Problems to model photospheric convective overshoot

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Abstract. In the art of computing stellar atmospheres and spectra the modeling of the hydrodynamical part has not kept pace with the improvements in the radiative aspects. For about 40 years convection is modelled by local mixing-length theory, assuming that convective energy flux is confined to unstable regions. But solar observations and common sense indicate that there are convective effects even outside. Detailed 2D radiation hydrodynamics simulations of the surface convection zone of the Sun and other stars show that internal, mechanical, and kinetic energy fluxes all contribute to the photospheric total convective flux, but with different signs and height dependences. They almost cancel each other in optically thin layers. Nevertheless, overshooting convective fluxes extend well into the stable photosphere up to the chromosphere and affect the temperature stratification.

1. Introduction

During the last decades the radiative part in modeling stellar atmospheres and spectra has been continuously improved: e.g. the number of included lines has reached awesome orders. NLTE effects can be taken into account. Nevertheless, the atmospheric models still rely on some sort of 1D hydrostatic approximation, describing the convective energy flux by the local mixing-length theory (MLT), where convective flux is confined to unstable (according to the Schwarzschild criterion) layers.

But solar observations indicate that overshooting convective flows affect the stable photosphere in a complex manner. Spatially resolved spectra of the granulation show temperature and velocity inhomogeneities: they result in asymmetries, blue shifts, broadening by micro- and macroturbulence in averaged lines profiles. This effects are not included in the currently used MLT versions, which still resemble the originally proposed by Böhm-Vitense (1958). A recently presented modification by Canuto & Mazzitelli (1991) still relies on the locality assumption and ignores overshoot. The ad hoc inclusion of overshoot in the ATLAS9 code of Kurucz (1992) does not seem to be really convincing.

Numerical 2D radiation hydrodynamics (RHD) simulations of stellar surface convection zones (Fig. 1, for details see Steffen 1991, Ludwig et al. 1994) offer a way of a qualitative and quantitative description of convection and overshoot. The equations account for time-dependence, compressibility, stratification, ionization processes and non-local radiative energy transport with grey or frequency-dependent opacities.

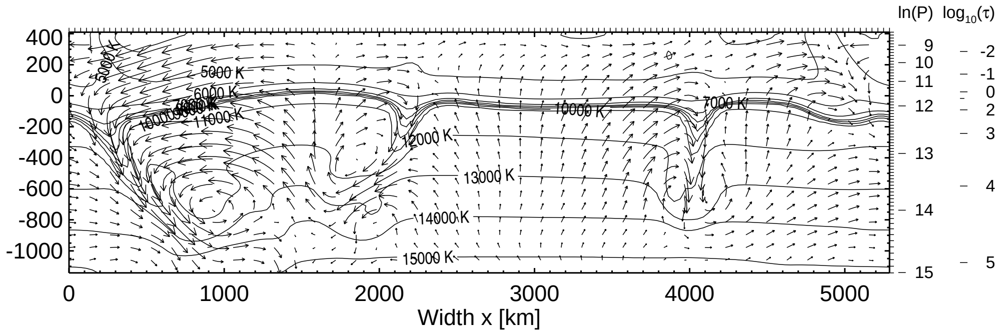

Figure 1. Snapshot of a solar model (L71D07) with $T_{\rm eff}$=5 770 K, $\log g$=4.44, solar composition, frequency-dependent opacities. The model comprises the photosphere and the upper part of the convection zone. The velocity field is indicated by short pseudo-streamlines followed over 30 s. Contour lines mark the temperature field in steps of 1 000 K. Small tick marks at the top and the right show the positions of the grid points (142×71). Two columns at the right show horizontally averaged quantities: the natural logarithm of the mean pressure and the logarithm of the optical depth $\tau_{\rm ross}$. The lower boundary allows the free in- and outflow of material. The top is open for waves. Periodic lateral boundary conditions are applied.

2. Convective effects on the photosphere: inhomogeneities

To compare the results of RHD simulations with standard atmosphere models it is necessary to derive an appropriate 1D stationary stratification, preserving the spectroscopic properties of the spatially and temporally resolved models. While it is one of the basic assumptions in modeling stellar atmospheres that the (possibly) inhomogeneous stellar surface can be described adequately by a 1D stratification, the construction of such a representation from a time-sequence of 2D models turns out to be not straightforward but has to be done with care.

For atmospheres of cool DA type white dwarfs an average of pressure p and temperature T^4 on levels of constant optical depths is appropriate (Steffen et al. 1995). In the solar case this is still a good choice. But the 1D stratifications derived by various ways of spatially averaging the 2D models yield spectra which do not match exactly the spatially averaged spectra, computed directly from the 2D models (Ludwig & Steffen 1995).

Further work will show if only the averaging method has to be improved or if a 1D stratification is indeed unable to represent all spectroscopic properties of the spatially inhomogeneous models. This problems will be ignored in this paper. A simple average on constant geometrical depth is used. This type of averaging is sufficient to show the effects of the various energy fluxes, even if it does not give the 1D stratification with the best spectroscopic representation of the 2D models. In layers with steep temperature gradient (cf. Fig. 1) and strong variation of the convective flux on small geometrical scales it is able to introduce errors. In optically thin regions a correlation between temperature and optical depth introduces deviations between different ways of averages.

3. Convective effects on the photosphere: overshoot

In Fig. 2 ATLAS9 solar models ($\alpha = 1.25$) with (OVERWT=1.0, thin solid line) and without overshoot (thin dashed line) are compared to a stratification derived from a RHD model sequence by horizontally and temporally averaging (thick lines). On the left the temperature (Fig. 2a), the temperature with 10fold increased differences to a grey hydrostatic temperature stratification (Fig. 2c), and convective velocities (Fig. 2e) are shown. On the right various energy fluxes are plotted on different scales (Fig. 2b,d,f).

ATLAS9 and RHD models have some properties in common: In optically thick layers convection carries most of the energy flux (Fig. 2b). The temperature gradient and the temperature is significantly lower than in a purely radiative grey hydrostatic model (Fig. 2a,c). To compensate this deficit in the deep layers the convective stratifications are slightly hotter than the purely radiative models in layers around $\log\tau{\sim}0$ to -1. In optically thin layers line cooling causes the temperature to fall below the value in the grey hydrostatic model.

As in the ATLAS9 model without overshoot in the model including it the convective flux is non-negative everywhere (Fig. 2b,d,f). In the overshoot model it only extends slightly into the stable layers and drops to zero rather abruptly. As the convective flux the temperature profile is only affected by overshoot in layers around $\log\tau{=}0$ (Fig. 2a,c).

Contrary to MLT models in the RHD simulations convection is not at all confined to the convectively unstable layers or its near surroundings. Instead convective motion extends over several pressure scale heights up to the top of the model volume without significant decline (Fig. 2e). The total convective flux of the RHD model decays slower than in the ATLAS9 models. Its extent into convectively stable layers is at first sight roughly similar to that of the ATLAS9 overshoot model (Fig. 2b). But a closer look (Fig. 2d) reveals that the RHD convective flux extends further into the stable photosphere and does not drop abruptly to zero, but becomes negative (around $\log\tau{=}$-0.9), has a minimum (around $\log\tau{=}$-1.2), increases until it goes through zero again (around $\log\tau{=}$-2.3), and becomes approximately constant at a positive value near the top of the model. The small bump in the temperature stratification of the ATLAS9 model with overshoot (around $\log\tau{=}0$) is not visible in the RHD stratification.

To interpret the RHD flux profile it is necessary to look at all the individual energy fluxes which contribute to the total average convective flux (Fig. 2d,f): $F_{\rm tot} = F_{\rm int} + F_{pv} + F_{\rm kin} + (F_{\rm vis})$. Only the flux $F_{\rm int}$ due to temperature differences of up- and downflowing material is included in standard MLT formulations. In the RHD simulations it is positive in and near the convection zone proper, where downflowing material is cooler than the mean. But in higher layers it becomes negative, because here downflows are correlated with temperature maxima (see the 5 000 K-isotherm in Fig. 1). But the flux of mechanical energy F_{pv}, which is also part of the enthalpy flux, has approximately the same size and is positive everywhere. By contrast the kinetic energy flux $F_{\rm kin}$ is negative everywhere. The contribution of the viscous energy flux $F_{\rm vis}$ is negligible. The amplitude of all these fluxes tend to decrease with decreasing density.

The large contributions of all these individual flux almost cancel each other. But the resulting small total convective flux in the photosphere reaches into optically very thin layers and its variation with height (and the corresponding

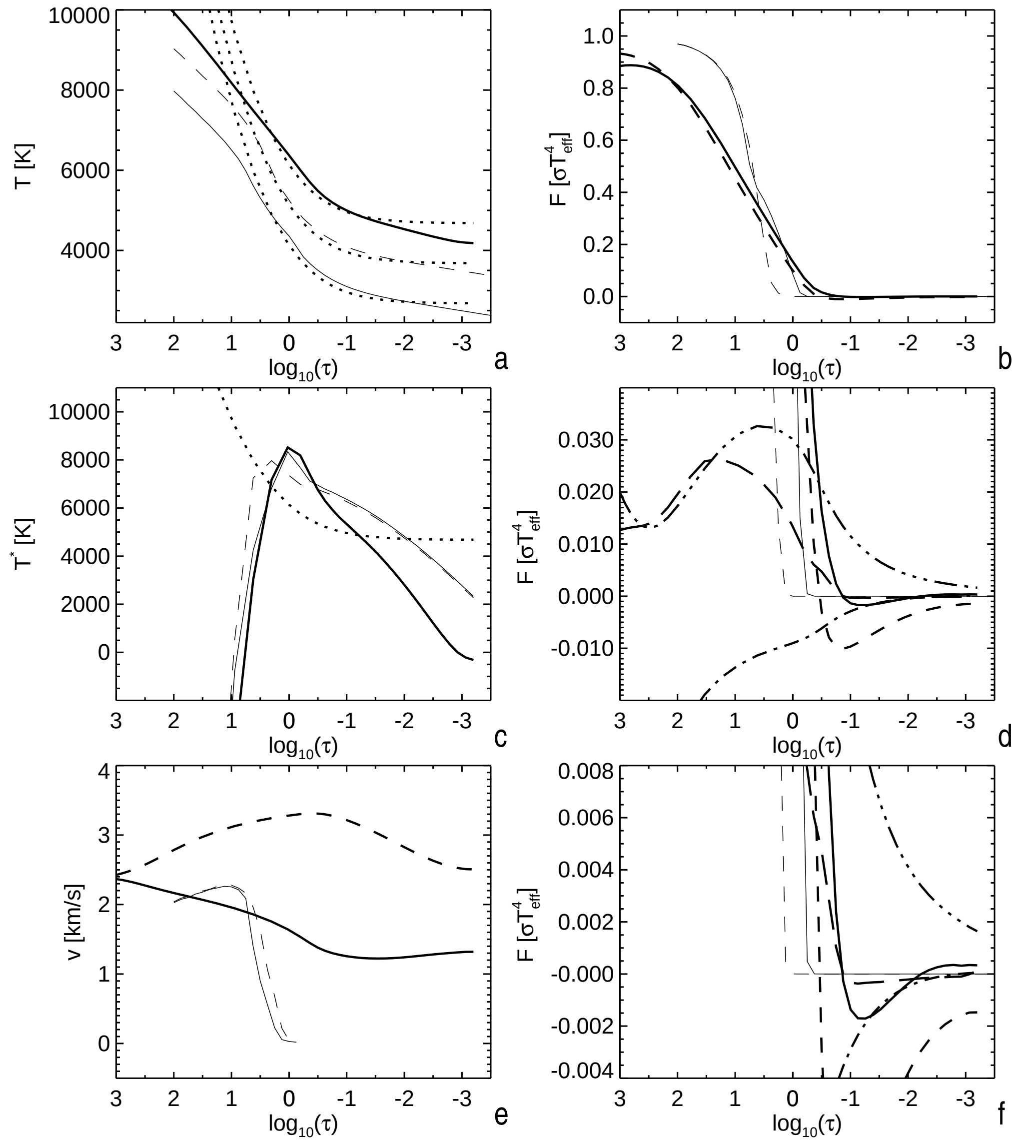

Figure 2. Sun: various quantities are plotted over optical depth $\tau_{\rm Ross}$. Thin lines: ATLAS9 models (dashed: no overshoot, solid: overshoot). Thick lines: averaged RHD stratification (model L71D07). **a**: temperature T (dotted line: grey purely radiative temperature profile). The ATLAS9 models are plotted additionally with a vertical shift of -1 000 K (thin dashed line, no overshoot) and -2 000 K (thin solid line, overshoot). **b,d,f**: energy fluxes: solid line: total convective flux, dashed line: $F_{\rm int}$, dashed-dotted line: $F_{\rm kin}$, dash-dot-dot-dot line: F_{pv}, long dashed line: $F_{\rm vis}$. **c**: temperature with increased differences to grey hydrostatic stratification: $T^* = (T - T_{\rm grey}) * 10 + T_{\rm grey}$. **e**: velocities: solid line: rms-value of the vertical velocity, dashed line: rms-value of the horizontal velocity.

variation of the radiative flux) has an effect on the temperature gradient. The relative contributions of the individual fluxes are not universal but depend on the stellar parameters. The non-zero convective flux leaving the model through the top is able to take over part of the heating of the chromosphere.

4. Conclusions

Detailed numerical 2D radiation hydrodynamics simulations of solar (and stellar) convective surface layers reveal:

- *There is convective overshoot* well above the convectively unstable layers. The picture underlying local MLT (and e.g. the CM model) is incorrect.
- *Internal, mechanical, kinetic energy fluxes* all contribute to the total convective flux, but with different signs and height dependences. They nearly cancel each other in the optically thin layers.
- The total convective flux in the photosphere has a complicated profile. The overshoot description of ATLAS9 only accounts for the positive convective flux in the stable region, but no correctly It ignores the layers with negative convective flux, which contribute to the cooling of the upper photosphere. Likewise the alternative assumption that the convective flux is positive in the unstable and negative in the stable (overshoot) layers is wrong.
- Because the total convective flux is a small sum of large terms, it is necessary to model each contribution with high precision which is difficult even in radiation hydrodynamics simulations. Tiny flux changes can result in large variations of the temperature profile. Simple analytic assessments of convective overshoot, which concentrate only on one contribution, will probably overestimate its influence.

With improved numerics and physics (spatial resolution of the grid, number of opacity bands, 3D, way of averaging ...) of radiation hydrodynamics simulations of stellar surface convection zones it becomes possible to reveal the whole complexity of the interaction between hydrodynamics and radiative transfer in stellar atmospheres.

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