Radiation-Hydrodynamics Simulations of Cool Stellar and Substellar Atmospheres

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Abstract. In the atmospheres of brown dwarfs, not only molecules but much larger and heavier “dust” particles can form. The latter 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 assuming the presence of dust and its resulting greenhouse effect in the visible layers. Apparently, hydrodynamical mixing can counteract the gravitational settling.

We present new 2D and 3D radiation-hydrodynamics simulations with CO5BOLD of the upper part of the convection zone and the atmosphere of cool stars and brown dwarfs in a range of temperatures and gravities that enable the formation of dust clouds in the visible layers.

We find that the differences between 2D and 3D models are remarkably small. Lowering the gravity has a somewhat similar effect on the surface intensity contrast as increasing the effective temperature. The biggest uncertainties of the simulations come from approximations made in the description of the dust chemistry. Global circulation and rotation likely play an important role.

1. Numerical simulations

We used CO5BOLD (Freytag et al. 2002; Wedemeyer et al. 2004) to perform 2D and 3D radiation hydrodynamics simulations of stellar surface convection for a grid of atmospheres with different dust formation regimes (M, L, and T spectral types), complementing our set of RHD models of cool stellar atmospheres (Freytag et al. 2010).
The equation of state accounts for the ionization of hydrogen and helium. The detailed opacity tables treat frequency dependence via an opacity-binning scheme. We use two different settings: global (aka “star-in-a-box”) models for extreme giants taking sphericity effects fully into account (Freytag et al. 2002; Freytag & Höfner 2008; Chiavassa et al. 2009, 2010). For dwarfs on the other hand, we use the local (aka “box-in-a-star”) setup, where a model represents only a part of the stellar surface in Cartesian geometry, ignoring sphericity effects entirely. See the paper by Freytag et al. (submitted to the special issue of JCP on computational plasma physics, ed. Barry Koren) for more details about the code.

The local models of brown dwarfs include a simple treatment of the formation and destruction of dust, as well as its gravitational settling and advection, and also the interaction with the radiation field. We extended our previous work (Freytag et al. 2010) and computed a grid in effective temperature and gravity of 2D models. We experimented with different descriptions of the dust formation process, but concentrate in this article on three 3D models with $300 \times 300 \times \sim 300$ grid points, that are about half as high as wide.

2. 3D models of M and brown dwarfs

![Figure 1](image.png)

Figure 1. Comparison of rms vertical velocities (left) and averaged temperature profiles (right) for three pairs of 2D/3D models.

Horizontal and temporal averages of the rms vertical velocity and the temperature are shown in Fig. 1, comparing the three 3D models from Fig. 2, Fig. 3, and Fig. 4 with corresponding 2D models from Freytag et al. (2010).

Figure 2 shows the evolution of surface intensity maps for an M dwarf, that resemble the familiar solar-like granulation pattern. The main differences are the smaller geometrical scale and velocities, lower contrast (close to the minimum in the Fig. 6), thinner intergranular lanes, and occasional knots (Ludwig et al. 2002). The average temperature structure is almost identical to a corresponding 2D model (black curves in the right panel in Fig. 1). However, the rms vertical velocity does show some – but not severe – differences between 2D and 3D. Noticeable is the steeper (approximately exponential, see Freytag et al. 1996; Ludwig et al. 2002, 2006) decay of the velocities...
in the overshoot region at the top of the convection zone in the 3D models. Even larger deviations between 2D and 3D occur in simulations of solar-like models.

Due to the relatively high temperatures, there is hardly any dust in this model. See Wende et al. (2009) for a more detailed analysis of 3D models in a gravity sequence of slightly hotter M stars.

In the sequence of intensity snapshots of an L-dwarf model in Fig. 3, the clouds are visible as dark irregular blobs on top of the uncorrelated convective granulation pattern, changing shape on time scales shorter than the typical granular time scale, because the formation of dust clouds is governed by short-period gravity waves. The temperature and density fluctuations are large enough to allow for new grain nuclei (seeds) to form. The 3D and 2D models in Fig. 1, agree rather well in their averaged properties, similar to the 2600 K case, above.
With further decreasing effective temperature, the dust layers become even thicker, finally obscuring the underlying granulation and determining the surface contrast completely. The sequence of intensity snapshots of an L/T-transition or early T dwarf in Fig. 4 shows the large contrast variations, that are induced in the cloud layers mostly by a single-mode gravity wave. The thin bright filaments are due to convection within the dust clouds. 2D and 3D models agree well in their averaged properties (Fig. 1). At these low effective temperatures, photospheric fluctuations are comparably small and there are hardly cases where the supersaturation is sufficient for nucleation to take place.
3. Model grid and intensity contrast

The grid of solar-metallicity CO5BOLD RHD models is displayed in Figs. 5 and 6, with contributions from Elisabetta Caffau, Andrea Chiavassa, Bernd Freytag, Arunas Kucinski, Hans-Günter Ludwig, Matthias Steffen, Astrid Wachter, and Sebastian Wende and solar models by Oskar Steiner, Thomas Straus, and Sven Wedemeyer-Böhm. The models comprise the solar-metallicity part of the CIFIST grid of solar-like 3D models (Ludwig et al. 2009), 3D M-dwarf models (Wende et al. 2009), local 2D “dusty” brown-dwarf models (Freytag et al. 2010), global 3D red supergiant (Freytag et al. 2002; Chiavassa et al. 2009, 2010) and AGB star models (Freytag & Höfner 2008), as well as more experimental models of e.g., A-type stars (in 2D or 3D) and cepheids (in 2D).
Figure 5. This figure shows part of the CO5BOLD model grid in a $\log T_{\text{eff}} - \log g$ diagram. Larger symbols mean lower gravity (and usually a larger stellar radius). Squares depict 3D models, triangles 2D models. Solar models have the $\odot$ symbol. Global models of red supergiants and AGB stars are marked as “proper” stars at the top. Red symbols indicate that the simulations have accounted for dust in some form. Models with non-solar metallicities (including white dwarfs) are not shown.

On the main sequence (smallest symbols), the contrast has a plateau for stars a bit hotter than the Sun, because convection does not carry the entire stellar flux anymore. The hottest objects in the plot are A-type stars, where the surface contrast even decreases, because the convection zones are thin and inefficient and radiative energy transport dominates, strongly reducing the contrast of the remaining granulation. On the other hand, the contrast decreases for stars cooler than the Sun, since the stellar energy flux decreases and convection can transport it with smaller temperature fluctuations. Beyond a minimum at around 2600 K, the contrast increases again, because fluctuating dust clouds start dominating the surface contrast (Figs. 3 and 4). The contrast decreases at the cool end due to the decreasing overall flux.

In general, lowering the gravity has a similar effect as increasing the effective temperature, but increases the contrast even further. Correspondingly, the largest surface contrast is seen in the AGB-star models with extremely low gravity.

2D models have a larger contrast than corresponding 3D models (compare triangles and squares at similar stellar parameters). Other types of dust (and/or dust schemes) as well as global fluctuations might change the picture for the cooler models.
4. Conclusions

In the RHD models of cool objects, gravitational settling of dust grains is counteracted by exponential overshoot close to the convection zone, by gravity waves (dominant in hotter objects), and convection at the top of the dust clouds (cooler objects) higher up in the photosphere (see Freytag et al. 2010). PHOENIX 1D model atmospheres using a mixing efficiency based on the COSBOLD RHD models reproduce well the color transition in the sequence of M, L, and T dwarfs (see the article of France Allard in these proceedings).

In contrast to solar-like models, there is no big difference between the horizontally averaged stratifications of 2D and 3D RHD models. Particularly the wave amplitudes in the upper atmospheres are not drastically different. However, 2D models have larger convective scales with a larger granular contrast and a larger scale height of overshoot velocities. At lower gravities, the dust density decreases but the clouds become thicker and reach higher up. Convective velocities increase, in agreement with MLT predictions. As a consequence, overshoot and wave velocities increase, too. Variations of the dust model, that we have used for our experiments, make little difference at higher effective temperatures but matter at the low-temperature end.
5. Outlook

Local radiation-hydrodynamics simulations of solar-like (not dusty, non-magnetic) stars down to M dwarfs with CO5BOLD or similar codes give reliable atmosphere models. In contrast, the modelling of dusty objects is still in its infancy. The existing models of M dwarfs, with atmospheric conditions close to the onset of dust formation, are already promising. However, cool brown dwarfs with their non-equilibrium chemistry might have more Earth-like conditions, where horizontal advection and the interaction of global and local phenomena have to be taken into account.

Development will focus on the improvement of dust description accounting for a better treatment of nucleation and for different grain sizes and species. While the mixing of material can be provided by the described mechanisms, the production and transport of seeds needs further attention.

New simulations will concentrate on extending the model grid towards lower effective temperatures (more “planet-like” cases) and lower gravities (younger objects), both in 2D and (in some cases) in 3D. The effects of rotation on local models will be explored.

The general trend of the development will be towards global models, that account for small scales (of granules and clouds) and global scales (“weather” patterns transporting material over large scales).

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