Numerical simulations of convection in A-stars

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Abstract. Radiation hydrodynamics simulations have been used to produce numerical models of the convective surface layers of a number of stars, including the Sun and other stars on or above the main-sequence, white dwarfs of type DA, and red supergiants.

While granulation of main-sequence solar-type stars resembles that of the Sun, the convective velocity fields of F-type stars are much more violent and accompanied by strong pulsations. The properties of the thin convection zone(s) of A-type stars differ again (see Fig. 1). In this contribution, the pattern and dynamics of their surface granulation, the photospheric velocity fields and their effect on line profiles are investigated, based on new 3-D models of surface convection in main-sequence A-type stars with T_{eff}=8500 K and 8000 K. Furthermore, we will look below the surface to study overshoot and the interaction of the surface convection zone and the deeper helium II convection zone.

Keywords. Convection, hydrodynamics, radiative transfer, methods: numerical, stars: atmospheres

1. Introduction
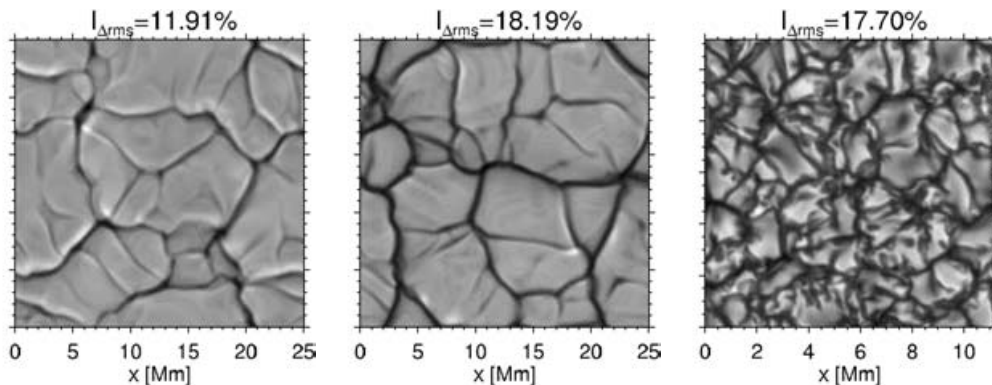
Figure 1. Grey surface intensity maps for model at85g44n16 (left: T_{eff}=8500 K, $\log g$=4.40); model at80g44n10 (center: T_{eff}=8000 K, $\log g$=4.40); model gt57g44n67 (right: T_{eff}=5770 K, $\log g$=4.44), cf. Table 1. The contrast is shown on top of each image. The granules on an A-star are significantly larger than on the Sun both absolutely and as measured, e.g., in pressure scale heights.

1.1. *Number of convection zones in A-type stars*

In the star modelling business it is common wisdom that surface convection in A-type stars reaches to a much smaller depth than in our Sun. However, the opinions about

the exact extent vary significantly: modellers of the internal stellar structure sometimes claim that there is no convection at all, based on the fact that it is too weak to affect the stellar radius. Similar arguments can be heard about atmosphere models: the stratification is essentially in radiative equilibrium and convection can be ignored. However, if diffusion processes are included in the structure equations, one convectively mixed zone is required to explain observed abundance patterns. Mixing-length theory, on the other hand, predicts two separate shallow convectively unstable zones.

Can these views be reconciled with the help of radiation hydrodynamics simulations?

1.2. *Numerical simulations with CO5BOLD*

Earlier numerical models of the helium II convection zone in A-type stars by Sofia & Chan (1984) or of both convection zones by Freytag *et al.* (1996) were restricted to two dimensions.

During this conference, the first 3-D radiation hydrodynamics simulations of surface convection in A-type stars performed with CO5BOLD are presented (see Table 1). The equations of hydrodynamics are numerically integrated on a Cartesian grid (with varying grid size in vertical direction) using an approximate Riemann solver of the Roe type, modified to account for an external (here constant) gravity field. Ionization is treated by means of a tabulated equation of state. Non-local radiative energy transfer is computed with a long-characteristics scheme for a number of representative rays. The code takes tabulated opacities (grey for the A-star models) as input. Strict LTE is assumed and scattering is not taken into account at present. Radiation pressure is ignored. The lateral boundaries are periodic. Further information can be found in Wedemeyer *et al.* (2004) or Freytag *et al.* (2004).

Table 1. Basic model parameters: model name, grid points in two horizontal and one vertical direction, geometrical extent horizontally and vertically, effective temperature, gravity, and a short description.

model	grid	extent Mm^3	T_{eff} K	$\log g$ (cgs)	comment
gt57g44n67	$400^2 \times 150$	$12^2 \times 3$	5770	4.44	reference solar model
at80g44n10	$180^2 \times 90$	$25^2 \times 12$	8000	4.40	cooler A-star, vertically not very extended
at85g44n13	$180^2 \times 90$	$25^2 \times 14$	8500	4.40	hotter A-star model, transition 2-D to 3-D
at85g44n16	$180^2 \times 110$	$25^2 \times 15$	8500	4.40	hotter A-star, large overshoot region

2. Results of the simulations

### 2.1. *Radiative versus hydrodynamic time-scales*

Efficient radiative energy exchange in A-type stellar atmospheres causes radiation to be the dominant form of energy transport. Furthermore, the radiative relaxation time-scales are extremely short, much smaller than, e.g.. in the Sun (compare the continuous lines in the top right panels in Figs. 2, 3, and 4). The time-step in CO5BOLD is bound by these time-scales due to the explicit nature of its solvers and is below 0.2 sec for model at85g44n16, even with multiple radiation transport steps per hydrodynamics step. Therefore, the computational effort for an A-type model is typically a factor 10 to 100 larger than for a solar model with comparable resolution.
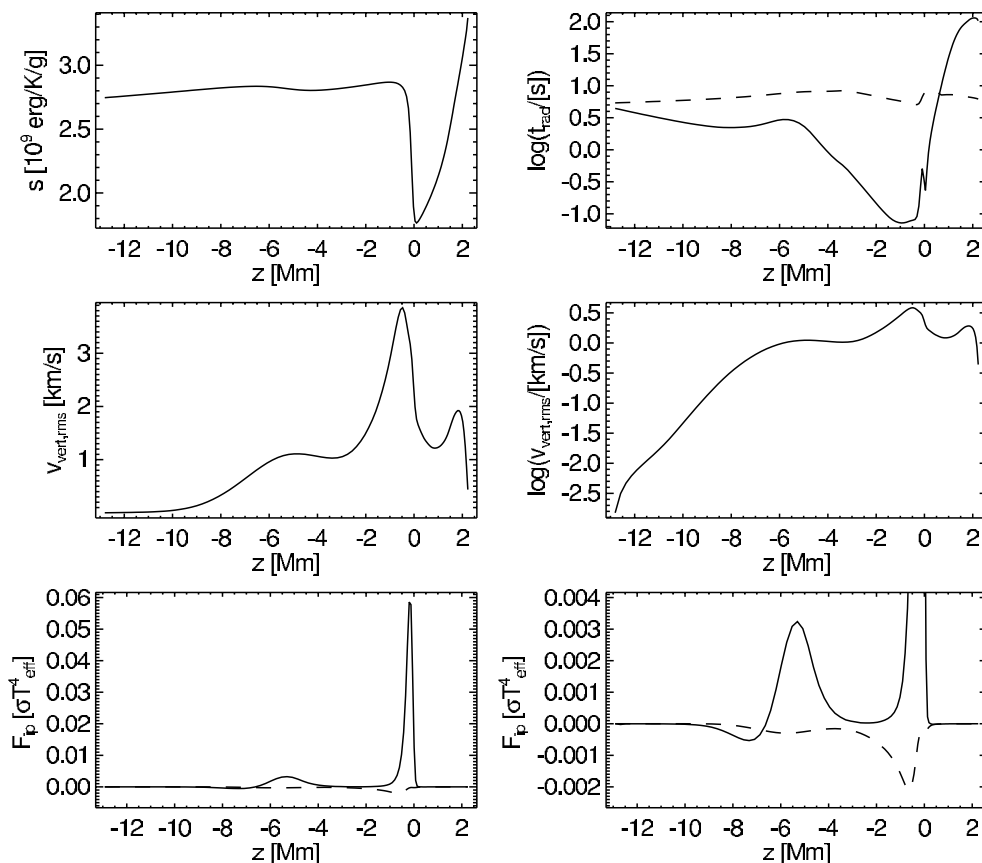
Figure 2. Various horizontally and temporally averaged quantities over height for model at85g44n16 (T_{eff}=8500 K): top left: specific entropy; top right: decadic logarithm of an estimate of the radiative relaxation time scale (continuous line) and grid cell sound crossing time (dashed line); middle left: root-mean-square of vertical velocity; middle right: decadic logarithm of root-mean-square of vertical velocity; bottom left and right: enthalpy flux (continuous line) and flux of kinetic energy (dashed line). The two small regions with negative entropy gradient indicate convective instability. Convection is inefficient in terms of energy transport, but can easily mix large regions.

2.2. *Granules on the Sun and A-type stars*

In Fig. 1 three snapshots showing the grey surface intensities of two A-type star models and a solar model are put side by side. The general appearance is somewhat different, although not dramatically. The intensity contrast is similar. However, it would decrease drastically for even higher effective temperatures. On the other hand, the granules are significantly larger in the A-type models than in the solar model, an effect that cannot be explained by the slight increase in the pressure scale height (see also, Freytag *et al.* (1997)). Instead, the faster moving intergranular lanes mean that granules are able to grow faster. Further the efficient radiation transport slows down the generation and growth of new downdrafts, causing granules to split at larger diameters (see Fig. 5).
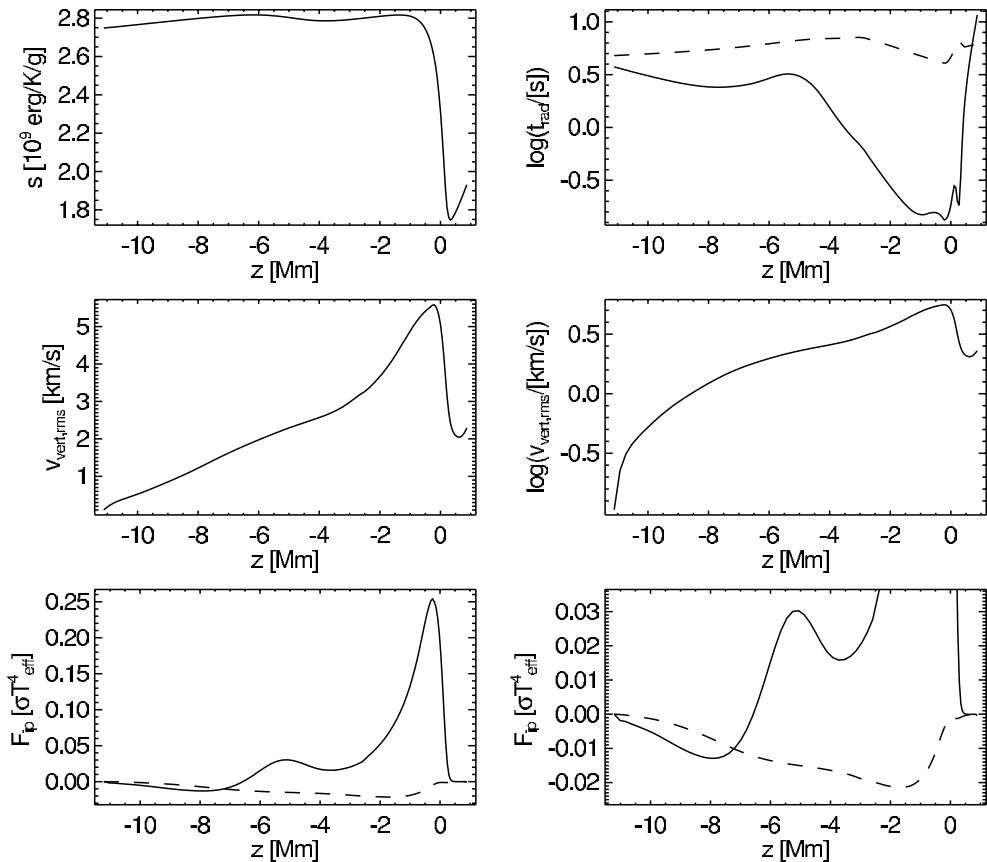
Figure 3. Various horizontally and temporally averaged quantities over height for model at80g44n10 (T_{eff}=8000 K). See Fig. 2 for further details. This model shows two separate instability zones in a similar way as the hotter model displayed in Fig. 2. However, convection is more efficient (larger fluxes and velocities) and overshoot is even stronger.

2.3. *Line profiles and bisectors*

As expected from the rather ordinary granular cell pattern in Fig. 1, the line profiles in Fig. 6 do not look peculiar at all. Their bisectors do not differ much from the solar ones and show the common C-shape.

This is at odds with the observations by Landstreet (1998) who found strange looking line profiles with wide wings and an "inverted C-shape" bisector.

This might be an observational problem, because the very few A-stars, which have a low enough $v \sin i$ to allow the detection of the photospheric velocity field, might also be peculiar otherwise. In fact, both of the A stars with $T_{eff} \sim 8000$ K listed by Landstreet (1998) are classified as peculiar (Am type) and are known to be spectroscopic binaries.

Or, there might be shortcomings in the simulations and assumptions valid for solar granulation models might not be appropriate: geometrically further extended models might show larger structures after a longer time-span than covered so far. A higher numerical resolution especially of layers near the steep subphotospheric temperature jump might alter the flow somewhat. The observed A-stars have slightly lower gravity than the presented models, which would cause an even steeper subphotospheric temperature jump.
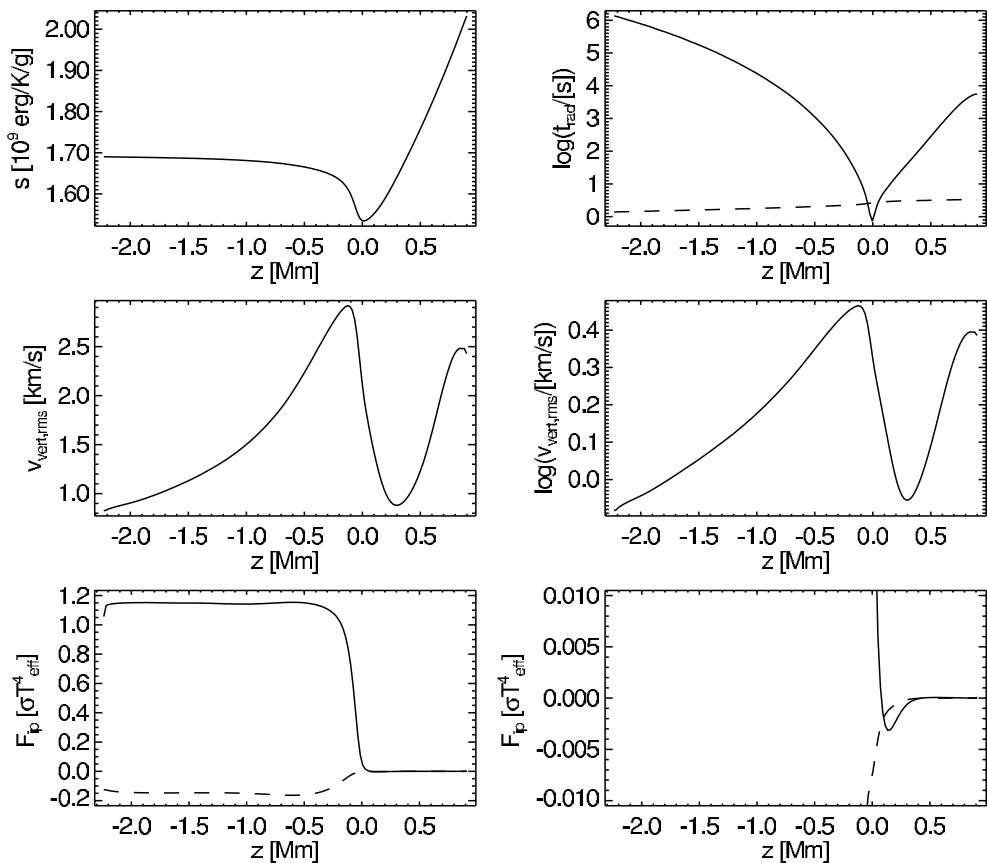
Figure 4. Various horizontally and temporally averaged quantities over height for model gt57g44n67 ($T_{\rm eff}$=5770 K). See Fig. 2 for further details. The entropy profile shows that only the top of the very deep solar convection zone (and the stable photosphere) are included in the model. In the deeper layers of the model convection provides virtually the entire energy flux.

Non-grey opacities will affect the mean photospheric temperature structure. Effects due to magnetic fields or rotation (thanks to Rainer Arlt for the hint) are not included at all, yet.

One possibility is, that the bright borders of some granules in Figs. 1 and 5 might become even more prominent, enough to change the shape of the line profiles.

However, based on the available models and observations no firm conclusions can be drawn at present.

2.4. *Overshoot*

The two small regions with negative entropy gradient in Figs. 2 and 3 (top left) indicate convective instability and correspond closely to predictions of the standard mixing-length theory. Significant velocities are found in and near these unstable zones, which mix the entire computational domain efficiently. The large central velocity peak in Fig. 2 (middle left) marks the hydrogen convection zone, the lower one the helium II convection zone. The photospheric peak close to the top at the right is caused by waves emitted by the instationary convective flow (have a look at the velocities in the upper photosphere in Fig. 7). Below the helium II convection zone the velocities decay approximately exponentially
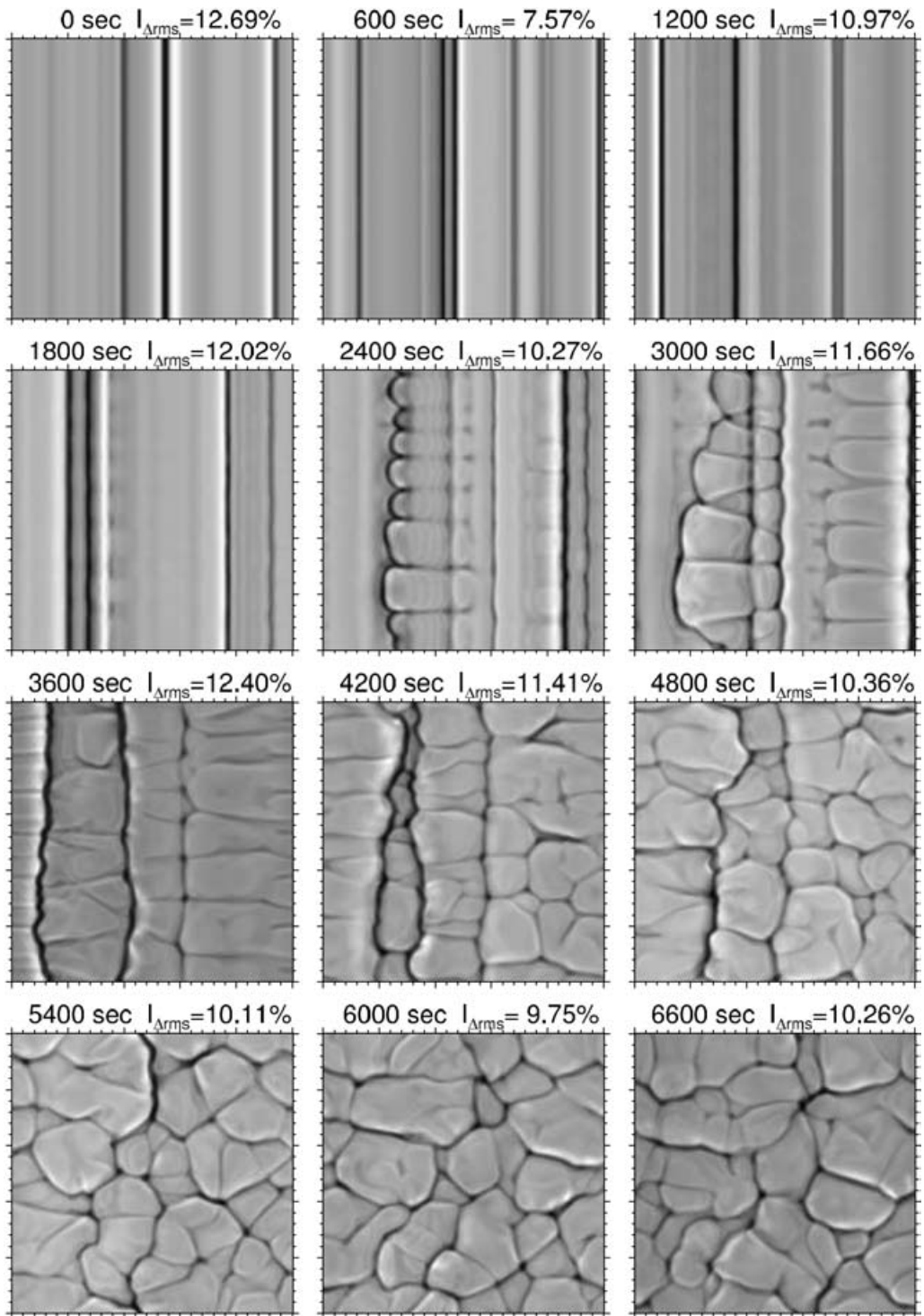
Figure 5. This sequence of grey intensity snapshots for model at85g44n13 (T_{eff}=8500 K) shows the transition from a flow with 2-D topology (inherited from the 2-D start model) to fully 3-D convection. The later frames show large granules with fast moving intergranular lanes. The model covers $25 \times 25 \, \mathrm{Mm}^2$. Time and contrast are shown in the title.
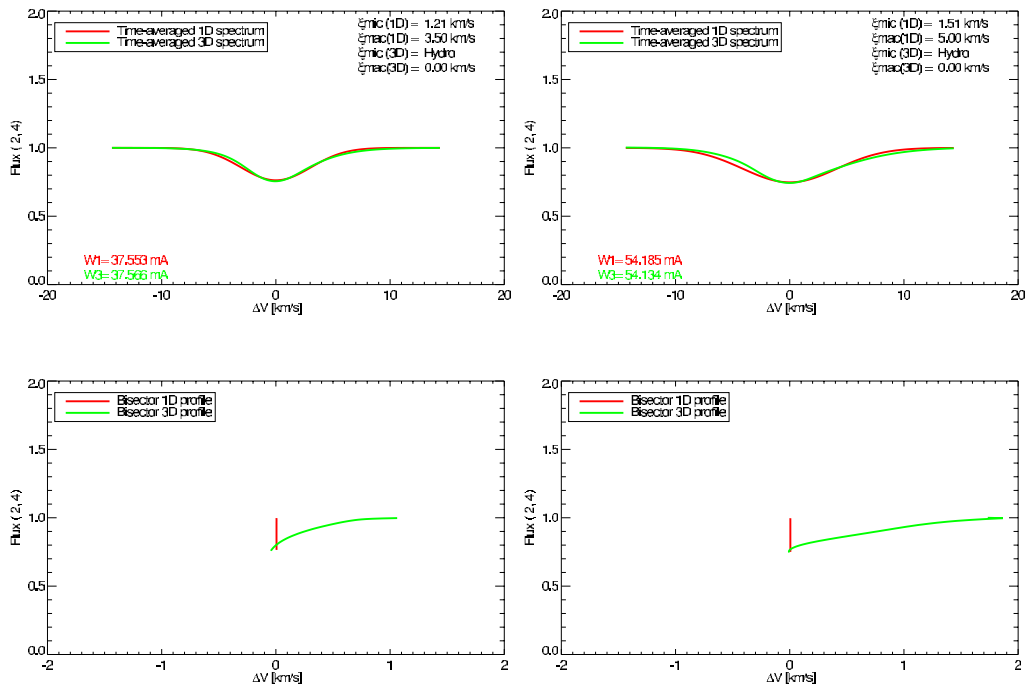
Figure 6. Flux line profiles and bisectors for model at85g44n16 (left: T_{eff}=8500 K), and model at80g44n10 (right: T_{eff}=8000 K). The dark (or red) symmetric profiles in the top row are computed from 1-D models generated from the the 3-D models by horizontal averaging with an appropriate value for the microturbulence. The lighter (or green) slightly asymmetric profiles are synthesized directly from the 3-D models taking into account the local velocities (and averaging afterwards over all columns in a model and a number of representative inclinations). The lower row shows the corresponding bisectors.

with depth, until they "hit" the closed bottom boundary. This happens, if the model is deep enough (Fig. 2, middle right). Otherwise, the computational domain is too shallow to allow the appearance of the exponential overshoot tail of the velocity (as in Fig. 3). For this cooler model, the lower convection zone is hardly discernible in the vertical velocity profile. However, in the flux profiles both zones can be distinguished. The energy fluxes show a significant overshoot beyond the unstable layers, too. The flux of kinetic energy is always non-positive. For even hotter models both instability zones will eventually merge to form one single convection zone.

3. Conclusions

First 3-D radiation hydrodynamics simulations of the photosphere and subphotospheric convection zone(s) of A-type stars have been presented.

They show, that there is no fundamental contradiction between the views presented in the introduction: The deviations from a radiative equilibrium stratification are small for the cooler A-type stars and vanish for the hotter ones, as predicted by the mixing-length theory. There are two separate instability zones. However, the regions with non-vanishing convective flux overlap for the cooler models. The convective overshoot above and below the unstable layers is so efficient that the velocity fields merge leading to complete mixing
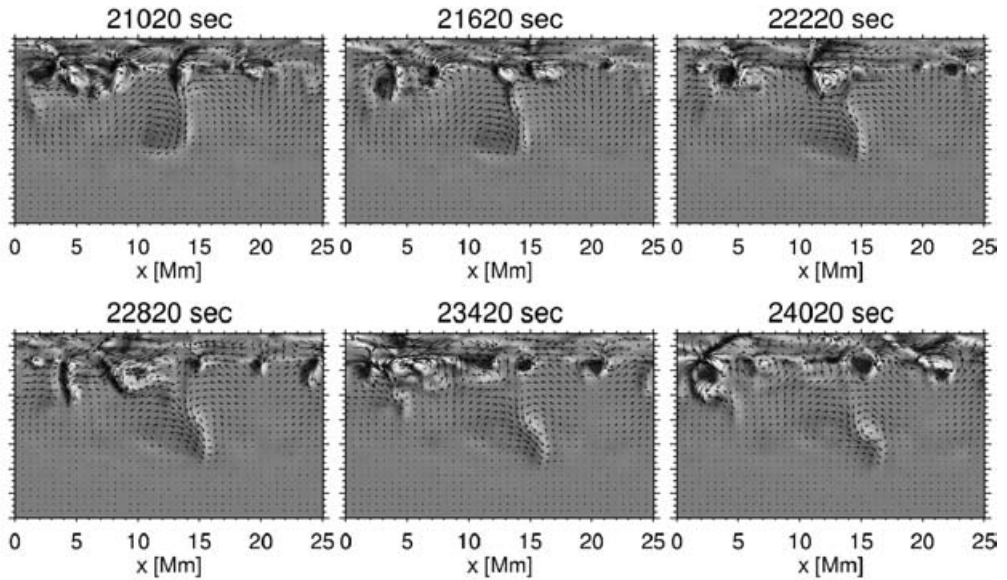
Figure 7. This sequence of vorticity slices (grey: small velocities; dark: clockwise motion; bright: counter-clockwise motion) from the 3-D model at85g44n16 shows the convective signature of the flow. The stellar surface ($\tau=1$) is approximately 2 Mm below the top of the box and the steep temperature (and density) jump has an imprint on the vorticity. Downdrafts usually do not reach very deep and tend to form horizontally moving surface eddies. However, occasionally a downdraft can reach the lower instability zone and generate a longer-lived structure (close to the center of the frames).

in the photosphere, between the instability zones, and in a layer of considerable extension below the helium II convection zone.

The granular flow in A-type stars organizes into larger cells than on the Sun. However, it shows normal solar-type topology and synthetic spectra display a solar-type bisector shape.

Acknowledgements

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Discussion

PISKUNOV: What causes the sharp horizontal strip in the pressure and velocity movies?

FREYTAG: The sharp opacity peak just below the photosphere causes a steep inward increase in temperature and corresponding drop in density. This jump shows up in many other quantities. For example, the density change is reflected in the velocity and is prominent in all gradient–like quantities like the velocity. The movie of the pressure fluctuations show the change of $\log(pressure)$ in time, scaled by a power of the temperature to enhance the tiny fluctuations in deeper layers relative to the larger photospheric value. This scaling also magnifies the fluctuations caused by overturning convective motions or waves "on top" of the subphotospheric temperature jump.

SHIBAHASHI: Your simulation reminds me of the stochastic excitation of p–modes in the Sun. Do you think that convection in A-type stars may induce the p–modes in these stars? How about the possibility of stochastic excitation in δ Sct stars?

FREYTAG: Actually, all simulations of convective zones on or above the main sequence show the stochastic excitation of p–modes in the computational box. However, the observable amplitude depends on the excitation, the damping, and the mass distribution. Stochastically excited p–modes in A stars would have very high order and a small amplitude, different from the observed radial or low–order modes.

KOCHUKHOV: (a) Do you expect that atmospheres of nonmagnetic A stars are well mixed due to convection and should not show vertical abundance stratification?
(b) How would the possible presence of a magnetic field change the picture?

FREYTAG: (a) All presented models do not include magnetic fields. The photopheric velocities are of the order of a few km s^{-1}. In the lower atmpsphere they are due to overturning convective motions (overshoot). In the upper atmosphere they are due to pressure waves generated by nonstationary convective motions. A nonmagnetic atmosphere should be mixed on a time scale of a few hours.
(b) The weak convection in A-type stars is very sensitive to all "obstacles". A magnetic field could easily suppress convection and its mixing of the atmosphere.

KUPKA: Have I understood your figure correctly that the bisectors obtained from your simulations are looking redwards? Because the observed ones are looking bluewards.

FREYTAG: Yes.

KUPKA: Could it be that this result changes if you evolve the simulations for longer time scales? You have started from a 2-D initial condition and the features in the He II ionisation region evolve on a much longer time scale.

ARLT: Is it possible to estimate the influence of the rotation of A stars on the results, since considerable Coriolis forces will be involved?

FREYTAG: I have done neither numerical simulations nor analytical calculations to estimate this influence. However, a strong Coriolis force should bend the downdrafts, favoring the development of fast–moving roll–like intergranular lanes. The depth of the region of material mixed by convective overshoot might be smaller.