The L to T Dwarf Transition

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Abstract

While the precise mechanism responsible for the L to T dwarf transition remains unclear, it is clearly caused by changing cloud characteristics. Here we briefly review data relevant to understanding the nature of the transition and argue that changing atmospheric dynamics produce the transition by opening holes through the global iron and silicate cloud decks. Other possibilities, such as a sudden vertical collapse in these cloud decks are also considered. Any acceptable model of the L to T transition must ultimately connect changing cloud properties to the underlying atmospheric dynamics.

Key words: Stars: brown dwarfs

1. Introduction

As the atmospheres of brown dwarfs cool with time, their spectral signatures reflect a progression of changes in their atmospheric chemical equilibrium and condensate structure. In M dwarfs the elements O, C, and N are predominantly found in H₂O, CO, and N₂ and the atmosphere is too warm for condensation of solids (Allard & Hauschildt 1995; Lodders 1999). As the effective temperature (Tₑff) falls, a variety of condensates form in the atmosphere, most notably iron and silicates. These condensates are apparently not well-mixed through the atmosphere, but are found in discrete cloud layers overlying the condensation level (Ackerman & Marley 2001; Marley et al. 2002; Tsuji 2002; Woitke & Helling 2004).

By the time the Tₑff falls to that of a late L dwarf the cloud layer is optically thick and affects either directly (as a major opacity source) or indirectly (by altering the atmospheric temperature/pressure profile) all spectral regions. The exact spectral signature of the cloud depends both on its vertical thickness and the particle size distribution of the condensates. In addition, as the atmosphere cools, chemical equilibrium begins to favor first CH₄ over CO and then NH₃ over N₂ (Tsuji 1964; Fegley & Lodders 1996). Thus CH₄ absorption in the K band begins to replace CO and NH₃ appears (Roellig et al. 2004) in the mid-infrared by the late L’s. By the early to mid T dwarfs the condensate cloud is forming quite deep in the atmosphere. In the relatively clear, cool atmosphere above the cloud, chemical equilibrium begins to strongly favor CH₄ and NH₃ and their spectral features, along with particularly strong bands of water, grow in prominence (Marley et al. 1996, Burrows et al. 1997, Allard et al. 2001, Burrows 2003).
2. Signatures of the L to T Transition

Below we summarize the characteristics exhibited by brown dwarfs at and near the L to T transition (approximately L8 to T5):

*Turn to the blue in J − K*: The colors of L dwarfs become progressively redder until they saturate at $J - K \sim 2$ at spectral type L8 (Knapp et al. 2004). This color then rapidly turns to the blue, reaching $J - K \sim -0.8$ by T8 or so.

*Color change at near constant $T_{\text{eff}}$*: Recent estimates of the bolometric $T_{\text{eff}}$ from Golimowski et al. (2004) have quantified the rapid rate of this color change, as shown in Figures 4 and 5. Most (> 80%) of the change is $J - K$ color is seen to occur over a very small $T_{\text{eff}}$ range near 1300 K. This is a remarkable result as it implies that brown dwarfs are undergoing substantial spectral and color changes over a very small temperature range.

*Brightening at J Band*: The L to T transition also appears to be associated with a brightening at J band from late L to early T (T4 or so) (Knapp et al. 2004). $H, K, L,$ and $M$ bands show no sign of such brightening (Knapp et al. 2004; Golimowski et al. 2004), while there is some evidence of a brightening at $Z$. It should be noted that the bolometric luminosity, as would be expected, does not increase across the transition (Golimowski et al. 2004).

*Resurgence of FeH*: Burgasser et al. (2002) argue there is evidence that, after decaying away as FeH is presumably lost to Fe drops and grains, the 0.997 µm FeH band shows
a resurgence in strength, coincident with the $J-K$ color change.

Model Spectral Fits: The comparison of models and data shown in Figures 1 through 3 provides additional information about the transition. In Figure 1 a cloudy model does a good job of reproducing the $K$-band spectra of an L5 dwarf. A model with no cloud opacity predicts too much methane absorption in both $K$ and $L$ bands as well as a too-deep water band. Comparing the cloudy and cloudless models for this object makes clear why the $J-K$ color is such an important diagnostic for the cloud. In the $L$ band the model gets the depth of the 3.3 $\mu$m methane band correct, which suggests the thermal structure of the model and the associated equilibrium methane abundance are reasonable.

By T2 (Figure 2), however, a model using the same cloud model (Ackerman & Marley 2001) is apparently somewhat too warm, predicting a bit too much CO and too little CH$_4$. At $K$ band the observed spectrum lies between this cloudy model and a cloudless model. The overall shape of the $L$ band spectrum, which probes higher in the atmosphere, seems to be best fit by a combination of the cloudy and cloudless models. Interestingly the amplitude of the methane feature at 3.3 $\mu$m is larger than either the cloudy or cloudless models predict, which may indicate that the temperature gradient in the photosphere above the cloud deck is steeper than either model predicts.

Finally by T5 (Figure 3) a model with no cloud opacity (but with condensation included in the equilibrium chemistry) fits very well both at $K$ and $L$ bands, implying that condensates play a very small role in controlling the thermal profile and emitted flux. The difference between the best fitting models for the T2 and the T5 dwarfs is only 100 K!

3. The Transition Mechanism

Any explanation of the L to T transition mechanism must be consistent with the evidence summarized above. The unmistakable gross explanation—that condensates have been lost from the atmosphere—belie the difficulty in explaining this loss is a self-consistent manner. That a sinking, finite-thickness cloud deck will eventually disappear from sight allowing the atmosphere above to cool has been apparent for some time (Marley 2000, Allard et al. 2001, Marley et al. 2002, Tsuji 2002). The difficulty lies in explaining the rapidity of the color change in light of the measured effective temperatures (Figures 4 and 5). For example while nicely accounting for the $J-K$ colors of the reddest L dwarfs, the model of Ackerman & Marley (2001) takes much too long to ultimately sink out of sight (Burgasser et al. 2002, Knapp et al. 2004).

In a series of papers Tsuji (Tsuji 2001, Tsuji & Nakajima 2003, Tsuji et al. 2004) proposed that a physically thin cloud, thinner than predicted by the Ackerman & Marley model, could self-consistently explain the rapid L to T transition. These ‘UCM’ models indeed exhibit a faster L to T-like transition, but as Figure 4 demonstrates the UCM models are not consistent with the observed rapidity of the color change. Even accounting for a likely spread in gravities across the transition can not account for the observations. In addition the UCM models, like the cloudy models of Marley et al., do not brighten in $J$ band across the transition. Tsuji et al. had to invoke an exceptionally large spread in atmospheric log $g$ of known sources across the transition in order to account for both the reddest and dimmest late L dwarfs and the brightest and bluest early T dwarfs. Finally the UCM models could not explain the resurgence in FeH that is observed across the transition.

To overcome the sort of difficulties faced by the Tsuji et al. models, Burgasser et al. (2002), following a suggestion from Ackerman & Marley (2001), hypothesized that at the L to T transition the global cloud deck rapidly breaks apart. Under this scenario holes in the cloud deck appear at $T_{\text{eff}} \sim 1300$ to 1400 K. In the molecular window regions, particularly $Z$ and $J$ bands, bright flux from deeply seated regions pours out of the holes left by the departure of the cloud deck. This outpouring of flux is then responsible for the rapid color change in $J-K$ (Figure 5), the brightening in $J$ (and apparently also $Z$) band, and the reappearance of FeH. The fact that the T2 dwarf (Figure 2) seems to be a composite of the cloud free and cloudy model spectra supports this interpretation.
Figure 5. Data points same as in Figure 4. Model curve is a composite of cloudy models (for $T_{\text{eff}} \geq 1400$ K) and clear (for $T_{\text{eff}} \leq 1400$ K) models (Marley et al. 2002) connected by a vertical line at $T_{\text{eff}} = 1400$ K, all for log $g = 5$.

Burgasser et al. suggest that the cloud holes appear when the combined iron and silicate clouds sink sufficiently deeply into the global convection zone. On Earth clouds tend to be more spatially uniform when they form in relatively shallow convective layers. Regions in which the convective layer is thick, such as near the equator, seem to be inhabited by towering cumulus clouds separated by cloud-free regions. The presence of some relatively cloud-free regions in the atmospheres of Venus and Jupiter provides evidence that cloud layers are generally not globally uniform in planetary atmospheres and supports the plausibility of the mechanism.

Finally Knapp et al. (2004) proposed a tertiary alternative in which the sedimentation efficiency of the cloud substantially increases at the transition. In this case the cloud remains homogeneous across the disk, but particle growth becomes much more efficient. Efficient growth leads to larger particles which more rapidly fall out of the atmosphere. This leads to optically thinner clouds. In the language of Ackerman & Marley (2001) this is described as $f_{\text{sed}} \to \infty$. As discussed elsewhere in these proceedings, Tsuji and collaborators now favor a sudden collapse of the global cloud deck ($T_{\text{crit}} \to T_{\text{cond}}$) at the transition. This is similar to the Knapp et al. (2004) suggestion with the exception that Tsuji et al. do not address the particle size.

Regardless of whether the L to T transition is explained by the appearance of holes in the global cloud deck or a sudden increase in the efficiency of condensate sedimentation, the root cause must lie with the atmospheric dynamics. What aspect of atmospheric circulation or dynamics would favor the appearance of holes or the sudden collapse of the cloud deck? Perhaps the behavior of condensates change when the cloud reaches a certain depth in the atmospheric convection zone or perhaps the second, detached convection zone found in brown dwarf atmosphere models (Marley et al. 1996, Burrows et al. 1997, Allard et al. 2001, Tsuji 2002) plays a role. Another possibility is that there is a change in the global atmospheric circulation that affects the behavior of the cloud decks. Schubert & Zhang (2000) found that brown dwarfs likely exhibit one of two styles of global atmospheric circulation: dominated by rotation, like Jupiter, or fairly independent of rotation, like the sun. Since the luminosity falls with age, the Rayleigh and Eckman numbers of brown dwarfs, which influence the regime in which the atmospheric dynamics falls, likewise vary with time. Perhaps the L to T transition is associated with a change between the two regimes. Until such possible mechanisms have been quantitatively addressed the nature of the L to T transition will remain the domain of plausible, if ad hoc, modeling.

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