

# Discovery of Four Field Methane (T-type) Dwarfs with the Two Micron All-Sky Survey<sup>1</sup>

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## ABSTRACT

We report the discovery of four field methane (“T”-type) brown dwarfs using Two Micron All-Sky Survey (2MASS) data. One additional methane dwarf, previously discovered by the Sloan Digital Sky Survey, was also identified. Near-infrared spectra clearly show the 1.6 and 2.2  $\mu\text{m}$  CH<sub>4</sub> absorption bands characteristic of objects with  $T_{\text{eff}} \lesssim 1300$  K, as well as broadened H<sub>2</sub>O bands at 1.4 and 1.9  $\mu\text{m}$ . Comparing the spectra of these objects with that of Gl 229B, we propose that all new 2MASS T dwarfs are warmer than 950 K, in order from warmest to coolest: 2MASS J1217-03, J1225-27, J1047+21 and J1237+65. Based on this preliminary sample, we find a warm T dwarf surface density of 0.0022 T dwarfs/sq. deg., or  $\sim 90$  warm T dwarfs over the whole sky detectable to  $J < 16$ . The resulting space density upper limit, 0.01 T dwarfs/pc<sup>3</sup>, is comparable to that of the first L dwarf sample from Kirkpatrick et al.

*Subject headings:* infrared: stars — stars: fundamental parameters — stars: individual  
(2MASSI J1047539+212423, 2MASSW J1217111-031113, 2MASSW J1225543-273947,

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2MASSW J1237392+652615, 2MASSW J1346464-003150) — stars: low mass, brown dwarfs

## 1. Introduction

Searches for brown dwarfs are meeting with increasing success in recent years. Proper-motion surveys (Ruiz et al. 1997), surveys of young clusters (Stauffer et al. 1989; Rebolo, Zapatero-Osorio, & Martín 1995), companion searches (Nakajima et al. 1995), radial velocity measurements (Mayor & Queloz 1995; Marcy & Butler 1995), and all-sky near-infrared and deep optical surveys (Delfosse et al. 1997; Kirkpatrick et al. 1999, hereafter K99) have identified an ever-growing number of confirmed substellar objects. Until recently, Gl 229B (Nakajima et al. 1995) stood out amongst those objects as the only known brown dwarf sufficiently cool ( $T_{eff} = 960 \pm 70$  K, Marley et al. 1996) to show  $\text{CH}_4$  absorption bands at 1.6 and 2.2  $\mu\text{m}$ . Analysis of preliminary data from the Sloan Digital Sky Survey (SDSS; York et al. 1999) has led to the discovery of the first field counterparts of Gl 229B (Strauss et al. 1999; Tsvetanov et al. 1999).

In this letter, we report the discovery of an additional four spectroscopically-similar dwarfs, which we designate as spectral class “T”<sup>11</sup> (K99), based on data from the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 1997); and the recovery of a T dwarf identified by SDSS. A brief summary of the selection process and initial follow-up of 2MASS T candidates is discussed in §2; near-infrared spectroscopy of the confirmed T dwarfs is discussed in §3; and a preliminary sequence and estimates of  $T_{eff}$  and the T dwarf space density are discussed in §4. Results are summarized in §5.

## 2. Candidate Selection

### 2.1. Search Criteria

Candidates were culled from two separate 2MASS data samples. The first (sample A), was taken from the 2MASS Spring 1999 Data Release,<sup>12</sup> 2483 deg<sup>2</sup> of northern hemisphere data containing approximately 20.2 million point sources. Candidates were constrained to have detections at J and H bands with  $J < 16$  (2MASS signal-to-noise ratio  $\sim 10$  limit),  $J-H < 0.3$  and  $H-K_s < 0.3$ ,  $|b| > 15^\circ$  (to eliminate source confusion in the plane), no minor planet correlations, and no optical counterparts (USNO-A: Monet et al. 1998) within 5". The adopted near-infrared

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<sup>11</sup>The primary defining feature of spectral class T is the appearance of the 1.6 and 2.2 micron overtone bands of  $\text{CH}_4$ . While these objects have also been called “methane” dwarfs, we note that the 3.3 micron fundamental  $\text{CH}_4$  band is predicted to appear at higher temperatures, i.e. perhaps amongst the latest-type L dwarfs.

<sup>12</sup>See the Explanatory Supplement to the 2MASS Spring 1999 Incremental Data Release by R. M. Cutri et al., which is at <http://www.ipac.caltech.edu/2mass/releases/spr99/doc/explsup.html>.

colors select objects similar to or cooler than Gl 229B, while excluding the overwhelming numbers of main sequence stars. Note that this may exclude L/T transition objects ( $0.6 \leq J-K_s \leq 2.1$ ), although the temperature range over which  $\text{CH}_4$  absorption causes this transition may be quite small (Reid et al. 1999). J- and H-band detections were required to exclude false sources, although a  $K_s$ -band detection was not required because of decreased sensitivity at this wavelength<sup>13</sup> (2MASS 99.9% completeness limit is  $K_s \sim 14.3$ ). Non-detections on POSS-I (Minkowski & Abell 1963) are imposed because these objects have extremely red optical-infrared colors (Gl 229B R-J  $\approx 9$ , Golimowski et al. 1998).

The second set (sample B) was taken from 3420 deg<sup>2</sup> ( $\approx 28$  million point sources) of northern and southern hemisphere data, with search criteria of  $J-H < 0.2$  and  $H-K_s < 0.2$ ,  $J < 16$ ,  $|b^{II}| > 20^\circ$ , no minor planet correlations, and no POSS-I or POSS-II (Reid et al. 1991) detections. Again, sources were required to have J- and H-band detections but not required to have  $K_s$ -band detections.

The search criteria selected 349 candidates from sample A and 319 candidates from sample B. Subsequent inspection of POSS and 2MASS data to rule out faint optical sources (background stars) and high proper motion stars eliminated all but 12 candidates from sample A and all but 11 from sample B. Three candidates from sample A and five from sample B were accessible for observation in May, and are listed in Table 1, which gives the object name (col. [1]), sample (col. [2]), and 2MASS J-, H-, and  $K_s$ -band photometry (cols. [3]-[5]). The two samples are spatially distinct, and can be considered complete in the region of sky observable during our investigation, 548 deg<sup>2</sup> in sample A and 1236 deg<sup>2</sup> in sample B.

One additional object, 2MASS J1225-27, which was previously identified as a T dwarf candidate (Burgasser et al. 1998), but is not a member of either sample, was also included in our follow-up and is listed in Table 1.

## 2.2. Imaging Data

The largest source of contamination among our T candidates is uncatalogued minor planets (Burgasser et al. 1998; K99), which have blue near-infrared colors ( $J-K_s \sim 0.3$ , Veeder et al. 1995; Sykes et al. 1999) and will not match a POSS-I or -II source because of motion. While catalogued minor planets are flagged by the 2MASS processing pipeline, uncatalogued minor planets remain, and re-imaging is required to eliminate them from the candidate pool.

Eighty-minute  $z'$  band (Fukugita et al. 1997) exposures were obtained for two candidates, 2MASS J1217-03 and 2MASS J1237+65, using the USNO Flagstaff 1.55m Tek2k Camera on 1999 May 19 (UT). The remaining targets in Table 1 were imaged at K-band using the Keck

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<sup>13</sup> $K_s$  non-detections are reported as limiting magnitudes (no object detected at given coordinates to 95% confidence level). In this case, the  $H-K_s$  color limit is still required to be less than 0.3 magnitude.

I Near Infrared Camera (NIRC; Matthews & Soifer 1994) on 1999 May 27 (UT). Results from these reimaging campaigns are summarized in Table 1, columns (6)-(8). In total, five of nine objects were confirmed at their expected positions. 2MASS J-band images of the new confirmed candidates are shown in Figure 1. Designated names (col. [1]), 2MASS J magnitudes and J-H, H-K<sub>s</sub>, and J-K<sub>s</sub> colors (cols. [2]-[5]), and estimated distances (col. [6]) are listed in Table 2.

### 3. Spectroscopic Data

An initial identifying optical (8000 - 11000 Å) spectrum for 2MASS J1237+65 was obtained from the Palomar 200" Double Spectrograph (Oke & Gunn 1982) on 1999 May 24 (Burgasser et al. 1999). The data identified this object as very cool, as it is similar in appearance to the optical spectrum of Gl 229B (Oppenheimer et al. 1998), though quite noisy due to the exceedingly faint signal.

All confirmed candidates were then spectroscopically observed in the near-infrared using the Keck I NIRC grism on 1999 May 27-28 (UT). A 120 line/mm grism with the HK order sorting filter was employed, for first order resolution  $\lambda/\Delta\lambda = 100$ ; wavelength resolution was 60 Å/pixel. Each target was imaged with NIRC in camera mode and then placed into either a 0".52 (for 2MASS J1217-03, J1225-27, and J1237+65) or 0".38 (for 2MASS J1047+21 and J1346-00) wide slit. Total integration times of 1000s were divided into five 200s exposures with 5" on-slit dithers between exposures. The spectra were then pairwise subtracted to remove sky background, and each spectrum extracted separately. Flat-fielding was performed by obtaining a spectrum of a diffusely illuminated dome spot with identical instrumental settings. Each target spectrum was divided by a spectrum of a nearby SAO F star to correct for telluric absorption, and photometric standards were observed for flux calibrations. Individual exposures for each object were then averaged into a single, final spectrum.

Reduced spectra for all new 2MASS T dwarfs are shown in Figure 2, along with Gl 229B<sup>14</sup> (Leggett et al. 1999). All but one of the objects, 2MASS J1225-27, were saturated at the H-band peak, resulting in a false “absorption” feature at 1.58  $\mu\text{m}$ . The region of saturation was at most 3 pixels wide. An extrapolation of each saturated H-band peak using the 2MASS J1225-27 spectrum is indicated by a dotted line; each spectrum is normalized to this revised H-band peak. The 1.6 and 2.2  $\mu\text{m}$  methane bands are quite obvious in all of the confirmed candidates, identifying all as T dwarfs. Broadened H<sub>2</sub>O absorption bands shortward of 1.5 and 2.05  $\mu\text{m}$  are also evident, consistent with those found in Gl 299B (Oppenheimer et al./ 1995). The 2.3  $\mu\text{m}$  CO band seen in the L dwarfs (K99) is either overwhelmed by CH<sub>4</sub> absorption or absent in the T dwarfs.

The spectra show significant variation in the ratio between the flux at 2.1 and 1.55  $\mu\text{m}$ . As Figure 2 indicates, the 2.1  $\mu\text{m}$  peak flattens from 2MASS J1217-03 down to 2MASS J1237+65.

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<sup>14</sup>The NIRC spectrum of the SDSS rediscovery, 2MASS J1346-00, will be presented in Burgasser et al. (1999).

In contrast, there is an apparent steepening in the core of the 1.6  $\mu\text{m}$   $\text{CH}_4$  band, which is flat for 2MASS J1217-03, but decreases from 1.6 to 1.8  $\mu\text{m}$  for 2MASS J1225-27, J1047+21, and J1237+65.

## 4. Discussion

### 4.1. A Preliminary Sequence and $T_{\text{eff}}$

According to Burrows et al. (1997), the dominant form of molecular carbon switches from CO to  $\text{CH}_4$  at  $T_{\text{eff}} \sim 1300$  K.  $\text{H}_2\text{O}$  vapor bands, which have a profound influence on the near-infrared spectra of M (Jones et al. 1994) and L (Delfosse et al. 1997) dwarfs, are also expected to be strong in T dwarfs. As Tokunaga & Kobayashi (1999) have shown,  $\text{H}_2$  collision-induced absorption (CIA) has a marked influence on the latest L dwarfs, noticeably depressing the spectrum in a broad region around 2.2  $\mu\text{m}$ . This has also been seen in the reflectance spectrum of Jupiter (Danielson 1966). For the lower  $T_{\text{eff}}$ 's of T dwarfs,  $\text{H}_2$  is expected to play a more dominant role.

Thus, for  $T_{\text{eff}} \lesssim 1300$  K, the major absorbers in the near-infrared (JHK) spectra are  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ , and  $\text{H}_2$ . Since CIA affects the K band more strongly than the H band, particularly toward lower temperatures, the ratio of the flux at H to that at K should increase with cooler effective temperatures. This reasoning is the basis of our preliminary spectral sequence as displayed in Figure 2: 2MASS J1217-03, J1225-27, J1047+21, J1237+65, and Gl 229B. The J band is even less influenced by CIA and little influenced by  $\text{CH}_4$ , so that the same argument should also hold true for J- $K_s$ ; that is, we expect that cooler T dwarfs also have bluer J- $K_s$  colors. Four of the five objects were not detected at  $K_s$  by 2MASS, however, so these color relations require further observational investigation.

If we assume that these dwarfs have  $8.5 < \log(\text{age, Gyr}) < 9.5$ , typical of isolated field objects, then based on the observed colors and the assumption that all of the objects are warmer than Gl 229B, the 2MASS T dwarfs are likely to have  $950 < T_{\text{eff}} < 1300$  K (see Figure 9 of Burrows et al. 1997). It must be stressed that this is a preliminary assessment of the temperatures of these objects, and no consideration for other spectral influences such as metallicity and gravity have been made. Better  $T_{\text{eff}}$  estimates of these T dwarfs will require model fitting of their spectra from the far optical through the near-infrared. This analysis will be left to a future paper.

### 4.2. Space Density and the Brown Dwarf Mass Function

As indicated in Table 2, objects appear to lie within the  $\text{J-H} < 0.2$  and  $\text{H-K}_s < 0.2$  color region specified for Sample B, even 2MASS J1047+21, which was selected from a slightly broader color cut. If we assume that these colors are typical for all methane dwarfs, then we can make a preliminary assessment of the warm ( $900 < T_{\text{eff}} < 1300$  K) T dwarf space density. With one

detection in 548 deg<sup>2</sup> of sample A and three detections in 1236 deg<sup>2</sup> of sample B, we obtain a mean surface density of 0.0022 T dwarfs deg<sup>-2</sup>, or 90 warm T dwarfs observable over the entire sky with  $J < 16$ . If we make the simplifying assumption that all four confirmed T dwarfs in our sample have the same luminosity as Gl 229B, then this J-band limit corresponds to a distance limit of  $\sim 13$  pc, and thus a space density of  $\approx 0.01$  warm T dwarfs pc<sup>-3</sup>. This value should be considered an upper limit, as the warmer T dwarfs likely sample beyond 13 pc. It is nonetheless comparable to the L dwarf density of 0.007 L dwarfs pc<sup>-3</sup> computed by K99. Comparison with the simulations of Reid et al. (1999) suggests a mass function  $\frac{dN}{dM} \propto M^{-1}$  in the T dwarf regime, comparable to the relation for local late M dwarf stars (Reid et al. 1999).

## 5. Summary

We have identified four new T dwarfs and one previously discovered T dwarf in 1784 deg<sup>2</sup> of 2MASS survey data. These objects all show the hallmark 1.6 and 2.2  $\mu\text{m}$  CH<sub>4</sub> absorption bands that are characteristic of objects with  $T_{\text{eff}} \lesssim 1300$  K. They show some variation in their H- to K-band flux ratios, likely due to the combined absorption of CH<sub>4</sub>, H<sub>2</sub>O, and H<sub>2</sub>. This allows us to make a preliminary attempt at a T dwarf spectral sequence. We determine a proemial space density estimate of  $\lesssim 0.01$  warm T dwarfs pc<sup>-3</sup>, comparable to the L dwarf density from K99.

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Table 1. 2MASS T Dwarf Candidates: Imaging Results.

Object <sup>a</sup> (1)	Sample (2)	J (3)	H (4)	K <sub>s</sub> (5)	Date (UT) (6)	Instrument (7)	Confirmed (8)
2MASS J1007406+180601	A	15.75 ± 0.06	15.70 ± 0.14	15.77 ± 0.24	27 May 1999	Keck NIRC	no <sup>b</sup>
2MASS J1047539+212423	A	15.82 ± 0.06	15.79 ± 0.12	> 16.29 <sup>c</sup>	27 May 1999	Keck NIRC	yes
2MASS J1059440+183442	A	15.95 ± 0.07	15.83 ± 0.15	15.65 ± 0.19	27 May 1999	Keck NIRC	no <sup>b</sup>
2MASSW J1217111–031113	B	15.85 ± 0.07	15.79 ± 0.12	> 15.91 <sup>c</sup>	19 May 1999	USNO Tek2k	yes
2MASSW J1225543–273947	—	15.23 ± 0.05	15.10 ± 0.08	15.06 ± 0.15	27 May 1999	Keck NIRC	yes
2MASSW J1237392+652615	B	15.90 ± 0.06	15.87 ± 0.13	> 15.90 <sup>c</sup>	19 May 1999	USNO Tek2k	yes
2MASSW J1346464–003150 <sup>d</sup>	B	15.86 ± 0.08	16.05 ± 0.21	> 15.75 <sup>c</sup>	27 May 1999	Keck NIRC	yes
2MASSW J2110230–285509	B	15.43 ± 0.05	15.31 ± 0.08	15.34 ± 0.15	27 May 1999	Keck NIRC	no <sup>b</sup>
2MASSW J2142333–035556	B	15.86 ± 0.06	15.69 ± 0.14	15.73 ± 0.24	27 May 1999	Keck NIRC	no <sup>b</sup>

<sup>a</sup>Source designations for 2MASS discoveries are given as “2MASSx Jhhmmss[.]s±ddmmss”, where the “x” prefix varies depending upon which catalog the object originates, in this case “I” for 1999 Spring Release Data and “W” for the survey’s working database. The suffix conforms to IAU nomenclature convention and is the sexagesimal R.A. and decl. at J2000 equinox.

<sup>b</sup>Probable uncatalogued asteroid.

<sup>c</sup>Not detected at K<sub>s</sub> band; given magnitude is a 95% confidence magnitude lower (bright) limit based on the background flux.

<sup>d</sup>This object was previously discovered by the Sloan Digitized Sky Survey (Tsvetanov et al. 1999).

Table 2. Confirmed 2MASS T dwarfs.

Object (1)	J (2)	J-H (3)	H-K <sub>s</sub> (4)	J-K <sub>s</sub> (5)	est. distance (pc) <sup>a</sup> (6)
2MASSW J1217111–031113	15.85 ± 0.07	0.06 ± 0.14	< –0.12	< –0.06	14
2MASSW J1346464–003150 <sup>b</sup>	15.86 ± 0.08	–0.19 ± 0.22	< 0.30	< 0.11	14
2MASSW J1225543–273947	15.23 ± 0.05	0.13 ± 0.10	0.04 ± 0.17	0.17 ± 0.16	10
2MASSI J1047539+212423	15.82 ± 0.06	0.03 ± 0.13	< –0.50	< –0.47	13
2MASSW J1237392+652615	15.90 ± 0.06	0.03 ± 0.14	< –0.03	< 0.00	14

<sup>a</sup>Distance estimates assuming G1 229B-like radii and J-band bolometric corrections, and  $T_{eff} = 1000$  K.

<sup>b</sup>This object was previously discovered by the Sloan Digitized Sky Survey (Tsvetanov et al. 1999).

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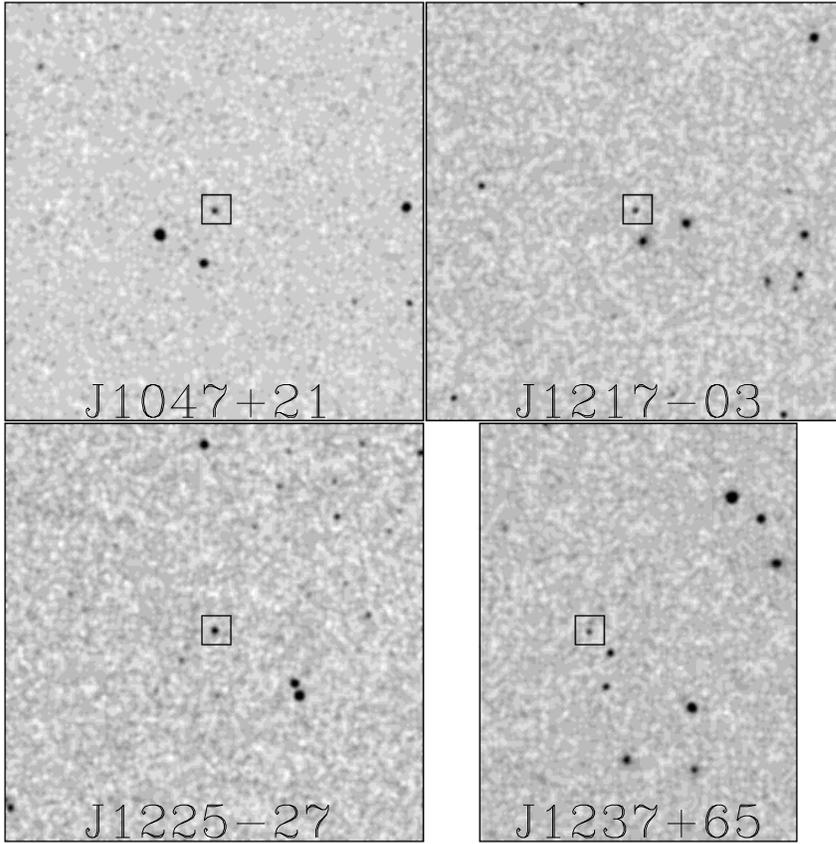


Fig. 1.— J-band images of the four new 2MASS T dwarfs: 2MASS J1047+21, J1217-03, J1225-27, and J1237+65. Fields are  $5' \times 5'$  (except for 2MASS J1237+65 which is  $3.8' \times 5'$ ) with north up and east to the left. A  $20'' \times 20''$  box is drawn around each T dwarf.

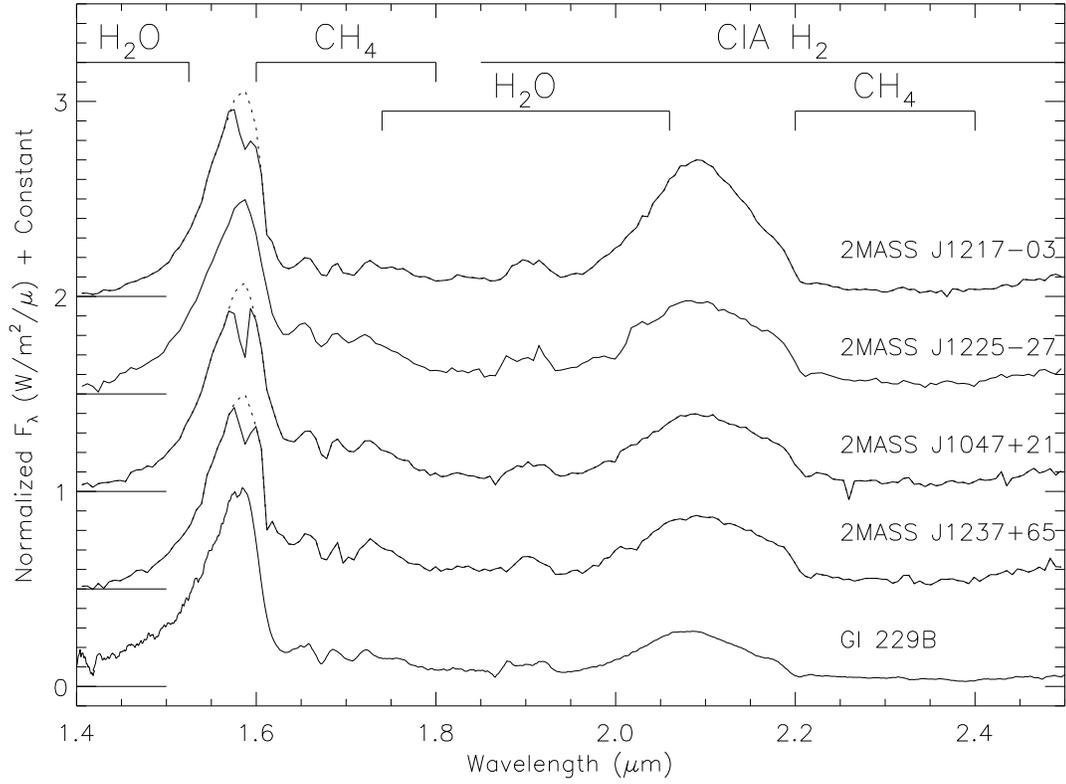


Fig. 2.— Near-infrared spectra (1.4 to 2.4  $\mu\text{m}$ ) of the four new 2MASS T dwarfs, taken with the Keck I NIRC grism, along with Gl 229B spectral data from Leggett et al. (1999). The Gl 229B data has been smoothed to match the resolution of our NIRC observations. Objects are displayed from top to bottom in a preliminary temperature sequence: 2MASS J1217-03, J1225-27, J1047+21, J1237+65, and Gl 229B. Absorption bands for  $\text{H}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{CH}_4$  are indicated. The “absorption features” seen at 1.58  $\mu\text{m}$  for all but 2MASS J1225-27 are due to saturation, and the dotted lines are extrapolations of the data in this region to fit to the 2MASS J1225-27 H-band peak. Spectra are normalized to their H-band peak.