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# Mid-infrared followup of cold brown dwarfs: Diversity in age, mass and metallicity

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**Abstract.** We use *Spitzer* IRAC 3.6–8.0 $\mu$m photometry of late-type T dwarfs to investigate various trends which can aid the planning and interpretation of infrared (IR) surveys for the coldest T or Y dwarfs. Brown dwarfs with effective temperature ($T_{\rm eff}$)<700 K emit>50% of their flux at $\lambda$>3 $\mu$m, and the ratio of the mid-IR to the near-IR flux becomes very sensitive to $T_{\rm eff}$. The color $H-[4.5]$ is a good indicator of $T_{\rm eff}$ with a weak dependence on metallicity ([m/H]) and gravity ($g$) while $H-K$ and $[4.5]-[5.8]$ are sensitive to [m/H] and $g$. Thus $T_{\rm eff}$ and $g$ can be constrained and mass and age can then be determined from evolutionary models. There are 12 dwarfs known with $H-[4.5]>3.0$ and $500 \lesssim T_{\rm eff}\,{\rm K} \lesssim 800$, which we examine in detail. The ages of these dwarfs range from very young (0.1–1.0 Gyr) to old (3–12 Gyr). The mass range is possibly as low as 5 $M_{\rm Jup}$ to 70 $M_{\rm Jup}$, and [m/H] also spans a large range of $\sim -0.3$ to $\sim +0.3$. The T8–T9 dwarfs found so far in the UKIRT IR Deep Sky Survey are unexpectedly young and low-mass. Extensions to the warm *Spitzer* and WISE space missions are needed to obtain mid-IR data for cold brown dwarfs, and to discover more of these rare objects.

## 1. INTRODUCTION

The last decade has seen a remarkable increase in our knowledge of the bottom of the main-sequence and of the low-mass stellar and sub-stellar (brown dwarf) population of the solar neighbourhood. Two new classes have been added to the spectral type sequence following M: L and T. T dwarfs with effective temperatures ($T_{\rm eff}$) as low as ~500 K are now known (Warren et al. 2007; Burningham et al. 2008; Delorme et al. 2008; Leggett et al. 2009) and we are truly finding objects that provide the link between the low-mass stars and the giant planets.

As $T_{\rm eff}$ decreases, brown dwarfs emit significant flux in the mid-infrared(IR) (e.g. Burrows et al. 2003; Leggett et al. 2009). Figure 1 demonstrates the rapidly increasing importance of this region for late-type T dwarfs; for dwarfs cooler than 700 K more than half the flux is emitted at wavelengths longer than 3 $\mu$m. Here we investigates photometric trends seen in very late-type dwarfs at mid-IR wavelengths, with the expectation that these longer wavelengths will be crucial for both the discovery and the understanding of the coolest T-type dwarfs, and even more so for the proposed cooler Y-type dwarfs. Our group was awarded time on the *Spitzer Space Telescope* (Werner et al. 2004) to obtain IRAC (Fazio et al. 2004) photometry of late-type T dwarfs found in the Large Area Survey (LAS) component of the UKIRT IR Deep Sky Survey (UKIDSS; Lawrence et al. 2007). Identification and classification of the LAS T dwarfs is described by Pinfield et al. (2008)

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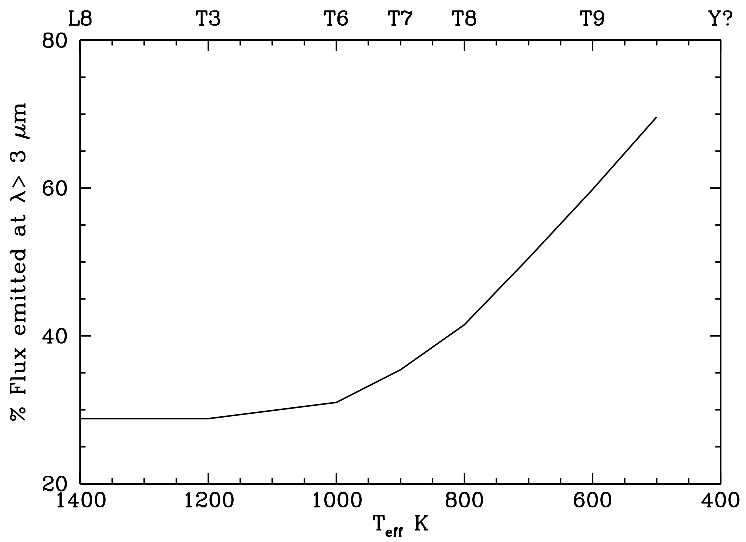


**Figure 1.** Percentage of total flux emitted at $\lambda > 3\,\mu$m, as a function of $T_{\rm eff}$, calculated from solar metallicity $\log g = 5.0$ models which include vertical gas transport. Cloudy models were used for $T_{\rm eff} > 1000$K and cloud-free for cooler temperatures.

## 2. THE SAMPLE

Figure 1 demonstrates the rapidly increasing ratio of the mid-IR flux to the near-IR flux for late-type T dwarfs. This means that a large wavelength baseline near-IR to mid-IR color should be a good indicator of $T_{\rm eff}$, and the $H - [4.5]$ color has been shown to be optimum (Warren et al. 2007; Leggett et al. 2009; Stephens et al. 2009). Leggett et al. (2009) show that expected variations in gravity ($g$) and metallicity ([m/H]), and in the gas transport efficiency, each impact $H - [4.5]$ by ~0.2 magnitudes. This is small given the large degree of sensitivity to $T_{\rm eff}$: $\Delta(H - [4.5]) \approx 0.7$ magnitudes for $\Delta T_{\rm eff} = 100$ K at $T_{\rm eff} = 600$ K for example.

We adopt $H - [4.5]$ as a primary reference color and have selected T dwarfs with IRAC photometry that have $H_{\rm MKO} - [4.5] > 3.0$, which our models imply have $T_{\rm eff} \lesssim 800$ K. Including the LAS T dwarfs with new IRAC photometry, 12 T dwarfs fall into this group. The dwarfs are listed in Table 1 together with some of their fundamental properties. All dwarfs with IRAC photometry that are T7.5 or later are included in this sample, except for the metal-rich T7.5 dwarf 2MASS J1217-03 (Saumon et al. 2007). Its exclusion is due to the (small) dependency of $H - [4.5]$ on [m/H]. Similarly, the relatively early-type very metal-poor dwarfs 2MASS J0937+29 (T6p) and 2MASS J1237+65 (T6.5e) have been included in our color-selected sample.

## 3. TEMPERATURE, METALLICITY AND GRAVITY

### 3.1 Photometric Indicators

Figure 2 shows a selection of color-magnitude diagrams for our sample, and Figure 3 color-color diagrams. Sequences are shown calculated by our cloud-free models which include chemical mixing by gas transport, for a range of $g$ and [m/H]. Although not perfect, the relative location of the objects in the plots is in agreement with our models. For example, metal-poor dwarfs are bright in Figure 2, and blue in $H - K$ and $[4.5] - [5.8]$ in Figure 3. The values of $T_{\rm eff}$ indicated for the sample in Figures 2 and 3 are consistent with other estimates (Table 1).

**Table 1.** T Dwarf Sample with $H_{MKO} - [4.5] > 3$.

| Name | Spec. | | Physical Parameters | | | | References[a] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Type | $T_{eff}$ K | log $g$ | [m/H] | $M_{Jup}$ | Age Gyr | Disc. | $\pi$ | Param. |
| 2MASS J0937347+293142 | T6p | 925–975 | 5.2–5.5 | −0.3 | 45–69 | 3–10 | 1 | 2 | 3 |
| 2MASS J12373919+6526148 | T6.5e | 800–850 | ∼5.0 | −0.2 | 20–40 | 1–4 | 4 | 2 | 5 |
| 2MASS J11145133−2618235 | T7.5 | 725–775 | 5.0–5.3 | −0.3 | 30–50 | 3–8 | 6 | | 7 |
| Gl 570D | T7.5 | 800–820 | 5.1 | 0.00 | 31–47 | 2–5 | 8 | 9 | 10 |
| HD 3651B | T7.5 | 780–840 | 5.3 | +0.15 | 40–72 | 3–12 | 11 | 9 | 12 |
| 2MASS J0415195−093506 | T8 | 725–775 | 5.0–5.4 | $\gtrsim 0$ | 33–58 | 3–10 | 1 | 2 | 13 |
| 2MASS J09393548−2448279[b] | T8 | 500–700 | 5.0–5.3 | −0.3 | 20–40 | 2–10 | 6 | | 14 |
| ULAS J101721.40+011817.9[c] | T8p | 750–850 | 4.0–4.5 | $\gtrsim 0$ | 8–12 | 0.1–0.4 | 15 | | **16** |
| ULAS J123828.51+095351.3 | T8.5 | 575–625 | 4.0–4.5 | $\gtrsim 0$ | 6–10 | 0.2–1.0 | 15 | | **16** |
| Wolf 940B[d] | T8.5 | 545–595 | 4.8–5.0 | **0 to+0.3** | 20–32 | 3.5–6 | 17 | 9 | 17 |
| ULAS J003402.77−005206.7 | T9 | 550–600 | 4.5 | $\gtrsim 0$ | 13–20 | 1–2 | 18 | 19 | 19 |
| ULAS J133553.45+113005.2 | T9 | 500–550 | 4.0–4.5 | $\gtrsim 0$ | 5–20 | 0.1–2 | 15 | 20 | 14 |

[a] Discovery, trigonometric parallax and parameter references are:
(1) Burgasser et al. (2002) (2) Vrba et al. (2004) (3) Geballe et al. (2009) (4) Burgasser et al. (1999) (5) Liebert & Burgasser (2007) (6) Tinney et al. (2005) (7) Leggett et al. (2007) (8) Burgasser et al. (2000) (9) ESA (1997) (10) Saumon et al. (2006) (11) Mugrauer et al. (2006) (12) Liu et al. (2007) (13) Saumon et al. (2007) (14) Leggett et al. (2009) (15) Burningham et al. (2008) **(16) This work** (17) Burningham et al. (2009) (18) Warren et al. (2007) (19) Smart et al. in prep. (20) Smart et al. (2009) priv. comm.

[b] Likely binary; a pair of 600 K dwarfs, or a 500 K and a 700 K brown dwarf pair (Burgasser et al. 2008; Leggett et al. 2009).

[c] If this spectrally peculiar object is a binary then $g$, mass and age, could be larger – log $g = 4.5$–5.0, masses ∼20 $M_{Jup}$, age ∼1 Gyr.

[d] Burningham et al. (2009) give [Fe/H] $= -0.06 \pm 0.20$ based on the $V - K$ color of Wolf 940 A; the photometric analysis presented here implies [m/H] between = 0.0 and +0.3 for the system.

2MASS 1237+65 has very strong Hα emission. Liebert & Burgasser (2007) discount the possibility that it is young and low-$g$, which would also be inconsistent with our analysis. They suggest that the object may be a close double system, and if the companion fills the Roche lobe then it must be cooler than 650 K. As no significant [4.5] excess is seen in Figure 2, our models imply that any companion would have $T_{eff} < 500$ K. The red $H - [4.5]$ for the dwarf is due to its low metallicity and not to the detected presence of a cool companion.

Figure 3 suggest that ULAS 1017+01 and ULAS 1238+09 are low gravity possibly metal-rich objects, similar to the other LAS very late-type T dwarfs ULAS 0034−07 and ULAS 1335+11, but not as cool. This low gravity for ULAS 1017+01 disagrees with the value determined by Burningham et al. (2008) based on near-IR data only and implies a very young age of 0.1–0.4 Gyr. This dwarf is spectrally peculiar; if the object is an unresolved 900+700 K or 800+600 K binary, then our model colors indicate that $g$ could be higher and the age would be ∼1 Gyr, more typical for a local disk dwarf.

Figures 2 and 3 allow us to constrain the metallicity of the Wolf 940 system: Burningham et al. (2009) give [Fe/H] $= -0.06 \pm 0.20$ based on the $V - K$ color of Wolf 940A but the photometric analysis presented here implies that [m/H] for the system is between 0 and +0.3. We can exclude the possibility that Wolf 940B is metal-poor.

### 3.2 The Low-Mass LAS Dwarfs

The 2MASS-selected dwarfs tend to be high-$g$ and/or low-[m/H] because they are selected for blue $H - K$ color (Figures 2 and 3). However the tendency for the LAS objects to be low-$g$ (Table 1) is difficult to understand. Figure 3 shows that the $YJH$ colors used to select the LAS dwarfs are not sensitive to $g$ or [m/H]. There should also be no $g$/age bias introduced by a brightness selection, as field

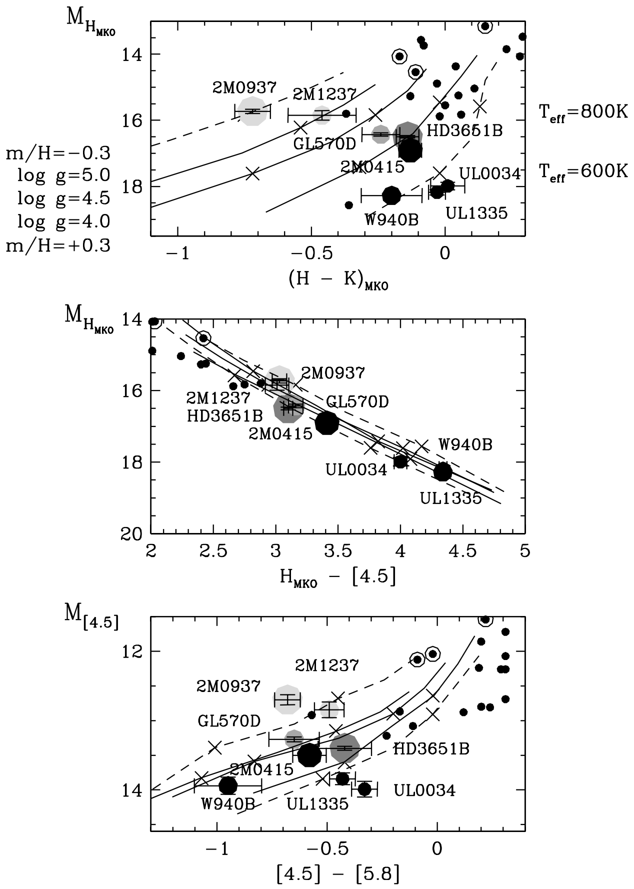


**Figure 2.** Color-magnitude plots for late T dwarfs. Small dots are a generic sample, known binaries are shown with ringed symbols. Larger symbols are the Table 1 dwarfs; largest to smallest circles represent $\log g \approx 5.4$, $\log g \approx 5.2$, $\log g \approx 5.0$ and $\log g \approx 4.3$. Dark to light grey circles are metal-rich, solar and metal-poor dwarfs; black are unknown [m/H]. Model sequences are shown with parameters indicated in the top panel. Crosses along the sequences indicate $T_{\rm eff} = 800$ K and 600 K.

brown dwarfs have an almost constant radius so that luminosity is effectively a function of $T_{\rm eff}$ only (Saumon & Marley 2008).

Simulations of the mass function (Burgasser 2004) show that the median field brown dwarf mass (and hence $g$) decreases to lower $T_{\rm eff}$ because lower mass brown dwarfs start off cooler than higher mass brown dwarfs. However the simulations indicate that, for a flat mass function (e.g. Metchev et al. 2008, Pinfield et al. 2008) and constant birth-rate, at $T_{\rm eff} \approx 600$ K the median mass would be 30–40 $M_{\rm Jup}$, age >6 Gyr and $\log g \approx 5$. The LAS T8–T9 dwarfs however appear to be generally younger than 2 Gyr and less massive than 20 $M_{\rm Jup}$. This puzzle will be re-examined when the sample of cold LAS brown dwarfs is larger.

## 4. CONCLUSIONS

The wavelength region beyond 3 $\mu$m makes up most of the emitted flux for dwarfs cooler than 700 K and is crucial for analysis of their photospheres. This region is extremely challenging from the ground and extensions to the warm *Spitzer* and WISE missions are desirable.

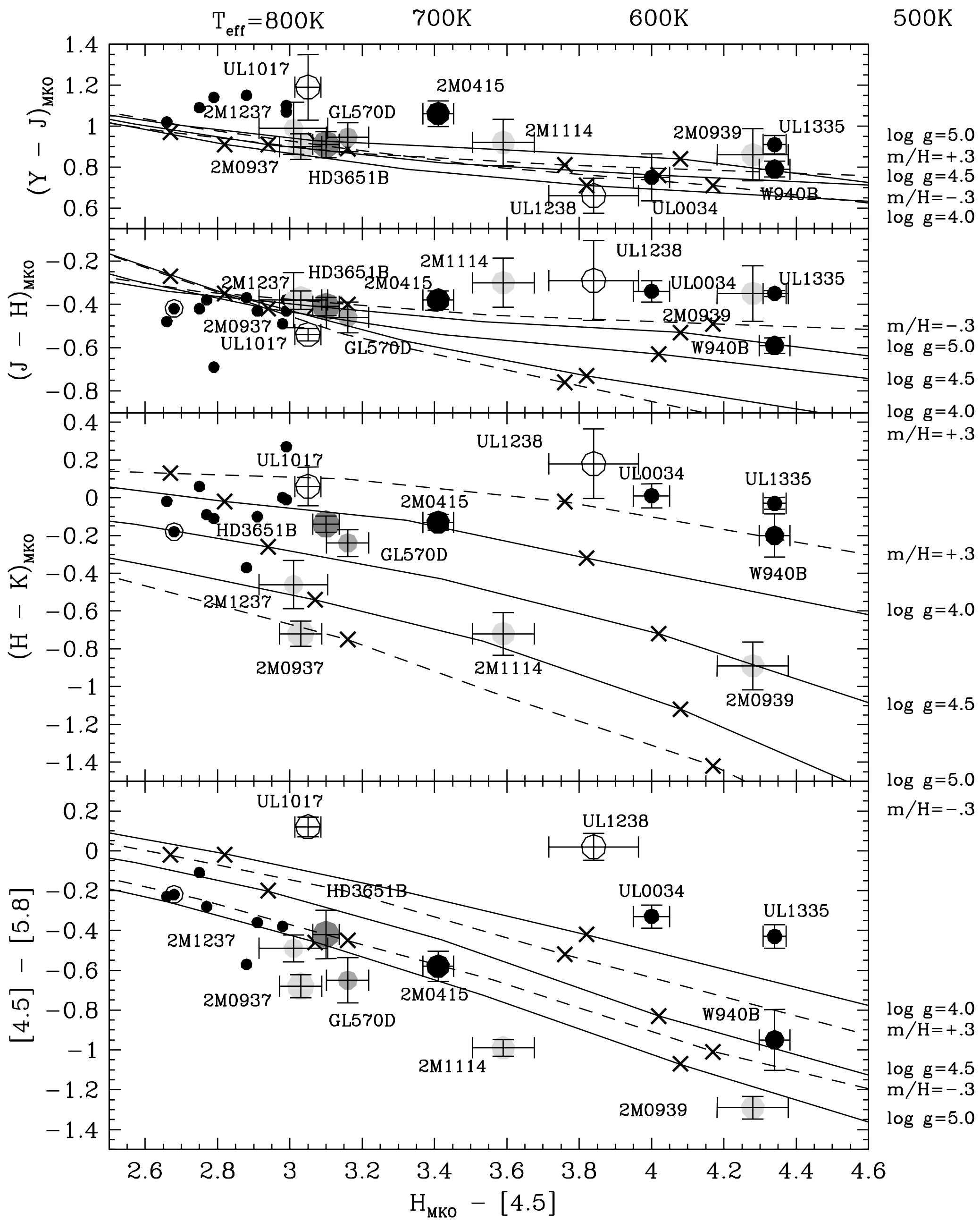


**Figure 3.** $H - [4.5]$ against $Y - J$, $J - H$, $H - K$ and $[4.5] - [5.8]$. Symbols are as in Figure 2 with open circles as unknown $g$. Model sequences are shown with parameters as indicated on the right axes. The $T_{\rm eff}$ values for the $\log g = 4.5$ [m/H] = 0 model are indicated on the top axis, and crosses along the sequences indicate the 800 K and 600 K points for each model set.

The long-baseline color $H-$ [4.5] provides a good indicator of $T_{\rm eff}$. $H - K$ and $[4.5] - [5.8]$ are sensitive to metallicity and gravity. As more data are obtained and the models improve it may be possible to separate these effects for independent determinations of these parameters.

The photometry suggests that four of the five ULAS T8–T9 dwarfs are younger than 2 Gyr and less massive than 20 $M_{Jup}$. This trend is not expected and not currently understood, we will revisit this as the UKIDSS survey continues and the sample size increases.

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