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The impact of surface dynamo magnetic fields on the chemical abundance determination

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Abstract. The solar abundances of Fe and of the CNO elements play an important role in addressing a number of important issues such as the formation, structure, and evolution of the Sun and the solar system, the origin of the chemical elements, and the evolution of stars and galaxies. Despite the large number of papers published on this issue, debates about the solar abundances of these elements continue. The aim of the present investigation is to quantify the impact of photospheric magnetic fields on the determination of the solar chemical abundances. To this end, we used two 3D snapshot models of the quiet solar photosphere with a different magnetization taken from recent magneto-convection simulations with small-scale dynamo action. Using such 3D models we have carried out spectral synthesis for a large set of Fe I, C I, N I, and O I lines, in order to derive abundance corrections caused by the magnetic, Zeeman broadening of the intensity profiles and the magnetically induced changes of the photospheric temperature structure. We find that if the magnetism of the quiet solar photosphere is mainly produced by a small-scale dynamo, then its impact on the determination of the abundances of iron, carbon, nitrogen and oxygen is negligible.

Keywords. MHD, dynamo, line: formation, radiative transfer, Sun: abundances, Sun

1. Introduction

Until recently, the solar chemical abundance determinations ignored the fact that the quiet solar photosphere is signifcantly magnetized, due to the ubiquitous presence of a complex, small-scale magnetic field with a mean field strength that is thought to be of the order of 100 gauss (e.g., Trujillo Bueno *et al.* 2004; Trujillo Bueno *et al.* 2006; Stenflo 2009; Sánchez Almeida, & Martínez González 2011; Martínez Pillet 2013). Magnetic felds can in principle affect the width and shape of spectral lines, both directly, via the Zeeman broadening, and indirectly, via the magnetically induced changes of the temperature and density of the atmospheric plasma in the line formation region (e.g., Borrero 2008;

Fabbian *et al.* 2010, 2012). Therefore, it is important to investigate how significant are the errors on the determination of chemical abundances when ignoring the fact that the quiet solar photosphere is significantly magnetized.

Borrero (2008) investigated this issue via spectral synthesis in a semi-empirical 1D model of the solar photosphere. He focused on the direct impact of magnetic fields on the abundances of Fe, Si, C, and O, and concluded that the magnetic fields of the quiet Sun are an unlikely source of errors in the solar abundance determinations. More recently, Fabbian *et al.* (2010, 2012) addressed this research problem following a more realistic approach for deriving the differential effects produced by magnetic fields on the solar iron abundance. They carried out a hydrodynamical simulation (characterized by $B = 0$ G) and several 3D magneto-convection simulations, each of them characterized by an initially imposed vertical field of 50 G, 100 G, and of 200 G (see discussion in Fabbian *et al.* 2010). They found that the average solar iron abundance obtained from spectral synthesis in their magneto-convection models can be $\sim 0.03 - 0.11$ dex larger than when using their zero-field model.

In the present paper we adsress the issue of a possible impact of the quiet Sun magnetism on the determination of the solar Fe, C, N, and O abundances. However, instead of using 3D models similar to those of Fabbian *et al.* (2010, 2012) our differential analysis is based on radiative transfer calculations in two 3D snapshot models taken from the recent magneto-convection simulation with small-scale dynamo (SSD) action carried out by Rempel (2014). Such fields are known in the literature as surface dynamo magnetic fields. Our main motivation for doing this investigation using Rempel's (2014) models is the following.

Magneto-convection simulations without small-scale dynamo action and with a net magnetic flux (such as those of Fabbian *et al.* 2010, 2012) show a signifcant number of kilogauss (kG) feld concentrations in the visible surface layers. As a result, the thermal structure in such 3D models is expected to have features qualitatively similar to those found in basic investigations on the photospheric temperature within and around kG magnetic flux concentrations, such as temperature enhancements above the visible surface layers (e.g., Fabiani Bendicho *et al.* 1992 and references therein).

In our opinion, a more suitable representation of the thermal and magnetic structure of the quiet solar photosphere is provided by magneto-convection simulations with zero net magnetic flux, such as those of Vögler & Schüssler (2007) and Rempel (2014). These magneto-convection numerical experiments show a complex, small-scale magnetic field that results from dynamo amplifcation of a weak seed field. In particular, the recent simulations carried out by Rempel (2014) show a very signifcant level of magnetic activity, with $\langle\mathrm{B}\rangle\approx160$ G in the low photosphere. This significant degree of small-scale magnetization is in agreement with the $\langle\mathrm{B}\rangle$ values inferred by Trujillo Bueno *et al.* (2004) and Shchukina & Trujillo Bueno (2011) from the scattering polarization observed in the Sr I 4607 Å line, although it must be noted that the decline with height of $\langle\mathrm{B}\rangle$ is more pronounced in Rempel's simulations.

2. Input data and method

We used two 3D snapshots from the magneto-convection simulations with small-scale dynamo action performed by Rempel (2014). In both 3D models the net magnetic flux is zero. The first snapshot, with vertical unsigned flux density $\langle | B_z | \rangle = 0.5$ G in the visible surface layers, represents the kinetic growth phase and is virtually unmagnetized. The second one, with $\langle | B_z | \rangle = 80$ G and $\langle B \rangle = 160$ G at the visible surface of the 3D model, corresponds to the stationary stage.

We used a large set of clean Fe I, C I, N I, and O I lines. The line list includes 66 Fe I, 26 C I, 9 N I, and 11 O I lines which span a wide range in wavelength, oscillator strength, excitation potential of the lower level, and effective Landé factor. These lines originate in a large domain of the solar photosphere. For most of the lines we adopted the "solar" oscillator strengths and observed equivalent widths given by Gurtovenko & Kostik (1989). For the rest of the lines these values were taken from Asplund *et al.* (2005), Borrero *et al.* (2003), Caffau *et al.* (2010), Kostik *et al.* (1996), and Lambert(1978). Such a large number of lines allows us to obtain statistically meaningful conclusions about possible differential abundance corrections due to the presence of a magnetic field.

In order to determine the abundance corrections due to the impact of the model's magnetic field we have developed a radiative transfer code based on the DELOPAR method proposed by Trujillo Bueno (2003), which allows us to compute the emergent Stokes profiles taking into account the Zeeman effect. We focus only on the emergent Stokes $I(\lambda)$ profiles because this is the observable we use for determining the abundance corrections. The intensity profiles were calculated at the solar disk center assuming LTE, for all the Fe I, C I, N I, and O I lines and at each point on the surface of the two 3D models used. The resulting emergent intensity profiles of each of these lines were spatially averaged over all surface points of the model under consideration, and for each line we computed the ensuing equivalent width. Any difference between the observed equivalent width and the calculated one was ascribed to an incorrect abundance, which we modified iteratively until reaching the best fit. We emphasize that in our study the determined abundance corrections were obtained from the equivalent widths of the Fe I, C I, N I, and O I lines.

We use abundance corrections (ΔA) for determining the direct and the indirect impact of photospheric magnetic fields on the solar iron abundance determination. We define $\Delta A = A(B_z = 80\text{G}) - A(B_z = 0.5\text{G})$, as the difference between the abundances fitted using the 3D model snapshots with $\langle| B_z |\rangle = 80$ G and $\langle| B_z |\rangle = 0.5$ G. The indirect effect induced by changes of the thermodynamical structure of the atmosphere was found using the same 3D snapshots, but with zero magnetic field at each spatial grid point. In order to derive the direct impact caused by the Zeeman broadening produced by the model's magnetic field, we calculated the differences between the abundances obtained from the $\langle| B_z |\rangle = 80$ snapshot and those obtained from the same snapshot but imposing B = 0 G.

3. Results and conclusions

From the results obtained we conclude the following.

• Abundance determinations carried out ignoring the Zeeman broadening of the photospheric Fe I, C I, N I, and O I lines tend to overestimate the abundance values. The direct effect (via Zeeman broadening) of the SSD photospheric magnetic fields presented in the MHD snapshots by Rempel (2014) on the Fe and CNO solar abundance determinations is very small. The most magnetically sensitive line (i.e., the Fe I 15648.5 Å line) gives the largest abundance error, namely $\Delta A = -0.02$ dex. The errors for other magnetically sensitive lines are even smaller. For the Fe I lines used in our study the mean value of the abundance corrections ΔA is only -0.0021 ± 0.0042 dex. The mean abundance corrections $\langle \Delta A \rangle$ for the CI, N I, and O I lines are -0.0017 ± 0.0017 dex, -0.0004 ± 0.0001 dex, and -0.0018 ± 0.0018 dex, respectively.

• The indirect effect of such fields (via the magnetically induced changes of temperature – optical depth stratification in the formation region of the Fe I, C I, N I, and O I lines) is opposite in sign. It means that abundance determinations which ignore the magnetically-induced changes of the solar atmospheric structure underestimate $A_{\rm Fe}$, $A_{\rm C}$, $A_{\rm N}$ and $A_{\rm O}$. Interestingly, the mean of the carbon, nitrogen, and oxygen abundance corrections needed to take into account the indirect effects are of the same order as the direct one, while the mean of the iron $\langle \Delta A_{\rm Fe} \rangle$-value is almost an order of magnitude larger than the abundance corrections coming to the direct effect. The Fe I lines with a low value of the excitation potential of the lower level (5247.05 Å, 5250.21 Å, 5225.53 Å) are most sensitive to the indirect effect. Their ΔA values are the largest $(0.05 - 0.07$ dex). Nevertheless, the mean indirect effect for the Fe I lines remains very small: $\langle \Delta A_{\rm Fe} \rangle = +0.016 \pm 0.012$ dex.

- The joint (direct+indirect) impact on the determination of the solar abundances of iron, carbon, nitrogen and oxygen is very small. The mean abundance errors for the Fe and C, N, and O elements turn out to be $+0.0142 \pm 0.0112$ dex, $+0.00001 \pm 0.0031$ dex, $+0.0016 \pm 0.0006$ dex, -0.0001 ± 0.0048 dex, respectively.

We finally conclude that if the magnetism of the quiet solar photosphere is mainly produced by a small-scale dynamo, then its impact on the abundance determination of Fe and of the CNO elements is negligible. The interested reader will find all the details of this investigation in Shchukina & Trujillo Bueno (2015) and Shchukina *et al.* (2015).

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