THE ONSET OF METHANE IN L DWARFS

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ABSTRACT

We have detected weak absorption features produced by the strong $\nu_3$ methane band at 3.3 $\mu$m in two L dwarfs, 2MASSW J1507476−162738 and 2MASSI J0825196+211552, classified as spectral types L5 and L7.5, respectively. These absorptions occur in objects warmer than any in which methane previously has been detected and mark the first appearance of methane in the ultracool star–to–brown dwarf spectral sequence.

Subject headings: infrared: stars — radiative transfer — stars: low-mass, brown dwarfs

1. INTRODUCTION

The growing population of ultracool stars and substellar objects has been divided observationally into two new spectral classifications (Kirkpatrick et al. 1999): T dwarfs (sometimes called methane dwarfs), which have methane absorption in the near-IR (1–2.5 $\mu$m; e.g., Oppenheimer et al. 1995; Geballe et al. 1996; Strauss et al. 1999; Burgasser et al. 1999; Tsvetanov et al. 2000), and the warmer L dwarfs with no detectable near-IR methane (e.g., Kirkpatrick et al. 1999; Martín et al. 1999). In the transition from L to T, the abundance of carbon monoxide decreases as methane becomes more stable against collisional dissociation, the overwhelming abundance of hydrogen drives chemical equilibrium toward higher abundances of methane, and the vibration-rotation bands of CH$_4$, along with those of H$_2$O, dominate the infrared spectrum of the object. However, the details of the transition, and in particular its rapidity as the effective temperature decreases, have been unclear.

Until recently no objects bridging the distinct CO/CH$_4$ spectral separation of the L and T dwarfs had been found. An estimate by Kirkpatrick et al. (2000) of the effective temperature of the L8 dwarf Gl 584C (2MASSW J1523226+301456), based on an assumed bolometric correction and comparison to Gl 229B, gave $T_{\text{eff}}$ ~ 1300 K, which led those authors to speculate that the gap in temperature between L dwarfs and known T dwarfs “must be much smaller than 350 K and possibly smaller than 100 K.” The sudden appearance of strong near-IR methane over such a small decrement in temperature would imply special atmospheric conditions, such as clouds suddenly forming or clearing, and would explain the lack of transitional objects. However, we note that Basri et al. (2000) find significantly higher temperatures, $T_{\text{eff}}$ ~ 1700 K, for the coolest L dwarfs. This discrepancy demonstrates that the transition from L to T dwarfs remains the least well-constrained portion of the brown dwarf sequence.

The recent detection of three dwarfs with weak but detectable methane bands in the 1.0–2.5 $\mu$m region (Leggett et al. 2000) now has begun to populate the gap between L dwarfs and the previously known methane-rich T dwarfs and suggests that observational selection effects and/or small number statistics may instead be the explanation of the missing transition objects.

Leggett et al. and Kirkpatrick et al. (1999) both propose that the T spectral sequence begin with the appearance of CH$_4$ at 1.0–2.5 $\mu$m. Regardless of the details of classification, the onset of methane absorption at any wavelength and the range of temperatures and spectral subclasses over which CH$_4$ increases in abundance and becomes dominant over CO are important diagnostics for the physical characterization of these objects.

In order to search for the earliest appearance of methane in the spectrum of cool dwarfs, we have conducted observations of L dwarfs near 3.3 $\mu$m where the strong $\nu_3$ band of CH$_4$ should first appear. This band has not been seen previously in any L dwarf. It is very deep and broad in the T dwarf Gl 229B (Oppenheimer et al. 1998) and should be strong in the transition objects observed by Leggett et al. (2000) and other T dwarfs but should disappear somewhere within the L spectral sequence. Our observations are part of an ongoing program to obtain spectra of L and late M dwarfs using the United Kingdom Infrared Telescope’s (UKIRT’s) Cooled Grating Spectrometer 4 (CGS4; Mountain et al. 1990). In this Letter we report the detection of weak absorption from the $\nu_3$ band of CH$_4$ in two L dwarfs, 2MASSW J1507476−162738 and 2MASSI J0825196+211552 (hereafter 2M 1507 and 2M 0825).

2. OBSERVATIONS AND ANALYSIS

On UT 2000 May 22 and 23 we used UKIRT and CGS4 with its 40 lines mm$^{-1}$ grating, 2 pixel (1’’2) wide slit, and 300 mm focal length camera to obtain 3.15–3.78 $\mu$m spectra of several L dwarfs. Pertinent details of the observations are given in Table 1. The above instrumental configuration yields a resolving power of $R \approx 600$. The array was read out once, at the end of each exposure (which was typically 0.5–1.5 s in duration, depending on the target brightness), and then reset; multiple exposures were combined in a preprocessor to obtain a single spectral frame. After the first integration the array was translated in the dispersion direction by 1 pixel and the multiple exposures were repeated; this ensured that all wavelengths were observed by at least 1 good pixel. Following the two integrations the telescope was nodded along the slit by 7’’2, and the observing procedure was repeated, in order to facilitate sky subtraction while maximizing the time on our source.
An average of pairs of differenced, nodded spectral images was produced by the CGS4 on-line data reduction program. The individual images making up this average spectral image were fielded, and bad pixels were masked out by the on-line program. Spectra were reduced further off-line using the FIGARO software package and following standard steps for CGS4 data. These steps include extraction of source spectra from designated array rows, wavelength calibration using argon lamp lines, and removal of telluric lines and flux calibration using similarly prepared spectra of standard stars.

The fully reduced spectra of three L dwarfs, 2MASSW J1506544+132106 (hereafter 2M 1506), 2M 1507, and 2M 0825 are shown in Figure 1. Based on the strength of features in the 0.8–1.0 μm portion of the spectrum, they have been classified L3 (2M 1506), L5 (2M 1507), and L7.5 (2M 0825) by Kirkpatrick et al. (2000). The spectrum of 2M 0825 has been rebinned by a factor of 4 to reduce the noise at the expense of lower resolution. Each spectrum has been normalized to its median flux and offset to allow for comparison of the relative strengths of absorption features.

No sign of a spectral absorption near 3.3 μm is seen in 2M 1506, but a weak feature of width ~0.03 μm is present in 2M 1507, and a stronger, although noisier, feature is present in 2M 0825. Both the positions and shapes of the spectral features match that expected for the Q-branch of the ν3 band of CH4. The wavelength of the observed feature extends longward from the strong telluric Q-branch absorption that occurs near 3.316 μm. The low-lying rotational levels of the ground state of methane are heavily populated in the Earth’s atmosphere, rendering the narrow interval 3.312–3.323 μm virtually unobservable (see Fig. 2). In warmer objects, however, higher J levels are populated and the Q-branch becomes significantly broader than the terrestrial band, extending mainly to longer wavelengths, and is detectable from the ground. The correspondence of a stronger absorption feature with a cooler spectral classification is in accord with expectations for CH4, which is chemically favored at lower temperatures (Fegley & Lodders 1996). Finally, the shape of the observed spectral feature agrees qualitatively with models of methane and water spectra at L dwarf temperatures as discussed below. Thus, we conclude that the absorption feature longward of 3.3 μm is the CH4 ν3 Q-branch.

In Figure 2 we compare the spectrum of 2M 1507 to model atmosphere spectra, one containing only water vapor and one with water vapor and methane. The model was computed using a line-by-line radiative transfer code, an atmospheric P-T profile for an object with $T_{\text{eff}} = 1800$ K and $g = 1000$ m s$^{-2}$, hot water and methane line lists (R. Freedman 1999, private communication), and a linear slope as needed to match to the slope of the observed spectrum. The models have been smoothed, normalized, and offset for comparison. Given the disagreements in the overall slope, the model spectra must be regarded as qualitative only, although the identification of individual

![Fig. 1.—Spectra of three brown dwarfs, 2M 0825, 2M 1506, and 2M 1507. The spectra have been rebinned, normalized, and offset as described in the text. The broad absorption feature at 3.33 μm is the ν3 Q-branch of CH4. It is present in both the L5 and L7.5 objects but is undetected in the L3.](image)

![Fig. 2.—Two model spectra for a brown dwarf of effective temperature 1800 K, one with only water vapor and one with water and methane (at one-third of the predicted abundance for CH4), are compared to the spectrum of 2M 1507. The model spectra have been smoothed with a 4 cm$^{-1}$ boxcar and normalized to their median values. The water model has been offset by 1.0, and the normalized spectrum of 2M 1507 has been offset by 0.5. The absorption feature at 3.32–3.35 μm in 2M 1507 corresponds with the CH4 ν3 Q-branch. The two vertical lines indicate the interval where terrestrial CH4 absorption is strong.](image)
spectral features is robust. The weak features in the spectrum of 2M 1507 match those in the spectrum of water except near 3.3 $\mu$m, where additional absorption from CH$_4$ is present.

3. DISCUSSION

In the brown dwarf literature much of the discussion about the transition from CO to CH$_4$ has focused on the temperature at which atmospheric abundances of CO and CH$_4$ in thermochemical equilibrium are equal. Authors have tended to equate this temperature with the effective temperature of the brown dwarf in making predictions of the location in the spectral sequence where methane will become detectable in the spectrum. While a useful shorthand, this approach greatly oversimplifies the question of CH$_4$ observability in brown dwarfs. First, it ignores the large differences in strengths between methane bands; the more frequently observed near-IR bands are 2 orders of magnitude weaker than the fundamental at 3.3 $\mu$m that is the focus of this work. Second, even in dwarfs with effective temperatures above the CH$_4$-CO equilibrium temperature ($\sim$1400 K at $P = 10$ bar, $\sim$1100 K at $P = 1$ bar), there exist overlying cooler layers where CH$_4$ is more abundant. Third, the drop-off of CH$_4$ abundance below the equilibrium point is slow so that even at relatively high temperatures the CH$_4$ abundance remains above $10^{-5}$ (Fegley & Lodders 1996; Burrows & Sharp 1999).

It is important to emphasize that CH$_4$ will be observable in the spectrum of an object when there is a sufficiently large column abundance above the optically thick lower boundary of the atmosphere as determined by cloud, H$_2$ continuum, and/or line opacities. This condition can be met for a wide range of possible model atmospheres and chemical profiles. Because of the strength of CH$_4$ band, unit optical depth occurs very high in the atmosphere. For a solar abundance of carbon entirely in methane, the band is already optically thick by 1 mbar in a 30 $M_j$ object. The temperatures at such pressures are always well below the effective temperature of the brown dwarf (Marley 2000). For a gray atmosphere this region of the atmosphere would be near 0.84T$_{eff}$, Brown dwarf atmospheres, however, are far from gray, and the upper atmosphere is much cooler. For the cloud-free model used to generate Figure 2, for example, the temperature at 1 mbar is closer to 0.67T$_{eff}$, or 1080 K. While still not within the methane stability region at this pressure (Fegley & Lodders 1996), the equilibrium methane abundance under such conditions is not negligible and is larger than that found in air at the effective temperature T$_{eff}$, of the brown dwarf. Dusty atmospheres are warmer at a given pressure, but the air temperature at $P < 1$ bar is still well below the effective temperature.

Although the models presented in Figure 2 are qualitative in the sense that no attempt is made to match the absolute flux levels or slope of the spectrum, models covering a range of effective temperatures give some insight into factors that control the appearance of CH$_4$ (K. S. Noll, T. R. Geballe, S. K. Leggett, & M. Marley 2000, in preparation). The effective temperature has little direct influence on the appearance of the model spectrum of either water or methane in the range 1400–2000 K; the relative strengths of features change slowly over that range. Thus, the choice of an 1800 K model P-T profile in Figure 2 is not necessarily indicative of the effective temperature of 2M 1507. The appearance of the spectrum at 3 $\mu$m is dictated much more strongly by the methane abundance profile as a function of temperature and pressure. Our models used the thermochemical abundance of methane predicted for a cloud-free atmosphere model by the chemistry of Burrows & Sharp (1999). In the model shown we have reduced the predicted methane abundance at each level by one-third (corresponding to somewhat higher temperatures) to better match the depth of the observed band. More realistic dusty atmosphere models are indeed warmer and have less methane at a given pressure level, but such models introduce many more variables than we wish to consider here.

Considerable confusion exists in characterizing the portion of the spectral sequence corresponding to the onset of methane. For example, Basri et al. (2000) find an effective temperature T$_{eff}$ = 1750 K for DENIS-P J0205–1159 from an analysis of Cs i and Rb i lines in its spectrum and, based on this temperature, classify it as an L5 dwarf. For DENIS-P J1228–1547, they obtain T$_{eff}$ = 1800 K, leading to a classification as an L4.5 dwarf. However, based on spectral morphology, Kirkpatrick et al. 1999 classify DENIS-P J0205–1159 as L7 and advocate an effective temperature closer to 1400 K. Similar discrepancies exist for other late L dwarfs as summarized by Martin et al. (1999), who offer a conversion from their classification scheme to that of Kirkpatrick et al. (1999, 2000).

Despite the caveats noted above, the weakness of the methane band in the L5 (by the Kirkpatrick scheme) object 2M 1507 tends to support a temperature considerably higher than 1400 K, where all of our models predict a very strong $\nu_1$ methane band. This same statement applies to the L7.5 object 2M 0825, where the weakness of the $\nu_1$ methane band is all the more surprising, Kirkpatrick et al. (2000) would argue for a temperature near 1400 K for this object. If the transformation offered by Martin et al. (1999) holds for this object it would be classified by them as roughly an L5.5, which in the Basri et al. (2000) scheme corresponds to an effective temperature of $\approx$1700–1750 K. If the relative classification of these two objects being separated by 2–2.5 classes is correct, it implies that the onset of methane in the L dwarfs is a gradual process relative to either the Kirkpatrick et al. or Martin et al. classification schemes. Whether this gradual onset is due to the spectral classes being separated by only small temperature increments or whether it is due to the fundamental chemistry of methane in these objects is unclear. Further modeling and additional spectra will help clarify this situation.

Finally, we comment on the ongoing development of classification schemes for substellar objects. Kirkpatrick et al. (1999) proposed the adoption of two new spectral classes, L and T, to cover stars and brown dwarfs from the end of the M dwarf spectral sequence. Preliminary models indicate that T$_{eff}$, of methane absorption occurs near spectral type L5 in the spectral sequence. Preliminary models indicate that T$_{eff}$ $\approx$ 1800 K or higher may be required to match the observed weak-
ness of the 3.3 μm fundamental band in both the L5 and L7.5 dwarfs. Our results, while preliminary, tend to support effective temperatures similar to those found by Basri et al. (2000) for late L dwarfs and are higher than those advocated by the classification scheme of Kirkpatrick et al. (1999), although the role of dust has yet to be fully explored. The term “methane dwarf,” a common alternative to the proposed designation of T dwarf, should be used with the understanding that it refers to specific overtone and combination bands in the near-IR and not to the composition of the brown dwarf atmosphere. Likewise, the designation L dwarf does not imply the undetectability of the strongest CH₄ bands.

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