

INTERPRETATION OF THE SPECTRA ORIGINATING FROM THE PHOTOSPHERES CONTAMINATED WITH DUST - EXPERIENCE IN L AND T DWARFS

T. Tsuji

Institute of Astronomy, School of Science, The University of Tokyo, Mitaka, Tokyo, 181-0015 Japan

ABSTRACT

An essential feature of substellar dwarfs compared with the Sun and stars is the formation of dust in their photospheres (not in the outer envelope). It appears that the observed data could be understood if the dust exists in a form of thin cloud deep in the photosphere rather than in the cooler surface region. Recent observations also show that the dust column densities in the observable photosphere are quite different for the same effective temperature, gravity, and metallicity, but the reason for such a sporadic variation is unknown. Moreover, the effect of dust cloud is difficult to discriminate from those by other basic parameters such as the effective temperature which also has significant effect on the dust column density. For this reason, the spectra of dusty dwarfs were in fact misinterpreted by ourselves and will be reanalyzed in this contribution. Also, even the spectral classification is not free from such a difficulty, as is evidenced by an odd “brightening” of M_{bol} plotted against the L and T types.

Key words: Brown dwarfs: model photosphere – Photospheres: dust – Spectra: classification

1. INTRODUCTION

It is only a decade ago that a genuine brown dwarf was discovered (??) and our experience in interpreting the spectra of brown dwarfs is still meager compared with the longer experience in the Sun and stars. A new feature in ultracool dwarfs such as brown dwarfs is the presence of dust in their photospheres, the possible importance of which has been recognized at an early time (??). But how to treat the dust formed in the photospheric environment was not known. If a simple thermodynamical equilibrium is assumed, dust certainly forms but how to sustain the dust in the photosphere was unknown and dust also tends to be over-produced compared to the known observations in general. Actually, dust in the observable photosphere should be controlled by such processes as nucleation, growth, segregation, precipitation, evaporation etc., and we proposed a simple model referred to as the unified cloudy model (UCM) to take into account these processes semi-empirically (??).

In the UCM, we assumed that dust forms at the condensation temperature T_{cond} , but dust soon grows to be too large at a slightly lower temperature which we referred to as the critical temperature T_{cr} and segregates from the gaseous mixtures. Thus dust forms a homogeneous cloud in the region where $T_{\text{cr}} \lesssim T \lesssim T_{\text{cond}}$. In this model, T_{cond} is essentially determined by the thermodynamical data but T_{cr} is not predictable at present. At first, we assumed that T_{cr} remains the same throughout L and T dwarfs for simplicity. Recent observations, however, revealed that T_{cr} , which is a measure of the thickness of the cloud (a larger deviation of T_{cr} from T_{cond} implies a thicker cloud), shows a sporadic variation even at the fixed effective temperature (Sect.2). Our UCM is already formulated to allow for the change of T_{cr} and its application to the new situation is straightforward. Compared with our previous interpretation of the spectra of L and T dwarfs based on a constant value of T_{cr} , our revised analysis allowing for the variation of T_{cr} in UCMs results in a drastic change in our understanding of L and T dwarfs.

2. INFRARED COLORS

It has been known that the infrared colors plotted against the spectral types show the red limit at late L dwarfs (??) and this may be because the dust column density in the observable photosphere is the largest in late L dwarfs. Although there were some scatters in the observed infrared colors, it appeared to be explained by our UCMs with $T_{\text{cr}} \approx 1800 \pm 100 \text{ K}$ (??) and we assumed a constant value of $T_{\text{cr}} = 1800 \text{ K}$ in our further applications of the UCMs (e.g. ??).

Recent observations, however, revealed that the infrared colors (??) show a large variation if they are plotted against T_{eff} based on the bolometric fluxes (??, ??) and parallaxes (??). The case of $J - K$ is shown in Fig.1. The variation may not be explained by the effect of $\log g$ and metallicity. The predicted values of $J - K$ for $T_{\text{cr}} = 1700, 1800, 1900 \text{ K}$ and T_{cond} (this case implies that dust disappears as soon as it is formed and thus there is effectively no dust) are overlaid on Fig.1. The variations of $J - K$ at a fixed T_{eff} are quite large, especially at around $T_{\text{eff}} = 1400 \pm 100 \text{ K}$, and it is clear that the assumption of a constant T_{cr} can no longer be supported.

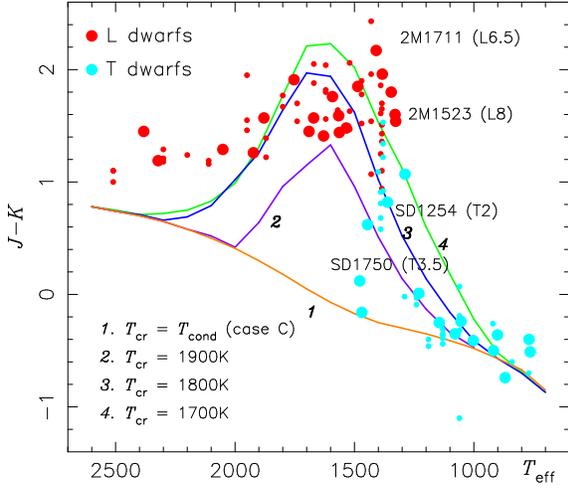


Figure 1. Observed $J - K$ and predicted ones for different T_{cr} values plotted against T_{eff} (large and small circles distinguish the T_{eff} values by the direct determinations and by estimations based on the $T_{\text{eff}} - \text{Sp. Type}$ relation, respectively).

3. DEGENERACY OF T_{eff} AND T_{cr} ON THE SPECTRA

The dust column density generally increases at lower T_{eff} (at fixed T_{cr}) and also at lower T_{cr} (at fixed T_{eff}). For this reason, the effects of T_{eff} and T_{cr} on the spectra so to speak degenerate and are difficult to discriminate unless one of them can be known by other methods. As an example, we reproduce the analysis of the L8 dwarf 2MASS 1523 based on $T_{\text{cr}} = 1800 \text{ K}$ (??) in Fig.2a, showing that this L8 dwarf can be accounted for by the UCM with $T_{\text{eff}} = 1500 \text{ K}$ (Cases I and II are based on the CH_4 opacities with the band model method and linelist, respectively). However, recent infrared photometry revealed that $T_{\text{cr}} \approx 1700 \text{ K}$ for 2MASS 1523 (Fig.1) and we analyzed the same spectra based on this T_{cr} value. The result shown in Fig.2b reveals that the UCM with $T_{\text{cr}} = 1700 \text{ K}$ and $T_{\text{eff}} = 1300 \text{ K}$

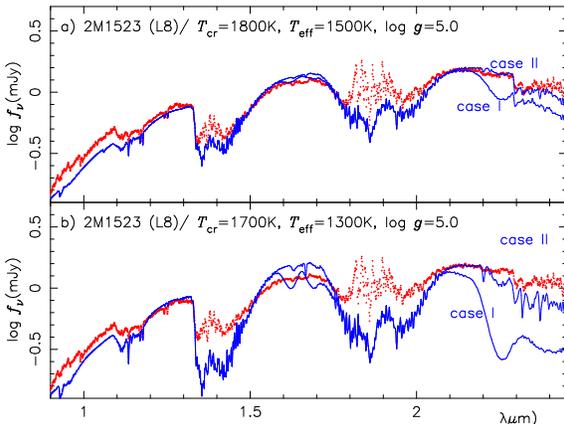


Figure 2. Spectrum of 2MASS 1523 (L8) and predictions based on UCMs of: a) $T_{\text{cr}} = 1800 \text{ K}$ & $T_{\text{eff}} = 1500 \text{ K}$ ($\log g = 5.0$). b) $T_{\text{cr}} = 1700 \text{ K}$ & $T_{\text{eff}} = 1300 \text{ K}$ ($\log g = 5.0$).

provides a reasonable fit except for the water band regions. Thus different combinations of T_{eff} and T_{cr} could explain the same spectrum so far as it is analyzed as a relative spectral energy distribution (SED).

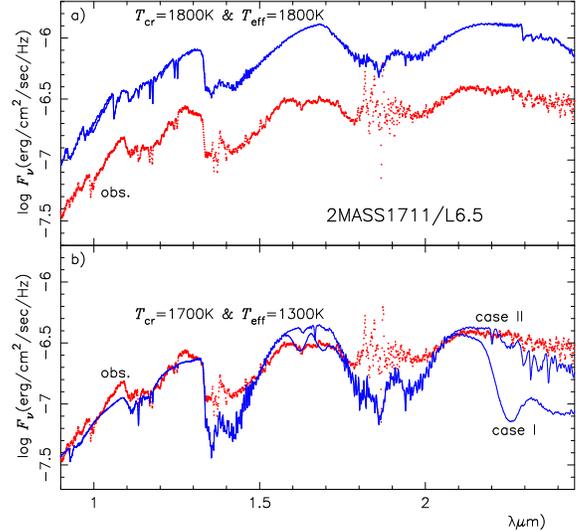


Figure 3. Observed SED of 2MASS 1711 (L6.5) reduced to an absolute scale (dots) is compared with the predicted ones (solid lines) characterized by: a) $T_{\text{cr}} = 1800 \text{ K}$ and $T_{\text{eff}} = 1800 \text{ K}$ ($\log g = 5.0$). b) $T_{\text{cr}} = 1700 \text{ K}$ and $T_{\text{eff}} = 1300 \text{ K}$ ($\log g = 5.0$).

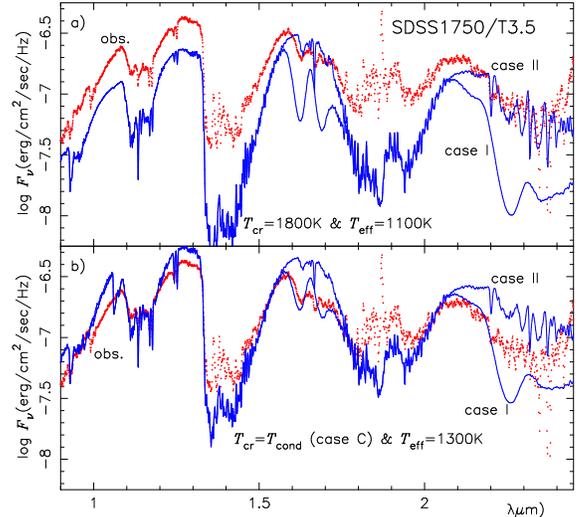


Figure 4. Observed SED of SDSS 1750 (T3.5) reduced to an absolute scale (dots) is compared with the predicted ones (solid lines) characterized by: a) $T_{\text{cr}} = 1800 \text{ K}$ and $T_{\text{eff}} = 1100 \text{ K}$ ($\log g = 5.0$). b) $T_{\text{cr}} = T_{\text{cond}}$ and $T_{\text{eff}} = 1300 \text{ K}$ ($\log g = 5.0$).

4. HOW TO ANALYZE THE SPECTRA

The ambiguity due to the degeneracy of T_{eff} and T_{cr} can be removed to some extent by transforming the observed

Table 1. Effective temperatures based on the UCMs with different T_{cr} values and empirical effective temperatures.

Object	Sp.type	$J - K$ (MKO)	$J - K$ (CIT)	$T_{\text{eff}} (T_{\text{cr}})$	$T_{\text{eff}} (T_{\text{cr}})$	T_{eff} (empirical)
		Knapp et al.(2004)	Vrba et al.(2004)	Tsuji et al.(2004)	Present results	Vrba et al.(2004)
2MASS 1711	L6.5	-	2.25	1800 K (1800 K)	1300 K (1700 K)	1545 K
2MASS 1523	L8	1.60	1.65	1500 K (1800 K)	1300 K (1700 K)	1330 K
SDSS 1254	T2	0.82	0.96	1300 K (1800 K)	1300 K (1800 K)	1361 K
SDSS 1750	T3.5	0.12	0.83	1100 K (1800 K)	1300 K (T_{cond})	1478 K

spectra to the SEDs on an absolute scale with the use of the measured parallaxes and assuming the Jupiter radius. As an example, it is immediately clear that the spectrum of 2MASS 1711 (L6.5) reduced to the emergent flux on an absolute scale (in unit of $\text{erg cm}^{-2} \text{sec}^{-1} \text{Hz}^{-1}$) cannot be fitted with the predicted spectrum based on the UCM with $T_{\text{cr}} = 1800 \text{ K}$ and $T_{\text{eff}} = 1800 \text{ K}$ (Fig.3a), even though the observed and predicted spectra can be fitted on the relative scale (i.e. by the shapes of the spectra) as done previously (??). The same observed spectrum is fitted better with the predicted one based on the UCM with $T_{\text{cr}} = 1700 \text{ K}$ and $T_{\text{eff}} = 1300 \text{ K}$ (Fig.3b), both on the absolute and relative scales. Note that $J - K$ (Fig.1) suggests even a lower value of T_{cr} . Thus the analysis of the SED on the absolute scale could discriminate the different possible combinations of T_{eff} and T_{cr} .

As another example, the SED of SDSS 1750 (T3.5) on an absolute scale can be fitted only marginally with the prediction based on the UCM with $T_{\text{cr}} = 1800 \text{ K}$ and $T_{\text{eff}} = 1100 \text{ K}$ (Fig.4a), and the predicted water bands appear to be too strong. The same observed SED is compared with the predicted one based on the UCM with $T_{\text{cr}} = T_{\text{cond}}$ and $T_{\text{eff}} = 1300 \text{ K}$ (Fig.4b). The observed and predicted SEDs now show better agreement both on the absolute and relative scales. Note that the infrared color suggests $T_{\text{cr}} \approx T_{\text{cond}}$ for this object (Fig.1).

5. HOW TO INTERPRETE THE SPECTRAL SEQUENCE

By the application of the UCMs assuming a fixed value of $T_{\text{cr}} = 1800 \text{ K}$ throughout, the spectra of cool dwarfs from L6.5 to T3.5 shown in Fig.5 could have been interpreted as a temperature sequence extending from 1800 K to 1100 K, as is reproduced in the 5-th column of Table 1 (??). The result of our reanalysis based on the SEDs on the absolute scale as outlined in Sect.4 is summarized in the 6-th column of Table 1. The new result shows a drastic difference as compared with the previous one: The spectral sequence extending from L6.5 to T3.5 is nothing to do with T_{eff} but can be interpreted as the effect of T_{cr} alone.

Now a problem is which is a correct solution. We prefer the new solution by the following reasons: First, the variable T_{cr} is more consistent with the recent observations of the infrared colors (Fig.1). Second, the resulting values of T_{eff} are more close to the recent empirical values reproduced in the 7-th column of Table 1 (??). Third, it

is evident that the analysis of the SEDs on the absolute scale should be preferred if possible, and the analysis of the SEDs on the relative scale (or the shape of the spectra) is misleading especially because of the degeneracy between T_{eff} and T_{cr} as shown in Sect.3.

In conclusion, the L - T spectral sequence shown in Fig.5 is not a temperature sequence but is due to the change of T_{cr} and hence of the thickness of the dust cloud. This conclusion is quite surprising in that T_{eff} plays little role in such a distinct change of spectra requiring the different spectral types L and T. This unexpected result is entirely due to dust, which should be more important than has been thought before. Also a parameter that specifies the nature of the dust cloud, T_{cr} in our UCM, is sometimes more important than T_{eff} in the characterization of cool dwarfs. Thus we confirm that T_{cr} should be regarded as a basic parameter together with T_{eff} and $\log g$.

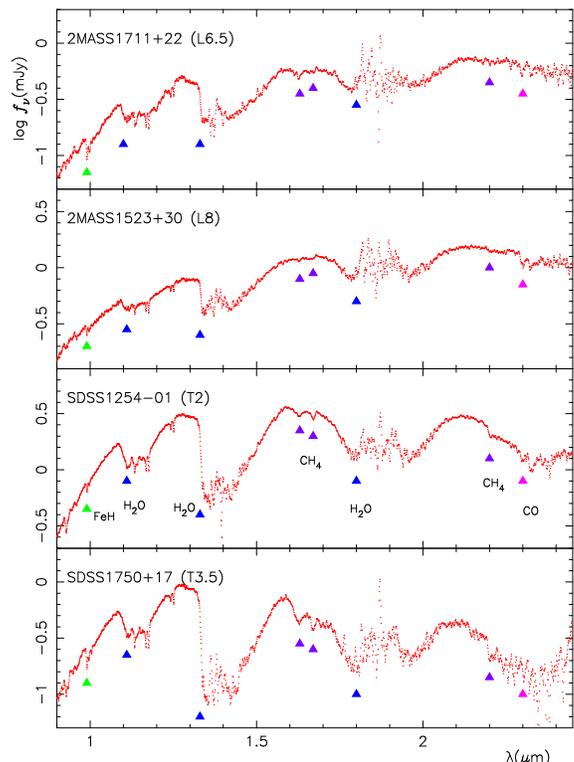


Figure 5. Spectral sequence from L to T which, however, is not a sequence of T_{eff} but of T_{cr} or of dust column density (Sect.5).

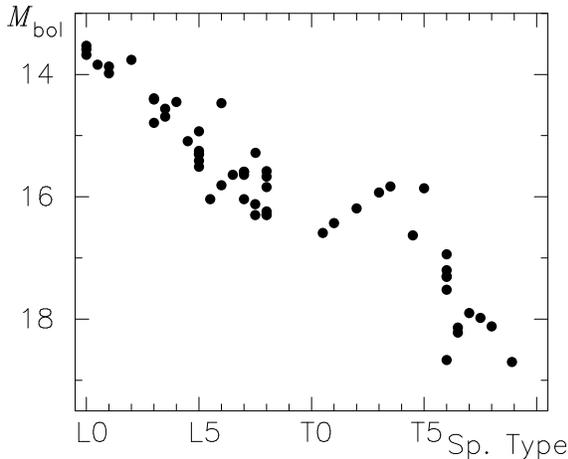


Figure 6. M_{bol} (Vrba et al. 2004) plotted against L-T types. An odd brightening indicates that the L-T spectral sequence may not be a temperature sequence, at least partly.

6. THE “ J -BRIGHTENING” IN THE SPECTRAL SEQUENCE

It is known that the absolute J magnitude plotted against the L-T type shows an odd brightening at early T types (??, ??, ??). It was suspected that this phenomenon may be due to some atmospheric effect, but no model including our UCM could explain this observation at all. The brightening is also observed in the H and K bands if not so pronounced as in the J band. But then the absolute bolometric magnitude, which largely depends on the J , H , and K fluxes, should also show the brightening and this is in fact found to be the case as shown in Fig.6. Since the L and T dwarfs are evolving on the cooling tracks, their bolometric luminosities should never show “brightening” if they are plotted against a correct temperature indicator. This result implies that the L-T spectral sequence may not be a temperature sequence, consistent with the conclusion of Sect.5, and the “ J -brightening” as well as the “ M_{bol} -brightening” may simply be an artifact of the L-T spectral classification, in which the effects of T_{eff} and T_{cr} are mixed as shown in Sect.3. Thus the so-called “ J -brightening” problem is solved or, more properly, this problem now disappeared. Instead a more serious problem of how to classify the spectra of ultracool dwarfs stands before us.

7. DISCUSSION AND CONCLUDING REMARKS

In the interpretation of the spectra of dust-contaminated object such as brown dwarfs, a parameter that specifies the thickness of the dust cloud, T_{cr} in our formulation or f_{sed} in that of ??, plays an important role. At present, it seems to be difficult to predict the value of T_{cr} based on basic physics, especially because it is sporadic rather than related to the other basic parameters (Sect.2). The variation of T_{cr} is especially large at $T_{\text{eff}} \approx 1400\text{K}$ where

the second convective zone appears in addition to the one deep in the photosphere (??). It may be possible that T_{cr} is related to the convective activities, but details are yet to be explored. Thus, in addition to the four parameters generally required to specify the stellar photosphere, i.e., chemical composition, T_{eff} , $\log g$, and micro-turbulent velocity, fifth parameter T_{cr} is needed for the characterization of dusty dwarfs.

It is to be noted that the turbulent velocity is still determined empirically since its discovery more than half a century ago (??) and not yet predictable based on basic physics for individual objects. At present, we must leave T_{cr} as an empirical parameter something like the turbulent velocity, but there are difficulties inherent to dust. For example, dust, unlike atoms and molecules, shows almost no clear spectral signature and it is difficult to estimate the dust column density directly. While dust plays significant role in defining the spectral characteristics, spectral classification had to be done on the spectral features originating from atoms and molecules (e.g. ??, ??, ??, ??), and such a difficulty should be fatal in the spectral classification of dusty objects.

Despite some formidable problems, recent progress in observation of such faint objects as brown dwarfs, not only in spectroscopy but also in photometry and astrometry, is quite marvelous, and a more consistent interpretation can be achieved by considering all these data collectively.

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