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Infrared Colors of L and T Dwarfs

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Abstract. We discuss the behaviour of the $JHKL'M'$ colors of L and T dwarfs, based on new photometric and spectroscopic data obtained at the United Kingdom Infrared Telescope in Hawaii. We have measured the first accurate M' photometry for L and T dwarfs. The K–M' colors of T dwarfs are much bluer than predicted by published models, suggesting that CO may be more abundant than expected, as has been found spectroscopically for the T6 dwarf Gl 229B. We also find that K–L' increases monotonically through most of the M, L, and T subclasses, but it is approximately constant between types L6 and T5, due to the onset of CH_4 absorption at the blue edge of the L' bandpass. The JHK colors of L dwarfs show significant scatter, suggesting variations in the amount and properties of photospheric dust, and indicating that it may not be possible to associate a unique T_{eff} with a given L spectral type. The $H-K$ colors of the later T dwarfs also show some scatter which we suggest is due to variations in pressure–induced H_2 opacity, which is sensitive to gravity (or age for a brown dwarf) and metallicity.

1. Introduction and Photometric Systems

This work is based on papers by Leggett et al. (2001) and Geballe et al. (2001a). Geballe et al. present a spectral classification scheme for L and T dwarfs (summarised elsewhere in these proceedings) and Leggett et al. present $ZJHKL'M'$ photometry of a sample of 58 late–M, L, and T dwarfs. The L and T dwarfs in these papers are primarily taken from recent results of red and near–infrared imaging sky surveys — the Deep Near–Infrared Survey (DENIS, e.g. Martín et al. 1999), the 2 Micron All–Sky Survey (2MASS, e.g. Kirkpatrick et al. 1999) and the Sloan Digital Sky Survey (SDSS, e.g. York et al. 2000). The data presented in this work were obtained at the United Kingdom Infrared Telescope (UKIRT) in Hawaii.

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Figure 1 shows $J-H$, $J-K$ and $K-L'$ colors as a function of spectral type, where the type is taken from Geballe et al. (2001a). Section 2 discusses the 1—2.5 μm colors of L and T dwarfs — J (1.25 μm), H (1.65 μm) and K (2.2 μm). Section 3 discusses the longer wavelength 3—5 μm colors — L' (3.8 μm) and M' (4.7 μm).

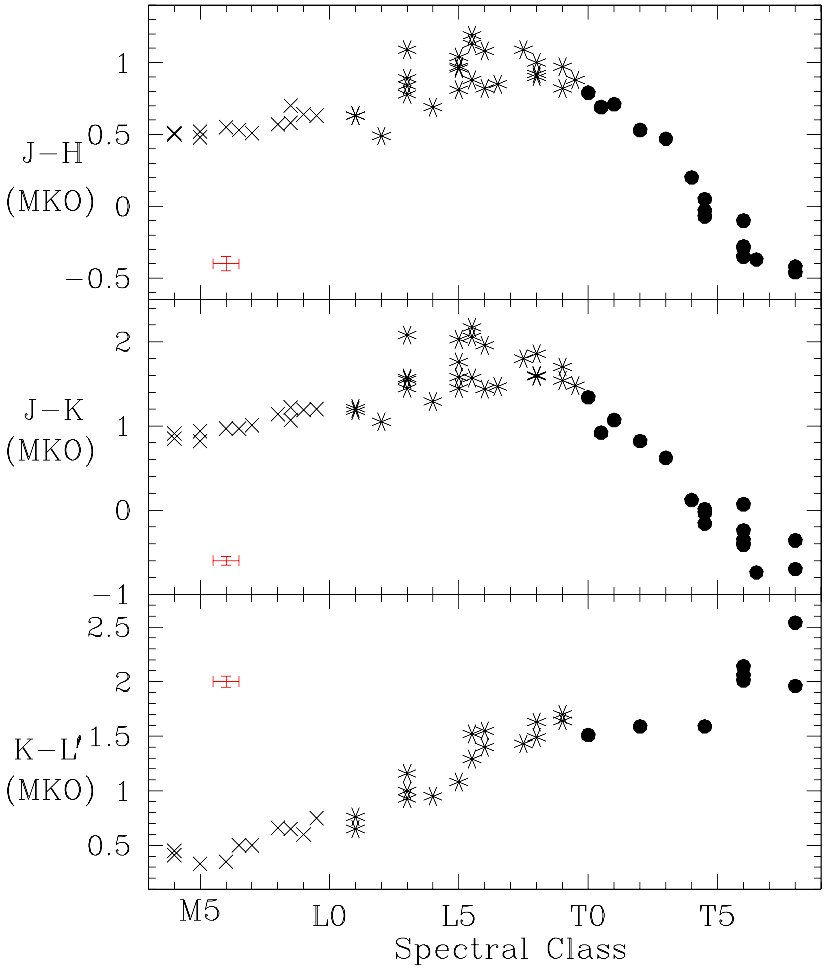

Figure 1. $J-H$, $J-K$ and $K-L'$ against spectral type for M dwarfs (crosses), L dwarfs (asterisks) and T dwarfs (filled circles); photometry from Leggett et al. 2001, spectral classification by Geballe et al. 2001a. Typical error bars are shown in red.

The infrared passbands are constrained by the transmission of the terrestrial atmosphere. Unfortunately, historically, there has not been a consensus on the exact specifications of the filters used by different observatories. Recently a group led by A. Tokunaga has defined a set of infrared filters well matched to the atmosphere (Simons & Tokunaga 2002, Tokunaga & Simons 2002); these filters are being widely adopted and are known as the Mauna Kea Observatory

(MKO) filter set. The colors in Figure 1 are on this system. Note that differences between colors measured on different photometric systems can be significant, especially in the case of T dwarfs, and colors available in the literature should not be compared without transforming between systems. This is discussed further in Sections 2 and 3.

2. 1—2.5 μm Colors (JHK)

Figure 2 shows the observed 1—2.5 μm flux distributions of an L and a T dwarf, with the important absorbing molecular species indicated along the top of the figure (see also the paper by Burgasser et al. in these proceedings, and Burgasser et al. 2001). We have overlaid J, H and K filter profiles from three photometric systems: 2MASS, UKIRT (prior to adoption of the MKO filters) and MKO. Note the significant differences between the filters and the very structured energy distributions within the bandpasses, especially for the T dwarfs. While differences between measured JHK magnitudes on these systems are only around 5% for L dwarfs, for T dwarfs the difference at K is ~10% and at J it is ~30%.

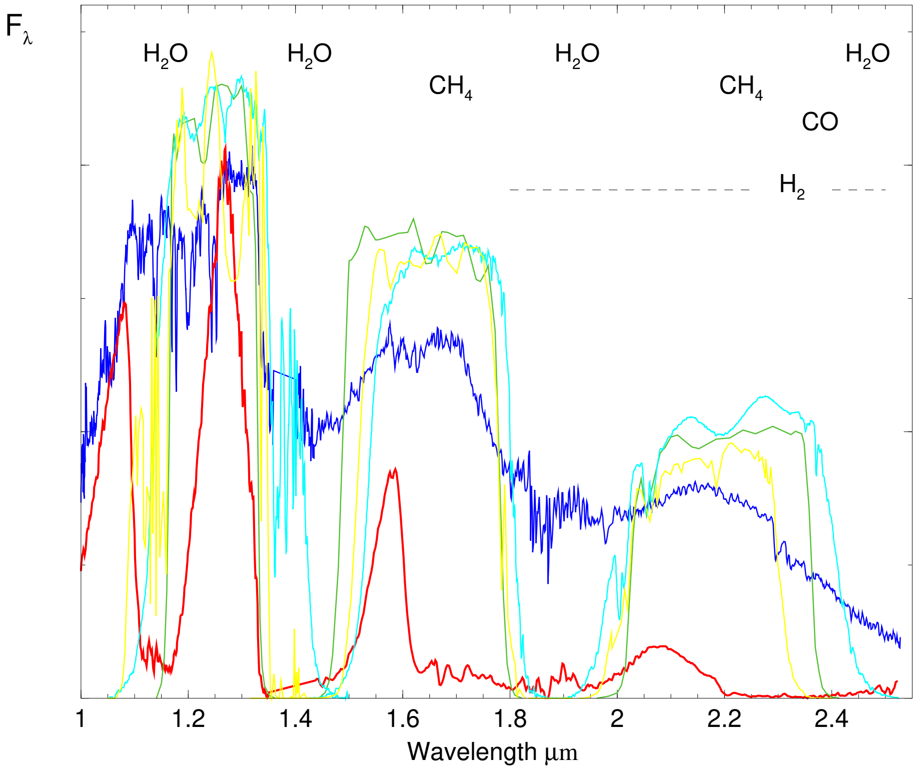

Figure 2. Observed spectra of an L1 dwarf (2MASSI J0746+20, Reid et al. 2001, blue line) and a T8 dwarf (Gl 570D, Geballe et al. 2001b, red line). J,H,K filter profiles are overlaid from the MKO (green), UKIRT (cyan) and 2MASS (yellow) photometric systems.

Methane (CH_4) absorption in the K band becomes important for spectral types L8 and later, and in the H band for types T0 and later (Geballe et al. 2001a). Hence the $J-H$ and $H-K$ colors become increasingly blue for the latest spectral types, as can be seen in Figure 1. Figure 1 also shows that while trends are apparent between color and type, for the L3—L8 dwarfs there is a large scatter in $J-H$ and $J-K$ as a function of type. The scatter is much larger than the measurement error, indicated by the error bar in the figure.

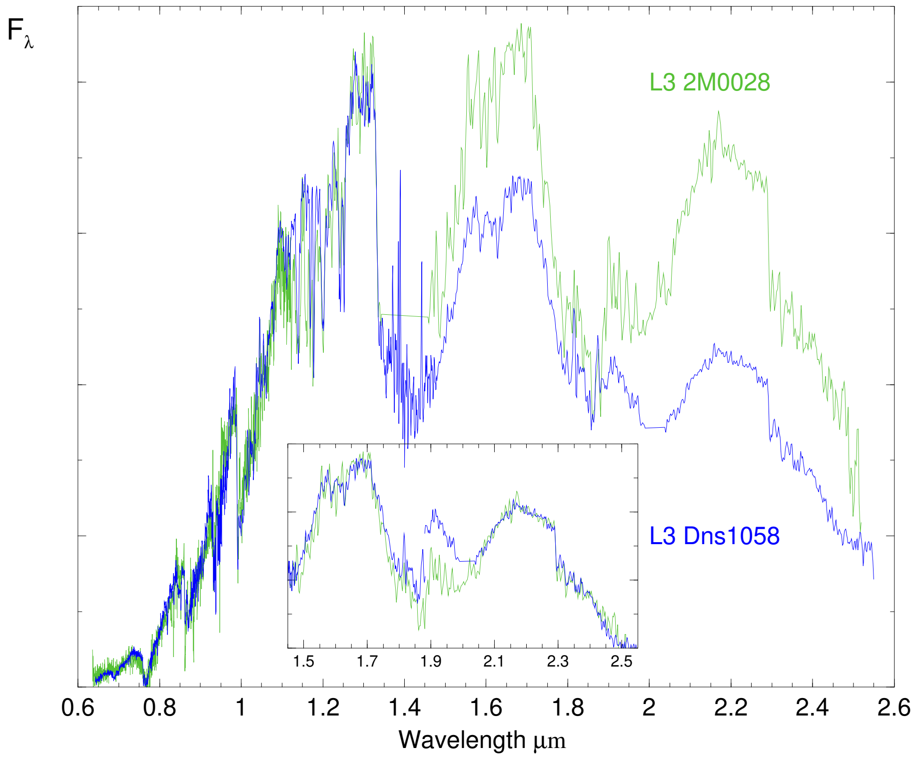

Figure 3. Observed relative flux distributions of two L3 dwarfs, from Geballe et al. 2001a; inset shows different scalings, see text.

Figure 3 explores this observed scatter further by superimposing the energy distributions of two objects both classified as L3; it can be seen immediately that they have very different $J-K$ color. However the inset shows that if the H and K spectral segments are separately scaled and overlaid, the agreement is excellent. That is, the slope of the red continuum, the wings of the water (H_2O) bands, and the depth of the carbon monoxide (CO) band all match and so indeed the objects are both L3 types. The difference in color is probably due to another important opacity source not yet mentioned: dust. At the temperatures of these photospheres, around 2000 K, grains are expected to form. This is discussed further by Marley et al. in these proceedings (see also Ackerman & Marley 2001 and Allard et al. 2001). This dust is expected to cause a warming of the photosphere and a redistribution of flux to the infrared. The scatter in color may indicate varying dust properties caused by differences in metallicity (which affects dust abundance), age (which limits settling time) and rotational velocity (which may inhibit dust settling). Detailed models are required before we can understand how dust can change the overall color of an L dwarf without affecting the dominant spectroscopic features.

Note also how very different the radiated energy is for these two L3 dwarfs over this wavelength range. One effect of the dust may be that a unique effective temperature cannot be associated with a given L spectral type. Bolometric magnitudes are needed to investigate this further.

Figure 1 shows there is also some scatter in the $J-K$ colors of the later T dwarfs. Figure 4 shows the relative flux distributions of two T8 dwarfs superimposed; the inset shows the H and K regions scaled separately. Again it can be seen that although the overall color is different, the H_2O and CH_4 absorptions match well, and they are both therefore classified as T8. At the effective temperatures of these atmospheres, around 1000 K, grains are expected to lie below the photosphere, and the absorption bands of CH_4 and H_2O are close to saturation. One opacity source that is still important is pressure–induced molecular hydrogen (H_2) absorption, which is an extremely broad feature that spans both the H and K bands but is strongest at K (see e.g. Borysow et al. 1997). The strength of this opacity is sensitive to gravity (or age, for a brown dwarf) and metallicity, and we suggest that the scatter seen in the K band colors of late T dwarfs is due to variations in these parameters.

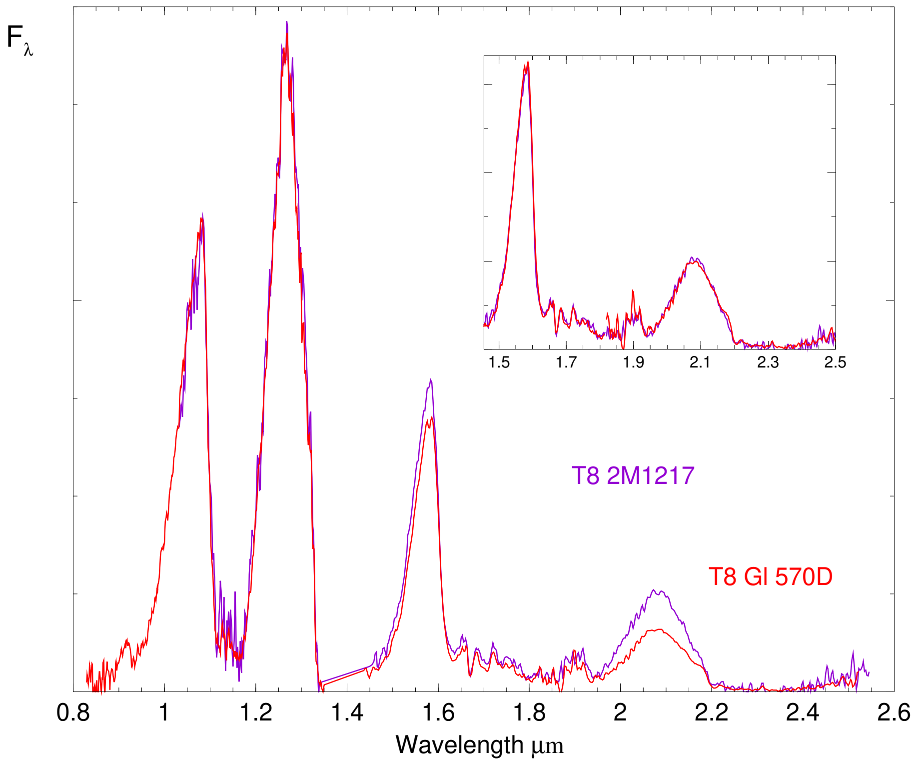

Figure 4. Observed relative flux distributions of two T8 dwarfs, from Geballe et al. 2001a; inset shows different scalings, see text.

3. 3—5 μm Colors (LM)

Figure 5 shows the 3—5.5 μm calculated energy distribution for two model atmospheres with effective temperatures appropriate for an L dwarf and a T dwarf. The observed flux distribution for a T dwarf is also shown. The principal absorbing species are indicated along the top of the figure and filter profiles are overlaid. The MKO L' and M' filter bandpasses are shown, as well as the earlier UKIRT L' profile and a wider M profile.

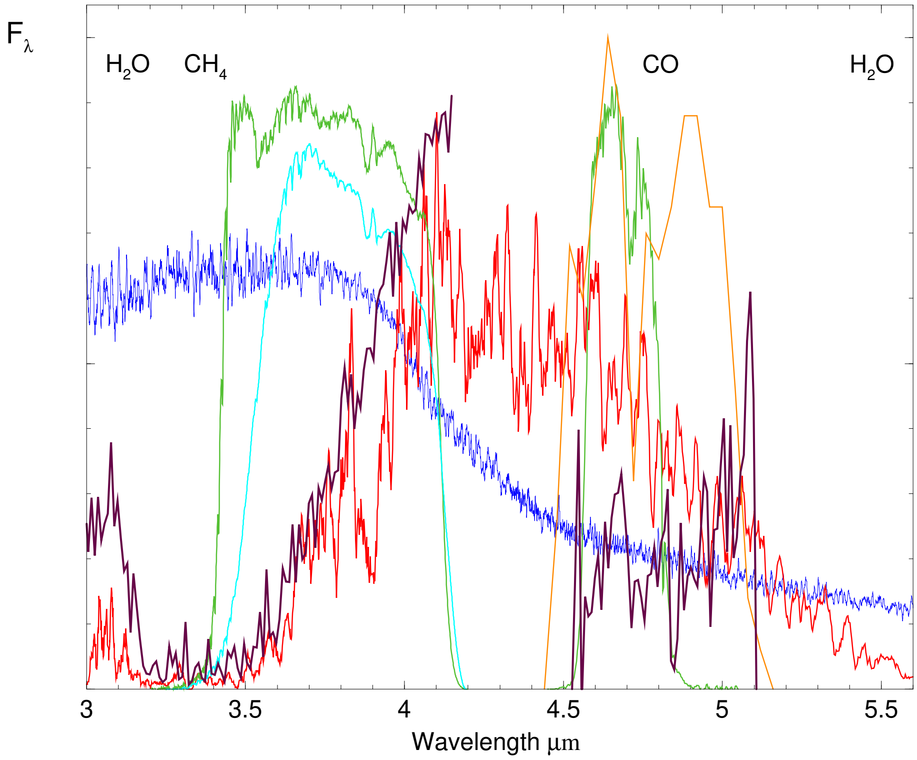

Figure 5. Calculated spectra for an L dwarf type atmosphere with $T_{\text{eff}} = 2000$ K (Allard et al. 2001, blue line), and for a T dwarf type atmosphere with $T_{\text{eff}} = 800$ K (model by D. Saumon and M. Marley, as presented in Geballe et al. 2001b, red line). Also shown is an observed spectrum for the T6 dwarf Gl 229B (Oppenheimer et al. 1998 and Noll et al. 1997, maroon). UKIRT (cyan) L', MKO (green) L' and M', and AAO (orange) M filter profiles are overlaid.

In the L band the important opacity sources are H_2O and CH_4. Noll et al. (2000) have shown that the 3.3 μm band of CH_4 is detected for spectral types around L5 and later. Figure 1 shows that our $K - L'$ colors are almost constant for types L6 to T5 most probably due to the onset of this absorption feature at the blue edge of our L' bandpass. For later types the band is saturated and $K - L'$ can increase again. Differences in the L$'$ bandpass can lead to magnitudes that differ by 20% for T dwarfs (see also Stephens et al., these proceedings and Stephens et al. 2001).

In the M band it can be seen that the model spectrum (red line) does not agree with the observed spectrum (maroon line). Noll et al. (1997) show that the shape of the observed Gl 229B spectrum indicates the presence of the fundamental vibration–rotation band of CO in this T6 dwarf. This is unexpected as at these temperatures all the carbon is expected to be in the form of CH_4. Possibly CO is being dredged up from hotter, deeper, layers of the atmosphere.

Table 1. $K - L'$, $K - M'$: Model Comparison

Type	$\sim T_{\rm eff}$ K	Observed Color	Calculated Dusty[a]	Settled[b]
		$K - L'$		
L1	2100	0.7	1.0	···
L8	1400	1.6	1.8	···
T0	1300	1.5	2.1	···
T6	950	2.0	3.3	2.3
		$K - M'$		
L4	1800	0.7±0.1	1.0	···
L8	1400	1.4±0.1	2.0	···
T2	1300—1000	1.2±0.2	2.1—3.3	···
T4.5	1300—1000	1.6±0.2	2.1—3.3	~3.0

[a]Chabrier et al. (2000) for ages 0.1—10 Gyr, corresponding to log g ≈4.2—5.4

[b]Burrows et al. (1997) for log g =4.5—5.0 corresponding to ages ≈0.3—1 Gyr

Leggett et al. (2001) give $K - L'$ colors for nineteen L dwarfs and eight T dwarfs and $K - M'$ colors for two L dwarfs and two T dwarfs. Table 1 presents these colors as a function of spectral type, where the $K - L'$ color has been averaged over type. The effective temperature for each type is shown, estimated using luminosity arguments as described by Leggett et al. The colors are compared to those calculated by two different models. The models differ primarily in their treatment of grain condensation: one has the grains distributed through the photosphere (the Dusty model, Chabrier et al. 2000), the other has them below the photosphere so that they do not contribute to the opacity (the Settled model, Burrows et al. 1997). L dwarfs should be well represented by the Dusty model, while T dwarfs should be closer to the Settled model. The $K - L'$ colors of the L dwarfs agree quite well with the Dusty model calculations, and those of the T dwarfs with the Settled model. However neither model agrees with the observed $K - M'$ colors for the late L dwarf and the two T dwarfs. The most likely explanation of the discrepancy would seem to be the unexpected absorption by CO in the M bandpass; more 5 μm spectra are required to confirm this. Such measurements will be more difficult than earlier anticipated as the 5 μm flux is around a factor of three smaller than predicted.

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