Convective mixing and dust clouds in the atmospheres of brown dwarfs

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Abstract. Observed spectra of brown dwarfs demonstrate that their atmospheres are influenced by dust. To investigate the mechanism that controls the formation and gravitational settling of dust grains as well as the mixing of fresh condensable material into the atmosphere, we performed 2D radiation-hydrodynamics simulations with CO5BOLD. The models comprise the upper part of the convection zone and the atmosphere with the dust cloud layers. We find that direct convective overshoot does not play a major role. Instead, the mixing in the clouds is controlled by gravity waves.

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INTRODUCTION

Temperatures in the atmospheres of brown dwarfs are so low that dust particles can form. These grains should sink under the influence of gravity into deeper layers and vanish from the atmosphere clearing it from condensable material. However, observed spectra can only be reproduced by models accounting for dust formation and its resulting greenhouse effect in the visible layers. The approaches to model dust within classical 1D hydrostatic stellar atmosphere models presented in [1] (see also Helling et al. in these proceedings) differ considerably and all rely on not well justified assumptions about the extent of the cloud layers or the amount of mixing.

Time-dependent RHD models can describe self-consistently the mixing of material beyond the classical boundaries of a convection zone, as demonstrated for instance for main-sequence A-type stars ([2]) or for M dwarfs ([3], [4]).

RADIATION HYDRODYNAMICS SIMULATIONS WITH DUST

We performed radiation-hydrodynamics simulations with CO5BOLD (see [5], [6], and also `http://www.astro.uu.se/~bf/co5bold_main.html`). Our 2D models of brown dwarfs have about 400x300 grid points. The side boundaries are periodic. The lower boundary is closed although the stellar convection zone should extend down

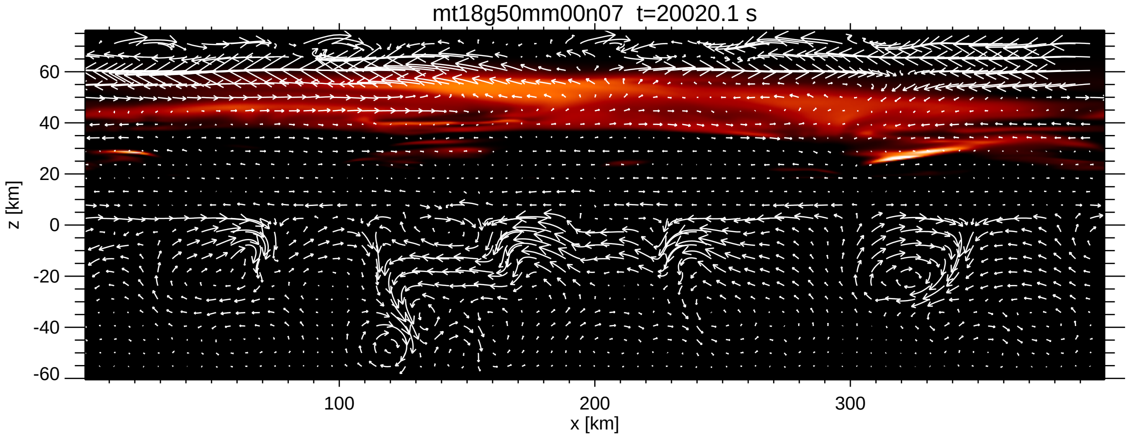

FIGURE 1. This snapshot from a brown dwarf simulation with $T_{\rm eff}$=1800 K, log g=5 shows the velocity field as pseudo-streamlines and color-coded the dust concentration. The flow in the lower part is due to the surface granulation of the stellar convection zone. The top is dominated by gravity waves.

the the center of the star. To keep the entropy close to a prescribed value, the internal energy in a few grid layers at the bottom of the model is adjusted. This mechanism acts as an energy source and replenishes the radiative energy losses through the top of the model.

The dust scheme is based on a simplified version of the dust model used in [7]: only one density field (instead of four as in [7]) describes the amount of dust, the other the amount of monomers. The numerical models include a simple treatment of the formation and destruction of Forsterite as well as its gravitational settling, its advection, and its interaction with the radiation field.

There is a clear separation between the convection zone in the lower part with the standard pattern of cool downdrafts in a warmer environment and the atmosphere with inhomogeneities induced by gravity waves. Figure 1 indicates the location of the actual dust clouds and shows their spatial variations. The concentration of dust and monomers (material that potentially can form dust) shows complete mixing in the convection zone, depleted layers at the top of the atmosphere (due to gravitational settling), and a partially mixed region in between.

The entropy profiles – averaged horizontally and in time — in Fig. 2 (top left) show a strong increase in the upper atmosphere, with only a minor drop at the top of the convection zone, and an almost flat distribution inside the convection zone. This indicates very efficient convection resembling typical conditions in the stellar interior. As shown in Fig. 2 (top right) the convective velocities fall significantly from the peak value inside the convection zone (on the right) to the top of the unstable layers, and even further (overshooting region). The scale height of *exponentially decreasing overshoot velocities* is so small that they do not induce significant mixing in the cloud layers. Above a local minimum in the vertical velocities, *gravity waves* dominate. Their average velocity amplitude is *very roughly proportional to the inverse square root of the density*. Their mixing efficiency increases rapidly in height – not only due to the increase in

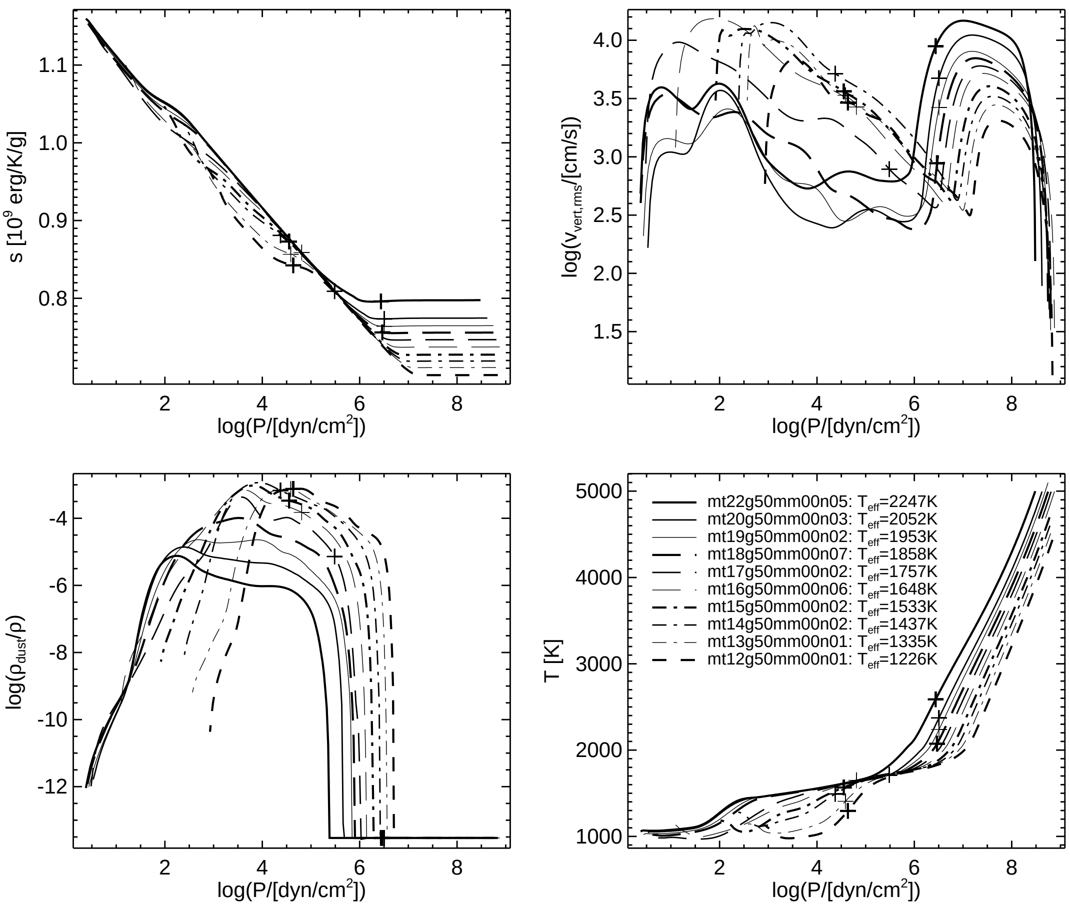

FIGURE 2. Top left: mean entropy over logarithm of pressure for various effective temperatures and $\log g$=5. The plus signs mark the layers with Rosseland optical depth unity. The legend is the same in all panels. Top right: logarithm of rms vertical velocity over logarithm of pressure. Bottom left: logarithm of dust concentration over logarithm of pressure. Bottom right: mean temperature over logarithm of pressure.

amplitude but also due to the increasing non-linearity. The complex dependence of wave amplitudes on height, effective temperature, gravity, boundary conditions, resolution, etc. is still under investigation.

Figure 2 (bottom left) shows the vertical extent of the dust clouds. At temperatures just low enough to allow the onset of dust formation, local temperature fluctuations modulate the dust density on short time scales given by the typical wave period. This leads to a *variation in the vertical thickness of the clouds*. In layers within the clouds, temperatures fluctuate causing evaporation/condensation cycles. Grain settling is balanced by *mixing induced by gravity waves*. However, at some height, the gravitational settling of dust grains becomes more efficient than the mixing and dust density and opacity drop rapidly. At the top of the clouds, braking waves occur and a local *dust convection zone* is forming. The influence of dust onto the temperature structure is demonstrated in Fig. 2 (bottom right), where you can see the relatively large temperature gradient inside the convection zone on the right, a fairly shallow slope below the cloud layers with values around 1600 K, the rapid drop within the clouds (due to the large dust opacities), a fairly low temperature (with values around 1000 K and small variations) in the essentially dust-free atmosphere, and in some cases a small increase at the top of the models due to dissipation of kinetic wave energy.

A problem in modelling the dynamics of dust clouds is the poorly known complex microphysics: a complicated chemical network of molecules with space and time dependent abundances can form dust via various processes, resulting in grains with different structures. And the dynamical behavior and optical properties all depend on the grain type. Furthermore, depletion leads to a change in the gas composition that affects equation of state and gas opacities. The current dust model in CO5BOLD is meant to cover the essential processes, but cannot account for all details that might possibly play a role.

Our time-explicit radiation hydrodynamics simulations are restricted by the Courant condition but can easily cover many convective turnover times or wave periods. However, dust settling time scales are significantly larger: it takes much longer for the dust clouds go into a statistically stable state than for the convective cells. This the reason why the current simulations are restricted to two dimensions.

CONCLUSIONS

The presented 2D radiation hydrodynamical models of brown dwarf atmospheres show that overshoot velocities decline roughly exponentially with distance from the convectively unstable regions, as found previously in e.g. A-type and M-type dwarfs. However, the velocities drop so steeply that they are only important close to the convection zone. Instead, gravity waves dominate the mixing of the upper atmospheric layers with amplitudes even growing with height. The induced mixing is sufficient to balance the settling of dust grains. At the top of the dust cloud layers braking waves and/or dust convection causes efficient stirring of material. Dust concentration and cloud thickness are modulated by the waves.

Models with higher effective temperature show a high-altitude haze of optically thin clouds. At lower effective temperatures thick and dense clouds exist but mostly below the visible layers, that are essentially depleted of the material that went into the dust. In between, dust is the dominating opacity source in the atmosphere.

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