IN THE CHARACTERIZATION OF ULTRACOOL DWARFS

TAKASHI TSUJI

Institute of Astronomy, School of Science, University of Tokyo 2-21-1, Osawa, Mitaka, Tokyo, 181-0015, Japan; ttsuji@ioa.s.u-tokyo.ac.jp

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ABSTRACT

Recent photometry of L and T dwarfs revealed that the infrared colors show a large variation at a given effective temperature, and within the framework of our unified cloudy model (UCM), this result can be interpreted as due to a sporadic variation of the critical temperature \(T_{cr}\), which is essentially a measure of the thickness of the dust cloud. In our previous applications of the UCMs, we assumed that \(T_{cr}\) is constant at about 1800 K in all the L and T dwarfs, but in view of the new observing result, we now allow \(T_{cr}\) to vary between the surface temperature \(T_{s}\) and the condensation temperature \(T_{\text{cond}}\) at given \(T_{\text{eff}}\) and \(\log g\). Then, the two-color diagram and the color-magnitude diagram can be well explained by the effects of \(T_{\text{eff}}\), \(\log g\), and \(T_{cr}\), but not by the effects of \(T_{\text{eff}}\) and \(\log g\) alone. This result implies that \(T_{cr}\) is one of the important parameters needed for characterization of dusty dwarfs. The effects of \(T_{\text{eff}}\) and \(T_{cr}\) on individual spectra, however, are difficult to discriminate, since \(T_{\text{eff}}\) at fixed \(T_{cr}\) on one hand and \(T_{cr}\) at fixed \(T_{\text{eff}}\) on the other essentially have the same effect on the spectra. We show that the degeneracy of \(T_{\text{eff}}\) and \(T_{cr}\) can be removed to some extent by the analysis of the spectral energy distribution on an absolute scale. The reanalysis of a selected sample of spectra revealed that the L–T spectral sequence may not necessarily be a sequence of \(T_{\text{eff}}\), but may reflect a change in the thickness of the dust cloud, represented by \(T_{cr}\) in our UCM. Although this unexpected result is based on a limited sample, an odd “brightening” of the absolute \(J\) magnitudes plotted against the L–T spectral types may also be an indication that the L–T spectral sequence is not necessarily a temperature sequence. This is because \(M_{bol}\) based on the same photometry data also shows a similar brightening. Thus, the “\(J\)-brightening” might not be due to any atmospheric effect and hence should not be a problem to be solved by model atmospheres, including the UCMs. Thus, almost all the available observed data are reasonably well interpreted by the UCMs, whose full capability emerges in the additional four parameters (i.e., chemical composition, \(T_{\text{eff}}\), \(\log g\), and microturbulent velocity) needed for characterization of dusty stellar spectra in general.

Subject headings: molecular processes — stars: atmospheres — stars: fundamental parameters — stars: late-type — stars: low-mass, brown dwarfs

1. INTRODUCTION

In any branch of natural science, classification of objects to study is a fundamental step, from which further developments are conceived and undertaken. Thus, it is quite natural that the spectral classification of ultracool dwarfs, including brown dwarfs, was initiated as soon as some dozens of dwarfs cooler than type M were discovered in the late 1990s. A new spectral class L was assigned to these objects, whose prototype is GD 165b (Becklin & Zuckermann 1988), and spectral subclasses were soon the (Becklin & Zuckermann 1988), and spectral subclasses were

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limit of \( J - K \) (Tsuji 2002, hereafter Paper I). Then it was possible to interpret the spectral sequence from L to T as a temperature sequence (Tsuji et al. 2004, hereafter Paper II).

Recent progress in observations, however, casts some doubts as to whether the L–T spectral types are simply an extension of the stellar spectral types to cooler temperatures. In particular, the effective temperatures based on the bolometric luminosities determined from the recent astrometry (Vrba et al. 2004) and photometry extended to \( L' \) and \( M' \) bands (Golimowski et al. 2004) appeared to be nearly constant between middle L and early T types (Vrba et al. 2004; Golimowski et al. 2004). This fact suggests that the L–T spectral sequence may not necessarily be a temperature sequence, and that the spectral sequence is controlled by parameter(s) other than \( T_{\text{eff}} \). In addition, it appears that the infrared colors extended to a large sample of L and T dwarfs (Knapp et al. 2004) show a large variation, especially if they are plotted against \( T_{\text{eff}} \). This fact implies that \( T_{\text{cr}} \), which is directly related to the infrared colors (as noted above), cannot be a constant throughout L and T dwarfs (as assumed in our Paper I and Paper II), but should show large changes independently of the basic stellar properties, such as \( T_{\text{eff}} \) and \( \log g \) (see §2.1 for details). Hence, any conclusion based on the assumption of a constant \( T_{\text{cr}} \) must be reconsidered.

In our UCMs, the property of the dust cloud is represented by a single parameter, \( T_{\text{cr}} \), which is a measure of the thickness of the dust cloud. This is essentially equivalent to specifying the dust column density in the cloud for the distribution of dust grains given by the static model photosphere. The cloud consists of grains smaller than the critical radius (Paper I), and the grain size is assumed to be small enough to be in the Rayleigh regime (i.e., \( r_{\text{gr}} \ll \lambda \)). No other details of the cloud are specified in the present UCMs. If we are to specify some details of the clouds, we must make some (possibly ad hoc) assumptions, since we do not know the details of how clouds are formed in the photospheres of cool dwarfs at present. Recall that \( T_{\text{cr}} \) is an empirical parameter and that it is not derived from any particular model of cloud formation. The new feature, that the thickness of the dust cloud changes unpredictably, implies that the cloud formation may take place under chaotic condition and/or may already be a meteorological phenomenon. Since theoretical prediction of an accidental event is more difficult, it may be useful to have emphasized an empirical approach before the more serious effort of detailed modeling of the cloud formation is done. It is to be remembered that a purpose of modeling is to describe complicated astronomical phenomenon by a simple picture as far as possible at first, and our UCM is currently at this stage.

In this paper, we hope to examine the extent to which our simple model can explain the available observed data on L and T dwarfs. First, we show that most observations, such as colors and magnitudes (§2), as well as spectra (§3), can be accounted for reasonably well by our UCMs if we assume that the critical temperature \( T_{\text{cr}} \) varies between the surface temperature (\( T_{\odot} \)) and the condensation temperature (\( T_{\text{cond}} \)) at fixed \( T_{\text{eff}} \) and \( \log g \). This fact confirms that the thickness of the dust cloud, or \( T_{\text{cr}} \) in our UCM, is an important parameter in interpreting the observed data of dusty dwarfs. Next, we discuss how the basic properties, including effective temperature, luminosity, and spectral classification, can be interpreted by the applications of the UCMs with the variable \( T_{\text{cr}} \) (§4). However, some conclusions are quite unexpected: For example, we show in this paper that the L–T spectral sequence is not necessarily a sequence of \( T_{\text{eff}} \), but that \( T_{\text{cr}} \) plays dominant role at least between middle L and early T types. This is because both \( T_{\text{eff}} \) and \( T_{\text{cr}} \) have a significant effect on the dust column density in the observable photosphere, and \( T_{\text{cr}} \) is sometimes more important than \( T_{\text{eff}} \) in characterizing the photosphere of dusty dwarfs. In our formulation of the UCMs, this new parameter \( T_{\text{cr}} \) distinguishes dusty dwarfs from other stars, which are characterized by four parameters, namely, chemical composition, \( T_{\text{eff}} \), \( \log g \), and microturbulent velocity.

2. COLORS AND MAGNITUDES

Recent infrared photometry revealed that infrared colors plotted against \( T_{\text{eff}} \) show a large variation, and this fact implies that the thickness of the dust cloud should be changing independently of \( T_{\text{eff}} \). In our UCMs, the critical temperature \( T_{\text{cr}} \) is introduced as a measure of the thickness of the dust cloud, but it was assumed that \( T_{\text{cr}} \) is constant throughout L and T dwarfs for simplicity in Paper I and Paper II. This is partly because the scatter of the infrared colors plotted against the spectral type appeared to be not so large as those plotted against \( T_{\text{eff}} \). In view of the new feature, however, we think it an oversimplification to assume a unique value for \( T_{\text{cr}} \). Furthermore, this assumption might have suppressed the potentiality that the UCMs could be able to have if they are applied more properly. We now regard \( T_{\text{cr}} \) as a free parameter to vary between the condensation and surface temperatures. Then, we demonstrate that such purely empirical data as the two-color and color-magnitude (CM) diagrams of L and T dwarfs can be explained with the three parameters \( T_{\text{eff}} \), \( \log g \), and \( T_{\text{cr}} \), while not at all by the two parameters \( T_{\text{eff}} \) and \( \log g \).

2.1. Infrared Colors and the Critical Temperature

Infrared colors plotted against L-T spectral types first show reddening from early to late L types and, after a reversal at late L, show bluing from early to late T types (e.g., Leggett et al. 2002). Recent progress in observations revealed some new features: First, thanks to the extended parallax data (Vrba et al. 2004) and bolometric corrections based on the \( L' \) and \( M' \) photometry (Golimowski et al. 2004), absolute bolometric luminosities are obtained for a large sample of L and T dwarfs. Then empirical effective temperatures can be derived, if the radii of L and T dwarfs are known. For this purpose, Vrba et al. (2004) assumed a constant radius of 0.9\( R_{\text{Jup}} \), while Golimowski et al. (2004) applied the radii based on evolutionary models. The resulting values of \( T_{\text{eff}} \) at 3 Gyr by Golimowski et al. (2004) mostly agree with those by Vrba et al. (2004) (see §4.2), which is to be expected since the parallax data and bolometric corrections are mostly the same in the two works. We plotted the observed colors on the Mauna Kea Observatory (MKO) system (Knapp et al. 2004) against the empirical values of \( T_{\text{eff}} \) (Vrba et al. 2004) rather than against the L-T spectral types in Figure 1, where \( T_{\text{eff}} \) values based on the bolometric luminosities are shown by the large circles and those based on the estimations with the \( T_{\text{eff}} \)-spectral type relation by the small circles. In Figure 1, L and T dwarfs are shown by the filled and open circles, respectively, and it appears that the transition from L to T types takes place at \( T_{\text{eff}} \approx 1400 \pm 100 \text{ K} \). It is remarkable in Figure 1 that the scattering is much larger especially at \( T_{\text{eff}} \approx 1400 \text{ K} \). A preliminary result that the infrared colors, such as \( J - K \), plotted against \( T_{\text{eff}} \) (and not against the L-T types) show a drastic change at the L-T transition was already noted by us (Tsuji 2005), independently by Marley et al. (2005), and also by Leggett et al. (2005).

Although it was known that the scatter of the infrared colors plotted against the spectral type are rather large in L dwarfs (e.g., Fig. 3 of Knapp et al. 2004), the plots of the same colors against
effective temperature revealed that the scatter is much larger, especially at around the L-T transition. It is remarkable that the plots of the same infrared colors against the spectral type and those against the effective temperature are so different. This means that an implicit assumption that the L-T spectral sequence is a temperature sequence may not necessarily be correct, even though this is a rather natural assumption in view of the smooth change of the infrared colors plotted against the spectral types. In fact, this conventional assumption now appears to be inconsistent with the recent empirical effective temperature determinations (e.g., Golimowski et al. 2004; Vrba et al. 2004).

The modest scatter of the infrared colors plotted against the L–T spectral types were already interpreted as due to variations in the altitudes, spatial distributions, and thicknesses of the...
clouds (Knapp et al. 2004). The scatter of the near-infrared colors at the same L spectral types was previously noted on the 2MASS data by Stephens (2003) and interpreted as due to the change of the cloud opacity, which depends on the sedimentation efficiency $f_{sed}$ of the cloud model of Ackerman & Marley (2001). In our UCM, the thickness of the dust cloud is represented by a parameter referred to as the critical temperature $T_{cr}$ (Tsuji 2002), but we assumed it to be a constant for simplicity in our previous applications of UCMs (e.g., Tsuji & Nakajima 2003; Tsuji et al. 2004). This assumption, however, should be reconsidered in view of the much larger scatter of the infrared colors, as revealed in Figure 1.

For this purpose, we first examine the effect of gravity and plot the predicted infrared colors based on the UCMs with log $g = 4.5$, 5.0, and 5.5 in Figure 1a ($T_{cr} = 1800$ K throughout). We applied the filter response functions (Tokunaga et al. 2002) to the predicted fluxes based on case I (band model) opacities for methane (see Paper II for details). Inspection of Figure 1a reveals that some scatter of the observed infrared colors can be explained as a gravity effect (e.g., $J - K$ at $T_{eff} \approx 1600$ K and $H - K$ at $T_{eff} \approx 1300$ K), and for this reason, we previously thought that the $J - K$ scatter could be explained by the gravity effect (Paper II). Such a gravity effect on the infrared colors was also discussed by Knapp et al. (2004) on the basis of the cloudy models by Marley et al. (2002). However, it is clear in Figure 1a that the large variations of the infrared colors near the L-T transition cannot be explained by the gravity effect. Note that the large variations of the infrared colors at $T_{eff} \approx 1400$ K has not been recognized before, and it is the smaller variations of the infrared colors plotted against the L-T spectral types that were thought to be interpreted as the effect of gravity in our Paper II. Now the situation is completely different because of the drastic changes of the infrared colors at $T_{eff} \approx 1400$ K, and we must now recognize that the large scatter of the infrared colors near the L-T transition cannot be explained by the effect of gravity.

Next, we overlaid the predicted colors based on the UCMs with $T_{cr} = 1700$, 1800, 1900 K, and $T_{cond}$ in Figure 1b ($T_{eff}$ = 5.0 throughout). Previously, we interpreted the scatter of the colors at their red limit in late L dwarfs as being approximately explained by $T_{cr} = 1800 \pm 100$ K. For this reason, we assumed that $T_{cr} = 1800$ K applies to all the cool dwarfs from L to T in our previous applications of the UCMs (Paper I and Paper II). However, this is clearly an oversimplification in view of the larger variation around the L-T transition at $T_{eff} \approx 1400$ K (Fig. 1), which has not been recognized before when the infrared colors were plotted against the L-T spectral type. Now, to explain the large variations of the infrared colors near the L-T transition, we must assume from Figure 1b that $T_{cr}$ in our UCM, or the thickness of the dust cloud, should be different at a given $T_{eff}$. Moreover, the variation of the thickness of the dust cloud should be quite drastic such that $T_{cr}$ changes from $T_{cond}$ to below 1700 K in our UCM. Note that the case of $T_{cr} \approx T_{cond}$ implies that the dust cloud effectively disappears.

In the UCMs, $T_{cond}$ is predictable on the basis of the thermochemical data and hence it is well defined for a given $T_{eff}$ and log $g$. In general, $T_{cond}$ is higher at higher gravities and/or lower effective temperatures, because of the higher gas pressures in these cases. For example, $T_{cond}$ values of iron are 1900 and 2200 K for models of $T_{eff}$ = 1800 and 1000 K, respectively (log $g$ = 5.0 throughout; see Fig. 3 in Paper I). We have already considered the possibility of variable $T_{cr}$, but in such a way that $T_{cr}$ depends on $T_{eff}$ and log $g$. In fact, the thickness of the cloud will be very thin in early L dwarfs for $T_{cr} \approx 1800$ K, since $T_{cond}$ will already be close to 1800 K for the models of relatively high $T_{eff}$ and, we considered the possibility that $T_{cr}$ may be lower for the models of high $T_{eff}$ (Paper I). With this possibility in mind, we have prepared the UCMs with several values of $T_{cr}$. However, the fact realized in nature turns out to be beyond what we have imagined: The variation of $T_{cr}$ appears to be independent of $T_{eff}$ and log $g$ (Figs. 1a and 1b) and to be quite large, but the origin of the variation cannot be understood at all.

The fact that the transition from L to T takes place at $T_{eff} \approx 1400$ K implies that $T_{eff}$ is an important factor in the L-T transition, but it is also clear that another effect plays a decisive role. Within the framework of our UCMs, this effect is identified with $T_{cr}$, which is a measure of the thickness of the dust cloud. It is as if something might have happened at $T_{eff} \approx 1400$ K to induce the change of the thickness of the cloud in such a way that L dwarfs with the lower values of $T_{cr}$ evolve to T dwarfs with the higher values of $T_{cr}$. The rapid and almost discontinuous change of the infrared colors at the L-T transition in a very small $T_{eff}$ range is also clearly illustrated in Figure 5 of Marley et al. (2005). Since the L-T transition is usually discussed in connection with the CM diagrams, we return to this subject in § 2.3.

A further complication is that $T_{cr}$ and $T_{eff}$ have nearly the same effect on the infrared colors. For example, we interpreted the reddening of the infrared colors in L dwarfs as due to the increase of the dust column density in the observable photosphere with decreasing $T_{eff}$. But the dust column density also increases with decreasing $T_{cr}$, even at fixed $T_{eff}$. Thus, $T_{cr}$ and $T_{eff}$ have the same effect on the infrared colors. In Figure 1b, it is possible to separate the effects of $T_{eff}$ and $T_{cr}$, because $T_{eff}$ was known by other method in this case. Generally, it is difficult to remove the degeneracy of $T_{cr}$ and $T_{eff}$ unless independent information on one of the two can be available. This problem will be further discussed in § 3.

### 2.2. Two-Color Diagram

We plot the observed $J - H$ against $H - K$ in the MKO system (Knapp et al. 2004) in Figure 2a, where L and T dwarfs are shown by filled and open circles, respectively. We overlaid the predicted colors based on the UCMs with log $g = 4.5$, 5.0, and 5.5, but with the constant value of $T_{cr} = 1800$ K throughout. The effect of gravity is minor in L and early T dwarfs, and the observed scatter of the colors cannot be attributed to the gravity effect for these dwarfs. On the other hand, the scatter of the observed colors in middle and late T dwarfs is well explained as the effect of gravity. Thus, we agree about the effect of gravity in T dwarfs with Knapp et al. (2004), who applied the models of Marley et al. (2002). Note that our UCMs cover the range of $T_{eff}$ between 700 and 2600 K. Thus, an object at the lower left corner, such as 2MASS J0937+2931 (T6p), may have log $g$ somewhat lower than 5.0 and $T_{eff}$ somewhat lower than 700 K from the colors alone if metallicity is normal.

In Figure 2b, we overlaid the predicted colors based on the UCMs with $T_{cr} = T_{0}$ (case B), 1700, 1800, 1900 K, and $T_{cond}$

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1. Note that the thickness of the cloud, or more properly, the dust column density in the observable photosphere, is not necessarily the same even if $T_{cr}$ is fixed, since $T_{cond}$ shows continuous changes through L to T dwarfs (see Fig. 3 in Paper I). In fact, this may be the reason that infrared colors, largely controlled by the dust extinction, change with $T_{cr}$. However, the change of the dust column density due to $T_{cr}$ itself introduced here is independent of $T_{eff}$ and of different nature.

2. In the early L dwarfs, observed colors appear to be redder than the predicted ones for any value of $T_{cr}$ in Fig. 1. This result may not necessarily be related to dust, but may be due to some other problems, such as of the gaseous opacities.
2.3. Color-Magnitude Diagram

Recent progress of astrometry and photometry of ultracool stars finally made it possible to compare CM diagrams with the theoretical evolutionary tracks of substellar objects. Our previous attempt on the \((M_J, J - K)\) diagram (Tsuji & Nakajima 2003), however, was not fully successful, but received some criticism. First, some early T dwarfs that show the so-called \(J\)-brightening were interpreted as very young low-mass objects, but such a hypothesis does not necessarily find observational support. The \(J\)-brightening seen on the plot of \(M_J\) versus spectral type may be an artifact of the \(L\text{–}T\) spectral sequence not representing a temperature sequence, as we show in §4.1, but the \(J\)-brightening on the CM diagram still remains to be explained. Second, some late L dwarfs are too faint to be explained by our previous analysis.

We must point out that our previous attempt was based on an assumption of a uniform value of \(T_{\text{cr}} \approx 1800\,\text{K}\) throughout the \(L\text{–}T\) dwarfs, but this assumption can no longer be supported as noted in §§2.1 and 2.2. We then examined the effect of changing \(T_{\text{cr}}\) on the CM diagram for the three evolutionary tracks of \(M = 10M_{\text{Jup}}, 42M_{\text{Jup}},\) and \(70M_{\text{Jup}}\) (Burrows et al. 1997) separately, and compared the results with the observed data on the MKO system (Knapp et al. 2004). We evaluate \(J - K\) and BC\(_J\) on the basis of the UCMs with different values of \(T_{\text{cr}}\), using the filter response functions of the MKO system (Tokunaga et al. 2003), and converted \((\text{Teff, Bol})\) to \((J - K, M_J)\) with the use of these results. First, the case of \(M = 10M_{\text{Jup}}\) are shown in Figure 3a for \(T_{\text{cr}} = 1700, 1800, 1900\,\text{K}\), and \(T_{\text{cond}}\) (case C). The agreement between observed and predicted loci is generally poor except for early and middle L dwarfs. This fact can be interpreted that the low-mass brown dwarfs are more difficult to observe because of their short lifetimes, and thus they may be undersampled in the currently observed sample of brown dwarfs.

The same analysis is done for the case of \(M = 42M_{\text{Jup}}\), and the results are shown in Figure 3b. In this case, most of the observed data points, except for late L dwarfs, are covered by the predicted tracks with the values of \(T_{\text{cr}}\) between 1700 K and \(T_{\text{cond}}\). The \(J\)-brightening of some early T dwarfs are now explained by the models with very thin clouds or with no cloud as the limiting case of reduced cloud thickness. This result is consistent with Figure 1b suggesting that \(T_{\text{cr}}\) should be quite high in some early T dwarfs, and with the suggestion from the two-color diagram discussed in §2.2 that the thickness of the cloud may be quite thin (i.e., \(T_{\text{cr}} > 1900\,\text{K}\)) in early T dwarfs.

Finally, the case of \(M = 70M_{\text{Jup}}\) is shown in Figure 3c, and now the very low luminosities of some late L dwarfs are explained by the models with the thick cloud (i.e., \(T_{\text{cr}} \approx 1700\,\text{K}\)). As to the very faint L dwarfs slightly below the predicted track for \(T_{\text{cr}} = 1700\,\text{K}\), possibilities of the lower \(T_{\text{cr}}\) and/or higher masses may be considered.

Summarizing, the observed \((M_J, J - K)\) diagram can be reasonably well reproduced with the evolutionary tracks by Burrows et al. (1997)\(^3\) and the UCMs in which the parameter \(T_{\text{cr}}\) is allowed to change by several hundred kelvins. The rapid bluing and brightening at the transition from \(L\) to \(T\) can be explained primarily by the immersion of the dust cloud from the optically thin cloud at high \(T_{\text{cr}}\).

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\(^3\) Some examples of the values of BC\(_J\) (CIT system) for several values of \(T_{\text{cr}}\) are given in Fig. 2 of Tsuji & Nakajima (2003).

\(^4\) In addition, the use of the isochrones by Chabrier et al. (2000) will result in the similar conclusion as can be inferred from our previous result (Tsuji & Nakajima 2003).
to the optically thick region at about $T_{\text{eff}} \approx 1400 \pm 100$ K, but at the same time, the thickness of the dust cloud should decrease as suggested by the increase of $T_{\text{cr}}$ (Fig. 1b). Such a change of the thickness of the dust cloud cannot be explained by the known theories of the structure and evolution of brown dwarfs, and a yet unidentified dynamical process is probably needed.

In a recent paper, Knapp et al. (2004) pointed out several difficulties in our previous model of the L-T transition (Tsuji & Nakajima 2003), but we hope that these issues are mostly resolved by our present version of UCMs with the variable cloud thickness. It is to be noted, however, that our UCMs assume a homogeneous cloud throughout. The possibility of clouds with holes was proposed to explain the rapid transition from L to T, as well as the $J$-brightening, by Burgasser et al. (2002b) and further discussed by Knapp et al. (2004), who referred to it as the patchy cloud model. We think that such an inhomogeneity is not necessarily required at present, although it may not be excluded a priori. In addition, Knapp et al. (2004) suggested another possibility referred to as the sudden downpour model, based on the cloudy models of Marley et al. (2002). In this model, the L dwarf first cools at essentially constant sedimentation efficiency $f_{\text{sed}}$ and then $f_{\text{sed}}$ begins to increase from $\approx 3$ to infinity at around $T_{\text{eff}} \approx 1300$ K. This rapid increase in $f_{\text{sed}}$ will bring rapid cloud thinning and hence rapid bluing infrared colors. We think that this model is more acceptable than the patchy cloud model. In fact, the sudden downpour model and our UCM with variable cloud thickness are essentially based on the same concept, in that both treatments specify the cloud properties with simple model parameters (the sedimentation efficiency $f_{\text{sed}}$ and the critical temperature $T_{\text{cr}}$, respectively). In any case, all these models, including the sudden downpour model, the patchy cloud model, and our UCM with variable cloud thickness, agree that the nature of the clouds changes drastically during the L-T transition at $T_{\text{eff}} \approx 1400 \pm 100$ K, and identifying the mechanism of driving such changes should be a key to understanding the transition from L to T types.

3. INFRARED SPECTRA

In general, stellar spectra can be characterized by four parameters, namely, chemical composition, $T_{\text{eff}}$, $\log g$, and microturbulent velocity $v_{\text{micro}}$. In the case of dusty dwarfs, however, an additional parameter that describes the nature of the dust cloud had to be specified for properly interpreting the infrared colors and magnitudes ($\chi^2$) and we introduced $T_{\text{cr}}$ for this purpose. In this paper, we assume standard composition throughout, and metallicity effects are not considered for simplicity. In addition, we assume $v_{\text{micro}} = 1$ km s$^{-1}$ throughout. Then the effectively important parameters are $T_{\text{eff}}$, $\log g$, and $T_{\text{cr}}$, and a problem is how to interpret the spectra of individual objects characterized by the three parameters. Our UCMs are already prepared for such applications, in that they are formulated with the critical temperature $T_{\text{cr}}$ as an important ingredient. The introduction of the new free parameter opens a possibility of more flexible analyses of the observed spectra. Our reanalysis reveals that the previous interpretation of the spectral sequence of ultracool dwarfs, as given in Paper II, was not correct, and we believe that we arrive at a more correct interpretation in this paper.

3.1. Degeneracy of the Effective and Critical Temperatures

With proper calibration, spectra observed with linear detectors can be regarded as a spectral energy distribution (SED) apart from an absolute scale. Such a relative SED is usually analyzed by means of the predicted SEDs based on models, but there is a
problem in the case of dusty dwarfs: The dust column density in the observable photosphere depends on $T_{\text{eff}}$ through its effect on $T_{\text{cond}}$ on one hand, and on $T_{\text{cr}}$ through its direct effect on the thickness of the cloud on the other hand. Thus, the spectra, which depend on the dust column density in the observable photosphere, depend on $T_{\text{eff}}$ as well as on $T_{\text{cr}}$. Then, the effects of $T_{\text{eff}}$ and of $T_{\text{cr}}$ cannot easily be separated on the observed spectra as well as on the infrared colors ($\S$ 2.1). Some examples of such a degeneracy between $T_{\text{eff}}$ and $T_{\text{cr}}$ are given below.

First, the observed spectrum of 2MASS 1711 (L6.5) could be fitted with the predicted one of $T_{\text{eff}} = 1800$ K on the assumption that $T_{\text{cr}} = 1800$ K (Fig. 4a), as in Paper II. However, it is more likely that $T_{\text{cr}} < 1700$ K, from the $J - K$ for this object (Table 1 and Fig. 1b). Then, the same observed spectrum can be fitted with the predicted one of $T_{\text{eff}} = 1300$ K on the assumption that $T_{\text{cr}} = 1700$ K (Fig. 4b). It is a bit surprising that a difference of only 100 K in $T_{\text{cr}}$ results in a difference of 500 K in $T_{\text{eff}}$.

Another complication due to dust is coupled here: As known from the fact that the same infrared color corresponds to two different values of $T_{\text{eff}}$ (Fig. 1), a very similar SED may result from objects of different $T_{\text{eff}}$ values, one relatively high and the other relatively low, as discussed in Paper II for the case of the L5 dwarf 2MASS 1507 (see its Fig. 13). For this reason, not only $T_{\text{eff}} = 1800$ K but also a lower $T_{\text{eff}}$ near 1300 K could explain the overall SED for the case of $T_{\text{cr}} = 1800$ K. The lower $T_{\text{eff}}$ cannot be rejected because of the strong

![Fig. 4.-Observed spectrum of 2MASS 1711 (L6.5), shown by the dots, compared with the predicted ones based on the UCMs of (a) $T_{\text{cr}} = 1800$ K, $T_{\text{eff}} = 1800$ K, and $\log g = 5.0$. (b) $T_{\text{cr}} = 1700$ K, $T_{\text{eff}} = 1300$ K, and $\log g = 5.0$.](image1)

![Fig. 5.-Observed spectrum of SDSS 1750 (T3.5), shown by the dots, compared with the predicted ones based on the UCMs of (a) $T_{\text{cr}} = 1800$ K, $T_{\text{eff}} = 1100$ K, and $\log g = 5.0$, and (b) $T_{\text{cr}} = T_{\text{cond}}$ (case C), $T_{\text{eff}} = 1300$ K, and $\log g = 5.0$.](image2)

### Table 1: Effective Temperatures

| Object          | Spectral Type | $J-K^a$ | $K-J^b$ | $d^c$ (pc) | $T_{\text{eff}} (T_{\text{cr}})^d$ (K) | $T_{\text{eff}} (T_{\text{cr}})^e$ (K) | $T_{\text{eff}}^f$ (K) |
|-----------------|--------------|---------|---------|-----------|--------------------------------------|--------------------------------------|-------------------|
| 2MASS 1711+22   | L6.5         | ...     | 2.25    | 30.20     | 1800 (1800)                          | 1300 (1700)                          | 1545              |
| 2MASS 1523+30   | L8           | 1.60    | 1.65    | 17.45     | 1500 (1800)                          | 1300 (1700)                          | 1330              |
| SDSS 1254-01    | T2           | 0.82    | 0.96    | 13.21     | 1300 (1800)                          | 1300 (1800)                          | 1361              |
| SDSS 1750+17    | T3.5         | 0.12    | 0.83    | 27.59     | 1100 (1800)                          | 1300 (1700)                          | 1478              |

*a* MKO system (Knapp et al. 2004).

*b* CIT system (Vrba et al. 2004).

*c* Distance based on the parallaxes by Vrba et al. (2004).

*d* Based on the analysis of the spectra with UCMs of the uniform value $T_{\text{cr}} = 1800$ K (Paper II).

*e* Based on the analysis of the absolute fluxes with UCMs of $T_{\text{cr}}$ inferred from the infrared colors (this paper).

*f* Based on the bolometric luminosity (Vrba et al. 2004).
methane bands predicted for this case. For $T_{\text{eff}} = 1700$ K, the situation is essentially the same but the methane bands are not so strong even for the case of $T_{\text{eff}} \approx 1300$ K because of the stronger dust extinction due to the thicker cloud for the lower value of $T_{\text{cr}}$, and there is no longer any reason why to reject this case.

As another example, the overall SED of SDSS 1750 (T3.5) can be fitted with the predicted one of $T_{\text{eff}} = 1100$ K on the assumption that $T_{\text{cr}} = 1800$ K (Fig. 5a), although the predicted water bands appear to be too strong (Paper II). The infrared colors of this object (Table 1), however, suggest that $T_{\text{cr}}$ should be quite high and may be as high as $T_{\text{cond}}$ (see Fig. 1b). Then, on the assumption that $T_{\text{cr}} = T_{\text{cond}}$ (case C or effectively no cloud), the same observed spectrum can be fitted with the predicted one of $T_{\text{eff}} = 1300$ K, and the water bands show even better agreement (Fig. 5b).

3.2. Reanalysis of the Spectral Energy Distributions

The ambiguity due to the degeneracy of $T_{\text{eff}}$ and $T_{\text{cr}}$ in the analysis of the spectra cannot be removed if only their shapes, or relative SEDs, are analyzed, as in § 3.1. This difficulty, however, may be relaxed to some extent if we reduce the observed spectra to the SEDs on an absolute scale. With the known distance, $d$, from recent astrometry measurements and with the assumption that the radius, $R$, is the same as Jupiter’s radius, the observed SED, $F_{\nu}$ (in units of Jy), can be transformed to an absolute scale, i.e., the emergent flux from the unit surface area of the object, $F_{\nu}$ (in units of ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$), by

$$\log F_{\nu} = \log f_{\nu} - 2 \log (R/d) - 23.4971.$$

Then, observed and predicted SEDs can be compared directly, leaving no further ambiguity of vertical shift. We reanalyze the spectra discussed in Paper II, but we reduce all the spectra to be analyzed in this subsection to the absolute scale with the use of the parallaxes by Vrba et al. (2004) and the assumption of $R = R_{\odot}$. The largest source of uncertainty in this transformation is the assumption on the radius, and a 30% error in the assumed radius (Burrows et al. 2001) results in an error of 0.2–0.3 dex on $\log F_{\nu}$.

In Figure 6, the observed SED of the L6.5 dwarf 2MASS 1711 represented by the dots is compared with the predicted one based on the UCM with $T_{\text{cr}} = 1800$ K and $T_{\text{eff}} = 1800$ K (labeled A in the top panel). This model was thought to fit reasonably well for this object in Paper II (see its Fig. 6). However, it now appears that the fit is very poor on the absolute scale, even though the overall shapes of the spectra agree rather well, as shown in Figure 4a. For this object, the empirical value of $T_{\text{eff}}$ is 1545 K and $J - K = 2.25$ (Vrba et al. 2004). These data may suggest that $T_{\text{cr}} \lesssim 1700$ K from Figure 1b. We then looked for a better fit in the SEDs predicted with the UCMs of $T_{\text{cr}} = 1700$ K and found that a model of $T_{\text{eff}} = 1300$ K (B in the bottom panel of Fig. 6) shows a relatively good fit, except that the water bands appear to be too strong. This is probably not a unique solution, but it is more consistent with the available observed data.

In Figure 7, the observed SED of the L8 dwarf 2MASS1523 is compared first with the predicted one with the UCM of $T_{\text{cr}} = 1800$ K and $T_{\text{eff}} = 1500$ K (A in the top panel). This model was deemed to be the best choice for this object on the basis of the analysis of the same spectrum without absolute calibration in Paper II (see its Fig. 8). In the top panel of Figure 7, the fit is very poor on the absolute scale, even though the overall shapes of the spectra agree rather well. For this object, empirical value of $T_{\text{eff}}$ is 1330 K and $J - K = 1.65$ (Vrba et al. 2004). These data may suggest that $T_{\text{cr}} \approx 1700$ K from Figure 1b. We then looked for a better fit with the UCMs of $T_{\text{cr}} = 1700$ K but found no reasonable solution. A model with $T_{\text{eff}} = 1300$ K (B in the bottom panel of Fig. 7) shows a difference of as large as 0.2 dex on $\log F_{\nu}$ even though $T_{\text{eff}}$ is close to the empirical value. To have a better fit on the absolute scale, $T_{\text{eff}}$ cannot be reduced further, but it will make the methane bands too strong and may not be acceptable. The difference of 0.2 dex is probably within the uncertainty of the absolute flux that arises because of our assumption on the radius as noted above, and we suggest that a possible solution is $T_{\text{cr}} \approx 1700$ K and $T_{\text{eff}} \approx 1300$ K.

In Figure 8, we show the observed SED of T2 dwarf SDSS 1254 by the dots and compared it with the predicted one based on the UCM of $T_{\text{cr}} = 1800$ K and $T_{\text{eff}} = 1300$ K (A in the top panel). This is the model shown in Figure 9 of Paper II and suggested to be the best model based on the fit of the overall shapes of the observed and predicted spectra. It is now confirmed that the fit is also fine in the absolute scale. In addition, $J - K = 0.82$ (Knapp et al. 2004) of this object may suggest that $T_{\text{cr}} \approx 1800$ K from Figure 1b. The value of $T_{\text{eff}}$ is only slightly lower than the empirical value of $T_{\text{eff}} = 1316$ K (Vrba

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5 Note that the predicted spectra show bifurcations in the region of methane bands near 1.6 and 2.2 $\mu$m, as the case I (band model opacity) or II (line list) opacities are used for CH$_4$. For details, see Paper II.

6 For the same reason, our previous interpretation in Paper II of 2MASS 1507 (LS) should also be reconsidered, and the low-temperature model with the lower value of $T_{\text{cr}}$ should apply rather than the high-temperature model with $T_{\text{cr}} = 1800$ K.
1900 K. It turns out that the lower values of 1800 K and on the absolute scale. Infrared colors suggest a lower fitted on the relative scale (Fig. 8 of Paper II), it is clear that they cannot be fitted on the absolute scale. Infrared colors suggest a lower $T_{\text{eff}}$ for this object (Table 1; Fig. 1b), and the predicted spectrum based on the UCM with $T_{\text{eff}} = 1700$ K, $T_{\text{cr}} = 1300$ K, and log $g = 5.0$ is shown by the solid line marked with B. The observed and predicted spectra cannot be fitted on the absolute scale as well, but it is to be noted that the uncertainty of the absolute scale is about 0.2–0.3 dex.

We examined the case of $T_{\text{eff}} = 1400$ K which required $T_{\text{cr}} = 1900$ K to reproduce the overall shape of the observed spectrum. This case (B in the bottom panel of Fig. 8) shows some deviation from the observed spectrum, although the deviation may be within the uncertainty of the absolute scale as noted above.

Finally, we examine the case of T3.5 dwarf SDSS 1750 in Figure 9, in which the observed SED is compared with the predicted ones from the two different UCMs. First, the case of $T_{\text{cr}} = 1800$ K and $T_{\text{eff}} = 1100$ K, which we accepted in Paper II, reproduces the relative SED reasonably well except that water bands are too strong, and we further suggested log $g = 5.5$ to reduce the water band strengths in Paper II (see its Fig. 10). The fit in the absolute scale for this model is not as good in Figure 9, even though it may be within the uncertainty of the absolute flux (A in the top panel). For comparison, a recent empirical value is $T_{\text{eff}} = 1478$ K (Vrba et al. 2004), about 400 K higher than the value based on the model fitting. In addition, this object is as blue as $J - K = 0.12$ (Knapp et al. 2004) and the dust cloud may have cleared already at $T_{\text{cr}} = 1300$ K, as can be inferred from Figure 1b. We then applied our model with $T_{\text{cr}} = T_{\text{cond}}$ (case C) and looked for the best fit. We found that a model of $T_{\text{eff}} = 1300$ K provides the best fit in both relative and absolute scales (B in the lower panel of Fig. 9). Another photometry suggests that $J - K = 0.83$ (Vrba et al. 2004) and we also examined the case of $T_{\text{cr}} = 1900$ K. It turns out that the lower values of $T_{\text{cr}}$ and/or the higher values of $T_{\text{eff}}$ do not improve the fit in either a relative or an absolute scale.

The possible best values of $T_{\text{eff}}$ based on the reanalysis outlined above are summarized in Table 1 together with some observed data and discussed in § 3.3.

3.3. Interpretation of the L–T Spectral Sequence

As an example of the L–T spectral sequence, we reproduce in Figure 10 the spectra of cool dwarfs from L6.5 to T3.5, which were discussed in some detail elsewhere (Nakajima et al. 2004). The spectra show systematic changes from the L dwarfs with H$_2$O bands of modest strengths and marginal CH$_4$ bands to the T dwarfs with strong bands of both H$_2$O and CH$_4$. In addition, the overall SEDs in the spectral range of Figure 10 change from red in the L dwarfs to blue in the T dwarfs. This spectral sequence could have been interpreted as a temperature sequence that extends from 1800 to 1100 K (reproduced in the col. [6] of Table 1), as long as we assume a uniform value of $T_{\text{cr}} = 1800$ K throughout L and T dwarfs (Paper II). This seemed to be a reasonable result for such a large and systematic change of the spectra and also fitted the general expectation that the L–T spectral classification may be an extension of the stellar spectral types beyond M to the cooler temperatures.

In § 3.2, we reanalyzed the same data reproduced in Figure 10 with the $T_{\text{cr}}$ values inferred from the $J - K$ values of individual
objects (Table 1 and Fig. 1b). Fitting of the observed and predicted spectra is done not only by the relative shape of the spectra but also by the use of the absolute flux scale based on the recent astrometry data. The result of the reanalysis turns out to be quite different, as summarized in the column (7) of Table 1. The spectra from L6.5 to T3.5 shown in Figure 10 can be interpreted by a uniform value of $T_{\text{eff}}$ throughout. Instead, the spectral sequence of Figure 10 can be explained by the change of $T_{\text{cr}}$ from about 1700 K to $T_{\text{cond}}$ (i.e., case C).7 An important conclusion is that the effect of $T_{\text{cr}}$ is sometimes more important than that of $T_{\text{eff}}$, and a change of spectra so drastic that it requires different spectral types, L and T, can be due to the change of $T_{\text{cr}}$ rather than of $T_{\text{eff}}$.

Thus, the present reanalysis shows a marked contrast to the previous analysis (Paper II), and it is quite unexpected that the L–T spectral sequence can no longer be regarded as a temperature sequence, but rather represents the change of the dust column density in the observable photosphere, at least between the middle L and early T dwarfs. Nevertheless, we should accept the new result, which is based on the analysis of the SEDs on an absolute scale. Even though the absolute flux may be uncertain by as much as $\Delta \log F_{\nu} \approx 0.2$–0.3 dex because of the uncertainty of the radius of an individual object, as noted in § 3.2, the ambiguity in the analysis of the relative SED should be still larger, as also shown in § 3.2. In addition, the critical temperature $T_{\text{cr}}$ is already selected to be consistent with the infrared colors (Fig. 1b), and the resulting $T_{\text{eff}}$ values agree with the recent empirical effective temperatures, which suggested an almost uniform value of $T_{\text{eff}} \approx 1400$ K in the same spectral range (Vrba et al. 2004; Golimowski et al. 2004). A systematic difference of 100 K remains to be explained, but such a difference may be within the error bars of the both analyses.

In this interpretation, L6.5 dwarf 2MASS 1711 and L8 dwarf 2MASS 1523 have the same $T_{\text{eff}}$ (Figs. 6 and 7), but we now discuss the first-order effect with models in which $T_{\text{cr}}$ and $T_{\text{cr}}$ are changed by a step of 100 K, and further fine tuning is certainly needed.
4. BASIC PHYSICAL PROPERTIES
OF ULTRACOOL DWARFS

Recent progress in observations of such faint objects as L and T dwarfs is quite substantial, especially in photometry (e.g., Leggett et al. 2002; Golimowski et al. 2004; Knapp et al. 2004) and astrometry (e.g., Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004). Thus, we now have reasonably accurate empirical data on luminosities and effective temperatures for a large sample of L and T dwarfs. At the same time, these new data uncovered a difficulty in the spectral classification of L and T dwarfs, which was essentially following the methodology of stellar spectral classification.

4.1. Luminosities

Recent progress in observations finally provided reasonably accurate absolute magnitudes (monochromatic as well as bolometric) for a large sample of L and T dwarfs (e.g., Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004). As an example, we reproduce the $M_J$ plotted against the L–T spectral types in Figure 11a with the data by Vrba et al. (2004; see their original plot as for more detail with error bars), showing the $J$-brightening at the early T dwarfs. It is known that the situation is more or less the same for $M_H$ and $M_K$ if not so pronounced as in $M_J$ (e.g., Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004). Then, these data may suggest that the bolometric magnitude $M_{bol}$ should also show the similar brightening, since most of the flux is emitted in $J$, $H$, and $K$ bands. We confirmed in Figure 11b that the absolute bolometric magnitude $M_{bol}$ plotted against the L–T spectral types with the data from Vrba et al. (2004) in fact shows the brightening at the early T dwarfs. The values of bolometric magnitude $M_{bol}$ used in Figure 11b are already based on the bolometric corrections by Golimowski et al. (2004) including the result of the $L'$ and $M'$ photometry. However, we examine the $M_{bol}$ values of Golimowski et al. (2004) based on a different photometric system in Figure 11c. The “brightening” may not be so clear as in Figure 11b, but the $M_{bol}$ also levels off between L5 and T4 in Figure 11c.

Although these results are quite unexpected, it is easier to interpret Figure 11b (or Fig. 11c) than Figure 11a: since the bolometric luminosities essentially reflect the cooling of brown dwarfs, the brightening (or the level-off) of the total luminosities is difficult to understand if they are plotted against a correct temperature indicator. A possible solution is that the bolometric magnitude $M_{bol}$ may not be so pronounced as in Figure 11a, but the $M_{bol}$ also levels off between L5 and T4 in Figure 11c.

4.2. Effective Temperatures

Effective temperature is one of the basic fundamental parameters that specify the nature of substellar as well as of stellar objects. Accurate determination of $T_{eff}$, however, is generally difficult because the total energy flux integrated over the whole spectral region is required on an absolute scale (i.e., in units of energy flux emerging from a unit surface area of the object). In the case of a star, observed bolometric flux can be converted to absolute emergent total flux if the stellar angular diameter can be measured. In the case of brown dwarf, the angular diameter is more difficult to measure at present, but its equivalence can be estimated if the distance is known, because of the
favorable nature of brown dwarfs that the radius is within 30% of Jupiter’s radius, independent of mass (e.g., Burrows et al. 2001).

Recently, reasonably accurate trigonometric parallaxes were made available thanks to the elaborate astrometric observations by several groups (e.g., Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004). These results are combined with the photometric observations well extended to the $L'$ and $M'$ regions (e.g., Leggett et al. 2002; Golimowski et al. 2004; Knapp et al. 2004), and empirical effective temperatures, as well as the absolute magnitudes, are determined for dozens of $L$ and $T$ dwarfs. An important finding is that the empirical $T_{\text{eff}}$ values by Vrba et al. (2004) and by Golimowski et al. (2004) show a large plateau between about L5 and T5, and notably, $T_{\text{eff}}$ between L8 and T2 is nearly constant. This result was also suggested by Nakajima et al. (2004) on the basis of the bolometric correction predicted with the use of the UCMs. The effect of $\log g$ may not be so large as to modify the qualitative nature of the spectra. Thus, the $L$-$T$ transition, as well as the change of the spectra between late-$L$ and early-$T$ types, should not be due to $T_{\text{eff}}$ and $\log g$ alone but may be governed by another parameter, which we have already identified with $T_{\text{cr}}$.

With the empirical $T_{\text{eff}}$ as the abscissa, we plot $M_J$ in Figure 12a. Since $T_{\text{eff}}$ is derived from $M_{\text{bol}}$, which is not fully independent of $M_J$, it is expected from the beginning that $M_J$ and $T_{\text{eff}}$ be somewhat related. Nevertheless, if the $J$-band flux suffers a serious atmospheric effect, such a smooth monotonic curve as Figure 12a may not necessarily be trivial. It is confirmed that the “brightening” such as shown in Figure 11a disappears if $M_J$ is plotted against effective temperature, and this fact can be regarded as a confirmation of the conclusion of § 4.1 that the $J$-brightening is a problem of $L$–$T$ classification rather than of $M_J$. In addition, it is to be noted that the scattering is rather small in Figure 12a except for in the $L$-$T$ transition region. We overlaid in Figure 12a the evolutionary tracks of $10M_{\text{Jup}}, 42M_{\text{Jup}}$, and $70M_{\text{Jup}}$ transformed to $M_J$ versus $T_{\text{eff}}$ from $M_{\text{bol}}$ versus $T_{\text{eff}}$ (Burrows et al. 1997) for different values of $T_{\text{cr}}$. It can be confirmed that the variable $T_{\text{cr}}$ in fact results in the scatter in $M_J$ at $T_{\text{eff}} \approx 1500$ K, where the effect of the dust clouds is the largest, but that the “atmospheric effect” is not so large as to produce the $J$-brightening.

To investigate the nature of the empirical $T_{\text{eff}}$, we also plot $M_{\text{bol}}$ against the empirical $T_{\text{eff}}$ (error bars in the original data are not shown but are typically $\pm 200$ K) in Figure 12b, and the evolutionary tracks for $10M_{\text{Jup}}, 42M_{\text{Jup}}$, and $70M_{\text{Jup}}$ (Burrows et al. 1997) are overlaid. The empirical values of $T_{\text{eff}}$ were derived, with the assumption of the uniform radius of $0.90R_{\text{Jup}}$ by Vrba et al. (2004) with their equation 7, and the results seem to be approximately equivalent to having derived $T_{\text{eff}}$ with the use of the evolutionary tracks for $42M_{\text{Jup}}$. Thus, the empirical $T_{\text{eff}}$ values are subject to some ambiguities due to the uncertainties of mass, radius, and/or age. Other authors (e.g., Golimowski et al. 2004; Knapp et al. 2004) applied the evolutionary tracks to convert $M_{\text{bol}}$ to $T_{\text{eff}}$, but the exact evolutionary status of an individual object is in any case unknown. For example, Golimowski et al. (2004) showed that the range of possible $T_{\text{eff}}$ derived from $L_{\text{bol}}$, assuming evolutionary models with ages of $0.1–10$ Gyr, is $\approx 300$ K. In Figure 12c, we also plot $M_{\text{bol}}$ against the empirical $T_{\text{eff}}$ derived for an age of $\approx 3$ Gyr by Golimowski et al. (2004). Except for a few cases, Figures 12b and 12c appear to be rather similar, and it looks as if most brown dwarfs are on the evolutionary tracks of $42M_{\text{Jup}}$. However, this is simply a consequence of the age of most brown dwarfs being assumed to be $\approx 3$ Gyr.

A similar difficulty has been noticed by Golimowski et al. (2004), who compared the diagrams of $M_J$, $M_L$, and $M_{\text{bol}}$ versus $T_{\text{eff}}$ with the predictions based on the models of Marley et al. (2002) for varying sedimentation efficiencies $f_{\text{sed}}$ (3, 5, and no cloud) and different values of $\log g$ (4.5, 5.0, and 5.5). Their results showed that the model predictions reproduce well the broad ranges of observed absolute magnitudes and effective

![Figure 12](image-url)
temperatures for a large sample of L and T dwarfs. Yet it appeared to be difficult to decide particular sets of model parameters because of the difficulty of knowing masses, ages, and metallicities of individual objects. Golimowski et al. (2004) also showed that the L3–T4.5 dwarfs generally have higher gravities than the T6–T9 dwarfs, and these results may be consistent with our Figure 12, in that earlier dwarfs generally tend to populate the evolutionary tracks of the higher mass models.

Despite the difficulty of observing such faint objects as brown dwarfs, one relief is that parallaxes could have been measured accurately. In fact, the recent achievement of measuring the parallaxes of dozens of ultracool dwarfs is the most important contribution to our understanding of brown dwarfs (e.g., see §§2.1 and 4.1). Once the object distance can be known accurately, we can expect to understand well the nature of the astronomical object. Nevertheless, it appears that the empirical \( T_{\text{eff}} \) values for individual objects are still uncertain to about \( \pm 200 \) K (Vrba et al. 2004; Golimowski et al. 2004; Knapp et al. 2004), and for this reason, it is still difficult to determine masses and/or ages of individual objects from the observed data at present. We must wait for direct measurements of radii or angular diameters for a final solution of this uncertainty. As a compromise, model analyses such as that given in §3 can be of some use in examining the consistency of various observed data and improving our knowledge of \( T_{\text{eff}} \) and other parameters.

4.3. Spectral Classification

A conclusion to be drawn from §§3.3 and 4.1 is that the L–T spectral classification may have a serious problem regarding its meaning as a temperature classification. The stellar spectral classification has been done on a purely empirical basis, and it was not intended to be a temperature sequence from the beginning. However, the great success of the stellar spectral classification established at the beginning of the 20th century is largely due to the finding that the spectral sequence is a temperature sequence. Later efforts to interpret the stellar spectral sequence in terms of temperature and other physical parameters finally resulted in establishing the present-day stellar astrophysics. The present L-T spectral classification has also been done on purely empirical basis (e.g., Kirkpatrick et al. 1999), and again it was not explicitly mentioned that the resulting spectral sequence will be a temperature sequence. Thus, it is left free as to how to interpret the L-T spectral types. However, the L and T types are conceived as extensions of the spectral type beyond M, and may implicitly be expected to be temperature indicators.

In any case, we should first understand what the present L-T spectral types mean. Although the reason for the difficulty in interpreting the L-T spectral types can be explained as due to the degeneracy of \( T_{\text{eff}} \) and \( T_{\text{cr}} \) on the spectra contaminated with dust (§3.1), at least partly, this problem may be most serious in the region around \( T_{\text{eff}} \approx 1400 \pm 100 \) K, where the transition from L to T takes place (Fig. 1). In other regions, however, the situation may be different, and the L-T spectral classification may be used as a temperature classification if applied with some cautions. We now apply our UCM as a working model to interpret the L-T classification in three different parts, namely, early L dwarfs (roughly \( T_{\text{eff}} > 1500 \) K), L-T transition region (1300 K \( \leq T_{\text{eff}} \leq 1500 \) K), and dust-cleared T dwarfs (\( T_{\text{eff}} < 1300 \) K). In the early L dwarfs, the dust clouds that occupy the region of \( T_{\text{cr}} \leq T \leq T_{\text{cond}} \) are entirely located in the optically thin region. In this case, the location of the lower boundary of the cloud at \( T \approx T_{\text{cond}} \) should be more important than that of the upper boundary at \( T \approx T_{\text{cr}} \), since the region near the upper boundary of the dust cloud will have little contribution to the dust column density because of the lower density there. For this reason, the spectra essentially depend on \( T_{\text{cond}} \), which in turn can be well interpreted in terms of \( T_{\text{eff}} \) and \( \log g \); this explains why the scatter is small in the early L dwarfs in Figure 1. At the same time, it is difficult to determine \( T_{\text{cr}} \) from the infrared colors (Fig. 1b).

From middle L to early T dwarfs, the L–T spectral classification met serious difficulty, as noted above. In this region, the lower boundary of the cloud at \( T \approx T_{\text{cond}} \) will be in the unobservable photosphere (i.e., \( \tau > 1 \)), and the thickness of the cloud in the observable photosphere is essentially determined by \( T_{\text{cr}} \), which is not controlled by \( T_{\text{eff}} \) nor by \( \log g \). For this reason, the spectra show little effect of \( T_{\text{eff}} \) but depend mostly on \( T_{\text{cr}} \). An actual example of this case is shown by the spectral sequence reproduced in Figure 10. The analysis outlined in §3.2 is based on a limited sample that, although limited, represents the general feature of the spectra between middle M and early T types. This is because a larger sample shows the same conclusion: First, empirical \( T_{\text{eff}} \) plotted against spectral types shows a large plateau in the middle part of the L–T sequence (Vrba et al. 2004; Golimowski et al. 2004; Nakajima et al. 2004; Leggett et al. 2005). Second, \( M_{\text{bol}} \) plotted against spectral types shows a brightening around early T types (Fig. 12b), which is difficult to understand if the spectral types are on a correct temperature sequence. Thus, the spectral classification between middle L and early T types may be radically reconsidered.

In the middle and late T dwarfs, the effect of the cloud diminishes because of the immersion of the cloud in the optically thick region, and gaseous opacities dominate. The upper boundary of the cloud may still be in the observable photosphere in the middle T dwarfs, but it seems that \( T_{\text{cr}} \) may be systematically high in these dwarfs (about 1900 K or higher from Figs. 1b and 2b). This fact suggests the possibility that the dust cloud is already quite thin in middle T dwarfs, but the reason for this is unknown. Finally, in the late T dwarfs, the dust cloud is in the optically thick region and no information on the cloud can be obtained from observations (Liebert et al. 2000). In this case, \( T_{\text{cond}} \), as well as \( T_{\text{cr}} \), has no effect on spectra or on colors. The scatter in colors at fixed \( T_{\text{eff}} \) is mostly due to gravity, as noted in §2.

Apart from the problems related to \( T_{\text{cr}} \), one difficulty in the classification of dusty dwarfs is that the dust itself shows no clear spectral signature and it is very difficult to estimate the dust column density directly from observations. The spectral classification had to be done with the use of the spectral features originating from atoms and molecules, while the spectra are largely controlled by dust. For example, methane bands that are used in the infrared classification show drastic change from L to T dwarfs (e.g., Fig. 10), but this is not due to a direct effect of the change of the methane abundance with \( T_{\text{eff}} \), but rather to an indirect effect of the change of the dust extinction with \( T_{\text{cr}} \) as discussed in §3.3. But there should be a case in which the methane bands actually change as a result of the change of the methane abundance with \( T_{\text{cr}} \). For this reason, methane bands cannot be indicators of temperature, and the situation may be more or less the same for other atomic and molecular features.

Another difficulty of the present L-T classification has also been pointed out, in that the L types based on the optical spectra and those on the near-infrared spectra differ by as much as three subtypes (e.g., Stephens 2003; Knapp et al. 2004; Leggett et al. 2005). This fact, however, may offer an interesting possibility of the two-dimensional spectral classification of ultracool dwarfs, if the optical types can be indicators of temperature and the infrared types of the dust opacities (Stephens 2003). In view of the difficulties outlined above, however, it seems to be more difficult to separate the effects of temperature and of dust.
opacities. For example, the effect of the dust column density is more serious as to produce such a large difference in spectral types from L6.5 to T3.5 for about the same $T_{\text{eff}}$ as shown in Figure 10 rather than results in just three subclasses at the largest in late L dwarfs.

The present L–T classification essentially follows the methodology of the stellar spectral classification (e.g., Kirkpatrick et al. 1999), which is a marvelous art to infer the basic stellar properties such as the effective temperature and luminosity by just looking at the low-resolution spectra. In the case of the spectra of cool dwarfs contaminated with dust, such a convention may be more difficult, not only because an additional parameter related to the dust clouds is required to characterize the spectra, but also because the dust itself shows no spectral signature. To specify the properties of the dust cloud, we introduced $T_{\text{cr}}$, which is a measure of the dust column density in our UCM, but the real difficulty is that the effects of $T_{\text{eff}}$ and $T_{\text{cr}}$ cannot be separated, even if the effect of log $g$ were known. It would be of course desirable to be able to know the basic parameters, such as $T_{\text{eff}}$, log $g$, and metallicity, and further some dust properties (e.g., $T_{\text{cr}}$ in our UCMs) by just looking at the low-resolution spectra. However, it seems to be a formidable problem to have a classification scheme similar to the stellar spectral classification for the spectra of dusty dwarfs, and a more detailed and careful examination of the spectra from the optical to infrared regime is required.

5. DISCUSSION AND CONCLUDING REMARKS

Recent observations of ultracool dwarfs revealed some confusion as to their interpretation, for example, the “brightening” in the infrared absolute magnitudes at the early T dwarfs on the L–T sequence as well as on the color-magnitude (CM) diagrams (e.g., Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004), the large scatter in the infrared colors (Knapp et al. 2004, and references therein), and a large plateau in $T_{\text{eff}}$–spectral type calibration between middle L and middle T (Vrba et al. 2004). We show in this paper that these difficulties are mostly resolved if we apply our UCMs properly, i.e., if we allow the critical temperature to change from as high as the condensation temperature to near the surface temperature. We have not yet considered another curious observation, that the absorption bands of FeH decrease first from early to late L types but strengthen again at early T types (Burgasser et al. 2002b; Nakajima et al. 2004). We have not enough data to analyze this problem in detail, but we suggest that this may be the same phenomenon as the $J$-brightening at the early T types. In other words, if the FeH band strength is plotted against $T_{\text{eff}}$ rather than L–T types, it will show a steady decrease; we hope that this will be confirmed by future observations. In addition, if this is confirmed, FeH would be a useful marker for spectral classification.

Within the framework of UCM, the critical temperature $T_{\text{cr}}$ shows such a large and unpredictable variation at a given $T_{\text{eff}}$, and this result implies that the dust column density in the observable photosphere differs largely for the same $T_{\text{eff}}$ (and other basic parameters). It is remarkable that the variation of $T_{\text{cr}}$ is especially large at $T_{\text{eff}} \approx 1400 \pm 100$ K, and T dwarfs in this region mostly show $T_{\text{cr}} \gtrsim 1800$ K, while L dwarfs $T_{\text{cr}} < 1800$ K (Fig. 1b). Then $T_{\text{cr}}$ is as high as 1900 K or near $T_{\text{cond}}$ in middle T dwarfs, as noted in §3.2.2 and 4.3. These results may indicate that the thickness of the dust cloud itself decreases after the L–T transition and further throughout T dwarfs. Thus, it appears that thinning of the dust cloud should be associated with the immersion of the cloud in T dwarfs, but it is not clear whether this is also the case in L dwarfs. A problem is whether the dust cloud will finally disappear in a late T dwarf or whether it still exists in the deeper layer. Unfortunately, this problem cannot be answered with observations, since no information is available from the optically thick region.

It is to be remembered that the immersion of the dust cloud in a cooler dwarf is a natural consequence of the change of the photospheric structure according as L dwarf evolve to T dwarf, and this is simply because the dust cloud always forms at about the same temperature, namely, at $T_{\text{cond}} \approx 2000$ K, which is in the optically thin (thick) region of the objects with relatively high (low) $T_{\text{eff}}$. However, the thinning of the dust cloud is more difficult to understand by such a simple picture. A known noticeable change of the photospheric structure at $T_{\text{eff}} \approx 1400$ K is the formation of the second (outer) convective zone (Paper I), which may have some impact on the formation and destruction of the clouds. Since the convective activities may depend on the age and evolutionary history of the cooling brown dwarfs, the nature of cloud including $T_{\text{cr}}$ may depend on such effects as well. However, the details of how the convective activity is related to the variation of $T_{\text{cr}}$ are unknown at present.

The critical temperature $T_{\text{cr}}$ and its variation should be a key in our understanding of the photospheric structure and hence of the observed properties of dusty dwarfs. In this paper, however, we leave $T_{\text{cr}}$ as a free parameter to be estimated from observations. It would be desirable, of course, to be able to determine $T_{\text{cr}}$, or more generally the upper boundary of the dust cloud, from the basic physics. However, this is highly model dependent at present. For example, Woitke & Helling (2004) recently proposed an interesting model in which a series of processes, such as nucleation, dust growth, gravitational settling, evaporation, and element replenishment, take place in a convective life cycle in the photosphere, and the structure of the dust cloud, including its upper boundary and dust properties like the grain size, can be determined by solving their moment equations in the circulating flow. In this model, however, everything depends on a parameter called the mixing timescale, which was assumed to be a measure of the efficiency of the convective activity including overshooting. But it is by no means clear whether the mixing will take place in such a way as to interact with the dust formation as nicely as assumed in their model. For example, the structural models of cool dwarfs show that convective zone is situated deeper in L dwarfs than in T dwarfs (e.g., Tsuji 2002), and hence mixing in the photosphere induced by the convection will be more effective in T dwarfs than in L dwarfs. Then, if the mixing plays a major role in cloud formation, a question is why T dwarfs are not dusty, while L dwarfs are.

Our major concern at present is to interpret observed data in terms of the basic stellar parameters, such as $T_{\text{eff}}$, log $g$, metallicity, and chemical composition. For this purpose, it is required to predict observables, such as colors, magnitudes, and spectra, and our empirical model, referred to as UCM, is developed primarily with such applications in mind. So far as the model is empirical, the cloud property $T_{\text{cr}}$ (i.e., the upper boundary of the cloud) is simply estimated empirically and hence free from any particular model of cloud formation, which is currently not well established. Such an empirical approach still plays an important role in our studies of stellar and substellar photospheres. For example, stellar convection theories, which we have also employed in our UCMs, mostly involve a parameter known as the mixing length, and the microturbulent velocity is usually determined empirically rather than evaluated theoretically for individual objects. Of course an empirical approach is only an initial step toward more complete modeling, but we must recognize that the stellar and substellar photospheres still involve formidable problems for which a fully theoretical solution is difficult at present.
Finally, it is to be noted that the critical temperature $T_{cr}$ is a parameter inherent to our UCMS, and the fifth parameter next to the $T_{eff}$, $\log g$, chemical composition, and microturbulent velocity need not necessarily be restricted to $T_{cr}$. For example, another parameter that characterizes the dust clouds, such as the sedimentation efficiency $f_{sed}$ in the models of Marley et al. (2002), plays a similar role as our $T_{cr}$, and their cloudy models have extensively been applied to the interpretation and analyses of the recent observations of L and T dwarfs (e.g., Knapp et al. 2004; Golimowski et al. 2004). From these analyses and from ours outlined in this paper, the cloudy models of Marley et al. (2002) and our UCMSs basically agree, in that the cloud properties depend on a dynamical process whose origin cannot be identified yet and whose effect had to be represented by a variable parameter, such as $f_{sed}$ or $T_{cr}$. In practical applications our $T_{cr}$ may have some advantages, in that it can easily be incorporated in the classical nongray theory. In addition, $T_{cr}$ has a clear physical meaning related to the thickness of the dust clouds, and hence can be inferred directly from the observed infrared colors. Furthermore, we have shown that almost all the data points in the large collective data, such as the two-color diagram and CM diagram, can be consistently interpreted with the $T_{cr}$ values in the appropriate range; this fact implies that $T_{cr}$ is a reasonable choice as a parameter for the characterization of dusty dwarfs.

In conclusion, we believe that we have now applied our UCMSs more properly to the interpretation and analysis of the observed data of dusty dwarfs, with the recognition that the parameter $T_{cr}$ takes different values in addition to $T_{eff}$ and $\log g$ (under the fixed chemical composition and microturbulent velocity). We certainly realized that dust plays an important role in determining the observed properties of cool dwarfs at an early time, but we did not fully understand its effect nor treat it properly until now. We should now recognize that the dust is one of the fundamental elements in the characterization of dusty dwarfs. Based on this recognition, we must reexamine the observed data in more detail and reconsider such a basic problem as the spectral classification of ultracool dwarfs, which cannot be a simple extension of the stellar spectral classification. A relatively short history of the studies on ultracool dwarfs including brown dwarfs was already quite intriguing, and thus such ultracool dwarfs will remain to be exciting subjects of further observational and theoretical challenges.

Note added in manuscript.—One difficulty in the present computation of the spectra of ultracool dwarfs was the lack of a reliable line list of methane, but we were able to access a new extensive line list by R. Freedman (2004, private communication) after this work was completed. This line list by Freedman has been generated based on the software package “The Simulation of XY Spherical Top Spectra,” developed at Laboratoire de Physique de l’Université de Bourgogne (http://www2.u-bourgogne.fr/LPUB/TSM/TDS.html). We found that the new line list (which consists of about 10 million lines) offered a substantial improvement over the previous line lists, as in the GEISA database (which consists of only some 50 thousand methane lines), and our case II spectra based the GEISA line list should now be replaced with the ones based on the Freedman’s line list (to be referred to as case III). The spectrum computed with the case III methane opacity just comes between those computed with the case I (representing the maximum estimate with the completely smeared-out band model) and the case II (underestimate with only low excited lines) opacities, as expected. This fact shows that the Freedman’s line list is an important step toward better methane opacity. However, we found that the methane opacity in the $H$-band region may be still underestimated with the Freedman’s line list; this fact may imply the extreme complexity of the methane spectra, especially in the combination bands such as found in the $H$-band region. Instead, the spectra in the $H$-band region could still be better represented by our case I spectra based on the band model opacity for methane. In fact, such colors as $J - H$ and $H - K$ could be reasonably well reproduced with the case I methane opacity, as already shown in Figure 1. Thus, we suggest that the spectra and colors based on the Freedman line list and/or those based on the band model opacity should be considered on case by case in actual applications. For this purpose, we uploaded the predicted spectra and colors based on the case I and case III methane opacities in our Web site, recently updated (http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucm).

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