum mass at [Fe/H] = $-2.4$ ($\sim$0.088 M$_{\odot}$) according to evolutionary models. Our analysis thus shows SDSS J0104+15 to be the most metal-poor and high-mass substellar object known to-date. We found that SDSS J010448.46+153501.8 is joined by another five known L subdwarfs (2MASS J05325346+8246465, 2MASS J06164006–6407194, SDSS J125637.16–022452.2, ULAS J151913.03–000030.0 and 2MASS J16262034+3925190) in a ‘halo brown dwarf transition zone’ in the $T_{\text{eff}}$–[Fe/H] plane, which represents a narrow mass range in which unsteady nuclear fusion occurs. This halo brown dwarf transition zone forms a ‘substellar subdwarf gap’ for mid L to early T types.

Key words: brown dwarfs – stars: chemically peculiar – stars: individual: SDSS J010448.46+153501.8 – stars: low-mass – stars: Population II – subdwarfs

1 INTRODUCTION
Theoretical studies have shown that primordial Pop III stars were predominantly very massive ($M \gtrsim 100$ M$_{\odot}$; Bromm, Coppi, & Larson 2002; Yoshida et al. 2006). However, Chieffi et al. (2001) and Siess, Livio, & Lattanzio (2002) have reported a mechanism to form metal-free intermediate and low-mass stars ($M = 1–8$ M$_{\odot}$), and more recently numerical simulations have demonstrated that metal-free stars with masses down to $\sim$0.1 M$_{\odot}$ can form due to recurrent/periodic gravitational instability (Clark et al. 2011; Greif et al. 2011; Basu, Vorobyov, & DeSouza 2012). The initial mass function at 0.01–4 M$_{\odot}$ (including brown dwarfs and stars) is likely independent of metallicity within 0.01–3 Z$_{\odot}$, according to numerical simulations of star formation from turbulent cloud fragmentation (Bate 2014).

Searches for very metal-poor (VMP, $-3 < \text{[Fe/H]} < -2$; Beers & Christlieb 2005) and Pop III stars have to-date generally focused on F- and G-type dwarfs, and G- and K-type turn-off stars, which are bright and can be studied fairly easily with high-resolution optical spectra (for metallicity determination). The majority of known VMP dwarf and giant stars have masses of 0.6–0.8 and 0.8–1.0 M$_{\odot}$, respectively. Very low mass stars (VLMS; $M \approx 0.08$–0.5 M$_{\odot}$) that are 4–10 mags fainter, have not previously been specifically targeted for VMP and Pop III stars in general. Although VLMS is the most numerous population, the number of known M-type VMP stars (Gizis 1997; Burgasser & Kirkpatrick 2006; Lépine & Scholz 2008; Zhang et al. 2013; Kirkpatrick et al. 2016; Lodieu et al. 2017) is significantly smaller than that of F- and G-type VMP stars (e.g. Soubiran et al. 2016). Mean-
while, substellar object with \([\text{Fe}/\text{H}] \lesssim -2.0\) has not been reported in the literature to-date.

The nuclear fusion in VLMS is dominated by the pp I chain reaction, which fuses hydrogen in the central part of VLMS, and the reaction efficiency is lower in stars with lower masses. Therefore, VMP VLMS reflecting the chemical composition of the gas from which they formed. They could provide crucial clues to the star formation history and the synthesis of chemical elements in the early Universe. M subdwarfs have masses in the range \(\sim 0.09-0.5 \, M_\odot\) and represent the majority of metal-deficient VLMS, according to the mass function of the Galactic halo (e.g. fig. 8 of Chabrier & Baraffe 2003). L subdwarfs are expected to be a mixture of the least massive metal-deficient stars and brown dwarfs across the hydrogen-burning minimum mass (HBMM; \(\sim 0.08-0.087 \, M_\odot\), depending on metallicity; Baraffe et al. 1997; Chabrier & Baraffe 1997). The most metal-poor L subdwarfs are particularly interesting, because they represent low-mass stellar and substellar formation within an extremely low-metallicity environment.

There are currently 36 L subdwarfs reported in the literature (see table 4 in Zhang et al. 2017 and table 4 in Lodieu et al. 2017). L subdwarfs are classified into three metallicity subclasses, subdwarf (sdL), extreme subdwarf (esdL) and ultra subdwarf (usdL), based on optical and near-infrared (NIR) spectra (Zhang et al. 2017), that extends and follows the nomenclature of subclasses of M subdwarfs (Lépine, Rich, & Shara 2007). The metallicity ranges of usdL, esdL, and sdL subclasses are: \([\text{Fe}/\text{H}] \lesssim -1.7, -1.7 < [\text{Fe}/\text{H}] \lesssim -1.0\) and \(-1.0 < [\text{Fe}/\text{H}] \lesssim -0.3\), respectively. The five most metal-poor objects were re-classified as L ultra subdwarfs (usdLs), including 2MASS J16262034+3925190 (2MASS metal-poor objects were re-classified as L ultra subdwarfs \(< Z. H. Zhang et al.

This is the second paper of a series under the title ‘Primeval very low-mass stars and brown dwarfs’. In the first paper of the series, we reported the discovery of six new L subdwarfs, defined a new classification scheme for L subdwarfs and derived the atmospheric properties of 22 late type M and L subdwarfs (Zhang et al. 2017). The observations of SDSS J0104+15 are presented in Section 2 of this paper. Section 3 presents constraints of characteristics of SDSS J0104+15, and discussions on the HBMM and the halo brown dwarf transition zone. Finally Section 4 presents a discussion of our results.

2 OBSERVATIONS

2.1 Photometry

SDSS J0104+15 was first detected in the IR band by the Digitized Sky Survey II on 1992 September 25. It was also detected by the SDSS in the \(r, i\) and \(z\) bands on 1999 October 13, and by the UKIDSS Large Area Survey (ULAS) in the \(J, H\) and \(K\) bands on 2008 October 20, and in the \(H\) and \(K\) bands on 2007 November 25. It was detected by the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) in the \(W1\) and \(W2\) bands on 2010 July 13. It was observed by the Pan-STARRS1 (PS1; Chambers et al. 2016) in the \(i_p, z_p\), and \(y_p\) bands with a mean epoch on 2012 December 27. Fig. 1 shows the SDSS i-band finder chart of SDSS J0104+15. It was selected as an ultracool subdwarf candidate by its red \(i-J\) and blue \(J-K\) colours, and was classified as an sdM9.5 subdwarf based on an optical spectrum (\(\lambda/\Delta \lambda \approx 350\)) obtained with the FOcal Reducer and
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low dispersion Spectrograph 2 (FORS2; Appenzeller et al. 1998) on the Very Large Telescope (VLT) on 2012 November 07 (Lodieu et al. 2017).

Fig. 2 shows the $i-J$ and $J-K$ colours of L subdwarfs compared to those of main sequence stars and brown dwarfs, with BT-Settl model colours (Allard, Homeier, & Freytag 2014) over plotted. SDSS J0104+15 is located below and to the left of the three previously known usdL subdwarfs, indicating that SDSS J0104+15 could have a lower metallicity. However, the low-resolution FORS2 optical spectrum is not good enough (in terms of wavelength coverage and resolution) for tight constraints of $T_{\text{eff}}$, $[\text{Fe/H}]$ and radial velocity (RV) of SDSS J0104+15.

2.2 VLT spectroscopy

We obtained an optical to NIR spectrum of SDSS J0104+15 with X-shooter (Vernet et al. 2011) on the VLT on 2016 September 10 under excellent seeing conditions (0.43 arcsec as measured by differential image motion seeing monitor) and an average airmass of 1.7. The X-shooter spectrum was observed in an ABBA nodding mode with a 1.2 arcsec slit which provides a resolving power of 6700 in the VIS arm and 4000 in the NIR arm. The total integration time was 3480 s in the visible (VIS) and 3600 s in the NIR. A wavelength and flux calibrated 2D spectrum of SDSS J0104+15 was reduced with European Southern Observatory (ESO) Reflex (Freudling et al. 2013). The 1D spectrum was extracted from the 2D spectrum with IRAF1 task APSUM. Telluric correction was achieved using the B9 star HD182719 which was observed a few minutes before SDSS J0104+15 at an airmass of 1.64. The spectrum of SDSS J0104+15 has signal-to-noise (SNR per pixel) of ~29 at 800 and ~10 at 1300 nm. Spectra plotted in Fig. 3 are smoothed by 101 pixels (boxcar smooth with IRAF SPLOT), which increased the SNR by a factor of 10 and reduced the resolving power to ~ 600–400.

1 IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
Figure 3. The optical–NIR spectrum of SDSS J0104+15 compared to SSSPM J1013−13. The spectrum of SSSPM J1013−13 is from Burgasser (2004b). Spectra are normalized near 800 nm. The spectrum of SDSS J0104+15 was smoothed by a boxcar function of 101 pixels to increase the signal to noise ratio. Telluric absorption regions are highlighted in yellow and have been corrected in our X-shooter spectrum. Lighter and thicker shaded bands indicate regions with weaker and stronger telluric effects.

Table 1. Properties of SDSS J0104+15.

| Parameter                  | Value          |
|----------------------------|----------------|
| SDSS α (J2000)            | 01:04:04.48.46 |
| SDSS δ (J2000)            | +15°35´01.8     |
| SDSS epoch                | 1999 October13 |
| SDSS r                    | 22.25 ± 0.17   |
| SDSS ε                    | 20.37 ± 0.05   |
| SDSS z                    | 19.28 ± 0.06   |
| Pan-STARRS1 i             | 20.52 ± 0.02   |
| Pan-STARRS1 z             | 19.49 ± 0.02   |
| Pan-STARRS1 y             | 19.09 ± 0.03   |
| UKIDSS Y                  | 18.48 ± 0.05   |
| UKIDSS J                  | 17.93 ± 0.05   |
| UKIDSS H                  | 18.06 ± 0.11   |
| UKIDSS K                  | 18.08 ± 0.17   |
| WISE W1                   | 16.61 ± 0.08   |
| WISE W2                   | 16.36 ± 0.25   |
| Spectral type             | usdL1.5 ± 0.5  |
| Distance (pc)             | 228±69         |
| μRA (mas yr⁻¹)            | 206.2 ± 4.2    |
| μDec (mas yr⁻¹)           | −179.1 ± 4.6   |
| Vtan (km s⁻¹)             | 276 ± 75       |
| RV (km s⁻¹)               | −26 ± 16       |
| U (km s⁻¹)                | −98 ± 40       |
| V (km s⁻¹)                | −261 ± 79      |
| W(km s⁻¹)                 | −100 ± 46      |
| T eff (K)                 | 2450 ± 150     |
| [Fe/H]                    | −2.4 ± 0.2     |
| [M/H]                     | −2.1 ± 0.2     |
| Mass (M⊙)                 | 0.086 ± 0.0015 |
| Age (Gyr)                 | 11–13          |

3 CHARACTERISTICS

3.1 Spectral classification

Fig. 3 shows the new optical–NIR spectrum of SDSS J0104+15 compared to that of a usdL0 subdwarf (SSSPM J1013−13; Burgasser 2004b; Scholz et al. 2004; Zhang et al. 2017). SDSS J0104+15 has stronger overall suppression in the NIR as well as a flatter K-band morphology, both of which can be accounted for (according to the model atmospheres) by stronger enhanced collision-induced H₂ absorption (CIA H₂; Bates 1952; Saumon et al. 2012). This is consistent with SDSS J0104+15 being more metal-poor than SSSPM J1013−13. Fig. 4 shows only the optical spectrum of SDSS J0104+15 compared to that of SSSPM J1013-13. These objects have similar optical spectral profiles, however SDSS J0104+15 has weaker TiO absorption bands at around 710 and 850 nm, offering further evidence that SDSS J0104+15 is lower metallicity than SSSPM J1013−13. Therefore, SDSS J0104+15 is likely an early type usdL subdwarf.

The slope of the spectra at 737–757 nm wavelength is used to assign spectral types of early L subdwarfs (Kirkpatrick et al. 2014; Zhang et al. 2017). In the 737–757 nm range, the slope of the spectrum is positive (i.e., the spectrum is red) for L0, flat for L0.5, and negative for L1 and later types (see fig. 10 in Zhang et al. 2017). In the 737–757 nm wavelength range, the slope of the spectra of early L-type objects is bluer at both lower [Fe/H] and T eff. Therefore, an esdL0.5 type spectrum has a higher T eff than an sdL0.5 type spectrum. Meanwhile, a usdL subclass spectrum has a later subtype than an sdL subclass spectrum with the same
We derived spectroscopic distance estimates for SDSS J0104+15 using the relationship between spectral type and $J$- and $H$- band absolute magnitude shown in fig. 16 of Zhang et al. (2017). We obtained distance constraints of $215\pm44$ pc and $241\pm49$ pc in the $J$ and $H$ bands, respectively. We adopt the average distance estimate and uncertainty of these $J$ and $H$ band estimates, giving $228^{+61}_{-49}$ pc. We estimated the Gaia $G$-band magnitude of SDSS J0104+15 to be $20.93 \pm 0.21$ using the relationship between $G - r$ and $r - i$ colours (Jordi 2014). This is close to the Gaia limit ($G \gtrsim 20.7$; Gaia Collaboration et al. 2016)s SDSS J0104+15 is thus a borderline Gaia object. It may be detected by Gaia in its final data release, but with a somewhat lower parallax accuracy compared to brighter ($G < 20$) objects.

The proper motion of SDSS J0104+15 was measured from SDSS $i$ and PS1 $i_{p1}$-band images which have a baseline of $13.2$ yr. We used the IRAF task GEOMAP to derive spatial transformations from the SDSS $i$ into the PS1 $i_{p1}$-band image. Thirteen reference stars around SDSS J0104+15 were used for the transformation. These transforms allowed for linear shifts and rotation. We then transformed the SDSS pixel coordinates of SDSS J0104+15 into the PS1 image using GEOMAP, and calculated the change in position (relative to the reference stars) between the two epochs. This analysis yield $\mu_{RA} = 206.2 \pm 4.2$ mas yr$^{-1}$ and $\mu_{Dec} = -179.1 \pm 4.6$ mas yr$^{-1}$. The errors on proper motion are computed from the root mean square of the position shifts of reference stars between SDSS and PS1 fields.

To facilitate RV determination for SDSS J0104+15 we obtained an X-shooter spectrum of an L1 dwarf (DENIS-P J1441–0945; Martín et al. 1999) with known RV ($-27.9 \pm 1.2$ km s$^{-1}$; Bailer-Jones 2004). We then cross correlated strong absorption lines (Rb I, Na I K I) in the optical and NIR between SDSS J0104+15 and DENIS-P J1441–0945. The RV of SDSS J0104+15 was found to be $-85 \pm 6$ km s$^{-1}$. The RV error is from the standard deviation of RV measurements from different absorption lines.

The Galactic $U/V/W$ space motions of SDSS J0104+15
Figure 6. The optical–NIR spectrum of SDSS J0104+15 compared to BT-Settl model spectra. The $T_{\text{eff}}$, [Fe/H] and $\log g$ of model spectra are indicated above their $K$-band spectra. Metallicity and $T_{\text{eff}}$ sensitive wavelength ranges (640–680, 705–730, 730–760 and 1230–1350 nm) are marked on the top. The spectrum of SDSS J0104+15 was smoothed by a boxcar function of 61 pixels to increase signal-to-noise ratio. SDSS ($r$, $i$ and $z$) and UKIDSS ($Z$, $Y$, $J$, $H$ and $K$) filters are marked at their effective wavelengths. Spectra are normalized at 800 nm. The axis tick-marks are spaced logarithmically for clearer display of the optical spectra. Telluric absorption regions are highlighted in yellow same as in Fig. 3.

were determined using our spectroscopic distance, RV and proper motion following Clarke et al. (2010). It has typical halo velocities: $U = -98 \pm 40$ km s$^{-1}$, $V = -261 \pm 79$ km s$^{-1}$ and $W = -100 \pm 46$ km s$^{-1}$ [see fig. 17 of Zhang et al. (2017) for comparison; here $U$ is positive in the direction of the Galactic anti centre, $V$ is positive in the direction of Galactic rotations $W$ is positive in the direction of the North Galactic Pole (Johnson & Soderblom 1987)]. Table 1 summarises the properties of SDSS J0104+15.

3.3 Atmospheric properties
We used the BT-Settl models (Allard, Homeier, & Freytag 2014) to constrain the atmospheric parameters of SDSS J0104+15. The BT-Settl atmospheric models can reproduce the overall observed spectra of M and L subdwarfs, and can closely reproduce a variety of optical and NIR spectral features. BT-Settl models are able to reproduce observed spectra rather better for M and L subdwarfs with [Fe/H] $< -1.0$ than for [Fe/H] $> -1.0$ (Zhang et al. 2017).

The model grids we used cover 2000 K $\leq T_{\text{eff}}$ $\leq$ 2600 K, $-2.5 \leq \text{[Fe/H]} \leq -0.5$ and $5.0 \leq \log g \leq 5.75$, with intervals of 100 K for $T_{\text{eff}}$, 0.5 dex for [Fe/H], and 0.25 dex for $\log g$, and account for $\alpha$-enhancement ($[\alpha/\text{Fe}] = +0.4$ is adopted for [Fe/H] $\leq -1.0$, and $[\alpha/\text{Fe}] = +0.2$ is adopted for [Fe/H] = $-0.5$). The relation between [M/H] and [Fe/H] is [M/H] $\approx$ [Fe/H] + 0.3 for scaled solar compositions with $[\alpha/\text{Fe}] = +0.4$, and [M/H] $\approx$ [Fe/H] + 0.15 for $[\alpha/\text{Fe}] = +0.2$. We used linear interpolation between some models if this yielded a significantly improved fit.

Surface gravity has the least effect on the spectral pro-
file of L subdwarfs compared to temperature and metallicity. Zhang et al. (2017) has shown that esdM7–esdL4 subdwarfs have a similar log $g$ of $\sim$5.5 dex, with their spectra being mainly affected by $T_{\text{eff}}$ and metallicity. Therefore, we used model spectra with log $g = 5.5$ dex for our comparisons with SDSS J0104+15 to find the closest model-fit $T_{\text{eff}}$ and [Fe/H]. While the BT-Settl models can reasonably reproduce the overall spectral profile of early L dwarfs, some detailed features are not reproduced that well (Zhang et al. 2017). Furthermore, some wavelength ranges are more sensitive to $T_{\text{eff}}$ and/or [Fe/H] than others. We therefore performed a by-eye comparison between model spectra and SDSS J0104+15, focusing on a set of sensitive well modelled wavelength regions.

The 640–680 nm wavelength region and TiO absorption band at 705–730 nm of L subdwarfs compared to temperature and metallicity. The most metal-poor substellar object

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**Figure 7.** A zoom in of Fig. 6 at red optical wavelength.

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The 640–680 nm wavelength region and TiO absorption band at 705–730 nm of L subdwarfs compared to temperature and metallicity. The most metal-poor substellar object

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The central temperature ($T_c$) of VLMS with 0.1–0.3 $M_\odot$ is independent of metallicity. Fig. 5 of Habib & Baraffe (1997) shows that the mass–$T_c$ relationships at 0.1–0.3 $M_\odot$ are the same for [M/H] = 0 and $-$1.5. The lower the metallicity, the lower the opacity and the more transparent the atmosphere, and the same optical depth lies at deeper layers with higher temperature in more metal-poor stars. Therefore, more metal-poor stars have higher $T_c$ than metal-rich stars with the same mass. However, a 10 Gyr metal-poor brown dwarf could have cooler $T_c$ than a metal-rich star with the same mass. This is because the HBMM is lower at higher metallicity than at lower metallicity, and the higher metallicity means higher opacity, which in turn produces higher $T_c$ by steepening the temperature gradient. For the same reason, a massive metal-poor brown dwarf could have the same mass as a least massive metal-rich star (Burrows et al. 2001).

Evolutionary models show that nuclear ignition still takes place in the central part of stars with mass slightly below $\sim$0.083 $M_\odot$ at [M/H] = $-$1.0, but cannot balance steadily the ongoing gravitational contraction, which defines the massive brown dwarfs (Chabrier & Baraffe 1997). The same occurs in stars with mass slightly below $\sim$0.072 $M_\odot$.
at [M/H] = 0. Therefore, the HBMMs are ~ 0.072 M⊙ at [M/H] = 0 and ~ 0.083 M⊙ at [M/H] = −1.0. The exact HBMM at [M/H] < −1.0 is not explicitly stated in Chabrier & Baraffe (1997) and Baraffe et al. (1997). The HBMM at primordial metallicity (Z = 0) is ~ 0.092 M⊙ according to Burrows et al. (2001). In this section we use the mass–$T_{\text{eff}}$ relations given by evolutionary models to try to deduce the HBMM at various metallicities.

Fig. 8 (a) shows the 10 Gyr mass–$T_{\text{eff}}$ relationships derived from evolutionary models of low-mass stars with [M/H] of −0.5, −1.0, −1.3, −1.5, and −2.0 (Chabrier & Baraffe 1997; Baraffe et al. 1997). Note that the [M/H] scale is not calibrated for α-enhancement. We converted the [M/H] to [Fe/H] scale with [M/H] = [Fe/H] + 0.3 ($\alpha$/Fe = +0.4) for [M/H] $\lesssim$ −1.0 and [M/H] = [Fe/H] + 0.2 ($\alpha$/Fe = +0.3) for [M/H] $<$ −0.5. These evolutionary models employed the base atmospheric models of Allard & Hauschildt (1995). The steepening of the mass–$T_{\text{eff}}$ relationship near the lower mass end reflects the onset of ongoing electron degeneracy in the stellar interior, which is the characteristic of the transition between the stellar and sub-stellar domains. $T_{\text{eff}}$ is a decreasing function of metallicity above the HBMM, but an increasing function of metallicity below the HBMM. A mass–$T_{\text{eff}}$ relationship at a certain [Fe/H] intersects with other relationships at different [Fe/H]. The intersection points with the relationships at higher [Fe/H] provide upper limits on the HBMM at the certain [Fe/H]. For example, the mass–$T_{\text{eff}}$ relationships at [Fe/H] = −1.3 and [Fe/H] = −0.7 intersect around 0.084 M⊙. Therefore, the HBMM at [Fe/H] = −1.3 is expected to be below 0.084 M⊙.

Fig. 8 (b) shows mass–$T_{\text{eff}}$ relationships that have been shifted along mass and $T_{\text{eff}}$ axes to best match with each other, at a projected position at [Fe/H] = −2.4. We shifted these relationships with steps of 0.0005 M⊙ and 10 K. These shifted final values of mass (in M⊙) and $T_{\text{eff}}$ (in K) are indicated on the plot. These relationships of different [Fe/H] have very similar profiles at 0.08–0.3 M⊙. This is likely because that the mass–$T_{\text{eff}}$ and mass–radius relationships at 0.1–0.3 M⊙ are very similar at different metallicity, and the steepening of the mass–$T_{\text{eff}}$ relationship near the lower-mass end are caused by the same physical reason, which is electron degeneracy in the stars at stellar-substellar transition. Therefore, the cross points of HBMMs on these relationships at different [Fe/H] are overlapped in Fig. 8 (b). The perpendicular line at the HBMM on these relationships is marked in Fig. 8 (b). The mass shift of a relationship at a certain [Fe/H] to match the relationship profile at [Fe/H] = −1.3, is also the HBMM shift relative to the HBMM at [Fe/H] = −1.3, which is 0.083 M⊙. Therefore, the HBMMs are 0.0875, 0.0855, 0.0845, 0.083, and 0.08 M⊙ at [Fe/H] = −2.3, −1.8, −1.6, −1.3, and −0.7, respectively, according to Fig. 8 (b). The corresponding $T_{\text{eff}}$ at 10 Gyr are 2739, 2549, 2479, 2359, and 2128 K, respectively. The HBMMs and $T_{\text{eff}}$ at these five [Fe/H] values are indicated as vertical dashed lines and horizontal dotted lines in Fig. 8 (a), respectively. The projected HBMM at [Fe/H] = −2.4 is around 0.088 M⊙. SDSS J0104+15 has a $T_{\text{eff}}$ = 2450 ± 150 K, indicated with a shaded-yellow belt in Fig. 8 (b). The corresponding mass of SDSS J0104+15 derived from the mass–$T_{\text{eff}}$ relationship at [Fe/H] = −2.4 is between 0.085 and 0.087 M⊙, which is indicated with a shaded-magenta belt. The mass uncertainty caused by $T_{\text{eff}}$ error (150 K) is 0.001 M⊙. The mass uncertainty caused by [Fe/H] error (0.2 dex) is around 0.008–0.001 M⊙, as the mass–$T_{\text{eff}}$ relationship at [M/H] = −1.5 was shifted by 0.002 M⊙ to match with the relationship at [M/H] = −2.0 (Fig. 8 b). Age uncertainty may affects our mass estimation by up to 0.0005 M⊙. Because the $T_{\text{eff}}$ of a massive brown dwarf drop by ~ 50–100 K from 10 Gyr to 11–13 Gyr (e.g. Baraffe et al. 2003). The square root of the sum of squares of all uncertainties is 0.0015 M⊙. Therefore, SDSS J0104+15 has a mass of 0.086 ± 0.015 M⊙.

Fig. 9 explores how the most metal-poor subdwarf population distribution maps onto the [Fe/H]–$T_{\text{eff}}$ plane for F, G, K, M, L and T types. 10 Gyr iso-mass contour lines are plotted to better visualize the HBMM at different [Fe/H]. Solid magenta contour lines are from Chabrier & Baraffe (1997) and Baraffe et al. (1997). We also show some interpolated contours (dashed magenta lines) based on mass–$T_{\text{eff}}$ relationships at different metallicity (which have very similar profiles; see Fig. 8 b). Blue contour lines are from Burrows et al. (1998), and will further aid discussion in Section 3.5. Guided by these model contour lines we have generated a HBMM limit in the [Fe/H]–$T_{\text{eff}}$ plane over the range $-2.3 \leq$ [Fe/H] $\leq -0.7$, which is shown as a solid green line that is well approximated by the straight line function:

$$T_{\text{eff}} = 1861 - 382 \times [\text{Fe/H}]$$

A green box area indicates the overlapped $T_{\text{eff}}$ region for
Figure 9. [Fe/H] and $T_{\text{eff}}$ of cool and ultra-cool subdwarfs. The shaded blue area indicates the approximate [Fe/H] range for the thick disc population (e.g. Spagna et al. 2010), with the thin disc population above and the halo population below. Black dotted lines indicate the boundaries between F, G, K, M, L, T, and Y types. Magenta lines indicate the 10 Gyr iso-mass contours (Chabrier & Baraffe 1997; Baraffe et al. 1997) with mass values (in $M_\odot$) marked below or next to each iso-mass line. The green solid line indicates the $T_{\text{eff}}$ of the HBMM at $-2.3 \leq [\text{Fe/H}] \leq -0.7$. Shaded green area is where both VLMS and massive brown dwarfs could appear depending on age. Blue iso-mass contour lines are based on calculations of Burrows et al. (1998). SDSS J0104+15 is the filled black square at [Fe/H] = $-2.4$. Yellow open circles are dwarf stars ($\log g > 3.5$) from the PASTEL catalogue (Soubiran et al. 2016). The red diamond near the 0.2 $M_\odot$ iso-mass contour is Kapteyn’s star (sdM1) measured by Woolf & Wallerstein (2005). Two black open squares are from Frebel et al. (2005) and Caffau et al. (2011). [Fe/H] measurements of two late type sdM, and three sdT subdwarfs come from their primary stars (Bowler, Liu, & Cushing 2009; Aganze et al. 2016; Murray et al. 2011; Pinfield et al. 2012; Mace et al. 2013). The esdM object on the 0.1 iso-mass line is a companion to a K subdwarf (Pavlenko et al. 2015). The remaining late type subdwarfs are from Zhang et al. (2017). Note the $T_{\text{eff}}$ of some objects are offset by $\pm 15$ K for clarify when they share the same $T_{\text{eff}}$ and [Fe/H].

Figure 9. Effective Temperature (K) versus [Fe/H]; 2MASS J0104+15 appears to be the most metal-poor brown dwarf identified to-date, and is also the most massive brown dwarf yet known.

The most metal-poor substellar object

Young brown dwarfs and older VLMS in the solar neighbourhood, VLMS just above the HBMM have $T_{\text{eff}} \gtrsim 2075$ K (Dieterich et al. 2014). Meanwhile, PP1 15 AB (Basri, Marcy, & Graham 1996), a young binary brown dwarf confirmed by the lithium test (Magazzu, Martin, & Rebol3 1993) in the Pleiades open cluster, has a $T_{\text{eff}}$ of 2800 ± 150 K (Rebol3 et al. 1996). The corresponding $T_{\text{eff}}$ of the HBMM ($\sim 0.092$ $M_\odot$) at primordial metallicity is $\sim 3600$ K (Burrows et al. 2001). We have thus extended our HBMM line to lower metallicity ([Fe/H] $< -2.3$) following a tangent function. This extended (green dashed) line approaches 3600 K at [Fe/H] = $-\infty$, and is described by:

$$[\text{Fe/H}] = -2.3 - 1.43 \times \tan \frac{T_{\text{eff}} - 1017}{548} \quad (2)$$

The corresponding 10 Gyr $T_{\text{eff}}$ at [Fe/H] = $-2.4$ is around 2777 K according to equation (2). We also conservatively extend the HBMM line to higher metallicity by joining it on to the right side of the green box, which provides a reference of $T_{\text{eff}}$ for the HBMM at [Fe/H] $> -0.7$. It can be seen that the 10 Gyr iso-mass lines for 0.085 and 0.083 $M_\odot$ turn to cooler $T_{\text{eff}}$ below the HBMM limit at [Fe/H] = $-1.7$ and [Fe/H] = $-1.3$, respectively. This is consistent with the steep $T_{\text{eff}}$ decent in the mass–$T_{\text{eff}}$ relationship below the HBMM, that is seen at different metallicities in Fig. 8.

SDSS J0104+15 is clearly on the substellar side of the HBMM limit, and according to our analysis joins five other halo L subdwarfs that are brown dwarfs; 2MASS J1626+39, SDSS J1256–02, ULAS J151913.03–000030.0 (ULAS J1519–00; Zhang et al. 2017), 2MASS J06164006–6407194 (2MASS J0616–64; Cushing et al. 2009), and 2MASS J05325346+824645 (2MASS J0532+82; Burgasser et al. 2003). SDSS J0104+15 appears to be the most metal-poor brown dwarf identified to-date, and is also the most massive brown dwarf yet known.

To aid early identification of metal-poor brown dwarfs we have transferred our stellar–substellar boundary line on to the $i–J$ versus $J–K$ colour-colour diagram, based on the observed colours of SDSS J0104+15 and the other objects with constrained $T_{\text{eff}}$ and [Fe/H] (from Zhang et al. 2017) in Fig. 9. This approximate stellar–substellar boundary is indicated in Fig. 2 as a black dashed line.

3.5 The halo brown dwarf transition zone

Returning to Fig. 9 the 10 Gyr iso-mass contours of Burrows et al. (1998, blue lines) span a very interesting region
of the metallicity–$T_{\text{eff}}$ plane. These models were calculated across 0.01–0.2 M$_\odot$ at $Z = 0.1, 0.01,$ and 0.001 Z$_\odot$ (i.e. [Fe/H] = −1.3, −2.3, and −3.3, respectively; [α/Fe] = +0.4 is adopted), with base atmospheric models from Allard & Hauschildt (1995). Each of these contour lines has three data points at [Fe/H] = −1.3, −2.3, and −3.3, and we note that the 0.08 and 0.083 M$_\odot$ iso-mass lines join almost seamlessly on those of Chabrier & Baraffe (1997) (with differences of only ∼10 K in $T_{\text{eff}}$ at [Fe/H] = −1.3). The mass–$T_{\text{eff}}$ relationship (in the range 0.01–0.2 M$_\odot$) shown by the Burrows models (e.g. fig 5; Burrows et al. 2001) leads to a transition zone below the HBBM and above $T_{\text{eff}} \approx 1200$ K, where object $T_{\text{eff}}$ is very sensitive to mass and metallicity. The internal energy of halo brown dwarfs in this transition zone is partially provided by unsteady nuclear fusion (e.g. fig. 8; Chabrier & Baraffe 1997). This transition zone is also manifest as a substellar subdwarf gap between the $T_{\text{eff}}$ evolutionary tracks of low-mass stars and brown dwarfs (e.g. fig. 8; Burrows et al. 2001), which should lead to a sparsity of objects in this region (e.g. fig. 10; Burgasser 2004a) due to the narrow mass range across a broad $T_{\text{eff}}$.

The transition zone region is clear in our Fig. 9, lying between the green HBMM limit and $T_{\text{eff}} \approx 1200$ K. The width of the $T_{\text{eff}}$ range of the transition zone increase from ∼1000 K at [Fe/H] = −1.0 to ∼1800 K at [Fe/H] = −3.3. Most of the esdL and usdL subdwarfs are in the transition zone except for some early type L subdwarfs that are VLMS just above the HBMM. SDSS J0104+15, 2MASS J1626+39, SDSS J1256−02, ULAS J1519−00, 2MASS J0616−64, and 2MASS J0532+82 are all in the transition zone.

Halo brown dwarfs with mass of ∼0.075–0.01 M$_\odot$ should have evolved to T and Y types after over ∼10 Gyr of cooling. However, we have not found such objects to-date (with expected $T_{\text{eff}} \lesssim 1200$ K and [Fe/H] $\lesssim$ −1.0). T and Y dwarfs have significantly higher number density in the solar neighbourhood (e.g. fig. 11; Kirkpatrick et al. 2012). If the dependence of substellar formation on metallicity is negligible (as suggested by numerical simulations; Bate 2014), the ratio between T/Y and L subdwarfs in the halo should be much higher than that of T/Y and L dwarfs, since old halo L subdwarfs cover a much narrower mass range. This points towards a large population of undiscovered T and Y subdwarfs in the local volume.

4 SUMMARY AND CONCLUSIONS

We have presented an X-shooter optical–NIR spectrum of SDSS J0104+15, and re-classified this object as a usdL1.5 subdwarf. We measured its astrometry and kinematics and SDSS J0104+15, and re-classified this object as a usdL1.5. We have presented an X-shooter optical–NIR spectrum of points towards a large population of undiscovered T and Y subdwarfs cover a much narrower mass range. This be much higher than that of T/Y and L dwarfs, since old the ratio between T/Y and L subdwarfs in the halo should dependance of substellar formation on metallicity is negligi- dwarfs have significantly higher number density in the solar (with expected

The transition zone is caused by a steep $T_{\text{eff}}$ decline in the mass–$T_{\text{eff}}$ relationships across the stellar–substellar bound- ary, due to unsteady nuclear fusion. It covers a narrow mass range but spans a wide $T_{\text{eff}}$ range, leading to a substellar subdwarf gap over the mid L to early T type range. Our $T_{\text{eff}}$ and [Fe/H] estimates for SDSS J0104+15 place it below the HBMM boundary making it the most metal-poor (and high-mass) brown dwarf yet known. Joining SDSS J0104+15 in the transition zone we identify 2MASS J0532+82, 2MASS J0616−64, SDSS J1256−02, 2MASS J1626+39, and ULAS J1519−00. The existence of substellar objects that are as metal poor as SDSS J0104+15 supports formation theories for stars in this mass and metallicity domain (Clark et al. 2011; Greif et al. 2011; Basu, Vorobyov, & Desouza 2012; Bate 2014).

Large scale NIR surveys, such as the ‘Visible and Infrared Telescope for Astronomy’ (VISTA; Sutherland et al. 2015) Hemisphere Survey (VHS; McMahon et al. 2013) have great potential to identify additional objects that are more metal poor and cooler than SDSS J0104+15. Improvements in ultra-cool model atmospheres will guide future searches for VMP VLMS and brown dwarfs. Accurate theoretical predictions of H-band flux are particularly important, because it is more difficult to detect these objects in the K band that is largely suppressed due to enhanced CIA H$_2$. Further more, the future ESA Euclid (Laureijs et al. 2011) spectroscopic cover surveys a wavelength range of 1100-2000 nm (approximately covering the J and H bands), and information from H band spectra will be very important for the characterization of these objects with Euclid.

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