Mem. S.A.It. Vol. 80, 643

Memorie della

Solar abundances and granulation effects

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Abstract. The solar abundances have undergone a major downward revision in the last decade, reputedly as a result of employing 3D hydrodynamical simulations to model the inhomogeneous structure of the solar photosphere. The very low oxygen abundance advocated by Asplund et al. (2004), A(O)=8.66, together with the downward revision of the carbon and nitrogen abundances, has created serious problems for solar models to explain the helioseismic measurements.
In an effort to contribute to the dispute we have re-derived photospheric abundances of several elements independently of previous analysis. We applied a state-of-the art 3D (CO5BOLD) hydrodynamical simulation of the solar granulation as well as different 1D model atmospheres for the line by line spectroscopic abundance determinations. The analysis is based on both standard disc-centre and disc-integrated spectral atlases; for oxygen we acquired in addition spectra at different heliocentric angles. The derived abundances are the result of equivalent width and/or line profile fitting of the available atomic lines. We discuss the different granulation effects on solar abundances and compare our results with previous investigations. According to our investigations hydrodynamical models are important in the solar abundance determination, but are not responsible for the recent downward revision in the literature of the solar metallicity.

Key words. Sun: abundances – Stars: abundances – Hydrodynamics

1. Introduction

In this work we would like to face the most common questions we are confronted with in the analysis of the photospheric solar abundances:

- "Are 3D models important in the abundances determination?"
- "Are 3D models responsible for the downward revision of the solar metallicity?"

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Our answer to the first question is yes. As we know from previous investigations (Caffau & Ludwig 2007), 3D solar metallicity models do not experience the over-cooling in the external layers, not detected in 1D models, that metal-poor 3D models show. One could then expect that 3D models are not fundamental for the solar abundance determinations. If for some elements (P, Eu, Hf) the granulation effects are in fact negligible, this is not the case for others, such as Fe, Th, and also oxygen. On top of that one should not forget that 1D models require some input parameters (mixing-length parame-

Table 1. Averaged 3D corrections in the case of $\xi_{\rm micro}$ = 1.0 km s^{-1} and $\alpha_{\rm MLT}$= 1.0.

EL	N	ion	Spec	CO^{5}BOLD	3D-1D$_{\rm LHD}$ [dex]	3D-⟨3D⟩ [dex]	role of 3D	Ref.
Li	1	Li I	I/F	1.03 ± 0.03			3D-NLTE	
C	43	C I	I/F	8.50 ± 0.06	+0.02	–0.03	$\xi_{\rm micro}$	
N	12	N I	I	7.86 ± 0.12	–0.05	–0.01	$\alpha_{\rm MLT}$	Caffau et al. (2009)
O	10	O I	I/F	8.76 ± 0.07	+0.05	+0.01	$\xi_{\rm micro}$	Caffau et al. (2008b)
P	5	P I	I/F	5.46 ± 0.04	+0.03	+0.01		Caffau et al. (2008a)
S	6	S I	F	7.16 ± 0.05	+0.04	+0.01	$\xi_{\rm micro}$	Caffau et al. (2007a)
Fe	38	Fe I	I	7.45 ± 0.06	+0.11	+0.03	$\xi_{\rm micro}$	
Fe	15	Fe II	I/F	7.52 ± 0.06	+0.08	+0.05	$\xi_{\rm micro}$	
Eu	5	Eu II	I/F	0.52 ± 0.03	+0.01	+0.02		Mucciarelli et al. (2008)
Hf	4	Hf II	I/F	0.87 ± 0.04	+0.02	+0.01		Caffau et al. (2007b)
Th	1	Th II	I/F	0.08 ± 0.03	–0.10		Line asymmetry	Caffau et al. (2007b)

Table 2. Influence of the microturbulence on the 3D corrections.

$\xi_{\rm 1D_{LHD}}$ km s^{-1}	$\left(\mathrm{A(Y)_{3D} - A(Y)_{1D_{LHD}}}\right)$ [dex] Flux	Intensity
0.6	+0.036	- -
0.9	- -	+0.037
1.2	+0.130	- -
1.5	- -	+0.139

ter, $\alpha_{\rm MLT}$, and microturbulence, $\xi_{\rm micro}$) implicit in 3D models; so that in the case such parameters are fundamental ($\alpha_{\rm MLT}$ for C, O, and Fe, $\xi_{\rm micro}$ for N) 3D models should be highly preferred.

Our answer to the second question is no. We would like to remark that this answer depends on the 1D reference model one is considering. For all the elements, except N and Th, our 3D model gives an abundance larger than the 1D model. Th is an exception because its lower 3D abundance is related to the fact that the line is on the red wing of a stronger Fe-Ni blend, and the asymmetry of this blend, correctly taken into account in 3D analysis, lowers the Th contribution (Caffau et al. 2007b). For N all the lines considered are of high excitation energy, so their 1D abundance is very sensitive on the choice of $\alpha_{\rm MLT}$. To try to catch the effects of granulation on the abundances determination, we selected 1D models sharing the micro-physics with our 3D solar model atmosphere. But the comparison of abundances derived from 1D and 3D models is not unambiguously defined, relying on the choice of $\alpha_{\rm MLT}$ and $\xi_{\rm micro}$.

2. Model atmospheres and observed data

Our photospheric solar abundance analysis was performed by using 3D-CO^{5}BOLD solar models (Freytag et al. 2002, 2003; Wedemeyer et al. 2004). The results here reported mostly rely on a solar model covering 1.2 h of solar time, with a box size of $5.6 \times 5.6 \times 2.3$ Mm^3, a resolution of $140 \times 140 \times 150$, 12 opacity bins based on opacities stemming from the MARCS stellar atmosphere package (Gustafsson et al. 2007, 2003). The model spans a range in optical depth of about $-6.7 < \log \tau_{\rm Ross} < 5.5$. For details see Caffau et al. (2008b).

We are here interested in the granulation effect on abundances, and for this reason we selected two 1D models that share the microphysics with CO^{5}BOLD:

- ⟨3D⟩, a 1D model obtained by temporal and horizontal average over surfaces of equal (Rosseland) optical depth of the 3D model;
- 1D$_{\rm LHD}$, a 1D, plane parallel model, which employs the same micro-physics as CO^{5}BOLD.

For the photospheric solar abundance determinations, as observed spectra, we considered the data described in Caffau et al.

Table 3. Photospheric solar abundances.

EL	N	CO^5BOLD	AG89	GS98	AGS05	AGSS09
Li	1	1.03 ± 0.03	1.16 ± 0.10	1.10 ± 0.10	1.05 ± 0.10	1.05 ± 0.10
C	43	8.50 ± 0.06	8.56 ± 0.04	8.52 ± 0.06	8.39 ± 0.05	8.43 ± 0.05
N	12	7.86 ± 0.12	8.05 ± 0.04	7.92 ± 0.06	7.78 ± 0.06	7.83 ± 0.05
O	10	8.76 ± 0.07	8.93 ± 0.035	8.83 ± 0.06	8.66 ± 0.05	8.69 ± 0.05
P	5	5.46 ± 0.04	5.45 ± 0.04	5.45 ± 0.04	5.36 ± 0.04	5.41 ± 0.03
S	9	7.16 ± 0.05	7.21 ± 0.06	7.33 ± 0.11	7.14 ± 0.05	7.12 ± 0.03
K	6	5.11 ± 0.09	5.12 ± 0.13	5.12 ± 0.13	5.08 ± 0.07	5.03 ± 0.09
Fe	15	7.52 ± 0.06	7.67 ± 0.03	7.50 ± 0.05	7.45 ± 0.05	7.50 ± 0.04
Eu	5	0.52 ± 0.03	0.51 ± 0.08	0.51 ± 0.08	0.52 ± 0.06	0.52 ± 0.04
Hf	4	0.87 ± 0.04	0.88 ± 0.08	0.88 ± 0.08	0.88 ± 0.08	0.85 ± 0.04
Os	3	1.36 ± 0.19	1.45 ± 0.10	1.45 ± 0.10	1.45 ± 0.10	1.40 ± 0.08
Th	1	0.08 ± 0.03	0.12 ± 0.06	*0.09 ± 0.02*	*0.06 ± 0.05*	0.02 ± 0.10
Z		0.0153	0.0189	0.0171	0.0122	0.0134
Z/X		0.0209	0.0267	0.0234	0.0165	0.0183

Note: AG89=Anders & Grevesse (1989), GS98=Grevesse & Sauval (1998), AGS05=Asplund et al. (2005), and AGSS09=Asplund et al. (2009).

(2008b) and spectra of solar intensity spectra for nine heliocentric angles observed at Kitt Peak with the McMath-Pierce Solar Telescope by W. Livingston.

3. 3D corrections and solar abundances

As we did in our previous work (Caffau & Ludwig 2007), we define two 3D corrections as: $A(Y)_{3D} - A(Y)_{1D_{LHD}}$ $A(Y)_{3D} - A(Y)_{\langle 3D \rangle}$ with Y the generic element and $A(Y) = \log \frac{n_Y}{n_H} + 12$. The first 3D correction takes into consideration the effects of convection on the 3D temperature structure, the latter one the effects of fluctuations around the mean stratification.

For the elements so far analysed we can say that the effects of granulation on the abundance analysis are not very large, but for the Sun, due to the high quality spectra and to the high precision request in the abundance determination, they are not negligible. In Table 1 the average, over all lines as well as disc-centre and disc-integrated when available, values are given. For all the elements considered, the granulation effects due to fluctuations around the mean stratification are small, being the highest of +0.05 for Fe II. $A(Y)_{3D} - A(Y)_{1D_{LHD}}$ on average is larger in absolute value, and can be as large as 0.1 dex (see iron).

Both 3D corrections are function of the microturbulence of the 1D models, and the first one of the mixing-length parameter as well.

We changed the microturbulence in a reasonable range for disc-centre and disc-integrated for 15 Fe II lines with 0.8 pm<EW<8.8 pm. The results are in Table 2. In Fig. 1 this behaviour is shown, for each Fe II line, in the disc-integrated case.

The choice of the mixing-length parameter for the $1D_{LHD}$ model influences mainly the lines formed deep in the photosphere, meaning atomic lines of high lower level energy. We considered 12 N I lines with 10.3 eV $< E_{low} <$ 11.8 eV, and changing α_{MLT} of $^{+1.0}_{-0.5}$ with respect to the reference value of 1.0, we obtained changes on $A(N)_{1D_{LHD}}$ of $^{-0.09}_{+0.05}$ dex, which translate in analogous changes in the 3D correction.

The solar abundances we derived with the CO^5BOLD model are listed in Table 3 and compared to other solar abundances compilations. The majority of the disagreement one can see in the table are due to improvements in the atomic data. The solar metallicity has been

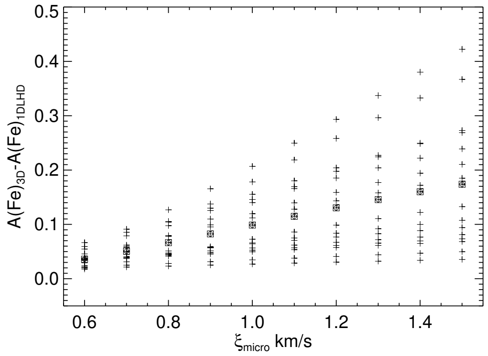

Fig. 1. The 3D correction as a function of micro-turbulence, for 15 Fe II lines (crosses). Squares depict the average over the 15 lines.

computed using the CO^{5}BOLD bases abundances, when avaliable, and the solar abundances from Lodders et al. (2009) for all other elements.

4. Conclusions

In the light of our work we think that the use of 3D models in the solar abundance determination is useful. This is for the following reasons:

– no constraint is necessary on α_{MLT} and ξ_{micro};
– a difference of few hundreds of dex in the abundance, negligible for the majority of the stellar analysis, is important in the solar context.

Acknowledgements. The authors E.C. and H.-G.L. acknowledge financial support from EU contract MEXT-CT-2004-014265 (CIFIST).

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