Part 7

Atmospheres and Internal Structure

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Photospheric Properties of L and T Dwarfs

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Abstract. The photospheric spectra of all L and T dwarfs contain strong molecular bands and alkali absorption features, and those of L and early T dwarfs are also affected by dust. Although work on atmospheric models is addressing the treatment of dust, and is increasing the completeness of molecular opacity linelists, the effective temperatures of L and T dwarfs cannot be derived confidently from the modelled spectral energy distributions. However, because the radii of brown dwarfs older than 0.1 Gyr vary little with mass, measurements of intrinsic luminosity (i.e. total integrated flux and parallax) accurately determine effective temperature. Using this method we find a well constrained relationship between the effective temperatures of L and T dwarfs and spectral type, but with temperature nearly constant from L7 to T4. More work is required to determine the uniqueness of this relationship and to constrain the masses and ages of brown dwarfs.

1. Setting L and T Dwarfs in Physical Context

Objects with masses below 0.1 $M_{\odot}$, and older than 1 Myr, have effective temperatures (T_{eff}) of $\lesssim$ 3500 K. Low mass stars fuse hydrogen in their cores such that T_{eff} stabilises. Brown dwarfs however, with masses $\lesssim$0.08 $M_{\odot}$, cool nearly continuously (there will be brief periods of hydrogen, deuterium and lithium burning for the highest mass brown dwarfs).

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Dwarfs classified as type M have T_{eff} in the approximate range 3700 K to 2200 K, L dwarfs have 2200 $\geq T_{eff}$ K $\geq$ 1400 and T dwarfs have $T_{eff} \leq$ 1400 K — see Leggett et al. (2000, 2002a) and further discussion below, and note that the lower limit for the T dwarfs is not yet defined. It is important to remember that a young brown dwarf can be any of M, L or T type, depending on its mass. Also, an L dwarf is not necessarily "brown" — early L dwarfs can have either stellar or sub–stellar masses, and knowledge of their age is required to distinguish between these possibilities. T dwarfs of any age, however, do necessarily have sub–stellar masses according to evolutionary models.

2. Atmospheric Properties

Molecular opacities are extremely important for dwarfs with T_{eff} <3000 K. Strong absorption bands due to H_2O are seen throughout the red and infrared regimes (where most of the light is emitted) for all M, L and T dwarfs. CO absorption bands are also seen in the infrared for M, L and T dwarfs — although as T_{eff} decreases below about 1800K carbon is increasingly tied up in CH_4, and the infrared bands of that species (together with H_2O) eventually dominate the energy distributions of the T dwarfs. Pressure–induced H_2 absorption is another important source of opacity in T dwarfs. This absorption, which is strongest around 2 μm, is extremely broad and does not have any sharp spectral signatures. NH_3 is expected to be a significant absorber for the coolest T dwarfs, however only a marginal detection has been achieved for the T6 dwarf Gl 229B (Saumon et al. 2000) implying that most of the nitrogen is still in the form of N_2, for known objects.

A significant chemical change that occurs for late M dwarfs and cooler objects is the condensation of grains in the atmosphere. Layers or clouds of dust form, the details of which are described elsewhere in these Proceedings. The dust has a heating effect on the photosphere, reddens the output energy distribution, and weakens (or veils) photospheric absorption features. The exact behaviour depends on the extent and location of the dust in the photosphere, and is wavelength dependent. The dust layer is expected to sink with decreasing temperature until it lies below the photosphere for mid– and late–T dwarfs. For such objects the dust does not directly impact the energy distribution, although its formation depletes some elements and weakens or removes their associated photospheric spectral features.

Figure 1 shows observed and calculated energy distributions for an L5 dwarf. The more obvious absorption features are identified. The observed spectrum is shown in black, and is a composite of two L5 dwarfs: the dataset short of 2.5 μm is for SDSS0539-00 and is from Geballe et al. (2002); the longer wavelength spectrum is for 2MASS1507-16 and is from Noll et al. (2000), who show that the fundamental 3.3 μm band of CH_4 is detected as early as L5. Synthetic spectra are shown in grey; these are calculated from T_{eff} = 1600 K models by Allard & Hauschildt (Allard et al. 2001) which treat dust formation in two very different ways. The dark grey spectrum is their Dusty model which keeps the dust in chemical equilibrium through the photosphere, and the lighter grey is their Cond model which has the dust gravitationally settled below the photosphere. Comparison of the model spectra shows that the dust reddens the

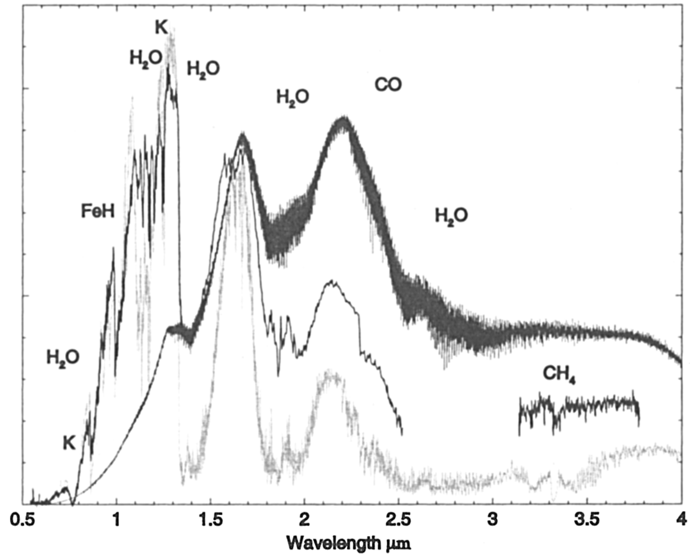

Figure 1. Spectral energy distribution (F_λ) of an L5 dwarf.

energy distribution and weakens the absorption bands. Allard et al. present these models as limiting cases — the truth lies somewhere between the two; see their paper (and contributions to these Proceedings) for further details.

Figure 2 shows observed and calculated energy distributions for the T6 dwarf Gl 229B. The lower panel shows the near–infrared region, the upper the L–and M–band region. The observed spectrum is shown in black and is a composite of data from Oppenheimer et al. (1998), Geballe et al. (1996) and Noll, Geballe & Marley (1997). The grey synthetic spectrum is a T_{eff} = 1000 K Cond model by Allard & Hauschildt (Leggett et al. 2002b). The "T" classification is defined by the presence of the CH_4 bands at *both* 1.6 μm and 2.2 μm (see e.g. Geballe et al., these Proceedings). H_2O is seen throughout the spectrum, alkali lines are still important in the red and near–infrared, and pressure–induced H_2 is important from 1.6 μm to 3.0 μm. Noll et al. showed that the fundamental CO band around 4.7 μm is present; this is surprising as at these temperatures carbon is expected to be completely in the form of CH_4. The presence of significant amounts of CO in other mid–T dwarfs appears to be confirmed by their fainter than expected M–band magnitudes (Leggett et al. 2002a). Saumon et al. (these Proceedings) describe how vertical transport from hotter layers can lead to non–equilibrium chemistry and detectable amounts of CO.

Models of the cool, high–pressure atmospheres of the L and T dwarfs are constantly improving. However several challenging problems remain: treatment of grain condensation and the location of dust clouds (note the sensitivity to dust treatment in Figure 1); incomplete molecular linelists (in particular for H_2O and CH_4, see mismatch of bands in Figure 2) and the possibility of non–equilibrium chemistry. Because of these problems it is not possible to accurately constrain atmospheric parameters based on spectral fitting. However, it is still possible to derive accurate effective temperatures, as shown in §3.

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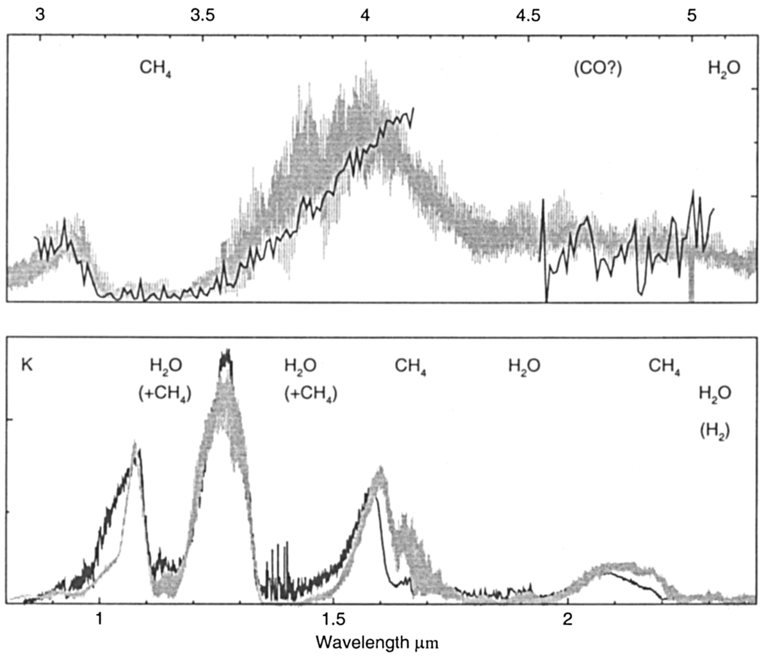

Figure 2. Spectral energy distribution (F_λ) of a T6 dwarf.

3. Derivation of Effective Temperatures

A characteristic of the electron–degenerate structure of brown dwarfs is that their radii are relatively insensitive to mass. For ages greater than 0.1 Gyr, brown dwarfs with a range of mass 0.3—60 $M_{Jupiter}$ have radii that range from about 0.8 to 1.4 $R_{Jupiter}$ (see Figure 3 of Burrows et al. 2001). As luminosity is proportional to $R^2T^4_{eff}$ this implies a range of less than 15% in effective temperature for a given luminosity; this tight relationship is demonstrated in Figure 3. Dotted lines show the relationship as a function of mass, for ages ranging from 0.1 to 10 Gyr, taken from the evolutionary models of Burrows et al. (1997) and Chabrier et al. (2000). The solid line is the 1 Gyr isochrone for masses indicated on the right axis.

To derive an accurate luminosity requires knowing both the integrated flux at the earth and the distance to the object. Trigonometric parallaxes for L and T dwarfs are being obtained by groups in both the northern and southern hemispheres, as described in these Proceedings. We have used the parallaxes of Dahn et al. (2002) and derived the integrated fluxes by summing flux–calibrated red and near–infrared spectra, and adding longer wavelength contributions based on extrapolations from L′ photometry. T_{eff} was then derived from this observationally determined luminosity. Figure 4 shows these values of T_{eff} plotted against the spectral types determined by Geballe et al. (2002). The sample includes three known equal–luminosity binary L dwarfs and temperatures have been derived for these objects by halving the observed luminosity of the pair.

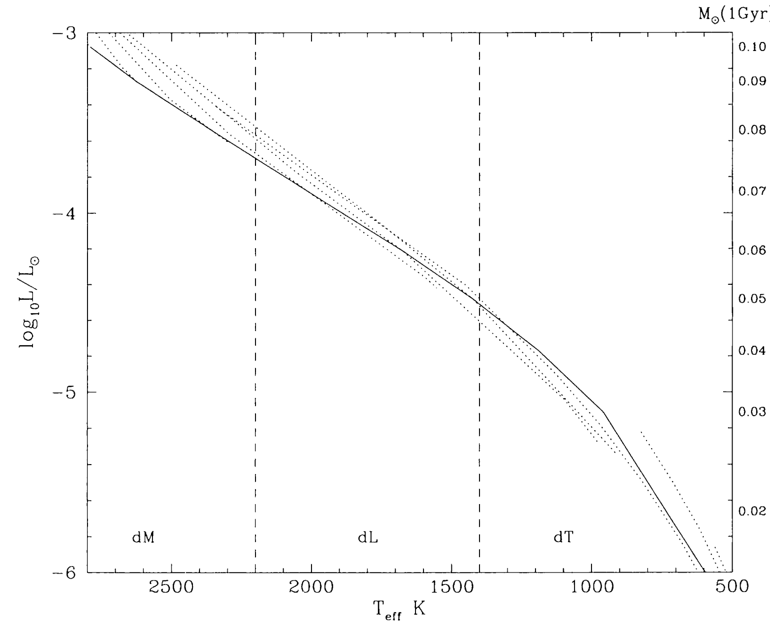

Figure 3. Relationships between luminosity and T_{eff} (see text).

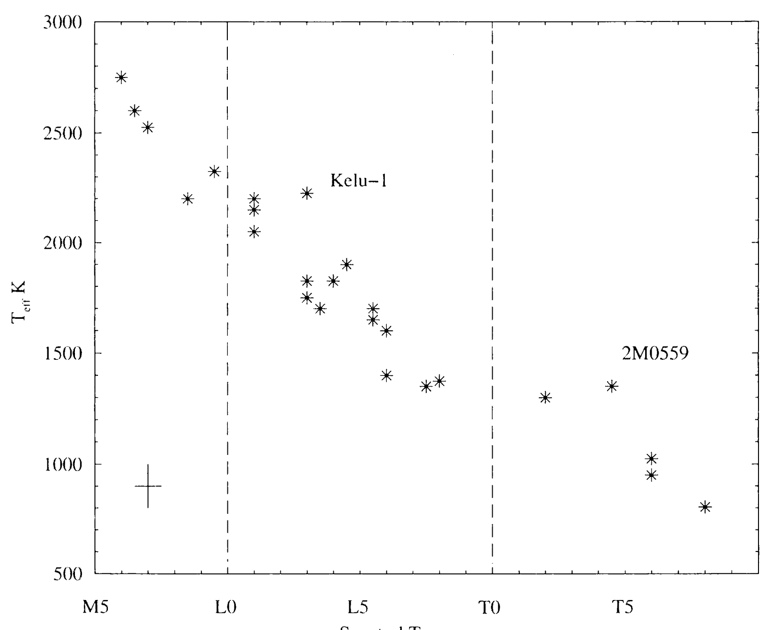

Figure 4. Derived T_{eff} (from observed luminosity) against type. The error bar indicates the uncertainty in spectral type (one half sub-type), and temperature. The latter is dominated by the unknown ages of the dwarfs, which we assume are in the range 0.1 to 10 Gyr.

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Two objects stand out above the sequence, Kelu-1 and 2MASS0559-14. If these are multiple systems the temperatures of the individual components would be lower, however they are unresolved in *HST* images (Martín, Brandner & Basri 1999a, Burgasser 2001). It is possible that Kelu-1 is younger than 0.1 Gyr, in which case its radius could be larger and T_{eff} lower (Martín et al. 1999b).

A trend is seen between temperature and type in Figure 4 for this sample of L and T dwarfs. An interesting feature is an apparent plateau at $T_{eff} = 1400$ K from L7 to T4. This implies that the significant spectral changes seen across the L to T transition — the onset of CH_4 absorption at near–infrared wavelengths — is not a temperature effect. Marley and collaborators (these Proceedings, Burgasser et al. 2002) show how the transition can also be explained in terms of disruption of the dust clouds. The plateau would suggest that the transition from late–L to mid–T types must happen very quickly (as these objects cool with age) and hence that not many very late L dwarfs or early T dwarfs will be found. As significant numbers of such objects *are* being found by for example the Sloan Digital Sky Survey (Geballe et al. 2002, Knapp et al. in preparation), it is possible that the degeneracy in temperature will be broken as more parallaxes are determined. Advances in this area will also require determination of the selection effects in the Sloan survey (work in progress) and understanding the correlation between temperature and spectral type (see §4.1).

4. Outstanding Issues

4.1. Correlation Between Spectral Type and T_{eff}

It has been shown that the near–infrared colors of L dwarfs display significant scatter with type (e.g. Dahn et al. 2002, Leggett et al. 2002a,c). That is, L dwarfs with the same key spectroscopic features (slope of the red pseudo–continuum, water band wing strength, CO bandhead drop) can have $J-K$ colors that differ by half a magnitude or more (e.g. the L3 dwarfs 2MASS0028+15 and DENIS 1058-15, whose energy distributions are shown in Figure 3 of Leggett et al. 2002c). This scatter is most likely due to differences in photospheric dust properties, in turn perhaps due to variation in metallicity, gravity, age or rotation. The very different energy distributions suggest that there may be scatter in luminosity and hence effective temperature. There may not be a unique correlation between T_{eff} and spectral type, where type is defined using red and near–infrared indices (see also Stephens et al., these Proceedings).

Some scatter in $J-K$ color is also seen for T dwarfs. The spectroscopic indicators can imply identical types for objects with colors that differ by 0.3 magnitudes or more (e.g. the T8 dwarfs 2MASS1217-03 and Gl 570D, see Figure 4 of Leggett et al. 2002c). The probable culprit is differences in the pressure–induced H_2 opacity, which is sensitive to gravity (equivalent to age for these objects) and metallicity. $J-K$ color may prove to be a useful gravity/age indicator for T dwarfs.

4.2. Determination of Gravity and Metallicity

While we have shown that effective temperatures of L and T dwarfs can be determined with confidence, it is very difficult to determine other atmospheric

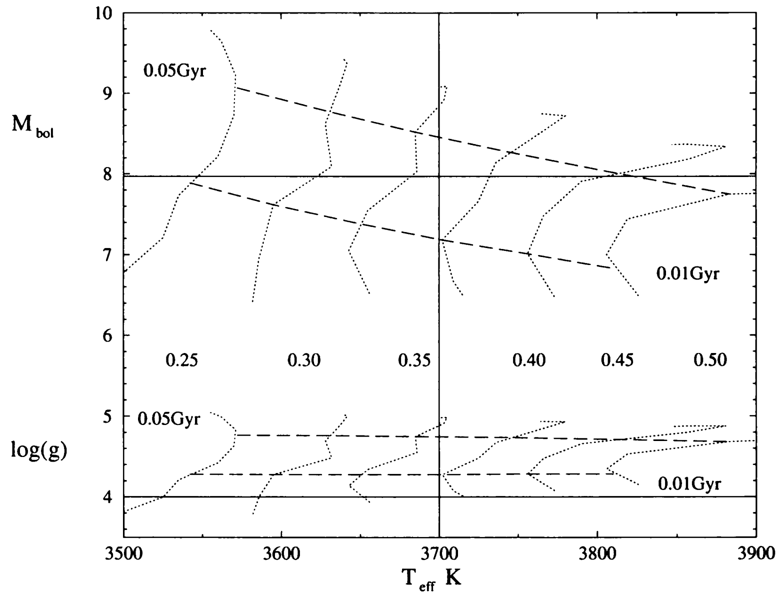

Figure 5. Solid lines show determined luminosity, gravity and temperature of Gl 229A. Dotted ~vertical lines show log(g) and M_{bol} as functions of T_{eff} from evolutionary models, for masses (solar units) as indicated. Dashed lines are isochrones from the same evolutionary models. Allowing for the formal error in log(g), M_{bol} and T_{eff}, Gl 229A is constrained to an age ~30 Myr and mass ~$0.38M_{\odot}$. Adapted from Leggett et al. 2002b.

parameters such as gravity and metallicity. An example of this is the study of the M,T–dwarf binary system Gl 229A,B (Leggett et al. 2002b). The observed red and infrared energy distributions of both components can be fit quite well by synthetic spectra. The fits indicate that the system is metal–poor, with $[m/H] \approx -0.5$, somewhat surprising as the kinematic population of the system is young disk. The fits also indicate low gravities for each component. The age of the M dwarf primary is constrained by the observed value of the bolometric luminosity, and by the model–derived values of T_{eff} and log(g), using evolutionary models for metal–poor dwarfs by Baraffe et al. (1998). Figure 5 plots the results, and shows that the luminosity, temperature and gravity are self–consistent, and, according to the evolutionary models, imply an age for the Gl 229 system of only around 30 Myr. This age is much younger than would be expected, despite the youthful kinematics of the system. The lack of Hα emission implies an age older than the Pleiades, and the binary is not associated with any young region. If the age is valid it implies a very small mass for Gl 229B of around 10 Jupiter masses. It is likely however that the result is incorrect and reflects remaining problems with model atmospheres of cool dwarfs, even relatively hot early–M dwarfs. It is known for example that the linelists for the important opacity sources TiO and H_2O are incomplete and the treatment of convection is a complex problem.

5. Conclusions

In recent years the community has seen many advances in the detection of brown dwarfs, and in their photometric, spectroscopic and astrometric follow–up. Increasingly complex atmospheric models are being developed, including weather–like effects and non–equilibrium chemistry. Although effective temperatures of L and T dwarfs now can be determined accurately, it is important to continue advancing on both observational and theoretical fronts, so that we can determine surface gravities and metallicities of brown dwarfs. Only then can we constrain age and hence the most fundamental parameter of all, mass.

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