ULTRACOOL SUBDWARFS: METAL-POOR STARS AND BROWN DWARFS EXTENDING INTO THE LATE-TYPE M, L AND T DWARF REGIMES

Adam J. Burgasser\textsuperscript{1}, J. Davy Kirkpatrick\textsuperscript{2}, and Sébastien Lépine\textsuperscript{3}

\textsuperscript{1}Dept. Physics \& Astronomy, UC Los Angeles, Los Angeles, CA 90095 USA;
\textsuperscript{2}Infrared Processing and Analysis Center, MS 100-22, California Institute of Technology, Pasadena, CA 91101 USA;
\textsuperscript{3}Dept. Astrophysics, Div. Physical Sciences, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024 USA

\textbf{Abstract}

Recent discoveries from red optical proper motion and wide-field near-infrared surveys have uncovered a new population of ultracool subdwarfs – metal-poor stars and brown dwarfs extending into the late-type M, L and possibly T spectral classes. These objects are among the first low-mass stars and brown dwarfs formed in the Galaxy, and are valuable tracers of metallicity effects in low-temperature atmospheres. Here we review the spectral, photometric, and kinematic properties of recent discoveries. We also examine L subdwarf classification, and discuss how a large, complete sample of substellar halo subdwarfs could probe the star formation history of the Galaxy’s Population II. We conclude by outlining a roadmap for future work to more thoroughly explore this old and very low-mass population.

Key words: Stars: low-mass, brown dwarfs — Stars: Population II — Subdwarfs

1. Cool Subdwarfs ca. Cool Stars 12

Subdwarfs are metal-deficient stars, classically defined as lying below the stellar main sequence in optical color-magnitude diagrams (Kuiper 1939). These objects are in fact not subluminous but rather hotter (i.e., bluer in optical colors) than equivalent mass main sequence dwarfs, a consequence of their reduced metal opacity (Sandage \& Eggen 1959). Cool subdwarfs (spectral types sdK and sdM) are typically found to have thick disk or halo kinematics, and in the latter case are presumably relics of the early Galaxy, with ages of 10–13 Gyr. Because low mass subdwarfs have lifetimes far in excess of the age of the Galaxy, they are important tracers of Galactic chemical history, and are representatives of the first generations of star formation.

At the time of the Cool Stars 12 meeting in Boulder, Colorado, USA, the coolest known subdwarfs (sd) and extreme subdwarfs (esd) – [Fe/H] \sim -1.2 and -2.0, respectively (Gizis 1997) – extended down to spectral types sdM7/esdM7, with effective temperatures $T_{\text{eff}} \gtrsim 3000$ K (Schweitzer et al. 1999; Leggett et al. 2000). As such, all cool subdwarfs known at that time were hydrogen burning low-mass stars. These objects had been predominantly identified from optical, typically photographic plate, proper motion surveys, including Luyten’s Half-Second Catalog (LHS; Luyten 1979a) and Two-Tenths Catalog (NLTT; Luyten 1979b), and the APM Proper Motion Survey (Scholz et al. 2000). Photographic plate surveys have the advantage of broad temporal baselines, as much as 50 years in the case of the APM survey, allowing determinations of proper motions down to 0″008-0″010 yr\(^{-1}\). The high space velocities of halo subdwarfs cause them to stand out from the overwhelming number of field stars with similar optical colors, particularly through the use of reduced proper motion (RPM) diagrams (Luyten 1925; Reid 1984; Warner 1972; see Figure 6).

At the same time, well over one hundred even cooler, roughly solar metallicity, dwarf stars and brown dwarfs had been identified in several wide field imaging surveys, including members of the new spectral classes L and T (Kirkpatrick et al. 1999; Burgasser et al. 2002; Geballe et al. 2002; also see S. Leggett, these proceedings). With $T_{\text{eff}}$ as low as 700 K (Golimowski et al. 2004), L and T dwarfs emit the majority of their luminous flux in the near-infrared; hence, the success of recent wide-field near-infrared surveys such as 2MASS (Cutri et al. 2003), DENIS (Epchtein et al. 1997), and SDSS (York et al. 2000) in uncovering them. Late-type M, L and T dwarfs have extremely red optical/near-infrared colors ($R-J > 5$; Dalba et al. 2002). Hence, these so-called ultracool stars and brown dwarfs (defined here as objects with spectral classes M7 and later; see Kirkpatrick et al. 1999) are generally missed in photographic plate surveys.

2. To the End of the sdM Sequence

New proper motion surveys based on photographic plates have recently pushed our compendium of cool subdwarfs to the end of the M spectral class. The surveys include the SUPERBLINK catalog (Lépine et al. 2002; Lépine et al. 2003d) and the SuperCosmos Sky Survey (SSS; Hambly et al. 2001a; 2001b; 2001c). The first has identified faint, high proper motion stars at northern declinations through image analysis of Digital Sky Survey scans of red photographic plates from the POSS-I (Abell 1959) and POSS-II (Reid et al. 1991) sky surveys. New discoveries (the “LSR” stars) include four subdwarfs as cool or cooler than the prior late-type record-holder, the sdM7 LHS 377 (Gizis 1997), and a handful of extreme subdwarfs within a subclass of the esdM7 APMPM 0559-29 (Schweitzer et al. 1999). The SSS cat-
alog also makes use of digitized data from POSS-I and POSS-II, but includes additional data from the ESO and UK Schmidt photographic surveys, including infrared $I_N$ (0.7-0.9 µm) plates from the UK Schmidt survey (Hartley & Dawe 1981). A recent catalog of 11,289 proper motion stars from the SSS survey around the southern Galactic cap is given in Porkorny et al. (2004). Besides the discovery of the closest brown dwarfs to the Sun (Scholz et al. 2003), two ultracool M subdwarfs have been identified amongst the “SSSPM stars”, including the latest-type M subdwarf known, the sdM9.5 SSSPM 1013−13 (Scholz et al. 2004; also see H. Zinnecker, these proceedings).

Figure 1. Optical spectra of the sdM8 LSR 1425+71 (top) and the solar metallicity M6 V field star LSR 2000+30 (bottom). These spectra demonstrate key metallicity diagnostics at optical wavelengths, including enhanced metal hydride bands (e.g., CaH bands at 6400 and 6800 ˚A), weakened oxide bands (e.g., TiO and VO bands at 6500, 7800 and 8500 ˚A), and strong atomic lines. (From Lépine et al. 2003c).

Figure 2. JHK_s color-color diagram of M (squares), L (triangles), and T (circles) dwarfs, comparing solar metallicity field objects (open symbols) to metal-poor subdwarfs and extreme subdwarfs (filled symbols). M dwarf colors are from Leggett (1992) and Gizis et al. (2000); colors for L and T dwarfs with small photometric errors ($\sigma_J < 0.05$ and 0.07 mag, respectively) are from 2MASS. The Bessell & Brett (1988) dwarf and giant tracks are superimposed for comparison. While late-type M and L dwarfs becoming increasing red in near-infrared color due to warm condensate dust radiation, subdwarfs are increasingly blue due to $H_2$ absorption. Note in particular the L subdwarfs 2MASS 1626+39 and 2MASS 0532+82 and the possible T subdwarf 2MASS 0937+29.

At longer wavelengths, collision-induced $H_2$ absorption centered near 2.1 µm (1-0 quadrupole; Saumon et al. 1994) becomes an increasingly important absorber in ultracool subdwarfs due to the reduction of competing opacities from metal-rich species. This broad absorption feature gives cool subdwarfs bluer near-infrared colors than equivalently-typed field dwarfs, as illustrated in Figure 2. CO and $H_2O$ bands in the near-infrared are also observed to be weaker in subdwarf spectra as compared to equivalently classified field dwarfs (Leggett et al. 2000; Burgasser 2004b).
3. L Subdwarfs

The first unambiguous L subdwarf, 2MASS 0532+82, was serendipitously identified in the 2MASS catalog. This high proper-motion source ($\mu = 2^{\prime\prime}.6$ yr$^{-1}$) has blue near-infrared colors ($J - K_s = 0.26$) and no optical counterpart in POSS red plates. While its photometric properties initially made it a solid T dwarf candidate, the observed spectrum of 2MASS 0532+82 (Figure 3) proved to be quite unlike any T dwarf identified to date. Its optical and J-band spectra closely resemble that of the L7 field dwarf DENIS 0205−11 with strongly pressure-broadened fundamental doublets of Na I and K I (Burrows et al. 2000), strong H$_2$O absorption in the optical and near-infrared, metal hydride bands, and a steep red optical slope. However, metal hydride absorptions are significantly enhanced in 2MASS 0532+82. This source even exhibits TiH absorption at 9400 Å, the first identification of the infrared band of this molecule in an astrophysical source$^1$ (Andersson et al. 2003; Burgasser 2004). M. Cushing, priv. comm.). Beyond 1.3 $\mu$m, the spectrum of 2MASS 0532+82 deviates from that of DENIS 0205−11, with a blue, relatively featureless slope and a notable absence of the 2.3 $\mu$m CO band. The blue slope arises from H$_2$ absorption, which is notably enhanced in this object.

The observed spectral peculiarities of 2MASS 0532+82 are analogous to the metallicity features seen in ultracool M subdwarf spectra, but extrapolated into the L dwarf regime. This argues that 2MASS 0532+82 is simply a metal-poor L subdwarf. The halo kinematics of 2MASS 1626+39 (Burgasser et al. 2004a), this object appears to progress in a natural sequence beyond the latest-type M subdwarfs (Figure 4), giving strong support to the interpretation that this object is simply a cooler, metal-poor star. Indeed, the discovery of three L subdwarfs in the proximity of the Sun (all three have $d < 50$ pc) indicates that such objects are not isolated oddballs but in fact a bona-fide class of low-temperature, metal-deficient, low-mass stars and brown dwarfs.

4. T Subdwarfs

At roughly the same time that 2MASS 0532+82 was announced, a second L subdwarf was identified in the LSR catalog, the high proper motion star ($\mu = 1^{\prime\prime}.46$ yr$^{-1}$) LSR 1610−00. As reported in Lépine et al. (2003a) this source exhibits features that are in common -- and in conflict -- with both late-type M and early-/mid-type L dwarf spectra. The spectral energy distribution of this source as derived from photometry is more similar to the former, with red near-infrared colors ($J - K_s = 0.89$) similar to a M7-M8 field dwarf. This stands in contrast to the weak TiO bands beyond 7500 Å and absence of optical VO bands. Metal hydride bands are present, and the 6800 Å CaH band is particularly strong, while FeH bands are actually weaker than those of mid-type L dwarfs. Most surprising are the presence of Rb I lines, which are only observed in the spectra of mid- and late-type field L dwarfs. The spectral features in LSR 1610−00 are similar to those of the sdM8 LSR 1425+71, with the exception of the Rb I lines and a steeper red optical spectral slope. Based on these diagnostics, Lépine et al. (2003a) propose that this object is another, perhaps earlier-type, metal-poor L subdwarf.

Recently, a third L subdwarf has been identified in the 2MASS database, 2MASS 1626+39 (Burgasser 2004a). This object was found in the same search sample from which 2MASS 0532+82 was selected. The spectrum of this object appears to progress in a natural sequence beyond the latest-type M subdwarfs (Figure 4), giving strong support to the interpretation that this object is simply a cooler, metal-poor star. Indeed, the discovery of three L subdwarfs in the proximity of the Sun (all three have $d < 50$ pc) indicates that such objects are not isolated oddballs but in fact a bona-fide class of low-temperature, metal-deficient, low-mass stars and brown dwarfs.

1 Optical bands of TiH between 5200−5400 Å had previously been identified in the spectra of M giants (Yerle 1979).

2 Indirect evidence for the existence of Population II brown dwarfs has previously been seen in halo and globular cluster mass functions, which are flat to slightly rising near the HBMM (John et al. 1995; Chris & Reid 1999; Piotto & Zoccali 1999; Digby et al. 2000).
Figure 3. The spectrum of 2MASS 0532+82 (thick black line) as compared to the L7 field dwarf DENIS 0205−11 (thin grey line). In all panels, spectral data for 2MASS 0532+82 have been shifted by its radial velocity ($V_{\text{rad}} = +195 \text{ km s}^{-1}$), and data for both sources are normalized at 1.27 µm. (a) Observed 0.63–2.35 µm spectrum, with NIRSPEC bands scaled to 2MASS photometry. (b) Top: FeH opacity spectrum. Bottom: J-band spectrum of 2MASS 0532+82, with line identifications for K I, Fe I, FeH, and H$_2$O. (c) Red optical spectrum, with key features indicated. Inset window shows a close-up of the 6350–7600 Å spectral region, highlighting strong CaH and weak TiO bands; no Li I or Hα lines are seen. (From Burgasser et al. 2003a)

sensitive, and therefore gravity-sensitive, features. Indeed, at least three other late-type T dwarfs, out of roughly 60 currently known, have similar spectral peculiarities (Burgasser et al., in prep.; also see S. Leggett, these proceedings). Such a high proportion of metal-poor subdwarfs in the T dwarf regime is inconsistent with the relative num-
bers of M- and L-type subdwarfs amongst field counterparts (generally 0.2-0.3%; Digby et al. 2003), arguing in favor of surface gravity being the dominant effect. However, the optical spectrum of 2MASS 0937+29 cannot be fit with any solar metallicity model currently available (Burgasser et al. 2003b). Clearly, further observational and theoretical work is required to disentangle the effects of gravity and metallicity in T dwarfs and ascertain the physical properties of 2MASS 0937+29. Because of the low atmospheric temperatures required to form the characteristic CH$_4$ bands that define the T class, any T subdwarf identified would necessarily be a substellar object.

5. Classification of Ultracool Subdwarfs

The most widely-adopted classification of M-type subdwarfs is that defined by Gizis (1997), which relies primarily on the strength of CaH (as a temperature index) and TiO (as a metallicity index) bands in the 6200-7400 Å region. As we progress to later spectral subtypes, however, these spectral features become less useful. TiO absorption weakens as this gas is sequestered into condensate species (at least for field dwarfs); while the spectral energy distribution shifts to longer wavelengths, resulting in little measurable flux at visible wavelengths. Recognizing this shortcoming, Lépine et al. (2003b) added an additional classification index, Color-M, to sample the spectral slope between 6500 and 8100 Å for M subdwarfs, similar to pseudocontinuum indices used by Kirkpatrick et al. (1991,1999) to classify M and L disk dwarfs. However, the Lépine subdwarf scheme continues to rely primarily on the Gizis (1997) TiO and CaH indices, and is therefore inappropriate for L subdwarfs. As new examples of ultracool subdwarfs are identified and observed, a revised optical classification relying on features at longer wavelengths will be needed. Diagnostics might include the 7900 and 8400 Å bands of VO and TiO, the 8600 and 9900 Å bands of CrH and FeH, the 9400 Å band of TiH, Cs I and Rb I alkali lines, and color indices sampling longer wavelengths. A logical step for future ultracool subdwarf classification is to utilize spectral diagnostics at both optical and near-infrared wavelengths. Figure 4 illustrates a roadmap for this direction, showing a low-resolution 0.7-2.5 μm spectral sequence of ultracool subdwarfs from sdM7 to sdL (Burgasser 2004b). Many of the metallicity spectral diagnostics discussed above appear to vary in a systematic way amongst the ultracool subdwarfs, including a weakening of the 0.85 μm TiO and 2.3 μm CO bands; strengthening of FeH and CrH bands at 0.86, 0.99, and 1.2 μm; strengthening lines of K I at 0.77, 1.17, and 1.25 μm; strengthening H$_2$O absorption at 1.3 μm; and spectral slopes that become increasing red shortward of 1 μm and increasingly blue at longer wavelengths. The regular evolution of these features in the spectra of Figure 4 is promising for the future classification of ultracool subdwarfs.

![Figure 4](image-url) A low-resolution spectral sequence of late-type M subdwarfs and the L subdwarf 2MASS 1626+39. Note the strong metal hydride bands (e.g., FeH at 0.99 and 1.2 μm), weak metal oxides bands (e.g., CO at 2.3 μm), and increasingly blue near-infrared spectral slopes. These spectra are quite unlike those of equivalently-typed disk dwarfs, which tend to have strong metal oxides (e.g., TiO and VO), weaker metal hydrides, and red near-infrared colors (J − K > 1). (From Burgasser 2004b).

Despite these optimistic signs, it is important to stress that before a formal scheme can be codified, more examples of these objects must be identified. Accurate spectral classification relies on the comparison of spectra to defined standard stars, and not the simple extrapolation of spectral indices.

6. Substellar Subdwarfs and Star Formation Rate

Most ultracool subdwarfs identified to date have kinematics consistent with membership in the halo (Population II) or thick disk (Intermediate Population II) of the Galaxy. Hence, an accurate assessment of the Luminosity Function (LF) of late-type M and L subdwarfs enables us to examine the low-mass end of the Mass Functions (MF) for these populations down to and below the HBMM. Furthermore, as long-lived sources, ultracool subdwarfs are
excellent tracers of physical conditions in the early Galaxy, including chemical enrichment.

Measuring the LF of ultracool subdwarfs is currently an intractable task due to paucity of sources known. However, a significant and complete sample of substellar subdwarfs could provide information on both the star formation history and MF of the Galactic halo and thick disk. This is because substellar objects continually evolve over time to lower luminosities and cooler effective temperatures due to the lack of sustained hydrogen fusion. As such, they make excellent chronometers. Figure 5 diagrams an application of this fact, comparing simulated LFs for two populations: one with a constant star formation rate over the age of the Galaxy (appropriate for a disk population) and one with a single 1 Gyr burst 10 Gyr in the past (appropriate for a halo population). In the $T_{\text{eff}}$ regime appropriate for L-type dwarfs, there is a clear deficiency of objects in the halo population, the result of the long-term thermal evolution of most brown dwarfs to cooler temperatures. There is no such depletion amongst the T-type dwarfs, and it has been shown that the LF of T dwarfs is highly sensitive to the underlying MF while the LF of L dwarfs is not (Burgasser 2004a; Allen et al. 2004). Hence, by measuring the space densities of both populations, one can conceivably measure both the MF and star formation history of a particular population. While such a measurement may be several years off, Figure 5 demonstrates how ultracool halo subdwarfs can ultimately be used to measure global Galactic properties.

7. Ultracool Subdwarfs ca. Cool Stars 13

Table 1 lists all ultracool subdwarfs known at (or soon after) the Hamburg Cool Stars 13 meeting. The shortness of this list betrays our limited understanding of these metal-poor cool stars and brown dwarfs, and it is clear that continuing work is needed to discover and characterize them.

One potentially powerful technique to identify new ultracool subdwarfs that has yet to be adequately explored is a near-infrared proper motion survey. It is clear from studies of late-type M, L and T dwarfs, and the few ultracool subdwarfs now known, that the optical bands used in contemporary proper motion surveys miss the peak of the spectral energy distributions of later-type objects. Examination of Figure 4 shows that surveys conducted around 1 μm (e.g., Z, Y, and J photometric bands) are optimally suited to detect ultracool subdwarfs, as verified by the identification of two L subdwarfs in the 2MASS survey. Red and infrared RPM diagrams, such as that illustrated in Figure 6, could help distinguish those objects. Work is currently in progress to match multiple-epoch observations in the 2MASS survey to identify very high proper motion sources that are potential ultracool subdwarfs; cross-correlation between the 2MASS, DENIS, and SDSS surveys could similarly identify high proper motion, near-infrared bright sources. However, these surveys sample a relatively narrow timeframe, roughly 2-5 years, restricting work to the highest motion, and hence most nearby, sources. A second epoch wide field survey is needed to detect motion from more distant high velocity stars, enabling a larger and more statistically complete sample. With the development of large-format near-infrared detectors, such surveys are possible and, indeed, already in development. These include the UKIRT Infrared Deep Sky Survey\(^3\) (UKIDSS; S. Leggett, these proceedings) and the VISTA telescope\(^4\) (McPherson et al. 2003). By using existing sky surveys for first epoch astrometry, such programs may ultimately produce ultracool subdwarf samples

---

\(^3\) See [http://www.ukidss.org/index.html](http://www.ukidss.org/index.html)

\(^4\) See [http://www.vista.ac.uk/index.html](http://www.vista.ac.uk/index.html)
Table 1. Known Ultracool Subdwarfs sdM7/esdM7 and Later.

| Name                | SpTa       | R - Jb     | Jb     | J - Ksb   | μ (yr⁻¹) | Reference                  |
|---------------------|------------|------------|--------|-----------|----------|----------------------------|
| APMPM 0559−29      | esdM7      | 3.2        | 14.89  | 0.43      | 0′′38    | Schweitzer et al. (1999)    |
| LHS 377             | sdM7       | 4.2        | 13.19  | 0.71      | 1′′25    | Gizis (1997)                |
| SSSPM 1930−43       | sdM7       | 3.6        | 14.79  | 0.70      | 0′′87    | Scholz et al. (2004)        |
| LSR 2036+50         | sdM7.5     | 3.9        | 13.61  | 0.68      | 1′′05    | Lépine et al. (2003b)      |
| LSR 1425+71         | sdM8       | 3.8        | 14.78  | 0.45      | 0′′64    | Lépine et al. (2003c)      |
| SSSPM 1013−13       | sdM9.5     | 4.4        | 14.59  | 0.24      | 1′′03    | Scholz et al. (2004)        |
| LSR 1610−00         | sdLc       | 4.6        | 12.91  | 0.89      | 1′′46    | Lépine et al. (2003a)      |
| 2MASS 1626+39       | sdL        | 5.4        | 14.44  | -0.03     | 1′′27    | Burgasser (2004b)           |
| 2MASS 0532+82       | sdL        | > 5.5      | 15.18  | 0.26      | 2′′60    | Burgasser et al. (2003a)   |
| 2MASS 0937+29       | sdT?d      | > 6        | 14.65  | -0.62     | 1′′62    | Burgasser et al. (2002)     |

aM subdwarf spectral types based on the optical classification scheme of Gizis (1997); an L subdwarf classification scheme has not yet been defined (see § 4).
bR magnitudes from the USNO B1.0 (Monet et al. 2003); JKs magnitudes from 2MASS (Cutri et al. 2003).
cCushing et al. (in prep.) have questioned the subdwarf status of LSR 1610−0040 as its near-infrared colors and spectrum are atypical of other late-type sdMs and sdLs. Its spectrum is clearly inconsistent with that of a disk dwarf, however, and further observational work is needed.
dSubsolar metallicity effects observed in the spectrum of this object may be confused with high surface gravity. See discussion in § 3.

Additional observational work is required for the existing set of ultracool subdwarfs. A subset of investigations currently possible include optical and near-infrared spectroscopy to investigate spectral diagnostics of temperature and metallicity; high-resolution spectroscopy to measure specific abundances and radial velocities; broadband imaging to measure bolometric corrections; and parallax measurements to determine absolute brightnesses, effective temperatures, and space motions. Observations at longer wavelengths (e.g., using the Spitzer telescope) may also provide new information on the atmospheric composition of these objects, particularly in regards to the presence and constituency of dust condensates. High-resolution imaging and/or high-resolution spectroscopic monitoring can probe multiplicity and binary distributions, a clue to formation mechanisms.

These observational advances must also be matched by improvements in theoretical evolutionary and spectral models for cool, metal-poor stars and brown dwarfs. The most recent theoretical work includes that of Baraffe et al. (1997) who have computed evolutionary models for subsolar metallicity stars down to the HBMM; Leggett et al. (2000) who have compared observational spectra of M subdwarfs down to sdM7 (LHS 377) to theoretical models developed by the Lyon group (Hauschildt et al. 1999); and Burrows et al. (2002) who examined metallicity effects in theoretical spectra of T dwarfs such as 2MASS 0937+29. Clearly, both evolutionary and spectral models will need to be expanded to address the properties of the recently discovered ultracool subdwarfs. In addition, chemical equilibrium models may need to be examined, as non-solar metallicities should have a significant effect on the abundances of the large enough to begin more global studies, such as measurement of the low-mass halo MF.

Figure 6. J-band RPM diagram for sources in the revised NLTT catalog (Salim & Gould 2003) and ultracool M (squares) and L (triangles) subdwarfs and extreme subdwarfs. The RPM, defined as  \( H_J = J + 5 \log \mu + 5 = M_J + 5 \log V_{\text{tan}} - 3.38 \), distinguishes field and halo stars by the higher tangential motions of the latter. This segregation is apparent amongst the bluer stars in the plot (note the two populations separated by a dashed line; the field dwarfs are to the right of the line), but can be somewhat muddled amongst the latest-type dwarfs. Nonetheless, ultracool extreme subdwarfs tend to lie at fainter RPMs than subdwarfs and field stars, while the latest-type objects tend to the lower right of the diagram, indicative of lower luminosities, redder colors, and (in the case of subdwarfs) high space velocities.
most spectrally active species in an ultracool subdwarf atmosphere, including the condensate species that dominate L field dwarf spectra. In this context, the interaction between observation and theory can be expected to be quite fruitful for this new class of subdwarfs in the years to come.

Acknowledgements
The authors thank J. Gizis, J. Liebert, and I. N. Reid for their helpful comments on the original manuscript. A. J. B. acknowledges support provided by NASA through Hubble Fellowship grant HST-HF-01137.01 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. S. L. is a Kalfiflech research fellow of the American Museum of Natural History. This publication makes use of data from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation. 2MASS data were obtained through the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References
Abell, G. O. 1959, PASP 67, 258
Allen, P., Koerner, D. W., & Reid, I. N. 2004, ApJ, submitted
Andersson, N., Balfour, W. J., Bernath, P. F., et al. 2003, JChPh 118, 3543
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1997, A&A 327, 1054
Bessell, M. S., & Brett, J. M. 1988, PASP 100, 1134
Burgasser, A. J. 2004a, ApJS 115, in press
—. 2004b, ApJ 614, in press
Burgasser, A. J., Kirkpatrick, J. D., Brown, M. E., et al. 2002, ApJ 564, 421
Burgasser, A. J., Kirkpatrick, J. D., Burrows, A., et al. 2003a, ApJ 592, 1186
Burgasser, A. J., Kirkpatrick, J. D., Cutri, R. M., et al. 2000, ApJ 531, L57
Burgasser, A. J., Kirkpatrick, J. D., Liebert, J., et al. 2003b, ApJ 594, 510
Burrows, A., Burgasser, A. J., Kirkpatrick, J. D., et al. 2002, ApJ 573, 394
Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Rev. of Modern Physics 73, 719
Burrows, A., Marley, M. S., & Sharp, C. M. 2000, ApJ 531, 438
Chamberlin, J. W., & Aller, L. H. 1951, ApJ 114, 52
Cutri, R. M., Skrutskie, M. F., Van Dyk, S., et al. 2003, 2MASS All Sky Data Release
Dahn, C. C., Harris, H. C., Vrba, F. J., et al. 2002, AJ 124, 1170
Dahn, C. C., Liebert, J., Harris, H. C., & Guetter, H. H. 1995, in The Bottom of the Main Sequence - and Beyond, Proceedings of the ESO Workshop Held in Garching, Germany, 10-12 August 1994; ed. C. G. Tinney (Springer-Verlag: Berlin), p. 239
Delfosse, X., Tinney, C. G., Forveille, T., et al. 1997, A&A 327, L25
Digby, A. P., Hambly, N. C., Cooke, J. A., et al. 2003, MNRAS 344, 583
Eggen, O. J., & Greenstein, J. L. 1965, ApJ 142, 925
Epchtein, N., de Batz, B., Capoani, L., et al. 1997, The Messenger 87, 27
Geballe, T. R., Knapp, G. R., Leggett, S. K., et al. 2002, ApJ 564, 466
Gizis, J. E. 1997, AJ 113, 806
Gizis, J. E., Monet, D. G., Reid, I. N., et al. 2000, AJ 120, 1085
Gizis, J. E., & Reid, I. N. 1999, AJ 117, 508
Golimowski, D. A., Leggett, S. K., Marley, M. S., et al. 2004, AJ 127, 3561
Hambly, N. C., Davenhall, A. C., Irwin, M. J., & MacGillivray, H. T. 2001a, MNRAS 326, 1315
Hambly, N. C., Irwin, M. J., & MacGillivray, H. T. 2001b, MNRAS 326, 1295
Hambly, N. C., MacGillivray, H. T., Read, M. A., et al. 2001c, MNRAS 326, 1279
Hartley, M., & Dawe, J. A. 1981, PASA 4, 251
Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ 512, 377
Kirkpatrick, J. D., Henry, T. J., & Irwin, M. J. 1997, AJ 113, 1421
Kirkpatrick, J. D., Henry, T. J., & McCarthy, D. W., Jr. 1991, ApJS 77, 417
Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 1999, ApJ 519, 802
Kuiper, G. P. 1939, ApJ 89, 549
Leggett, S. K. 1992, ApJS 82, 351
Leggett, S. K., Allard, F., Dahn, C., et al. 2000, ApJ 535, 965
Lépine, S., Rich, R. M., & Shara, M. M. 2003a, ApJ 591, L49
—. 2003b, AJ 125, 1508
Lépine, S., Shara, M. M., & Rich, R. M. 2002, AJ 124, 1190
—. 2003c, ApJ 585, L69
—. 2003d, AJ 126, 921
Lodders, K. 2002, ApJ 577, 974
Luyten, W. J. 1925, ApJ 62, 8
—. 1979a, LHS Catalog (Minneapolis: Univ. Minn. Press)
—. 1979b, NLTT Catalog (Minneapolis: Univ. Minn. Press)
McLean, I. S., McGovern, M., Burgasser, A. J., et al. 2003, ApJ 596, 561
McPherson, A. M., Craig, S. C., & Sutherland, W. 2003, SPIE 4837, 82
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ 125, 984 (USNO-B1.0 Catalog)
Mould, J. R. 1976, ApJ 207, 535
Piotto, G., & Zoccali, M. 1999, A&A 345, 485
Pokorny, R. S., Jones, H. R. A., Hambly, N. C., & Pinfield, D. J. 2004, A&A 421, 763
Reid, I. N. 1984, MNRAS 206, 1
Reid, I. N., Brewer, C., Bruccato, R. J., et al. 1991, AJ 102, 1428
Salmi, S., & Gould, A. 2003, ApJ 582, 1011
Sandage, A. R., & Eggen, O. J. 1958, MNRAS 119, 278
Saumon, D., Bergeron, P., Lunine, J. I., et al. 1994, ApJ 424, 333
Scholz, R.-D., Irwin, M., Ibata, R., et al. 2000, A&A 353, 958
Scholz, R.-D., Lehnmann, I., Matute, I., & Zinnecker, H. 2004, A&A in press
Scholz, R.-D., McCaughrean, M. J., Lodieu, N., & Kuhlbrodt, B. 2003, A&A 398, L29
Schweitzer, A., Scholz, R.-D., Stauffer, J., et al. 1999, A&A 350, L62
Yerle, R. 1979, A&A 73, 346
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ 120, 1579
Warner, J. F. 1972, MNRAS 155, 463