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Testing 3D solar models against observations

Center-to-limb variations of oxygen lines, spatially-resolved line formation and probing for departures from LTE

T. M. D. Pereira[1,2], M. Asplund[3], and D. Kiselman[2]

[1] Research School of Astronomy and Astrophysics, Australian National University, Cotter Rd., Weston, ACT 2611, Australia, e-mail: tiago@mso.anu.edu.au
[2] The Institute for Solar Physics of the Royal Swedish Academy of Sciences, AlbaNova University Center, 106 91 Stockholm, Sweden
[3] Max-Planck-Institut für Astrophysik, Postfach 1317, D–85741 Garching b. München, Germany

Abstract. We present results from a series of observational tests to 3D and 1D solar models. In particular, emphasis is given to the line formation of atomic oxygen lines, used to derive the much debated solar oxygen photospheric abundance. Using high-quality observations obtained with the Swedish Solar Telescope (SST) we study the center-to-limb variation of the O I lines, testing the models and line formation (LTE and non-LTE). For the O I 777 nm triplet, the center-to-limb variation sets strong constraints in the non-LTE line formation, and is used to derive an empirical correction factor ($S_{\rm H}$) to the classical Drawin recipe for neutral hydrogen collisions. Taking advantage of the spatially-resolved character of the SST data, an additional framework for testing the 3D model and line formation is also studied. From the tests we confirm that the employed 3D model is realistic and its predictions agree very well with the observations.

Key words. line: formation – Sun: photosphere – Sun: granulation – Sun: abundances – Convection

1. Introduction

Three-dimensional, time dependent hydrodynamical simulations of stellar atmospheres represent a paradigm change in the modeling of stellar atmospheres (Asplund, 2005). Unlike their one-dimensional counterparts, they treat convection self-consistently without the need for broadening parameters such as micro and macroturbulence. Their realistic description of the motions and velocities in the photosphere leads to an excellent agreement between the predicted and observed line shapes and shifts (Asplund et al., 2000).

Asplund et al. (2005) have revised the solar chemical composition, using photospheric lines and the 3D solar model of Stein & Nordlund (1998). The solar abundances found (in particular C, N and O) were systematically lower than previous studies, implying a lower solar metallicity. A consequence of the new solar abundances is that the previously excellent

Send offprint requests to: T. M. D. Pereira agreement between solar interior models and helioseismology is lost (Bahcall et al., 2005; Basu & Antia, 2008). The new chemical composition of Asplund et al. (2009) results in a slightly higher solar metallicity, but *per se* is not enough to reconcile the solar interior models with helioseismology. To trust the results from the 3D models, more testing is needed. Our objective is to test the 3D model and line formation used by Asplund et al. (2009). In particular for oxygen lines, because oxygen is determinant in the downward revision of the solar abundances. This contribution summarizes the findings of Pereira et al. (2009b) and Pereira et al. (2009a), where the center-to-limb variation and spatially-resolved line formation of oxygen lines is tested.

2. Observations and photospheric models

Using the Swedish 1-m Solar Telescope (SST) with the TRIPPEL spectrograph, we obtained high spatial and spectral resolution observations at several positions in the solar disk. The lines observed include five atomic oxygen lines at 615.81 nm, 630.03 nm and the three lines around 777 nm. Stray light in the telescope was estimated and corrected for. The observations are detailed in Pereira et al. (2009b).

We test these observations against a new 3D model atmosphere (Trampedach et al. 2009, in preparation). It was computed with the STAGGER MHD code (Nordlund & Galsgaard, 1995; Gudiksen & Nordlund, 2005), and consists of a 240^3 grid with a physical size of 6×6×4 Mm. It includes an improved treatment of radiation, with a 12-bin multi-group opacity binning scheme. For the line formation calculations the original simulation was interpolated to a 50×50×82 grid to save computing time. The simulation snapshots used here cover ≈45 minutes of solar time.

In addition, we also compare the center-to-limb variation predicted by two 1D models: the semi-empirical model of Holweger & Müller (1974) and the LTE, line-blanketed MARCS model (Gustafsson et al., 2008).

Oxygen line formation calculations were done in LTE and NLTE, using our LTE code and the MULTI3D code (Botnen, 1997; Botnen & Carlsson, 1999; Asplund et al., 2003). A 23-level model atom was used (see details in Pereira et al., 2009a). For the O I 615.81 nm and [O I] 630.03 nm lines we show the LTE results, because the NLTE effects are weak in

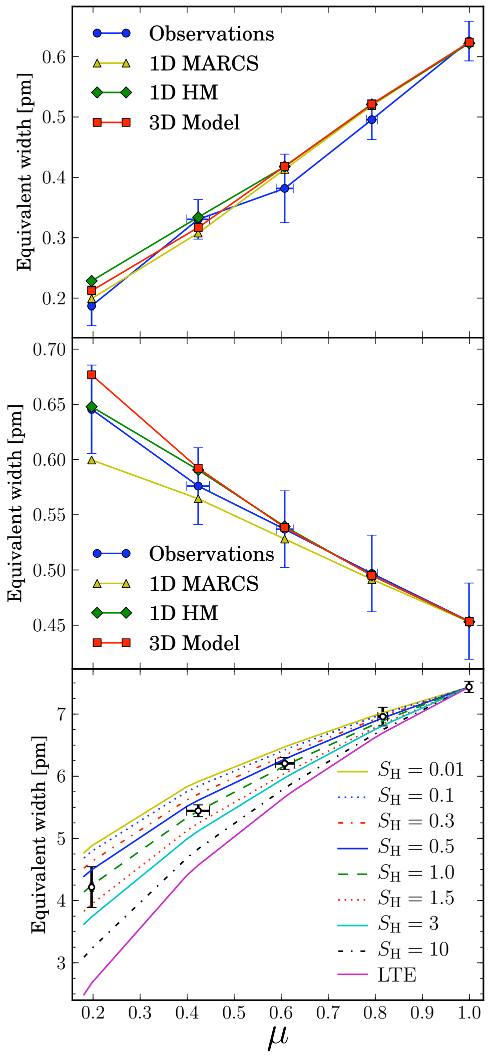

Fig. 1. Center-to-limb variation of the oxygen lines. *Top:* O I 615.81 nm line (including blends). *Middle:* [O I] 630.03 nm line (including blends). *Bottom:* O I 777.41 nm line, only for the 3D model and for different scalings of the H I collisions.

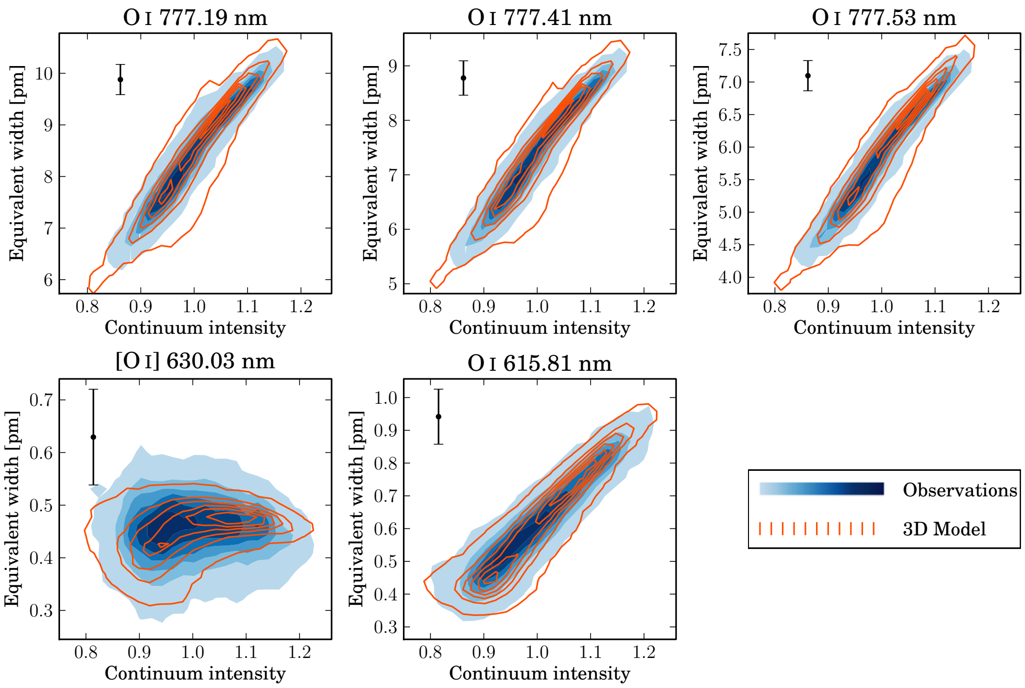

Fig. 2. Distribution of equivalent widths over the solar granulation at disk-center, for five oxygen lines. The 3D model results have been degraded to account for the atmospheric turbulence and the telescope's resolution. For each spatially-resolved spectrum the equivalent width has been computed and the resulting histogram of points is represented by the contours, as a function of the normalized local continuum intensity. The line profiles of the O I 777 nm lines were computed in NLTE, for $S_{\mathrm{H}} = 1$. For the other two lines LTE was assumed.

those lines. For the O I 777 nm lines NLTE calculations were carried out for several values of S_{H}, a scaling factor for the collisions with H I from the classical formulæ (Drawin, 1968; Steenbock & Holweger, 1984). Nearby blends were included in the calculations of the 615.81 nm line (in particular, CN and C_2 molecular blends) and the 630.03 nm line (in particular, the Ni I blend).

3. Center-to-limb variation

In Fig. 1 we show the center-to-limb variation of some of the lines. For the 615.81 nm and 630.03 nm lines the 3D model predictions agree well with the observations. For these lines there is only a small difference between the different models.

For the O I 777 nm lines, the efficiency of the collisions with neutral hydrogen in the NLTE calculations is unknown. Following Allende Prieto et al. (2004), we use the center-to-limb variation of these lines to derive an empirical estimate of S_{H}, the multiplier factor by the classical collision rates. We show only one representative line, and only for the 3D model. Of the S_{H} values used, we find that $S_{\mathrm{H}} = 1$ gives the best agreement with the observations. In Pereira et al. (2009a) a further refinement of this value is made, and the best fitting value is found to be $S_{\mathrm{H}} \approx 0.85$. For these lines, one can very clearly rule out LTE as an acceptable approximation. The 777 nm results for the 1D Holweger–Müller model are very similar to those of the 3D model. The MARCS model fails to reproduce the observations, regardless of the S_{H} used.

4. Spatially-resolved line formation

In Fig. 2 we show the distribution of the equivalent widths in the disk-center granulation. The results from the 3D model have been convolved with a point-spread function to account for the atmospheric smearing and the telescope's resolution, and with a Gaussian to account for the spectrograph's instrumental profile. The oxygen abundance was adjusted so that the predicted mean temporal and spatial equivalent widths matched the observed.

For the O I 777 nm lines the NLTE results are shown, with $S_{\rm H} = 1$. It is comforting to find that $S_{\rm H} = 1$ gives the best agreement also here.

5. Conclusion

We looked at the center-to-limb variation and spatially-resolved line formation of oxygen lines, comparing new observations with the 3D model. These lines are an important test of the model, because oxygen is very relevant in the recent revisions of the solar chemical composition.

Overall there is a very good agreement between the predictions from the 3D model and the observations. Both in the center-to-limb variation and the spatially-resolved line formation for oxygen. These results give us confidence that the 3D model is realistic and appropriate to derive the solar chemical composition, in particular the oxygen abundance.

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