Radiation-Hydrodynamics Simulations of Cool Stellar and Substellar Atmospheres

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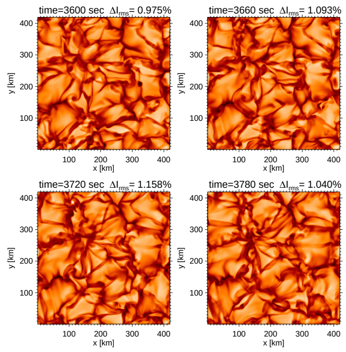
Abstract

In the atmospheres of brown dwarfs molecules can condensate and form "dust", which 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 containing the dust cloud layers. The calculations cover a range of temperatures and gravities of stars. We find that the differences between 2D and 3D models are remarkably small. Lowering the gravity has a somewhat similar effect as increasing the effective temperature. The biggest uncertainties of the simulations come from approximations made in the description of the dust chemistry. Global effects likely play an important role.

Numerical simulations

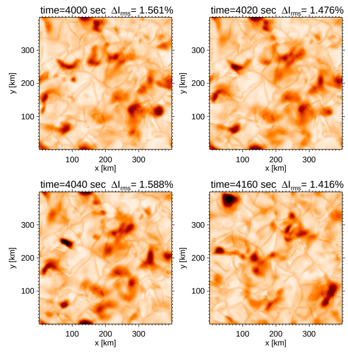
We used CO5BOLD to perform 2D and 3D radiation hydrodynamics simulations for a grid of atmospheres with different dust formation regimes (M, L and T spectral types), complementing our set of RHD models of cool stellar atmospheres. The local models include a simple treatment of the formation and destruction 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: A&A 513, 19) 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 poster on three 3D models with $300\times300\times\sim300$ grid points.

M dwarf 2600 K, logg=5



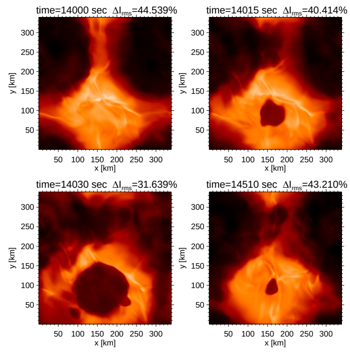
This sequence of plots displays the frequency-integrated intensity for an M dwarf with a time step of 1 minute showing a familiar solar-like granulation pattern. The average temperature structure is almost identical to a corresponding 2D model. However, the rms vertical velocity does show some – but not dramatic – differences between 2D and 3D, as expected from simulations of solar-like models. Due to the relatively high temperatures, there is hardly any dust in this model.

L dwarf 2200 K, logg=5



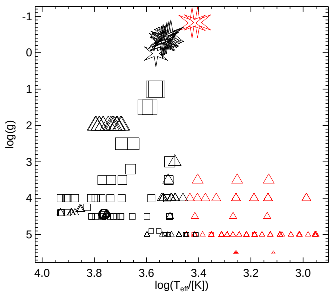
In this (non-equidistant in time) sequence of intensity snapshots of an L-dwarf model the clouds are visible as dark irregular blobs on top of the convective granulation pattern, changing shape on time scales shorter than the typical granular time scale: the formation of dust clouds is governed by short-period gravity waves. The temperature and density fluctuations are large enough to allow for new seeds to form. 2D and 3D models agree rather well in their averaged properties.

T dwarf 1500 K, logg=5



With decreasing effective temperature the dust layers become thicker, finally obscuring the underlying granulation and dominating the surface contrast. This sequence of intensity snapshots of an T dwarf 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. At lower effective temperatures, there are hardly cases where the supersaturation is sufficient for nucleation to take place.

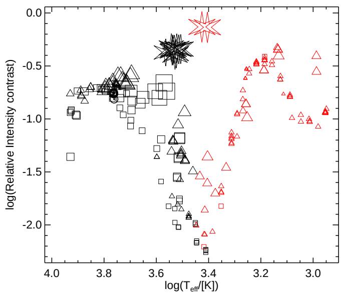
Model grid



This figure shows part of the CO5BOLD model grid in a $\log T_{\mathrm{eff}} - \log g$ diagram with contributions from Elisabetta Caffau, Andrea Chiavassa, Bernd Freytag, Arunas Kucinskas, Hans-Günter Ludwig, Matthias Steffen, Astrid Wachter, Sebastian Wende (and solar models by Oskar Steiner, Thomas Straus, Sven Wedemeyer-Böhm).

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.

Intensity contrast



This plot shows the relative intensity contrast versus T_{eff} for the same models and with the same symbols as in the figure on the left.

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 contrast decreases for cooler stars, 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. 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. The largest surface contrast is seen in the AGB star models. 2D models have a larger contrast than 3D models. Other types of dust (and/or dust schemes) as well as global fluctuations might change the picture for the cooler models.

Results

- In the RHD models, gravitational settling of dust grains is counteracted by exponential overshoot close to the convection zone and by gravity waves (dominant in hotter objects) and convection at the top of the dust clouds (cooler objects) higher up in the photosphere.
- In contrast to solar-like models, there is no big difference between the mean structures of 2D and 3D models.
- At lower gravities, the dust density decreases but the clouds become thicker and reach higher up.
- Variations of the dust model we have experimented with make little difference at higher effective temperatures but matter at the low-temperature end.
- The mixing of material can be provided by the described mechanisms. But what about the production/transport of seeds?
- Local models of solar-like stars down to M dwarfs give reliable atmospheres (ignoring e.g. magnetic spots).
- Cool brown dwarfs with their non-equilibrium chemistry have more earth-like conditions. Horizontal transport and the interaction of global and local phenomena have to be taken into account.

Outlook

- Improvement of dust description (grain sizes, nucleation, species).
- New models: cooler, some in 3D, some with rotation. Towards global models.