ON THE SOLAR NICKEL AND OXYGEN ABUNDANCES

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ABSTRACT

Determinations of the solar oxygen content relying on the neutral forbidden transition at 630 nm depend upon the nickel abundance, due to a Ni i blend. Here, we rederive the solar nickel abundance, using the same ab initio three-dimensional hydrodynamic model of the solar photosphere employed in the recent revision of the abundances of C, N, O, and other elements. Using 17 weak, unblended lines of Ni i together with the most accurate atomic and observational data available, we find log \( \epsilon_{\text{Ni}} = 6.17 \pm 0.02 \) (statistical) \( \pm 0.05 \) (systematic), a downward shift of 0.06–0.08 dex relative to previous abundances based on one-dimensional model atmospheres. We investigate the implications of the new nickel abundance for studies of the solar oxygen abundance based on the \([\text{O} i] 630 \text{ nm}\) line in the quiet Sun. Furthermore, we demonstrate that the oxygen abundance implied by the recent sunspot spectropolarimetric study of Centeno & Socas-Navarro needs to be revised downward from log \( \epsilon_{\text{O}} = 8.86 \pm 0.07 \) to 8.71 \( \pm 0.10 \). This revision is based on the new nickel abundance, the application of the best available \( g f \) value for the 630 nm forbidden oxygen line, and a more transparent treatment of CO formation. Determinations of the solar oxygen content relying on forbidden lines now appear to converge around log \( \epsilon_{\text{O}} = 8.7 \).

Key words: line: formation – line: profiles – Sun: abundances – Sun: atmosphere – Sun: photosphere – techniques: polarimetric

1. INTRODUCTION

The reference solar oxygen abundance has been revised over the past decade from log \( \epsilon_{\text{O}} = 8.93 \pm 0.04 \) (Anders & Grevesse 1989) via 8.83 \( \pm 0.06 \) (Grevesse & Sauval 1998, GS98) to 8.66 \( \pm 0.05 \) (Asplund et al. 2005, AGS05). This downward slide has been brought on by the combined influences of three-dimensional photospheric models, treatment of departures from local thermodynamic equilibrium (LTE), identification of blends, improved atomic data, and better observations (Allende Prieto et al. 2001; Asplund et al. 2004). The new abundances of oxygen and other elements have solved many outstanding problems, but ruined agreement between helioseismological theory and observation (see, e.g., Basu & Antia 2008). This has prompted a re-analysis of photospheric models, resulting in support for high (Ayers et al. 2006; Centeno & Socas-Navarro 2008; Ayres 2008), low (Scott et al. 2006; Socas-Navarro & Norton 2007; Koesterke et al. 2008; Meléndez & Asplund 2008), and intermediate (Caffau et al. 2008) solar oxygen abundances.

Many of these analyses rely upon the forbidden oxygen line at 630.0304 nm, known to contain a significant blend from Ni i (Allende Prieto et al. 2001; Johansson et al. 2003). The strength of this blend, and therefore the \( \epsilon_{\text{O}} \) indicated by \([\text{O} i] 630 \text{ nm}\) depends critically upon the solar nickel abundance (\( \epsilon_{\text{Ni}} \)). This is no less true of the ingenious spectropolarimetric studies of Centeno & Socas-Navarro (2008) than of any other study based on \([\text{O} i] 630 \text{ nm}\). We show that \( \epsilon_{\text{Ni}} \) is model dependent, contradicting claims by Centeno and Socas-Navarro that their technique allows a nearly model-independent analysis of \( \epsilon_{\text{O}} \).

2. MODEL ATMOSPHERES AND OBSERVATIONAL DATA

We used the same three-dimensional LTE model atmosphere and line-formation code as in earlier papers (e.g., Asplund et al. 2000b, 2004), described by Asplund et al. (2000a). We performed comparative calculations with three one-dimensional models: HM (Holweger & Müller 1974), MARCS (Gustafsson et al. 1975; Asplund et al. 1997), and 1DAV (a contraction of the three-dimensional model into one dimension by averaging over surfaces of equal optical depth). Each one-dimensional model included a microturbulent velocity \( \xi_t = 1 \text{ km s}^{-1} \). We averaged simulated intensity profiles over the temporal and spatial extent of the model atmosphere, and compared results with the Fourier Transform Spectrograph (FTS) disk-center atlas of Brault & Neckel (1987, see also Neckel 1999). We removed the solar gravitational redshift of 633 m s\(^{-1}\), and convolved simulated profiles with an instrumental sinc function of width \( \Delta \sigma = c/R = 0.857 \text{ km s}^{-1} \), reflecting the FTS resolving power \( R = 350,000 \) (Neckel 1999). We obtained abundances with the three-dimensional model from profile fitting via a \( \chi^2 \)-analysis, fitting local continua independently with nearby clear sections of the spectrum. For one-dimensional models, we used the equivalent widths of three-dimensional profile fits.

3. ATOMIC DATA AND LINE SELECTION

Our adopted Ni i lines and atomic data are given in Table 1. The paucity of good lines and atomic data in the optical precludes any meaningful analysis of Ni i in the Sun. The most accurate Ni i oscillator strengths come from the laboratory

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7 Most results were obtained while these authors were at the Australian National University Research School of Astronomy and Astrophysics, Mt Stromlo Observatory, Cotter Rd., Weston Creek, ACT 2611, Australia.
FTS branching fractions (BFs) of Wickliffe & Lawler (1997), put on an absolute scale with the time-resolved laser-induced fluorescence (TRLIF) lifetimes of Bergeson & Lawler (1993). A small number of high-quality TRLIF lifetimes of Bergeson & Lawler (1993). Radiative damping is from VALD (Kupka et al. 1999). Transition designations are from Wickliffe & Lawler (1997), except for Ni488.7 nm, for which the designation is from VALD. For most lines, we used collisional broadening parameters calculated for individual lines by P. Barklem (1999, private communication; now in VALD, Barklem et al. 2000). Equivalent widths are from profile fits using the three-dimensional model.

We took wavelengths and excitation potentials from Litzen et al. (1993), and radiative damping from the Vienna Atomic Line Database (VALD; Kupka et al. 1999). For most lines, we used collisional broadening parameters calculated for individual lines by P. Barklem (1999, private communication; now in VALD, Barklem et al. 2000). For the remainder we interpolated in the tables of Anstee & O'Mara (1995) and Barklem & O'Mara (1997) where possible. For Ni i 488.7 nm we used the traditional Unsöld (1955) formula with a scaling factor of 2.0. Transition designations are from Wickliffe & Lawler (1997), except for Ni i 481.2 nm, where the designation is from VALD. Apart from the slightly stronger 617.7 nm line, all our lines are quite insensitive to the adopted collisional broadening. The broadening treatment of Ni i 488.7 nm thus has no impact on our abundance determination, nor does the ambiguity in the identification of the upper level of Ni i 481.2 nm (Johansson et al. 2003).

Table 1
List of Neutral Nickel Lines

| Atomic Levels | Isotope | Wavelength (nm, air) | Ex. Pot. (eV) | log g.f. (Eff.) | Ref. (g.f) | log γad (W) | σ (fm) | α (pm) | W_e (pm) | log ε Ni | Weight |
|---------------|--------|----------------------|--------------|----------------|----------|--------------|--------|--------|----------|----------|--------|
| 3d(^2)5s4p(3P) | ^5Ni | 474.01658 | 3.480 | -1.730 | WL | 7.899 | 844 | 0.281 | 1.60 | 6.18 | 1 |
| 3d(^2)5s4p(3P) | ^6Ni | 481.19772 | 3.658 | -2.006 | J03 | 8.285 | ... | ... | 2.12 | 6.20 | 1 |
| 3d(^2)5s4p(3P) | ^5Ni | 481.19926 | 3.597 | -1.620 | WL | 8.053 | 743 | 0.236 | 1.58 | 6.17 | 1 |
| 3d(^2)5s4p(3P) | ^6Ni | 488.67108 | 3.706 | -1.780 | WL | 8.211 | ... | ... | 0.90 | 6.13 | 1 |
| 3d(^2)5s4p(3P) | ^6Ni | 490.09708 | 3.480 | -1.670 | WL | 8.062 | 693 | 0.238 | 1.79 | 6.17 | 1 |
| 3d(^2)5s4p(3P) | ^5Ni | 497.61348 | 3.606 | -1.250 | WL | 7.962 | 843 | 0.282 | 2.86 | 6.13 | 2 |
| 3d(^2)5s4p(3P) | ^6Ni | 515.79805 | 3.606 | -1.510 | WL | 8.093 | 691 | 0.236 | 1.86 | 6.13 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 550.40945 | 3.834 | -1.700 | WL | 8.063 | 713 | 0.240 | 0.97 | 6.18 | 1 |
| 3d(^2)5s4p(3P) | ^6Ni | 567.51054 | 3.847 | -1.200 | WL | 8.280 | 695 | 0.216 | 0.31 | 6.16 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 574.92795 | 3.941 | -2.526 | WL | 7.944 | 832 | 0.284 | 0.44 | 6.17 | 2 |
| 3d(^2)5s4p(3P) | ^6Ni | 574.93039 | 3.941 | -2.112 | WL | 7.944 | 832 | 0.284 | 0.44 | 6.17 | 2 |
| 3d(^2)5s4p(3P) | ^6Ni | 617.66780 | 4.088 | -0.816 | WL | 8.162 | 826 | 0.284 | 6.54 | 6.17 | 2 |
| 3d(^2)5s4p(3P) | ^6Ni | 617.68200 | 4.088 | -0.402 | WL | 8.162 | 826 | 0.284 | 6.54 | 6.17 | 2 |
| 3d(^2)5s4p(3P) | ^6Ni | 620.46048 | 4.088 | -1.100 | WL | 8.244 | 719 | 0.247 | 2.11 | 6.19 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 622.39710 | 4.105 | -1.466 | WL | 8.322 | 872 | 0.283 | 2.79 | 6.17 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 622.39914 | 4.105 | -1.052 | WL | 8.322 | 872 | 0.283 | 2.79 | 6.17 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 637.82328 | 4.154 | -1.386 | WL | 8.317 | 825 | 0.283 | 3.20 | 6.20 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 637.82580 | 4.154 | -0.972 | WL | 8.317 | 825 | 0.283 | 3.20 | 6.20 | 3 |
| 3d(^2)5s4p(3P) | ^6Ni | 641.45884 | 4.154 | -1.180 | WL | 8.369 | 721 | 0.249 | 1.68 | 6.20 | 2 |

Notes. Wavelengths and excitation potentials are from Litzen et al. (1993). Radiative damping is from VALD (Kupka et al. 1999). Transition designations are from Wickliffe & Lawler (1997) except in the case of 481.2 nm, for which the designation is from VALD. References for g.f values are WL: Wickliffe & Lawler (1997) and J03: Johansson et al. (2003). For lines with isotopic components g.f values are effective only, rescaled to reflect the (terrestrial) isotopic fractions of Rosman & Taylor (1998). Collisional damping parameters σ and α are courtesy of P. Barklem (1999, private communication; now in VALD, Barklem et al. 2000). Equivalent widths are from profile fits using the three-dimensional model.

Table 2
Logarithmic Solar Nickel Abundances (Mean ± 1 Standard Deviation)

| Ref. log W_e (Ni i lines) | Three-Dimensional | IDAV | HM | MARCS | Meteoritic |
|---------------------------|-------------------|------|----|--------|------------|
| 3.97 ± 0.02              | 6.17 ± 0.02       | 6.17 ± 0.02 | 6.26 ± 0.02 | 6.16 ± 0.02 | 6.19 ± 0.03 |

4. NICKEL RESULTS

The mean nickel abundances we found using different model atmospheres are given in Table 2. The examples of profile fits to
Ni lines with the three-dimensional model are given in Figure 1, exhibiting similarly impressive agreement with observation as seen with other species (e.g., Asplund et al. 2000a, 2004). None of the models shows abundance trends with equivalent width (Figure 2), excitation potential or wavelength, and the scatter is universally low, boding well for the internal consistency of all models. Very little difference exists between three-dimensional and 1DAV abundances, implying that the mean temperature structure rather than atmospheric inhomogeneities is the main reason for the difference between the three-dimensional and HM results. The three-dimensional $\epsilon_{\text{Ni}}$ is in excellent agreement with the meteoritic value AGS05, whereas the HM value is not.

The revised solar nickel abundance presented here has a direct impact upon any derivation of the oxygen abundance using the model atmosphere (+0,05 dex), and potential systematics arising from the model atmosphere (+0,05 dex). AGS05 gave $\epsilon_{\text{Ni}} = 6.23 \pm 0.04$, from Reddy et al. (2003) using an ATLAS9 model (Kurucz, http://kurucz.harvard.edu/grids.html). Previous reviews (e.g., GS98) adopted 6.25 $\pm$ 0.09, by Béjmont et al. (1980) using the HM model. Our value is 0.06–0.08 dex lower than earlier ones, and 0.09 dex less than our own HM-based estimate. There is currently no evidence for non-LTE effects on our chosen lines in the Sun (Asplund 2005), but without a dedicated study we cannot rule them out. After adjusting for gf values and equivalent widths, we find abundances 0.06 and 0.07 dex higher with the HM model than Béjmont et al. for the two lines in common. We have not been able to trace the exact cause of these disparities, but tentatively attribute them to differences in radiative transfer codes, continuum opacities, and implementations of the HM model.

5. IMPLICATIONS FOR THE SOLAR OXYGEN ABUNDANCE

The revised solar nickel abundance presented here has a direct impact upon any derivation of the oxygen abundance using the
[O\textsc{i}] 630 nm line, as this line is blended with one from Ni\textsc{i} (Allende Prieto et al. 2001).

Centeno & Socas-Navarro (2008) used the Stokes V profile of [O\textsc{i}] 630 nm to find an atomic ratio $\epsilon_{O,\text{atomic}} / \epsilon_{Ni} = 210 \pm 24$ in a sunspot. They adopted an outdated $gf$ value for the [O\textsc{i}] 630 nm line (see Storey & Zeippen 2000), causing an overestimation of the ratio by 15% (+0.06 dex). They assumed $\log \epsilon_{Ni} = 6.23$ to find $\epsilon_{O,\text{atomic}}$ and converted this to a bulk $\epsilon_{O}$ by calculating that 51% of oxygen resides in molecules. This is a reasonable assumption; in sunspots the only significant oxygen-bearing molecule is CO, which (roughly) forms as many molecules as there are carbon atoms available, due to the low temperatures. This number thus mirrors the assumed C/O ratio at the start of the calculation. That ratio only depends weakly on the choice of the three-dimensional or HM model, as seen in the shift from 0.49 ± 0.11 to 0.54 ± 0.10 between GS98 and AGS05. A more straightforward way of estimating the contribution from CO would be to say that the maximum $\epsilon_{CO}$ is given by the adopted carbon abundance: $\epsilon_{O} \approx \epsilon_{O,\text{atomic}} + \epsilon_{C} - \epsilon_{Ni}$.

Centeno and Socas-Navarro claimed a nearly model-independent analysis because neither their CO correction nor nickel-to-atomic-oxygen ratio relied on an atmospheric model, and they believed $\epsilon_{Ni}$ to be well established. The first statement is approximately true in the current debate, and the second is true of photospheric (but not sunspot) models. Here, we have shown that $\epsilon_{Ni}$ is a model-dependent quantity, however. The determination of $\epsilon_{O}$ via Centeno and Socas-Navarro’s method is thus manifestly model dependent, so there is no longer any reason to prefer placing a prior on the C/O ratio than on $\epsilon_{C}$ directly. Using our new nickel abundance, correcting the [O\textsc{i}] 630 nm $gf$, adopting the $\epsilon_{C}$ of AGS05 and fully propagating all errors, we find an oxygen abundance of $\log \epsilon_{O} = 8.71 \pm 0.10$ instead of their 8.86 ± 0.07. Had we adopted the traditional sunspot model of Maltby et al. (1986) instead of the one inferred from spectrum inversion by Centeno and Socas-Navarro, we would have found 8.67 ± 0.10. Retaining Centeno and Socas-Navarro’s prior on the C/O ratio (with the error therewith given by AGS05), one would obtain 8.74 ± 0.10 with their sunspot model and 8.66 ± 0.10 with the Maltby et al. model. Clearly their method is not as model insensitive as Centeno and Socas-Navarro argued.

Our new Ni abundance also modifies analyses of [O\textsc{i}] 630 nm in the quiet solar spectrum. Allende Prieto et al. (2001), Asplund et al. (2004), and Ayres (2008) all allowed the Ni contribution to vary freely in their three-dimensional profile fitting of the 630 nm feature, while Caffau et al. (2008) fixed it with the $\epsilon_{Ni}$ of GS98. With the Ni abundances from Table 2 and the laboratory $gf$ value of the Ni\textsc{i} blend (Johansson et al., 2003), we can now accurately predict the Ni contribution to [O\textsc{i}] 630 nm. Independent of the adopted one-dimensional or three-dimensional model atmosphere, it is 0.17 pm in disk-center intensity, and 0.19 pm in flux. In terms of oxygen abundance, this implies a decrease by 0.04 dex to $\log \epsilon_{O} \approx 8.65$ for the analysis of Asplund et al. (2004), further improving the excellent agreement between different indicators. The derived abundance of Ayres (2008) would decrease to about 8.77 while that of Caffau et al. (2008) would increase to approximately 8.72. Because we now know the strength of the Ni blend, it is surprising that these two studies yield different results for the remaining contribution from oxygen, as they both rely on the same three-dimensional CO\textsuperscript{BOLD} model. Since Caffau et al. employed several three-dimensional snapshots whereas Ayres used only one, we tentatively consider the former more reliable. No Ni abundance has yet been estimated with the C0\textsuperscript{BOLD} model, but regardless of its value our conclusions about the strength of the Ni\textsc{i} 630 nm blend, and thus its impact on oxygen abundances found by different authors, would remain unchanged. The difference of approximately 0.07 dex in the revised Asplund et al. (2004) and Caffau et al. (2008) abundances from [O\textsc{i}] 630 nm probably reflects the different mean temperature stratifications of the two three-dimensional models.

Given our reappraisal of the oxygen abundances of Centeno & Socas-Navarro (2008), Asplund et al. (2004), and Caffau et al. (2008), together with the recent study of Meléndez & Asplund (2008) using the [O\textsc{i}] 557.7 nm line, it now seems that the results from forbidden oxygen lines are beginning to converge around $\log \epsilon_{O} = 8.7$. While this agreement might come as a relief to some, it only serves to sharpen the current discrepancy between spectroscopy and helioseismology.

We would like to take this opportunity to commemorate the work and life of Sverner Johansson, his contribution to atomic spectroscopy in general and to nickel and [O\textsc{i}] 630 nm in particular. P.S. thanks IAU Commission 46, the ANU and the Australian Research Council for financial support.

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