**Abstract.** Mid-infrared data, including Spitzer warm-IRAC [3.6] and [4.5] photometry, is critical for understanding the cold population of brown dwarfs now being found, objects which have more in common with planets than stars. As effective temperature ($T_{\text{eff}}$) drops from 800 K to 400 K, the fraction of flux emitted beyond 3 \( \mu \)m increases rapidly, from about 40\% to >75\%. This rapid increase makes a color like $H$-[4.5] a very sensitive temperature indicator, and it can be combined with a gravity- and metallicity-sensitive color like $H$-[K] to constrain all three of these fundamental properties, which in turn gives us mass and age for these slowly cooling objects. Determination of mid-infrared color trends also allows better exploitation of the WISE mission by the community. We use new Spitzer Cycle 6 IRAC photometry, together with published data, to present trends of color with type for L0 to T10 dwarfs. We also use the atmospheric and evolutionary models of Saumon & Marley to investigate the masses and ages of 13 very late-type T dwarfs, which have $H$-[4.5]>3.2 and $T_{\text{eff}} \approx 500$ K to 750 K.
1. Introduction

The last decade has seen a remarkable increase in our knowledge of the bottom of the stellar main-sequence and of the low-mass stellar and sub-stellar (brown dwarf) population of the solar neighborhood. Two classes have been added to the spectral type sequence following M — L, and T; T dwarfs with effective temperatures \( T_{\text{eff}} \) as low as 500 K are now known and we are truly finding objects that provide the link between the low-mass stars and the giant planets. As \( T_{\text{eff}} \) decreases, brown dwarfs emit significant flux at mid-infrared wavelengths (e.g. Burrows et al. 2003; Leggett et al. 2009). At \( T_{\text{eff}} = 1000 \text{ K} \) 30% of the total flux is emitted at wavelengths longer than 3 \( \mu \text{m} \), while at 600 K 60% of the flux is emitted in this region (according to our models).

Figure 1 shows spectral energy distributions (SEDs) for a 750 K T8 dwarf and a 600 K T9 dwarf; the flux emerges from windows between strong bands of, primarily, \( \text{CH}_4 \) and \( \text{H}_2\text{O} \) absorption. As the temperature drops from 750 K to 600 K, the ratio of the mid- to the near-infrared flux increases dramatically, and more flux emerges through...
the windows centered near 5 µm and 10 µm. Filter passbands are indicated for the near-infrared YJHK MKO-system (Tokunaga et al. 2002), as well as the Spitzer IRAC bands (Fazio et al. 2004) and the three shortest-wavelength WISE bands (Liu et al. 2008). The IRAC and WISE filters sample regions of both high and low flux, thus both cameras are sensitive to cold brown dwarfs, which can be identified by extreme colors in their respective photometric systems.

We used Spitzer Cycle 6 time to obtain IRAC photometry of late-type T dwarfs. Here we combine these data with published photometry to examine trends in colors with spectral type, which will be useful for the design and use of ongoing and planned infrared surveys. We also examine in detail the colors of the 500 \( \leq T_{\text{eff}} \leq 800 \) dwarfs for correlations with the photospheric parameters effective temperature, gravity, and metallicity. We find that various colors do provide indicators of temperature and gravity, which in turn constrains mass and age when combined with evolutionary models.

2. Trends with Type, and Survey Sensitivities

Figure 2 shows absolute IRAC \([3.6],[4.5],[5.8]\) and \([8.0]\) magnitudes as a function of spectral type. For the latest-type T dwarfs, because of the redistribution of the flux to the mid-infrared, the drop in intrinsic brightness at these wavelengths is much less than in the near-infrared. At YJHK there is an increase of 4 to 5 magnitudes from
Figure 3. IRAC colors as a function of spectral type; infrared spectral type is used for both L and T dwarfs. Green points are known binary systems. Typical uncertainties are indicated. $T_{\text{eff}}$ values on the top axes are from the Stephens et al. (2009) empirical $T_{\text{eff}}$:type relationship.

Figure 3 shows various colors as a function of type. T5 and later types become rapidly redder in $[3.6]-[4.5]$ and $[5.8]-[8.0]$, but bluer in $[4.5]-[5.8]$. The dispersion for these types is relatively small compared to the photometric uncertainties. Some scatter however is seen in $[4.5]-[5.8]$, most likely due to variations in the CO absorption, which impacts the [4.5] flux and which is gravity- and metallicity-sensitive.

3. Temperature, Metallicity and Gravity

We now examine observed and modeled trends for the coolest dwarfs in our sample. The color $H-[4.5]$ is a sensitive indicator of $T_{\text{eff}}$ for late-type T dwarfs (Warren et al. 2007, Stephens et al. 2009, Leggett et al. 2010a). Here, we select dwarfs with $H-[4.5]>3.2$, which produces a sample cooler than $\sim800$ K. Thirteen objects fall into this category, and are listed in Table 1. Figure 4 shows $H-K$ and $[4.5]-[5.8]$ as a function of $H-[4.5]$, and Figure 5 shows $M_H$ and $M_{[4.5]}$ as a function of $H-K$, $H-[4.5]$ and $[4.5]-[5.8]$. Note that [5.8] photometry is not available for dwarfs observed in the post-
cryogenic *Spitzer* mission. Model sequences with a range of gravity and metallicity are also shown (Marley et al. 2002; Saumon & Marley 2008).

Figure 4. Temperature-sensitive $H-[4.5]$ against gravity- and metallicity-sensitive $H - K$ (top) and $[4.5]-[5.8]$ (bottom); dwarfs with $H-[4.5]>3.2$ are identified and studied in detail. For these objects, symbol color indicates metallicity: black is unknown, green is solar, and cyan is metal-poor. Size indicates gravity: largest to smallest filled circles have log $g > 5$, ~5.0 and ~4.5; triangles have unconstrained gravity. Model sequences with log $g = 4.0$, 4.5 and 5.0 and $[m/H]=0$ are shown as solid lines, and log $g = 4.5$ with $[m/H]= -0.3$ and +0.3 as dashed lines. Crosses indicate the locations along the sequences of the $T_{\text{eff}} = 800$ K and 600 K points.

Some of these objects are well-studied, and we indicate in the figures metallicity and gravity where these are known; these and other parameters are listed in Table 1.
Table 1. Sample of Very Late-Type T Dwarfs with $H - [4.5] > 3.2$.

| Name            | Spectral Type | $T_{\text{eff}}$ (K) | $\log g$ | [m/H] | Mass (Jupiter) | Age (Gyr) | References$^a$ |
|-----------------|---------------|-----------------------|----------|-------|----------------|-----------|---------------|
| CFBDS 0301-16   | T7            | 700 - 750             | ~5.0     | ~0.0  | 20 - 40        | 0.4 - 4.0 | 1 2           |
| 2MASS 1114-26   | T7.5          | 725 - 775             | 5.0 - 5.3| -0.3  | 30 - 50        | 3 - 8     | 3 4           |
| SDSS 1416+13B   | T7.5          | 500 - 700             | 4.8 - 5.6| $\leq -0.3$ | 20 - 45 | 2 - 10    | 5 6 5, 7     |
| 2MASS 0415-09   | T8            | 725 - 775             | 5.0 - 5.4| $\geq 0$ | 33 - 58 | 3 - 10    | 8 9         |
| 2MASS 0939-24   | T8            | 500 - 700             | 5.0 - 5.3| -0.3  | 20 - 40        | 2 - 10    | 3 10         |
| Ross 458C       | T8.5          | 700 - 750             | ~4.5     | 0.0   | 7 - 20         | 0.1 - 1.0 | 11 2         |
| Wolf 940B       | T8.5          | 585 - 625             | 4.8 - 5.2| 0.1   | 24 - 45        | 3 - 10    | 12 13        |
| ULAS 1302+13    | T8.5          | 650 - 700             | 4.0 - 4.5| $> 0$  | 5 - 15         | 0.1 - 0.4 | 14 2         |
| ULAS 1238+09    | T8.5          | 575 - 625             | 4.0 - 4.5| $\geq 0$ | 6 - 10 | 0.2 - 0.6 | 15 16        |
| CFBDS 0059-01   | T9            | 500 - 550             | 4.5 - 5.0| $\sim 0$ | 10 - 30 | 1 - 10    | 17 2         |
| ULAS 0034-00    | T9            | 550 - 600             | 4.5     | $\geq 0$ | 13 - 20 | 1 - 2     | 18 19        |
| ULAS 1335+11    | T9            | 500 - 550             | 4.5     | $\geq 0$ | 5 - 20 | 0.1 - 2   | 15 10        |
| UGPS 0722-05    | T10           | 480 - 560             | 4.0 - 4.5| $\sim 0$ | 5 - 15 | 0.2 - 2.0 | 20 20        |

$^a$ References are to discovery (A) and parameter derivation (B). (1) Reylé et al. (2010); (2) this work; (3) Tinney et al. (2005); (4) Leggett et al. (2007); (5) Burningham et al. (2010b); (6) Scholz (2010); (7) Burgasser et al. (2010); (8) Burgasser et al. (2002); (9) Saumon et al. (2007); (10) Leggett et al. (2009); (11) Goldman et al. (2010); (12) Burningham et al. (2009); (13) Leggett et al. (2010b); (14) Burningham et al. (2010b); (15) Burningham et al. (2008); (16) Leggett et al. (2010a); (17) Delorme et al. (2008); (18) Warren et al. (2007); (19) Smart et al. (2010); (20) Lucas et al. (2010).

It can be seen that, while there is not exact agreement between models and data, the general trends are reproduced, with metal-poor and high-gravity dwarfs being blue in $H - K$ and $[4.5] - [5.8]$, and slightly redder in $H - [4.5]$. The $H - K$ color is impacted by pressure-induced $H_2$ opacity which is sensitive to metallicity and to a lesser extent gravity. The $[4.5]$ flux is impacted by a gravity- and metallicity-sensitive CO band.

There is degeneracy between the effects of gravity and metallicity, but there is an indication that $H - K$ is more sensitive to metallicity and $[4.5] - [5.8]$ to gravity, as the models calculate. The location of the dwarfs in Figures 4 and 5 relative to benchmark dwarfs, allows temperature, metallicity and gravity to be newly estimated for four dwarfs, and these parameters are given in Table 1. Note that these values do not rely on the absolute values implied by the models, but instead the models are used in a relative sense, using well-studied dwarfs as benchmarks.

4. Conclusions

The IRAC data implies that the majority of the UKIDSS 500 K to 600 K dwarfs are young and low mass, a result not currently understood in terms of selection effects or the mass function. Photometric data at wavelengths longer than 3 $\mu$m are both important and useful for the latest-type T dwarfs with $500 \leq T_{\text{eff}} K \leq 800$, and will be even more so for the cooler objects expected to be found by WISE and other sky surveys. It is only possible to get such data from the ground for very bright objects and mid-infrared space missions are crucial for continued progress in this field.
Figure 5. Absolute $H$ and [4.5] magnitudes as a function of various colors. Symbols and line types are as in Figure 4.

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