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CONVECTIVE MIXING AND DUST CLOUDS IN BROWN DWARF ATMOSPHERES

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Abstract. 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 of brown dwarfs, we performed 2D radiation-hydrodynamics simulations with CO5BOLD. We find that direct convective overshoot does not play a major role. Instead, the mixing in the clouds is controlled by gravity waves.

1 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 Helling et al. (2008) 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 (Freytag et al. 1996) or for M dwarfs (Ludwig et al. 2002, 2006).

2 Radiation-hydrodynamics simulations including dust

We performed 2D radiation-hydrodynamics simulations of brown dwarf atmospheres with CO5BOLD, see Freytag et al. (2002), Wedemeyer et al. (2004). The adopted dust scheme is based on a simplified version of the dust model used in Höfner et al. (2003). It includes 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 and the atmosphere with inhomogeneities induced by gravity waves in the upper half of Fig. 1. As shown in Fig. 2 (left panel) 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, instead. Their mixing efficiency increases rapidly with height – not only due to the increase in amplitude but also due to the increasing non-linearity. Figure 2 (center) 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 (right panel).

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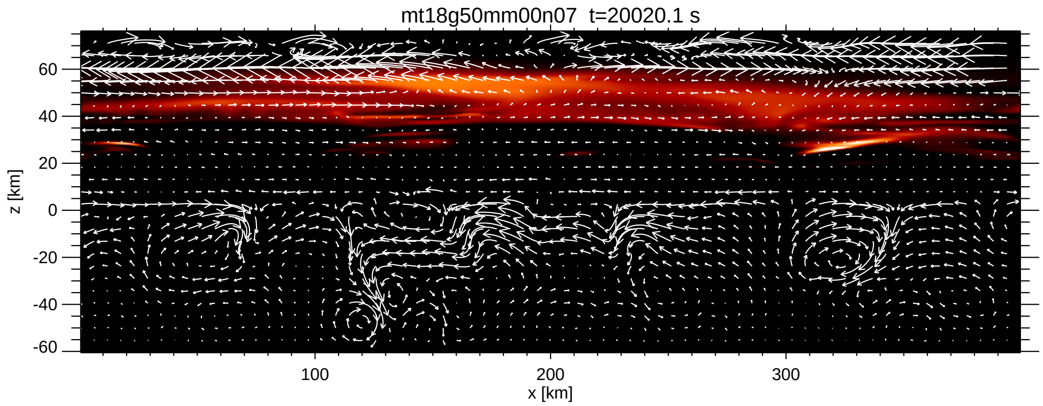

Fig. 1. This snapshot from a brown dwarf simulation with $T_{\rm eff}$=1858 K, log g=5 shows the velocity field as pseudo-streamlines and color-coded the dust concentration.

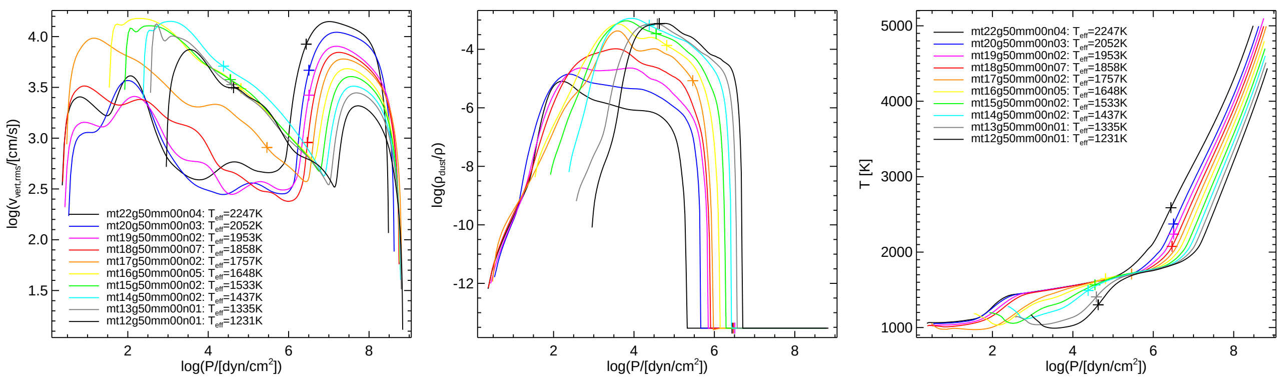

Fig. 2. Various quantities over logarithm of pressure for various effective temperatures (see legend) and log g=5. The plus signs mark the layers with Rosseland optical depth unity. From left to right: logarithm of rms vertical velocity, logarithm of dust concentration, mean temperature.

3 Conclusions

Our 2D radiation hydrodynamical models of brown dwarf atmospheres show that – instead of exponentially declining overshoot – gravity waves dominate the mixing of the upper atmospheric layers with amplitudes growing with height. The induced mixing is sufficient to balance the settling of dust grains. 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 an important opacity source in the atmosphere.

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