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Brown dwarfs of the Galactic halo

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Abstract. Two new late-type L subdwarfs were discovered in our recent search of UKIDSS and SDSS. We discuss the signatures of halo brown dwarfs based on known and new L subdwarfs. These indicate that the halo stellar/substellar $T_{\rm eff}$ gap is likely between esdL4 and esdL6.

Key words. brown dwarfs – subdwarfs – stars: Population II

1. Introduction

Brown dwarfs (BDs) have masses below the hydrogen burning minimum mass (HBMM), which is between 0.075 and 0.092 $M_\odot$ for solar and zero metallicity, respectively, according to theoretical models (e.g. Burrows et al. 2001). Since BDs keep cooling throughout their life time, massive BDs of the Galactic halo will have significantly cooler atmospheres than very low-mass stars, and correspondingly different observational parameters allowing them to be distinguished. To-date, nine L subdwarfs at the stellar/substellar boundary have been discovered (Burgasser et al. 2003; Burgasser 2004; Cushing et al. 2009; Sivarani et al. 2009; Lodieu et al. 2010, 2012; Kirkpatrick et al. 2010). 2MASS J05325346+8246465 (2MASS J0532; Burgasser et al. 2008) has a model predicted mass ($\sim 80 M_{\rm Jup}$) below the HBMM. Whether other known L subdwarfs are BDs or not has not been discussed.

We have initiated a project to search for L subdwarfs with UKIDSS (Lawrence et al. 2007) and SDSS (York et al. 2000). As a result, two late-type L subdwarfs have been confirmed with continuous optical and near infrared (NIR) spectra obtained with X-Shooter (Vernet et al. 2011). These new discoveries allow us to discuss the signatures of BDs of the Galactic halo or substellar subdwarfs.

2. Late-type L subdwarfs

L subdwarfs have $T_{\rm eff}$ between 1300 and 2500 K and are a mixture of metal deficient very low-mass stars and BDs. L subdwarfs are red in optical wavelengths, and bluer than the same spectral type L dwarfs in the NIR. They could thus by referred to as 'purple' dwarfs (Zhang et al. 2013b). L subdwarfs exhibit characteristic spectral signatures of strong metal

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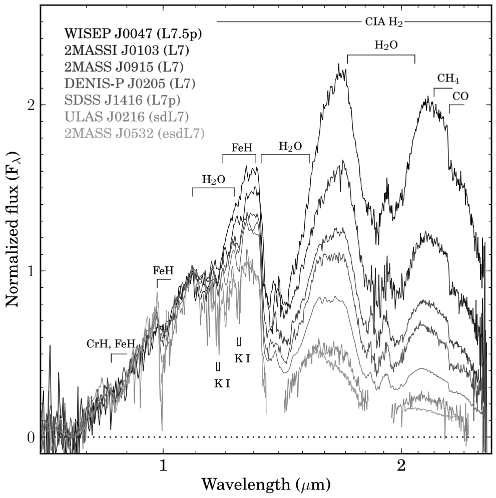

Fig. 1. Spectral sequence of L7 dwarfs and subdwarfs. Spectra are normalized at $1.08\,\mu$m. WISEP J004701.06+680352.1 (WISEP J0047) is from Gizis et al. (2012); 2MASSI J0103320+193536 (2MASSI J0103) is from Cruz et al. (2004); DENIS-P J0205.4-1159 (DENIS-P J0205) is from Burgasser et al. (2010); SDSS J1416 is from Schmidt et al. (2010). See Zhang et al. (2013a) for optical spectra.

hydrides (e.g. FeH at $1\,\mu$m), weak or absent metal oxides (e.g. CO at $2.3\,\mu$m), and enhanced collisionally-induced H_2 absorption (CIA H_2; e.g. Saumon et al. 2012). Figure 1 shows a spectral sequence of L7 dwarfs with a range of metallicities. As we move from the red L7 to the esdL7 spectra we can see that CIA H_2 and $1\,\mu$m FeH features strengthen, and the $2.3\,\mu$m CO feature weakens.

2MASS J0532 was the first L subdwarf discovered by Burgasser et al. (2003), while 2MASS J06164006−6407194 (2MASS J0616) is an outer halo L subdwarf discovered by Cushing et al. (2009). Figure 2 shows that 2MASS J0532 (Burgasser et al. 2003) and 2MASS J06164006−6407194 (2MASS J0616) both have very strong CIA H_2, and thus are very metal-poor. Based on this, we suggest their reclassification as extreme subdwarfs. ULAS J0216 in Figure 1 and ULAS J1519 in Figure 2 are two new L subdwarfs confirmed from our programme with X-Shooter. ULAS J0216 lies between SDSS J1416 and 2MASS J0532 in the spectral sequence in Figure 1. It thus follows naturally to classify ULAS J0216 as an sdL7, 2MASS J0532 as esdL7, and 2MASS J0616 as esdL6 subdwarfs.

3. Halo brown dwarfs

The massive BDs in young open clusters ($\lesssim$ 100 Myr) have spectral types of late-type M. BDs in the Galactic disc usually have spectral types of early-type L and later. After about 10 Gyr of cooling, the BDs of the Galactic halo would have $T_{\rm eff} \lesssim 1700$ K, corresponding to spectral type of late-type L and T. The evolutionary models show that there is a $T_{\rm eff}$ gap around 1600 K between most low-mass stars and most massive BDs older than $\sim$ 10 Gyr (e.g. Burrows et al. 2001), because BDs are cooling down while low-mass stars keep shining. Simulations of substellar mass function also suggest there is a lack of objects at 1200 K $\lesssim T_{\rm eff} \lesssim$ 2000 K in the halo (Burgasser 2004). Due to the differential cooling of massive BDs and very low-mass stars of the halo, they should have more distinguishable spectral features than those of the disc.

Figure 2 shows spectra of five L extreme subdwarfs and six M7-L2 dwarfs. All spectra are normalized at $1.65\,\mu$m where H_2O has an opacity minimum (Burrows et al. 2001). The $1.4\,\mu$m H_2O absorption band gets deeper continuously from M7 to L2 dwarfs at the stellar/substellar transition. The depth of the $1.4\,\mu$m H_2O band changes suddenly from esdL4 to esdL6 subdwarfs. SDSS J1256 and 2MASS J1626 are much more luminous than 2MASS J0616 and 2MASS J0532 according to the relationships of absolute magnitude and spectral type (Zhang et al. 2013b). These might indicate that the halo stellar/substellar $T_{\rm eff}$ gap is between esdL4 and esdL6.

ULAS J1519 has significantly deeper $1.4\,\mu$m H_2O absorption band than 2MASS J1626. 2MASS J1626 and ULAS J1519 have comparable $1.4\,\mu$m H_2O bands as late M dwarfs (disc low-mass stars) and early-type L dwarfs (disc BDs) respectively. ULAS J1519 also has much stronger $1.15\,\mu$m H_2O band than 2MASS J1626. The strengthened H_2O absorption bands at 1.4 and $1.15\,\mu$m could be indicators of a substellar subdwarf. 2MASS J0532,

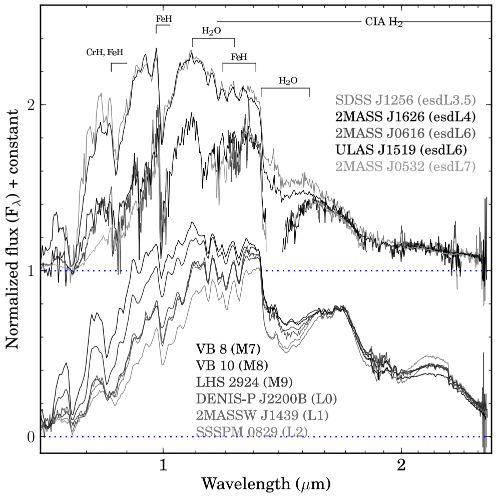

Fig. 2. Optical and NIR spectra of four L extreme subdwarfs. Deep 1.4 μm H_2O absorption in ULAS 1519 and 2MASS J0532, which are different from 2MASS J1626, indicates that they might be halo BDs or substellar subdwarfs. Spectra are normalized at 1.65 μm, but SDSS J1256 is normalized to SDSS J1626 at 1.08 μm.

2MASS J0616, 2MASS J0645 (Kirkpatrick et al. 2010), ULAS J1519 and ULAS J0216 could be BDs of the Galactic halo. Spectral types of halo BDs might start from esdL6 (possibly sdL5 for less metal-poor objects). No subdwarf would has spectral types of esdL5 or usdL5 in the Galaxy after $\gtrsim 10$ Gyr of cooling. Further analysis of a larger sample of L subdwarfs based on the latest model grids and new astrometric observations are needed to confirm this hypothesis.

4. Conclusions

FeH at 1 μm and CO at 2.3 μm are good indicators of L subdwarfs. H_2O at 1.4 and 1.15 μm are good indicators of halo brown dwarfs. Three known and two new late-type L subdwarfs are found to be very strong candidates of halo brown dwarfs. We also find that the substellar subdwarf gap is likely between spectral types esdL4 and esdL6.

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