Dust formation in Brown Dwarfs

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Introduction

Brown Dwarf atmospheres provide favorable conditions for the gas - solid phase transition due to their low temperatures and high densities. Observations of unexpectedly weak molecular absorption bands and saturated near-IR water bands are indications for the presence of dust in such atmospheres. The consideration of dust in hydrostatic model atmospheres of Brown Dwarfs has led to a better agreement with observations due to the depletion of various heavy elements in the gas phase and the occurrence of a stronger backwarming (Tsuji *et al.* 1996a, Tsuji *et al.* 1996b, Pavlenko *et al.* 2000). The dust has been assumed to be in phase equilibrium with the gas (Burrows & Sharp 1999, Lodders 1999) and its distribution has often been prescribed. The gas - solid phase transition, however, is a non-equilibrium process and the grain size distribution is not a priori known for Brown Dwarf atmospheres. Furthermore, dust formation is a time-dependent process.

In this presentation, the stability of solid compounds and the efficiency of nucleation are examined for typical conditions in Brown Dwarf atmospheres in comparison to M dwarfs and Jupiter-like gas planets. We additionally present first results of numerical calculations for atmospheres of Brown Dwarfs including a detailed time-dependent, phase non-equilibrium description of the formation of core-mantle grains. Dust properties like the amount and the sizes of the solid particles are results of the calculation.

Limits of Stability Consideration

Following a typical trajectory of a Brown Dwarf atmosphere in the (T, $n_{<\mathrm{H}>}$) plane, high temperature compounds like $CaTiO_3$, $Mg_{2x}Fe_{2-2x}SiO_4$, Al_2O_3 or TiO_2 may be expected to form first, if only stability arguments are considered (see also Burrows & Sharp 1999, Lodders 1999). The description of the formation of such heterogeneous particles, however, is still a matter of debate, since the nominal molecules of these solid compounds are often only present in negligible amounts (e.g. Fe_2SiO_4, Al_2O_3) or even completely absent (e.g. $CaTiO_3$) in the gas phase. Nevertheless, the rich variety of molecular species of comparable abundances in an oxygen-rich gas suggests the formation of such heterogeneous dust.
Figure 1 depicts the stability limits $S = 1$ ($S = p_n/p_{\mathrm{vap}}$ – supersaturation ratio) in the (T, $n_{<\mathrm{H}>}$) plane for various oxygen bearing solid materials without element depletion by dust formation. Below these curves the respective solids are thermodynamical stable which suggests a "condensation" sequence for decreasing temperature. This conclusion is not as straightforward as it might seem, since regarding the first condensate the stability of macroscopic dust grains is a *necessary*, but *not* a sufficient condition for the dust formation process. The formation of solid particles has to proceed via the formation of seed particles (nucleation) which is followed by grain growth towards macroscopic sizes. Thereby, a large supersaturation has to be achieved which results in a considerable *gap* between typical nucleation and stability (i.e. sublimation) temperatures of plane solids. This can be seen from comparing the various M-dwarf, Brown Dwarf,

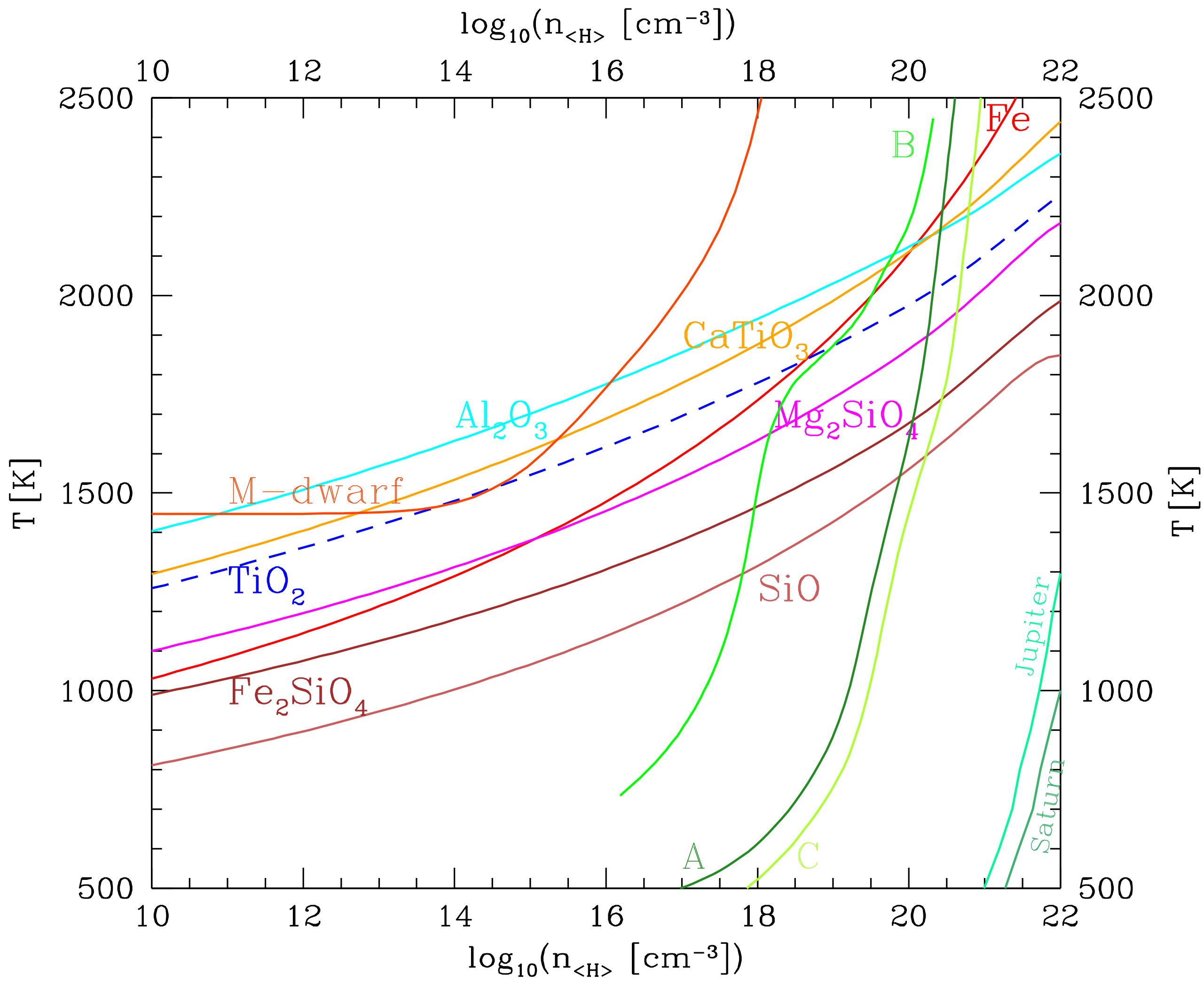

Figure 1: Sublimation temperature ($T(S=1)$) of various solid compounds as a function of the total hydrogen density $n_{<\mathrm{H}>}$ in a gas of solar abundances. (T, $n_{<\mathrm{H}>}$) structures for model atmospheres of typical M-dwarfs (Hausschild, private communication), Brown Dwarfs (Tsuji, private communication), and gas planets (Fegley & Lodders 1994) are also indicated.

and gas planet trajectories in Fig. 1 with those in Fig. 2.

Candidates for the First Condensate

Despite its obvious pertinence, a reliable description of the heterogeneous nucleation process under oxygen-rich astrophysical conditions is still missing and the identification of the key molecules for the nucleation process is still under discussion, especially in such cool and dense objects like Brown Dwarfs. Accompanied by the limited knowledge of the chemical pathway to larger clusters and the corresponding chemical reaction rates, definite statements are difficult to make.

Previous studies have mainly adopted concepts based on the classical homogeneous nucleation theory (i.e. Gail & Sedlmayr 1998) which has been successfully applied to AGB stars (Jeong 2000).

Promising astrophysical seed candidates are titanium dioxide and iron clusters, which appear in appropriate amounts in cold oxygen-rich gases; Iron seeds maybe even more favorable in the most dense atmospheres ($n_{<\mathrm{H}>} > 10^{19}\mathrm{cm}^{-3}$) (Fig. 2) or in regions of high iron concentration (John & Sedlmayr 1997). Other possible high temperature condensates like corundum $(\mathrm{Al_2O_3})_N$ or silicon monoxide $(\mathrm{SiO})_N$ are almost negligible since their nucleation rates are very low (Fig. 2). They may rather serve as growth species than as first nuclei. The first nucleating and thus most important species determines the number of grains. This may well differ between different astrophysical objects: titanium dioxide nucleates more efficiently under the conditions in Brown Dwarfs compared to gas planets, for which iron seems to be a better candidate for initiating dust formation. In M-dwarfs, iron and titanium dioxide seeds are of negliable importance and well as corundum and silicates.

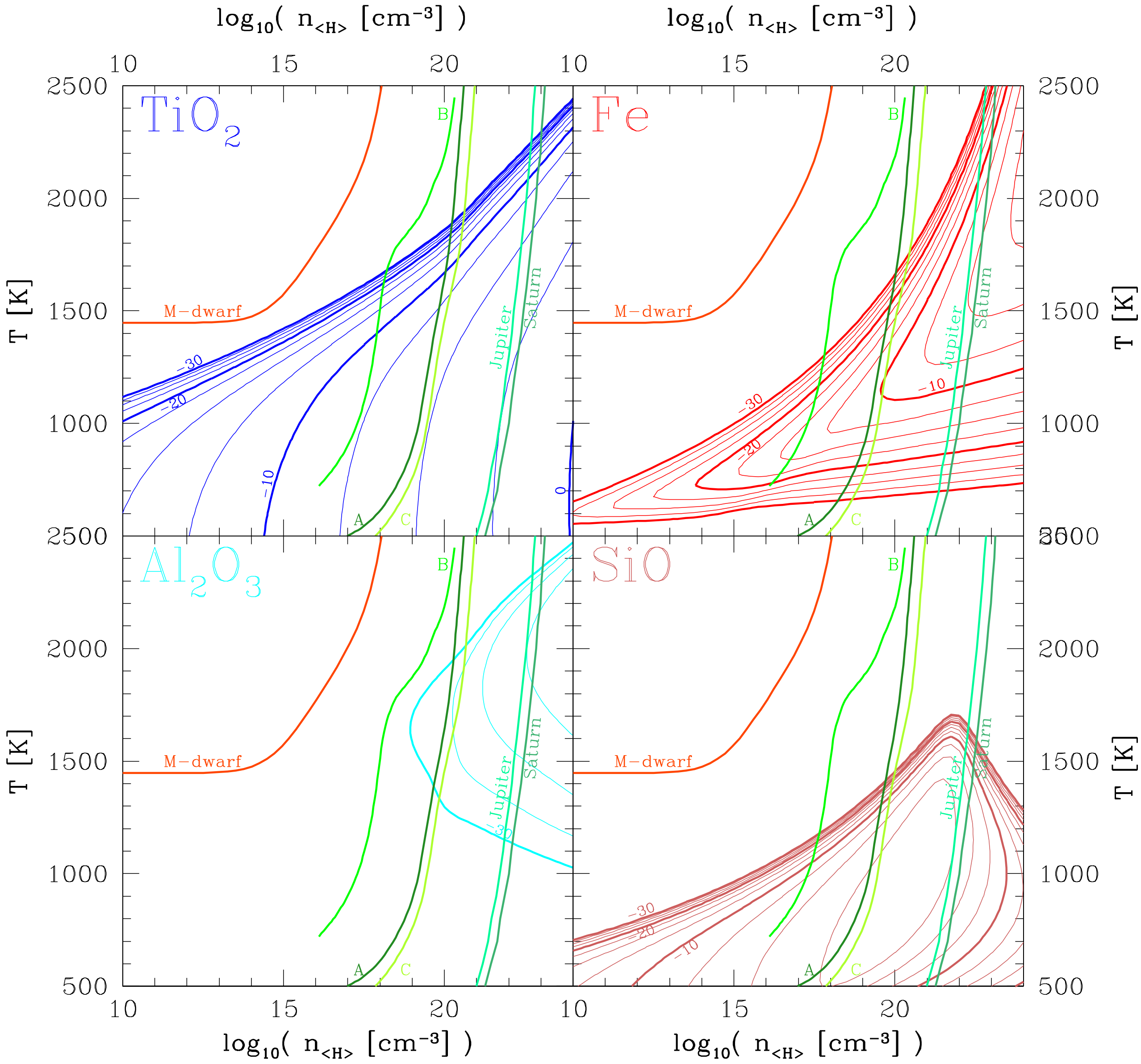

Figure 2: The nucleation rate of $(\mathrm{TiO_2})_N$, $(\mathrm{Fe})_N$, $(\mathrm{Al_2O_3})_N$, and $(\mathrm{SiO})_N$. (T, $n_{<\mathrm{H}>}$) structures for model atmospheres of typical M-dwarfs (Hausschild, private communication), Brown Dwarfs (Tsuji, private communication), and gas planets (Fegley & Lodders 1994) are superimposed.

It is, however, delicate to investigate possible gas - solid phase transitions in the high temperature and high density regime and the possibility of a gas-liquid phase transition should also be kept in mind!

Dust formation in the atmospheres of Brown Dwarfs

In order to study dust formation, growth, and evaporation in a Brown Dwarf-like environment, we constructed a simple time-dependent model considering a gas box (element) moving through the atmosphere which is based on Tsuji's model A. The box arises from the inner parts of the atmosphere and moves back inward with a prescribed velocity of 1/10 of the local sound velocity. Within this box, we calculate the time-dependent evolution of the dust complex using the moment method for dust growth and evaporation (Gail & Sedlmayr 1988, Dominik *et al.* 1993). Our model includes nucleation according to the modified classical homogeneous nucleation theory and heterogeneous growth and evaporation of dust particles and the corresponding depletion of the dust forming species in the gas phase. TiO_2 is considered as primary seed (thermodynamical data from Jeong *et al.* 2000) and the growing species are TiO_2, Al_2O_3, MgO, Fe, SiO_2. This setup allows us to present a first study of the evolution of the dust component under Brown Dwarf conditions.
The temporal evolution inside the probing box for which the local Brown Dwarf temperature and density have been adopted is depicted in Fig. 3. A temperature of about 2000K has been reached after about 60 s and effective nucleation sets in, resulting in an immediate increase of the number of dust particles (1st panel). A small mantle of Al_2O_3 and Fe has grown on the first nuclei resulting in the small peak of $\langle a \rangle$ after $t \approx 63$ s. First Al and Fe are completely depleted

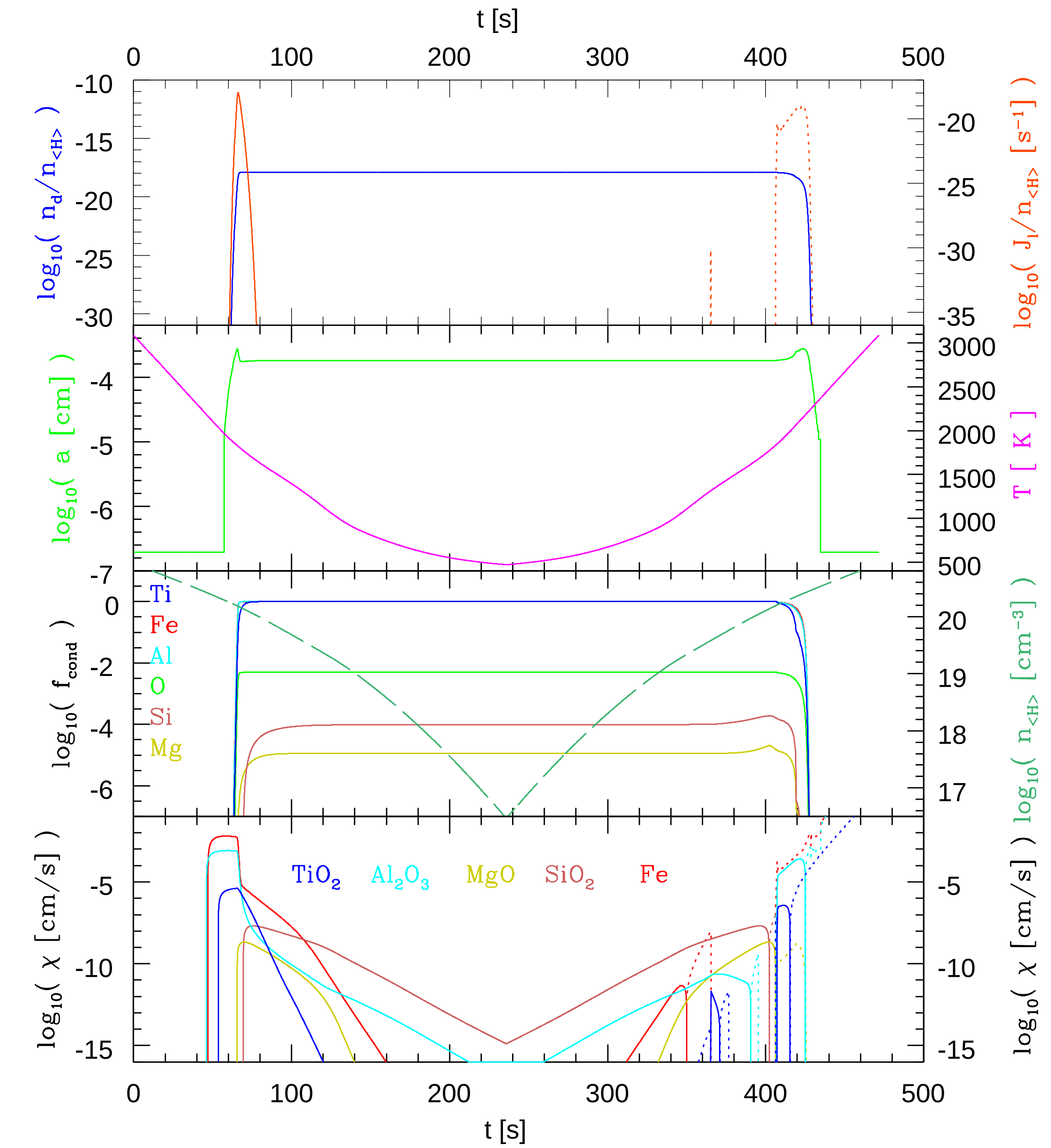

Figure 3: Resulting dust quantities in a gas cell as function of time moving with subsonic velocity through a Brown Dwarfs atmosphere adopted from Tsuji's model A (private communication).

1st Panel: blue - number of dust grains per H atom $n_{\rm d}/n_{<\rm H>}$, solid red - nucleation rate per H atom $\log J_*/n_{<\rm H>}$ $[\rm s^{-1}]$, dotted red - evaporation rate per H atom $\log J_{\rm ev}/n_{<\rm H>}$ $[\rm s^{-1}]$, **2nd Panel**: magenta - temperature T [K], green - mean particle radius $\langle a\rangle$ [cm], **3rd Panel**: degree of condensation for elements involved in the dust formation (colors see plot), dashed green - total density of hydrogen $n_{<H>}$ $[\rm cm^{-3}]$, **4th Panel**: solid lines - net growth velocity $\chi_{\rm gr}$ $[\rm cm\,s^{-1}]$, dotted line - net evaporation velocity $\chi_{\rm ev}$ $[\rm cm\,s^{-1}]$

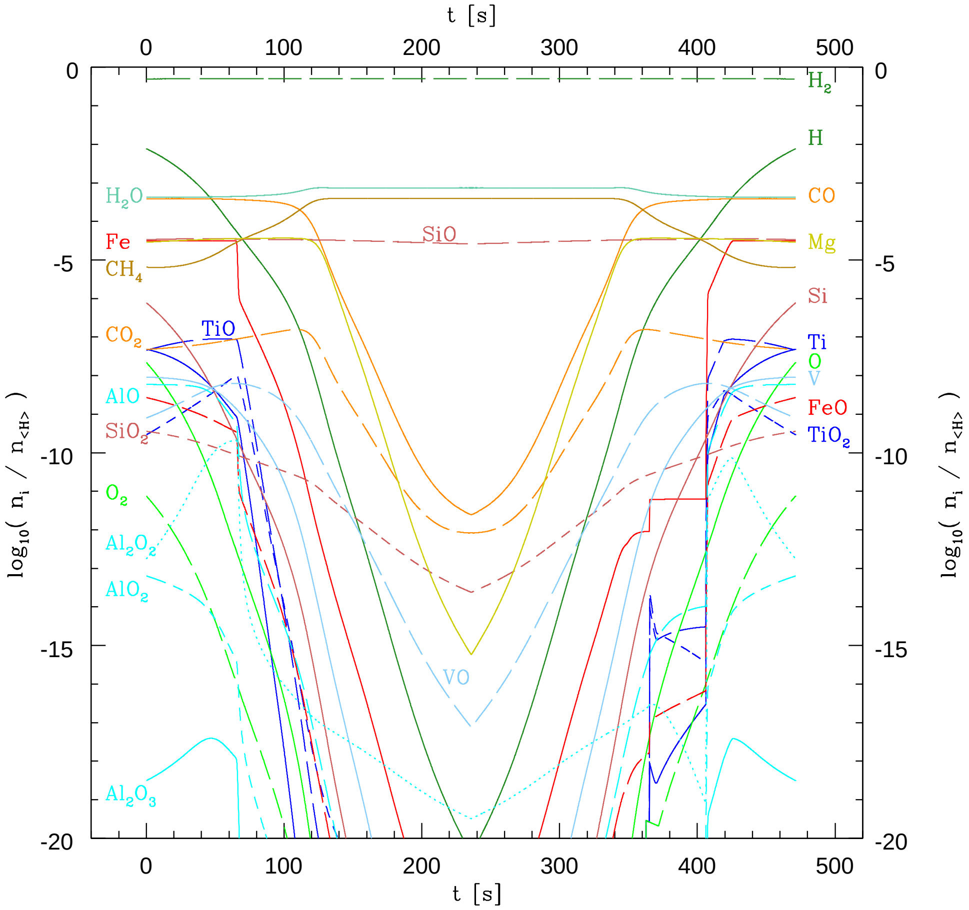

Figure 4: Resulting chemical equlibrium concentrations in a gas box as a function of time moving with sub-sonic velocity through a Brown Dwarf atmosphere. The atmospheric structure is adopted from Tsuji's model A (private communication).

followed by Ti (compare 3rd panel). In this case the nucleation rate drops and consequently, the particle number reaches its maximum value. Only SiO_2 and MgO are left for further particle growth, but the mean particle size is 0.2 magnitudes smaller than at the beginning of dust formation, since these molecules are not very abundant in this warm region. As the test box travels further outwards, conditions for nucleation and dust growth get worse, because the growth velocities χ drop considerably for all condensing species (4th panel).

On its way back into the deeper, hot and dense layers of the atmo-

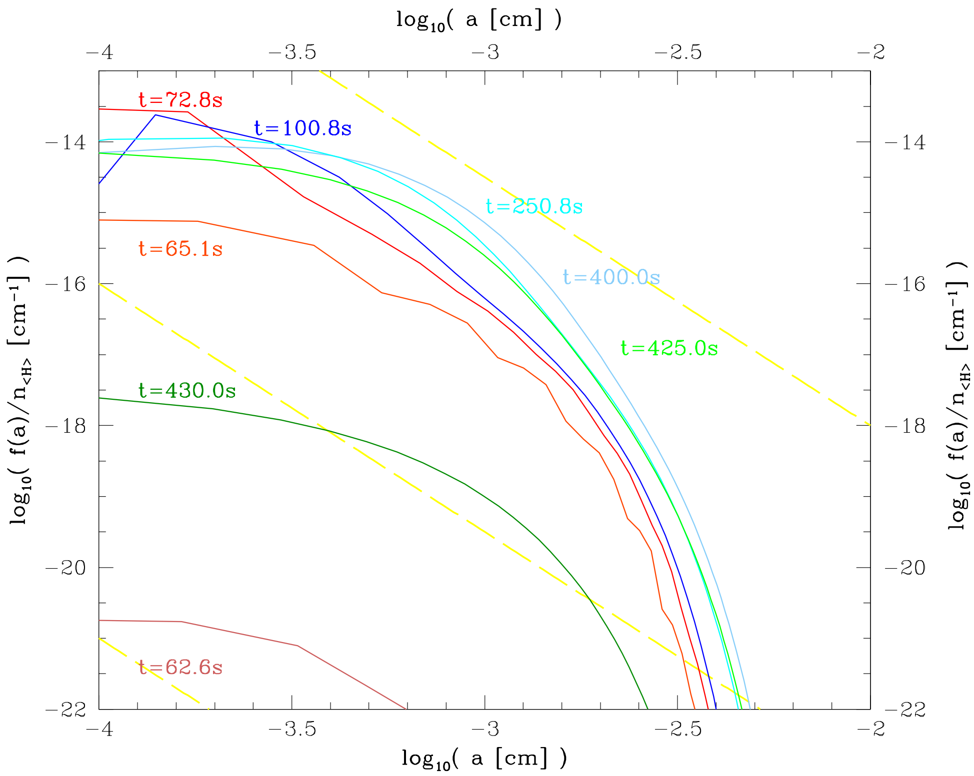

Figure 5: Grain size distribution functions at different instants of time. For comparison, a power law distribution $f(a) \sim a^{-3.5}$ based on Mathis *et al.* 1977 is depicted (yellow).

sphere, evaporation alters the dust grains. As the evaporation rate increases (1st panel), the number of dust particles decreases resulting in a slight increase of the mean particles radius after $t \approx 420\,$s. This increase is caused by the growth of SiO_2 and MgO since Si and Mg have not been fully consumed during the previous dust growth phase. Reaching the deep regions of the atmosphere all dust has been vanished. The corresponding temporal evolution of the chemical equlibrium concentrations in the gas phase is shown in figure 4. Figure 5 shows the resulting size distribution function for the dust grains at different times. Mainly particles of moderate sizes $(1 \ldots 3\mu\mathrm{m})$

are formed. The temporal evolution of the grain size distribution can easily be followed.

Conclusion

- We have shown that stability sequences are not sufficient to decide which species nucleates first since a large supersaturation ratio has to be achieved causing a gap between nucleation and sublimation temperatures.
- Titanium-oxides are suggested as the most promissing nucleation candidate in Brown Dwarfs according to modified nucleation theory. Assuming solar chemical abundances, iron seems to be a good candidate as nucleating species in gas planets.
- Our first studies of the evolution of the dust under conditions typical for a Brown Dwarf atmosphere show moderate particle sizes which are related to the formed number of particles. The number of particles depends on the thermodynamical conditions of their site of formation. These are solely results of a simple model and a more sophisticated description for the whole atmosphere including radiation hydrodynamics and dust formation is under construction.
- The resulting size distribution function depends on the "history" of the dust complex and is consequently time dependent and is not sufficiently described by a power law.

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