Confrontation of Stellar Surface Convection Simulations with Stellar Spectroscopy

M. Asplund

Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark (e-mail: martin@nordita.dk)

Å Nordlund

Astronomical Observatory, NBIfAFG, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark (e-mail: aake@astro.ku.dk)

R. Trampedach

Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48823, USA (e-mail: art@sol2.pa.msu.edu)

Abstract. In order to estimate the accuracy of state-of-the-art 3D hydrodynamical surface convection simulations, predictions for various spectroscopic diagnostics have been investigated and compared with observations: the emergent flux distribution, limb-darkening, detailed lineshapes, -asymmetries and -shifts, and the hydrogen Balmer lines. The agreement is in general very satisfactory, though some room for further improvement still remains when using the simulations as model atmospheres for spectral line calculations. The remaining discrepancies provide important insight on how to improve the realism of the simulations even further.

1. Introduction

For late-type stars the convection zone extends to the surface and thereby directly affects the emergent photospheric spectrum. The interpretation of the stellar spectrum when e.g. deriving elemental abundances for such stars is therefore sensitive to the convection treatment in the atmospheric layers. The advent of realistic 3D, hydrodynamical surface convection simulations of solar-type stars now provides the opportunity to go beyond standard analyses. Such simulations successfully reproduce the detailed granulation topology and flow pattern, the observed continuum brightness contrast and spectral line shapes as well as helioseismological constraints (cf Nordlund & Stein, these proceedings), without invoking any free or adjustable parameters such as the mixing length, micro- and macroturbulence. Here we confront the simulations with additional spectroscopic diagnostics for the case of the Sun, in order to further study how realistic the convection simulations are in terms of stellar spectroscopy before applying similar simulations to other solar-type and metal-poor stars (Trampedach et al; Allende Prieto et al., these proceedings).
2. Convection simulations and radiative transfer

The solar convection simulations utilized in the present study are based on a realistic equation-of-state (Mihalas et al. 1988), opacities (Gustafsson et al. 1975; Kurucz 1993) and detailed radiative transfer, which includes the important line-blanketing (Nordlund 1982). The simulation consists of 100x100x82 grid-points, extending 6x6 Mm horizontally and from -0.6 Mm to 2.9 Mm vertically. A shorter run covering ~ 20 min at the higher resolution 200x200x82 which also extends up to -1.0 Mm has also been performed, in order to study the effects of resolution and height-extension. The spectral line calculations have been carried out from time sequences of the simulation covering ~ 40 min interpolated to a finer vertical resolution in the line-forming region.

3. Spectral lines

The granulation pattern, which consists of warm upflows and cool downflows, causes characteristic line asymmetries with typical C-shape line bisectors. The resulting line profiles are thus sensitively dependent on the atmospheric structure and velocity fields (cf. Nordlund & Stein, these proceedings).

With the current best numerical resolution, the resulting spatially and temporally averaged line profiles show excellent agreement with the observed profiles for weak Fe I and Fe II lines, as illustrated in Fig. 1. It is important to emphasize that no tunable parameters, such as micro- or macroturbulence, besides the abundance have been used for the predicted profiles. The physical origin of both these two concepts is thus the velocity amplitude between up- and downflows and the (anti-)correlations between temperature and velocity in the solar photosphere. The fact that the predicted lines are of sufficient width directly implies that the photospheric velocity field is appropriate. Furthermore, the resulting line bisectors agree in general very well with observations, as also evident from Fig. 1. Note that the line shifts are on an absolute velocity scale, which means that the predicted shifts for individual weak lines are accurate to within ±100 m s⁻¹; most of the uncertainty actually arises from not having sufficiently accurate laboratory wavelengths. However, for stronger lines the bottoms of the
bisectors are in general redshifted relative to observations by \( \sim 100 \text{ m s}^{-1} \). The reason for this discrepancy is not yet properly understood but the agreement improved when increasing the numerical resolution and the height-extension, suggesting that the solution lies in a correct description of propagating waves in the upper photosphere.

A preliminary analysis of the photospheric Fe abundance using the profiles of 30 weak and intermediate strong Fe I lines results in 7.46 \( \pm \) 0.05, i.e. in close agreement with the meteoritic evidence which suggests 7.50 \( \pm \) 0.01. Since this estimate has been obtained without the questionable concepts of microturbulence, collisional damping enhancement factors (Anstee & O'Mara 1991) and equivalent widths, it provides strong support for the “low” (\( \approx \) meteoritic) photospheric Fe abundance advocated by Holweger et al. (1995), in particular since our 15 analysed weak Fe II lines return an abundance of 7.47 \( \pm \) 0.09.

The wings of the hydrogen Balmer lines are formed in the deep photosphere and thus are sensitive probes of the convection efficiency and temperature structure in these layers. In Fig. 2 the predicted profile of H\( \alpha \) is compared with observations. The line wing behaviour indicates that the photospheric temperature structure in the simulations may be slightly too steep. (Or, in terms of a change in \( T_{\text{eff}} \), a \( \approx 50 \text{ K} \) lower \( T_{\text{eff}} \) would be needed.) There may, however, still remain problems with the theoretical line broadening; the 3D Balmer lines are very similar to predictions from recent 1D MARCS model atmospheres (Gustafsson et al. 1975 and later updates).

In summary, the surface convection simulations perform very satisfactory in terms of spectral line formation, both for line shapes and asymmetries, though the Balmer lines suggest that the temperature gradient may be slightly too steep.
Figure 3. The predicted (solid line) limb-darkening curves compared with observations (diamonds). Also shown are the predictions from a 1D MARCS model atmosphere (dashed line).

4. Flux distribution and limb-darkening

The predicted emergent flux distributions from the simulation agree quite well with the observed solar spectrum. There is still a tendency for slightly too much flux in the UV, which reflects the well-known “missing UV-opacity problem” also present in classical 1D models. The accumulated flux is, however, accurate to within 0.5%, illustrating that the energy balance in the simulations is essentially correct (Nordlund & Stein, these proceedings).

The emergent intensities at various aspect angles (limb-darkening) probe the atmospheric structure in the lower photosphere. Fig. 3 shows the theoretical limb-darkening which are are in reasonable agreement with the observed curves (Neckel & Labs 1994) though in general slightly too strong in the UV-blue. This may suggest that the temperature structure close to the continuum forming layers could be somewhat too steep, in accordance with the findings from the Balmer lines, or problems with opacities. Theoretical 1D model atmospheres in general show too strong limb-darkening, as illustrated in Fig. 3.

References