Problems in Modeling Photospheric Convective Overshooting

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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 has been modeled 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 these regions. Detailed two dimensional radiative hydrodynamical simulations of the surface convection zone of the Sun and other stars show that the 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 aspects of 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 one dimensional 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, and broadening by micro- and macroturbulence in averaged lines profiles. These effects are not included in the currently used MLT versions, which still resemble the one originally proposed by Böhm-Vitense (1958). A recent modification by Canuto and Mazzitelli (1991) still relies on the locality assumption and ignores overshooting. The ad hoc inclusion of overshooting in the ATLAS9 code of Kurucz (1992) is not really convincing.

Numerical two-dimensional radiative hydrodynamical (RHD) simulations of stellar surface convection zones (Figure 1, for details see Steffen 1991, Ludwig et al. 1994) offer a qualitative and quantitative description of convection and overshooting. The equations account for time-dependence, compressibil-
Figure 1. Snapshot of a solar model (L71D07) with $T_{\text{eff}} = 5770 \text{ K}$, $\log g = 4.44$, 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 1000 K. Small tick marks at the top and the right show the positions of the grid points ($142 \times 71$). Two columns at the right show horizontally averaged quantities: the natural logarithm of the mean pressure and the logarithm of the optical depth $\tau_{\text{Ross}}$. The lower boundary allows the free in- and outflow of material. The top is open for waves. Periodic lateral boundary conditions are applied.

...ity, stratification, ionization processes, and non-local radiative energy transport with grey or frequency-dependent opacities.

2. Convective Effects in the Photosphere: Inhomogeneities

To compare the results of RHD simulations with standard model atmospheres 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 one-dimensional stratification, the construction of such a representation from a time-sequence of two-dimensional 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 and 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. These 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. Figure 1) and strong variation of the convective flux on small geometrical scales it may introduce errors. In optically thin regions a correlation between temperature and optical depth introduces deviations between different ways of averaging.

3. Convective Effects in the Photosphere: Overshooting

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

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

In the ATLAS9 models the convective flux is non-negative everywhere, even with the overshooting option switched on (Figure 2b,d,f). In the overshooting 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 overshooting in layers around $\log \tau = 0$ (Figure 2a,c).

Contrary to MLT models, in the RHD simulations convection is not at all confined to the convectively unstable layers or its vicinity. Instead convective motion extends over several pressure scale heights up to the top of the model volume without significant decline (Figure 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 overshooting model (Figure 2b). But a closer look (Figure 2d) reveals that the RHD convective flux extends further into the stable photosphere and does not drop to zero abruptly, 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 overshooting (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 (Figure 2d,f): $F_{\text{tot}} = F_{\text{int}} + F_{\text{pu}} + F_{\text{kin}} + (F_{\text{visc}})$. Only the internal energy flux $F_{\text{int}}$, which is due to temperature differences of up- and downflowing material, is included in MLT formulations. In the RHD simulations it is positive within and near the unstable zone. Here downflowing material is cooler than the mean. But in
Figure 2. For the Sun: various quantities are plotted over optical depth $\tau_{\text{Ross}}$. Thin lines: ATLAS9 models (dashed: no overshooting, solid: overshooting). 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 -1000 K (thin dashed line, no overshooting) and -2000 K (thin solid line, overshooting). b, d, f: energy fluxes: total convective flux (solid line), $F_{\text{int}}$ (dashed line), $F_{\text{kin}}$ (dashed-dotted line), $F_{\text{pr}}$ (dash-dot-dot-dot line), $F_{\text{visc}}$ (long dashed line). c: temperature with increased differences with respect to grey hydrostatic stratification: $T^* = (T - T_{\text{grey}}) \times 10 + T_{\text{grey}}$. e: velocities: rms-value of the vertical velocity (solid line), rms-value of the horizontal velocity (dashed line).
higher layers it becomes negative, because here downflows are correlated with temperature maxima (see the 5000K-isotherm in Figure 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 $F_{kin}$ is negative everywhere. The contribution of the viscous energy flux $F_{visc}$ is negligible. The amplitude of all these fluxes tend to decrease with decreasing density.

The large contributions of all these individual fluxes almost cancel each other. But the resulting small total convective flux in the photosphere extends into optically very thin layers, and its variation with height (and the corresponding variation of the radiative flux) affects the temperature gradient. The relative contributions of the individual fluxes 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 radiation hydrodynamics simulations of solar convective surface layers show (see also Nordlund and Dravins 1990):

- *There is convective overshooting* well above the convectively unstable layers. The picture underlying local MLT (and, e.g., the Canuto Mazzitelli model) is incorrect.

- *Internal, mechanical, and kinetic energy fluxes* all contribute to the total convective flux, but with different signs and height dependences. They nearly cancel each other in optically thin layers.

- The total convective flux in the photosphere has a *complicated profile*. The overshooting description of ATLAS9 only accounts for the positive convective flux in the stable region, but incorrectly. It ignores the layers with negative convective flux, which contributes 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 (overshooting) layers is wrong.

- Because the total convective flux is a small sum of large positive and negative terms, it is necessary to model each contribution with high precision which is difficult even in radiative hydrodynamical simulations. Tiny flux changes can result in large variations of the temperature profile. Simple analytic assessments of convective overshooting, which concentrate only on one contribution, might overestimate its influence.

With improved numerics and physics (spatial resolution, number of opacity bands, 3D, averaging...) of radiative hydrodynamical 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.

References