A REAPPRAISAL OF THE SOLAR PHOTOSPHERIC C/O RATIO

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ABSTRACT

Accurate determination of photospheric solar abundances requires detailed modeling of the solar granulation and accounting for departures from local thermodynamical equilibrium (LTE). We argue that the forbidden C I line at 8727 Å is largely immune to departures from LTE, and can be realistically modeled using LTE radiative transfer in a time-dependent three-dimensional simulation of solar surface convection. We analyze the [C I] line in the solar flux spectrum to derive the abundance log \( \epsilon(C) = 8.39 \pm 0.04 \) dex. Combining this result with our parallel analysis of the [O I] 6300 Å line, we find C/O = 0.50±0.07, in agreement with the ratios measured in the solar corona from gamma-ray spectroscopy and solar energetic particles.

Subject headings: convection — line: formation — Sun: abundances — Sun: photosphere

1. INTRODUCTION

Pursuit of quantitative stellar spectroscopy not infrequently introduces new puzzles as old puzzles are probed. Recent determinations of the solar photospheric abundances of carbon and oxygen exemplify this claim. In a thorough review of light element photospheric abundances, Holweger (2001) recommends the abundances log \( \epsilon(C) = 8.592 \pm 0.108 \), and log \( \epsilon(O) = 8.736 \pm 0.078 \) on the usual scale with log \( \epsilon(H) = 12.0 \). These results based on 1D NLTE analyses of permitted lines of C I and O I include corrections for the effects of solar granulation based on 2D modeling. Prior to Holweger’s reassessment, the accepted carbon abundance was lower (log \( \epsilon(C) = 8.52 \pm 0.06 \)) and that of oxygen higher (log \( \epsilon(O) = 8.83 \pm 0.06 \); Grevesse & Sauval 1998). With the reassessment, the carbon-to-oxygen ratio is increased. More intriguingly, the errors assigned to the new solar abundances would formally allow a carbon-to-oxygen ratio greater than one. Such a ratio is exceedingly puzzling in that it implies remarkable abundance differences between the photosphere and the corona, the outer planets, and unevolved stars and interstellar gas in the solar neighborhood. Lowering the oxygen abundance and keeping the high value for the carbon abundance leads also to a conflict with the strength of observed water and methane bands in the spectra of very cool stars (Tsuji 2002). Recognizing the controlling influence of the CO molecule on the partial pressures of carbon and oxygen, the simple observation of very weak C \( \Pi \) bands and strong TiO bands in sunspot spectra shows that the carbon-to-oxygen ratio must be less than unity. Yet, a precise determination of the photospheric ratio is of great interest.

In this paper, we reconsider the carbon abundance provided by the forbidden carbon line at 8727 Å. We reanalysis follows our successful study of the forbidden oxygen line at 6300 Å, which gave the abundance log \( \epsilon(O) = 8.69 \pm 0.05 \) with a 3D hydrodynamical model photosphere simulating the solar granulation (Allende Prieto, Lambert, & Asplund 2001a). The principal advantages of a forbidden line over permitted lines are twofold: (i) the line’s \( gf \)-value is most probably more accurately known than the \( gf \)-values of the permitted lines, and (ii) the line is formed very close to LTE, which is not true for the permitted lines. We argue that the possible downsides with the [C I] line, namely its relative weakness and possible blends, can be adequately addressed.

2. MODEL ATMOSPHERES AND LINE SYNTHESIS

Our line profile calculations follow very closely those of Allende Prieto et al. (2001a) for the [O I] line at 6300 Å. We used a three-dimensional time-dependent hydrodynamical simulation of the solar surface as a model atmosphere (Asplund et al. 2000a and references therein). The calculated flux profiles for the forbidden [C I] line at 8727.1 Å and a Si I line at 8728 Å result from the average of a time sequence of flux profiles computed from 100 snapshots, which are equally spaced over 50 minutes of solar time. For each snapshot, the integration over the solar disk makes use of intensity profiles for 4 \( \times \) 4 angles, accounting for the (solid body v sin i = 1.9 km s\(^{-1}\)) rotational broadening (Dravins & Nordlund 1990). The Uppsala opacity package (Gustafsson et al. 1975 with subsequent updates) was the source of the continuum opacities, partition functions, ionization potentials, and other basic data for the line synthesis as well as for the simulation. Collisional differences between 2D and 3D (Asplund et al. 2000b)
broadening was evaluated using the Unsöld’s approximation (Unsöld 1955) for the [Cl] line and the neighboring Si I line.

The [Cl] 8727.1 Å line was identified in the solar spectrum by Lambert & Swings (1967a). They remarked upon a potential blending line of Fe I, but deemed its contribution to be negligible. Kurucz (1993) calculated $\log gf = -3.93$ for this iron line, which leads to an equivalent width of $\sim 0.5$ mÅ. Kurucz also calculated the transition probabilities for the other 5 lines in the multiplet, and four of them appear in the solar spectrum. Using the measured equivalent widths ($12 \leq W_\lambda \leq 40$ mÅ) to scale the $\log gf$’s of these four lines, we estimate an equivalent width of $\sim 0.18 \pm 0.13$ mÅ$^2$. Nave et al. (1994) in a thorough reinvestigation of the laboratory Fe I spectrum did not list the Fe I line with its predicted wavelength of 8727.130 Å, but four stronger lines of the same multiplet were measured. Three of the four measured lines appear relatively unblended in the solar spectrum. Normalizing the line strengths measured by Nave et al. to the relative LS-coupling strengths, we can scale the observed equivalent widths and obtain a third estimate of the equivalent width of the 8727.130 Å line: $0.11 \pm 0.02$ mÅ. Given that the solar feature has an equivalent width of about 6 mÅ, the Fe I contribution is very small and can be neglected. Gustafsson et al. (1999) eliminate the CN Red system as another contributor of a blend.

The predicted [Cl] rest wavelength is 8727.126 Å with an uncertainty of about 0.015 Å (Moore 1993). After correction for the gravitational redshift, the center of the feature in the solar spectrum is observed at 8727.133 ± 0.009 Å (as determined with the method described in Allende Prieto et al. 2002). For weak lines, we expect a significant convective blueshift (Allende Prieto & García López 1998). Therefore, the predicted wavelength is likely to be in error by as much as its full quoted uncertainty. Different calculations report results for the Einstein $A$-value which have converged to $A = 0.640$ s$^{-1}$ or $\log gf = -8.136$ – see Galavis et al. (1997), and Hibbert et al. (1993). A strong Si I line affects the continuum in the vicinity of the [Cl] line. The NIST database quotes a measured wavelength of 8728.011 Å for this transition. We adopted $\log gf = -0.37$ in order to match the observed line reasonably well.

3. COMPARISON WITH THE OBSERVED SPECTRUM

We compare our calculated line profiles with the Fourier transform solar flux spectrum of Kurucz et al. (1984). The [Cl] lies in the scan # 13, which includes the telluric O$_2$ line at 6883.8335 Å, used to normalize the frequency scale. This scan has a spectral resolving power in excess of half a million, and a maximum signal-to-noise of 2600.

The Si I line dominates the shape of the local continuum in the region of the [Cl] line. The abundance of silicon has been recently studied using the same 3D model atmosphere employed here (Asplund 2000). Recent 1D NLTE calculations suggest that photospheric Si I lines are not much affected by departures from LTE (Wedemeyer 2001). Since the line’s $gf$-value is uncertain, we considered the factor $\log gf(Si)$ and a multiplicative correction to the local continuum level as free parameters with which to adjust the continuum in the vicinity of the [Cl] line. A variation in the central wavelength of the Si I line has a similar effect as a change in the strength of the line.

The velocity shift between Kitt Peak National Observatory and the Sun at the time of the observations has been corrected typically within several m s$^{-1}$, but other factors (setting of frequency scale in FTS, conversion to air wavelengths, correction of individual scans with partial wavelength coverage, change of velocity shift over long integrations, etc.) can degrade the absolute accuracy of the wavelength scale up to 0.1 km s$^{-1}$ (Kurucz et al. 1984). The gravitational redshift for photospheric photons intercepted at Earth is $V_g \simeq GM_{\odot}/(R_{\odot}c) \simeq 0.6336$ km s$^{-1}$. Seasonal variations produced by the ellipticity of Earth’s
orbit are about 0.1 m s\(^{-1}\), Earth’s surface gravity induces a correction of about 0.2 m s\(^{-1}\), and uncertainties in the solar radius and \(GM_\odot\) can hamper \(V_g\) by about 0.3 m s\(^{-1}\).

We are using a hydrodynamical model atmosphere which has been shown to predict the convective shifts of photospheric lines of weak and moderate strength within 0.1 km s\(^{-1}\) (Asplund et al. 2000a). Therefore, we should be able to predict the measured wavelength of the [C I] with an uncertainty of about 0.15 km s\(^{-1}\) (≃ 0.004 Å), an estimate significantly smaller than for Moore’s wavelength. We consequently adjust the wavelength of the line to best match the observations.

We proceed to compare our calculated profiles to the solar observations adopting different values for the wavelength of the forbidden line \(\lambda_{[\text{C I}]}\). For each adopted \(\lambda_{[\text{C I}]}\), we minimize the \(\chi^2\) between the observed and calculated spectra by changing the abundance of carbon \(\log \epsilon (\text{C})\), a multiplicative correction factor to the local continuum, and \(\log [gf\epsilon (\text{Si})]\). There are obvious blends on both sides of the [C I] line. The line at 8726.8 Å is a CN line (Gustafsson et al. 1999), but other lines are unidentified. We believe there are no blends within the [C I] profile, but, if we are in error, the determined carbon abundance is an upper limit.

First, we fitted 1 Å around the [C I] feature, between 8726.6 and 8727.6 Å in the solar atlas, using the Nelder-Mead simplex method (Nelder & Mead 1965; Press et al. 1986). We obtain the best fit, illustrated in Fig. 1, for \(\log \epsilon (\text{C}) = 8.39\) dex. We emphasize that the fit is achieved without invoking micro- or macroturbulence; the line profile is predicted from the convective flows without additional parameters. By selecting a narrow interval excluding the core of the Si I blending line, we are in effect adjusting the line’s damping constant to get the optimum fit to the wing around the [C I] line; the line depth in a damping wing scales as the product of the abundance and the damping constant. Next, we repeated the experiment for a more restricted wavelength interval, between 8726.9 and 8727.25 Å. The carbon abundance changed by less than 0.01 dex, the multiplicative factor to adjust the continuum level changed by only 0.0003, and the best values for the wavelength of the [C I] are by less than 0.001 Å. Our best fit yielded a reduced \(\chi^2\) and the carbon abundance as a function of the central wavelength for the [C I] transition, when the more restricted wavelength interval is considered.

The rest wavelength of the [C I] line that minimizes the \(\chi^2\) is 8727.139 ± 0.004 Å, after correction for the gravitational redshift. The synthetic spectra predict a blueshift of about 0.25 km s\(^{-1}\) for the line, i.e., a laboratory wavelength of 8727.146 Å. This differs from Moore’s wavelength of 8727.126 Å obtained not from laboratory measurements of the line but from ultraviolet lines connecting the ground configuration levels to excited levels. In the introductory remarks to her table of C I energy levels, she draws attention to Kaufman & Ward’s (1966) revisions of ultraviolet wavelengths which imply revised energies for the ground configuration. These revisions predict a wavelength of

![Fig. 2](image_url)
8727.141 Å in good agreement with our solar-based wavelength, even though the uncertainty remains at about 0.01 Å.

The internal uncertainty in the fit for the carbon abundance can be estimated as 0.01 dex by confronting the expected accuracy in $\lambda_{[C II]}$ (0.004 Å, which includes the observational share of the error), with Fig. 2. Judging from the scatter in the most recently calculated $A$-values, the derived carbon abundance is hardly affected by this factor ($\sigma(\log \epsilon(C)) \approx 0.005$ dex). Other systematic errors may arise from the uncertainties in the adopted continuum opacities, equation of state, etc., probably about 0.02 dex. Finally, if the contribution of the Fe I line discussed in §2 to the observed absorption is close to the lower limit of our estimates, the effect on the derived carbon abundance is truly negligible, but if it is close to the upper limit, that could decrease log $\epsilon(C)$ by $\simeq$ 0.03 dex. Conservatively, we derive log $\epsilon(C) = 8.39 \pm 0.04$. As shown by Stülenburg & Holweger (1990), the forbidden line at 8727.1 Å is immune to departures from LTE, and therefore our LTE calculation of the line formation in a 3D LTE model is likely to provide a reliable abundance.

It is interesting to compare our 3D result to a standard analysis using one-dimensional model atmospheres. Use of the solar semi-empirical model atmosphere derived by Allende Prieto et al. (2001b), and the micro- and macro-turbulence derived with the model ($\xi = 1.1$ km s$^{-1}$, macro=1.54 km s$^{-1}$), leads to log $\epsilon(C) = 8.47$ dex, the Holweger-Müller model gives log $\epsilon(C) = 8.48$ dex, and a flux-constant MARCS model atmosphere log $\epsilon(C) = 8.41$ dex.

4. THE SOLAR CARBON ABUNDANCE AND C/O RATIO

Our determination of the solar carbon abundance (log $\epsilon(C) = 8.39$) from the forbidden line at 8727.1 Å is lower than the most recent estimates based on this line. Our lower abundance is mainly caused for two reasons: a revised $f$-value ($\simeq -0.07$ dex), and the use of a 3D model atmosphere ($\simeq -0.08$ dex).

Other indicators of the solar photospheric carbon abundance are available. C I, CH, and C$_2$ lines have received significant attention in the literature and suggest, when analyzed with empirical or theoretical 1D model atmospheres, higher abundances than our determination from the [C I] line (see, e.g. Grevesse et al. 1991). Pending a full reanalysis with the 3D model, we note that the C abundance from the molecular lines will be reduced in the change from a 1D to 3D model due to the high temperature sensitivity of molecule formation and the presence of cooler gas in the 3D model (Asplund & García Pérez 2001). To assess the effect on the C I lines, we selected the weakest and least blended 13 lines in overlapping lists of solar lines used previously by Biémont et al. (1993) and Stülenburg & Holweger (1990), also Holweger 2001. Analysis of the published equivalent widths for the center of the solar disk spectrum with the $gf$-values in the NIST database and the 3D model gives the LTE abundance log $\epsilon(C) = 8.44 \pm 0.06$. NLTE 3D calculations are not available, but if the 1D corrections for NLTE effects from Stülenburg & Holweger are adopted, the abundance is lowered to log $\epsilon(C) = 8.42 \pm 0.06$, a value in harmony with our result from the [C I] line. Our preliminary conclusion is that the lower carbon abundance is not contradicted by other indicators.

Combining the updated solar abundances of carbon and oxygen from the forbidden lines, we obtain a number-density ratio C/O = 0.50 $\pm$ 0.07. Independent estimates of the C/O ratio can be obtained for the solar wind and the corona. The C/O ratio has been measured from gamma-rays produced by the interaction of particles produced in solar flares with the surrounding medium. Solar Maximum Mission (SMM) data for a flare observed in 1981 yielded C/O = 0.42 $\pm$ 0.09 (Murphy et al. 1990; Fludra et al. 1998). Ramaty et al. (1996) derived 0.35 $<$ C/O $<$ 0.44 for 19 events observed by SMM. More recently Murphy et al. (1997) obtained 0.54 $\pm$ 0.04 from CGRO data of a flare observed in 1991. Solar energetic particles detected near Earth can themselves be studied to determine relative abundances. Reames (1995) reviews solar energetic particles derived from solar energetic particles. Compared to photospheric abundances, elements with a low first-ionization potential (FIP) ($\lesssim 9$ eV) are enhanced in the corona, but those with a higher FIP are not. As carbon and oxygen have a similar, high, FIP, this effect is not expected to disturb their ratio greatly from its photospheric value. For ‘gradual’ events associated with coronal mass ejections, the C/O ratio shows very little variation from one event to another: Reames gives C/O = 0.465 $\pm$ 0.009. For events associated with flares, C/O = 0.434 $\pm$ 0.030. These results are in good agreement with our ‘forbidden’ photospheric value.

The revised abundances of carbon and oxygen in the Sun compare very well with the abundances (gas plus dust) derived from recombination lines in the Orion nebula (Esteban et al. 1998): log $\epsilon(C) = 8.49 \pm 0.12$, and log $\epsilon(O) = 8.72 \pm 0.07$ (C/O = 0.59). They are also in good agreement with the average values found in B-type stars in the field: log $\epsilon(C) = 8.31$, and log $\epsilon(O) = 8.58$ (C/O = 0.54), as well as in clusters: log $\epsilon(C) = 8.35$, and log $\epsilon(O) = 8.69$ (C/O = 0.46) (Kilian 1992, 1994; Adelman Robinson & Wahlgren 1993; Gies & Lambert 1992; compiled by Snow & Witt 1996).

Revision of the solar C and O abundances using their forbidden lines brings these abundances into line with recent results for B stars and the Orion nebula. One may speculate that this close correspondence in compositions may extend to other elements, for example, nitrogen, through revisions to either the solar, stellar or nebular abundances. Unfortunately, the [N I] lines are too weak for positive identification in the solar spectrum (Lambert & Swings 1967b). Nitrogen is represented by weak N I lines for which Holweger (2001) gives log $\epsilon(N) = 7.93 \pm 0.11$ after including NLTE effects and a correction for granulation. Combining the N/O ratios measured for solar energetic particles with the photospheric abundance of oxygen gives a nitrogen abundance which is about 0.1 dex lower than Holweger’s, and in better agreement with nearby B stars and the gas in Orion.

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