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THE MISSING LINK: EARLY METHANE ("T") DWARFS IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We report the discovery of three cool brown dwarfs that fall in the effective temperature gap between the latest L dwarfs currently known, with no methane absorption bands in the 1–2.5 μm range, and the previously known methane (T) dwarfs, whose spectra are dominated by methane and water. The newly discovered objects were detected as very red objects in the Sloan Digital Sky Survey imaging data and have *JHK* colors between the red L dwarfs and the blue Gl 229B–like T dwarfs. They show both CO and CH_4 absorption in their near-infrared spectra in addition to H_2O, with weaker CH_4 absorption features in the *H* and *K* bands than those in all other methane dwarfs reported to date. Due to the presence of CH_4 in these bands, we propose that these objects are early T dwarfs. The three form part of the brown dwarf spectral sequence and fill in the large gap in the overall spectral sequence from the hottest main-sequence stars to the coolest methane dwarfs currently known.
Subject headings: stars: low-mass, brown dwarfs — surveys

1. INTRODUCTION

Brown dwarfs, gravitationally condensed objects whose masses are too low for equilibrium hydrogen burning, occupy the mass range between the lowest mass stars (~0.07 $M_\odot$; Burrows et al. 1997) and the giant extrasolar planets (~0.01 $M_\odot$; Marcy & Butler 1998). The lowest mass stars and brown dwarfs that are only slightly cooler than M dwarfs are classified as spectral type "L" (Kirkpatrick et al. 1999; Martín et al. 1997) and have T_{eff} in the range of ~1500–2000 K. Determining whether L-type objects are brown dwarfs is difficult because the luminosities and effective temperatures of brown dwarfs are a function of both age and mass (e.g., Burrows et al. 1997). The first unambiguous brown dwarf, Gl 229B, was discovered by Nakajima et al. (1995) as a companion to a nearby M dwarf. This object is cooler than any L dwarf and has CH_4 in its atmosphere, implying $T_{eff} < 1300$ K (e.g., Fegley & Lodders 1996) and a substellar nature. The recent discoveries of methane dwarfs (tentatively given a "T" spectral classification) in the field by Strauss et al. (1999), Burgasser et al. (1999, 2000), Cuby et al. (1999), and Tsvetanov et al. (2000) demonstrate that objects like Gl 229B can form singly.

A striking characteristic of known T dwarfs is the similarity of their spectra, which resemble those of the gaseous solar system planets and are very different from even the coolest L dwarfs. The L dwarf spectra are characterized by the disappearance of the TiO and VO bands (which are strong in M dwarf spectra), the presence of atomic alkali lines and CO bands, and increasing depth of the H_2O bands as T_{eff} decreases. The T dwarfs are characterized by very deep H_2O and CH_4 bands in the 1–3 μm region. Alkali metal features are present between the bands, but the 2.3 μm CO bands are absent because of reduced CO abundance and the overwhelming strength of the CH_4 absorption.

A large remaining gap in the stellar-to-gas giant planet spectral sequence lies between the previously observed types L and T. In this Letter, we report photometry and 0.8–2.5 μm spectroscopy of three very red, faint objects identified in the imaging data of the Sloan Digital Sky Survey (SDSS) and observed at the United Kingdom Infrared Telescope (UKIRT) and the Hobby-Eberly Telescope (HET). These objects have spectra intermediate between those of the previously known L and T dwarfs, showing the onset of CH_4 absorption at 1.6 and 2.2 μm, while still retaining observable CO absorption at

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TABLE 1
COORDINATES AND PHOTOMETRY

J2000 POSITION		AB MAGNITUDES[a]		UKIRT-UFTI			UKIRT-IRCAM		
R.A.	Decl.	i^*	z^*	J	H	K	J	$J-H$	$H-K$
05 39 51.99	−00 59 02.0	19.04 ± 0.02	16.73 ± 0.01	13.85 ± 0.03	13.04 ± 0.03	12.40 ± 0.03	13.94	0.97	0.53
08 37 17.21	−00 00 18.0	(23.51 ± 0.42)	19.95 ± 0.09	16.90 ± 0.05	16.21 ± 0.05	15.98 ± 0.05	17.08	0.93	0.11
10 21 09.69	−03 04 20.1	(23.73 ± 0.58)	19.28 ± 0.05	15.88 ± 0.03	15.41 ± 0.03	15.26 ± 0.05	16.12	0.74	0.08
12 54 53.90	−01 22 47.4	22.22 ± 0.28	18.00 ± 0.04	14.66 ± 0.03	14.13 ± 0.03	13.84 ± 0.03	14.90	0.84	0.15

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds; i^* and z^* are asinh magnitudes on the AB system (Lupton et al. 1999). Zero flux corresponds to i^* = 23.89 and z^* = 22.47.

[a] Values in parentheses are not statistically significant.

2.3 μm. We propose that they represent the warm end of the T spectral sequence, yet to be defined in detail.

2. OBSERVATIONS

2.1. *SDSS Photometry and Object Selection*

The three objects described here were selected from SDSS photometric data. SDSS photometry is obtained with a CCD camera at the Apache Point Observatory (APO), which images the sky almost simultaneously in five filters: u', g', r', i', and z' (the data presented here use a preliminary calibration; while we denote the bands by u', etc., the magnitudes are denoted by u^*, etc.). The details of the data acquisition and the photometric and astrometric calibration are described by Gunn et al. (1998), York et al. (2000), and R. H. Lupton et al. (2000, in preparation). SDSS photometry is in the AB_ν system (Fukugita et al. 1996), and the magnitude scale is modified to deal with low signal-to-noise ratios (Lupton, Gunn, & Szalay 1999).

The L and T dwarfs identified in the SDSS (e.g., Strauss et al. 1999; Fan et al. 2000) are undetected in the u' and g' bands. The L dwarfs have $i^*-z^*>1.6$, while the T dwarfs have $i^*-z^*>3$. We prepared a candidate L and T dwarf list for follow-up observations by searching the SDSS data for point sources with $i^*-z^*>1.6$. Because of their extremely red colors, some very red, faint objects are detected only in the z' band, and a search for them can be contaminated by defects. Therefore, additional constraints were imposed: (1) all objects blended with neighbors, or affected by data defects, were removed; (2) an object was required to be detected at $\geq 3\ \sigma$ twice (in both i' and z', in two observations of that region of sky, or detected in the Two-Micron All-Sky Survey [2MASS] database); (3) a z'-band–only single detection was required to have $z^*<19.0$. The three objects discussed in this Letter were selected from a total sky area of 225 deg^2, giving an approximate and very preliminary surface density similar to the 1 per 75 deg^2 for SDSS T dwarfs found by Tsvetanov et al. (2000).

Table 1 gives, for the three new objects, the J2000 position (accurate to 0″.2) and AB magnitudes at i' and z'. Table 1 also lists photometry obtained for the L dwarf SDSS 0539 (Fan et al. 2000). Hereafter, we identify the objects by the first four digits of their right ascension. SDSS 0837 was found in two SDSS runs, 1999 March 21 and 2000 February 8; the z^* values agree to 0.1 mag and the positions to 0″.3. SDSS 1021 is a z'-only detection in data from 2000 February 12 and is also in the 2MASS database. The brightest object, SDSS 1254, has z^* = 18.0 and was found in data taken on 2000 February 2. Finding charts for the new objects are shown in Figure 1.

2.2. *UKIRT Photometry*

J, *H*, and *K* photometry was obtained using UKIRT's near-infrared camera, the UKIRT Fast Track Imager (UFTI), for SDSS 0837 and SDSS 1254 on 2000 March 2 and for SDSS 0539 and SDSS 1021 on 2000 March 14. Both nights were photometric, with seeing ∼0″.8. The results are given in Table 1 in the UKIRT (not AB) system—we give *JHK* on the UFTI system as well as colors on the established IRCAM system for comparison with earlier work. Figure 2 shows a composite color-color plot containing the data from Table 1 and, for comparison, a sample of late M and L dwarfs as well as the SDSS T dwarfs SDSS 1624 and SDSS 1346 (Strauss et al. 1999; Tsvetanov et al. 2000), whose spectra closely resemble that of Gl 229B. Lower limits are shown for i^*-z^* for the z'-only detections. The late M and L dwarfs show a steady progression toward redder $J-K$ and i^*-z^* colors with later spectral type; however, the T dwarfs have redder i^*-z^* colors and

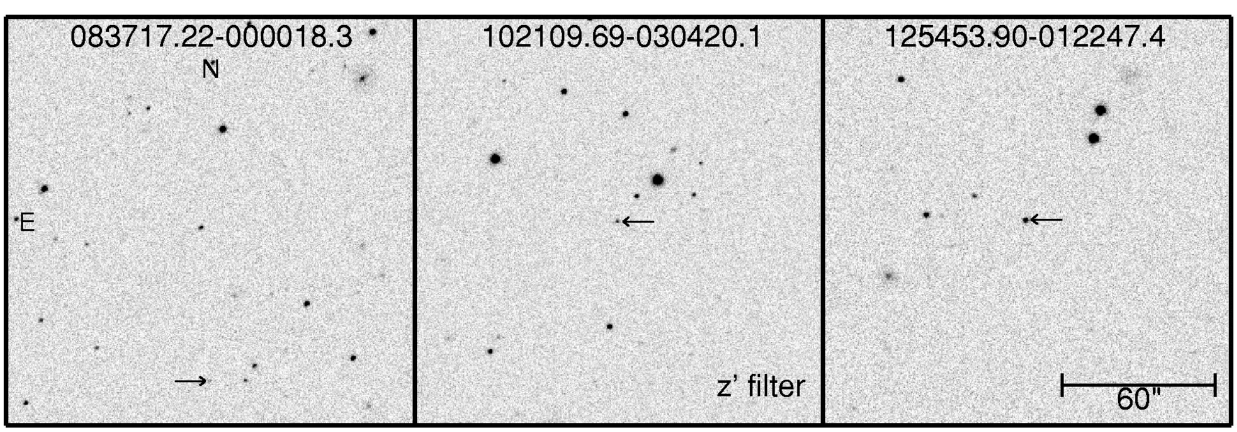

FIG. 1.—Finding charts for the new early T dwarfs

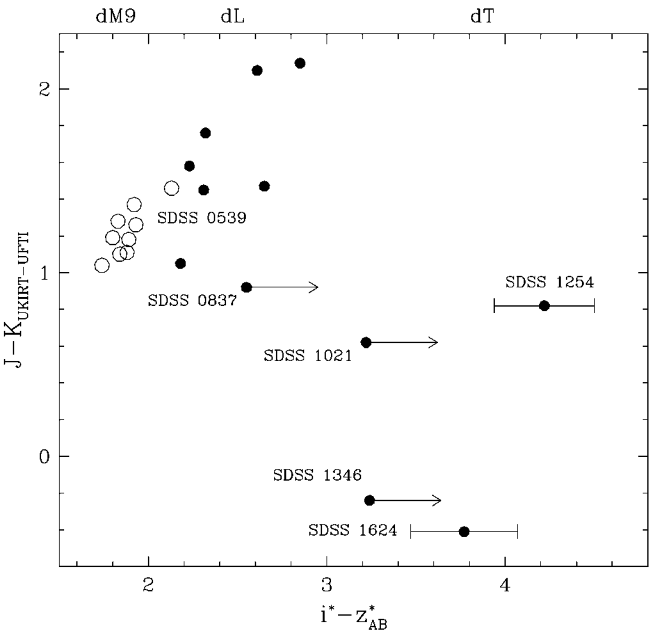

FIG. 2.—SDSS i^*-z^* against UKIRT-UFTI $J-K$; the open circles have $J-K$ from 2MASS. Errors in i^*-z^* are $\leq \pm 0.15$ mag, except where indicated; the measurement error and system differences in the 2MASS $J-K$ are ~0.2 mag, and the error in the UKIRT $J-K$ is 0.05 mag.

bluer $J-K$ colors because of the strong absorption by CH_4 in the *H* and *K* bands. The $J-K$ colors of the new objects lie between those of the previously known L and T dwarfs.

2.3. *HET Spectroscopy*

A red spectrum of SDSS 1254 was obtained on 2000 February 29 with the Low-Resolution Spectrograph (Hill et al. 1998a, 1998b; Schneider et al. 2000) at the prime focus of the of the HET (Ramsey et al. 1998). The spectrum covers the wavelength range of 5100–9800 Å at a resolution of ~20 Å, but no flux is detected below ~6500 Å.

2.4. *UKIRT Spectroscopy*

Spectra of the objects in Table 1 were obtained in the *J*, *H*, and *K* bands at UKIRT on 2000 February 28–March 1 and March 13–15 using the facility spectrograph CGS4 (Mountain et al. 1990) at $R \sim 400$. Integration times were 30–60 minutes per band. Telluric absorption was removed, and the broadband spectral shapes were corrected by comparison with spectra of bright F stars (with photospheric lines removed) taken immediately before and/or after each observation. The spectra in each band were scaled to match the UKIRT magnitudes using the UFTI filter profiles. UKIRT *z*-band spectra were also obtained for SDSS 1254 and SDSS 0539. For SDSS 1254, the HET spectrum is used for $\lambda < 0.84$ μm, and for SDSS 0539, the red APO spectrum (Fan et al. 2000) is used for $\lambda < 0.89$ μm.

The final flux-calibrated spectra are shown in Figures 3 and 4. Figure 3 shows the spectrum of SDSS 1254 split into four panels, with the main absorption features marked. Figure 4 compares the spectra of the new objects with those of the L5 dwarf SDSS 0539 (Fan et al. 2000) and the T dwarf SDSS 1624 (Strauss et al. 1999). The spectra show increasingly red colors at $\lambda < 1$ μm, probably due to pressure broadened Na I and K I absorption (Burrows, Marley, & Sharp 2000) combined

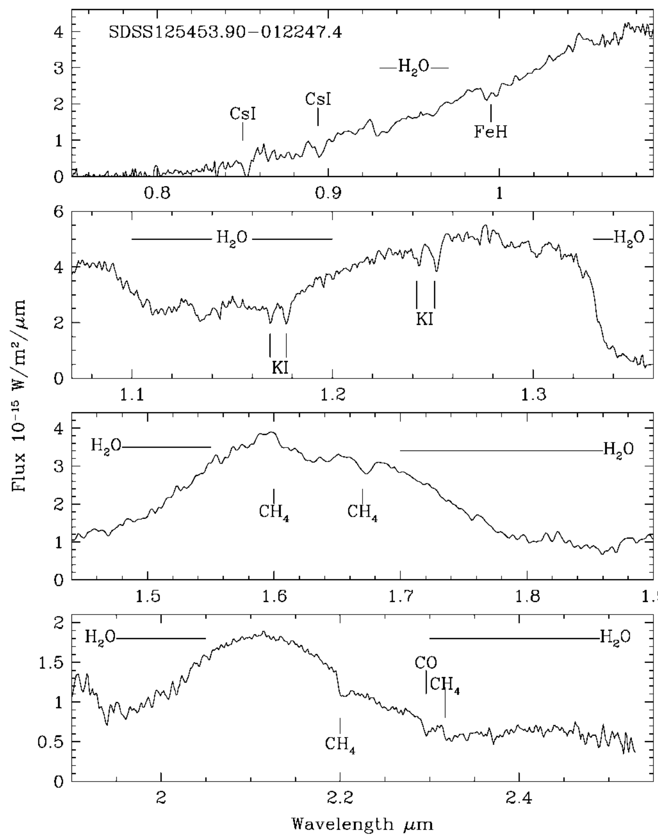

FIG. 3.—UKIRT *z*, *J*, *H*, and *K* spectra of SDSS 1254. The *z* spectrum (*top panel*) is extended to shorter wavelengths by the HET spectrum. The data are scaled to absolute values using UKIRT photometry. Atomic lines (Cs I and K I), narrow molecular features (FeH and CH_4), and band heads (CH_4 and CO) are indicated by vertical lines, while the broad H_2O bands are indicated by horizontal lines.

with decreasing $T_{\rm eff}$; increasing absorption in the H_2O bands at 1.15, 1.4, and 1.9 μm; increasing absorption at 1.6–1.7 μm and longward of 2.2 μm by CH_4 combination and overtone bands; and decreasing absorption in the CO 2.3 μm band. In particular, the absorption maxima of the CH_4 $2\nu_2 + \nu_3$, $2\nu_3$, and $\nu_2 + \nu_3$ bands at 1.63, 1.67, and 2.20 μm, respectively, become progressively deeper. The CO (2–0) band head at 2.294 μm is seen in the new objects, but the CO (3–1) band head at 2.323 μm is absent; it is considerably weaker at these temperatures and also is overwhelmed by the strong CH_4 $\nu_3 + \nu_4$ absorption at 2.315 μm.

3. DISCUSSION AND CONCLUSIONS

The spectra in Figure 4 reveal a clear spectral sequence. Thus, SDSS 0837, SDSS 1254, and SDSS 1021 are examples of the sought-after "L/T transition" objects. However, as shown in Figure 4, they might more properly be regarded as examples of early T dwarfs, where the T spectral type is defined by the presence of CH_4 absorption in the *H* and *K* bands. The strongest short-wavelength infrared band of CH_4 is the ν_3 band centered at 3.3 μm, and objects in which this band is present, but in which the shorter wavelength bands reported here are absent, must exist over a narrow temperature range. However, measurements at 3.3 μm are considerably more difficult from the ground than are *H* and *K* band measurements, and objects that show only the 3.3 μm CH_4 band perhaps should be classified as L rather than T (Kirkpatrick et al. 1999 suggest that the T

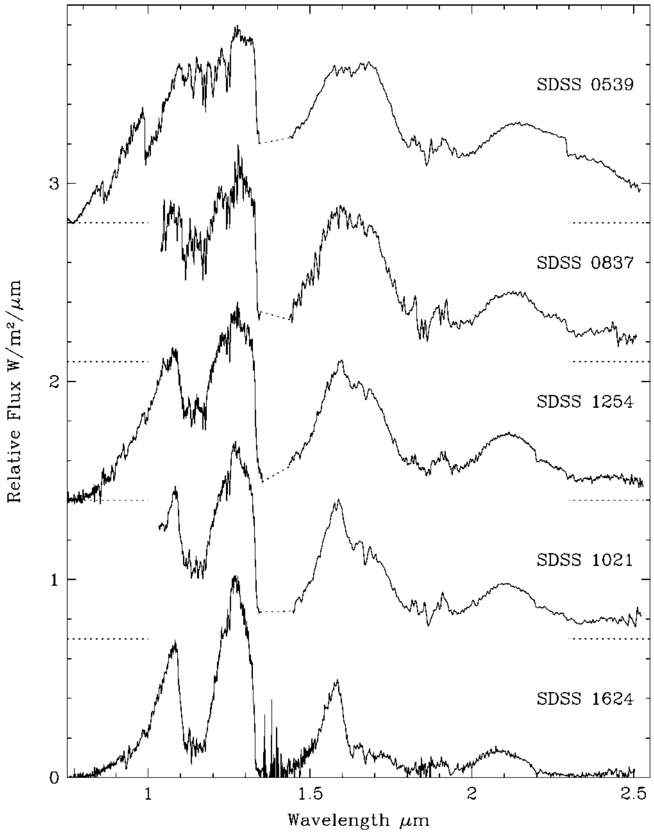

FIG. 4.—T dwarf spectral sequence. The spectra of the three early T dwarfs (SDSS 0837, SDSS 1254, and SDSS 1021) are ordered by increasing CH_4 absorption. Also shown are the L dwarf SDSS 0539 (~L5, Fan et al. 2000; optical data from Fan et al.) and the later T dwarf SDSS 1624 (Strauss et al. 1999). No data were obtained near 1.4 μm because of telluric H_2O absorption. The spectra are scaled to the flux peak at 1.27 μm and offset; the dotted lines indicate zero levels.

class be defined by the presence of CH_4 absorption in the K band). Since the three objects presented here are at the CO/CH_4 transition temperature, they are likely to have $T_{\rm eff} \approx$ 1300 K (Fegley & Lodders 1996) and therefore masses of 20–70 $M_{\rm Jup}$ for ages in the range of 0.3–5 Gyr (Burrows et al. 1997).

Figure 2 shows that SDSS easily identifies T dwarfs by their extremely red $i^* - z^*$ color, including the early T dwarfs identified in the present Letter. On the other hand, the $J - K$ colors are similar to those of the common M dwarfs, and these early T objects are thus very difficult to select on the basis of the near-infrared colors alone (although the later T dwarfs are blue and *can* be selected this way). Many more L and T dwarfs will be found in the SDSS imaging data.

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[17] The SDSS Web site is located at http://www.sdss.org/.

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