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Discovery of a Bright Field Methane (T-type) Brown Dwarf by 2MASS

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ABSTRACT

We report the discovery of a bright ($J = 13.83 \pm 0.03$) methane brown dwarf, or T dwarf, by the Two Micron All Sky Survey. This object, 2MASSI J0559191-140448, is the first brown dwarf identified by the newly commissioned CorMASS instrument mounted on the Palomar 60-inch Telescope. Near-infrared spectra from 0.9 - 2.35 μm show characteristic CH_4 bands at 1.1, 1.3, 1.6, and 2.2 μm , which are significantly shallower than those seen in other T dwarfs discovered to date. Coupled with the detection of an FeH band at 0.9896 and two sets of K I doublets at J-band, we propose that 2MASS J0559-14 is a warm T dwarf, close to the transition between L and T spectral classes. The brightness of this object makes it a good candidate for detailed investigation over a broad wavelength regime and at higher resolution.

Subject headings: infrared: stars — stars: individual (2MASSI J0559191-140448) — stars: fundamental parameters — stars: low mass, brown dwarfs

1. Introduction

T dwarfs are brown dwarfs that exhibit methane absorption bands at 1.6 and 2.2 μm (Kirkpatrick et al. 1999), and thus have effective temperatures $T_{eff} \lesssim 1200\text{-}1300$ K (Fegley & Lodders 1996; Burrows & Sharp 1999; Kirkpatrick et al. 2000). The prototype for this class, Gl 229B (Nakajima et al. 1995; Oppenheimer 1999), was identified as a cool companion to the nearby M1V

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star Gl 229A. Recently, seven field objects (Strauss et al. 1999; Burgasser et al. 1999; Cuby et al. 1999; Tsvetanov et al. 2000) and another companion object (Burgasser et al. 2000a) have also been identified as T dwarfs. The rapid discovery of these cool brown dwarfs has been driven by new sky surveys, such as the Two Micron All Sky Survey (Skrutskie et al. 1997, hereafter 2MASS) and the Sloan Digital Sky Survey (Gunn & Weinberg 1995); and deep near-infrared surveys, such as the ESO New Technology Telescope Deep Field (Arnouts et al. 1999).

The T dwarfs identified to date are remarkably similar to Gl 229B, with colors in the range $-0.2 \lesssim J-K_s \lesssim 0.2$. Near-infrared spectra are correspondingly similar (Strauss et al. 1999; Burgasser et al. 2000a), likely due to the saturation of H_2O and CH_4 bands that dominate this wavelength regime. Subtle differences in the magnitudes and shapes of H- and K-band flux peaks are observed, due to increased CH_4 , H_2O , and H_2 collision-induced absorption (CIA) toward cooler effective temperatures (Burgasser et al. 1999; Tsvetanov et al. 2000), and variations in the depths of near-infrared H_2O and CH_4 bands are discerned when compared to Gl 229B (Nakajima et al. 2000; Burgasser et al. 2000a). Nonetheless, the similarity of the near-infrared spectra suggests that either the objects thus far identified are very similar in temperature, around 1000 K (Marley et al. 1996), or that near-infrared features are fairly insensitive to temperature, making the definition of a T dwarf spectral sequence in this wavelength regime a difficult proposition, at least at low resolution.

We report the discovery of a T dwarf by 2MASS which is unique among its counterparts, as it shows significant differences in its near-infrared features while retaining defining CH_4 bands. This object, 2MASSI J0559191-140448 (hereafter 2MASS J0559-14), is also 0.4 mag brighter than Gl 229B and more than 1 mag brighter than the field T dwarfs discovered thus far. It is the first brown dwarf to be identified by the newly commissioned Cornell Massachusetts Slit Spectrograph (Wilson et al. 2000, hereafter CorMASS), mounted on the Palomar 60-inch telescope. In §2 we discuss the selection of 2MASS J0559-14 from 2MASS data and its spectral identification by CorMASS. In §3 we discuss the observed spectral features and argue that 2MASS J0559-14 is a warm T dwarf, possibly close to the transition temperature between L and T spectral classes. We discuss the brightness of this object and its role in future spectroscopic investigation of the T dwarf class in §4.

2. Identification of 2MASS J0559-14

2.1. Selection and Confirmation

2MASS J0559-14 was initially selected as a T dwarf candidate from the 2MASS point-source working database. Details on the selection criteria for 2MASS T dwarfs are discussed in Burgasser et al. (2000a). Using the Palomar 60-inch Infrared Camera (Murphy et al. 1995), we successfully re-imaged this candidate on 23 September 1999 (UT) at J-band, confirming it as a bona-fide candidate (i.e., not a minor planet or artifact). 2MASS J0559-14 is the brightest 2MASS T dwarf candidate

confirmed to date, with $J = 13.83 \pm 0.03$ (Table 1); it is also the reddest candidate confirmed, with $J - K_s = 0.22 \pm 0.06$. Optical SERC-EJ (Morgan et al. 1992) and J-band 2MASS images of the 2MASS J0559-14 field are shown in Figure 1; no optical counterpart is seen to $B_J \sim 23$.

2.2. Spectral Identification with CorMASS

Low-resolution near-infrared spectral data of 2MASS J0559-14 were obtained on 24 October 1999 (UT) using CorMASS. This newly commissioned instrument is an $R \sim 300$ prism cross-dispersed near-infrared spectrograph, with a 256×256 NICMOS3 array and a 40 lines mm^{-1} grating, blazed at $4.8 \mu\text{m}$. CorMASS was designed primarily for the spectral classification of candidate low-mass objects color-selected from the 2MASS database. The instrument’s echelle format provides simultaneous coverage of the $z\text{JHK}$ bands, for $0.8 \lesssim \lambda \lesssim 2.5 \mu\text{m}$. The fixed slit has a width of $2''$ and a length of $15''$. Further details on this instrument can be found in Wilson et al. (2000).

Conditions during the observations were not photometric, and estimated seeing was $\sim 1''.5$, with variable thin cirrus throughout the night. Total on-source time was 2400 seconds divided into sets of 300-second integrations, nodding $\sim 5''$ along the slit between exposures. Spectra were reduced using standard IRAF routines. After correction for bad pixels, flat field and flux calibration images were corrected for NICMOS3 reset-decay bias (also known as shading) as follows: a quadratic was fit to a row-by-row clipped median of the top quarter of the array, the portion unused by the spectrograph. The fit was extrapolated to 128 rows for the top two quadrants, duplicated for the bottom two quadrants, and subtracted row-by-row from all pixels. All images were flat-fielded with a pixel responsivity solution from the APFLATTEN task using dome flats from all five nights of the run summed together. Nodded image pairs for the science object were subtracted against each other to remove sky background and reset-decay bias. The APALL task was used for spectral extraction. Wavelength calibration was accomplished using spectral observations of the planetary nebula NGC 7027 obtained on 25 October 1999 (UT). Flux calibration was done by dividing by the reduced spectrum of the A2V standard HD 77281 (Elias et al. 1982), which was observed at similar airmass as 2MASS J0559-14 and hand corrected for stellar H Paschen and Brackett recombination lines. The ratio was then multiplied by a 8810 K (Tokunaga 2000) blackbody to complete the flux calibration. Finally, all 300-second observations for each order were weighted by the spectra mean and combined with the SCOMBINE task using a trimmed average. Orders were stitched together with SCOMBINE after hand deletion of noisy data at the ends of the orders.

The spectrum of 2MASS J0559-14 is shown in Figure 2, along with optical ($0.87\text{-}1.0 \mu\text{m}$; Burgasser et al. 2000b) and near-infrared ($1.0\text{-}2.35 \mu\text{m}$; Strauss et al. 1999) data for SDSSp J162414.37+002915.6 (hereafter SDSS 1624+00). The combined SDSS 1624+00 spectrum was smoothed to the resolution of CorMASS. Spectra for both objects are normalized to one at $1.27 \mu\text{m}$ (J-band peak). Close up views of $0.88\text{-}1.01$ and $1.15\text{-}1.345 \mu\text{m}$ are shown in Figure 3.

3. Discussion of the Near-Infrared Spectrum

3.1. Spectral Features

Table 2 summarizes the spectral features detected in 2MASS J0559-14, with identifications from Pearse & Gaydon (1963), Danielson (1966), Wiese, Smith, & Glennon (1966), and Phillips et al. (1987). Only major absorption bands of H₂O and CH₄ are tabulated. The characteristic CH₄ bands at 1.6 and 2.2 μm are present, as are bands at 1.1 and 1.3 μm identified from laboratory data (Fink & Larson 1979) which are blended with H₂O bands at the same wavelengths. An FeH feature is seen at 0.9896 μm (0-0 band of A⁴ Δ -X⁴ Δ) which has also been identified in SDSS 1624+00 (Burgasser et al. 2000b). We do not detect the higher order 0-1 FeH band at 1.191 μm , which is seen to weaken in the latest L dwarfs (McLean et al. 2000). Two sets of K I doublets are noted at 1.1690 & 1.1773 μm (4p ²P₀ – 3d ²D) and 1.2432 & 1.2522 μm (4p ²P₀ – 5s ²S), as is Cs I at 0.8943 μm (6s ²S_{1/2} – 6p ²P_{1/2}). We do not detect the 2-0 X¹ Σ^+ -X¹ Σ^+ band of CO at 2.3 μm .

Comparison between 2MASS J0559-14 and SDSS 1624+00 reveals significant differences in spectral morphology. In Figure 2, it is apparent that the slope between 0.9 and 1.05 μm is shallower in 2MASS J0559-14, likely due to decreased absorption by the pressure-broadened K I doublet at 0.7665 and 0.7699 μm (Liebert et al. 2000). CH₄ and H₂O features are generally weaker in 2MASS J0559-14, as noted by the significantly weakened 1.1 - 1.2 μm trough between *z*- and J-band peaks. The decreased CH₄ opacity noticeably affects the shape of the J-band peak near 1.27 μm , as the weak CH₄ wings at 1.24 and 1.30 μm carve out less flux on either side of the peak. In Figure 2, a significant flux offset is readily apparent at the base of the 1.6 μm CH₄ band in 2MASS J0559-14, and relative enhancement of flux at both H- and K-bands in this object is almost certainly due to decreased H₂ CIA (1-0 Quadrupole), H₂O, and CH₄ opacity.

3.2. 2MASS J0559-14 is a Warm T dwarf

The weak CH₄ bands seen in 2MASS J0559-14 are unique among the current sample of T dwarfs, and the reduced opacity can be most readily explained if this object is warmer than other known T dwarfs. At higher effective temperatures, the dominant carbon-bearing species changes from CO to CH₄ at small optical depth, so that the CH₄ column density will be less than that of cooler T dwarfs, and observed band strengths correspondingly weaker. Increased thermal flux will also be seen at the base of these bands, particularly at 1.6 μm , which is unaffected by H₂O absorption. The lower CH₄ column density directly affects the H₂O column density, via the reaction $\text{CO} + 3 \text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$, leading to shallower bands at 1.1 and 1.45 μm . Water can also be heated and dissociated by dust layers deep in the photosphere (Leggett, Allard, & Hauschildt 1998). Finally, decreased H₂ CIA opacity at K-band, congruous with reduced CH₄ and H₂O opacity, will result in redder J-K_s colors with warmer T_{eff}. These features are observed in 2MASS J0559-14,

and its warm temperature is independently supported by the detection of the $0.9896 \mu\text{m}$ FeH band, which is present but weakening in the latest L dwarfs (Kirkpatrick et al. 1999). A similar argument has been made for SDSS 1624+00 by Burgasser et al. (2000b), which was one of only three T dwarfs in that paper to show this feature. SDSS 1624+00 has been shown to be a warm object via optical continuum measurements between broadened Na I and K I features (Liebert et al. 2000), while Nakajima et al. (2000) argue that this object is both warmer and dustier than Gl 229B based on its shallower CH_4 and H_2O bands. By analogy, 2MASS J0559-14 should be warmer still. The detection of excited K I lines at J-band, which are seen to weaken in the latest L dwarfs (McLean et al. 2000), is further evidence of the warmth of this object.

The spectral features in 2MASS J0559-14 suggest that it is close to the L/T transition temperature. The lack of CO detection at $2.3 \mu\text{m}$ is not necessarily contradictory to this hypothesis, as overlying CH_4 absorption beyond $2.2 \mu\text{m}$ may mask this weaker feature. Naturally, metallicity, dust, and gravity could also play roles in the band strengths seen in 2MASS J0559-14; however, temperature is likely to be the dominant determinant given the concordance of spectral features as discussed above. We can make a conservative T_{eff} constraint for this object based on the temperature of Gl 229B, which is clearly cooler, and a temperature estimate of the L8V companion dwarf Gl 584C (Kirkpatrick et al. 2000); this translates into a range of $1000 \lesssim T_{eff} \lesssim 1300 \text{ K}$. Parallax and bolometric luminosity measurements of this object would allow a direct determination of temperature.

4. The Brightness of 2MASS J0559-14

The relative brightness of 2MASS J0559-14 as compared to other T dwarfs suggests that it may be a nearby brown dwarf. We can estimate its distance using simple scaling arguments based on Gl 229B⁷. First, if we assume this object has the same intrinsic luminosity as Gl 229B, we estimate its distance to be 4.6 pc. However, 2MASS J0559-14 is probably a warmer object than Gl 229B, so it should be more distant. An alternate estimate can be made if we adopt a radius $R \approx R_{Gl229B}$ and bounding $T_{eff} \lesssim 1300 \text{ K}$, so that $L \lesssim 2.2 \times 10^{-5} L_{\odot}$. Using a Gl 229B bolometric correction, we obtain $M_J \gtrsim 14.2$ and thus $d \lesssim 8.4 \text{ pc}$. Note, however, that an L8V has $M_J = 15.0$ (Kirkpatrick et al. 2000), implying that our BC_J value may be too high; indeed, BC_J may be only 1.3 for an L8V (Reid et al. 1999). Adopting a smaller BC_J yields a smaller distance. Therefore, barring multiplicity, 2MASS J0559-14 is probably 5-8 pc distant, and likely falls within the 8 pc nearby star sample defined by Reid & Gizis (1997).

The brightness of this object allows substantial follow-up over a broad wavelength range, particularly for $\lambda > 2.5 \mu\text{m}$, where the fundamental absorption bands of H_2O ($2.7 \mu\text{m}$), NH_3 (3.0

⁷In this section we adopt the following values for Gl 229B: $d = 5.77 \pm 0.04 \text{ pc}$ (Perryman et al. 1997), $T_{eff} = 960 \pm 70 \text{ K}$ (Marley et al. 1996), $R \approx R_{Jup} = 7.1 \times 10^9 \text{ cm}$ (Burrows & Liebert 1993), $J = 14.32 \pm 0.05$, $L = (6.6 \pm 0.6) \times 10^{-6} L_{\odot}$, and $BC_J = 2.2 \pm 0.1$ (Leggett et al. 1999).

μm), CH_4 (3.3 μm), H_2S (3.8 μm), and CO (4.7 μm) are found. The latter 1-0 $X^1\Sigma^+ - X^1\Sigma^+$ band of CO can aid in constraining its atmospheric abundance (Noll, Geballe, & Marley 1997), essential in testing hypotheses of mixing (Oppenheimer et al. 1998; Griffith & Yelle 1999) and transparency (Lodders 1999) in T dwarf atmospheres. Deuterated molecules, such as CH_3D , are of interest for study in the 3-5 μm range, as they yield information on the Deuterium burning history of these brown dwarfs. Mid-infrared wavelengths (8 - 14 μm) are sensitive to vibration-rotation bands of alkali chlorides and sulfides, which are more abundant than their atomic alkali counterparts at low temperatures and high pressures (Lodders 1999) and may serve as excellent temperature discriminants. This region also contains the strong fundamental ν_2 band of NH_3 (10.5 μm) and various silicate features.

Additionally, optical spectra shortward of 0.9 μm are critical in determining the behavior of the alkalis in cool brown dwarfs, particularly pressure-broadened Na I (0.5890 & 0.5896 μm) and K I (0.7665 & 0.7699 μm) doublets, and Cs I lines at 0.8521 and 0.8943 μm , which may also be used as temperature discriminants (Reid et al. 2000; Burrows, Marley, & Sharp 2000; Basri et al. 2000). While these features have been seen in T dwarfs such as SDSS 1624+00 (Liebert et al. 2000), detailed investigation of Li I (0.6708 μm) and Rb I (0.7800 & 0.7948 μm) lines have been hampered by the lack of detectable flux at these wavelengths. Investigation in this spectral regime is currently underway.

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Fig. 1.— SERC-EJ Optical and 2MASS J-band images of the 2MASS J0559-14 field. Images are $5' \times 5'$ with North up and East to the left. A $20'' \times 20''$ box is drawn around the location of the T dwarf in both images.

Fig. 2.— Near-infrared spectrum of 2MASS J0559-14 (solid line) obtained by CorMASS. Overlaid are SDSS 1624+00 data from Burgasser et al. (2000b) and from Strauss et al. (1999) for 0.87 - 1 μm and 1 - 2.35 μm , respectively (dashed line). Both spectra are normalized to one at the 1.27 μm peak. Prominent molecular bands of H_2O , CH_4 , and H_2 (collision-induced absorption) are indicated, as is an FeH band at 0.9896 μm and the K I wing at z -band.

Fig. 3.— Two detailed regions of Figure 2 showing (a) 0.88 - 1.01 μm and (b) 1.15 - 1.345 μm . Spectra are normalized as in Figure 2. Features of FeH (0.9896 μm), K I (1.1690, 1.1773, 1.2432, 1.2522 μm), and Cs I (0.8943 μm) are indicated, as are H_2O and CH_4 bands.

Table 1. Photometric Properties of 2MASS J0559191-140448^a

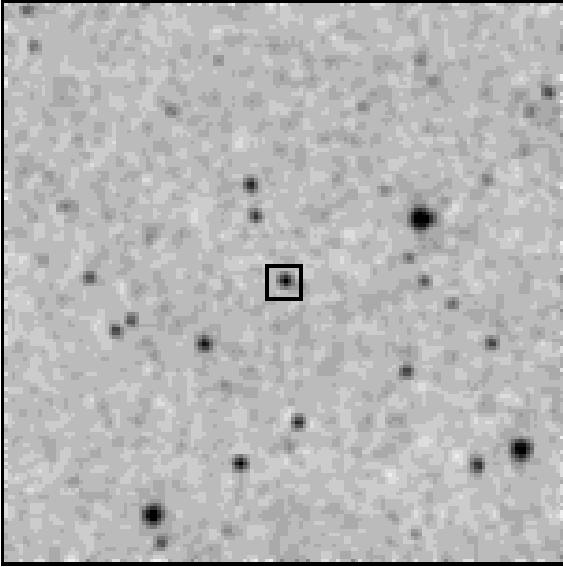
J	H	K _s	J - H	H - K _s	J - K _s	Estimated Distance (pc)
13.83±0.03	13.68±0.04	13.61±0.05	0.15±0.05	0.07±0.06	0.22±0.06	5 - 8 ^b

^aSource designations for 2MASS sources in the Incremental Release Catalogs are given as “2MASS Jhhmmss[.]s±ddmmss”. The suffix conforms to IAU nomenclature convention and is the sexagesimal R.A. and decl. at J2000 equinox.

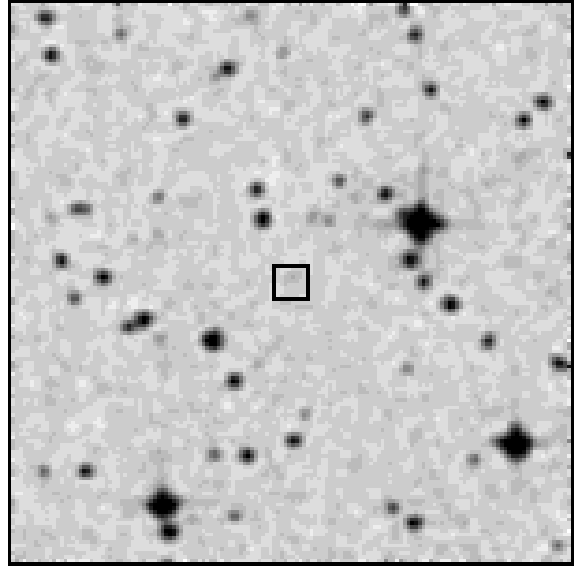
^bSee §4 for discussion.

Table 2. Near-Infrared Features Detected in 2MASS J0559-14.

Feature	λ (μm)	Transition	Reference for Transition
Cs I	0.8943	$6s \ ^2S_{1/2} - 6p \ ^2P_{1/2}$	Wiese, Smith, & Glennon (1966)
K I	broadened up to ~ 0.9	$4s \ ^2S_{1/2} - 4p \ ^2P_{3/2,1/2}$	Burrows, Marley, & Sharp (2000)
H ₂ O	0.925 - 0.95	$\nu_2 = 0, \nu_1 + \nu_3 = 3$	Auman (1967)
H ₂ O	0.95 - 0.985	$\nu_2 = 2, \nu_1 + \nu_3 = 2$	Auman (1967)
FeH	0.9896	0-0 band of $A^4\Delta-X^4\Delta$	Phillips et al. (1987)
H ₂ O	1.07 - 1.11	$\nu_2 = -1, \nu_1 + \nu_3 = 3$	Auman (1967)
CH ₄	1.1 - 1.24	$3\nu_3$	Danielson (1966)
H ₂ O	1.11 - 1.16	$\nu_2 = 1, \nu_1 + \nu_3 = 2$	Auman (1967)
H ₂ O	1.16 - 1.23	$\nu_2 = 3, \nu_1 + \nu_3 = 1$	Auman (1967)
K I	1.1690	$4p \ ^2P_0 - 3d \ ^2D$	Wiese, Smith, & Glennon (1966)
K I	1.1773	$4p \ ^2P_0 - 3d \ ^2D$	Wiese, Smith, & Glennon (1966)
K I	1.2432	$4p \ ^2P_0 - 5s \ ^2S$	Wiese, Smith, & Glennon (1966)
K I	1.2522	$4p \ ^2P_0 - 5s \ ^2S$	Wiese, Smith, & Glennon (1966)
CH ₄	1.3 - 1.5	$\nu_2 + 2\nu_3$	Danielson (1966)
H ₂ O	1.33 - 1.43	$\nu_2 = 0, \nu_1 + \nu_3 = 2$	Auman (1967)
H ₂ O	1.43 - 1.52	$\nu_2 = 2, \nu_1 + \nu_3 = 1$	Auman (1967)
CH ₄	1.6 - 1.8	$2\nu_3$	Danielson (1966)
H ₂ O	1.71 - 1.80	$\nu_2 = -1, \nu_1 + \nu_3 = 2$	Auman (1967)
H ₂ O	1.80 - 2.08	$\nu_2 = 1, \nu_1 + \nu_3 = 1$	Auman (1967)
CH ₄	2.2 - 2.6	$\nu_2 + \nu_3$	Danielson (1966)
H ₂	centered at 2.4	1-0 Quadrupole (CIA)	Danielson (1966)



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