Ultracool Subdwarfs:
Subsolar Metallicity Objects Down to Substellar Masses

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Abstract. In the past few years, astronomers have uncovered several very low-temperature, metal-poor stars with halo or thick disk kinematics and peculiar spectral and photometric properties, so-called ultracool subdwarfs. These include the first examples of L subdwarfs - metal-poor analogs of the L dwarf spectral class - and slightly metal-deficient T dwarfs. Ultracool subdwarfs provide useful empirical tests of low temperature atmosphere and evolutionary models, and are probes of the halo mass function down to and below the (metal-dependent) hydrogen burning limit. Here I summarize the optical and near-infrared spectroscopic properties of these objects, review recent research results, and point out scientific issues of interest in this developing subject.

1. Introduction

Ultracool subdwarfs (UCSDs) are metal-deficient, very low mass stars and brown dwarfs with late spectral types. They are the metal-poor analogs of ultracool dwarfs (spectral types M7 and later) and represent the low effective temperature \( T_{\text{eff}} \lesssim 3000 \) K \cite{Leggett2000}, extensions of the M subdwarf (sdM) and extreme subdwarf (esdM) classes \cite{Gizis1997}. Cool and ultracool subdwarfs typically exhibit halo kinematics, and were presumably formed early in the Galaxy’s history. These low mass objects are important tracers of Galactic structure and chemical enrichment history and are representatives of the first generations of star formation. UCSDs encompass the new spectral class of L subdwarfs (sdL; \cite{Burgasser2003a,Lepine2003}) and metal-poor T dwarfs (e.g., \cite{Burgasser2006}), reaching masses below the hydrogen burning minimum mass.

This contribution provides an update on the state of UCSD research since a first review was made at Cool Stars 13 by \cite{Burgasser2005}. Here I focus on observed spectral properties (§2), new discoveries (§3) and considerations for spectral classification (§4), and then briefly touch on other issues under investigation (§5).

2. Ultracool Subdwarf Spectral Properties

Like ultracool dwarfs, UCSDs exhibit complex optical and near-infrared spectral energy distributions dominated by strong, overlapping molecular absorption bands; numerous neutral metal line features; and red optical spectral continua \cite{Gizis1997,Lepine2003,Lepine2004,Scholz2004,Burgasser2007}. They are distin-
guished spectroscopically by signatures of metal deficiency, notably enhanced metal hydride and weakened metal oxide absorption bands (Mould & Hyland 1976), and blue near-infrared colors resulting from collision induced H₂ absorption (Saumon et al. 1994). These spectral peculiarities are more pronounced in lower metallicity subdwarfs (Figure 1). The reduction in TiO and VO opacity at optical wavelengths allows for the emergence of several weaker lines not generally seen in solar metallicity M dwarfs, including Ca I, Ca II, Rb I, and Ti I. The smooth continuum opacity of H₂ results in damped H₂O and CO bands at near-infrared wavelengths, so the latest-type and most metal-poor UCSDs exhibit bland spectral energy distributions longward of 1.5 µm (Leggett et al. 2000; Cushing & Vacca 2006, see Figure 1).

![Figure 1](image)

Figure 1. (Left) Comparison of M dwarf (top, and dashed lines), mild subdwarf (middle) and subdwarf (bottom) spectra, illustrating how reduced metallicity and metal oxide opacity allows for the emergence of weaker atomic metal lines. This figure also demonstrates that intermediate metallicity “mild” (d/sd) UCSDs are readily distinguishable from their dwarf and subdwarf counterparts (from Burgasser, Cruz & Kirkpatrick 2007). (Right) Low resolution near-infrared spectra of four UCSDs. Note the relatively smooth and featureless spectra of the two latest-type objects beyond 1.5 µm, caused by strong H₂ absorption, and the peak in flux around 1 µm (from Burgasser 2004).

Reiners & Basri (2006) have recently presented high resolution spectra for UCSDs, providing the first rotational velocity and accurate radial velocity measurements for these sources. The high $v \sin i = 65 \pm 15$ km/s of the L subdwarf 2MASS J0532+8246 (Burgasser et al. 2003a) suggests that the lowest mass halo stars may not lose their angular momentum as efficiently as more massive stars. They also find that one of the first L subdwarfs to be identified, LSR 1610-0040 (Lépine, Rich, & Shara 2003b), has mixed M dwarf and subdwarf spectral features, a conclusion also reached by Cushing & Vacca (2006) on the basis of near-infrared spectroscopy. This source appears to be peculiar, even among the small number of UCSDs now known.
3. New Discoveries

Burgasser, Cruz & Kirkpatrick (2007) provides a compendium of 16 currently known UCSDs, an increase of 60% since Cool Stars 13. This increase has been driven by new proper motion search programs using red optical photographic plate surveys (e.g., SUPERBLINK, Lépine, Shara, & Rich 2002, and the Super-COSMOS Sky Survey [SSS], Hambly et al. 2001) and serendipitous discoveries in near-infrared catalogs such as 2MASS. New discoveries include two ultracool extreme subdwarfs (Burgasser & Kirkpatrick 2006; Burgasser, Cruz & Kirkpatrick 2007), tripling the number of known ultracool esdMs; and a new L subdwarf, SDSS 1256-0224, reported by Sivarani, Kembhavi & Gupchup (2007).

While red optical proper motion surveys have been successful, the spectral energy distributions of cooler UCSDs peak around 1 μm (a balance of reduced $T_{\text{eff}}$ and increased absorption by H$_2$; see Figure 1), so near-infrared measurements become increasingly useful. Indeed, the UKIDSS survey with its 1 μm $Y$-band should be highly sensitive to UCSDs (Hewett et al. 2006). The recent inception of near-infrared proper motion surveys (e.g. Deacon, Hambly & Cooke (2005); Artigau et al. (2006); J. D. Kirkpatrick, 2007, in prep.) will likely expand the known UCSD population substantially in the near term.

4. Ultracool Subdwarf Classification

Spectral types for UCSDs are currently based on extrapolations of schemes developed for earlier-type M subdwarfs (Gizis 1997), based on TiO and CaH bands in the 6200–7300 Å region. These features become inadequate in the UCSD regime as TiO and CaH bands decline due to condensation (e.g. Lodders 2002); wide, pressure-broadened Na I and K I lines suppress adjacent features (Burrows & Volobuyev 2003); and the sources themselves become exceedingly faint at optical wavelengths. Gizis & Harvin (2006) and Burgasser, Cruz & Kirkpatrick (2007) have suggested the use of the same red optical features used to classify L dwarfs as diagnostics for UCSD classification, and the direct comparison of L subdwarf spectra to L dwarf spectral standards (see Figure 2). At near-infrared wavelengths, useful diagnostics are largely limited to the $J$-band region (Figure 1), and work is progressing in this direction (Burgasser et al., in prep.).

An issue to consider in the classification of UCSDs is the division of metallicity classes. Strong, blanketing molecular bands results in greater spectral sensitivity to metallicity and chemistry effects. The current population of UCSDs may already span a fairly broad range of metallicities, as suggested by comparisons to atmospheric models (Scholz et al. 2004b, see Figure 2 above); and the metallicities of early-type sdMs may not (and perhaps need not) correspond to those of late-type sdMs and sdLs. In addition, even slightly metal-poor ([M/H] ≥ -0.5) “mild” UCSDs are spectrally distinct (Figure 1), and a “d/sd” designation for these objects has been suggested. This group would encompass slightly metal-poor T dwarfs, distinguished by depressed $K$-band peaks (due to H$_2$ absorption) and enhanced $Y$-band peaks (possibly related to the red wing of the K I doublet at 0.77 μm; Burgasser, Kirkpatrick & Burrows 2006); and several recent discoveries of so-called “blue” L dwarfs (Cruz et al. 2003; Knapp et al. 2004; Chiu et al. 2006) that may also be metal-poor.
Figure 2. (Left) Red optical spectra of the L subdwarf 2MASS J1626+3925 (black line) and the L4 dwarf spectral standard 2MASS J1155+2307 (red dashed line). Their rough agreement suggests a means of classifying L subdwarfs (Gizis & Harvin 2006; Burgasser, Cruz & Kirkpatrick 2007), with deviations indicative of metallicity effects (adapted from Burgasser, Cruz & Kirkpatrick 2007). (Right) Color-color diagram of known UCSDs compared to metal-dependent evolutionary and atmospheric models. While current models may not accurately match observations (§5), it is interesting to note the range in metallicities suggested by this comparison (from Scholz et al. 2004b).

5. Other Issues

I briefly summarize other issues that have arisen in recent studies of UCSDs. The interested reader is encouraged to examine the literature for further discussion.

Dust Formation: One of the defining properties of L field dwarfs is the formation of condensate dust in their photospheres, driving the depletion of gaseous TiO, VO, CaH, Al I, Ca I and Ti I in the photosphere (Burrows & Sharp 1999; Lodders 2002). However, several late-type subdwarfs exhibit features from these species when it is absent in their dwarf counterparts (Burgasser et al. 2003a; Scholz et al. 2004b; Reiners & Basri 2006, see Figure 2 above). Their persistence suggests that condensate formation may be inhibited in metal-poor atmospheres; chemical modeling of this effect is needed.

Spectral Modeling: Attempts to derive physical properties for UCSDs based on spectral model fits have met with mixed results (e.g. Schweitzer et al. 1999; Lépine, Shara, & Rich 2004; Burgasser, Cruz & Kirkpatrick 2007). The difficulties stem from the same issues that arise when modeling ultracool dwarf spectra; e.g., complex molecular opacities, and chemistry and condensate grain formation. There are new concerted efforts to develop better metal-poor atmosphere models in the UCSD regime (Burrows, Sudarsky & Hubeny 2006; Schweitzer, Hauschildt & Wawrzyn, these proceedings).

Binaries: Binary systems are useful laboratories for studying detailed properties, testing formation theories and finding low temperature sources as companions (see splinter session overview by H. Bouy). There have been a couple of studies targeting M subdwarfs for companions (Zapatero Osorio & Martin 2004, Gelino & Kirkpatrick, these proceedings) with as yet no reported UCSD discoveries.

Distance Measurements: These are perhaps the most crucial observations needed, as only two UCSDs have reported parallaxes. Such measurements make possi-
ble the construction of absolute magnitude, luminosity and $T_{\text{eff}}$ scales, and facilitate comparisons to spectral and structural models.

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