T Dwarf Discoveries by 2MASS

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Abstract. Over a dozen T dwarfs, brown dwarfs that exhibit methane absorption features at 1.6 and 2.2 µm, have been discovered by the 2MASS survey. We discuss how the search for these objects has been made, point out some of the limitations of using near-infrared data to find the warmest T dwarfs, and highlight a few of the more interesting T dwarfs that have been identified in 2MASS data.

1. Introduction

T dwarfs are brown dwarfs that exhibit CH$_4$ absorption features at K-band (Kirkpatrick et al. 1999). These objects have effective temperatures $T_{\text{eff}} \lesssim 1300 - 1500$ K (Fegley & Lodders 1996), and are thus the coolest brown dwarfs so far detected. Until recently, only one object of this type was known, Gl 229B (Nakajima et al. 1995), a low-luminosity companion with $T_{\text{eff}} \sim 1000$ K and substellar mass $M \sim 40 M_{\text{Jup}}$ (Allard et al. 1996; Marley et al. 1996). The first field T dwarf, SDSS 1624+00, was identified by Strauss et al. (1999) in the Sloan Digital Sky Survey (SDSS; York et al. 2000); additional discoveries were soon made using the Two Micron All Sky Survey (2MASS; Burgasser et al. 1999, 2000a, 2000c, 2001b), SDSS (Tsvetanov et al. 2000; Leggett et al. 2000), and the New Technology Telescope Deep Field (Cuby et al. 1999). The detection of so many cool brown dwarfs (23 at the time of this writing) emphasizes how ubiquitous these objects are likely to be, despite their only recent identification; Reid et al. (1999) estimate that there may be up to twice as many brown dwarfs in the Galaxy as stars.

In this article, we focus on 2MASS T dwarf discoveries, of which 16 have so far been made. In §2 we discuss the search process used to identify T dwarfs in 2MASS near-infrared (NIR) data, and some of the limitations encountered in identifying warm T dwarfs (i.e., L/T “transition objects”). In §§3-5 we summarize three discoveries: the coolest known brown dwarf Gl 570D, the H$\alpha$ emitter 2MASS 1237+65, and the brightest T dwarf so far identified, 2MASS 0559-14. We summarize future progress in §6.

$\text{1} M_{\text{Jup}} \equiv 1 \text{ Jupiter mass} = 1.9 \times 10^{30} \text{ g} \approx 0.1 M_\odot$.  

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Figure 1. NIR color-color diagram of 2MASS point sources (points), T dwarf discoveries by 2MASS (filled circles) and SDSS (open circles), and Gl 229B (square). Arrows indicate upper limits. The Bessell & Brett (1988) dwarf and giant tracks are overlaid (solid lines), as are the color constraints made for the June 1999 sample (dashed lines).

2. The 2MASS T Dwarf Search

CH₄, H₂O and H₂ collision-induced (CIA) absorption force the spectral energy distributions of T dwarfs to peak in the NIR at J-band (1.25 µm). As a case in point, Gl 229B has an absolute J-band magnitude M_J = 15.4 (1.1 mJy at 1.25 µm), while M_r > 23.3 (< 0.0014 mJy at 0.7 µm), M_i = 21.2 (0.0084 mJy at 0.85 µm), M_K = 15.6 (0.38 mJy at 2.2 µm) and M_L ′ = 13.4 (0.13 mJy at 3.7 µm; Matthews et al. 1996; Leggett et al. 1999). This is in contrast to the Fν peak wavelength of 5 µm for a 1000 K blackbody. NIR surveys, such as 2MASS (Skrutskie et al. 1997), are thus especially tuned to detect the maximum flux from these otherwise dim objects. 2MASS is currently completing a whole-sky survey to SNR = 10 limits of J = 15.8, H = 15.1, and K_s = 14.3; at these magnitudes, it is capable of detecting objects like Gl 229B out to distances of 12, 8.3, and 5.8 pc, respectively, although fainter sources are certainly attainable.

Figure 1 shows a NIR color-color plot of a sample of point sources obtained from the 2MASS Second Incremental Data Release[2]. The positions of currently known T dwarfs are indicated, along with the Bessell & Brett (1988) dwarf and giant tracks. Note that 2MASS T dwarf discoveries (filled circles) begin at the blue end of the dwarf track, while warm T dwarfs identified by SDSS (open circles at upper right) lie along an extension of the giant track redward of J-H ≥

[2]http://www.ipac.caltech.edu/2mass/releases/second/index.html
Between these lies the NIR main sequence, and the majority of point sources detected by 2MASS. The contamination of these background sources forces us to constrain our search to J-H and H-K$_s$ ≤ 0.3 (dashed lines). Based on 2MASS completeness limits, we set a J-band magnitude limit of 16 and require J- and H-band detections, although no constraint is made at K$_s$-band. The faintness of Gl 229B in the optical (R - J ∼ 9; Golimowski et al. 1998) allows us to rule out objects with associated optical counterparts (USNO-A2.0 catalog; Monet et al. 1998); we also eliminate catalogued minor planets. Finally, candidates are constrained to Galactic latitudes |b| ≥ 15° in order to avoid source confusion.

In June 1999, we extracted 48,339 candidates from 18,360 sq. deg. (44.5% of the sky) of 2MASS point source data. Optical images of each candidate field, obtained from the CADC DSS server, were examined to rule out faint counterparts or close doubles. Second-epoch NIR imaging of remaining candidates was then done to eliminate uncatalogued minor planets, which have similar colors as T dwarfs. Finally, NIR spectroscopy confirmed T dwarf status via identification of the 1.6 and 2.2 µm CH$_4$ bands.

Figure 2 shows NIR spectral data for a sample of 2MASS T dwarfs, obtained at the Keck 10m using the Near-Infrared Camera (NIRC; Matthews & Soifer 1994), along with data for Gl 229B (Oppenheimer et al. 1998). Molecular absorption bands of CH$_4$ and H$_2$O are clearly evident, while suppression of flux at K-band is also due to H$_2$ CIA. The slight bend in the J-band peak at 1.25 µm is due to an unresolved K I doublet, which is clearly evident in higher resolution data (Strauss et al. 1999). One striking feature of these spectra is that they are not identical. The prominent 1.6 µm CH$_4$ band shows a gradual deepening from 2MASS 0559-14 to Gl 570D, as do combined CH$_4$ and H$_2$O absorption bands at 1.15 and 1.4 µm. At the same time, the 1.25 µm K I feature disappears, while the K-band peak changes from a sharp bandhead at 2.2 µm to a more gradual drop-off longward of 2.1 µm. We believe these spectral morphology changes are primarily due to temperature differences between the objects. Deeper molecular bands initially result from increasing CH$_4$ and H$_2$O number densities in the photosphere via the reaction CO + 3H$_2$ → CH$_4$ + H$_2$O. At lower temperatures, the reduction of higher energy “wing” transitions increases the contrast between the band cores and adjacent continuum. K I doublet lines at 1.2432 and 1.2522 µm, caused by the higher order 4p $^2$P$_0$ - 5s $^2$S transition, weaken with decreasing temperatures, and perhaps additionally through conversion of atomic potassium into KCl (Lodders 1999). Increased H$_2$ opacity toward lower temperatures (Lenzuni, Chernoff, & Salpeter 1991) results in increased absorption beyond 2.1 µm.

In all, 13 T dwarfs have now been identified in the June 1999 sample, which has been nearly completely followed up (Burgasser et al. 2001b). Table 1 shows the number of detections, area surveyed, and estimated space densities of this sample and those of Burgasser et al. (1999), Strauss et al. (1999) and Tsvetanov et al. (2000), and Leggett et al. (2000). Note that the SDSS space densities are generally higher than those from 2MASS searches. While this discrepancy may be due to small number statistics in the SDSS results, the color constraints imposed by background sources in 2MASS data certainly eliminates some T dwarfs.
Figure 2. (Left) NIRC spectra of 2MASS T dwarfs and Gl 229B (Oppenheimer et al. 1998). Major absorption features of CH$_4$, H$_2$O, H$_2$, and K I are indicated. (Right) Close-up view of the K-band peaks.

dwarfs. SDSS i*-z* colors delineate cool brown dwarfs due to their extreme redness from 0.8–1 µm (Fan et al. 2000; Figure 3 below), quite unlike main sequence stars. As such, SDSS should be able to produce a more complete sample of T dwarfs by including the warm L/T “transition” objects, while 2MASS likely samples a larger volume due to greater detectability at J-band.

| Sample $^a$ | June 1999 | B99 | ST00 | Le00 |
|-------------|-----------|-----|------|------|
| No. Detections | 13 | 4 | 2 | 3 |
| Area Searched (sq. deg.) | 18360 | 1784 | 130 | 225 |
| Est. Space Density (pc$^{-3}$) | 0.003 | 0.010 | 0.045 | 0.0095 |

$^a$B99 = Burgasser et al. (1999); ST00 = Strauss et al. (1999) and Tsvetanov et al. (2000); Le00 = Leggett et al. (2000).

3. Gliese 570D

Gl 570D (Burgasser et al. 2000a) was identified in the June 1999 sample as a field T dwarf candidate, but is located only 258±0.4′′ from Gl 570ABC. This triple system consists of a K4V primary separated by ∼ 25′′ from a close M1.5V-M3V binary. NIR spectral data for Gl 570D are shown in Figure 2. Deep CH$_4$
and H$_2$O absorption bands, as well as the absence of the 1.25 µm K I feature, indicate that it is a very cool object.

Companionship was verified via common proper motion by a second 2MASS observation of the field 14 months after the initial catalog imaging. The proper motion of the system (2$''0.012 \pm 0''002$ yr$^{-1}$; Perryman et al. 1997) was clearly resolved, given the 0''.3 astrometric accuracy of 2MASS point source data. Based on the distance to Gl 570A (5.91 ± 0.06 pc; Perryman et al. 1997), Gl 570D has $M_J = 16.47 \pm 0.07$, nearly a full magnitude dimmer than Gl 229B ($M_J = 15.51 \pm 0.09$; Leggett et al. 1999). Estimates based on empirical bolometric corrections, as well results from evolutionary models (Burrows et al. 1997) yield $T_{\text{eff}} = 750 \pm 50$ K, ($\sim$ 200 K cooler than Gl 229B) and $M = 50 \pm 20 M_{\text{Jup}}$. Gl 570D is the coolest brown dwarf so far detected; but, because the Gl 570 system is rather old ($\tau \sim 2$-10 Gyr), it may actually be more massive than Gl 229B. Companion brown dwarfs such as these, including recent L dwarf companion discoveries (Kirkpatrick et al. 2000b; Wilson et al. 2000), will help tie spectral types to absolute magnitudes, as well as provide age information – valuable empirical constraints for evolutionary models.

4. 2MASS 1237+65

2MASS 1237+65 (Burgasser et al. 1999) is a faint ($J = 16.03 \pm 0.09$) T dwarf undetected at K$_s$-band by 2MASS. Optical spectra of this and two other T dwarfs (SDSS 1624+00 and SDSS 1346-00; Strauss et al. 1999; Tsvetanov et al. 2000) were obtained using the Keck 10m Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995), in the wavelength range 6300 to 10100 Å at 9 Å resolution. Figure 3 shows the reduced spectra, with prominent features of Cs I, FeH, CH$_4$, and H$_2$O indicated. The broad absorption responsible for the rapid ramp-up from 8000 to 10000 Å is likely due to the pressure-broadened K I doublet at 7665 and 7699 Å (Burrows et al. 2000; Liebert et al. 2000).

Also indicated in Figure 3 is H$\alpha$ emission at 6563 Å, clearly seen in 2MASS 1237+65. This emission line was observed to persist over three days, and subsequent observations have confirmed its presence over timescales exceeding 6 months. While H$\alpha$ emission is prevalent in late M dwarfs and early L dwarfs, Kirkpatrick et al. (2000a) and Gizis et al. (2000) have shown that the incidence and strength of emission drops off precipitously beyond spectral type M7V, with no objects later then L5V showing H$\alpha$ in emission. Observations of other T dwarfs (Burgasser 2001a) show a similar lack of activity as measured by the H$\alpha$ line. By estimating the bolometric flux of 2MASS 1237+65, we measure $\log(f_{H\alpha}/f_{\text{bol}}) = \log(L_{H\alpha}/L_{\text{bol}}) = -4.2$, consistent with the activity level of late dMe field stars (Hawley et al. 1996). Given these clues, 2MASS 1237+65 must have a unique activity mechanism in order to sustain its relatively high level of emission. We have proposed that 2MASS 1237+65 may be a close, interacting binary, in which a lower mass secondary (and thereby larger brown dwarf, as $d\ln R/d\ln M = -1/3$ for degenerate dwarfs) is losing mass to the primary via

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4R. M. Cutri et al. 1999, Explanatory Supplement of the 2MASS Incremental Data Release (http://www.ipac.caltech.edu/2mass/releases/second/doc/explsup.html).
Roche lobe overflow, causing shock heating in the latter’s atmosphere. In order to sustain mass-loss, the physical separation of the primary and secondary must be on the order of 10 Jupiter radii; thus, photometric monitoring will likely provide the best test for this scenario. Regardless, the activity in 2MASS 1237+65 remains an intriguing puzzle.

5. 2MASS 0559-14

The majority of T dwarfs identified by 2MASS and SDSS have J-band magnitudes between 15 and 16, placing them between 6 pc (for the coolest objects such as Gl 570D) and ~15 pc, depending on temperature and duplicity. Nevertheless, we have identified one object, 2MASS 0559-14 (Burgasser et al. 2000c), which is significantly brighter, with $J = 13.83 \pm 0.03$. This is over one magnitude brighter than any other 2MASS T dwarf so far discovered, and nearly 0.4 mag brighter than Gl 229B at J-band. In addition, 2MASS 0559-14 is the reddest T dwarf identified in the June 1999 sample, with $J-K_s = 0.22 \pm 0.06$. A rough estimate based on the absolute J-band magnitudes of the L8V Gl 584C (15.0; Kirkpatrick et al. 2000a) and Gl 229B (15.5; Leggett et al. 1999), places 2MASS 0559-14 at about 5 pc (if it is single)[5].

5 This argument assumes that $M_J$ monotonically decreases from L8V through type T. This relation may not hold if CH$_4$ and H$_2$O bands strengthen significantly over a small $T_{eff}$ range, possibly redistributing flux into the J-band window.
NIR spectral data for 2MASS 0559-14 is shown in Figure 2. The most striking feature about this object is its significant deviation in spectral morphology from the other T dwarfs shown. While cool brown dwarfs such as Gl 229B and Gl 570D show deep H$_2$O and CH$_4$ absorption bands at 1.15, 1.4, 1.6–2.0, and 2.2 $\mu$m, 2MASS 0559-14 has significantly shallower absorption troughs, most notably at the 1.6 $\mu$m CH$_4$ band. We argue that these features, along with detectable 0.9896 $\mu$m FeH (which weakens toward the late L dwarfs) and strong 1.2 $\mu$m K I, suggest that 2MASS 0559-14 is significantly warmer than other 2MASS discoveries. Leggett et al. (2000) have recently identified three SDSS T dwarfs which have even shallower CH$_4$ absorption at H- and K-bands, as well as a residual CO bandhead at 2.3 $\mu$m. These objects are probably warmer still, right at the transition between the latest L dwarfs and the onset of CH$_4$ absorption in the NIR.

6. Future Progress

In just over one year, an entire population of cool T dwarfs has been discovered. A great deal remains to be learned about these objects, including absolute magnitudes, space motion, duplicity, variability, activity, space density, and ultimately their contribution to the stellar/substellar mass function and the mass budget of the Galaxy. While over a dozen T dwarfs have been identified in 2MASS data, more than one-half of the sky and a great deal of color space remains to be investigated. In addition, as SDSS begins routine survey operations, the opportunity to cross-correlate 2MASS and SDSS data will allow more sophisticated and hence more complete searches for brown dwarfs in the field. Given the estimates shown in Table 1, it is likely that we will find anywhere from 2 to 20 T dwarfs within 5 pc of the Sun, significantly influencing the nearby star sample. Finally, it is now possible to develop a new classification for T dwarfs, in analogy to the L dwarf spectral class derived by Kirkpatrick et al. (1999). Ironically, the future looks quite bright for brown dwarf research.

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