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Chemical composition of dust clouds in turbulent brown dwarf atmospheres

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Abstract. Brown dwarf atmospheres are largely convective. These convective gas flows collide and feed back a whole spectrum of turbulent fluctuations into the atmospheric fluid field. Resulting non-static density and temperature fields influence the local chemistry concerning gas phase and dust formation. Numerical simulations are used to show the large and inhomogeneous changes of the gas phase chemistry in a turbulent dust forming cloud region of a brown dwarf atmosphere. The relaxation time scale of the gas phase composition towards steady state is considerably longer than for the dust component.

Keywords. Turbulence, convection, astrochemistry, methods: numerical, stars: low-mass, brown dwarfs, infrared: stars

1. Introduction

Brown dwarfs are very cool, faint, and compact objects. They are the only stars which form dust in their atmosphere. These very dense brown dwarf atmospheres are highly convective, just as planetary atmospheres are. Non-static density and temperature fields result and influence the ability of the atmosphere to form clouds spatially very heterogeneously due to the strong dependence of gas - solid/liquid phase transition on temperature (Helling *et al.* 2001). Once present, dust particles grow and change their relative chemical composition again depending strongly on the local temperature. The local temperature is determined by the turbulent fluid field and by the cooling ability of the radiating dust particles. A complex interaction circle establishes which eventually determines the chemical composition of a dust cloud, and consequently its spectral appearance (Helling *et al.* 2006).

2. Approach

The hydrodynamic equations are coupled to element conservation equations and dust moment equations (Helling *et al.* 2001) which describe the formation of seed particles ($TiO_{2[s]}$) and the growth/evaporation of a grain mantle (TiO_2[s], SiO_2[s], Mg_2SiO_4[s], Al_2O_3[s], and Fe[s]; Helling & Woitke 2006). Radiative cooling is treated in a relaxation towards radiative equilibrium. The initial conditions are dust free. The equations are solved numerically in a hydro-code (Smiljanovski *et al.* 1997).

Two different turbulence models are applied in our numerical simulations:
Figure 1: The initial conditions for the hydrodynamic equations are set by Gaussian expansion waves which model colliding turbulence eddies (Helling *et al.* 2001). Figure 1 shows the time-evolution at the site of superposition.
Figure 2: The boundary conditions are transparent and a spectrum of superimposed waves (N=100) is initiates which continuously drives turbulence (Helling *et al.* 2004). Figure 2 depicts the time evolution at the center of the test volume.

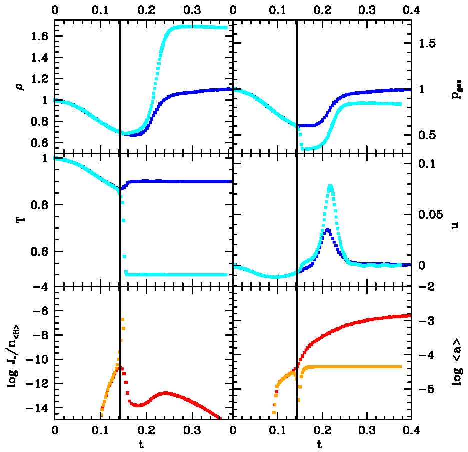

Figure 1. Time evolution at the site of two superimposing expansion events. ($T_{\rm RE} = 0.9T_{\rm ref}$ – dark colors/black, $T_{\rm RE} = 0.5T_{\rm ref}$ – light colors/dark gray)

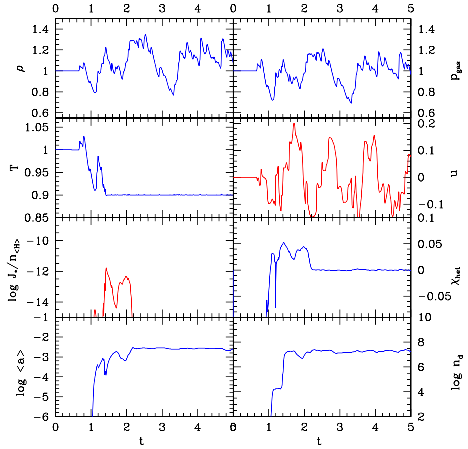

Figure 2. Time evolution at the center of a dust cloud with turbulent boundaries.

The parameter of the simulations are: $T_{\rm ref}$= 1900 K, $\rho_{\rm ref} = 10^{-3.5}{\rm g/cm}^3$, $v_{\rm ref} = 0.1c_{\rm s}$, $l_{\rm ref} = 10^5$cm; $T_{\rm RE}$ - radiative equilibrium temperature (see Figs. 1, 2), and the dust species to be formed.

3. Results

3.1. *Hydrodynamics and dust formation*

Turbulence → Dust Formation: Turbulence initiates dust formation by locally depressing the temperature below the nucleation threshold (vertical black line Fig. 1, and Fig. 2). Dust Formation→ Turbulence: Once the dust has formed, it is a strong radiative cooling source which quickly adjusts the local temperature to the radiative equilibrium temperature $T_{\rm RE}$ of the atmospheres radiation field (vertical black line (Fig. 1). It follows an *implosion* of the dust forming area which results in a local velocity peak. The height of this peak depends on the temperature difference $\Delta T = T_{\rm local} - T_{\rm RE}$ (compare light / dark colors in Fig. 1). The *velocity peak is retarded* with respect of the maximum dust formation activity. All effects become stronger in a turbulent environment (Fig. 2).

3.2. *Chemical composition*

Dust composition (Fig. 3): The initial phase of dust formation is determined by the highly time-dependent dust growth kinetics. The later time variability (here $t > 1.15$ s) of the dust composition can be directly related to the variability of the local temperature (e.g. t = 1.2 s; Figs. 3, 4). The cross chemical composition of the grains changes from high-temperature (TiO_2[s], Al_2O_3[s], Fe[s]) to low temperature condensates (Mg_2SiO_4[s], SiO_2[s]) with decreasing temperature due to radiative cooling by the dust. This high/low temperature condensate hierarchy does not change, if more solids are taken into account. Gas-phase composition (Fig. 4): The LTE composition of the remaining gas-phase changes initially with the local temperature and density. After the formation of dust is completed (here $t \approx 2.2$ s) the gas composition is still changing due to ongoing element depletion by dust formation. This behavior results from a relaxation toward phase equilibrium where the dust growth and evaporation reactions finally balance each other (Helling &

Woitke 2006). The abundance of many of the gas species drops by orders of magnitudes thereby developing into a highly depleted gas phase.

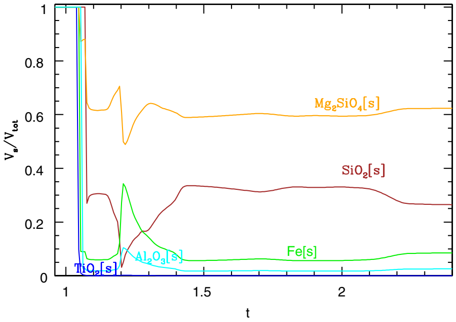

Figure 3. Dust composition in a turbulent cloud.

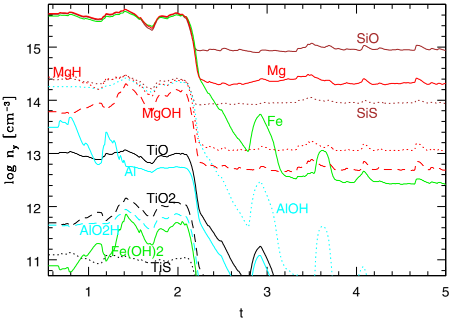

Figure 4. Composition of the remaining gas phase in a turbulent cloud.

4. Conclusion

The composition of the dust in turbulent brown dwarf atmospheres is *chemically heterogeneous* in general and *highly variable* during the formation process. Three time scale influence the chemistry:

⋆ $\tau_{\rm turb}^{\rm dinit}$: time needed for sufficient turbulent superposition to initiate dust formation
⋆ $\tau_{\rm dust}^{\rm S=1}$: time needed to reach phase equilibrium
⋆ $\tau_{\rm gas}^{\rm depl}$: depletion time scale towards phase equilibrium.

Consequently, element abundance determinations for dust forming and dust containing brown dwarf atmospheres will depend on a careful description of the dust complex in model atmosphere simulations.

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