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Simulations of dust clouds in the atmospheres of substellar objects

Theory toddles after observations

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Abstract. The atmospheres of brown dwarfs allow the formation of dust grains and their rain-out into deeper, invisible layers. However, observed spectra of L dwarfs can only be reproduced when static 1D models account for dust formation and its resulting greenhouse effect in the visible layers. Time-dependent hydrodynamical processes can mix up the material giving rise to complex unsteady weather phenomena on these objects. We performed radiation hydrodynamics simulations in two and three dimensions of the atmospheres of brown dwarfs with CO5BOLD, including a treatment of dust particles. We find that exponential overshoot (close to the gas convection zone), gravity waves (weak omni-present mixing), and convection within dust layers (in the thick clouds in cooler models) contribute to the atmospheric mixing, which is far from being a stationary process. The presence of dust in the atmospheres is accompanied by large temporal and spatial intensity fluctuations.

Key words. numerical simulations – radiation hydrodynamics – stellar convection – stellar pulsations – brown dwarfs – very low mass stars

1. Introduction

To reproduce and explain the observed spectra of brown dwarfs requires atmosphere models that account not only for the complex chemistry but also for the more or less unknown cloud physics in these objects (Helling et al., 2008a). In late M to L dwarfs PHOENIX Dusty models (Allard et al., 2001) work reasonably well, simply assuming that dust grains remain wherever they form, whereas for late T dwarfs the PHOENIX Cond models, that assume all condensable material to have vanished from the atmosphere, work better. However, for the L/T transition a simple switch between Dusty/Cond models is not satisfactory and a more detailed cloud model is required.

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Tsuji (2002) uses a free parameter for the temperature of the upper limit of the cloud deck and Burrows et al. (2006) parametrize the spatial extent of the clouds, whereas Ackerman & Marley (2001) model the dust mixing by a diffusion process with an adjustable coefficient. Helling et al. (2008b) use a parametrized mixing time scale based on RHD (radiation hydrodynamics) models of M dwarfs by Ludwig et al. (2006).

We extended the latter simulations and computed with the CO^5BOLD code (Freytag et al., 2002; Wedemeyer et al., 2004) a temperature sequence (3000 K down to 900 K at log g=5) of local 2D RHD atmosphere models (and one 3D model, so far) of M, L, and T dwarfs. The code solves the coupled equations of compressible hydrodynamics and non-local frequency-dependent (five bins) radiation transport on a Cartesian grid.

Additional fields describe the densities of dust and monomers. For most of the simulations we use a model of Forsterite dust that accounts only for the monomer density and one dust density per grid cell, resulting in single-sized grains. However, the grain radius can vary from cell to cell. Nucleation is not treated explicitely and is assumed to be "easy": if there is a positive supersaturation, grains can form and grow (see Freytag et al. 2009, in prep.).

In addition, we developed a more complex dust scheme accounting for a size spectrum in each grid cell, which requires several additional density fields (typically eight). In this model we treat nucleation in detail, which means that nucleation occurs only in regions with significant supersaturation.

2. Results

Figure 1 shows a vertical slice through the 3D model. The lower half of the computational box comprises the surface layers of the gas convection zone. The atmosphere above is filled with gravity waves and has an irregular dust cloud layer.

The transition from the initial 2D configuration to a fully 3D flow field is demonstrated for the emergent intensity in Fig. 2, showing

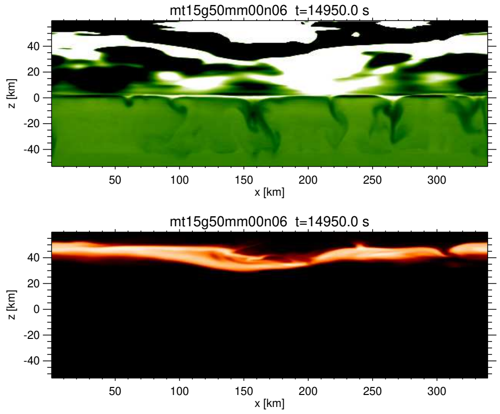

Fig. 1. Vertical slice through a 3D model with $T_{\rm eff}$=1500 K and log g=5 showing entropy fluctuations (horizontal average subtracted) in the upper panel and the dust concentration in the lower panel.

the fluctuations in the cloud layers, and the vertical velocity below the top of the convection zone in Fig. 3, exhibiting the usual granulation pattern. Figure 4 demonstrates that the choice of the position of the upper boundary and the switch from 2D to 3D has little influence on the rms vertical velocities. Above the gas convection zone there is a thin overshoot layer with exponentially declining velocities (Freytag et al., 1996) that do not reach the Forsterite dust clouds but might have an influence onto the mixing of material that forms dust at higher temperatures. Gravity waves grow with height in the convectively stable atmosphere. They provide a ubiquitous but inefficient mixing (due to the almost reversible wave motions). Most of the large-scale intensity fluctuations in Fig. 2 are due to gravity waves. Where the dust densities – and opacities – are large enough, convective flows within the dust clouds provide additional mixing. They have no obvious signature in Fig. 4 but cause the bright filaments in Fig. 2 and become more pronounced at lower-temperature models.

Figure 5 shows that the peak atmospheric rms-velocities (squares in the left panel) do not just follow the monotonic decay of the maximum rms-velocities in the gas convection zone (crosses in the left panel) with $T_{\rm eff}$ but have a bump around $T_{\rm eff}$=1500 K due to dust convec-

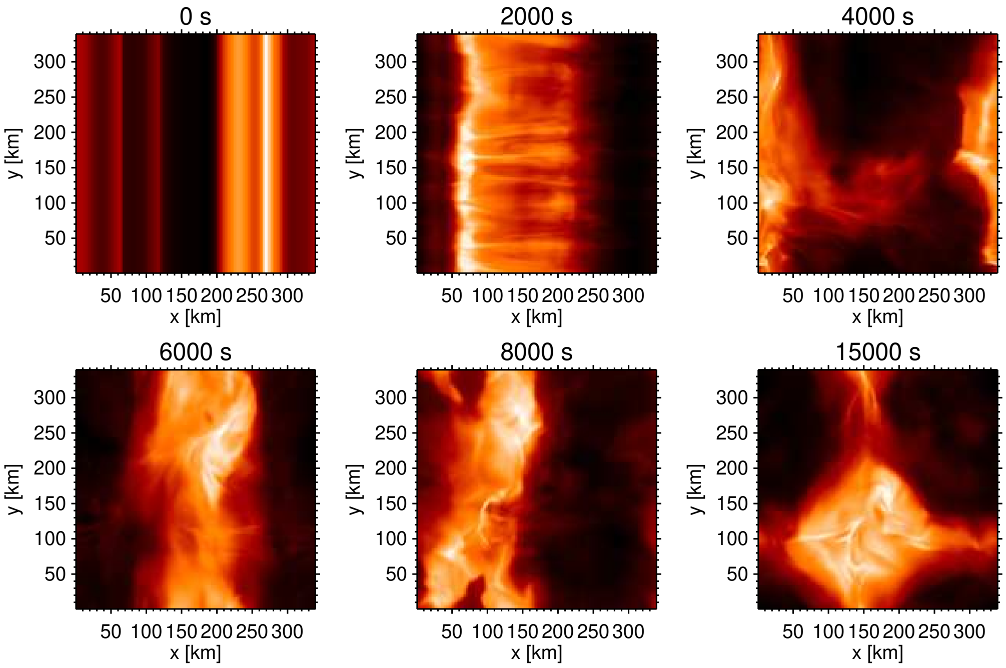

Fig. 2. Sequence of emergent intensity images for 3D model mt15g50mm00n06 showing the transition of the cloud pattern from 2D to 3D.

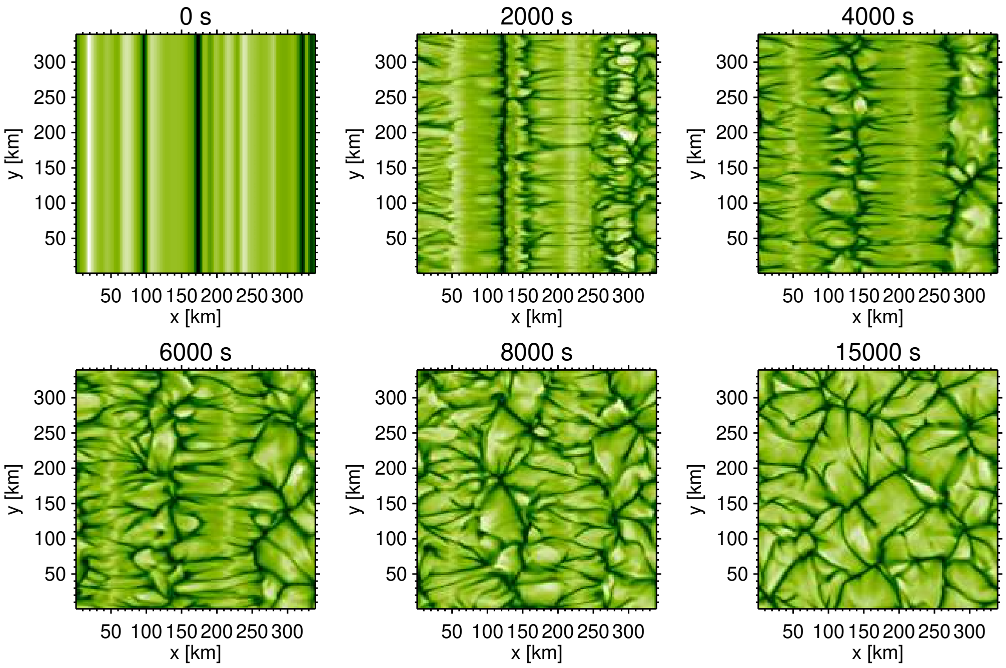

Fig. 3. Sequence of horizontal slices with the vertical mass flux below the top of the convection zone for 3D model mt15g50mm00n06 showing the transition from a 2D to a 3D configuration for the granulation.

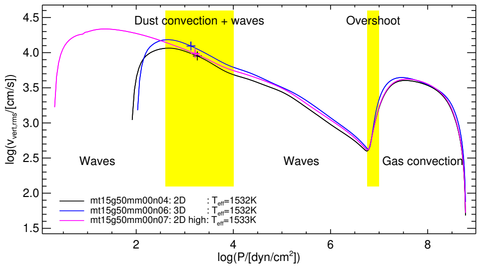

Fig. 4. Logarithm of rms vertical velocity over logarithm of pressure for three models with $T_{\rm eff}$~1500 K, log g=5. The 3D model has slightly larger velocities than the corresponding 2D model. The velocities of the extended 2D model agree well with the shallower 2D model except – of course – close to the upper boundary.

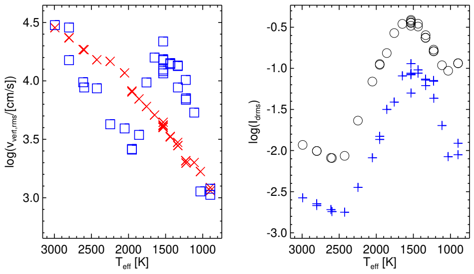

Fig. 5. Left panel: logarithm of rms vertical velocities over effective temperature for the entire model list; crosses: maximum convective velocity, squares: maximum atmospheric velocity. Right Panel: logarithm of intensity contrast over effective temperature for the entire model list; circles: total contrast (spatial plus temporal contribution), plus signs: temporal variation of mean intensity only.

tion. The right panel in Fig. 5 shows the dependence of the spatial contrast (circles) and the temporal variations of the mean intensity (plus signs) on effective temperature. Models with $T_{\rm eff}$≥2600 K have only small values due to the expected low contrast of the surface granules. However, below 2500 K the fluctuations in the dust clouds seen in Fig. 2 begin to have an impact leading to large values at $T_{\rm eff}$~1500 K. However, these fluctuations occur on small scales and should only be taken as indication that indeed dust clouds can cause significant surface inhomogeneities. The spatial scales covered by the existing models are too small to account for the large brightness fluctuations observed by Artigau et al. (2009).

The cooler models show intensity fluctuations on a time scale of up to a minute due to gravity waves, of several minutes due to the overturning time scale of dust convection, and of hours due to changes in the dust cloud "activity". The latter is more pronounced in the models that account for an entire spectrum of grain sizes: the rainout of clouds, the collection of material at the bottom of cloud layers, and the intermittent upwelling of material back into upper layers occur in cycles and leads on the average to thinner clouds.

The occurence of exponential overshoot, gravity waves, and dust convection is a robust result of our simulations and stable against parameter changes. They certainly play a role for the mixing in substellar atmospheres. However, the size spectrum of the grains, nucleation, and the role of large-scale horizontal transport of material deserves further investigation and model refinement – with a close look at existing and forthcoming observations.

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