The Transition from L to T: Chemistry and Classification

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T. R. Geballe
Gemini Observatory, 670 N. A 'ohoku Place, Hilo, HI 96720

X. Fan
Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

D. A. Golimowski
Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218

G. R. Knapp
Princeton University Observatory, Princeton, NJ 08540

S. K. Leggett
Joint Astronomy Centre, 660 N. A 'ohoku Place, Hilo, HI 96720

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Abstract.

The growing numbers of brown dwarfs have largely been divided into two new spectral classes, L and T. Subclassification systems for L, based on optical (0.6–1.0 μm) spectra, have existed since 1999, but there is a need for infrared systems for both spectral classes. The differences in the infrared (1.0–2.5 μm) characteristics of L spectra and T spectra observed prior to 2000 are huge, all then-known T dwarfs showing strong methane absorption bands, and all L dwarfs devoid of these bands. However, in the last 2-3 years a significant number of brown dwarfs with infrared spectra in transition between the L and first observed T types have been discovered. The spectra of late L dwarfs and these "transition objects" can be put into a well ordered sequence of increasing H_2O and CH_4 band strengths and decreasing CO band strengths. Specific infrared spectral indicators have been found that allow the L and T sequences to be linked and the boundary between L and T to be precisely defined. In current T classification schemes the transition objects are defined as early T dwarfs. We recommend that the boundary between the L and T classes be defined as the first appearance of methane absorption just longward of 1.60 μm, in the *H* band.

1. Introduction

The boundary between the L and T spectral sequences is commonly agreed to correspond to the major change in the infrared spectrum of the brown dwarf, brought about by the appearance of methane absorption in the 1.0–2.5 μm region. That, however, is not a sufficiently precise definition for accurate spectral classification. This paper describes some details of the infrared spectroscopic phenomena that occur near the L/T boundary and suggests a specific definition of that boundary.

Kirkpatrick et al. (1999; hereafter K99) pointed out an important advantage of using infrared wavelengths for classification of L dwarfs; namely, that most of the luminosity of those objects is in the J, H, and K bands. That advantage is even greater for the T dwarfs, which put a greater proportion of their feeble radiation into the infrared. Clearly, if classification is to be possible for more than just the brightest brown dwarfs and at more than the largest telescopes, it is essential to develop an infrared classification scheme. The great interest in studying brown dwarfs in star-forming regions, many of which are optically obscured, also points to the need for such a scheme.

Nevertheless, optical classification schemes for L dwarfs already exist (Martín et al. 1999, hereafter M99; K99) with the one developed by K99 in most frequent use. Devising an infrared ($\lambda > 1$ μm) classification system for T dwarfs, and a parallel infrared system for L dwarfs, raises important issues related to consistency between infrared and optical systems, which inevitably delve deeply into the physical natures of these remarkable objects and to the question of the definition of the boundary between L and T.

2. Infrared Spectral Phenomenology

At infrared wavelengths the spectroscopic and photometric differences between L and T dwarfs are dramatic (Fig. 1). The spectrum of a mid-L dwarf is badly eaten away by absorption bands of H_2O and CO. Nevertheless, the wavelength of maximum flux density, 1.3 μm, is close to that expected for a blackbody at the effective temperature of the dwarf, and the broad band JHK colors are not far from those naively expected for a blackbody-like spectrum. However, the effects of molecular absorption in L dwarfs, large as they are, pale in comparison to the effects on the infrared spectra of Gl 229B and similar T dwarfs. Great swaths of continuum flux are removed from them by absorption bands of methane and water vapor. An object with an effective temperature of 950 K, such as Gl 229B, naively would be expected to emit its peak flux density at a wavelength just longward of 3 μm. Instead the peak is found at almost a factor of three shorter wavelength, and no flux at all is emitted near 3.2–3.5 μm, where the strongest lines of the fundamental C-H stretching band of methane are found. Largely because of the placement of the CH_4 and H_2O bands, the JHK colors of Gl 229B resemble those of the hottest stars, whereas L dwarfs retain very red JHK colors to the end of the sequence. In the key 1.0–2.5 μm region the spectral change from mid-class at L to mid-class at T is a greater transformation than between any two other adjacent spectral types.

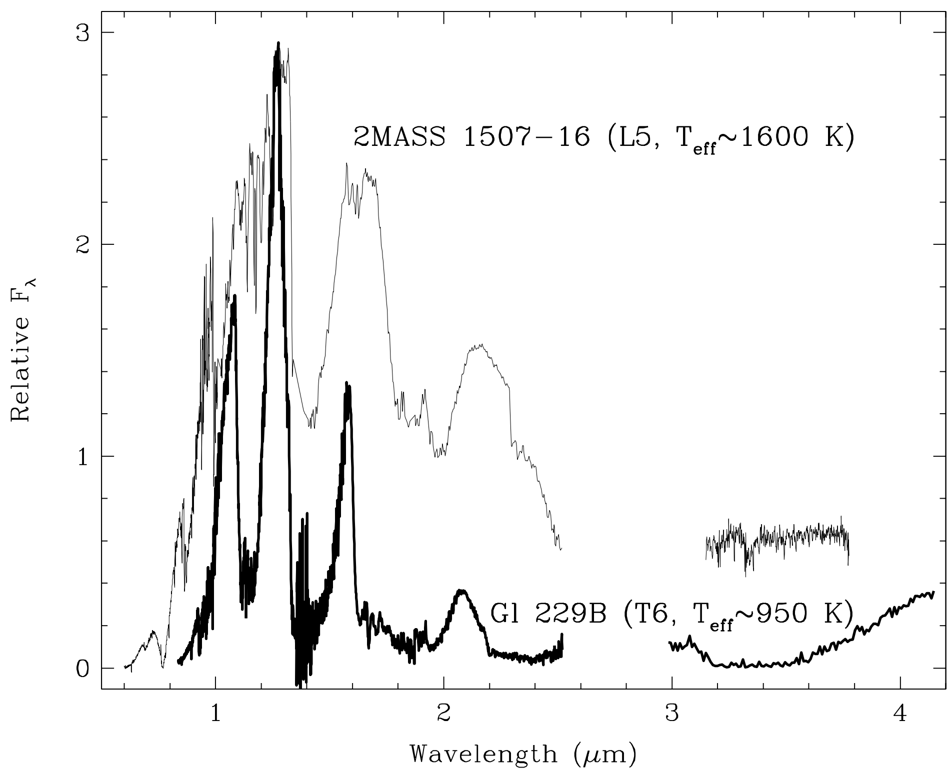

Figure 1. Spectra of the mid-L dwarf 2MASS 1507-16 (upper line; data from Reid et al 2000, Noll et al. 2000, and Knapp et al. in preparation) and the classic T dwarf Gl 229B (data from Geballe et al. 1996, and Oppenheimer et al. 1998). The spectra are scaled to the same J band peak flux density and have the same zero level.

As mentioned above, the transformation is largely due to the onset of methane absorption in numerous bands spread across the 1–3 μm region (it is also due in part to the increasing strengths of several water bands). The methane band strengths increase as carbon is transferred from carbon monoxide, where it resides in the mid-L dwarfs, to methane, where most of it is located in mid-T and later dwarfs. Carbon monoxide is the most stable molecule, with a dissociation energy of 11.1 eV. The dissociation energy of CH_4 is only 4.5 eV. Conversion occurs because there is several thousand times more hydrogen available than oxygen, so that once the photosphere has cooled to the point at which methane begins to become stable against collisional dissociation, the overwhelming hydrogen abundance drives the reactions involving carbon-bearing molecules that push carbon into bonding with hydrogen. The transition from CO to CH_4 is pressure dependent (e.g., Burrows and Sharp 1999), occuring at higher temperatures in higher pressure atmospheres. Hence in the photospheres of more massive brown dwarfs the transition from CO to CH_4 takes place at higher temperatures.

3. Observations of Brown Dwarfs in Transition

Less than three years ago it was not obvious that one needed to accurately know the spectroscopic details of the L–T transition. The first several field T dwarfs that were found, mainly by the Sloan Digital Sky Survey (SDSS) and the Two Micron All Sky Survey (2MASS), looked remarkably like Gl 229B (Strauss et al. 1999, Burgasser et al. 1999, Cuby et al. 1999, Tsvetanov et al. 2000), with dominant methane and water absorption bands obliterating any remaining weak CO features in the H and K bands. At that time, none of the late L dwarfs that had been observed showed any sign of methane absorption in those bands. This dichotomy suggested that the transition of an L dwarf to a T dwarf might be a very rapid one - covering a nearly negligible range in effective temperature. In 2000, however, the first so-called"transition objects" were discovered in the SDSS. The first three of these, in which both CH_4 and CO bands could be seen in the K band (Leggett et al. 2000), spanned the spectral gap very evenly between the latest L dwarfs and the then-known T dwarfs.

It is now known that a significant fraction of brown dwarfs are in this gap. For example, of the 42 L and T dwarfs surveyed by Geballe et al (2002; hereafter G02) and classified L1–T8, roughly 30% are classified between L7 and T4. Although the sample is not volume-complete and selection certainly affects the sample, the large percentage suggests that the range in effective temperature of the transition objects is significant. It is not yet clear how wide it is or whether there is a unique relationship between effective temperature and infrared spectral appearance in these subclasses (see Leggett et al. in these Proceedings). Photospheric clouds of dust grains may alter the spectra emerging from transition objects (see Allard et al., Marley et al., Stephens et al., and Tsuji et al. in these Proceedings), but their effects and the spectral variations they produce are only beginning to be understood.

Table 1. Methane Bands (1-3 μm)

Band Name	Central Wavelength[a] (μm)	Absorption Band Intensity[b] (cm^{-2} atm^{-1} at 300 K)
ν_3	3.31	260.
ν_1+ν_4	2.37	5.9
ν_3+ν_4	2.32	10.0
ν_2+ν_3	2.20	1.5
ν_3+2ν_4	1.79	
ν_1+ν_2+ν_4	1.73	
ν_2+ν_3+ν_4	1.71	
2ν_3	1.66	1.6
ν_2+2ν_3	1.33	

[a] Herzberg (1950)
[b] Pugh & Rao (1976). Band intensities at typical T dwarf temperatures have not been measured, but it is not expected that the relative strengths of the bands will differ substantially from estimates based on the above values.

4. Boundary Classification Issues and Procedures

It is generally accepted that the transition objects should be classified as T dwarfs along with the Gl 229B - like objects. They lie beyond the existing L classifications, which already have many subclasses - the K99 scheme has nine and the M99 scheme has seven. Assigning the transition dwarfs to the T sequence puts the L/T boundary near the onset of methane absorption. However, there are many bands of methane, which have different band strengths - widely different in some cases (see Table 1), and hence, even ignoring other opacity sources, they will first appear at different photospheric temperatures. Indeed Noll et al. (2000) found that the 3.3 μm band becomes clearly detectable at about L5 (see Fig. 1), well before bands at shorter wavelengths are obvious.

Because of the relatively poor sensitivity of L band spectroscopy compared to spectroscopy at shorter infrared wavelengths, there is little interest in using the strong 3.3 μm methane band for classification. There is a general consensus that the 1.0–2.5 μm region should be used for classifying the T sequence (e.g., Burgasser et al. 2002, G02). Accurate spectroscopic behavior of late L and early T dwarfs in that wavelength interval must be observed and understood in order to make an intelligent choice of where the L/T boundary should lie.

In defining infrared subclasses near the boundary, one also must keep in mind the need to smoothly conjoin the L and T sequences. Achieving continuity is not trivial, because the L sequence is defined on the basis of optical indices and the T sequence is to be defined on the basis of infrared indices. Some overlap of the two is acceptable, but it is important to avoid creating a gap in which some objects neither meet the criteria for an L classification nor for a T classification.

The procedure G02 adopted to address these potential problems was: (1) find one or more ways of classifying L and T dwarf infrared spectra, (2) Define an infrared classification scheme for L dwarfs to match as well as possible the existing K99 optical scheme, (3) Define the boundary, based on spectral appearance, ease of use, and consistency with the optical L scheme, and (4) extend the classification scheme smoothly into the T regime (as discussed by Burgasser, these Proceedings).

5. Critical Observational Phenomena

Examination of the spectra of late L and early T dwarfs has led to the discovery of three phenomena which are helpful in classifying dwarfs near the boundary and in precisely defining the boundary.

(1) G02 found that the strength of the H_2O band at 1.4 μm increases through the sequence of L and T dwarfs. This was first noticed for L dwarfs by M99 and was also seen by Burgasser et al. (2002) for T dwarfs. While the wavelengths associated with methane bands are prime candidates for defining T indices, the strength of this water band is also useful, not only as a T index, but also as a link between infrared and optical L classification schemes. G02 were able to associate an H_2O band index with L spectral type to an average accuracy of about one spectral subclass.

(2) In the K band near 2.2 μm, CH_4 absorption first appears in dwarfs that are optically classified as late L. The absorption is present in the spectra of several optically classified L8 dwarfs (see Fig. 2), one L7, and perhaps even earlier (McLean et al. 2001, G02). Defining an index based on this feature also can help ensure there is no large gap or overlap between the L and T classes.

(3) Absorption by CH_4 bands in the J and H windows is not evident until beyond the end of the currently defined L sequence (McLean et al 2001, G02). In particular, as the flux density longward of 2.2 μm decreases in late L dwarfs, due to the onset of CH_4 absorption, there is no indication of CH_4 absorption in the H band (Fig. 2). A clear spectral signature of methane, the dip in the spectrum at 2.20 μm is already present before methane begins to depress the H band flux density longward of 1.60 μm.

6. Definition of the L/T Boundary

The above phenomena suggest a number of ways of defining the boundary. Of these, probably the two most attractive are as follows.

(1) Define the boundary to correspond to the methane absorption in the K band and water absorption in the H band that are slightly greater than those measured in optically classified L8 dwarfs.

(2) Define the boundary to correspond to the first appearance of CH_4 absorption in the H band.

We believe that the second of these is the better choice. It is simpler (and perhaps also more appealing) to define the boundary as the onset of H band methane absorption than basing it on incremental increases in pre-existing bands that may or may not correlate well. Furthermore, the H band methane absorption is a clearer signature than the K band feature and it occurs at a wavelength where the continuum is strong, so the sensitivity to a weak absorption is greater than it is near the K band methane feature.

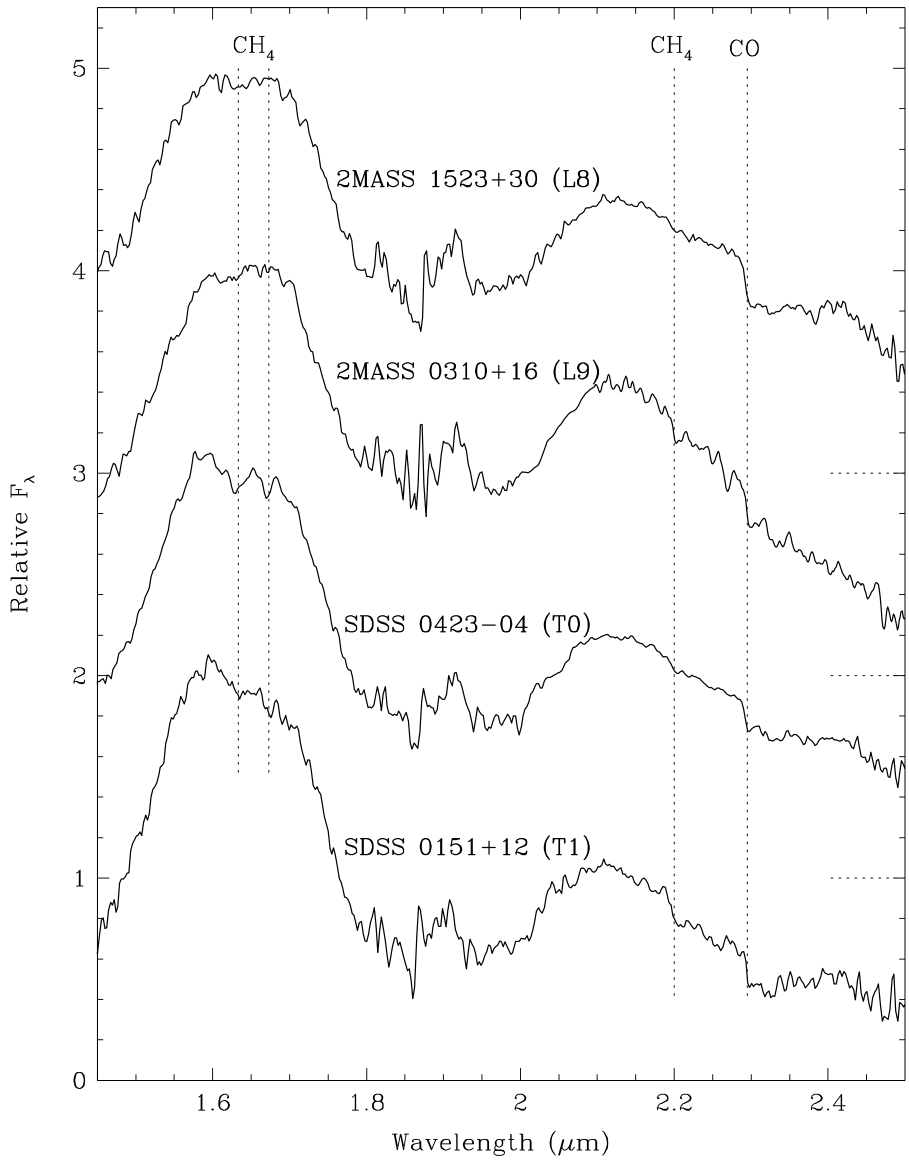

Figure 2. Spectra of four brown dwarfs near the L/T boundary. The data and infrared classifications are from G02 (*K* band data for 2MASS 0310+16 originally from Reid et al. 2001). The 2MASS objects are both classified as L8 by Kirkpatrick et al. (2000). The three upper spectra are offset, with zero levels for each denoted by horizontal dotted lines. Locations of key spectral features of CH_4 and CO are shown.

One possible drawback is that the favored definition allows the possibility of a gap between the existing L classes and the T classes. Dwarfs that are later than the optically defined L8 subclass may possess K band methane absorption deeper than an L8 dwarf, but still no H band methane. One could designate for such objects a new L9 subclass, the possible need for which was foreseen by K99. Examination by G02 of CH_4 and H_2O band strengths in late L spectral types suggested that it may be useful to define such a subclass (see Fig. 2). Resolving this issue requires more and better infrared spectra of late-type, optically classified L dwarfs, as well as optical classification of late L and early T dwarfs that at present are classified on the basis of their infrared spectra only.

7. Recommendation

Much remains to be learned about the atmospheres of brown dwarfs in transition between the L and T spectral classes. Nevertheless, we recommend that the boundary between L and T dwarfs be defined as the first appearance of methane absorption edge in the H band longward of 1.60 μm. As methane absorption in the K band is observed to appear at earlier spectral types than in the H band, this is equivalent to defining the beginning of the T sequence as the appearance of methane in both the H and K bands.

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