Infrared Spectroscopy of Brown Dwarfs: the onset of CH_4 absorption in L dwarfs and the L/T transition

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Abstract. We present infrared spectra of brown dwarfs with spectral types from mid-L to T. The 0.9-2.5 μm spectra of three dwarfs found by the Sloan Digital Sky Survey contain absorption bands of both methane and carbon monoxide and bridge the gap between late L and previously observed T dwarfs. These dwarfs form a clear spectral sequence, with CH_4 absorption increasing as the CO absorption decreases. Water vapor band strengths increase in parallel with the methane bands and thus also link the L and T types. We suggest that objects with detectable CO and CH_4 in the H and K bands should define the earliest T subclasses. From observations of bright ($K \leq 13$ mag) L dwarfs found by 2MASS, we find that the onset of detectable amounts of CH_4 occurs near spectral type L5. For this spectral type methane is observable in the 3.3 μm ν_3 band only, and not in the overtone and combination bands at H and K.

1 Introduction

The infrared spectra of T type brown dwarfs are profoundly affected by the molecules methane (CH_4) and water (H_2O). Huge bites are taken out of the spectra by absorption bands of these molecules. At other infrared wavelengths, adjacent to some of these absorption bands, the atmospheres of the dwarfs are remarkably transparent. A photosphere with an effective temperature of 950 K, the value for Gliese 229B, might naively be expected to emit its maximum flux density near the peak of a blackbody of that temperature, i.e., just longward of 3 μm. However, as is shown in Fig. 1 (upper panel) the maximum for Gl 229B occurs in the J band, near 1.2 μm, almost a factor of three shorter wavelength. The strongest band of CH_4 is in fact centered at 3.3 μm (very close to the peak of a 950 K black body) and virtually no radiation emerges from the brown dwarf near that wavelength. In the J, H, and K bands the locations of the CH_4 and H_2O absorptions give a T dwarf roughly the JHK colors of a very hot star.

The infrared spectrum of an L dwarf (Fig. 1, lower panel) also is badly eaten away by molecular absorptions, many of which are different than those affecting a T dwarf. However, the maximum flux density occurs close to 1.5 μm, the peak

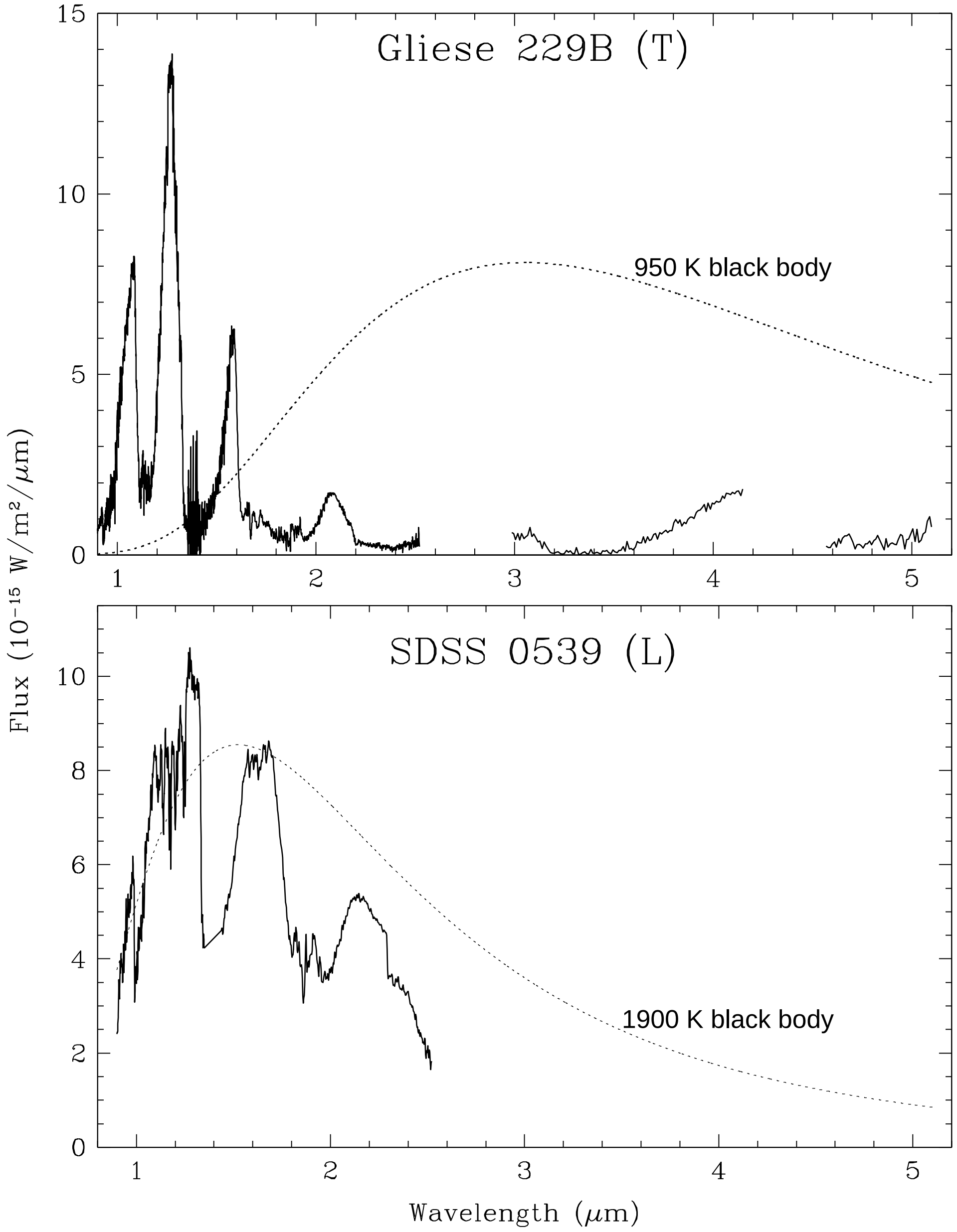

Fig. 1. Spectra of representative T and L type brown dwarfs, Gl 229B [1,2,3] and SDSS 0539 [4] compared with black body functions (of arbitrary strengths) corresponding to the effective temperatures of the brown dwarfs. The original Gl 229B data have been recalibrated [5,6].

of a blackbody whose temperature is ~2000 K, roughly the effective temperature of the dwarf. In addition, the JHK colors of L dwarfs are much closer to what one naively would expect for an object of that temperature.

Thus in the key J, H, and K bands the spectral transition of a brown dwarf from L to T is a huge change, much greater than between any other two neighboring spectral types. The transformation is largely due to the increasing stability of methane at lower temperatures, its increasing abundance as the overwhelming presence of hydrogen drives the chemical equilibrium of carbon-bearing species toward dominance by CH_4, and the resulting onset of strong absorption by CH_4 in a variety of combination and overtone bands in the 1-2.5 μm region.

The bands of CH_4 in the 1-2.5μm interval are strong in T dwarfs, but do not correspond to fundamental vibrations of the molecule. Those much stronger bands occur at longer wavelengths where, because of poor atmospheric transmission and high sky and telescope backgrounds, few spectra of L and T dwarfs have been obtained.

2 T-Dwarf spectra before 2000

Following the discovery of Gl 229B, it took five years before the Sloan Digital Sky Survey (SDSS), the Two-Micron All Sky Survey (2MASS), and the European Southern Observatory (ESO) found additional T dwarfs [7,8,9,10]. The 1-2.5 μm spectra of the objects they discovered are nearly identical to that of Gl 229B. There are in fact some differences between them, probably related to differences in temperature and surface gravity, but they are fairly subtle. At the end of 1999 no objects were known with spectra located in the huge gap, demonstrated in Fig. 1, between the latest L type, which showed no CH_4 absorption at 1-2.5 μm and the T types, in which very strong CH_4 bands are present. It was not clear at the time whether this lack was an observational selection effect or indicated that the transition from latest L-types to then known T-types was rapid compared to the overall cooling time of an L dwarf, encompassing only a relatively narrow temperature range.

It now is evident that the lack of objects in the transition region was largely observational selection. This is demonstrated in Fig. 2, in which $J-K$ is plotted vs. $i-z$ for L and T dwarfs. The area at the top left of the figure is the domain of the L dwarfs, the area at bottom right is the domain of the classical T dwarfs. In 1999 the majority (5) of all (8) published T dwarf identifications were from 2MASS, which surveys the sky at J, H, and K *only.* In Fig. 2 it can be seen that the T dwarfs have blue or bluer $J-K$ colors than all but the hottest stars. Objects with such colors form a very small subset of the 2MASS catalogue. Determining if such objects are candidate brown dwarfs is relatively straightforward, requiring comparison with the Palomar Sky Survey. However, if, as expected, during the transition between L and T, brown dwarfs follow a direct path in Fig. 2 between these two domains, their $J-K$ colors will pass through the same range of values as the myriads of cool main sequence stars and they will be photometrically indistinguishable from such stars by 2MASS.

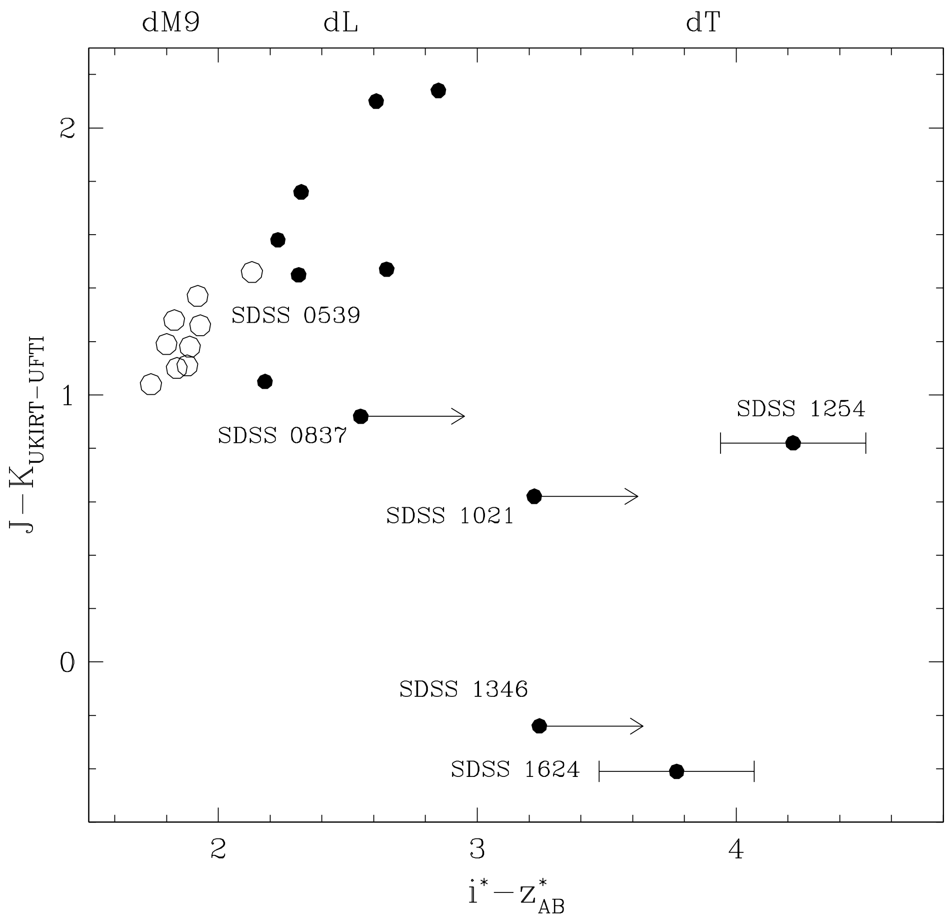

Fig. 2. UKIRT(UFTI) J-K vs. SDSS $i-z$ [4]. The objects in the top left quadrant are late M and L dwarfs; those at the bottom are classical T dwarfs.

In contrast, the transition objects would be expected to develop even redder and more unusual $i-z$ colors and, as in the case of T dwarfs, to be readily singled out by SDSS. However, by the end of 1999 the two objects at the bottom of Fig. 2 were the only SDSS objects known to be later than L.

3 Transition Objects

In early 2000 three new objects were identified as candidate T dwarfs by SDSS, on the basis of their $i-z$ colors. JHK photometry at UKIRT [4] showed that these objects (SDSS 0837, SDSS 1021, and SDSS 1254) inhabited the region

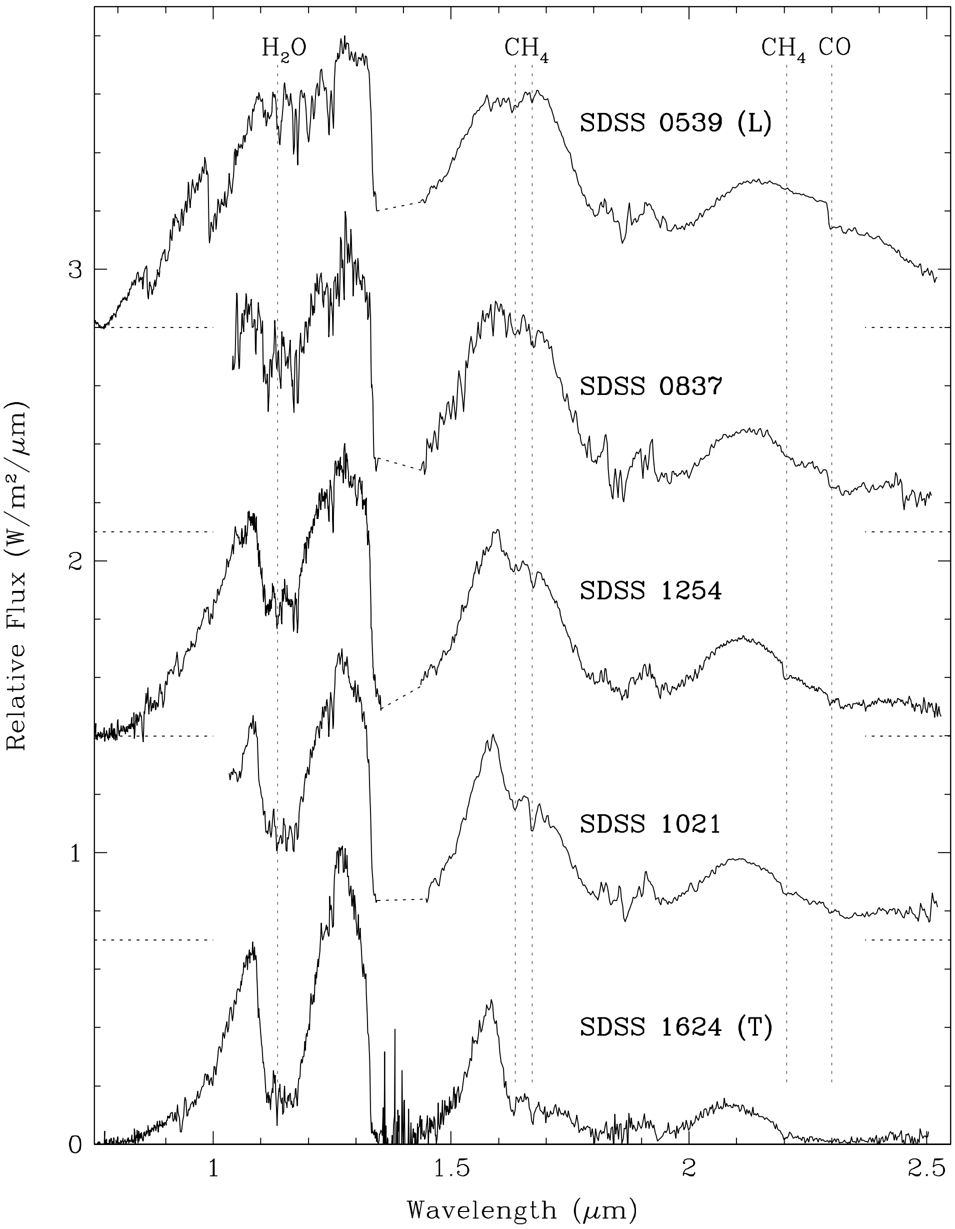

Fig. 3. Spectra of three transition objects together with a mid-L dwarf (top) and a classical T dwarf (bottom) [4]. The dashed vertical lines mark the wavelengths of bands (or, in the case of CO, the 2-0 band head) whose strengths change rapidly in the transition region. The horizontal dashed lines are zero flux density levels for the individual spectra.

in Fig. 2 between the previously known L and T dwarfs. Spectra of them were obtained at the United Kingdom Infrared Telescope (UKIRT) in late February and March, 2000 and are displayed in Fig. 3, together with those of a mid-L dwarf and a previously known SDSS T dwarf. These three spectra fortuitously delineate the transition between L and T fairly evenly, with CO overtone bands at 2.3-2.4 μm gradually disappearing from top to bottom in the figure and the methane bands at 1.6-1.8 μm and 2.2-2.5 μm gradually strengthening. One of the largest spectral changes is in the strength of the water band ($\nu_1 + \nu_2 + \nu_3$) at 1.15 μm. That band is weak in the L dwarf at the top of Fig. 3, but increases steadily in the transition objects, and is nearly totally absorbing in the classical T dwarf.

At the time of this conference, SDSS has discovered comparable numbers of classical T dwarfs and transition objects. Although the numbers of each are few, they suggest that both transition dwarfs and classical T dwarfs occupy substantial temperature ranges. Hence it is likely that many more of each kind will be found by SDSS.

4 Methane absorption in L dwarfs

As mentioned earlier, the most intense bands of methane occur outside the JHK region, at longer wavelengths. The strongest of these is the ν_3 band centered at 3.3 μm. This band, one-hundred or more times stronger than the any of the CH_4 bands in the 1-2.5 μm interval, ought to appear at higher temperatures than the 1-2.5 μm bands and must already be very strong in the transition objects discussed above. Thus, one would predict that in a late L dwarf the ν_3 band should be detectable, as perhaps the first sign of the change taking place in its atmospheric chemistry.

In May 2000 we used UKIRT and CGS4 to search for this band in a set of L dwarfs of different spectral types. As shown in Fig. 4 a broad absorption feature, which we identify as the Q branch of the ν_3 band of CH_4, was detected in the two latest objects observed, 2MASS 1507 and 2MASS 0825 [11], classified as L5 and L7.5, respectively [12]. The observed feature is slightly shifted with respect to the strong Q branch absorption in the earth's atmosphere, due to the higher temperatures in the dwarfs, which cause the excitation of higher J levels of the molecule. The extension of the absorption to longer wavelengths makes the Q branch more readily detectable from the ground. We also obtained a spectrum of 2MASS 1507 in the K band, finding no evidence for methane absorption in that band. No K band spectrum of the later object, 2MASS 0825 was obtained.

Models of L dwarf spectra in the 3-4 μm region (Fig. 5) show the growth of methane absorption with decreasing effective temperature. Methane abundances at each layer of the model atmosphere were calculated using published chemical equilibrium abundance profiles [13]. The strength of the methane absorption is weakly dependent on model assumptions about cloud structure; the models in Fig. 5 are for a clear atmosphere. The weakness of the observed methane Q branches in the spectra of 2MASS 1507 and 2MASS 0825 (Fig. 4) and the ab-

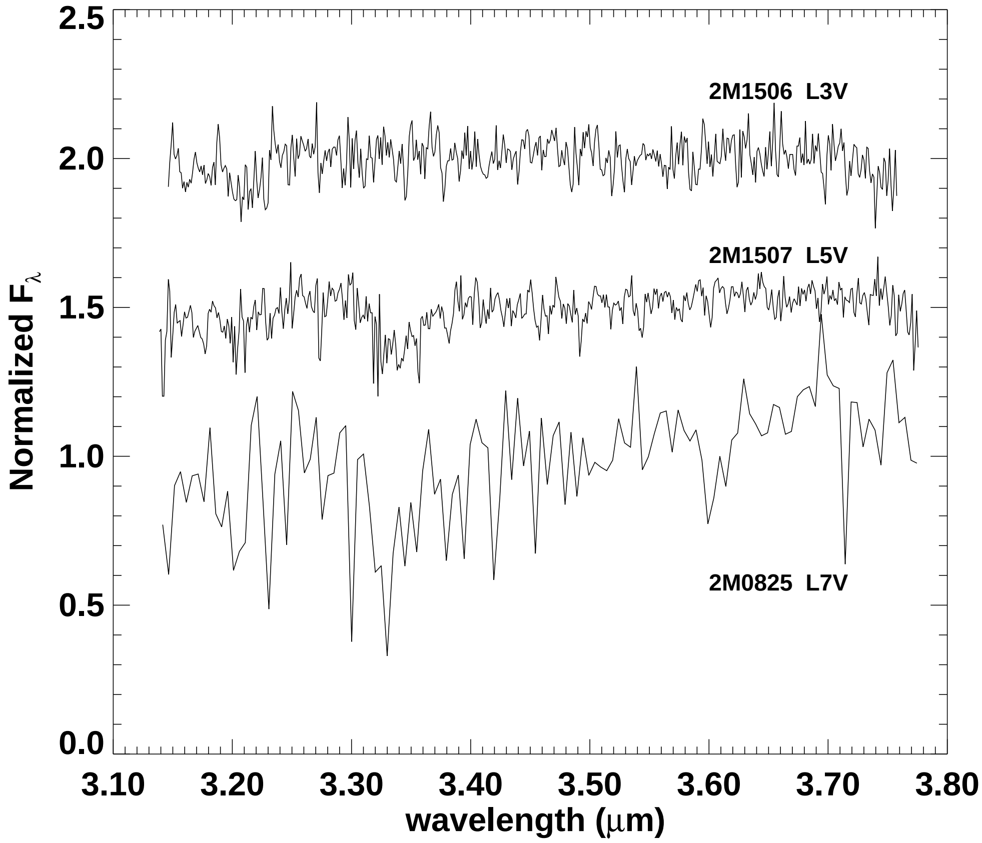

Fig. 4. Spectra of three L-type brown dwarfs in the region of the methane ν_3 fundamental band [11]. The broad absorption present in the two later type dwarfs is the methane Q-branch.

sence of absorption due to the P and R branches suggest that these dwarfs have effective temperatures near 1800 K. This is in general agreement with temperatures suggested in [14], but higher than the temperature inferred in [15] for these spectral classes. Because of methane's temperature-sensitive chemistry and because methane is expected to be found well above any condensation clouds, the ν_3 band promises to be an effective indicator of temperature for late L dwarfs.

5 Classification issues

The discovery of transition objects and the detection of absorption by methane in L-type dwarfs bring to the fore several issues pertaining to classification and terminology.

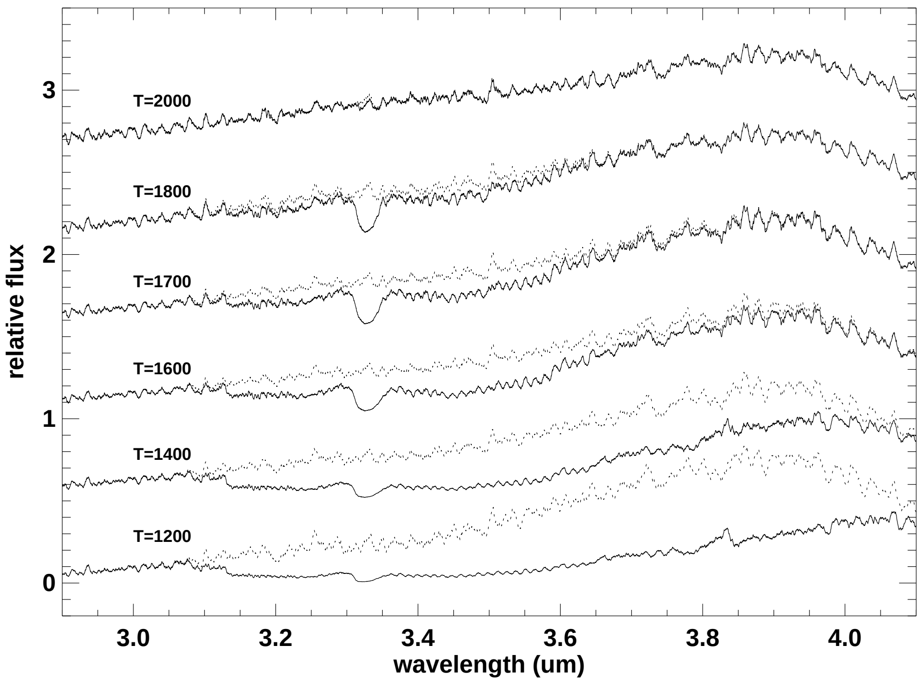

Fig. 5. Model 2.9-4.1 μm spectra for dwarfs with effective temperatures ranging from 1200 K to 2000 K. Dashed curves contain no methane, and the spectral features are primarily due to water vapor. Solid curves have absorption from both H_2O and CH_4. The ν_3 Q branch first becomes detectable at $T_{eff} \approx 1900$ K. The P and R branches begin to significantly suppress the surrounding H_2O pseudo-continuum by $T_{eff} \approx 1700$ K.

1. *Do the three "transition objects" belong to type L or T?* Our view is that these objects should define the earliest part of the T sequence, which up to now shows very little spectral variation compared to that of type L. Moreover, the latter class appears to be running short of available subtypes in the classification systems proposed at present.

2. *However they are classified, what spectral features should be used in defining the transition sub-types?* As is shown in this paper, large changes between the spectra of late L-type and classical T-type objects occur in the 1-2.5 μm region. These changes are much greater than those that occur at shorter wavelengths for the same objects. Furthermore, because the optical–near infrared colors of "transition" dwarfs and classical T dwarfs both are extremely red, they are as or more tractable to observe in the J, H, and K bands than at optical wavelengths, Many of them are easily observable in these bands by 4 meter class telescopes. These characteristics make 1-2.5 μm the most attractive interval for defining the classification scheme. Because of their strong variation with temperature we

regard the methane bands at 1.6-1.7 μm and 2.2-2.4 μm and the water band at 1.15 μm (see Fig. 3) as promising candidates to employ in defining sub-types. Although the methane bands at 2.2 μm and longer are stronger that the bands at 1.6-1.7 μm, contamination of the former by CO and the variable depression of the continuum peak near 2.1 μm by the H_2 pressure-induced dipole absorption (which is more pressure sensitive than temperature sensitive) may make use of the K band problematic.

3. *Should the discovery of CH_4 at 3.3 μm in mid and late L types affect the proposed L and incipient T classification schemes?* We believe not. In large part the reasons have to do with practicality. Accurate ground-based measurements in the L band are considerably more difficult to obtain than similar measurements at shorter wavelengths. In the L band obtaining signal-to-noise ratios sufficiently high for purposes of classification will be possible for only a small fraction of all L-type dwarfs, compared to the much larger fractions that will be observable spectroscopically at optical and shorter infrared wavelengths. Thus we suggest that dwarfs showing the ν_3 and (possibly) longer wavelength fundamental bands of CH_4, but not the combination bands in the 1-2.5 μm region should remain as L-types.

Although we have suggested that the 3 μm methane band not enter into classification schemes, we point out that until a more comprehensive set of JHK-band spectra are in hand for late L (in currently proposed schemes) and "transition" dwarfs, it probably is premature to define the L-T boundary. Finally, the detection of methane in L-type objects indicates that the term "methane dwarf," which previously has been used interchangeably with "T dwarf," should now be used with caution.

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