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Photospheric Dust in Cool Dwarfs

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Abstract. We investigate the optical and infrared spectra for a range of cool dwarfs. For M dwarfs we find that the match between observation and theory is much improved when comparisons are made with models allowing for the formation of dust. We present two compelling pieces of evidence for dust (1) a reverse in TiO band strengths in the spectra of late-type M dwarfs at wavelengths shorter than 0.75 microns and (2) an excellent fit to the infrared spectrum of the brown dwarf candidate GD165B. We believe that the lack of accounting for dust significantly hampers our ability to make reliable predictions for properties of objects around the M dwarf – brown dwarf transition. At lower temperatures a dust-free model well explains the SED of the ≈1000 K brown dwarf Gl229B. Although chemical equilibrium means that dust should form in Gl229B, the dust may be in clouds below the photosphere. Such a meteorological model is currently beyond the scope of the models presented here. We suggest a number of observational and theoretical tests to empirically constrain the properties of photospheric dust.

1. Introduction

Although the theory of low-mass stars (< 0.7 M$_\odot$) has a long pedigree (for a review see Allard et al. 1997), models have had relatively little success in matching observed spectral energy distributions. It has long been realised that much of this problem may lie with the lack of good molecular data. However additional reasons have also been advanced. (1) Brett (1995) propose the neglect of chromospheric heating and the simple treatment of convection. (2) Jones et al. (1995) propose that the discrepancy with regard to fitting water vapour absorption bands lies in part with the simplistic treatment of water vapour line broadening. (3) Tsuji et al. (1996a) propose that the lack of treatment of dust opacity has been the root of the problems and showed that dusty models explain the photometry of the brown dwarf candidate GD165B (Tsuji et al. 1996b).

Here we present comparisons between observed spectra and photometry for M dwarfs and brown dwarfs and the models of Tsuji et al. (1996a) to test the effects of grain formation in low-mass objects. All the synthetic spectra presented here are for solar metallicity, log $g = 5.0$ and a microturbulent velocity of 1 km/s. Firstly we focus on the region shortward of 1 μm where (1) the

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effects of dust formation can most clearly be distinguished from the problems with reliable modelling of water vapour absorption bands and (2) the effects of dust formation will be largest, e.g. fig. 2, Tsuji et al. (1996a). We then move to longer wavelengths and look for the presence of dust in the spectral energy distribution (SED) of the brown dwarf candidate GD 165B and the brown dwarf Gl 229B.

2. Spectral evidence for dust

In Fig. 1 we show a spectral sequence made by dividing one standard spectrum by another around two spectral types cooler. The sequence extends from M2V/M4V to M8V/M9.5V. It can be seen that there is a dramatic change in the spectra shortward of 0.75 μm around M7V and more subtle changes at longer wavelengths around M8V. This should be compared with the equivalent plot for the synthetic spectra. Fig. 2 illustrates that around 2500 K the models predict changes in spectral characteristics around 0.67 and 0.71 μm which are similar in form to Fig. 1 when dust is included in the models. The feature at 0.80 μm is not well reproduced and is due to a lack of reliable data for VO whose influence is overestimated by the models (e.g. fig. 12, Brett 1995).

We have investigated dust-free models from 1000–3800 K with metallicities ranging from solar to −2 dex and solar metallicity dusty models from 1000–2700 K. We have not investigated the effect of changing gravity on the models, however based on the work of Jones et al. (1996) we expect that gravity differences will be small. Although there are changes in the characteristics of the spectra due to temperature (around 1500 and 2300 K) and metallicity, we have not found any combinations of hotter/cooler pairs of dust-free models which are close to reproducing the observations. We have only been able to model the change in spectral characteristics around M7V by the inclusion of dust.

2.1. Gravity dependence

In Fig. 3 we illustrate that dust absorption appears to be gravity dependent. We plot one of the Pleiades brown dwarfs, Teide 1 (spectral type M8), together with the 'standard' M8 dwarf vB 10 and the very late-type object BRI 0021-0214 (M9). The TiO absorption bands can be seen to be much weaker in BRI 0021-0214. In addition vB 10 has weaker TiO absorption bands than Teide 1 although since they are the same spectral type, their bands strengths should be the same. This is also the case for the other confirmed Pleiades brown dwarf Calar 3 and for the spectra of the new, very late-type Pleiades brown dwarf candidates (Zapatero-Osorio et al. 1997). This indicates that dust formation has significant gravity sensitivity and so the next grid of dusty models will include a range of gravities.

The explanation that the apparent 'lack of TiO absorption' is due to dust seems to offer a good explanation of why $R-I$ (and other optical) colours, e.g., Bessell (1991) do not increase monotonically with spectral type for the latest M dwarfs. This lack of a reliable relationship between optical colours and spectral type or luminosity has been a major problem for the selection of late-type M dwarfs from optical surveys, however it may be possible with the aid of two different colours to use the gravity sensitivity of photospheric dust as a means

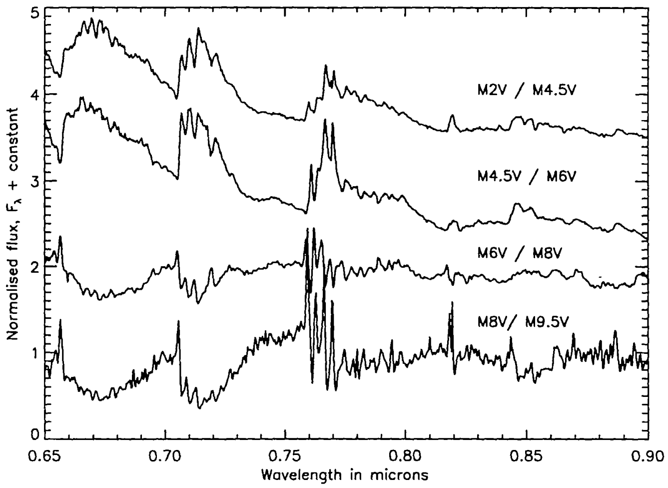

Figure 1. A sequence of 'divided' spectra which have been offset from one another. Working from top down, the uppermost spectra represents M2V/M4.5V (Gl411/Gl268ab), then M4.5V/M6V (Gl268ab/Gl406), M6V/M8V (Gl406/vB10) and M8V/M9.5V (vB10/BRI0021-0214). All the spectra are from Kirkpatrick et al. (1991) except BRI0021-0214 which is from Martín et al. (1996).

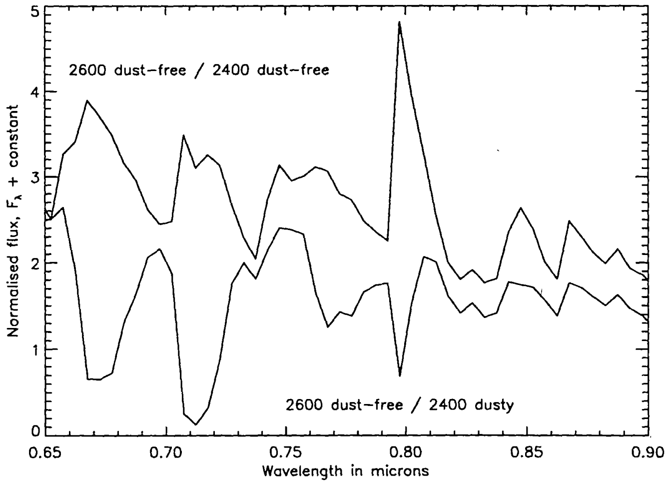

Figure 2. Both spectra are a hotter model divided by a cooler one in the same fashion as the observations in Fig. 1. In both cases the hotter model is a 2600 K dust-free model; in the upper plot the cooler model is a 2400 K dust-free model; in the lower plot the cooler model is a 2400 K dusty model.

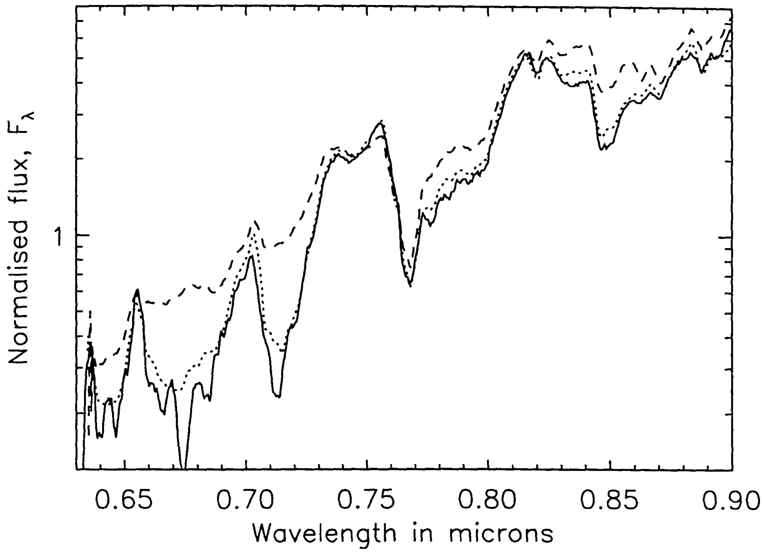

Figure 3. Comparison of the spectra of BRI 0021-0024 (dashed line), Teide 1 (solid line) and vB10 (dotted line) from Martín et al. (1996).

to classify objects of different ages. In particular such an indicator could be very useful for selecting young brown dwarfs.

2.2. Grain sizes

For M dwarfs later than around spectral type M6 to the brown dwarf candidate GD 165B the preliminary grid of dusty models does a good job of explaining the observed spectral discrepancies relative to the dust-free models. However the models only include dust grains with radii of 0.1 μm. In Fig. 4 (Marley, private communication) we show the relative importance of different sized dust grains at impeding radiation of different wavelengths. The model is for fosterite (only one of a number of species of grain likely to be important) and indicates a number of interesting spectral features that can be searched for. Although based on Figs 1, 2 and 4, 0.1 μm seems an appropriate initial choice.

2.3. GD165B and Gl229B

Figs 5 and 6 show dust and dust-free models for the benchmark objects GD 165B (>M10.5 from Kirkpatrick et al. 1993) and Gl 229B (new class of object, spectral type T - see Allard 1997). Although there is only around 800K difference in temperature (roughly equivalent to four spectral types at M6V) their SED's are very different. Given the uncertainties in molecular opacities they are both well modelled. For GD 165B by a *dusty* 1800K model and for Gl 229B by a *dust−free* 1000K model (where dust formation has been artificially suppressed, in violation of chemical equilibrium). This indicates that although GD 165B has an abundance of photospheric dust, any photospheric dust in Gl 229B must be in relatively small clouds or be below the photosphere. The limited observations available support the hypothesis that dust forms in stellar through to

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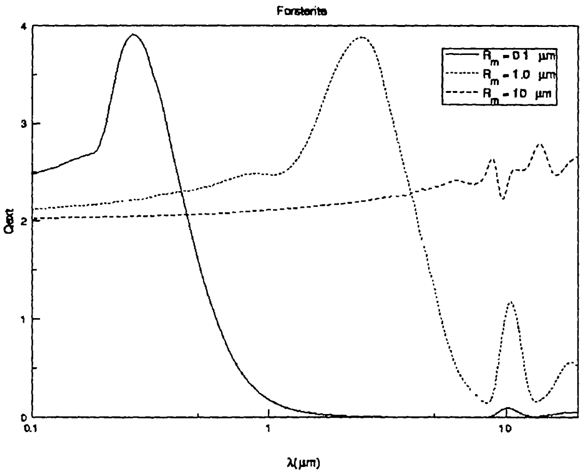

Figure 4. The calculation is for fosterite, which is Mg_2SiO_4. Three different particle sizes are plotted. In each case a log-normal size distribution is assumed with a width parameter of 1.3. The large bump is real and is a natural result of Mie scattering. If a narrower size distribution is assumed a lot of high frequency stuff appears in the plot. The plotted quantity is Qext, called the extinction efficiency. The optical depth arising from a column of particles with number density N particles cm^{-2} is given by $Q_{\mathrm{ext}} \times N \times \pi R_{\mathrm{mean}}^2$ where R_{mean} is the mean particle size.

sub-stellar photospheres, first as a gas-dust reasonably homogeneous mixture and then forms clouds. The spectral differences between GD165B and Gl229B indicate that at lower temperatures dust resides below the photosphere. In future modelling of dusty photospheres it will thus be desirable to implement meteorological techniques to allow for segregation of the gas-dust mixture into clouds.

3. Discussion

Empirically we have shown good evidence for dust from spectral types of around M6 to M10.5. Given the uncertainties in the molecular data the fit to the observed spectra is a lot better than we might expect. The observations might also be explained by a combination of inadequacies in unaccounted for absorption bands between the TiO and VO bands, the presence of a temperature minimum, a chromosphere and an overly simplistic treatment of the molecular opacities. Although it is important to investigate these uncertainties we favour an explanation which is substantially due to dust because with a classical treatment of dust it is possible to explain the long-standing problem of fitting the observed water bands (Tsuji et al. 1996a) and at the same time elegantly explain the behaviour of the short wavelength spectra. We briefly suggest a number of observational and theoretical programmes and problems relevant to dust in cool dwarfs.

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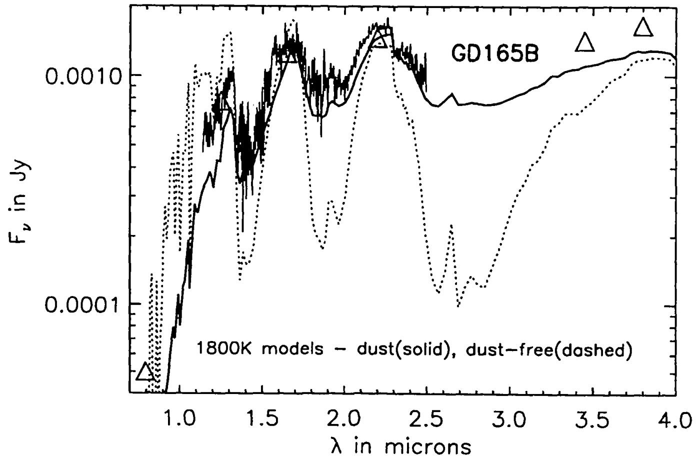

Figure 5. A comparison of SED of GD165B with 1800 K models. The photometric measurements (triangles) are from Becklin & Zuckerman (1988), Tinney et al. (1993) and Jones et al. 1996. The infrared spectrum is from Jones et al. (1994).

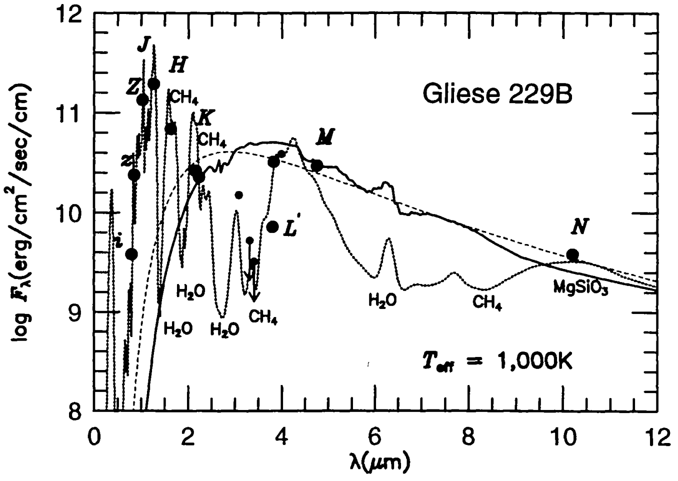

Figure 6. Predicted SED based on a dust-free model of $T_{\rm eff}$ = 1000K (updated from Tsuji et al. 1996b) shown by the dotted lines is compared with the observed SED of Gl229B (Nakajima et al. 1995; Matthews et al. 1996) shown by the filled circles (large and small circles indicate broad and narrow band data, respectively. Circles with arrows indicate upper limits). The predicted SED based on our dusty model is also shown by the solid line (on which absorption due to solid MgSiO3 is marked), but cannot be matched with the observed one at all. The dashed line is the blackbody curve of $T_{\rm eff}$K.

- The influence of dust should be considered in the derivation of evolutionary tracks for objects below 3000 K, particularly in order to investigate its effect on the hydrogen-burning limit.

- We caution against the use of spectral features on their own to assign spectral types in late-type M stars, e.g. the VO-band index of Kirkpatrick et al. (1995).

- The models employed in this paper include dust grains of Al_2O_3 (corundum), Fe (iron) and $MgSiO_3$ (enstatite). Based on fig. 1 (Tsuji et al. 1996a), Al_2O_3 dust grains are responsible for most of the changes seen in the spectra presented here. By careful observations of atomic Al and Mg lines across the transition from dust-free to dusty spectra it should be possible to place constraints on the dust mass and thus the efficiency of dust formation as a function of temperature, pressure and abundance.

- Spectra should be investigated for variability to constrain the presence of dust clouds and spots in late-type objects. Based on the spectra that we have available for vB10 we do find a significant difference between them, this has also been noticed for a larger sample of observations by Kirkpatrick (private communication). However to reliably test this it is necessary to use data taken using the same observational setup and data reduction procedures.

- Spectra at shorter wavelengths than investigated here are expected to have a stronger dust signature and thus can yield an empirical high temperature limit to Al_2O_3 dust formation. In principle short wavelengths which can be efficiently observed are expected to be the most sensitive to photospheric dust (see Fig. 4) and can directly show the empirical limit of dust formation.

- Investigation of whether radiation pressure on dust is sufficient to expel matter directly from the photosphere and is thus an underlying cause of stellar mass-loss, e.g., in cool giants (Tsuji 1996).

- Dust modelling can increase in sophistication: a more detailed treatment and variety of species of dust grains may be considered. It is important to investigate the likely evolution of a cool photosphere through different phases: (1) Supersaturation - dust does not form, (2) Detailed balance - dust and gas well mixed, (3) Segregation - sedimentation of dust.

- Late-type Pleiads show stronger TiO bands for a given spectral type. Such a difference can be explained by the gravity dependence of dust formation. This property and its effect on spectra and colours (particularly in optical bands) may be used to distinguish young brown dwarfs from field M dwarfs.

- The lack of ability to accurately model spectral features considerably limits the usefulness of spectroscopic tests that can currently be made on a brown dwarf candidate. For the lithium test the discrepancy between observed values (equivalent widths of around 1 Å) and theoretical values (in excess of 5 Å, e.g., Pavlenko et al. 1995) mean that at present it can only be used as an "on/off" test. Presumably the lack of incorporation of photospheric dust in models has led to the prediction of too strong lithium lines.

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