3D Simulation of Surface Convection and Spectral Line Formation in A-type Stars

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We present first numerical simulations of 3D radiative convection in the surface layers of main sequence A-type stars with $T_{\rm eff}=8000$ and 8500 K, $\log g = 4.4$, recently performed with the CO^5BOLD radiation hydrodynamics code. The resulting models are used to investigate the structure of the H+HeI and the HeII convection zones in comparison with the predictions of local and non-local convection theories, and to determine the amount of 'overshoot' into the stable layers below the He II convection zone. The simulations also predict how the topology of the photospheric granulation pattern changes from solar to A-type star convection. The influence of the corresponding photospheric temperature and velocity fields on the shape of spectral lines is demonstrated by computing synthetic line profiles and line bisectors for some representative examples, allowing us to confront the 3D model results with observation.

3D Convection Models

Hydrodynamics. The CO^5BOLD code is based on a conservative finite volume approach using an approximate Riemann solver of Roe type together with a *van Leer* reconstruction scheme.
Radiation transport. The 3D non-local radiative transfer is solved on a system of *long* rays, employing a modified Feautrier scheme. In this exploratory study, we adopt the grey approximation, using realistic Phoenix-OPAL Rosseland mean opacities.
Equation of state. The tabulated EOS account for partial ionization of hydrogen and helium, and for H_2 molecule formation / dissociation.
Geometry. The simulations are performed on a Cartesian grid, assuming periodic lateral boundary conditions, and closed top & bottom.

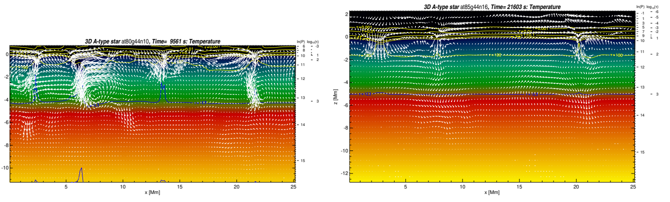

Fig. 1: Arbitrary snapshots from the 3D simulations of convection in the surface layers of two different A-type stars, showing the velocity field and temperature distribution in a vertical slice. **Left:** $T_{\rm eff}=8000$ K, $\log g=4.4$, geometrical size $25.2\times25.2\times12.0$ Mm, $180\times180\times90$ grid cells (Model 1). **Right:** $T_{\rm eff}=8500$ K, $\log g=4.4$, geometrical size $25.2\times25.2\times15.0$ Mm , $180\times180\times110$ grid cells (Model 2). The pressure stratification and the vertical optical depth are indicated to the right of each panel.

Vertical Structure, Comparison with MLT

Mean Entropy Stratification

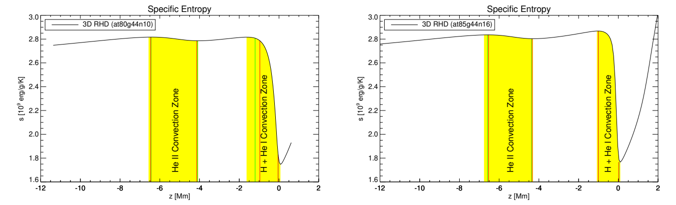

Fig. 2: *Mean entropy* $\langle s(z)\rangle_{x,y,t}$ for Model 1 (left) and Model 2 (right). In both cases, the entropy stratification indicates two separate convection zones ($ds/dz<0$, yellow). The borders of convective instability according to models based on standard mixing-length theory (MLT) are indicated as red ($\alpha=0.5$) and green ($\alpha=1.0$) vertical lines.

Mean Vertical Velocity Field

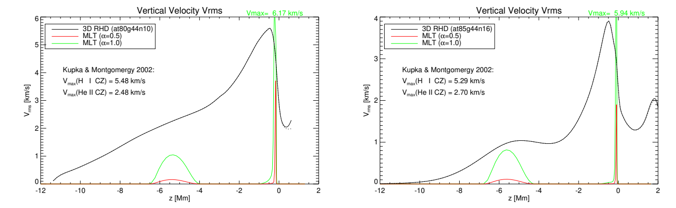

Fig. 3: *Mean vertical velocity* $\sqrt{\langle V_z^2(z)\rangle_{x,y,t}}$, compared with mixing-length models. According to 3D hydrodynamics, both convection zones are connected by convective flows, and 'overshoot' below the He II convection zone is substantial. Velocity scale height of exponential tail: $H_v/H_p \gtrsim 0.7$ (Model 1), $H_v/H_p \approx 0.4$ (Model 2).

Mean Energy Fluxes

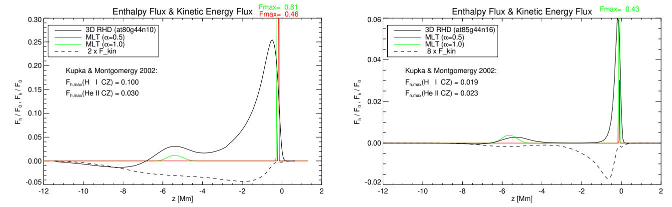

Fig. 4: *Mean enthalpy flux* $\langle \rho V_z h\rangle_{x,y,t}$, compared with mixing-length results. Like in the solar granulation, the 3D simulations give a *mean kinetic energy flux* $\langle \rho V_z \vec{V}^2/2\rangle_{x,y,t}$ which is directed downwards at all heights.

Horizontal Structure & Synthetic Line Profiles

Solar and A-type Star Granulation Pattern

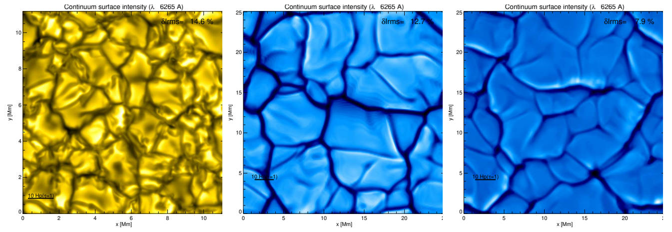

Fig. 5: Emergent continuum intensity at $\lambda6265$ Å resulting from 3D hydrodynamical simulations of the solar granulation **(left)** and of surface convection in main-sequence A-type stars with $T_{\rm eff}=8000$ K **(middle)** and $T_{\rm eff}=8500$ K **(right)**.

Emergent Line Profiles ($\mu=1$)

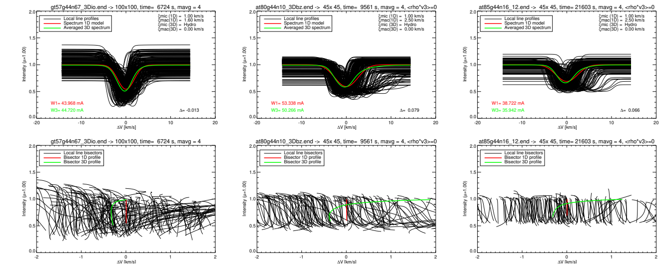

Fig. 6: Spatially resolved and averaged line profiles (**top**) and line bisectors (**bottom**) of Fe I $\lambda6265$ Å, computed from the snapshots shown in **Fig. 5** for vertical lines-of-sight ($\mu=1$). The asymmetry of the *flux profiles* is qualitatively similar.

Conclusions The analysis of our 3D hydrodynamical simulations (**Fig. 1**) indicates a severe failure of local mixing-length theory in the regime of A-type star shallow surface convection (**Figs. 3, 4**). The non-local convection model by Kupka & Montgomery (MNRAS 330, L6, 2002) gives a much better description of the velocity field, but alarming differences remain in the energy fluxes: our 3D models do NOT show any positive kinetic energy fluxes in the photosphere. Due to more efficient radiative energy exchange, the granules at the surface of A-type stars are relatively larger than on the Sun, and show less sub-structure (**Fig. 5**). The filling factor of dark areas is $f_d\approx0.32$, compared to $f_d\approx0.53$ for the Sun. Synthetic LTE line profiles based on the current 3D convection models of A-type stellar atmospheres show a depressed *red* wing (**Fig. 6**), in contradiction to the observed line asymmetry (Landstreet, A&A 338, 1041, 1998). The reason for this discrepancy remains to be investigated.

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