

# Convection and the solar abundances: Does the sun have a sub-solar metallicity?

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**Abstract.** In the Sun, the convection zone reaches up to the solar photosphere and can thus directly influence the emergent spectrum. Traditionally, the effects of convection has been modelled with the local mixing length theory in theoretical 1D hydrostatic model atmospheres. In a different approach, we have performed realistic time-dependent, 3D, radiative-hydrodynamical simulations of the outer layers of the solar convection zone, including the photosphere. Both the different mean stratification and the presence of atmospheric inhomogeneities in 3D impact the spectral line formation. In a series of papers, we have applied our 3D solar model atmosphere to the problem of the solar chemical composition. Furthermore, we have adopted the best possible atomic and molecular line data and taken into account departures from LTE in the line formation when necessary. The inferred C, N, O and Ne abundances are all significantly lower than estimated from previous 1D modelling by 0.2-0.3 dex. These results have significant implications for a range of topics in contemporary astrophysics, including causing a severe headache for helioseismology.

**Keywords.** Convection, hydrodynamics, line: formation, line: profiles, radiative transfer, Sun: abundances, Sun: atmosphere, Sun: granulation

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## 1. Introduction

The solar chemical composition is a fundamental yardstick in astronomy against which the elemental abundances of all other cosmic objects are measured be it planets, stars, galaxies or the diffuse matter in between them. As a consequence, careful compilations of the solar abundances, such as the works by Anders & Grevesse (1989) and Grevesse & Sauval (1998) are widely used; indeed the former is the fourth most cited astronomy article of all time. Given the great importance of such data, it is prudent to ask how reliable they are. It has often been argued that typical solar abundances of individual elements are known to an accuracy of  $\sim 10\%$ , which for most purposes is an acceptable uncertainty. Recent work, however, suggests that this is a far too optimistic stand-point and that the truth may well be that the most abundant metals like C, N and O have been over-estimated by as much as a factor of two (Asplund *et al.* 2004, 2005a,b). While a factor of two is often not critical in astronomy, in the case of the solar chemical composition it is a rather dramatic revision that has caused quite a stir.

Stellar elemental abundances are never more trustworthy than the adopted input physical data used in the analysis, most notably the transition probabilities for the spectral lines in question. Atomic physicists are steadily making progress in this respect and, although much work still remains, the situation regarding the solar abundances is quite satisfactory with a few notable exceptions. It is important to remember though that one never *observes* the elemental abundances of stars, they are *derived* from an observed spectrum using models of the stellar atmosphere and spectral line formation process. Because

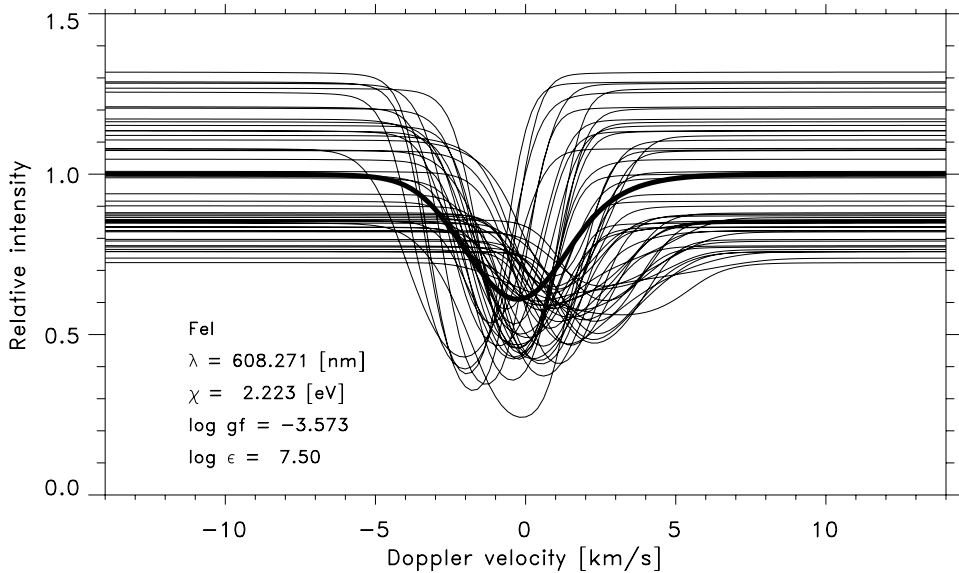
of short-comings in the modelling, the dominant uncertainty in abundance analyses is almost always systematic in nature. To further improve the accuracy thus requires more work on developing realistic model atmospheres and taking into account departures from local thermodynamic equilibrium (LTE) in the spectrum formation.

As the convection zone reaches up to the optical surface in the Sun, granulation directly influences the spectrum formation both by modifying the mean stratification and by introducing inhomogeneities and velocity fields in the photosphere. Traditionally, convection is incorporated in theoretical 1D model atmospheres through the rudimentary mixing length theory Böhm-Vitense (1958) or, as often done in the solar case, to rely on semi-empirical model atmospheres like the Holweger & Mueller (1974) model, in which the temperature structure is inferred from observations, notably continuum center-to-limb variation and spectral line strengths. Due to the lack of Doppler-shifts induced by the convective motion, all 1D modelling predict insufficient line broadening that has to be introduced ad-hoc by the micro- and macroturbulence concepts. An alternative approach is to make use of 3D, time-dependent radiative-hydrodynamical simulations of solar surface convection in which 3D line formation calculations are performed. In such models the convective energy transport is self-consistently calculated and the full 3D, dynamical nature of the solar atmosphere is accounted for, leading arguably to more reliable results. For a comprehensive review on 3D model atmospheres and non-LTE line formation and their impact on solar and stellar abundance analysis the reader is referred to Asplund (2005).

## 2. 3D hydrodynamical model atmospheres and line formation

Following pioneering work by Åke Nordlund and Bob Stein (e.g. Nordlund 1982; Stein & Nordlund 1998) we have continued to improve the realism of 3D hydrodynamical simulations of the solar atmosphere. These 3D models are local simulations, i.e. the hydrodynamical conservation equations together with the equation of radiative transfer are solved in a small but representative volume of the upper convection zone, photosphere and lower chromosphere. The numerical resolution of the solar simulation employed for the abundance analysis described herein is  $200 \times 200 \times 82$  gridpoints, which corresponds to a physical dimension of  $6.0 \times 6.0 \times 3.8$  Mm of which about 1.0 Mm is located above continuum optical depth unity. The horizontal extension is sufficient to cover about 10 granules at any time. The 3D radiative transfer is solved at each time-step using a realistic equation-of-state (Mihalas *et al.* 1988) and opacities (Gustafsson *et al.* 1975; Kurucz 1993) with the opacity binning technique (Nordlund 1982). It is noteworthy that these 3D models do not contain any adjustable free parameters to improve the agreement with observational constraints besides those used to characterize the stars: the entropy of the inflowing material at the bottom boundary (which determines the resulting effective temperature), the surface gravity and the chemical composition.

From the full solar simulation we have extracted a time-series of 100 snapshots covering 50 min solar-time, which is used as a 3D model atmosphere in which 3D spectral line formation computations are performed. In most cases, (strong) LTE is assumed: the Saha and Boltzmann distributions are assumed valid and  $S_\nu = B_\nu(T)$ . We have verified that the spectral lines under consideration in the solar abundance analysis are minimally affected by continuum scattering. Some lines, such as the O I 777 nm triplet, however, experience significant departures from LTE, in which case full 3D non-LTE line formation calculations have been carried out using the code MULTI3D (Botnen 1997; Asplund *et al.* 2003).

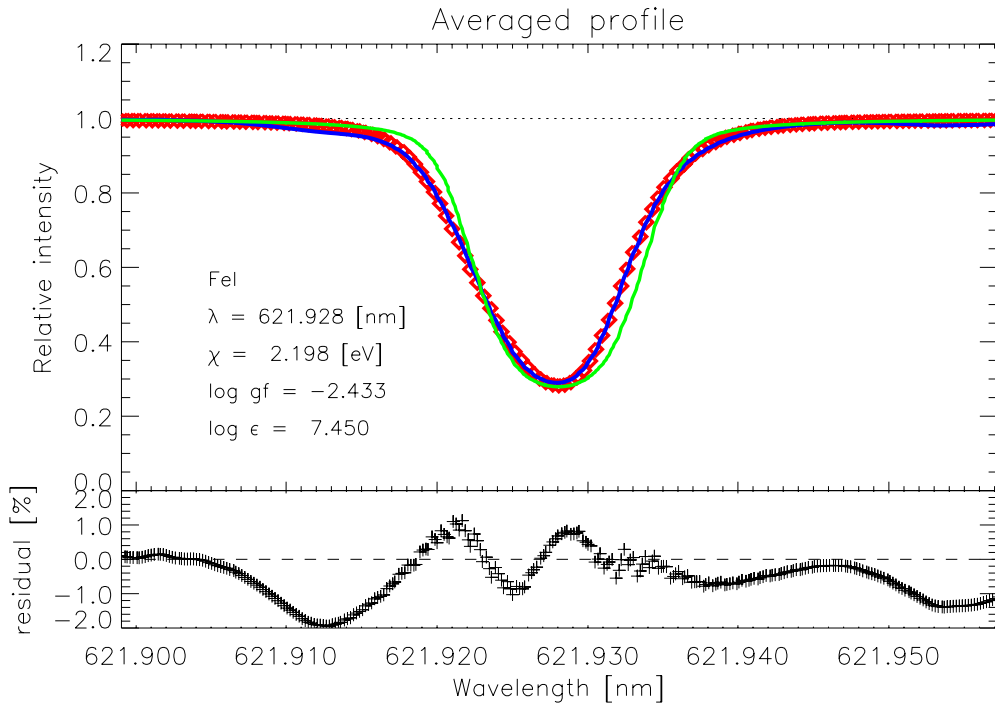


**Figure 1.** The spatially resolved profiles for a typical Fe I line across the solar granulation pattern. Note the bias in line strengths towards upflows.

The strengths and shapes of lines vary dramatically across the solar surface, as seen in Fig. 1. In the upflows the continuum intensity is high and the lines are strong because of the steep temperature gradient while the red-shifted downflows give rise to much weaker lines. The resulting temporally and spatially averaged line profiles are asymmetric with a distinct C-shape and a convective blue-shift for most lines (e.g. Dravins & Nordlund 1990, Asplund *et al.* 2000a,b). The exact line profile is a very sensitive measure of the convective velocities, continuum brightness contrast and temperature structure across the granulation pattern and can thus be used as excellent test of the realism of the simulation and line formation. As obvious from Fig. 2 the agreement is quite satisfactory. It should be emphasized that this is achieved without invoking any ad-hoc line broadening; the Doppler shifts from the convective motions and oscillations together with the intrinsic atomic broadening are sufficient. In contrast, no fully satisfactory fit can be obtained in 1D even when tuning the micro- and macroturbulence parameters. Even the detailed line asymmetries, the so-called line bisectors, are excellently reproduced in 3D, including the absolute line shifts (Fig. 3). Also the statistics of the spatially resolved line profiles are almost perfectly described with this 3D solar atmosphere model (e.g. Cauzzi *et al.* these proceedings).

### 3. The solar chemical composition

In a series of papers (Asplund *et al.* 2000c, 2004, 2005a,b; Asplund 2000, 2004; Scott *et al.* 2006) we have performed a re-analysis of the solar chemical composition using a carefully constructed 3D solar convection simulation with the correct nominal solar effective temperature (Asplund *et al.* 2000b); see also Steffen *et al.* (these proceedings) for similar 3D calculations using completely independent codes but with gratifyingly similar results. Besides the application of a 3D model atmosphere, other notable ingredients of the analysis are the use of non-LTE calculations for lines susceptible to departures from

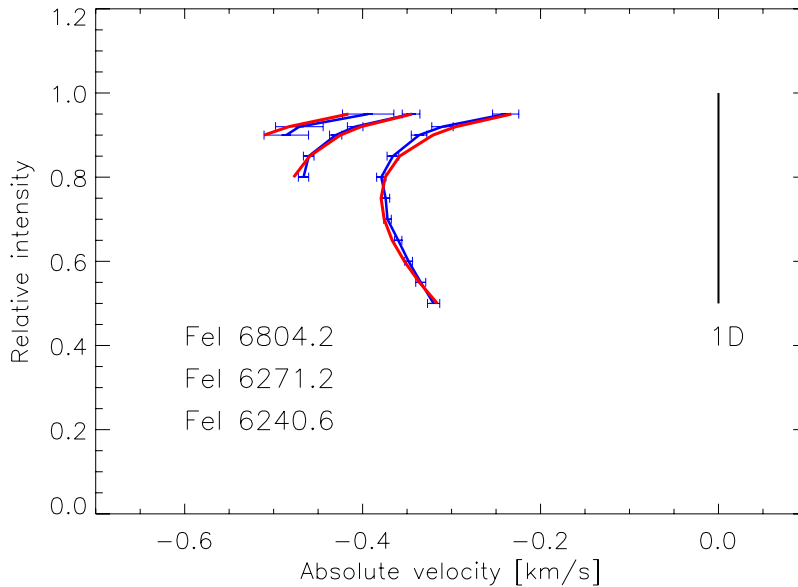


**Figure 2.** The predicted temporally and spatially averaged 3D profile (dark solid line) compared with the observed solar disk-center line (diamonds). Note the excellent agreement as seen in the residuals (the discrepancies in the far red and blue wings are due to unaccounted for blends). Also shown is the best-fitting 1D line profile after having optimized the micro- and macroturbulence (grey solid line).

LTE and carefully evaluated atomic and molecular data. It should be emphasized that in fact all three factors – 3D, non-LTE and input data – play roughly equal role overall in the drastic lowering of the solar C, N and O abundances in our work compared with those found in Anders & Grevesse (1989) and Grevesse & Sauval (1998).

To date we have performed at least a preliminary a solar abundance analysis of all elements up to Ni in the period table. The largest differences with previous studies are found for C, N and O. These are the only elements for which the abundances can be derived from a wealth of different indicators: forbidden, low excitation and permitted, high excitation atomic lines as well as various molecular transitions of electronic, vibrational and rotational nature. Table 1 summarizes the new 3D-based results for C and O (Asplund *et al.* 2004, 2005; Scott *et al.* 2006) together with the corresponding estimates for two widely used 1D model atmospheres. In contrast to the 1D cases, the agreement between different indicators is very good in the 3D analysis: all diagnostics agree to within 0.1 dex while the discrepancy is as large as 0.3 dex with the Holweger & Mueller (1974) model. This is a strong argument in favour of the new lower abundances.

To exemplify, the case of O is used here. The main reason for the low [O I]-based abundance is the discovery that the [O I] 630 nm line is in fact significantly blended by a Ni I line (Allende Prieto *et al.* 2001). Because the predicted profiles of basically all lines agree very well with observations, whenever this is not the case one can be fairly confident that it is due to blending. The Ni I blend has subsequently been confirmed by laboratory measurements by Johansson *et al.* (2003). In fact, taking at face value the new *gf*-value for the Ni I line together with our preliminary 3D-based solar Ni abundance

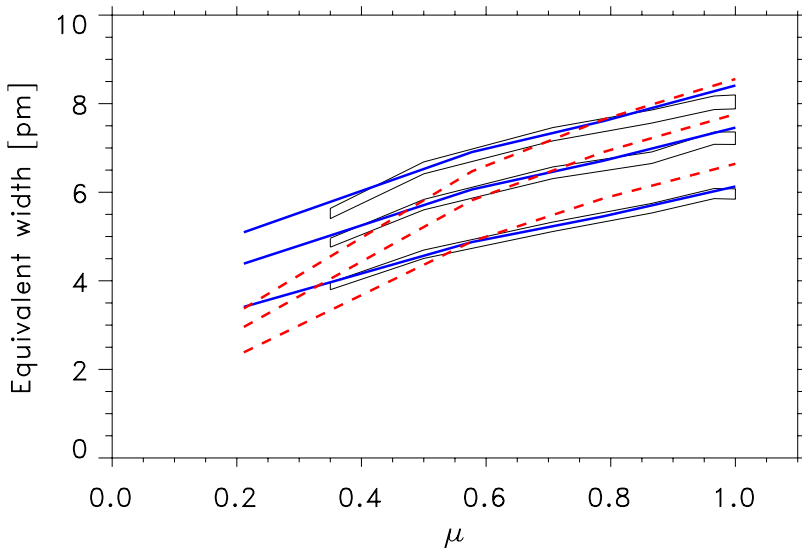


**Figure 3.** A comparison between the predicted and observed (solid lines with error bars) line bisectors for a few Fe I lines on an absolute wavelength scale. In 1D models all lines are perfectly symmetric with no line shift.

**Table 1.** The derived solar C and O abundances based on different atomic and molecular indicators using a 3D hydrodynamical model of the solar atmosphere together with the corresponding 1D results for the theoretical MARCS model atmosphere and the semi-empirical model of Holweger & Mueller (1974). The quoted uncertainty is only the line-to-line scatter.

lines	$\log \epsilon_{C,O}$		
	3D	HM	MARCS
[C I]	8.39	8.45	8.40
C I	$8.36 \pm 0.03$	$8.39 \pm 0.03$	$8.35 \pm 0.03$
CH, $\Delta v = 1$	$8.38 \pm 0.04$	$8.53 \pm 0.04$	$8.42 \pm 0.04$
CH, A-X	$8.45 \pm 0.04$	$8.59 \pm 0.04$	$8.44 \pm 0.04$
C <sub>2</sub> Swan	$8.44 \pm 0.03$	$8.53 \pm 0.03$	$8.46 \pm 0.03$
CO, $\Delta v = 1$	$8.40 \pm 0.01$	$8.60 \pm 0.01$	$8.55 \pm 0.02$
CO, $\Delta v = 2$	$8.37 \pm 0.01$	$8.69 \pm 0.02$	$8.58 \pm 0.02$
[O I]	$8.68 \pm 0.01$	$8.76 \pm 0.02$	$8.72 \pm 0.01$
O I	$8.64 \pm 0.02$	$8.64 \pm 0.08$	$8.72 \pm 0.03$
OH, $\Delta v = 1$	$8.61 \pm 0.03$	$8.87 \pm 0.03$	$8.74 \pm 0.03$
OH, $\Delta v = 0$	$8.65 \pm 0.02$	$8.82 \pm 0.01$	$8.83 \pm 0.03$

( $\log \epsilon_{Ni} = 6.17 \pm 0.09$ , Scott *et al.*, in preparation) would lower the [O I] abundance slightly further. For the O I lines, the main explanation for the low abundance is non-LTE effects, which amount to  $\approx -0.25$  dex for the 777 nm triplet. It was previously often argued that the non-LTE effects were small, mainly in order to obtain similarly high O abundances as for molecular lines. The observed center-to-limb variation of the 777 nm triplet clearly



**Figure 4.** The LTE (dashed lines) and non-LTE (solid lines) center-to-limb variation of the strength of the O I 777 nm triplet compared with observations (boxes).

demonstrates that these lines are not formed in LTE, as shown in Fig. 4. These non-LTE calculations have been done without the poorly known inelastic H collisions but even adopting the classical and highly questionable Drawin formulae would only increase the O abundance by  $< 0.1$  dex (Allende Prieto *et al.* 2004). Quantum mechanical calculations and laboratory measurements for other elements suggest that the Drawin formula overestimates the collisional cross-sections by several orders of magnitude (Asplund 2005). With the most recent electron collisional cross-section calculations (Barklem 2006) the non-LTE effects in fact become slightly larger, lowering the O abundance further (Fabian *et al.*, in preparation). In the case of the OH-lines, the 3D model atmosphere is the main culprit. The presence of temperature inhomogeneities and the somewhat cooler mean temperature stratification compared with the Holweger & Mueller (1974) model atmosphere makes the molecular lines significantly stronger and hence lowers the derived abundance.

#### 4. Discussion

The main result from the new 3D-based solar abundance analysis is the significantly lower C, N and O abundances by  $\sim -0.2$  dex compared with previous estimates. These new low abundances finally bring the Sun into agreement with the solar neighborhood as measured by nearby OB-type stars and the local interstellar medium, further strengthening our case. However, the lowering of the solar abundances wrecks havoc with the previous impressive agreement between the predicted solar interior sound speed and that measured with helioseismology (see Delahaye & Pinsonneault 2006 and references therein). Many explanations have been put forward (missing opacity, underestimated diffusion, accretion of low-metallicity gas, internal gravity waves, underestimated solar Ne abundance, erroneous solar abundance analysis etc) but to date no satisfactory solution has been found to this dilemma.

It would be foolish to assume that the work presented here represent the final word on the solar abundances: history keeps reminding us that systematic errors are almost

always underestimated. It is therefore paramount to continue to confront the 3D hydrodynamical solar model atmosphere and 3D line formation against additional observational constraints to verify their realism and suitability for abundance analysis purposes. Ayres *et al.* (2006) have argued that our 3D solar model predict too steep continuum center-to-limb variation but on the other hand the temperature-sensitive H lines are better described with the 3D model than for example with the Holweger & Mueller (1974) model (Pereira *et al.*, in preparation). Further work is clearly needed here. We are also constructing a new 3D solar model with hopefully an improved radiative transfer treatment using selective opacity sampling (Trampedach *et al.*, in preparation), which will eventually be used for abundance analysis.

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### Discussion

CHRISTENSEN-DALSGAARD: As a comment: helioseismology is fine; the sound-speed determination stands. And a question: in comparing the solar abundance with neighbouring stars, should one take into account differences in birthplace?

ASPLUND: Yes, the measured oscillations and the inferred sound speed are not at fault. The problem is either with the predicted solar structure or our new solar abundances. It is of course correct that one should compare with the abundances of stars the Sun was born with 4.5 Gyr ago. Indeed that was one proposed explanation for its apparent high metallicity compared with the present-day solar neighborhood based on the old solar abundances: the Sun might have migrated from a Galactocentric radius of  $\sim 3$  kpc to 8 kpc today (adopting an abundance gradient of  $\sim -0.04$  dex/kpc as most commonly advocated today). I'm told by experts in the field that this is very unlikely given the circular orbit the Sun has now.

BRUN: What is the role or influence of rotation on your result? How confident are you when comparing the revised solar abundance with neighborhood stars that could also have a "new revised" lower abundance and thus the Sun would still be "metallic"?

ASPLUND: The direct impact of rotation on the resulting atmospheric structure in the relatively small simulation box we are employing is negligible; the by far dominant process is granulation in determining the temperature structure and atmospheric inhomogeneities. Thus, the spectral line formation and the derived elemental abundances are not significantly affected by our neglect of rotation in the convection simulations. The comparison with present-day solar neighborhood is done using H II regions, ISM, and O and B type stars. Hot stars do not have a convective atmosphere and thus the analysis of their spectra are not affected by the type of 3D convection calculations we are performing.

ROXBURGH: Have you tested how sensitive the results are to changes of parameters in the model e.g. the boundary conditions and the subgrid modelling?

ASPLUND: Yes, we have done quite extensive testing of the various numerical details of the simulations. For example, exactly how the boundary conditions are implemented is of little consequence, mainly since the lower and upper level are located at sufficiently large physical distances from the spectral line formation region. Similarly, tests have revealed that the details of how the subgrid modelling, or in our case the numerical viscosity, is implemented does not significantly modify the emergent spectrum and the derived elemental abundances, mainly since the line formation is heavily biased towards the up-flowing regions (larger area, steeper temperature gradient, higher continuum intensities), which are divergent flows with very little vorticity. We have also verified that the current numerical resolution is sufficiently high not to impact the results.

LUDWIG: For clarification: how much weight have you put on the molecular lines in the overall assessment of the solar oxygen abundance?

ASPLUND: As all the various abundance indicators for oxygen (high-excitation permitted and low-excitation forbidden atomic lines, vibration-rotational and pure rotational OH lines) imply quite similar results in 3D, we include all of them in the mean abundance, weighted with their standard deviations from different lines in each category. In practice the molecules are given roughly equal weight to the atomic lines. The dominant uncertainties are still likely systematic. Fortunately all indicators have quite different sensitivities to for example the temperature structure at different depths and hence one may expect that the overall agreement gives an estimate of the total error.