Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Infrared Classification of L and T Dwarfs

T. R. Geballe[1], G. R. Knapp[2], S. K. Leggett[3], X. Fan[4], and D. A. Golimowski[5]

Abstract.
We use new and published medium resolution 0.6–2.5 μm spectra of L and T dwarfs to develop a unified classification system for both of these new spectral classes. Two indices of the system at 1.2 μm and 1.5 μm are based on nearby absorption bands of water vapor and two are associated with methane bands near 1.6 μm and 2.2 μm. The 1.5 μm index is monotonic through the L and T sequences, and forms the backbone of the system; the indices for the other bands provide extensive, but only partial, coverage. We correlate the 1.5 μm index with continuum indices shortward of 1 μm devised by others for classifying L dwarfs, in order to obtain a tight link between optical and infrared classifications. Our proposed system defines ten spectral subclasses for L (L0–L9) and nine for T (T0–T8). The boundary between L and T is defined to be the onset of absorption by methane in the H band. Methane absorption in the K band near 2.2 μm is found to begin approximately at L8.

1. Introduction

The recent discoveries of ultracool stellar dwarfs and brown dwarfs have produced a need for an extension of the current system of stellar classification, whose latest spectral class has been M since near the very inception of classification. New spectral classes designated L and T have been proposed and are widely used now to describe the ultracool dwarfs. The L class (Martín et al. 1999, hereafter M99; Kirkpatrick et al. 1999, hereafter K99) is generally recognized to extend from the end of the M dwarf sequence ($T_{eff} \sim 2200$ K) roughly to the temperature (~ 1400 K) at which methane absorption becomes apparent in the H and K bands, signifying that CH_4 is beginning to replace carbon monoxide (CO) as the dominant carbon-bearing molecule. The T class (K99) includes dwarfs with temperatures from $\sim$1400 K down at least to the coolest (~ 800 K) extra-solar objects currently measured, and probably beyond.

[1]Gemini Observatory, Hawaii

[2]Princeton University Observatory

[3]Joint Astronomy Centre, Hawaii

[4]Institute for Advanced Study, Princeton

[3]The Johns Hopkins University, Baltimore

M99 and K99 have developed classification systems for the L sequence, based on spectral features and continuum slopes in the optical (0.6–1.0μm). The M99 system defines subclasses L0–L6, the K99 system L0–L8. Using photometry and infrared (1.0–2.5 μm) spectroscopy Leggett et al. (2000) found the first examples of dwarfs in the transition region between the basic L and T spectral properties. Burgasser et al. (2000) have observed a dozen T dwarfs at 1.0-2.5 μm and have demonstrated the potential for defining a T sequence based on infrared indices. Neither the details of a T classification scheme nor the manner by which the two classes might be smoothly conjoined has yet been proposed. Keys to determining these are: (1) obtaining a larger set of infrared spectra of L and T dwarfs; (2) observing in finer detail the transition between the classes; and (3) developing an accurate infrared classification scheme for L dwarfs to complement the optical schemes. The last is essential, because late L and T dwarfs cannot be easily classified optically due to their faintness. Several groups already have begun exploring infrared schemes for L dwarfs (Delfosse et al. 1999; Tokunaga & Kobayashi 1999; Reid et al. 2001; Testi et al. 2001).

This paper briefly describes a unified classification system that we have developed for L and T dwarfs. Details are found in Geballe et al. (2001; hereafter G01) and Leggett et al. (2001). A classification system for T dwarfs has also recently been proposed by Burgasser et al. (2001).

2. Observations and Analysis: Indices for 1.0–2.5 μm

Our work uses new and published spectra of 25 L dwarfs and 17 T dwarfs in the 0.6-2.5 μm region. Many of these objects have been discovered in the Sloan Digital Sky Survey. Some are 2MASS and DENIS objects classified previously by M99, K99, and Kirkpatrick et al. (2000). Most of the spectra were obtained by us, using CGS4 at the United Kingdom Infrared Telescope (UKIRT) and in a few cases with NIRSPEC at the Keck II telescope. We also use a few spectra from Reid et al. (2001). The final reduced 1.0-2.5 μm portions of the spectra are at resolving powers near 400. We have examined these spectra for the most useful set of infrared indices for classification. Successful indices should be monotonic across large swaths of the L and T sequences, based on individual spectral features or on continuum behavior over relatively narrow wavelength regions, and measurable at sites with average atmospheric transparency and intermediate-sized telescopes.

We have found four indices in the 1.0–2.5 μm region that satisfy our criteria. Two of these, near 1.15 μm and 1.5 μm, are associated with prominent water bands and two, near 1.6 μm and 2.2 μm, with methane bands. Their locations are shown in Fig. 1, superposed on spectra of a mid-L and a mid-T dwarf. Each index is a ratio of fluxes in two narrow wavelength intervals, one of which is on a portion of the molecular absorption band and the other of which is on nearby continuum. All four measure the increasing strengths of these bands with later spectral type. The 1.5 μm index is monotonic across the entire L sequence. The 2.2 μm index is useful from mid-L to the latest T dwarfs, while the other two indices are useful only for T dwarfs. For L dwarfs we also use two optical continuum indices "PC3" and "Color-d" from M99 and K99, respectively (we have slightly modified the K99 index) to aid in classification.

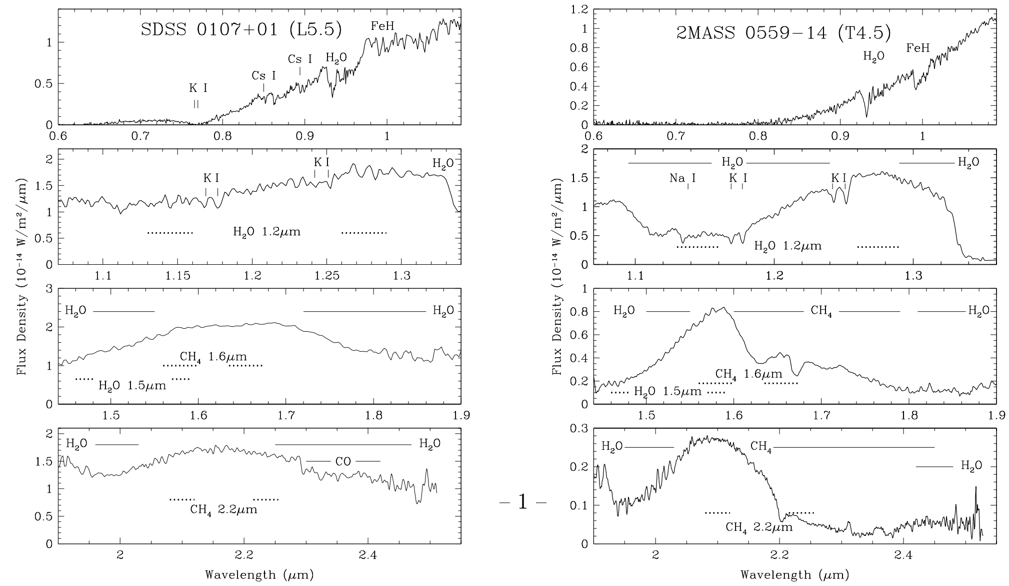

Figure 1. Spectra of a mid-L dwarf and a mid-T dwarf from 0.6 to 2.5 μm. The wavelengths of prominent spectral lines and bands are marked, and the wavelength ranges where the water and methane indices are calculated are indicated by dotted lines.

Table 1. Values of Indices[a] for L and T Subtyping

Name	PC3[b] [0.823–0.827]/ [0.754–0.758]	Color-d[c] [0.96–0.98]/ [0.735–0.755]	H_2O 1.2μm [1.26–1.29]/ [1.13–1.16]	H_2O 1.5μm [1.57–1.59]/ [1.46–1.48]	CH_4 1.6μm [1.56–1.60]/ [1.635-1.675]	CH_4 2.2μm [2.08–2.12]/ [2.215–2.255]
L0	2.4-2.6	4.5-5.5		1.20-1.27		
L1	2.6-2.85	5.5-6.5		1.27-1.35		
L2	2.85-3.25	6.5-7.5		1.35-1.43		
L3	3.25-4.25	7.5-10.		1.43-1.50		0.91-0.94
L4	4.25-6.0	10-17		1.50-1.55		0.94-0.98
L5		17-23		1.55-1.60		0.98-1.025
L6		23-25		1.60-1.65		1.025-1.075
L7				1.65-1.70		1.075-1.125
L8				1.70-1.80		1.125-1.175
L9				1.80-1.95		1.175-1.25
T0			1.5-1.7	1.95-2.2	1.02-1.07	1.25-1.40
T1			1.7-1.9	2.2-2.5	1.07-1.15	1.40-1.60
T2			1.9-2.15	2.5-3.0	1.15-1.30	1.60-1.95
T3			2.15-2.5	3.0-3.5	1.30-1.50	1.95-2.75
T4			2.5-3.0	3.5-4.5	1.50-1.80	2.75-3.8
T5			3.0-4.5	4.5-5.5	1.80-2.50	3.8-5.5
T6			4.5-6.5	5.5-7.0	2.5-4.0	5.5-8.5
T7			6.5-10.	7.0-9.0	4.0-6.0	8.5-12.
T8			10.-15.(?)	9.0-12.(?)	6.0-9.0(?)	12.-18.(?)

[a]Indices are flux ratios over the wavelength intervals in microns specified under the index names

[b]Index defined by M99

[c]Index wavelength intervals slightly modified from the original definition in K99

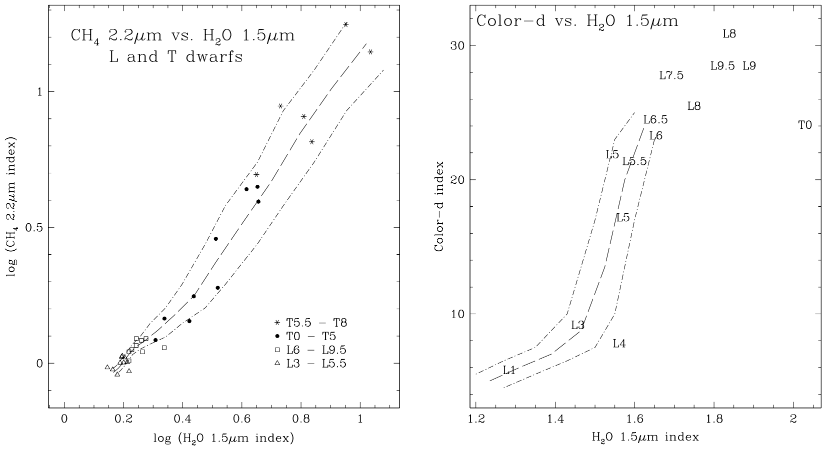

Figure 2. Left-hand panel: methane 2.2 μm index plotted against the water 1.5 μm index. The dashed line connects the mean values for the subclasses according to the definitions in Table 1; the dot-dashed lines differ from the mean by one subclass. Right hand panel: modified 2MASS optical "Color-d" index (K99, G01) plotted against the 1.5 μm index for L dwarfs and one T0 dwarf. The dashed line connects the midpoints of the range of each subclass where both are defined; the dash-dot lines deviate from the mean by one subclass. Alphanumeric symbols are classifications of observed dwarfs.

3. The Classification System

Table 1 lists the values of the above six indices for each subclass. In specifying them we used the following approach.

- We defined ranges for the PC3, Color-d, and 1.5 μm indices to make our classifications generally consistent with those of M99 and K99 for L0–L5.
- We define a specific, and we believe sensible, phenomenological boundary between the L and T classifications: the appearance of methane absorption in the H band near 1.6 μm.
- We define late L subtypes by extended the 1.5 μm and 2.2 μm indices smoothly from L5 to this boundary, where the the 1.6 μm index begins to increase. This is best done by having ten L subtypes (L0–L9), and thus our system corresponds more closely to that of K99 than M99.
- We define T subclasses by continuing the smooth progression of the 1.5 μm and 2.2 μm indices, supplemented with 1.15 μm and 1.6 μm indices, leaving room in a system of ten subclasses for a T9 type, yet to be discovered.

Using this procedure we obtain self-consistent classifications for nearly all of the L and T dwarfs in our sample. Final assignments, reported in G01, are made by averaging the classifications from each index. Typical uncertainties are ± 1 subclass for L dwarfs and ± 0.5 subclasses for T dwarfs. Figures 2 illustrates

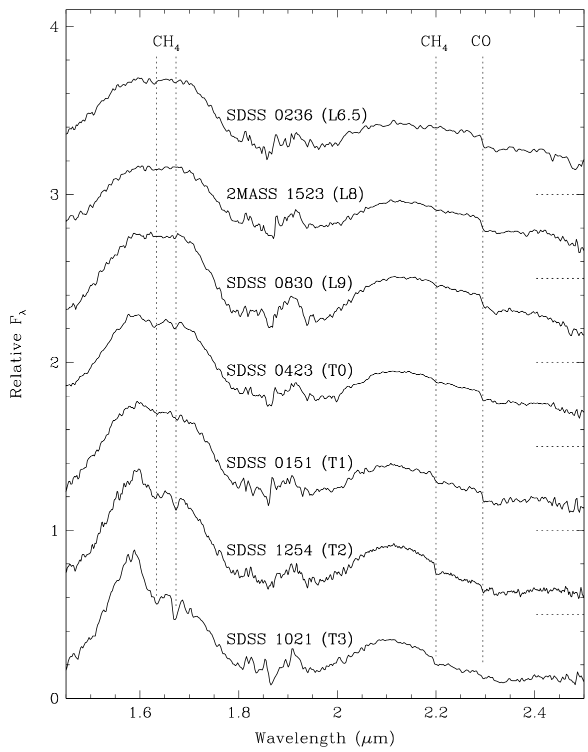

Figure 3. Spectra from 1.5 to 2.5 μm of late L and early T dwarfs, showing the onset of absorption by methane. Horizontal dashed lines below each spectrum indicate zero flux levels. Vertical dashed lines mark the wavelengths of spectral features. Classifications are from G01. Spectra of SDSS 1021-03 and SDSS 1254-01 are from Leggett et al. (2000).

the degree of self-consistency for two pairs of indices. Although more data are required, the right hand panel shows that the optical and infrared systems can be tightly linked in the L0–L6 range by the Color-d and 1.5 μm indices.

4. The L–T Boundary

Figure 3 shows representative 1.5–2.5 μm spectra of dwarfs spanning the L–T boundary. The 2.2 μm methane band is first evident at L8, roughly 2 subclasses prior to the onset of H band methane absorption. The first clear visual indication is a slight inflection at 2.20 μm due to the sharp Q branch of the $\nu_2+\nu_3$ band, but the effect of the broader absorption from the P and R branches is apparent in the index. By T0, where the H band methane absorption first appears, the depression due to the 2.2 μm methane band is more prominent and the CO band head at 2.29 μm has become weak. By T3 the CO band head is barely detectable and the dominant aborber at that wavelength is the strong $\nu_3+\nu_4$ band, which is centered at 2.32 μm.

5. Concluding Remarks

In our proposed classification system the L and T sequences are seamlessly attached via indices common to both. The system also is tied to the optical systems of M99 and K99 via optical and infrared indices applicable to L0–L6 dwarfs. Spectra of additional L and T dwarfs are needed to improve the accuracy of both the subclass definitions and the optical-infrared link. It is likely that the coolest T dwarfs currently observed, here classified T8, are near the end of the T sequence, as all absorption bands on which the classification is based are approaching totality at T8 (G01). However, once cooler dwarfs are discovered it may be necessary to alter the definitions of the T subclasses. Finally, it is likely that a two-dimensional classification system will be required to incorporate the effects of surface gravity and possibly other factors such as photospheric dust.

Acknowledgments. UKIRT is operated by the Joint Astronomy Centre on behalf of the U.K. Particle Physics and Astronomy Research Council. We thank the staffs of UKIRT and the Keck Observatory for their support. The Sloan Digital Sky Survey (SDSS) is a joint project of the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS telescopes, is operated by the Astrophysical Research Consortium (ARC). Funding for the project has been provided by the Alfred P. Sloan Foundation, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS web site is http://www.sdss.org/

References

Burgasser, A. J., Kirkpatrick, J.D., & Brown, M.E., 2001a, in 'Proc. of the Meeting on Ultracool Dwarfs', I.A.U. 24th Gen. Assembly, eds. H.R.A. Jones, M. Gerbaldi, & I.A. Steele (Heidelberg: Springer-Verlag), in press

Burgasser, A. J., et al., 2001, ApJ, Dec. 20, in press

Delfosse, X., Tinney, C. G., Forveille, T., Epchtein, N., Borsenberger, J., Fouqué, P., Kimeswenger, S, & Tiphène, D. 1999 A&AS, 135, 41

Geballe, T. R., et al. 2001, ApJ, Dec. 20, in press (G01)

Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802 (K99)

Leggett, S. K., et al. 2000, ApJ, 536, L35

Leggett, S. K., Golimowski, D. A., Fan, X., Geballe, T. R., Knapp, G. R., et al. 2001, ApJ, Dec. 20, in press

Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., & Zapatero-Osorio, M. R. 1999, AJ, 118, 2466 (M99)

Reid, I.N., Burgasser, A.J., Cruz, K.L., Kirkpatrick, J.D., & Gizis, J.E. 2001, ApJ,

Testi, L., et al. 2001, ApJ, 552, L147

Tokunaga, A. T., & Kobayashi, N. 1999, AJ, 117, 1010