

Clouds and Clearings in the Atmospheres of the L and T Dwarfs

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Abstract. A sophisticated approach to condensate opacity is required to properly model the atmospheres of L and T dwarfs. Here we review different models for the treatment of condensates in brown dwarf atmospheres. We conclude that models which include both particle sedimentation and upwards transport of condensate (both gas and particles) provide the best fit for the L dwarf colors. While a globally uniform cloud model fits the L dwarf data, it turns to the blue in $J - K$ too slowly to fit the T dwarfs. Models which include local clearings in the global cloud deck, similar to Jupiter's prominent five-micron hot spots, better reproduce the available photometric data and also account for the observed resurgence of FeH absorption in early type T dwarfs.

1. Introduction

Long before the first discoveries of brown dwarfs, it was recognized that condensates would play a critical role in controlling their atmospheric opacity, at least

in certain effective temperature ranges (Stevenson 1986; Lunine et al. 1989). It was also evident that the correct choice for the vertical distribution of the condensates was not obvious (Lunine et al. 1989). Condensates might be well mixed in the atmosphere above their condensation level, or might coalesce into large particles, fall below their condensation level and be removed from the atmosphere. Of course many intermediate cases are possible as well.

After the discovery of what came to be known as the L and T dwarfs, modelers initially focused on simple end cases. Condensates were either assumed to have either completely settled from the atmosphere or else were mixed uniformly throughout the observable atmosphere. The prior approach works reasonably well for objects like Gl 229 B (Allard et al. 1996; Marley et al. 1996; Saumon et al. 2000; Tsuji et al. 1996), while the latter works for very late M and early L dwarfs like Kelu 1 (Ruiz, Leggett & Allard 1997). Neither approach, however, could adequately reproduce the colors, let alone the spectra of the latest Ls or the 'transition' late L/early T objects, like SDSS 1254 (Fig. 1). Models (Fig. 1) in which the condensates are absent from the atmosphere produce $J - K$ colors that are much bluer than the observed L dwarfs. The blue color arises from water, pressure-induced H_2 , and for lower effective temperatures ($T_{\text{eff}} < 1400$ K) CH_4 absorption in K band. Models with condensates distributed uniformly through the atmosphere match the early Ls in which the condensate column optical depth is small, but are much redder than the colors of the later L dwarfs. The reason is that as the cloud deck falls progressively deeper in the atmosphere the column abundance of dust gets progressively larger. Since the cloud is forming at higher gas densities the abundance of condensates to be mixed upwards from cloud base is larger with falling effective temperature. Thus an outside observer sees an ever increasing dust optical depth until the observer is effectively looking at a dirt-filled atmosphere. Like blackbodies, such objects becomes progressively redder in $J - K$ as they cool. These models cannot reproduce the observed transition from red to blue in $J - K$ between the L and T dwarfs.

An obvious shortcoming of the first generation models is that none of them employed cloud decks like those seen throughout the solar system. Condensates in planetary atmospheres are generally neither completely settled out of the atmosphere nor distributed uniformly to the top of the atmosphere. Rather they tend to exist in horizontally-extended cloud decks. The H_2SO_4 clouds of Venus, stratiform water clouds on Earth, the ammonia cloud decks on Jupiter, and the methane clouds in Uranus and Neptune are all examples of this.

To demonstrate that a vertically constrained cloud deck would qualitatively be more in line with the available data, Marley (2000) constructed a simple model in which all clouds were 1 scale height thick. He showed that such a model produced less red $J - K$ colors than well mixed models and also naturally explained the turnover in $J - K$ color from the red L dwarfs to the blue T dwarfs. As the cloud forms progressively lower in the atmosphere as the object cools, the cloud disappears while the clear atmosphere above takes on the appearance of the cloud-free models. Tsuji (2001) also used a simple model with a finite-thickness cloud to make the same point.

Given the apparent importance of correctly modeling cloud behavior, Ackerman & Marley (2001) developed a more rigorous cloud model for use in sub-stellar atmosphere models. The model attempts to capture the key 'zeroth order'

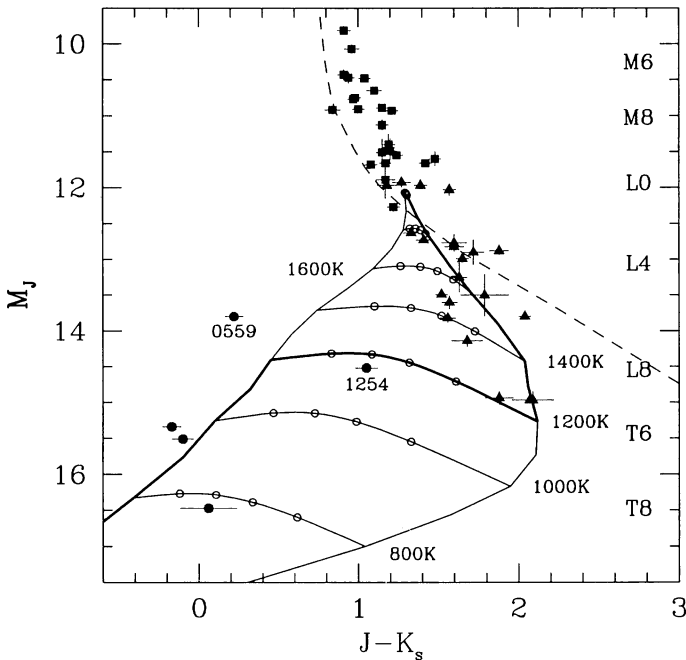


Figure 1. Near-infrared color-magnitude diagram of M, L, and T dwarfs. The absolute J magnitudes and $J - K_s$ infrared colors are shown for a sample of M (filled squares), L (filled triangles), and T (filled circles) dwarfs with known parallaxes. The positions of 2MASS 0559 and SDSS 1254 are indicated. The predicted colors and magnitudes for the DUSTY (dashed line), clear (left thin line), and cloudy (right thin line; $f_{\text{sed}} = 3$) (the variable formerly known as f_{rain}) atmosphere models are plotted as a function of T_{eff} at constant gravity, $g = 10^5 \text{ cm s}^{-2}$ (typical for very low mass main-sequence stars and evolved brown dwarfs). Connecting the cloudy and clear tracks are the predicted fluxes for partly cloudy models at $T_{\text{eff}} = 800, 1000, 1200, 1400, 1600,$ and 1800 K. The circles indicate the cloud coverage fraction in steps of 20%. The apparent evolutionary track of brown dwarfs based on the empirical data is indicated by the thickened line, which crosses from the cloudy to clear track at $T_{\text{eff}} \sim 1200$ K. Figure adapted from Burgasser et al. (2002).

physics which influence the vertical condensate abundance and size profiles in a realistic (but 1-D) atmosphere. This model was used by Marley et al. (2002) and Burgasser et al. (2002) to model the atmospheres of L and T dwarfs. Other workers have recently turned to the work of Rossow (1978), originally developed to study the microphysics of clouds in planetary atmospheres, to model cloud behavior in substellar atmospheres. Finally Tsuji (2002) has further developed his model in which the cloud top temperature is an adjustable parameter. In Section 2 we review and compare these cloud models. In Section 3 we summarize the results of Burgasser et al. in applying the Ackerman & Marley cloud model to L and T dwarfs and consider the role of dynamically-induced holes in the global cloud coverage.

2. A Comparison of Cloud Models

Calculating the opacity of condensates in an atmosphere requires estimating the distribution of particles over space and particle size. Estimates of condensate opacities in brown dwarf atmospheres have all assumed a steady state, horizontally homogeneous distribution. Beyond those common assumptions, a number of distinct approaches have appeared in the literature in recent years, ranging in complexity from (a) the simple approach of Tsuji (2002), in which the size of cloud particles is fixed, as are the temperatures at the bottom and top of the cloudy layer; (b) the more physically motivated method of Ackerman & Marley (2001), in which the size of cloud particles and the profile of condensate mass are coupled through an eddy mixing assumption and a parameter describing the sedimentation efficiency; and (c) the more detailed approach of Cooper et al. (2002), in which a number of time microphysical and transport time constants are evaluated in the spirit of Rossow (1978). We briefly describe and compare these three approaches below.

2.1. Tsuji (2002)

Tsuji (2002) simply assumes that all condensate particles are 10 nanometers in radius, and are vertically located between their condensation temperature (establishing cloud base for each condensate, assuming solar abundances) and a prescribed temperature corresponding to cloud top for all species. No mention is made of the assumed vertical distribution of condensate mass. Likely possibilities include the assumption of a uniform mixing ratio or concentration.

All particles are prescribed to have a single fixed radius, which is described as the critical radius corresponding to the Gibbs free energy of formation of a molecular cluster, in which the surface tension is just offset by the supersaturation of a condensing gas. Assumed values of critical supersaturations and surface tensions are not given, so the validity of a uniform critical radius for all species is not easily evaluated. Tsuji argues that particles larger than this critical radius will grow and sediment out, and therefore only particles at this critical radius can remain within the cloud layer. These arguments assume that there are no vertical motions within the cloudy air to offset sedimentation, and that the formation of the particle clusters does not deplete the supersaturation that gave rise to them. It is not clear how this first argument is to be considered consistent with other elements of the atmospheric model, in which convective

velocities are shown to vary between 10 and 80 m/s, which are strong enough to offset the sedimentation of particles hundreds of microns in radius. Furthermore, the notion that particles in long-lived clouds are limited to their critical radius is clearly invalid in the only atmosphere in which we have direct cloud microphysical measurements. Water cloud particles in the terrestrial troposphere typically range in modal size from 10 to 100 microns. In the terrestrial stratosphere sulfuric acid cloud particle sizes are of order microns, still over one hundred times that assumed by Tsuji.

Condensates (such as enstatite) that form at levels cooler than the prescribed cloud top temperature are assumed to not exist in the model atmospheres. Tsuji suggests that such condensates nucleate on other condensed species, and therefore rapidly sediment out, a process akin to seeding terrestrial cumulus clouds with large condensation nuclei to enhance precipitation. However, depending upon the meteorological and background aerosol conditions, increasing the concentration of condensation nuclei can instead suppress precipitation in terrestrial clouds (e.g., Ackerman et al. 1993). This second possibility is ruled out by Tsuji's model.

For the same cloud top temperatures, Tsuji finds that cloud opacities in the atmospheres of T dwarfs are greatly reduced from that in L dwarfs because the clouds that form in the former (colder) atmospheres are limited (by virtue of his cloud-top temperature cutoff) to levels below the photosphere. This result effectively reproduces the result of earlier models that assume cloud layers are limited to one scale height in depth (e.g., Marley et al., 2000).

Tsuji's choice of cloud top temperature does reproduce the limiting value of $J - K \sim 2$ seen in the latest L dwarfs as well as several other observed trends in the available data (Tsuji 2002). However since his model photometry is not combined with an evolution model to provide radii, hence absolute magnitudes, it is not clear if these 'Unified' models are able to reproduce the observed rapid transition in $J - K$ from the Ls to the Ts discussed in Section 3.

2.2. Ackerman & Marley (2001)

The treatment of Ackerman & Marley has been inaccurately described (by Cooper et al., 2002) as being based on microphysical time scales. Instead the microphysical time scale approach pioneered by Rossow (1978), in which highly uncertain estimates are made for a number of microphysical processes, was bypassed by Ackerman & Marley in favor of a much simpler approach, in which a steady-state balance between sedimentation (of condensate) and mixing (of condensate and vapor) is solved at each model level. This advective-diffusive balance provides the profile of condensed mass in their model atmospheres. Condensate size distributions at each model level are represented as a log-normal distribution that is coupled to the advective-diffusive steady-state profile. The width of the distribution is a free parameter (a fixed geometric standard deviation of 2 is assumed), while the other two unknowns in the size distribution (total number concentration and modal radius) are calculated from, respectively, the steady-state condensate concentration and the sedimentation flux. The sedimentation flux is calculated by integrating particle sedimentation velocity over the log-normal particle size distribution.

The Ackerman & Marley treatment of mean particle size can be viewed as resembling an extremely simplified variant of the Rossow time scale approach in that the mean particle size calculation does use particle sedimentation speeds, and Rossow's sedimentation time scale calculation also uses particle sedimentation speeds. Rossow divides the atmospheric scale height by the sedimentation speed to calculate a time scale, but ignores eddy mixing time scales in his analysis, and instead compares the sedimentation time scale to time scale estimates for particle condensation, coagulation, or gravitational coalescence. In contrast, Ackerman & Marley effectively compare particle sedimentation speed to the convective velocity scale to calculate mean particle size.

A notable extension of the Ackerman & Marley approach beyond preceding efforts along the same lines (e.g., Lunine et al., 1989) is to incorporate a sedimentation scaling factor in their computations of advective-diffusive balance and the mean particle size. This factor was originally called f_{rain} (for "rain factor"), but rain is associated by some researchers in the astrophysics field with the process that has been termed "rain-out", in which all condensate is removed from a saturated layer, and furthermore rain is a term specific to condensed water. Hence, a more appropriate description of the scaling factor would be "sedimentation factor" or f_{sed} . Ackerman & Marley found that $f_{\text{sed}} = 3$ reasonably reproduces the observations of Jupiter's ammonia ice cloud, and results in a condensate opacity scale height of approximately 1/4 of a pressure scale height.

The Ackerman & Marley model has a small number of free parameters, but only f_{sed} has been adjusted to fit observations in practice. The other free microphysical parameters, the geometric standard deviation of the particle size distributions and the supersaturation that persists after condensation, are fixed at 2 and 0, respectively. The remaining free parameters relate to the difficulty of calculating eddy diffusion coefficients from mixing length theory in stable regions of the atmosphere. In such regions they calculate the mixing length by scaling the atmospheric scale height by the ratio of the local to the adiabatic temperature lapse rate, with a minimum scaling fixed at 0.1. They also specify that the minimum eddy diffusion coefficient is fixed (currently at $10^5 \text{ cm}^2/\text{s}$) to represent residual sources of turbulence such as breaking buoyancy waves.

2.3. Cooper et al. (2002)

Cooper et al. (2002) and Allard et al. (this volume) draw on the approach of Rossow (1978) to compute cloud models. While Rossow's treatment of microphysical time constants has its appeal, it also has a number of stumbling blocks. To highlight some of the assumptions inherent in such a method we scrutinize in this section an adaptation of the Rossow approach by Cooper et al. (2002)¹.

For their profiles of condensate mass, Cooper et al. evidently assume that all the condensate resides within one pressure scale height above the base of each condensate cloud. It is not immediately obvious from their description how the condensate mass is distributed vertically within that scale height. They state that all the supersaturated vapor above cloud base condenses, as assumed by Ackerman & Marley (2001). Recall that Ackerman & Marley calculate vertical

¹Comments here refer to the pre-publication version of Cooper et al. that appeared on astro-ph on May 15, 2002.

profiles through the assumption of advective-diffusive steady-state. Cooper et al. calculate profiles of convective velocity scale (though unlike Ackerman & Marley, they do not give their formulation), which they use to calculate convective time scales to estimate particle sizes (described below). However, Cooper et al. do not state whether or not (or how) they might use the convective velocity scale to calculate their vertical distribution of condensate mass. It may be the case that they are calculating an advective-diffusive steady-state profile, as done by Ackerman & Marley, except that Cooper would presumably assume all the vapor to be condensed and that $f_{\text{sed}} = 1$, which would be somewhat consistent with a condensate scale height matching the pressure scale height. However, such a profile would not be entirely consistent with their description, which states that 100% of the available vapor condenses within one scale height of cloud base. Perhaps the condensate profile within that scale height assumes that the vapor plus condensate is well mixed (uniform mixing ratio). Or perhaps they use the method of Lewis (1969) without stating so directly. As described further in the review of other models by Ackerman & Marley, the approach of Lewis is easiest to understand in terms of a parcel in an updraft, in which all the condensate sediments at exactly the updraft speed. Ackerman & Marley show that the Lewis model of Jupiter's ammonia cloud gives the equivalent condensate profile for the Ackerman & Marley model with $f_{\text{sed}} \approx 5$. Hence if Cooper et al. are using the method of Lewis (1969) to calculate their condensate profile, their clouds are more physically compact than those of the baseline Ackerman and Marley model (with $f_{\text{sed}} = 3$), in contrast to the opposite conclusion stated by Cooper et al.

To calculate the size of condensate particles, Cooper et al. evidently assume a monodisperse distribution as done by Tsuji, rather than distributing the condensate over a range of sizes as done by Ackerman & Marley. Our only evidence of this assumption is their omission of any mention of droplet size distributions. Further unlike Ackerman & Marley but like Tsuji, Cooper et al. also assume that the particle size is fixed with altitude, as stated in their Section 6.3, although they show a profile of particle sizes in their Figure 5, which is somewhat puzzling.

Cooper et al. (2002) essentially apply a hybrid approach toward calculating the size of condensate particles. In convective regions they effectively calculate their particle size through a simplified form (by virtue of their monodisperse size distribution) of the treatment by Ackerman & Marley (2001), in which Cooper et al. assume $f_{\text{sed}} = 1$. In radiative regimes Cooper et al. use a modification of the Rossow (1978) treatment to calculate particle size. For this detailed treatment, Cooper et al. estimate time scales for sedimentation, heterogeneous nucleation, homogeneous nucleation, coagulation (collision from thermal motions), and coalescence (collisions from differential sedimentation speeds). Rossow argues that the condensational time scale for cloud particles is much longer than the nucleation time scale in planetary atmospheres because cloud particles heterogeneously nucleate on condensation nuclei at a rapid rate compared to the cooling rate of the cloudy atmosphere. Hence, Rossow ignores the nucleation time scales in calculating characteristic particle sizes. In contrast, Cooper et al. consider the process of homogeneous nucleation to be important in the water and iron clouds of brown dwarf atmospheres, and therefore estimate nucleation time scales. These detailed calculations require estimating a number of addi-

tional parameters, such as surface tension, which requires estimating whether the cloud particles are crystalline, glassy, or liquid. Cooper et al. do not state their assumptions regarding this difficult issue. Furthermore, in his treatment of nucleation and condensation time scales, Rossow shows that they must be considered in tandem to calculate a growth rate. That is, the overall condensational time scale is equal to inverse of the sum of the growth rate of the particle masses plus the growth rate of the total number of particles. However, Cooper et al. treat the nucleation rate as a growth process on its own, a divergence from the method of Rossow that is not obviously justifiable, nor is the departure explained.

Other important parameters that must be estimated in their approach include the maximum supersaturation, and the coagulation and coalescence efficiencies. Additionally, the shape and breadth of the size distributions must be estimated to calculate coagulation and coalescence time scales. Cooper et al. provide no information regarding their assumed size distributions for these purposes, but presumably for their estimates of coagulation and particularly coalescence time scales they assume that their size distributions have some breadth, since a monodisperse size distribution would lack dispersion of terminal sedimentation speeds, and hence coalescence will be inoperative.

3. The L to T Transition

Marley et al. (2002) employed the Ackerman & Marley (2001) cloud model to compute atmosphere models for L and T dwarfs. Burgasser et al. (2002) combined these models with the evolution calculation of Burrows et al. (1997) to prepare a M_J vs $M_J - M_K$ color magnitude diagram (Fig. 1). Since Burrows et al. used an earlier set of atmosphere models (that utilized the Lunine et al. (1986) dust model) as atmospheric boundary conditions, Figure 1 is not entirely self-consistent. However since model radii vary relatively little over the magnitude range plotted, this is not an important source of error. In the future we will present an entirely self-consistent evolutionary calculation.

Figure 1 compares cloudy ($f_{\text{sed}} = 3$) and cloud-free models of L and T dwarfs with parallaxes measured by the Flagstaff USNO group (Dahn et al. 2002; Harris, this volume). Also shown is the track predicted by the well-mixed DUSTY models of Chabrier et al. (2000). The main conclusion to be drawn is that neither the cloud-free nor the DUSTY models fit the colors of the L-dwarfs. The cloudy models better fit the data, including the saturation in $J - K$ at around 2 seen in the latest L dwarfs. Models that do not include particle sedimentation produce redder colors because more condensate mass remains in the atmosphere. Models with more efficient sedimentation, in contrast, produce colors intermediate between the clear and the $f_{\text{sed}} = 3$ case.

Interestingly Ackerman & Marley find that the value of f_{sed} which best fits the (poorly constrained) particle size and vertical profile of Jupiter's ammonia cloud deck is also 3. More sophisticated dynamical studies of giant planet and brown dwarf atmospheric convection may ultimately shed light on the mechanisms underlying this result.

The challenge facing any model with a global, 1-D, cloud is that the $J - K$ colors of brown dwarfs swing from the red to the blue over a very small interval

in effective temperature and M_J . This is shown by the data in Figure 1 as well as other parallax data presented at the workshop by Tinney and collaborators (this volume). María Zapatero Osorio presented colors and J magnitudes of objects in the σ Orionis cluster (this volume) that are also consistent with the rapid change in color. It is very difficult for a globally uniform cloud to make such a sudden transition since the cloud base and, more importantly, the optical depth of the overlying gas change slowly with effective temperature. The $f_{\text{sed}} = 3$ model in Fig. 1 typifies this relatively slow transition.

The rapid transition suggests that something special may be happening at the L to T transition. One possibility might be that the global atmospheric dynamics change in such a way to rapidly favor more efficient particle sedimentation (larger f_{sed}) at the transition. A second possibility, originally suggested by Ackerman & Marley (2001), is that horizontal patchiness, or holes, develop in the cloud layer at the L to T transition. Holes, or optically thin regions in the global cloud deck, cover less than 10% of Jupiter's disk. At most thermal wavelengths optical depth unity is reached near or above these cloud tops, so the reduced cloud opacity in the holes is of little consequence. Near $5 \mu\text{m}$, however, there is a minimum in the combined H_2O , CH_4 , and H_2 gas opacity. Over most of the planet the cloud deck provides an opacity 'floor' at this wavelength, but in the cloud holes flux from deeper, warmer, and thus brighter regions can emerge. Essentially all of Jupiter's $5 \mu\text{m}$ radiation emerges through these 'hot spots', which were first recognized in the 1960's (Gillett, Low & Stein 1969). A $5 \mu\text{m}$ image of Jupiter is shown in Figure 2. The long path lengths through the atmosphere into the hole regions allow relatively rare species, such as PH_3 and GeH_4 , to be detected in Jupiter's atmosphere (Kunde et al. 1982).

Burgasser et al. (2002) argue that a similar gas opacity window exists at $1 \mu\text{m}$ in late-L/early-T dwarfs, and deeper, hotter layers can be probed at this wavelength in breaks in the upper condensate cloud decks. They point to the rapid change in $J - K$ color at the L to T transition as well as the observed resurgence in FeH absorption in the earliest T dwarfs (after monotonically declining through the L dwarfs) as supporting that clouds are patchy on brown dwarfs as well. In the L dwarfs gaseous FeH abundance presumably declines as iron and silicates condense into clouds, leading to a simultaneous increase in the $J - K$ color as the atmosphere becomes cloudier. Near the bottom of the L dwarf sequence holes begin to appear in the clouds, allowing bright, blue (in $J - K$) flux to emerge. This flux pulls the integrated color over the disk blueward and can even lead to a brightening at J band (Fig. 1). Simultaneously FeH gas, lying below the cloud base, again becomes detectable through the holes.

The patchy cloud model predicts that the effective temperature range of the earliest (T0 to T5) dwarfs is very small, the variations in spectral properties depending more on the fractional cloud cover than a varying effective temperature. There are some indications that this is true (Leggett et al., this volume), although more work is needed. Furthermore the patchy model suggests that the early T dwarfs will exhibit substantial variability in the infrared. At this conference evidence was presented that the T2 dwarf SDSS 1254 is indeed apparently variable in J and H bands (Artigau et al., this volume).

The mechanism responsible for clearings in Jupiter's cloud deck is still not perfectly understood, although downdrafts of warm, dry air are likely involved

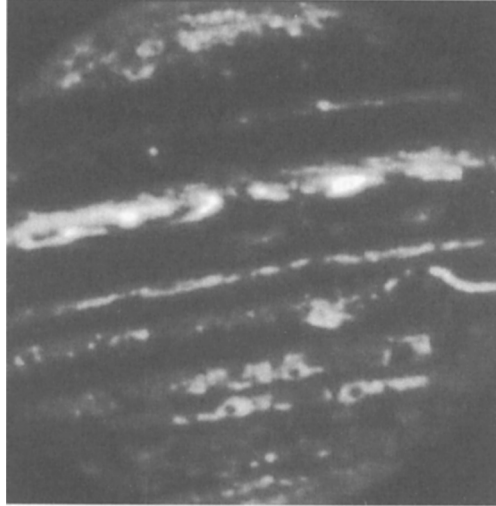


Figure 2. This image of Jupiter was taken at a wavelength centered on $4.78\ \mu\text{m}$ (narrow-band M filter) on July 26, 1995 from the NASA Infrared Telescope Facility. It shows thermal emission originating from so-called “hot spots” which are relatively cloud-free areas in the atmosphere that allow thermal radiation from warmer atmospheric depths. The Galileo probe entered into such a region on Dec. 7, 1995 (Orton *et al.* 1996). Image courtesy Glenn Orton, the IRTF, and NASA.

(Showman & Dowling 2000). The principle brown dwarf cloud decks (iron and silicate) will become subject to such vertical flows when both the cloud base and the cloud tops become well seated in the atmospheric convection zone. In earlier type dwarfs much of the cloud opacity lies within the statically stable radiative zone where vertical motions are substantially smaller. Clouds in these regions may be similar to the stratospheric photochemical hazes of Jupiter and Titan, which are globally fairly uniform.

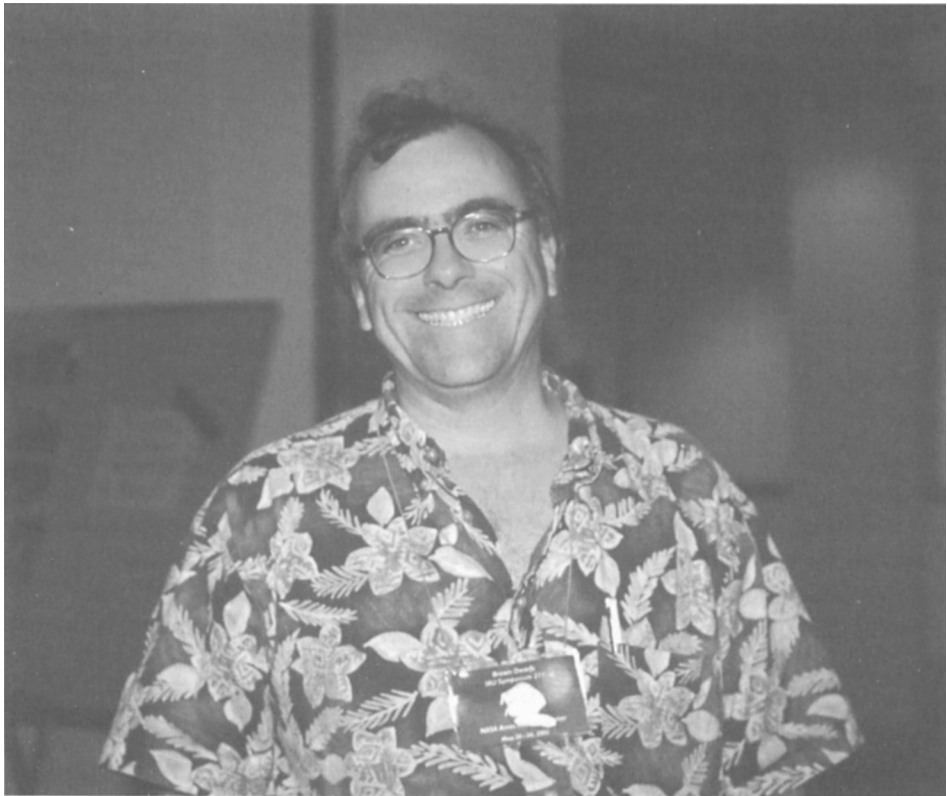
4. Summary

It appears that a complete description of the behavior of L and T dwarfs will require a thorough understanding of the behavior of condensates in their atmospheres. In doing so models must simultaneously and self-consistently account for a number of influences including particle nucleation, sedimentation, and vertical transport. Other influences, including large scale atmospheric dynamics which may be responsible for cloud patchiness, may also be important. Given this daunting task, it is worth remembering that even after half a century of dedicated effort, such key properties as the particle sizes and vertical structure of most of the cloud decks in the solar system are still poorly known. The mechanisms responsible for those characteristics which are constrained are themselves only partly understood. Despite these challenges a coherent story for the behavior of L and T dwarf condensates is emerging, although our understanding is certainly still not complete. Clouds vary in time and in space and we should perhaps not be surprised that weather prediction is a challenging business.

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