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PRECIPITATING CONDENSATION CLOUDS IN SUBSTELLAR ATMOSPHERES

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ABSTRACT

We present a method to calculate vertical profiles of particle size distributions in condensation clouds of giant planets and brown dwarfs. The method assumes a balance between turbulent diffusion and sedimentation in horizontally uniform cloud decks. Calculations for the Jovian ammonia cloud are compared with results from previous methods. An adjustable parameter describing the efficiency of sedimentation allows the new model to span the range of predictions made by previous models. Calculations for the Jovian ammonia cloud are consistent with observations. Example calculations are provided for water, silicate, and iron clouds on brown dwarfs and on a cool extrasolar giant planet. We find that precipitating cloud decks naturally account for the characteristic trends seen in the spectra of L- and T-type ultracool dwarfs.

Subject headings: planetary systems — stars: low-mass, brown dwarfs

1. INTRODUCTION

The visual appearance and spectrum of every solar system body with an atmosphere depends strongly on the character and distribution of atmospheric condensates. This is particularly true for the giant planets, for which optically thick cloud decks dominate the appearance of the planets at most continuum wavelengths in both the reflected solar and the thermal infrared. Condensates also play a role in controlling the spectra of at least some brown dwarfs and most extrasolar giant planets. Indeed, one suggested classification scheme (Sudarsky, Burrows, & Pinto 2000) for extrasolar planets hinges on the specific atmospheric condensates present. Yet, despite the importance of condensates, there exists no simple model for predicting the parameters most relevant to radiative transfer: the vertical profile of condensate mass and its distribution over particle size.

Chemical equilibrium models (e.g., Lewis 1969; Fegley & Lodders 1994) predict which species are expected to condense in an atmosphere, yet they provide no guidance as to the expected particle sizes. Other models (e.g., Rossow 1978; Lunine et al. 1989; Carlson, Rossow, & Orton 1988) predict some parameters but lack a simple, self-consistent recipe for exploring the possible phase space in which clouds might exist.

A single example motivates the need for cloud models in substellar atmospheres. With increasingly later spectral type, the warm L dwarfs become progressively redder in their $J-K$ color (e.g., Kirkpatrick et al. 1999; Martin et al. 1999; Fan et al. 2000). Spectral fitting and models (e.g., Leggett, Allard, & Hauschildt 1998; Chabrier et al. 2000; Marley 2000) demonstrate that this is because of the progressive appearance of more silicate dust in the cooling brown dwarf atmospheres. Yet the cooler T-type brown dwarfs, such as Gl 229B, have blue colors in $J-K$ (e.g., Leggett et al. 1999; Tsvetanov et al. 2000). The spectra and colors of these cool brown dwarfs can only be fit by atmosphere models that assume the silicate dust has settled below the visible atmosphere (e.g., Allard et al. 1996; Marley et al. 1996; Tsuji et al. 1996). Models in which the dust does not settle (Chabrier et al. 2000) produce T-dwarf colors that are at least 2 to 3 mag redder than observed. Marley (2000) has demonstrated that a simple model in which all clouds are a single scale-height thick can explain this behavior, but the assumed distribution was prescribed rather than being calculated from any model physics. Correct modeling of the atmospheres of cooling brown dwarfs and the ultimate assignment of an effective temperature scale to the L dwarf spectral sequence (e.g., Kirkpatrick et al. 1999; Basri et al. 2000) requires a characterization of clouds. The ideal model would have a small number of free parameters, predict the vertical distribution and particle sizes of the condensates, and yet be simple enough to be included into model atmosphere codes that iteratively search for self-consistent atmospheric structures. No such ideal model yet exists.

We aim to fill this void by presenting a simple model describing precipitating clouds in substellar atmospheres. We limit our treatment to condensation clouds and, hence, do not consider photochemically driven hazes likely to appear in illuminated stratospheres. We depart from previous work by explicitly treating the downward transport of raindrops with sizes greater than that predicted from the convective velocity scale. Including rainfall produces clouds of thinner vertical extent, which can better reproduce observations of Jupiter's ammonia cloud. The resulting model is general enough to be applied to iron and silicate clouds appearing in brown dwarf atmospheres (e.g., objects with effective temperatures, $T_{\rm eff} \sim 1500$ K) as well as the atmospheres of cool extrasolar giant planets ($T_{\rm eff} \sim 400$ K) in which water clouds dominate the atmosphere. The few free parameters in the model can produce clouds with dramatically different characteristics; ultimately, observations will constrain these parameters and, one hopes, provide information on the underlying atmospheric dynamics and cloud physics.

In this paper, we first summarize previous cloud modeling efforts, then describe the new model. We use the ammonia cloud of Jupiter as a framework for describing the model physics and evaluating the model performance. Finally, we illustrate model applications by considering water, silicate, and iron clouds in the atmospheres of brown dwarfs and a cool extrasolar giant planet.

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2. PREVIOUS MODELS

A great range of models have been used to represent clouds in the terrestrial atmosphere, which vary in the complexity by which atmospheric dynamics and cloud microphysics are treated. The most detailed models simulate three-dimensional cloud-scale motions and resolve the size distributions of cloud droplets (and the aerosols on which they form) and treat the interactions between dynamics, microphysics, and radiative transfer. The computational demands of such complex models limit their domain sizes to a few kilometers in each dimension. Present global-scale (general circulation) models greatly simplify the representation of clouds by parameterizing cloud-scale motions as well as cloud microphysical processes, and such simplifications lead to profound uncertainties in climate predictions from their simulations. Both types of models, as well as a range of intermediate models, can be considered appropriate for modeling the terrestrial atmosphere by virtue of the wealth of observational data available to constrain them; whether or not the unknowns in such models are uniquely constrained by the data constitutes a debate beyond the scope of this study.

The relative scarcity of observational data for clouds in extraterrestrial atmospheres is far less constraining. Leading uncertainties include the characteristics of atmospheric dynamics and the populations of nuclei on which cloud droplets form. Hence, we consider it appropriate to model extraterrestrial clouds using much simpler treatments.

Perhaps the simplest approach to modeling clouds is through a Lagrangian parcel model, in which the base of a cloud appears where the adiabatic cooling of an air parcel in an updraft results in saturation (ignoring any supersaturation associated with barriers to cloud droplet formation). Further cooling condenses vapor in excess of saturation onto cloud particles. The particles grow through condensation and coalescence until their sedimentation velocities exceed the updraft speed and then fall out of the parcel. A number of problems arise in the formulation of updraft parcel models, among them: ignoring parcels in downdrafts, treating the mixing between parcels, treating the source of condensates into a parcel caused by sedimentation from above, and determining updraft speeds.

Another simple approach, which we employ here, is through a one-dimensional Eulerian framework, in which turbulent diffusion mixes a condensable vapor upward, while maintaining a constant mixing ratio (equivalently, mole fraction) below the cloud. Temperature and, hence, the saturation mixing ratio in the air column decrease with altitude, and the cloud base again appears where the saturation mixing ratio matches the subcloud mixing ratio. Above the cloud base, turbulent diffusion works toward maintaining a constant total mixing ratio ($q_t = q_v + q_c$), which is the sum of the vapor (q_v = moles of vapor per mole of atmosphere) and condensate (q_c = moles of condensate per mole of atmosphere) mixing ratios, while sedimentation reduces q_t by transporting condensate downward. Note that by ignoring horizontal variability, any differences between (cloudy) updrafts and (potentially cloud-free) downdrafts are neglected.

A number of models for tropospheric condensation clouds have appeared in the planetary and astrophysical literature. Here we summarize a selection of them that contribute to the present work.

2.1. *Lewis* (1969)

Lewis (1969) represents a foundation in the study of tropospheric clouds in the giant planets. In that work, the term "precipitation" is used in the narrow sense used by chemists, in which condensates appear where the local saturation vapor pressure is exceeded by the actual vapor pressure rather than in the broader sense employed by meteorologists, which additionally denotes sedimentation of the condensates (hereafter we use the term in this broader sense). Although there is no mention of sedimentation by Lewis, the treatment does imply certain assumptions. Starting below the cloud base and working upward, at each computational level the Lewis model assumes that all the condensate remains at the level where it appears. Considered in the framework of a parcel in an updraft, the Lewis model assumes that all condensate rains out with a fallspeed matching the updraft velocity. Were sedimentation slower, condensate would be transported upward (as discussed by Weidenschilling & Lewis 1973); were sedimentation faster, condensate would be transported downward. Hence, the Lewis (1969) assumption regarding sedimentation is an unstated compromise between those two possibilities.

We implement the Lewis model by starting below the cloud base (where $q_c = 0$ and $q_v = q_{\mathrm{below}}$) and condensing all vapor in excess of saturation at each successive level upward:

$$q_c(z) = \max\,[0, q_v(z - \Delta z) - q_s(z)]\,, \tag{1}$$

$$q_v(z) = \min\,[q_v(z - \Delta z), q_s(z)]\,, \tag{2}$$

where z is altitude and q_s is the vapor mole fraction corresponding to the saturation vapor pressure at that altitude. The first and second cases on the right-hand side correspond to cloud-free and cloudy conditions, respectively. Note that under all conditions $q_t(z) = q_v(z - \Delta z)$ in the Lewis model, reflecting the assumption that only vapor is transported upward.

Beyond this simple model, Lewis (1969) considered the partitioning of chemical species in some detail and also calculated pseudo-adiabatic lapse rates. Here we simply assume that each condensate results from the saturation of a single condensable and fix the lapse rate as input from observations or an external model.

For an example, we calculate an ammonia cloud profile from the Lewis model (Fig. 1) using the Jovian temperature profile from *Voyager* (Lindal et al. 1981), the relation for vapor pressure given in Appendix A, and a subcloud mole fraction of 3×10^{-5} (a wide range of abundances below the expected base of the Jovian ammonia cloud have been reported; we adopt the value at 0.6 bars retrieved by Kunde et al. [1982] for the Northern Equatorial Belt, which also agrees with the best-fit values of Carlson, Lacis, & Rossow [1993] and Brooke et al. [1998]). The cloud base appears at 0.42 bars, where the temperature is 129 K. Although absent in the figures of Lewis (1969; likely caused by reduced vertical resolution), in our interpretation of that model, the vapor is not entirely depleted in the lowest reaches of the cloud (where $q_c < q_t$); hence, q_c increases above the cloud base. Such an increase is found in terrestrial clouds of moderate vertical extent, where $q_c < q_t$, and hence q_c increases with altitude throughout their depths. However, at greater altitudes in this deep ammonia cloud, the vapor is so effectively depleted by condensation at the low temperatures

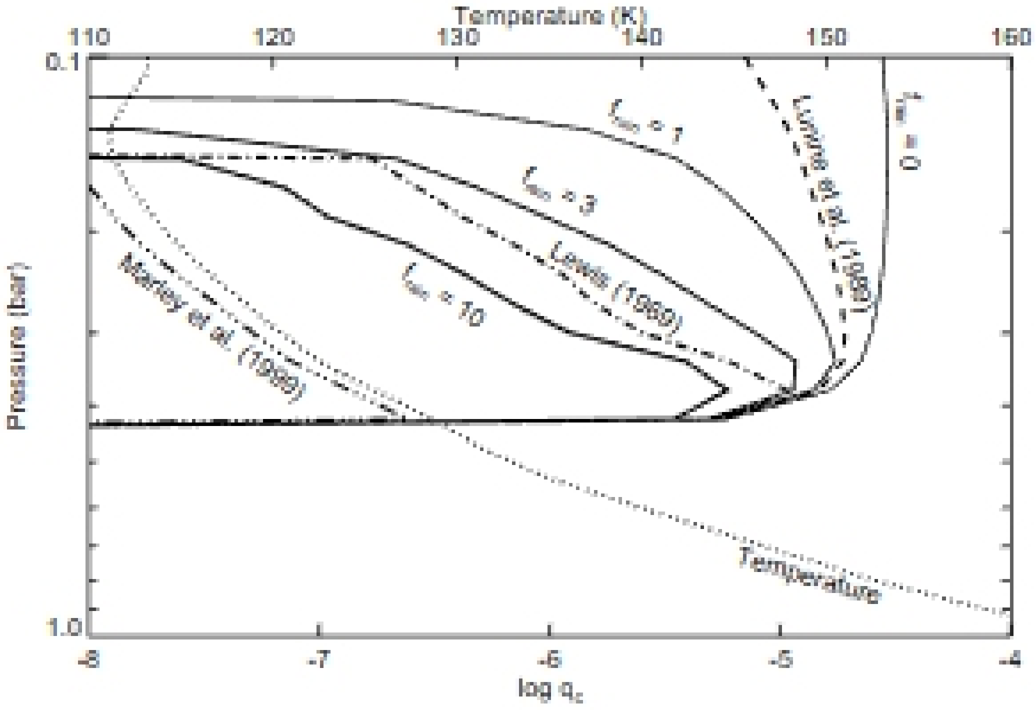

FIG. 1.—Vertical profiles of mole fraction (mixing ratio by volume) of condensed ammonia (q_c) from the present model of Jovian ammonia cloud with different values $f_{\rm rain}$ and from our adaptations of other models as labeled. The vertical coordinate is atmospheric pressure. The dotted line is the temperature profile. The kinks in the condensate profiles are caused by ripples in the temperature profile.

that $q_v \ll q_t$, leading to a cold degeneracy, $q_c(z) \approx q_t(z) = q_s(z - \Delta z)$, in which decreasing temperatures result in q_c diminishing with altitude. Note that the condensate abundance drops off rapidly above ~0.13 bars because of increasing temperatures. Hence, the temperature minimum quite reasonably produces a cold trap in the Lewis model.

Condensate particle sizes, the other ingredient needed for predicting cloud opacity, are not considered by Lewis (1969) or Weidenschilling & Lewis (1973).

2.2. *Carlson et al.* (1988)

In their theoretical characterization of cloud microphysics of the giant planets, Carlson et al. (1988) employ the formalism of Rossow (1978) to calculate time constants for droplet condensation within cloudy updrafts (assuming a supersaturation of 10^{-3}), droplet coalescence (assuming the mean collision rate is described by particles with a mass ratio of 2), and sedimentation through an atmospheric scale height. From these time constants, estimates are made of the predominant size of cloud particles at cloud base for a number of condensates. For the Jovian ammonia cloud, Carlson et al. estimate a mass-weighted droplet radius of ~10–30 μm.

Carlson et al. (1988) make no attempt to calculate vertical profiles of condensate mass. For profiles of vapors that condense into multiple forms (such as ammonia, which can also condense onto a cloud of NH_4SH below the ammonia cloud), saturation is assumed above the cloud base.

A shortcoming to the approach of Carlson et al. (1988) is that their microphysical time constants strongly depend on a number of uncertain factors, chief among them completely unknown supersaturations, which govern droplet growth rates caused by condensation. Supersaturations in a cloudy updraft are determined by balance between the source caused by adiabatic cooling and the sink caused by condensation. Uncertainties in updraft speeds and the populations of condensation nuclei (and hence cloud droplets) both contribute to the uncertainty in supersaturations realized in extraterrestrial clouds. Furthermore, the time constants Carlson et al. (1988) use for gravitational coalescence assume that the collection efficiency is unity, and those for sedimentation effectively assume a fixed width of the size distribution. Rather than attempting to constrain the many degrees of freedom using such a detailed approach, we choose instead to reduce the number of assumptions by simplifying the description of cloud microphysics.

2.3. *Lunine et al.* (1989)

Lunine et al. (1989) consider a range of possible iron and silicate clouds in brown dwarfs; the possibilities differ in the nature of the balance between sedimentation and turbulent mixing. The framework is based on a theoretical investigation into iron clouds deep in the Jovian atmosphere by Prinn & Olaguer (1981), which in turn draws on an analysis of sulfuric acid clouds on Venus (Prinn 1974). These models represent a fleshing out of the discussion of vertical transport of condensates by Weidenschilling & Lewis (1973).

Two fundamental cloud types are treated by Lunine et al. (1989). The first is "dustlike" (using the terminology of Prinn & Olaguer 1981), in which cloud particles grow and efficiently sediment out, resulting in relatively thin clouds limited by the local vapor pressure, as in the model of Lewis (1969). These dustlike clouds are assumed to prevail in the radiative region (stratosphere), where the temperature profile is stable and convection is suppressed.

The second fundamental type in the Lunine et al. (1989) study is a tropospheric cloud, in which downward transport by sedimentation opposes upward transport by turbulent mixing. For this cloud type, two variations are considered by Lunine et al. (1989). For the first variation, described as "frozen-in," cloud particles are so small that sedimentation is overwhelmed by upward transport caused by turbulent mixing. In this case, the atmosphere is well mixed with respect to condensate; hence, q_c is independent of altitude above the cloud base. For the second variation, which is intermediate to the dustlike and frozen-in cases, particles grow large enough in "convective" clouds to develop appreciable sedimentation velocities, and their downward sedimentation is balanced by their turbulent transport upward. For their calculations of specific brown dwarf models, Lunine et al. (1989) consider only the two endmembers of their cloud spectrum, corresponding to dustlike and frozen-in clouds.

Their intermediate case serves as a starting point for our model of condensate mass profiles. Our interpretation of the convective cloud model of Lunine et al. (1989) as applied to the Jovian ammonia cloud is shown in Figure 1. Note that we have refined that model slightly, allowing the atmospheric properties to vary with height above the cloud base and relaxing their assumption that $q_c = q_t$. The condensate mass is seen to be significantly enhanced above the cloud base for that model: at the tropopause (where there is no cold trap in this case) q_c is enhanced a thousandfold over that computed by the Lewis (1969) model. Thus, the treatment in which Lunine et al. (1989) assume particle sedimentation to balance turbulent transport results in a cloud not so different from their frozen-in case (as depicted by the curve in Fig. 1 labeled $f_{\rm rain} = 0$). Evidently, the sedimentation in this convective cloud model is far less effective than that assumed by Lewis (1969). As described below, for our calculations of condensate mass profiles, we extend the Lunine et al. (1989) approach by applying a scale factor to the particle sedimentation.