Formation of convective structures in stellar atmospheres

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Abstract

Convection is a ubiquitous phenomenon in cool stars. Its interplay with radiation leads to the formation of coherent flow structures – granular cells – on the visible surfaces of these stars. We model the processes with the 3D radiation-hydrodynamics code CO5BOLD in stars of different atmospheric parameters. We find that the granular cell size scales with the atmospheric pressure scale height for stars with a surface gravity $\log g$>1.0. However, the scaling breaks down for red supergiants having lower surface gravities. This qualitatively different behaviour is likely linked to sphericity effects and mainly to a larger contribution of radiation to the energy transport in the stellar envelope.

Stellar granulation

The observed pattern of solar granulation is well reproduced by numerical simulations which also confirm that the typical structure size scales with the atmospheric pressure scale height. Based on such a scaling law, Schwarzschild estimated in 1975 that only a few 100 granules would cover the surface of cool giants. That, however, is still too large a number to account for the observed irregular brightness fluctuations.

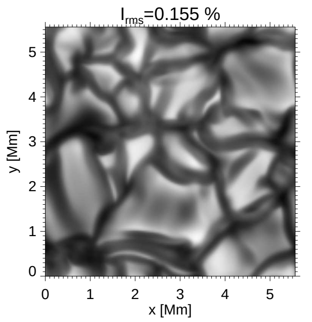
Radiations hydrodynamics simulations of red supergiants show that there are indeed just a few global convection cells on the surfaces of these stars that can explain the observed large-scale structures and fluctuations in overall brightness and line profile.

In this contribution we demonstrate the limits of a simple scaling of convective structure sizes with the pressure scale height.

Numerical simulations

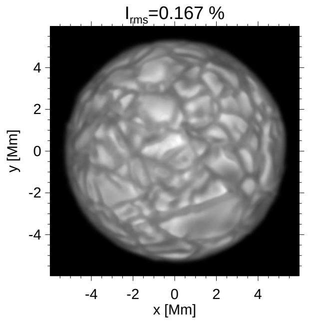
We model stellar surface convection with the 3D radiation-hydrodynamics code *CO5BOLD*. We use two different settings: global (aka "star-in-a-box") models for extreme giants taking sphericity effects fully into account, and local (aka "box-in-a-star") models representing only a part of the stellar surface in Cartesian geometry where sphericity effects are ignored entirely.

Sun: local model



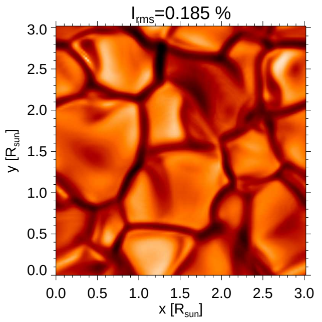
This image shows the emergent intensity from a radiation hydrodynamics model of the sun (d3gt57g44n57, $T_{\rm eff}$=5770 K, $\log g$=4.44). The typical structure size (of ≈1000 km) is related to the local pressure scale height (≈130 – 250 km). The intensity contrast is specified at the top.

Sun: global model



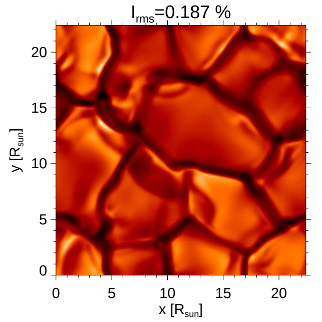
This toy-model (st57g44n24) represents a miniature sun with only 10 Mm diameter illustrating sphericity effects. By artificially adjusting the gravitational potential the atmospheric parameters are the same as in the real sun ($T_{\rm eff}$=5770 K, $\log g$=4.44). An extended upflow region in the lower right produces large expanding granules, whereas the small granules in the upper right indicate a region with converging flow over a downdraft.

Giant 1: local model



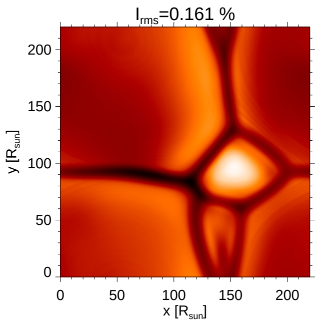
This image illustrates the granular size in a local giant model with a surface gravity of $\log g$=2.0 (d3t50g20mm00n2, $T_{\rm eff}$=5000 K).

Giant 2: local model



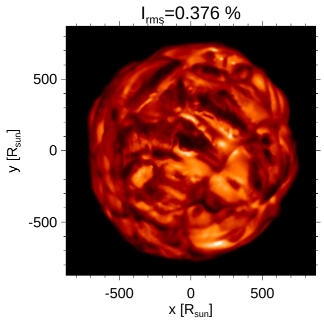
In this local giant model with $\log g$=1.0 (d3t36g10mm00n02, $T_{\rm eff}$=3600 K) the atmospheric pressure scale height is about ten times larger than in Giant 1 and the granular size grows correspondingly.

Supergiant: local model



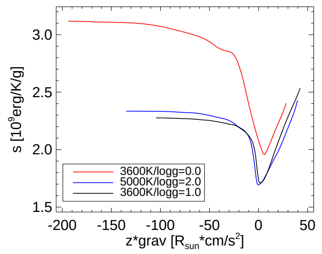
However, for this local model with $\log g$=0.0 (d3t36g00mm00n02, $T_{\rm eff}$=3600 K) of a supergiant the scaling of the box size by another factor 10 compared to the previous model gives a too small computational volume to include the granular cells. Due to the increased influence of the radiative energy transport convection changes its character and the convective energy flux dominates nowhere – in contrast to the models with higher surface gravity.

Supergiant: global model



In this global model (st35gm03n11, $T_{\rm eff}$=3460 K, $\log g$=-0.25) of a red supergiant like Betelgeuse the huge envelope convection cells and smaller surface granules are not clearly visible due to the influence of waves that transform within the photosphere into shocks running into the outer atmosphere.

Entropy versus height



The plot of entropy over height (scaled with the gravity) for three local giant models shows the significant difference between the $\log g$=0 case and the other two: not only is the jump in entropy larger but the superadiabatic region extends further in, too.

Conclusions

- The granule sizes in late-type stars with deep solar-like convection zones scales with the pressure scale height for gravities larger than about one.
- Efficient radiation in cool supergiants causes larger granules.
- Sphericity related sub-surface flows modulate the granular cell size at the surface.

Outlook

To improve the quality of the models the radiation transport needs to be refined. The wavelength dependence of the radiation field should be accounted for in the giant models. Moreover, scattering in the continuum should be included, in particular for metal-poor giants.