The Role of Dust Clouds in the Atmospheres of Brown Dwarfs

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Abstract. The new spectroscopic classes, L and T, are defined by the role of dust clouds in their atmospheres, the former by their presence and the latter by their removal and near absence. Moreover, the M to L and L to T transitions are intimately tied to the condensation and character of silicate and iron grains, and the associated clouds play pivotal roles in the colors and spectra of such brown dwarfs. Spanning the effective temperature range from $\sim 2200$ K to $\sim 600$ K, these objects are being found in abundance and are a new arena in which condensation chemistry and the optical properties of grains is assuming astronomical importance. In this short paper, I summarize the role played by such refractories in determining the properties of these “stars” and the complexities of their theoretical treatment.

1. The Importance of Dust Clouds in Cool Atmospheres

As the temperatures of a stellar atmosphere decrease below $\sim 4000$ K, molecules form and begin to dominate. Water and carbon monoxide are two of the first to make their mark, but despite the low elemental abundance of titanium ($\sim 10^{-7}$) and vanadium, TiO and VO too emerge in the M dwarf range as distinctive signatures in the optical. Figure 1 portrays the elements in order of abundance, shows the major molecules into which these elements partition as the temperature decreases, and suggests which species predominate due to their relative abundance. However, as $T_{\text{eff}}$ decreases further and approaches $\sim 2200$ K, many of the more refractory elements condense out into clouds of dust. Figure 2 depicts many of the corresponding condensation curves at solar metallicity. Titanium begins to form perovskite (CaTiO$_3$) and higher oxides, followed near $\sim 1700$−$1800$ K by vanadium, which first forms condensed VO. Importantly, calcium-aluminum and calcium-magnesium silicates (such as akermanite, diopside, hibonite, and grossite) form and sequester many refractory elements into grains, whose depletion is indirectly manifest by the gradual disappearance of atomic lines of titanium, calcium, aluminum, and silicon. More importantly, a haze is formed that thickens into formidable clouds whose continuum opacity begins to redden the object’s near-infrared spectrum. This reddening signals the appearance of the new spectroscopic class of L dwarfs. Indeed, the M to L transition is caused by the formation of dust (and the simultaneous disappearance of TiO and VO). The entire L dwarf sequence is dominated by the prevalence of dust clouds and is defined by red $J-K$ colors. Since the calcium and aluminum abundances are $\sim 10\times$ smaller than the magnesium and silicon abundances, trapping the former into the most refractory compounds in stoichiometric ratios leaves plenty of the...
latter to form magnesium silicates, such as enstatite (MgSiO$_3$) and forsterite (Mg$_2$SiO$_4$), at temperatures below $\sim$1850 K. These species of dust, along with iron droplets and numerous compounds all along the olivine and pyroxene sequences, constitute the opaque clouds that determine L dwarf properties.

Since the base of a cloud is found near its condensation line, which in temperature-pressure space is mostly a function of temperature, a cloud’s geometric thickness may be some fraction of a pressure scale height. As $T_{\text{eff}}$ decreases, though the cloud’s optical thickness increases further it is progressively more deeply buried. Figure 3 portrays the positions of the radiative-convective boundaries, the photospheres, and the realm of the relevant condensation curves for a $T_{\text{eff}}$ sequence of self-consistent atmosphere models. When $T_{\text{eff}}$ reaches $\sim$1000-1200 K, the $\sim$1500–2200 K region of the atmosphere where refractory clouds reside has been buried so deeply that silicates, though present, are of secondary importance in the emergent spectrum. At this point, the atmosphere is depleted of refractory metal elements and emerges into the T dwarf realm. This is the L to T dwarf transition, characterized by such a clearing. Hence, the appearance and disappearance of dust is of central importance in distinguishing the M, L, and T dwarf spectral classes. Were it not for dust, the L dwarfs would not exist as a spectroscopic type.

Moreover, the edge of the hydrogen-burning main sequence, in fact what determines a star, is in the middle of the L dwarf sequence (not at the end of the M dwarf sequence!). Hence, the opacity of silicate grains plays a central role in determining what is and is not a star. Currently, we estimate that the solar-metallicity stellar edge is near L4/5, a $T_{\text{eff}}$ of $\sim$1700 K, a bolometric luminosity of $\sim$6x10$^{-5}$ L$_{\odot}$, and a mass of $\sim$0.074 M$_{\odot}$ (Burrows et al. 2001), but we really don’t know. This is a curious state of affairs after more than 100 years of astrophysics and is one more indication of the importance of dust in astronomy.

2. Complications of Cloud Modeling

Unfortunately, to understand the M→L→T sequence and their spectra in detail requires a mastery of not only the chemical condensation sequences and the consequent elemental depletions (“rainout”; Burrows & Sharp 1999) in a gravitational field, but the spatial extent, particle size and shape distributions, grain optical properties, and meteorology of clouds as well. These complications do not confront one who models most other types of “stars” and make brown dwarf theory rather more challenging.

These challenges have not yet been adequately met. There are many reasons, a few of which I now identify. At a given pressure, the refractories included in Fig. 2 appear in a narrow range of temperatures. Furthermore, just a bit later than the early L dwarfs the optical depths of such clouds are likely to be sufficient to trip convection (and the associated updrafts and downdrafts) where there are clouds. Hence, after the early Ls (for which the first condensates inhabit a stably-stratified radiative zone) every condensate whose condensation curve intersects a dwarf’s $T/P$ profile will most probably reside in a common convection zone. It does not make sense to assume that each condensate is a separate, isolated layer. Rather, as the $T_{\text{eff}}$ decreases and the first clouds thicken, convection is tripped in the atmosphere. The kinetics of such a soup
of growing condensates in or out of a convective zone is a daunting problem, though grain growth in the brown dwarf context has been receiving some attention of late (Ackerman & Marley 2001; Cooper et al. 2003; Helling et al. 2001, 2004; Woitke & Helling 2003, 2004). Note that below the cloud base in the inner convective zone is the “infinite” reservoir of heavy elements that extends throughout the dwarf and that sets the heavy-element abundance boundary condition. However, the heavy elements that may have once existed in the upper atmosphere before condensation do not all remain in the cloud once formed. How much cloud material does remain in the cloud depends on the dynamics of the cloud itself.

Clearly, the equilibrium particle size distribution, achieved through the balance of growth processes in the convective zone and grain destruction at and below the $T/P$-profile/condensation-curve intercept, is very poorly constrained by theory. Furthermore, the optical constants of heterogeneous grains of indeterminate composition and layering are not easily derived from first principles. Qualitatively, it is clear that the modal particle size of grains in stable radiative zones is smaller ($\sim 0.1-5.0 \, \mu m$) than in turbulent convective zones ($\sim 10-150 \, \mu m$), but confidence in the current analytic estimates should not be great. Unfortunately, modeling requires a handle on particle growth and size, composition, optical properties, and cloud spatial extent, all in the context of a consistent radiative-convective atmosphere model with, perhaps, non-equilibrium chemistry.

3. Anomalies in Brown Dwarf Atmospheres

There are numerous unexplained facts concerning brown dwarf spectra, many of which are related to dust physics. The brightening in the $J$ band (Dahn et al. 2002; Tinney, Burgasser, & Kirkpatrick 2003; Vrba et al. 2004) is the most intriguing anomaly. Its explanation must be the rapid thinning out of the clouds in the spectrum-forming region of the brown dwarf atmosphere during the L→T transition. Figure indicates why on generic grounds one would expect such a brightening to be in the $J$ and $Y/Z$ ($\sim 1.0-1.1 \, \mu m$) bands, if anywhere. But how the effective opacity of the silicate clouds decreases so quickly with $T_{\text{eff}}$ and spectroscopic subtype to yield heavy-element depleted T-dwarf atmospheres has yet to be explained. Current models are not adequate (Tsuji, Nakajima, & Yanagisawa 2004; Allard et al. 2001; Marley et al. 2002; Burrows, Sudarsky, & Hubeny 2006). Burgasser et al. (2004) have postulated the break up of the clouds near a $T_{\text{eff}}$ of 1200–1300 K and the appearance of holes, whose filling fraction increases across the L→T transition until that fraction is unity. A virtue of this model is the natural explanation of the apparent resurgence of the FeH features in the early- to mid-T dwarfs (Burgasser et al. 2004; McLean et al. 2003; Cushing, Rayner, & Vacca 2005). The FeH abundances near the photospheres should be waning; holes could allow us to see more deeply to the higher-temperature regions in which the FeH abundance is large. Knapp et al. (2004) suggest an increase in the “sedimentation efficiency” of the clouds, with a concomitant rapid increase in the silicate particle size. Liu & Leggett (2005), Burgasser et al. (2005), and Burrows, Sudarsky, & Hubeny (2006) suggest some role for binarity (“crypto-binarity”) at the L to T transition. The binary fraction
of T dwarfs is not negligible and $\sim 0.75$ mag ($2.5 \times \log_{10} 2$) is near the magnitude of the few excesses measured.

Burrows, Sudarsky, & Hubeny (2006) have shown that when calcium-aluminate, silicate, and Fe clouds first form they do so in the radiative region, that as $T_{\text{eff}}$ decreases an isolated convective zone emerges, and that for even lower $T_{\text{eff}}$s the two convective zones join. Figure 3 depicts this merger and the relative positions of the photospheres and the radiative-convective boundaries. However, it remains to be seen what happens to the particle sizes and cloud morphology when these regions merge. Shaw (2003) and Kostinski & Shaw (2005) investigate the dependence of runaway droplet growth and rainout on the presence in convective clouds of large velocity shears and on intermittency in the turbulence. Could the merger of the outer convective cloud with the inner convective zone lead to regions of such large shears, in which particle growth on the timescales available is more rapid, and, hence, lead to very large particles? Could the merger lead to the irreversible partial flushing of cloud material into the interior? After the joining of the convective zones, is the timescale for grain growth too long for the convecting feedstock to avoid being dragged into the hot interior before forming opaque grains? Is a critical $T_{\text{eff}}$/gravity threshold for rapid grain coalescence and growth reached, beyond which the average particle is too large to contribute significant opacity (Liu, Daum, & McGraw 2005)? Or does the scale height of the silicate cloud collapse at some $T_{\text{eff}}$ threshold? The answers to these questions require a multi-dimensional approach both to grain kinetics and growth and to convective cloud structures and motions, all properly coupled.

4. Rainout and the Importance of Alkali Metals

One of the curiosities of brown dwarf spectra is the prevalence and importance in the optical and near infrared of just two doublets, the sodium D lines centered at 0.589 $\mu$m and the corresponding potassium resonance lines at $\sim 0.77$ $\mu$m. In fact, these two features, by dint of their breadth at the high pressures encountered in brown dwarf atmospheres, dominate the spectra from $\sim 0.5$ $\mu$m to $\sim 1.0$ $\mu$m of all dwarfs later than late-Ls. Since cool atmospheres are partially or totally depleted of the heaviest elements, and these alkali lines are strong, there are few other significant contributions to the opacity over this octave. One of the results is that the combination of absorption by Na-D in the yellow, the low temperatures that put the optical in the Wien tail, and the behavior of the red wing of the potassium doublet all conspire to make it impossible for brown dwarfs to be brown. The color “brown” needs some yellow, denied to the object because of the Na-D absorption feature. The result is a “magenta” dwarf, much closer to purple than to brown.

Whither the primacy of these neutral alkali metals? As discussed above, condensation of refractory compounds depletes the atmosphere of, for example, Ca, Al, Mg, and Si. However, Na and K are not as refractory and would condense out at lower temperatures nearer $\sim 1400$ K. Moreover, they would condense into the feldspars high albite and sanadine, and such feldspars require silicon and aluminum. But, since Al and Si elements have already rained out at higher temperatures and settled, they are not available. The upshot is that these most abundant of alkalis persist in their nascent atomic form to even lower temper-
atures below \( \sim 1000 \) K, at which point they condense predominantly into \( \text{Na}_2\text{S} \) and \( \text{KCl} \). The result is that atomic sodium and potassium are in evidence over a broad range of \( T_{\text{eff}} \)s in the brown dwarf realm. This, and their strong spectral influence, combine to determine brown dwarf optical and near-IR spectra and colors from \( T_{\text{eff}} \)s of \( \sim 1300 \) K to \( \sim 500 \) K. Figures 5 and 6 from Burrows, Marley, \& Sharp (2000) depict examples of the dependence of alkali chemistry on atmospheric temperature, without and with rainout. As a comparison between these figures demonstrates, rainout extends the domain of importance of atomic Na and K below where equilibrium chemistry would have depleted them. In any case, dust plays a central role, however indirect, in the spectra of brown dwarfs.

5. Conclusions

The physics and chemistry of dust and clouds have emerged as important components in brown dwarf theory. Dust determines the position of the edge of the hydrogen-burning main sequence, is responsible for an entire spectroscopic class (the L dwarfs), and significantly affects the abundances and alters the spectra of brown dwarf atmospheres. However, the treatment of silicate clouds in theoretical models is still rather primitive. Therefore, the condensation, optical properties, grain growth physics, and meteorology of refractories in brown dwarfs deserves and is getting more attention. Nevertheless, it is fascinating that something so prosaic could have so many effects, direct and indirect. The reader should be aware that I have listed here only a few of the most interesting.

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Figure 1. This figure depicts the trend of elemental abundance with atomic weight and identifies the dominant chemical forms of each in the context of brown dwarf atmospheres.
Figure 2. Solar-metallicity condensation curves (temperature in Kelvin versus pressure in atmospheres) for many of the most important refractory species thought to appear in the atmospheres of brown dwarfs and L dwarfs. The most refractory compound is the calcium aluminate grossite ($\text{CaAl}_4\text{O}_7 \equiv \text{CaO} + 2(\text{Al}_2\text{O}_3)$). Corundum ($\text{Al}_2\text{O}_3$), as such, does not generally form. $\text{CaMgSi}_2\text{O}_6$ is diopside, $\text{Mg}_2\text{SiO}_4$ is forsterite, $\text{MgSiO}_3$ is enstatite, $\text{MgAl}_2\text{O}_4$ is spinel, and $\text{Ca}_2\text{MgSi}_2\text{O}_7$ is akermanite. The dotted curves correspond to the refractory titanium compounds. Liquid Fe is the solid curve at a slightly shallower slope than those for the calcium/aluminum/magnesium condensates (solid). Included for comparison are the condensation curves for water ($\text{H}_2\text{O}$) and ammonia ($\text{NH}_3$). Notice how the condensation curves of the refractory compounds densely inhabit a narrow range of T/P space and that there is a noticeably wide gap between this refractory band and water. See text for a discussion of the salient features of this figure. [Taken from Burrows, Sudarsky, & Hubeny 2006]
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Figure 3. Temperature-pressure profiles for a set of models with constant surface gravity, \( \log_{10} g (\text{cm s}^{-2}) = 5.0 \) and particle size, 100 microns, for different effective temperatures ranging from \( T_{\text{eff}} = 2200 \text{ K} \) (leftmost curve) to 700 K (rightmost curve). The positions where the local temperatures are equal to the effective temperatures (which indicate approximate locations of the photospheres) are shown as asterisks. The cloud bases are depicted as dashed lines; the black dots show the position of the boundaries of the convection zone(s). Notice the occurrence of two distinct convection zones for \( T_{\text{eff}} = 1700 \text{ K} \) and 1800 K. [Taken from Burrows, Sudarsky, & Hubeny 2006]
Figure 4. Abundance-weighted comparison of forsterite opacity for 30-µm and 100-µm modal particle sizes with that of the total gas opacity at a pressure of 1 bar and temperature of 1500 K. In the $Y/Z$ and $J$ bands, forsterite can be a dominant opacity source, depending upon the depth of the cloud layer in the atmosphere. [Taken from Burrows, Sudarsky, & Hubeny 2006]
Figure 5. The abundances of alkali metal compounds and atoms under the assumption of chemical equilibrium, without rainout, in a representative brown dwarf atmosphere. [Taken from Burrows, Marley, & Sharp 2000]
Figure 6. The same as Fig. 5 but with rainout. Note that the sequestration of aluminum and silicon in more refractory species deeper in the atmosphere at higher temperatures undermines the formation of the feldspars of sodium and potassium. This allows the atomic form of these alkalis to survive to lower temperatures and enhances and extends the predominance of the resonance lines of atomic sodium and potassium over brown dwarf spectra. It is only at still lower temperatures that sodium and potassium (near $\sim$900-1000 K) condense out into Na$_2$S and KCl and that their effects on brown dwarf spectra from $\sim$0.5 $\mu$m to $\sim$1.0 $\mu$m abate. [Taken from Burrows, Marley, & Sharp 2000]