The Abundances of Oxygen and Carbon in the Solar Photosphere

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Abstract. A series of recent studies has placed the best estimates of the photospheric abundances of carbon and oxygen at $\log \epsilon = 8.39$ and $8.66$, respectively. These values are $\sim 40\%$ lower than earlier estimates. A coalition of corrections due to the adoption of an improved model atmosphere, updated atomic data and non-LTE corrections, and a reevaluation of the effect of blending features, is responsible for the change. The adopted hydrodynamical model of the solar surface is an important element to the update, but using a theoretical 1D model atmosphere leads to an average oxygen abundance modestly increased by 0.09 dex, and a carbon abundance only 0.02 dex higher. Considering a state-of-the-art 3D hydrodynamical model of the solar surface yields consistent results from different sets of atomic and molecular lines. Systematic errors are likely to dominate the final uncertainties, but the available information indicates they are limited to $< 0.1$ dex. The new abundances are closer to expectations based on the compositions of other nearby objects, although a fully consistent picture, considering galactic chemical evolution and diffusion at the bottom of the solar convection zone, is still lacking.

1. Introduction

Spectroscopic analyses of normal hydrogen-rich stars naturally derive abundance ratios to hydrogen, as this element (either in atoms or forming $\text{H}^-$) dominates the opacity at optical and longer wavelengths. An abundance determination is based upon a physical model of the outer layers of the star, from where the observed photons escape. Usually, such model relies on the assumption of plane-parallel homogeneous layers in hydrostatic and thermodynamic balance. The complexities of a real star’s envelope (e.g. hydrodynamics, magnetic fields, and rotation) are neglected, in order to make the problem tractable, and the model has only a few parameters such as the total energy flux and surface gravity, which can be determined from observations.

A model is constructed assuming an initial set of chemical abundances. The negative temperature gradient in the stellar atmosphere creates absorption lines which strength is proportional to the absorber’s density relative to hydrogen. The actual abundance determination is performed by calculating a spectrum based on the adopted model atmosphere, comparing it to the observed lines, and adjusting the abundance as needed. If necessary, the cycle is iterated by computing a new model, until convergence. Besides the model, transition probabilities are the most critical ingredient, and despite the success of quantum mechanics, accurate calculations are still only possible for relatively simple atoms and molecules. For others, we rely on laboratory measurements.
Systematic and random errors in the observations have steadily been reduced in parallel with progress in instrumentation. Errors associated with the underlying approximations in the interpretation of spectra are a more hairy issue. Grevesse & Sauval (1999) examined the history of solar iron abundance determinations starting with the analysis by Henry Norris Russell in 1929. The most salient feature was a fast increase of about an order of magnitude between the results derived in the 60’s and those published in the 80’s, which was caused by erroneous transition probabilities. By looking at their plot, one would suggest that analyses may be converging at $\log \epsilon^1(\text{Fe}) \simeq 7.5$, with $\sigma \simeq 0.1$ dex.

More recently, Gustafsson (2004) has made a similar study for the case of oxygen. The situation with this element is somewhat different, and could be described as a steady decrease with significant scatter. Unlike the iron case, oxygen is a simpler atom which is successfully modeled under LS coupling, and Gustafsson attributes the scatter mainly to differences in the analysis: employed spectral lines, model atmospheres, and the calculation of theoretical spectra.

Most elements observed and studied in the solar photosphere have a similar abundances pattern as those found in a special type of meteorites: the CI (type I, C1, or Ivuna-type) carbonaceous chondrites (see, e.g., Anders & Grevesse 1989). This very rare class of meteorites, of which only five falls are known, appears to have preserved the original composition of the solar nebula, with the exception of the most volatile elements: H, C, N, O, and the noble gases. Meteoritic abundances are usually given relative to silicon, and using this element to bridge with photospheric abundances, the agreement is better than 10% for 31 elements and better then 15% for 41 (Lodders 2003). The number density ratio Fe/Si derived in recent analyses of the solar spectrum is 0.87, while in CI meteorites is 0.863 (Asplund et al. 2000b, Asplund 2000, Lodders 2003) – a stunning agreement.

Unfortunately, the carbon and oxygen cases have no solid reference, and we are left to figure out their abundances from solar observations alone. We will not discuss whether the larger scatter in the historical evolution of the solar oxygen abundance determinations is related to this fact, and we will focus on the technical aspects. The motivation for this review is, primarily, the recent jumps in the value of the solar carbon and oxygen abundances as estimated from photospheric oxygen lines in the solar spectrum. The recent series of studies on this subject was driven by the availability of three-dimensional radiation hydrodynamical simulations of solar surface convection (for a review see Asplund 2005). As we shall see, however, the new models are only partly responsible for the proposed abundance change. We will discuss how confident we can be about the new values, and what pieces of the puzzle still do not fit, trying to put the finger in the wound in order to stimulate further work in areas where needed the most.

The first section is devoted to the difficulties involved in an analysis of oxygen lines in the solar spectrum. Section 3 repeats the same exercise for carbon. Section 4 is an attempt to summarize the main uncertainties still present in current abundance determinations, and suggest directions for future research. Section 5 looks at other objects in the solar neighborhood to see whether current

$\epsilon(X) = \frac{N(X)}{N(\text{H})} \times 10^{12}$, where $N$ represents number density.
values of the solar abundance make sense in a broader context. Section 6 closes this piece with a discussion and a summary.

2. Spectroscopic determination of the solar photospheric oxygen abundance

Despite an atomic system amenable to accurate quantum mechanical calculations, the analysis of oxygen in the solar spectrum involves extra difficulties compared to the case of iron. The solar spectrum offers only a handful of oxygen absorption lines, and they tend to form far from local thermodynamic equilibrium (LTE) conditions, which makes their calculation more difficult and more dependent on collisional interactions. Notable exceptions are the forbidden transitions that connect the atom’s lowest states.

2.1. Atomic forbidden lines

Of the six forbidden transitions that connect the lowest three states of oxygen, there are three that fall in the optical and (albeit weak) are measurable in the solar spectrum (Lambert 1978). The \(^1\)D to \(^1\)S transition at 557.7 nm is badly blended with C\(_2\) lines. The other two lines \((^3\)P \(J=2,1\) to \(^1\)D at 630.0 nm and 636.3 nm) coincide in wavelength with a Ni I and a couple of CN transitions, respectively, but the contribution of these blends, although uncertain, is less significant. After estimating the strength of the potential blending features, Lambert (1978) used these weak lines to derive an oxygen abundance of \(\log \varepsilon(O) = 8.92\).

The recent turmoil started precisely with a reanalysis of the forbidden line at 630.0 nm. Despite the transition probability of the Ni I remained highly uncertain, Allende Prieto, Lambert & Asplund (2001) realized that its strength could be inferred, independently of the oxygen abundance, by taking advantage of the new generation of hydrodynamical models of the solar surface. Solar photospheric absorption lines are asymmetric and blue-shifted from their rest wavelength by up to 500 m s\(^{-1}\) as a result of convective motions in the solar envelope – what is observed in images of the solar surface as granulation. Classical model atmospheres, built under the assumption of hydrostatic equilibrium, predict perfectly symmetric line profiles. State-of-the-art hydrodynamical models, in turn, predict convective line asymmetries and shifts in good agreement with those observed, typically within 50 – 100 m s\(^{-1}\) (Allende Prieto et al. 2002; Asplund et al. 2000a).

The rest wavelengths of the oxygen and nickel transitions were already known with an accuracy of 0.2 – 0.3 pm (1 pm \(\equiv 10^{-12}\) m). By modeling the oxygen abundance, the strength of the Ni I blending contribution \((gf \times \varepsilon(Ni))\), and a continuum normalization factor for the observed line profile, Allende Prieto et al. concluded that evidence pointed to a lower oxygen abundance than earlier estimates, \(\log \varepsilon(O) = 8.69 \pm 0.05\) dex. The revision was associated with a much larger contribution from the Ni I line (~ 30 %, or an abundance change of 0.13 dex), and a different thermodynamical structure of the hydrodynamical simulations compared to the classical model atmospheres used previously (0.08 dex), both working in the same direction.
More recently, Johansson et al. (2003) performed laboratory measurements of the Ni I transition overlapped with [OI] 630.0 nm, providing a transition probability as well as wavelengths for the components associated with the two most abundant isotopes, $^{58}$Ni and $^{60}$Ni, which together account for over 94% of the nickel on Earth. If the analysis of the solar feature is repeated accounting for the isotopic shift ($\delta \lambda \simeq 2$ pm), the result remains the same. However, if the photospheric nickel abundance adopted by Grevesse & Sauval (1998) is combined with the line strength inferred by Allende Prieto et al., the resulting $f$-value would be $\sim 0.2$ dex smaller than the laboratory measurement, which has an uncertainty of 0.05 dex. Embracing the laboratory $f$-value and the photospheric nickel abundance would imply a further reduction to the oxygen abundance by about 18% or 0.08 dex, but Koesterke et al. (see poster in these proceedings) have found that the resulting spectrum is not compatible with the observed feature. It remains to be seen if a 3D-based analysis of nickel in the Sun reduces this problem, but if we compare the meteoritic Ni/Si ratio of 0.048 with the photospheric value of $\simeq 0.05 - 0.06$, there is not enough room to accommodate the change in strength implied by the updated value of the transition probability.

A subsequent reanalysis of the weaker 636.3 nm forbidden transition, using the same model yielded an abundance consistent with the value from the transition at 630.0 nm (Asplund et al. 2004). We recall that this feature was blended with two CN transitions, and the correction in this case is mainly linked to the change in model atmosphere, i.e. 1D vs. 3D, given the large sensitivity of molecular species to temperature inhomogeneities. The hydrodynamical simulations have a horizontal average temperature lower than classical one-dimensional models in the outer layers, and temperature inhomogeneities further enhance the strength of the CN blending transition, resulting on a lower oxygen abundance.

### 2.2. Atomic permitted lines

Asplund et al. (2004) collated the list of oxygen lines observed in the solar spectrum and selected a subset of six permitted transitions with accurate $f$-values and clean profiles. Some of these lines are suspected to suffer marked departures from local thermodynamical equilibrium since the early work by Mihalas & Henshaw (1966) and Altrock (1968). The analysis of oxygen lines in a three-dimensional solar-like model atmosphere considering non-LTE was pioneered by Kiselman & Nordlund (1995). Interestingly, the calculated non-LTE corrections for these lines from classical 1D models and from the hydrodynamical simulations are quite similar, and always work reducing the abundances derived assuming LTE by an amount that ranges between 0.03 and 0.3 dex. Purely 3D effects are usually smaller ($< 0.03$ dex).

Approximate cross-sections for the collisional processes are typically used in the non-LTE calculations. The relevant particles are electrons and hydrogen atoms. Measurements of electron collisional excitation rates are limited to transitions from the ground state. Widely-used general recipes based on the van

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2 Horizontal average, in this context, refers to the mean value over a surface with a constant optical depth, rather than over a constant geometrical depth.
Regemorter (1962) formula can be widely applied, but are uncertain by a few orders of magnitude (see, e.g., Allende Prieto et al. 2003). More refined calculations exist for some transitions. Recent independent calculations for low-lying states by Zatsarinny & Tayal (2003) and Barklem (2007) typically agree within 70%.

The situation is worse for hydrogen collisions. A recipe originally proposed by Steenbock & Holweger (1984) based on Drawin’s approximation (Drawin 1968, 1969) has been broadly used, despite it has been shown to overestimate the rates by several orders of magnitude for alkalis (Belyaev & Barklem 2003). This situation has led some modelers to neglect hydrogen collisions altogether in their calculations. While their effect is extremely important for low metallicity stars, it induces only modest changes in the inferred oxygen populations under solar conditions.

The non-LTE abundances derived by Asplund et al. are in the range 8.60–8.65, depending on the line, with an average result of 8.64 (σ = 0.02) dex. These calculations neglect inelastic hydrogen collisions. The center-to-limb variation of permitted oxygen lines has been repeatedly used to demonstrate the need to consider departures from LTE in their formation, but the same observations also favor including hydrogen collisions (Allende Prieto, Asplund & Fabiani Bendicho 2004). If this path is taken, the average oxygen abundance from permitted lines would increase to 8.70 (σ = 0.04) dex.

As an example of the typical scatter found in oxygen non-LTE calculations in the literature, we examine the 777.4 nm line, part of the infrared (5S–5P) triplet. Asplund et al. inferred an abundance correction of −0.24 dex for the 3D simulation, −0.27 dex for the Holweber-Müller model (Holweger & Müller 1974), and −0.23 for a solar MARCS model; Allende Prieto et al. (2004), using a different model atom and statistical equilibrium solver, derived a correction of −0.22 dex for a Kurucz solar model. These figures neglect inelastic hydrogen collisions. Allende Prieto et al. found an abundance correction of −0.16 when H collisions were included using the recipe mentioned above. Another study by Holweger (2001), based on a third choice of model atom and the Holweber-Müller atmosphere, but considering hydrogen collisions as above, arrived at a smaller correction of −0.06 dex. Hydrogen collisions in the non-LTE calculations are likely the dominant contribution that sets the systematic errors in the abundances from permitted lines at about 0.10 dex.

2.3. Molecular lines: OH

Asplund et al. (2004) considered in their analysis OH pure rotation and OH vibration-rotation lines. The vast number of transitions and relatively small overlapping problems in the infrared are an advantage compared to using atomic lines. Sadly, molecule formation is extremely temperature sensitive, and using a hydrodynamical model produces much larger corrections than for atomic transitions. The high sensitivity to temperature also implies a higher susceptibility to the details involved in the numerical simulations, such as resolution or boundary conditions. The formation of the lines in higher layers and therefore lower temperatures results in a similar abundance correction compared to permitted lines.
density also increases the risk for errors in the computed electron density, based
on LTE and chemical equilibrium for all relevant species.

Despite the concerns, the average abundance derived from the solar 3D sim-
ulation by Asplund et al. from vibro-rotational and pure rotational transitions
agree remarkably well with each other: 8.61 ($\sigma = 0.03$) and 8.65 ($\sigma = 0.02$),
respectively. As expected, these figures involved substantial corrections in com-
parison with a 1D analysis: they are lower by about 0.2 dex.

The fact that the corrections associated with the introduction of hydrody-
namics are larger for molecular transitions than for atomic lines underlines that
both indicators cannot agree with both kinds of models. This is evident in Table
1. Indeed, the difference between the oxygen abundance inferred from atomic
and molecular transitions is significantly smaller with the new hydrodynamical
model than with the classical semi-empirical Holweger-Müller model. The solar
1D MARCS model studied by Asplund et al. turned out to take a more moder-
ate position: with this model, atomic O and OH vib-rotational lines converged
at an abundance of 8.72 – 8.74, while only the OH rotational transitions pointed
to a higher value by 0.1 dex.

Table 1. Average oxygen abundance (and standard deviation) inferred from
different indicators. Adapted from Asplund et al. (2004). The mean values in
the last line of the table are a straight average including the non-LTE calcu-
lations that neglect hydrogen collisions. There are no published calculations
with the HM and MARCS models including inelastic hydrogen collisions, but
a study of the infrared triplet with a solar Kurucz model and the 3D analysis
for many lines indicate that the resulting abundance will be $\simeq +0.05$ dex
higher than neglecting H collisions.

<table>
<thead>
<tr>
<th>lines</th>
<th>3D</th>
<th>HM</th>
<th>MARCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O I]</td>
<td>8.68 (0.01)</td>
<td>8.76 (0.01)</td>
<td>8.72 (0.01)</td>
</tr>
<tr>
<td>O I (without H coll.)</td>
<td>8.64 (0.02)</td>
<td>8.64 (0.08)</td>
<td>8.72 (0.03)</td>
</tr>
<tr>
<td>O I (with H coll.)</td>
<td>8.70 (0.04)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>OH vib-rot</td>
<td>8.61 (0.03)</td>
<td>8.87 (0.03)</td>
<td>8.74 (0.03)</td>
</tr>
<tr>
<td>OH rot</td>
<td>8.65 (0.02)</td>
<td>8.82 (0.01)</td>
<td>8.83 (0.03)</td>
</tr>
<tr>
<td>Average</td>
<td>8.65 (0.03)</td>
<td>8.77 (0.10)</td>
<td>8.75 (0.05)</td>
</tr>
</tbody>
</table>

2.4. Molecular lines: CO

CO transitions offer a less direct path to the oxygen and carbon abundances. In
a very recent paper by Scott et al. (2006), a solar hydrodynamical model, the
same used in the studies described above, was used to analyze $^{12}$C$^{16}$O, $^{13}$C$^{16}$O,
and $^{12}$C$^{18}$O vibration-rotation lines in the disk-center solar spectrum. These
authors find that the strongest $^{12}$C$^{16}$O lines, which form in very high layers, are
not well reproduced by the model when the same abundances derived from other
atomic and molecular lines are used, but weaker lines are perfectly consistent
with the results from other features. Not everybody is convinced, however, that
a consistent picture is in place, and Ayres, Plymate & Keller (2006) conclude
that a semi-empirical analysis of CO lines assuming the ratio C/O = 0.5 results
Carbon and Oxygen in the Solar Photosphere

in an oxygen abundance significantly higher than those derived by Asplund et al. (see also Ayres’ contribution in this volume).

3. Spectroscopic determination of the solar photospheric carbon abundance

The photospheric carbon abundance has also recently undergone a significant revision from values in the range log $\epsilon$(C) = 8.5 – 8.6 (Anders & Grevesse 1989, Grevesse & Sauval 1998, Holweger 2001) to log $\epsilon$(C) = 8.39. The decrease was again proposed after a reanalysis of a forbidden line (872.7 nm), which in parallel to the case of oxygen, has been shown to be fairly immune to departures from LTE (Allende Prieto, Lambert & Asplund 2002). No blending features were detected, but the revision was driven by improved quantum-mechanical calculations of the transition probability (0.07 dex) and the introduction of a hydrodynamical solar model (0.08 dex).

The analysis was later extended to include permitted lines, as well as CH vibro-rotational lines and C$_2$ electronic transitions by Asplund et al. (2005). Their study considered 16 atomic permitted transitions in the optical and infrared. For these lines, non-LTE abundance corrections were estimated in the range $-0.03$ to $-0.15$ dex, depending on the line, based on 1D models due to the need to consider a complex model atom to properly account for the departures from LTE. Here again, hydrogen collisions were not considered, and if included with the Steenbock-Holweger recipe the non-LTE corrections would likely be reduced by half (St"urenburg & Holweger 1990).

As for oxygen, the introduction of the hydrodynamical model affects molecules the most, and a much more homogeneous answer is obtained with the 3D model than with the classical Holweger-Müller model (see Table 2). With the 1D solar MARCS model, we find again an intermediate level of scatter, which essentially leads to the same average abundance as in 3D.

Table 2. Average carbon abundance (and standard deviation) inferred from different indicators. Data from Asplund et al. (2005).

<table>
<thead>
<tr>
<th>lines</th>
<th>3D</th>
<th>HM</th>
<th>MARCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C I]</td>
<td>8.39 (0.04)</td>
<td>8.45 (0.04)</td>
<td>8.40 (0.04)</td>
</tr>
<tr>
<td>C I (1D NLTE)</td>
<td>8.36 (0.03)</td>
<td>8.39 (0.03)</td>
<td>9.35 (0.03)</td>
</tr>
<tr>
<td>CH vib-rot</td>
<td>8.38 (0.04)</td>
<td>8.53 (0.04)</td>
<td>8.42 (0.04)</td>
</tr>
<tr>
<td>C$_2$ Swan</td>
<td>8.44 (0.03)</td>
<td>8.53 (0.03)</td>
<td>8.46 (0.03)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>8.39 (0.03)</td>
<td>8.48 (0.07)</td>
<td>8.41 (0.05)</td>
</tr>
</tbody>
</table>

4. Where do we stand and what remains to be done.

Most of the results discussed above come from a set of recent papers by the same group. Although several hydrodynamical simulations of solar surface convection can be found in the literature, only one of them has been extensively applied
to the calculation of detailed solar spectra. The exception to this statement is the independent study by Holweger (2001; see also Steffen & Holweger 2002) who analyzed several forbidden and permitted lines atomic lines considering 2D effects (in LTE), and 1D non-LTE corrections to arrive at a mean oxygen abundance of 8.74 (0.08) dex; 0.08 dex higher than the value recommended by Asplund et al. (2004).

Despite the remarkable success of the simulations of Stein & Nordlund (1998) and Asplund et al. in reproducing solar data and eliminating the need for 'ad hoc' turbulence, the lack of studies based on alternative models is unsatisfactory. Hydrodynamics are a big improvement, but the increased computational burden requires sacrificing detail in the radiative term of the energy balance equation. At least two of the most important tests available for validating a model of the solar surface are yet to be done: center-to-limb variation and absolute fluxes. The impact of the magnetic fields on the observed profiles is probably very small (Khomenko et al. 2005), but there is not yet consensus about the topology and strength of the magnetic fields that permeate the solar photosphere.

Apart from a model of the lower atmosphere, many other important ingredients are involved in the abundance determinations: partition functions, excitation energies, damping constants, continuum opacities, etc. Most have non-linear effects on the inferred abundances, and a Monte-Carlo approach is necessary to derive reliable uncertainties. As described in previous sections, blending features (especially relevant to weak oxygen forbidden lines), and departures from LTE (in particular, the impact of inelastic hydrogen collisions on permitted lines) cannot yet be considered a solved problem.

A quick look at the straight average abundances in Tables 1 and 2 leads to an interesting conclusion. The proposed abundances from a 3D analysis are only ∼0.1 dex or less lower than the equivalent results from a 1D analyses. The historical account given in the previous sections shows that the predictive power of a hydrodynamical model, and the high homogeneity of the abundances derived in 3D from different indicators have been instrumental in the revision. Nonetheless, an important part of the responsibility for the final outcome is linked to a combination of updated atomic data, recent high-quality observations, and non-LTE corrections. As a result, if one were to choose ignoring the results based on hydrodynamical models, sticking to the one-dimensional MARCS structures\(^4\), the preferred values for the oxygen and carbon abundances would still be \(\log \epsilon(O) = 8.75\), and \(\log \epsilon(C) = 8.41\), respectively.

5. The solar neighborhood

We cannot seek help to determine or refine the solar abundances from other nearby stars. But it is quite interesting to compare the solar values with other objects in the solar neighborhood and see if the overall abundances make sense in the context of galactic chemical evolution. We briefly review results from nearby H II regions, the local ISM, massive stars, and point the reader to Jorge

\(^4\)The Holweger-Müller model is not considered, as it leads to a much larger scatter among different indicators.
Melendez's poster (in these proceedings) for an analysis of disk giants. A recent investigation of solar analogs indicates that previously reported offsets between the abundance ratios in the Sun and nearby late-type stars are likely the result of systematic errors, and the Sun appears now chemically very similar to its G-type neighbors with the same iron abundance (Allende Prieto 2007). A more detailed discussion about nearby FGK dwarfs is deferred, given the difficulties to constrain ages from stellar evolution models for unevolved stars.

5.1. HII regions

An extensive analysis of recombination transitions in galactic HII regions has been recently performed by Esteban et al. (2005). Unlike collisionally excited lines, the strength of recombination transitions is insensitive to the presence of suspected temperature fluctuations – and therefore a more solid diagnostic. HII regions trace tightly the abundance gradient of carbon and oxygen in the galactic disk between 6.3 to 10.5 kpc from the galactic center (dlog $\delta$/$dR = −0.10$ and $−0.04$ dex/kpc, respectively). Interpolating the results at the solar circle ($R \simeq 8$ kpc) carbon and oxygen abundances of 8.57 and 8.69 dex are derived. Corrections of 0.08–0.10 dex are estimated for the the amounts trapped into dust. The final figures are higher than the preferred solar photospheric abundances by 0.13 dex and 0.26 dex for carbon and oxygen, respectively, matching the increases due to chemical evolution predicted by Carigi et al. (2005) in the 4.6 Gyr since the formation of the Sun (0.13 and 0.28 dex) but leave no room for diffusion at the bottom of the convection zone expected by solar evolution models (0.07 dex; see Lodders 2003).

5.2. The local ISM

The oxygen abundance in diffuse nearby ISM clouds has been surveyed using weak absorption features in the UV. The results are fairly uniform and yield an average oxygen abundance of log $\delta$(O) = 8.54 (Oliveira et al. 2005 and references therein). This value is quite close to the revised photospheric abundance if $\sim 30\%$ of oxygen is depleted into dust grains, but leaves no room for either diffusion in the Sun or chemical evolution in the ISM. A larger depletion in dust grains in the form of silicates or oxides seems unlikely (Linsky et al. 2006). Measuring the ratio C/H is a harder task, but Slavin & Frisch (2006) derived a lower limit of log $\delta$(O) = 8.52 and more likely 8.6 – 8.9 for the local interstellar cloud toward $\epsilon$ CMa, which could accommodate both a reduction in the solar photosphere and an increase in the ISM since the solar formation.

5.3. OB stars

Massive stars can be used, similarly to H II regions, to trace the current composition of the gas in the galactic disk at different galactocentric distances. Photospheric lines of carbon and oxygen in these stars usually require substantial non-LTE corrections, which were considered by Daflon & Cunha (2004) in a study sampling objects between $R = 5$ and 13 kpc from the galactic center. Although the scatter is significantly larger than that found for H II regions, radial variations are clearly detected with dlog $\delta$/d$R \sim −0.03$ dex/kpc for carbon and oxygen. At the solar circle, the average abundances are about $0.1 – 0.2$ lower
than solar photospheric values, which again, taken at face value, cannot be reconciled with chemical evolution in the ISM or metal diffusion at the bottom of the solar convection zone.

6. Summary and conclusions

Recent studies of the solar spectrum have arrived at abundances of carbon and oxygen which are about 0.2 dex lower than earlier estimates. The revision comes as the result of a conspiracy of corrections, and it is the outcome of a comprehensive and critical reanalysis of the available abundance indicators, considering improved model atmospheres, updated atomic data, non-LTE corrections (affecting permitted atomic transitions), and a reevaluation of the effect of blending features. The presence of temperature inhomogeneities has the largest impact on molecular species, while atomic permitted lines are only weakly affected. Thus, the use of a hydrodynamical model of the solar surface is an important element to the correction, but using a theoretical hydrostatic model atmosphere leads to an average oxygen abundance modestly increased by 0.09 dex, and a carbon abundance only 0.02 dex higher.

As oxygen and carbon are the most abundant elements after hydrogen and helium, the revised abundances have a significant impact on the overall metallicity of the Sun. The metal mass fraction is reduced from the Grevesse & Sauval (1998) reference of $Z = 0.017$ to 0.014 just due to the change in carbon and oxygen. If other elements recently revised are considered then $Z$ will further decrease to 0.012 (Asplund et al. 2005).

The revised values have been welcome by researchers on L and T spectral types, as they lead to improvements in the comparison with observed spectra (Burrows, Sudarsky & Hubeny 2006). The new abundances are also more in line with those found in other objects in the solar neighborhood although, as discussed in §5, our picture of the chemical patterns in the solar neighborhood is still incomplete; overall, the solar neighborhood would be more comfortable with an even lower solar oxygen abundance. On the other hand, when the updated abundances are used to calculate models of the solar interior, the resulting structures are incompatible with helioseismic data (see, e.g., Bahcall et al. 2005, Basu & Antia 2004). Models based on the new values predict the wrong value for the radius of the convection zone, and the radial variation of the sound speed inferred from seismic inversions is up to 10% different from model predictions, while the older abundances yielded a much better agreement with deviations of just a few percent.

If the revised abundances are correct, the blame must be somewhere else. The reported problems could be ameliorated, if not cured, with a new source of extra opacity below the convection zone. A recent update from the Opacity Project goes in that direction, but the calculations are still far from accounting for the necessary extra opacity (Seaton & Badnell 2004, Badnell et al. 2005). A significant increase of the solar neon abundance, which is inferred from the ratio Ne/O in solar energetic particles and the photospheric oxygen abundance, has been proposed (Antia & Basu 2005, Bahcall, Basu, & Serenelli 2005), and supported by analyses of nearby stars (Cunha et al. 2006, Drake & Testa 2006; see also the corresponding contributions in these proceedings), but this solution
has found opposition from solar specialists (Schmelz, this volume; Young 2005) and may be incompatible with the sound speed profile of the Sun (Delahaye & Pinsoneau 2006). Another possibility would be an enhancement of opacity induced by gravity waves at the base of the convection zone (Arnett, Meakin & Young 2005, Press & Rybicki 1981). Most likely not all bets are on the table, but one hopes that at the resolution of this puzzle something new will be learnt about the Sun.

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