

## A REAPPRAISAL OF THE SOLAR PHOTOSPHERIC C/O RATIO

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### ABSTRACT

An 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  $\log \epsilon(\text{C}) = 8.39 \pm 0.04$  dex. Combining this result with our parallel analysis of [O I]  $\lambda 6300$ , we find  $\text{C/O} = 0.50 \pm 0.07$ , 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

Not infrequently, the pursuit of quantitative stellar spectroscopy 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  $\log \epsilon(\text{C}) = 8.592 \pm 0.108$  and  $\log \epsilon(\text{O}) = 8.736 \pm 0.078$  on the usual scale with  $\log \epsilon(\text{H}) = 12.0$ . These results based on one-dimensional non-LTE analyses of permitted lines of C I and O I include corrections for the effects of solar granulation based on two-dimensional modeling.<sup>1</sup> Prior to Holweger's reassessment, the accepted carbon abundance was lower [ $\log \epsilon(\text{C}) = 8.52 \pm 0.06$ ], and that of oxygen higher [ $\log \epsilon(\text{O}) = 8.83 \pm 0.06$ ; 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 1. 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 lead 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<sub>2</sub> 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 Letter, we reconsider the carbon abundance provided

<sup>1</sup> We note that Holweger defines the granulation corrections as the difference between the two-dimensional result and the case for the one-dimensional spatial average of the two-dimensional model atmosphere. Holweger's approach therefore only accounts for the temperature inhomogeneities but not the different overall temperature structures in hydrodynamical and hydrostatic models. Finally, we note that there are systematic differences between two dimensions and three dimensions (Asplund et al. 2000a)

by the forbidden carbon line at 8727 Å. Our reanalysis follows our successful study of the forbidden oxygen line at 6300 Å, which gave the abundance  $\log \epsilon(\text{O}) = 8.69 \pm 0.05$  with a three-dimensional hydrodynamical model photosphere simulating the solar granulation (Allende Prieto, Lambert, & Asplund 2001b). The principal advantages of a forbidden line over permitted lines are twofold: (1) the line's *gf*-value is most probably more accurately known than the *gf*-values of the permitted lines, and (2) 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. (2001b) 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. 2000b 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  $v \sin i = 1.9 \text{ km s}^{-1}$ ) 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 broadening was evaluated using the Unsöld's approximation (Unsöld 1955) for the [C I] line and the neighboring Si I line.

The line [C I]  $\lambda 8727.1$  was identified in the solar spectrum by Lambert & Swings (1967a). They remarked on a potential blending line of Fe I but deemed its contribution to be negligible. Kurucz (1993)<sup>2</sup> calculated  $\log gf = -3.93$  for this iron line, which leads to an equivalent width of  $\sim 0.5 \text{ mÅ}$ . Kurucz also

<sup>2</sup> See <http://kurucz.harvard.edu>.

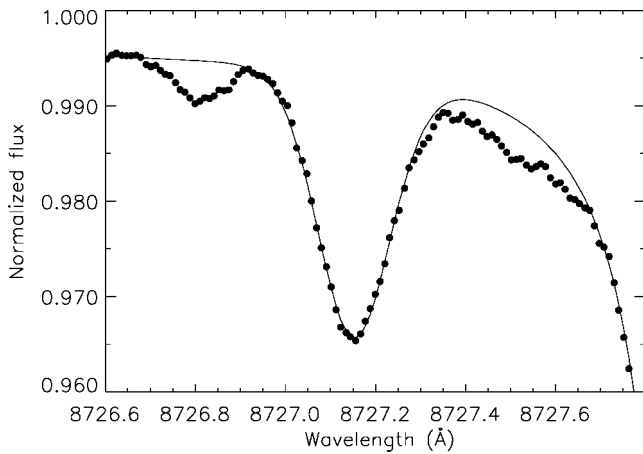


FIG. 1.—Comparison between the observed (filled circles) and synthetic line profiles for [C I] at 8727.1 Å. Four parameters have been adjusted to minimize the  $\chi^2$ : the wavelength of the [C I] line, a multiplicative correction to the continuum level, the strength of the strong Si line at 8728.0 Å ( $\log [gf\epsilon(\text{Si})]$ ), and the carbon abundance, which is found to be  $\log \epsilon(\text{C}) = 8.39 \pm 0.04$  dex.

calculated the transition probabilities for the other five lines in the multiplet, and four of them appear in the solar spectrum. Using the measured equivalent widths ( $12 \text{ m}\text{\AA} \leq W_\lambda \leq 40 \text{ m}\text{\AA}$ ) to scale the  $\log gf$ 's of these four lines, we estimate an equivalent width of  $\sim 0.18 \pm 0.13 \text{ m}\text{\AA}$ .<sup>3</sup> 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:  $0.11 \pm 0.02 \text{ m}\text{\AA}$ . 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 [C I] 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  $8727.133 \pm 0.009 \text{ \AA}$  (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 that have converged to  $A = 0.640 \text{ s}^{-1}$  or  $\log gf = -8.136$  (see Galavis, Mendoza, & Zeppen 1997 and Hibbert et al. 1993). A strong Si I line affects the continuum in the vicinity of the [C I] line. The National Institute of Standards and Technology (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 [C I] lies in scan 13, which includes the telluric O<sub>2</sub> 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 ratio of 2600.

The Si I line dominates the shape of the local continuum in the region of the [C I] line. The abundance of silicon has been recently studied using the same three-dimensional model atmosphere employed here (Asplund 2000). Recent one-dimensional non-LTE 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  $\log [gf\epsilon(\text{Si})]$  and a multiplicative correction to the local continuum level as free parameters with which to adjust the continuum in the vicinity of the [C I] 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 the Kitt Peak National Observatory and the Sun at the time of the observations has been corrected typically within several meters per second, but other factors (such as the setting of the frequency scale in the Fourier transform spectrograph [FTS], the conversion to air wavelengths, the correction of individual scans with partial wavelength coverage, the change of velocity shift over long integrations, etc.) can degrade the absolute accuracy of the wavelength scale up to 0.1 km s<sup>-1</sup> (Kurucz et al. 1984). The gravitational redshift for photospheric photons intercepted at Earth is  $V_g \approx GM_\odot/(R_\odot c) \approx 0.6336 \text{ km s}^{-1}$ . Seasonal variations produced by the ellipticity of Earth's orbit are about 0.1 m s<sup>-1</sup>; Earth's surface gravity induces a correction of about 0.2 m s<sup>-1</sup>; and uncertainties in the solar radius and  $GM_\odot$  can hamper  $V_g$  by about 0.3 m s<sup>-1</sup>. We are using a hydrodynamical model atmosphere that has been shown to predict the convective shifts of photospheric lines of weak and moderate strength within 0.1 km s<sup>-1</sup> (Asplund et al. 2000b). Therefore, we should be able to predict the measured wavelength of [C I] with an uncertainty of about 0.15 km s<sup>-1</sup> ( $\approx 0.004 \text{ \AA}$ ), 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 with 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 Figure 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 [C I] by less than 0.001 Å. Our best fit yielded a reduced  $\chi^2$  (37 frequencies and

<sup>3</sup> The quoted uncertainties in this Letter represent 1  $\sigma$  values.

4 degrees of freedom) of 0.87, and therefore the chance probability for this is  $P = 0.3$ . These figures are based on the signal-to-noise ratio of  $\sim 2100$  derived by examination of an apparently clean segment of the spectrum around  $8731.7 \text{ \AA}$ . Figure 2 shows the variation of the 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  $8727.139 \pm 0.004 \text{ \AA}$ , after correction for the gravitational redshift. The synthetic spectra predict a blueshift of about  $0.25 \text{ km s}^{-1}$  for the line, i.e., a laboratory wavelength of  $8727.146 \text{ \AA}$ . This differs from Moore's (1993) wavelength of  $8727.126 \text{ \AA}$  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 that imply revised energies for the ground configuration. These revisions predict a wavelength of  $8727.141 \text{ \AA}$  in good agreement with our solar-based wavelength, even though the uncertainty remains at about  $0.01 \text{ \AA}$ .

The internal uncertainty in the fit for the carbon abundance can be estimated as 0.01 dex by confronting the expected accuracy in  $\lambda_{[\text{C I}]}$  ( $0.004 \text{ \AA}$ , which includes the observational share of the error) with Figure 2. Judging from the scatter in the most recently calculated  $A$ -values, the derived carbon abundance is hardly affected by this factor ( $\sigma[\log \epsilon(\text{C})] \approx 0.005 \text{ dex}$ ). 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  $\log \epsilon(\text{C})$  by  $\approx 0.03 \text{ dex}$ . Conservatively, we derive  $\log \epsilon(\text{C}) = 8.39 \pm 0.04 \text{ dex}$ . As shown by Stürenburg & Holweger (1990), the forbidden line at  $8727.1 \text{ \AA}$  is immune to departures from LTE, and therefore our LTE calculation of the line formation in a three-dimensional LTE model is likely to provide a reliable abundance.

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

#### 4. THE SOLAR CARBON ABUNDANCE AND C/O RATIO

Our determination of the solar carbon abundance [ $\log \epsilon(\text{C}) = 8.39$ ] from the forbidden line at  $8727.1 \text{ \AA}$  is lower than the most recent estimates based on this line. Our lower abundance is mainly caused by (1) a revised  $f$ -value ( $\approx -0.07 \text{ dex}$ ) and (2) the use of a three-dimensional model atmosphere ( $\approx -0.08 \text{ dex}$ ).

Other indicators of the solar photospheric carbon abundance are available. C I, CH, and C<sub>2</sub> lines have received significant attention in the literature and suggest, when analyzed with empirical or theoretical one-dimensional 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 three-dimensional model, we note that the C abundance from the molecular lines will be reduced in the change from a one- to three-dimensional model because of the high-temperature sensitivity

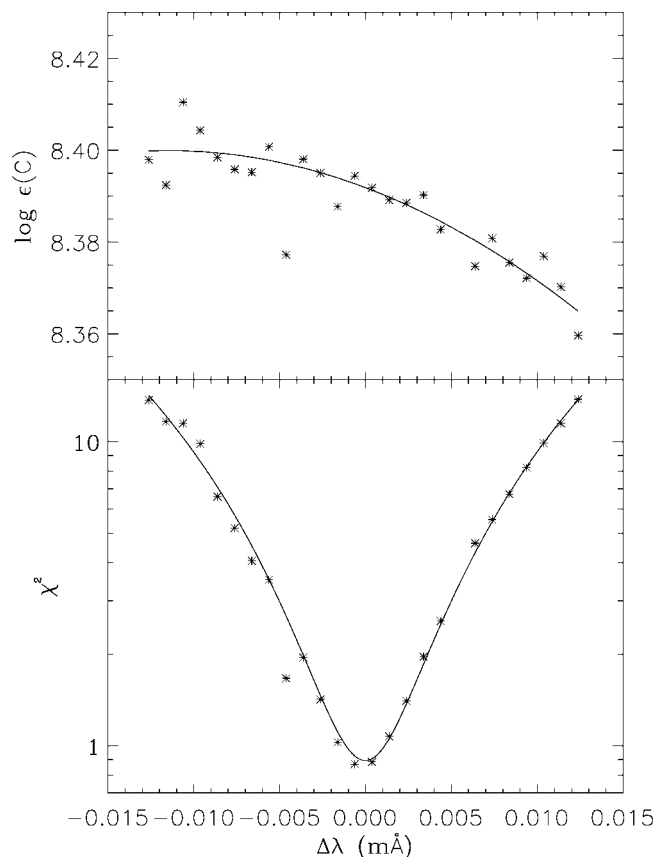


FIG. 2.—Derived carbon abundance and minimum value of the reduced  $\chi^2$  as a function of the displacement of the central wavelength for the [C I] transition. The best fit is achieved for  $\lambda_{[\text{C I}]} = 8727.139 \pm 0.004 \text{ \AA}$ , which is adopted as the zero wavelength shift in the figure. The solid lines are least-squares second-order polynomials fitted to the data.

of molecule formation and the presence of cooler gas in the three-dimensional 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 Stürenburg & Holweger (1990, see 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 three-dimensional model gives the LTE abundance  $\log \epsilon(\text{C}) = 8.44 \pm 0.06$ . Non-LTE three-dimensional calculations are not available, but if the one-dimensional corrections for non-LTE effects from Stürenburg & Holweger are adopted, the abundance is lowered to  $\log \epsilon(\text{C}) = 8.42 \pm 0.06$ , 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  $\text{C/O} = 0.50 \pm 0.07$ . 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  $\text{C/O} = 0.42 \pm 0.09$  (Murphy et al. 1990; Fludra et al. 1999). Ramaty, Mandzhavidze, & Kozlovsky (1996) derived  $0.35 < \text{C/O} < 0.44$  for 19 events observed by *SMM*. More recently, Murphy et al. (1997) obtained  $0.54 \pm 0.04$  from *Compton Gamma Ray Observatory* data of a flare observed in 1991. Solar energetic particles detected near Earth can themselves be

studied to determine relative abundances. Reames (1995) reviews coronal abundances derived from solar energetic particles. Compared with photospheric abundances, elements with a low first-ionization potential (FIP;  $\leq 9$  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 for-

bidden 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 non-LTE 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 that is about 0.1 dex lower than Holweger’s, in better agreement with nearby B stars and the gas in Orion.

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