Metal-Depleted Brown Dwarfs

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Abstract  This chapter reviews our current knowledge of metal-poor ultracool dwarfs with spectral types later than M7. The current census of M, L, and T subdwarfs is explored. The main colour trends of subdwarfs from the optical to the mid-infrared are described and their spectral features presented, which led to a preliminary and tentative spectral classification subject to important changes in the future when more of these metal-poor objects are discovered. Their multiplicity and the determination of their physical parameters (effective temperature, gravity, metallicity, and mass) are discussed. Finally, some suggestions and future guidelines are proposed to foster our knowledge on the oldest and coolest members of our Galaxy.

Introduction

M dwarfs represent the majority of stars in the solar neighbourhood (Kirkpatrick et al. 2012) and in our Galaxy where the mass function peaks (e.g. Chabrier 2003). At lower masses, three new classes have defined during the past two decades: the L dwarfs whose atmospheres are affected by dust (Kirkpatrick et al. 1999; Martín et al. 1999), the T dwarfs shaped by methane and water absorption bands (Leggett et al. 2000; Geballe et al. 2002; Burgasser et al. 2002; 2006), and the Y dwarfs with the potential presence of ammonia at infrared wavelengths (Cushing et al. 2011; Kirkpatrick et al. 2012). The classification of L dwarfs is mostly morphological but the large variety of sources discovered in optical and infrared large-scale surveys triggered a preliminary spectral scheme incorporating a new parameter: gravity (i.e. ages) as proposed by two independent teams (Cruz et al. 2009; Allers et al. 2007; Allers and Liu 2013). However, the spectral classification of metal-poor L dwarfs remains in its infancy due to the small sample existing in the literature. Nonetheless, recent discoveries offered new hints to elaborate a tentative spectral sequence.

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Metal-poor dwarfs belong to the spectral class VI in the Morgan-Keenan scheme (Morgan et al. 1943). They are also known as subdwarfs and often abbreviated “sd” (Joy 1947; Gizis 1997; Lépine et al. 2007). They usually exhibit bluer optical and infrared colours than their solar-like analogues (Lodieu et al. 2017) and show distinct spectral features such as the weakening of TiO bands (i.e. less TiO opacity implying more flux radiated from deeper and hotter layers of the atmosphere), strengthening of CaH bands, and strong collision-induced hydrogen absorption beyond 1μm (Gizis 1997; Lépine et al. 2007). They typically have high proper motions and large radial velocities translating into space motions compatible with membership to the thick disk and halo (Schmidt 1975). This population of metal-poor dwarfs is important for several reasons. Firstly, they represent key tracers of the history of our Galaxy because they are very old. Secondly, the knowledge of their physical parameters will impact on the study of globular clusters whose main populations are metal-poor and old. Thirdly, the census of metal-poor stars and brown dwarfs helps the determination of the luminosity and mass functions early on in the formation of our Galaxy to gauge the impact of metallicity in star formation processes. Unfortunately, metal-poor stars are not so numerous compared to their solar-like counterparts with only three subdwarfs of the ~250 systems located within 10 pc (μ Cas AB; Kapteyn’s star; CF Uma).

This review will focus mainly on ultracool subdwarfs (UCSDs) with spectral types later than M7 and metallicities (Fe/H) equal or less than −0.5 dex unless otherwise stated. For more massive subdwarfs, readers are referred to one of the section dedicated to M subdwarfs in the book of [Reid and Hawley 2005]. The coolest L-type subdwarfs might be brown dwarfs but none of them has been unambiguously proven to be substellar at the time of writing (Lodieu et al. 2015). A few T-type metal-poor dwarfs have been announced as companions to bright stars with well-determined metallicities (Pinfield et al. 2012; Burningham et al. 2013) but only one has a metallicity below −0.5 dex, WISE J20052038+5424339 (Mace et al. 2013).

This review summarizes the techniques employed over the past decades to identify metal-poor low-mass stars and brown dwarfs, and describes the main spectral features leading to a preliminary and tentative classification scheme for UCSDs. The colours of UCSDs are mentioned and compared to those of nearby field M and L dwarfs. Our current knowledge on the multiplicity of UCSDs and the actual estimates of the physical parameters of the lowest mass metal-poor stars and brown dwarfs are also presented here. Finally, future needs are highlighted to characterise in more details the population of UCSDs and their physical parameters.

Census of ultracool subdwarfs

Dedicated searches for metal-poor stars and brown dwarfs usually focus on proper motion surveys to bias their final sample towards high velocity objects, thus halo stars (Schmidt 1975). Most of the late-M subdwarfs have been identified in photographic plates from the Digital Sky Survey and the SuperCOSMOS Sky Survey.
Metal-Depleted Brown Dwarfs

(Gizis 1997; Gizis and Reid 1997; Gizis et al. 1997; Schweitzer et al. 1999; Lépine et al. 2003; Scholz et al. 2004a,b; Lodieu et al. 2005; Lépine et al. 2007), and more recent all-sky or large-scale surveys such as the Two Micron All Sky Survey (2MASS; Burgasser and Kirkpatrick 2006; Cushing et al. 2009), the Sloan Digital Sky Survey (SDSS; Lépine and Scholz 2008; Sivaram et al. 2009; Zhang et al. 2013), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lodieu et al. 2012, 2017), and the Wide field Infrared Survey Explorer (WISE; Kirkpatrick et al. 2014, 2016).

Over the past years, the number of L subdwarfs has grown rapidly and is now just slightly over 30. The first one was identified in 2MASS (Burgasser et al. 2003) followed by other discoveries in the same database (Burgasser 2004; Cushing et al. 2009), SDSS (Sivarani et al. 2009; Schmidt et al. 2010; Bowler et al. 2010), WISE (Kirkpatrick et al. 2014, 2016), and cross-correlations of various surveys (Lodieu et al. 2010, 2012, 2017; Zhang et al. 2017b,a).

In the T dwarf regime, a few examples of metal-poor T dwarfs have been reported as companions to brighter stars with well determined metallicities both in UKIDSS (Pinfield et al. 2012; Burningham et al. 2013) and WISE (Mace et al. 2013). Nonetheless, their metallicities generally do not exceed −0.5 dex, except in the case of WISE J200520+542433 with Fe/H = −0.64 dex (Mace et al. 2013).

Colours

Due to the dearth of metals in their atmospheres, UCSDs tend to exhibit on average bluer colours than their solar-type analogues (Fig. 1). Moreover, they lie below solar-metallicity dwarfs in reduced proper motions (left panel in Fig. 1) which constitute powerful tools to identify UCSDs (Lépine et al. 2007; Lépine and Scholz 2008; Kirkpatrick et al. 2016; Lodieu et al. 2017). This section summarises differences reported in the literature going from blue to red wavelengths. These differences helped out increasing the numbers of UCSDs over the past years and represent key indices for upcoming surveys like the Large Synoptic Survey Telescope (LSST; Ivezic et al. 2008) and the Euclid mission (Mellier 2016).

- Their locus in a \((g - r, r - i)\) colour-colour diagram is distinct from their solar-type counterparts. Selecting sources with \(g - r > 2\) mag and \(g - i > 3\) mag will strongly bias the photometric selection towards metal-poor M dwarfs (Fig. 2 in Lépine and Scholz 2008).
- Their \(r - z\) colours are bluer than field M dwarfs by at least 1 mag (Fig. 2 in Lépine and Scholz 2008).
- The optical-to-infrared colours (e.g. \(i - J\)) of UCSDs are bluer as metallicity decreases, yielding a flattening of the far-red part of their optical spectra (Gizis 1997; Lépine et al. 2007; Lodieu et al. 2017; Zhang et al. 2017b).
- Their infrared colours (e.g. \(J - K < 0.7\) mag) are much bluer than solar-type M dwarfs due to the strong pressure-induced \(H_2\) opacity beyond 1 micron (Lodieu et al. 2017; Zhang et al. 2017b).
Subdwarfs of type M and L typically fall bluewards in near-infrared to mid-infrared colours (e.g. $J - w1$, $J - w2$, $H - w2$) of their solar-metallicity counterparts due to the increasing influence of collision-induced hydrogen absorption (Kirkpatrick et al. 2016; Lodieu et al. 2017).

Their mid-infrared colours look similar to those of their solar-type analogues although opposite trends have been reported in the literature: red in Kirkpatrick et al. (2016) and blue in Lodieu et al. (2017).

Fig. 1 Reduced proper motion (left) and ($J - w2, J - K_s$) colour-colour diagrams for main-sequence stars, M, L, and T dwarfs of different metallicities. Figures taken Kirkpatrick et al. (2016).

Spectral features

The main spectral features indicative of low metallicity are the strengthening of the CaH bands and weakening of the TiO bands around 620–740 nm and the effect of the collision-induced absorption beyond 1000 nm. However, there are other features which can be employed to distinguish UCSDs from their solar-type cousins over the optical-infrared wavelength range (Gizis 1997; Lépine et al. 2007; Burgasser et al. 2007; Kirkpatrick et al. 2016; Zhang et al. 2017b), as enumerated below:

1. The CaH bands around 640–700 nm is stronger with lower metallicity but is also dependent on temperature in the 3600–3200 K range.
2. The TiO bands at ~720 nm, 780 nm, and 850 nm are weaker with lower metallicity. The bluest of these bands, however, becomes more sensitive to temperature than metallicity for late-type M subdwarfs. Below 3200 K, the strength of the TiO band at 720 nm is not monotonic anymore with decreasing metallicity, making the classification of late-M and early-L subdwarfs based on spectral indices more unreliable.
3. The VO band at 800 nm is a strong indicator of metallicity in L dwarfs: it weakens as Fe/H decreases.
4. The CO band at 2300 nm weakens as metallicity decreases and eventually disappears in extreme and ultra-subdwarfs.
5. The near-infrared flux beyond 1000 nm becomes more depressed with lower metallicity due to the strong collision-induced H\textsubscript{2} absorption.

Spectral types

The first spectral classification of M subdwarfs has been proposed by Gizis (1997), dividing M dwarfs into three main classes: solar-type M dwarfs with metallicity Fe/H around 0, M subdwarfs (sdM) with FeH $\sim -1.2 \pm 0.3$ dex, and extreme M subdwarfs (esdM) with approximate Fe/H of $-2.0 \pm 0.5$ dex. This classification scheme is based on the strength of the TiO and CaH bands in the 620–740 nm optical range. Spectral indices have been defined to infer both metal class and spectral type. Ten years later, Lépine et al. (2007) revised the boundaries of the original metal classes based on a larger sample (factor of five bigger) of known metal-poor single and multiple systems. They introduced a new parameter, $\tau_{\text{TiO}/\text{CaH}}$, as well as an additional metal class with metallicities even lower than the esdM, the ultrasubdwarfs (usdM), to taken into account the positions of known binaries sharing the same metallicity in the (early-)M dwarf regime. They also proposed spectral standards for each metal class and spectral types ranging from M0 to M8. The quality of the optical spectra of the sdM, esdM, and usdM templates has been improved by Savcheva et al. (2014) by stacking all SDSS spectra available per subtype and per metal class (Fig. 2). Jao et al. (2008) presented new thoughts about the naming and spectral classification of subdwarfs based on a sample of 88 K3–M6 sources. They propose to use the class VI of the Morgan-Keenan scheme instead of the terminology “sd” to name subdwarfs, a prefix that can be confused with the hotter sdO/sdB-type star which also appear sub-luminous in the HR diagram. And they showed the influence of gravity in the spectra of M subdwarfs and suggested to avoid classification based solely on spectral indices.

In the L dwarf, the current classification is only tentative due to the small number of L subdwarfs announced to date and the narrow range of physical parameters. Nonetheless, several groups attempted to extend the M dwarf classification into the L regime. Zhang et al. (2017b) built on the extensions proposed by Burgasser et al. (2007) and Kirkpatrick et al. (2016), keeping the concept of the three metal classes proposed by Lépine et al. (2007) and applying it to the L subdwarfs (sdL, esdL, and usdL). Their spectral classification is based on the comparison of spectra of about 30 L0–L8 subdwarfs with those of solar-type L dwarf standards defined in the literature (e.g. Kirkpatrick et al. 2000). They focused on key features sensitive to metallicity and temperatures (their Table 3 and previous section) to evaluate the differences in the optical (CaH and VO bands around 700 nm, VO band at 800 nm, strength of the K\textsubscript{1} doublet at 770 nm, TiO band at 850 nm) and in the infrared (FeH band at
990 nm, CO band at 2300 nm, and the depression in the \( H \) and \( K \) passbands due to the collision-induced \( \text{H}_2 \) absorption), yielding a revised classification of known metal-poor L dwarfs that can be used for future discoveries (Fig. 3).

![Fig. 2. Sequence of M-type subdwarfs (sdM; left), extreme subdwarfs (esdM, middle), and ultra-subdwarfs (usdM; right). Figure taken from Savcheva et al. (2014) with an earlier version shown in Lépine et al. (2007).](image)

**Multiplicity**

The multiplicity fraction and binary properties of UCSDs is poorly constrained for two main reasons. On the one hand, most of the known UCSDs have been identified very recently and, on the other hand, they are faint both at optical and infrared wavelengths. High-resolution imaging is feasible for a limited sub-sample because bright reference stars are needed to close the loop as in the case of adaptive optics for example.

Only a limited number of surveys have been conducted to look at the multiplicity of metal-poor M dwarfs over a wide range of separations. Jao et al. (2009) found that the multiplicity rate of \( K \) and M subdwarfs is slightly lower than their solar-type counterparts (26±6\% vs 36±5\%) from an optical speckle survey. The total multiplicity fraction of M subdwarfs can be divided up as follows: 3\% have companions within 10 au, another 3\% within the 10–100 au range, 14\% beyond 100 au, and the remaining 6\% are spectroscopic binaries. Combining the outcome of a Hubble survey of 28 metal-poor M dwarfs of Riaz et al. (2008) with high spatial lucky imaging observations of 24 M subdwarfs, Lodieu et al. (2009) resolved only one system with a projected separation of 0.7 arcsec (LHS 182), deriving a binary frequency of 3.7±2.6 (1\( \sigma \) confidence limit) for M subdwarfs (mainly M0–M5). This result is in
Fig. 3 Optical and near-infrared spectra of L4, L6, and L7 dwarfs/subdwarfs with different subclasses. Spectra have been normalised at 0.89 µm. The missing wavelength region in the spectrum of 2M0532 (1.008–1.153 µm) has been replaced by the best BT-Settl model fit in magenta (T eff = 1600 K, [Fe/H] = 1.6 dex, and log(g) = 5.25 dex). Figure from Zhang et al. (2017b).

line with the two companions exhibiting Hα in emission among a sample of 68 LHS objects (2.9%; Gizis 1998).

Finally, only three M subdwarfs with metallicities below −0.5 dex and masses less than 0.5 M ⊙ have dynamical mass measurements. They belong to two double-lined eclipsing binaries with resolved orbits: the secondary of the µ Cas AB system with a mass of 0.17 M ⊙ (Drummond et al. 1995) and both components of the G006-026 BC system whose masses span 0.43–0.47 M ⊙ (Jao et al. 2016).
At the time of writing, no mass estimate independent of evolutionary models exist for UCSDs because they are either too faint or no eclipsing/spectroscopic binary exist for direct dynamical mass measurement.

Currently, the range of physical parameters for UCSDs originates from the direct comparison of observed optical and/or near-infrared spectra with state-of-the-art evolutionary models. Burgasser et al. (2008) identified a subdwarf with the latest spectral type reported to date (2MASS J0532+8246; sdL7), lying at the stellar/substellar boundary. These authors fitted the full spectral energy distribution (SED) of 2MASS J0532+8246 with the NextGen models (Baraffe et al. 1998), deriving an effective temperature (T$_{\text{eff}}$) of 1730±90 K and a mass in the range 0.0744–0.0835 M$_\odot$ for metallicities between 0 and $-2.0$ dex and ages of 10–15 Gyr. However, the lithium feature at 6707.8 Å has not been detected in higher resolution spectra (Lodieu et al. 2015), suggesting a minimum mass of 0.06 M$_\odot$ (Magazzu et al. 1992; Rebolo et al. 1996). Burgasser et al. (2009) repeated a similar process for a warmer L subdwarf classified as sdL4 (Sivarani et al. 2009) and derived a mean T$_{\text{eff}}$ of 2300±200 K, log(g) = 5.0–5.5 dex, and metallicity between $-1.0$ and $-1.5$ dex using the Drift-Phoenix models (Helling et al. 2008). Zhang et al. (2017b) extended such a procedure to six new L subdwarfs identified in the cross-match of SDSS and UKIDSS as well as all previously known L subdwarfs as of 2017. They determined T$_{\text{eff}}$ and metallicities for 22 L subdwarfs, extreme subdwarfs, and ultrasubdwarfs with spectral types in the L0–L7 range by direct comparison with the BT-Settl models (Allard et al. 2012), yielding temperatures of 1500–2700 K for metallicities between $-1.0$ and $-2.0$ dex. On average, the T$_{\text{eff}}$ of subdwarfs are 100–400 K higher than solar-metallicity L dwarfs depending on the spectral sub-type and metal class. Some of these L subdwarfs might be brown dwarfs rather than very low-mass stellar members of the halo based on the latest BT-Settl models (Zhang et al. 2017a) but the exact location of the stellar/substellar boundary at low metallicity still requires dynamical measurements.

Future work

The past two decades have witness the existence of M, L, and T subdwarfs and the first spectral classification of this metal-poor population. The advent of large-scale surveys at both optical and infrared wavelengths (2MASS, SDSS, UKIDSS, WISE) have increased the numbers of UCSDs and extended the sequence to cooler metal-poor L and T dwarfs. However, our knowledge of UCSDs still remains in its infancy. A number of improvements and discoveries are required to take up this field to the next level.

• The improvement in the determination of physical parameters of subdwarfs requires the fitting of optical and infrared spectral energy distributions of several
hundreds of spectra to complement the extensive work on the properties and kinematics of subdwarfs by Savcheva et al. (2014).

- The saturation of the $\tau_{\text{TiO/\text{CaH}}}$ index around $\sim$M8–M9 suggests that a revision of the current spectral classification scheme is needed. Moreover, a near-infrared spectral classification is also necessary to classify future discoveries in large-scale infrared surveys.

- The progress in the accuracy of metallicity scale for ultracool subdwarfs calls for searches of close-in and/or wide companions to brighter subdwarfs with well-determined metallicities.

- Searches for M, L, and T subdwarfs should be enhanced to improve the determination of the object density as a function of metallicity and allow for a determination of the luminosity and mass functions in a distance or magnitude-limited volume.

- The discovery of short-period binaries and eclipsing binaries is heavily needed to infer model-independent masses over a wide range of masses and metallicities.

The future of the field sounds bright with upcoming deep photometric surveys such as the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008) and the Euclid mission (Mellier 2016) and large-scale spectroscopic campaigns planned with WHT/WEAVE (Dalton et al. 2012) and VISTA/4MOST (de Jong et al. 2014). Let’s look forward to the first substellar subdwarfs and long-waited mass determinations!

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Acknowledgements NL is supported by programme AYA2015-69350-C3-2-P from Spanish Ministry of Economy and Competitiveness (MINECO). NL thanks ZengHua Zhang for his input on the review.