Another forbidden solar oxygen abundance: the [O1] 5577 Å line

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ABSTRACT

Context. Recent works with improved model atmospheres, line formation, atomic and molecular data, and detailed treatment of blends have resulted in a significant downward revision of the solar oxygen abundance.

Aims. Considering the importance of the Sun as an astrophysical standard and the current conflict of standard solar models using the new solar abundances with helioseismological observations we have performed a new study of the solar oxygen abundance based on the forbidden [O1] line at 5577.34 Å, not previously considered.

Methods. High-resolution (R > 300 000), high signal-to-noise (S/N > 1000) solar spectra of the [O1] 5577.34 Å line have been analyzed employing both three-dimensional (3D) and a variety of 1D (spatially and temporally averaged 3D, Holweger & Müller, MARCS and Kurucz models with and without convective overshooting) model atmospheres.

Results. The oxygen abundance obtained from the [O1] 5577.3 Å forbidden line is almost insensitive to the input model atmosphere and has a mean value of log $\epsilon_O = 8.71 \pm 0.02$ (or from using the different model atmospheres). The total error (0.07 dex) is dominated by uncertainties in the log gf value (0.03 dex), apparent line variation (0.04 dex) and uncertainties in the continuum and line positions (0.05 dex).

Conclusions. The oxygen abundance derived here is close to the 3D-based estimates from the two other [O1] lines at 6300 and 6363 Å, the permitted OI lines and vibrational and rotational OH transitions in the infrared. Our study thus supports a low solar oxygen abundance (log $\epsilon_O = 8.7$), independent of the adopted model atmosphere.

Key words. Sun: abundances – Sun: photosphere – line: identification – molecular data

1. Introduction

In recent years a significant reduction in the solar oxygen abundance has been proposed from log $\epsilon_O \equiv \log(N(O)/N(H))+12 = 8.93$ (Lambert 1978; Sauval et al. 1984; Grevesse et al. 1984; Anders & Grevesse 1989) to log $\epsilon_O \approx 8.7$ or even lower (Allende Prieto et al. 2001, 2004; Holweger 2001; Asplund et al. 2004; Meléndez 2004; Socas-Navarro & Norton 2007; Caffau et al. 2008; but see Ayres et al. 2006; Ayres 2008; and Centeno & Socas-Navarro 2008 for a different conclusion). This large revision in the oxygen abundance has important consequences in many areas of astrophysics. In particular, solar models computed with the low oxygen abundance do not agree with precise helioseismological measurements (see Basu & Antia 2008 and references therein).

If the revised solar oxygen abundance is correct, this would imply that the standard solar structure model may be missing (or have a too simplified treatment of) important physical processes, which would carry over to errors in the calculations of stellar evolution in general. On the other hand, if the fault lies with the new solar photospheric abundance analyses it raises concerns about how well we understand stellar atmospheres and spectral line formation in general with wider implications for Galactic chemical evolution studies relying on accurate stellar abundance measurements. Indeed, the oxygen content in metal-poor stars is currently under debate (see Asplund & García Pérez 2001; Meléndez et al. 2001, 2006, and references therein).

Since the Sun is used as a fundamental reference in most areas of astrophysics, it is important to study all spectral features available for its abundance analysis. Recent studies have mainly used the [O1] 6300, 6363 Å forbidden lines, the O1 7777 Å triplet, pure rotation OH lines as well as the fundamental vibration-rotation OH lines (Allende Prieto et al. 2001, 2004; Asplund et al. 2004), from which log $\epsilon_O = 8.66 \pm 0.05$ has been recommended (Asplund et al. 2004). Meléndez (2004) presented a study of the first-overtone OH lines, which are unfortunately too weak for a precise determination of the oxygen abundance, but within the uncertainties these lines also support a low solar oxygen abundance.

Another independent way to estimate the solar oxygen abundance is using the forbidden line at 5577.34 Å. This line has been disregarded in the past due to blending with C2 lines (e.g. Altrock 1968; Lambert 1978). Here, we present the first detailed study of the [O1] 5577 Å line, carefully taking into account the blends by C2 lines. The advantage of this feature is that the C2 blends introduce a large asymmetry in the profile, allowing one to readily constrain their contribution. Another advantage is that there are other nearby C2 lines that can be used to calibrate the blending of C2 lines, and therefore to determine a reliable solar oxygen abundance.
within 0.007 dex; had we instead opted for the position of the [O i] line is marked with an arrow. The resulting solar C abundance is log ε C = 8.42 which with the 5577.3 Å feature implies a solar O abundance of log ε O = 8.73.

2. Analysis

We used the Delbouille et al. (1973) disk-center solar spectrum (often called the Liege solar atlas), the Brault & Neckel (1987) disk-center intensity atlas (see Neckel 1999), and the Kurucz et al. (1984) solar-flux spectrum. These solar spectra are of extremely high resolution (resolving power R ~ 500 000–700 000) and have a S/N of several thousands at 5577 Å. The solar oxygen abundance obtained with these different atlases agree within σ = 0.04 dex. In Fig. 1 the Delbouille et al. (1973) solar spectrum around the 5577.3 Å [O I] line is shown as open circles.

The oscillator strength for the [O I] 5577 Å line is well determined: the mean of the available calculations is log gf = −8.25 ± 0.03 (Galavis et al. 1997; Baluja & Zeippen 1988; Fischer & Saha 1983; Nicolaides & Sinanoğlu 1973). We adopted log gf = −8.28 from Galavis et al. (1997), which is on the same scale as the log gf value adopted for the 6300, 6363 Å forbidden lines (Asplund et al. 2004) within 0.007 dex; had we instead opted for the mean value of the above-mentioned theoretical gf-values our derived O abundance would be 0.03 dex lower. The excitation potential of the [O I] 5577 Å line is 1.967 eV. According to the NIST database1 the observed and Ritz wavelengths are 5577.34 and 5577.339 Å, respectively. Small errors in the wavelength translate into only small uncertainties (at the level of 0.01 dex) in the O abundances.

We included in the spectral synthesis other atomic and molecular (C2 Swan and CN red systems) lines present around 5577 Å, but the main contributors to the 5577.3 Å feature are three lines: the [O I] line and the P127 and P226 lines of the C2 (1–2) band. Atomic lines were taken from the latest Kurucz line lists2 and the CN line list described in Meléndez & Barbuy (1999) was adopted. The line list for the 0–1 and 1–2 bands of the C2 Swan system was constructed in a similar way to the 0–0 band described in Meléndez & Cohen (2007), but with the line positions taken primarily from Tanabashi et al. (2007) and complemented with Phillips & Davis (1968) data for the higher excitation lines not included by Tanabashi et al. Relative oscillator strengths for the 0–1 and 1–2 bands were taken from Kokkin et al. (2007), normalizing those values to the laboratory oscillator strength of the 0-0 band recommended by Grevesse et al. (1991), f00 = 3.03 × 10−2. The rotational strengths were computed following Kovacs (1961) and the rotational dependence of the band strengths was taken into account (Dwivedi et al. 1978).

A set of different model atmospheres was employed: a three-dimensional hydrodynamical model of the solar atmosphere (Asplund et al. 2000; here denoted 3D) and its temporal and spatial average (here: ⟨3D⟩) (Asplund et al. 2004), MARCS model (Asplund et al. 1997), Kurucz overshooting (Castelli et al. 1997) and the latest no-overshooting (Castelli & Kurucz 2004) models and the semi-empirical Howegwer-Müller (1974) model. The spectral line formation was calculated in 3D and 1D using the same spectrum synthesis code as described in Asplund et al. (2004). The 1D calculations were also performed using the 2002 version of MOOG (Sneden 1973); the different 1D calculations with different codes agree at the level of 0.01 dex.

The contribution from the two C2 lines (P127 and P226) to the 5577.3 Å feature can be well constrained from the red asymmetry in the profile. In addition there are many neighboring C2 lines of very similar excitation potential and line strengths and therefore of basically identical line formation. Note that the error in the relative strengths of the C2 lines is negligible, as the rotational strengths are precisely given by their Hönl-London factors (Kovacs 1961). Figure 1 shows the best fit to the 5575–5580 Å region of the Liege disk-center atlas based on the 3D-averaged model atmosphere; the locations of the most important C2 lines are marked with vertical lines. Clearly the overall agreement is quite satisfactory. Also encouraging is that the solar C abundance thus estimated is as expected for the different model atmospheres (Asplund et al. 2005). As seen in Fig. 2, the profile of the [O I]+C feature is very well described with this C abundance and a solar oxygen abundance of log ε O = 8.733 with the (3D) model. The resulting disk-center intensity equivalent width for only the [O I] line is 1.23 mÅ, which corresponds to log ε O = 8.72 for the full 3D model. The Kurucz et al. (1984) solar-flux and the Brault & Neckel (1987) intensity spectrum gave an O abundance 0.01 dex higher and ~0.07 dex lower, respectively. Results for different model atmospheres are similar, as shown in Table 1, thus the [O I] 5577 Å line is almost insensitive to the adopted model atmosphere.

The predicted profile for the neighboring feature at 5577.55 Å is too weak using the C abundance from the overall fit to all C2 lines in the wavelength window 5575–5580 Å (Fig. 2), suggesting that it is blended. Scouing available atomic databases did not reveal any likely candidates. We have therefore tentatively assigned the blending line as being due to Fe i but the exact choice is unimportant. Relying solely on the P25 transition and without accounting for this blend, the estimated C abundance would have been 0.03 dex higher. Because of the larger contribution from C2 the [O I] part of the 5577.3 Å feature must decrease correspondingly, leading to a much reduced solar O abundance: log ε O ≈ 8.6. In this case, however, the profile fit is very unsatisfactory, in particular in the red wing, as evident in Fig. 2.

The main errors are the uncertainties in the log gf value of the [O I] line (assumed here to be 0.03 dex, which is the σ between the different calculations; c.f. Galavis et al. 1997; 2 Note that the abundance quoted here is only from the Liege intensity atlas (Figs. 1 and 2). The final abundance given in Table 1 is based on the mean from the three different solar atlases.

Fig. 1. Observed solar spectrum (Delbouille et al. 1973) between 5575 and 5580 Å (red circles) and the best fit employing the (3D) model (solid blue line). The locations of the most prominent C2 lines used to estimate the C abundance are denoted with vertical lines, while the position of the [O i] line is marked with an arrow. The resulting solar C abundance is log ε C = 8.42 which with the 5577.3 Å feature implies a solar O abundance of log ε O = 8.73.

1 http://physics.nist.gov/PhysRefData/ASD/index.html
2 http://kurucz.harvard.edu/
Table 1. Solar oxygen abundance from different model atmospheres.

<table>
<thead>
<tr>
<th>Lines</th>
<th>3D</th>
<th>(3D)</th>
<th>Holweger-Müller</th>
<th>MARCS no overshooting</th>
<th>Kurucz no overshooting</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O i] 5577 Å</td>
<td>8.70 ± 0.08</td>
<td>8.71 ± 0.08</td>
<td>8.73 ± 0.08</td>
<td>8.70 ± 0.08</td>
<td>8.74 ± 0.08</td>
</tr>
<tr>
<td>[O i]</td>
<td>8.69 ± 0.05</td>
<td>8.73 ± 0.05</td>
<td>8.75 ± 0.05</td>
<td>8.71 ± 0.05</td>
<td>8.77 ± 0.05</td>
</tr>
<tr>
<td>O i</td>
<td>8.67 ± 0.05</td>
<td>8.68 ± 0.05</td>
<td>8.64 ± 0.08</td>
<td>8.72 ± 0.05</td>
<td>8.67 ± 0.05</td>
</tr>
<tr>
<td>OH</td>
<td>8.61 ± 0.10</td>
<td>8.68 ± 0.10</td>
<td>8.85 ± 0.10</td>
<td>8.73 ± 0.11</td>
<td>8.80 ± 0.10</td>
</tr>
<tr>
<td>Average</td>
<td>8.67 ± 0.04</td>
<td>8.70 ± 0.04</td>
<td>8.71 ± 0.10</td>
<td>8.72 ± 0.04</td>
<td>8.73 ± 0.07</td>
</tr>
</tbody>
</table>

* Average abundance from the Delbouille et al. (0.02 higher), Braith & Neckel (0.04 lower) and Kurucz et al. (0.03 higher) atlases.

Fig. 2. Upper panel: an enlargement of the observed (red circles, Delbouille et al. 1973) and (3D)-based theoretical profiles (solid blue line) shown in Fig. 1. The dotted lines show the separate contribution of [O i] and other lines labeled accordingly. The 5577.54 Å P 325 C 2 line is blended with an unknown feature, assumed here to be Fe I. Lower panel: same as above but assuming instead that the red feature is entirely due to P 325 C 2. Applying this 0.03 dex higher C abundance to the [O i] + C 2 blend implies a smaller left-over contribution for [O i] and thus a 0.13 dex lower O abundance at the expense of a significantly poorer profile fit.

Asplund et al. (2004) have determined the solar oxygen abundance from the [O i] 6300, 6363 Å forbidden lines, O i permitted lines, and the pure rotation and fundamental vibration-rotation OH lines, employing a 3D hydrodynamical simulation of the solar atmosphere as well as a 1D MARCS (Asplund et al. 1997) and the Holweger & Müller (1974) semi-empirical model atmospheres. Meléndez (2004) has added oxygen abundances determined from the first-overtone OH lines, as well as computed the solar oxygen abundance for the above features using the (3D) and Kurucz (Castelli et al. 1997) convective overshooting models. Here we add the 5577.3 Å forbidden line for the five model atmospheres described above, and we also have determined oxygen abundances for the latest Kurucz (Castelli & Kurucz 2004) model without convective overshooting.

The results of the different computations are summarized in Table 1, where the mean oxygen abundance for the forbidden lines now includes the 5577.3 Å line. The mean value given for the infrared OH lines includes all the OH features mentioned above, but giving half-weight to the pure rotation and the first-overtone line, because the pure rotation lines are quite sensitive to the detailed structure of the model atmosphere, while the first-overtone lines are very weak and the observational error is high. For the O i lines we adopt the mean non-LTE results of

4 According to Tanabashi et al. (2007) the line positions for those C 2 lines are not very precise, hence we allowed small changes by up to 0.01 Å in wavelength. Also, note that Allende Prieto & García López (1998) have shown that the Delbouille et al. solar disk-center intensity atlas has slight errors in its absolute wavelength calibration, although probably not over a wavelength scale of a few Å, which is relevant here.
Allende Prieto et al. (2004) and Asplund et al. (2004), with and without including inelastic H collisions, respectively. As discussed by Asplund (2005), the H collisions are based on the classical but highly uncertain formula by Drawin (1968), yet the O abundance with (and without) collisions is only +0.03 higher (lower) than the mean O abundance adopted here. We also show in the last row the averaged solar oxygen abundance for each model atmosphere. In obtaining this mean value, half weight has been given to the result obtained from the molecular lines, because of their strong model atmosphere sensitivity.

As can be seen, all model atmospheres favor a low solar oxygen abundance: log $\epsilon_O \approx 8.7$. The reduction in the solar oxygen abundance from the historical value of $\approx 8.9$ (Anders & Grevesse 1989)\(^5\) to the present level is therefore not primarily driven by the use of a 3D hydrodynamic model. In this context, improvements in the input atomic and molecular data, more realistic non-LTE calculations and a more careful treatment of blends are equally important. The average O abundance for the realistic non-LTE calculations and a more careful treatment of text, improvements in the input atomic and molecular data, more

\[^{5}\text{It should be noted that the solar O abundance of 8.83 given in the compilation of Grevesse & Sauval (1998) is only a preliminary analysis based on a Holweger-Müller (1974) model with a modified temperature structure to remove various abundance trends with excitation potential and line strengths for species such as Fe, OH and CH.}\]

4. Conclusions

A low oxygen abundance is obtained from the [OI] 5577.3 Å line, almost independent of the adopted model atmosphere: log $\epsilon_O = 8.71 \pm 0.02 \pm 0.07 (0.02 \text{ dex})$ is the $\sigma$ from using different models, and 0.07 dex is the error due to uncertainties in the log $gf$ value (0.03 dex), apparent line variation (0.04 dex) and uncertainties in the continuum and line positions (0.05 dex)). This value is close to the results of Asplund et al. (2004) and Meléndez (2004) for other solar oxygen abundance indicators ([OI], [OI] and OH lines). Including those abundances and employing six different 3D and 1D model atmospheres, we estimate a solar O abundance of log $\epsilon_O = 8.70 (\sigma = 0.02)$ with only a small sensitivity to the model atmosphere employed.


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