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DETERMINING INTERSTELLAR CARBON ABUNDANCES FROM STRONG-LINE TRANSITIONS

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ABSTRACT

Carbon is arguably the most important element in the interstellar medium, yet its abundance in gas and dust is poorly understood due to a paucity of data. We explore the possibility of substantially increasing our knowledge of interstellar carbon by applying and assessing a new method for determining the column density of the dominant ion of interstellar carbon in diffuse neutral lines of sight. The method relies on profile fitting of the strong transition of C II at 1334 Å in spectra continuum normalized with stellar models. We apply our method to six sight lines for which the carbon abundance has previously been determined with a weak intersystem absorption transition. Our strong-line method consistently shows a significantly lower gas-phase C abundance than the measurements from the weak lines. This result implies that more carbon could reside in dust than was previously thought. This has implications for dust models, which often suffer from a lack of sufficient carbon to plausibly explain extinction. There is no immediately clear explanation for the difference found between the strong- and weak-line C II determinations, but there are indications that the results from the method presented here have advantages over the weak-line column densities. If this is the case, then the reported oscillator strength for the C II transition at 2325 Å may be too small. Our findings further suggest that damping wings modeled with a single absorption component may not produce accurate abundances. This problem could affect a large number of H I abundances determined through absorption line analysis that are reported in the literature.

Key words: ISM: abundances – line: profiles – methods: analytical

1. INTRODUCTION

Determining column densities for some of the most abundant elements in the interstellar medium (ISM) can be elusive. In some cases, the difficulty arises because the absorption transitions for the dominant ion have either very large or very small oscillator strengths. This is the case for carbon, which has several important functions in interstellar environments. In the gaseous form, C plays a crucial role in interstellar molecular chemistry and interstellar cloud cooling through fine structure lines. Carbon that exists as dust, evidenced by spectral features attributed to amorphous carbons (Duley & Williams 1981), graphite (Draine 1989), and polycyclic aromatic hydrocarbons (Joblin et al. 1992; Draine & Li 2007), may be the main heat source for the diffuse ISM (Bakes & Tielens 1994) and the dominant contributor to interstellar extinction (Mathis 1996; Whittet et al. 1997; Draine 2003). Without knowing the abundance of C in the gas and dust phases of the ISM, these processes cannot be fully understood.

The dominant carbon ion in diffuse neutral interstellar clouds is C II; it produces very strong features at 1036 and 1334 Å ($\log f\lambda = 2.232$ and 2.106, respectively; Morton 2003) and a weak intersystem feature at 2325 Å ($\log f\lambda = -3.954$; Morton 2003). Thirteen of the 14 neutral-cloud interstellar C abundances currently reported in the literature are determined from the 2325 Å transition of C II (Hobbs et al. 1982; Cardelli et al. 1993, 1996; Sofia et al. 1997, 1998, 2004); one determination is from 158 μm emission (Dwek et al. 1997). Absorption from the weak transition was favored for deriving abundances because it is on the linear portion of the curve of growth (Cartledge et al. 2003); however, these determinations are few because of the strict requirements for high spectral resolution and high signal-to-noise observations.

The strong transitions of C II have been basically ignored in the determination of interstellar carbon abundances because of the difficulties involved in extracting accurate column densities from the data. Specifically, it was nearly impossible to get reliable column densities by fitting damping wings to a complex, multi-component absorption profile that was normalized with an uncertain stellar continuum. Although continuum reconstruction methods remain the most used for determining other species' abundances, such as interstellar H I (e.g., Diplas & Savage 1994; Shull & van Steenberg 1985), strong-line methods are prone to large uncertainties when the stellar continuum and absorption component structure are not well defined. The lack of a reliable process to extract information from the strong-line carbon transitions was unfortunate because a substantial archive of high-quality strong C II observations exists in the Space Telescope Science Institute's (STScI) archive of data.

In this paper, we explore a method whereby reliable interstellar C II abundances can be extracted from the strong transition feature at 1334 Å. In Section 2, we describe the method and the data to which it is applied. Section 3 gives the results from the strong-line abundance determinations and their implications.

2. DATA AND ABUNDANCE DETERMINATION METHOD

Our goal is to determine reliable interstellar C II column densities from the strong 1334 Å transition through profile fitting of the interstellar absorption feature. To do this properly requires high-resolution, high signal-to-noise spectra, accurate continuum fitting, and some knowledge of the sight-line component structure. In order to assess the results, it would be useful to compare our column densities with determinations made from the weak absorption transitions along the same sight lines.

2.1. Data Sample

We used the target sight lines of Sofia et al. (2004) for our study, specifically HD 27778, HD 37021, HD 37061, HD 147888, HD 152590, and HD 207198. We used this sample because each of the targets has the required high-quality observations of the strong 1334 Å transition as well as reported C ii abundances from the weak-line transitions at 2325 Å, to which our results can be compared. Further, the available observations for these sight lines contain other spectral features that are needed for determining total carbon abundances (e.g., CO, C i, C ii*, H i, and H_2). None of the 1334 Å C ii transitions used here have been exploited previously to determine interstellar carbon abundances.

The data for this study were taken from the STScI archive and relied on the standard pipeline calibration available as of 2008 August. The spectra are all Space Telescope Imaging Spectrograph (STIS) echelle (E140H) observations taken for one of the two *Hubble Space Telescope* (*HST*) Guest Observer programs, GO 8273 (HD 27778, HD 37021, HD 37061, HD 147888, and HD 207198) or GO 9855 (HD 152590). Descriptions of the observations can be found in Cartledge et al. (2001) and Cartledge et al. (2008), respectively. When more than one observation was made for an object, the individual spectra were merged with a weighted co-addition. The associated errors were propagated accordingly.

2.2. Continuum Fitting

The pipeline-calibrated STIS spectra are in units of flux and heliocentric wavelengths. In order to model the absorption, it was necessary to normalize the line flux to the continuum level. As noted above, this is one of the difficult processes that made working with the strong-line data unreliable in the past. We have solved the problem of accurately separating the Lorentzian damping wings from the continuum by using models to fit the stellar spectra. Specifically, we use the library of synthetic spectra of stars covering the ultraviolet wavelength range produced by the Instituto Nacional de Astrofisica, Optica y Electronica (INAOE, Mexico), the Brera Astronomical Observatory, and the Bologna Astronomical Observatory (Rodriguez-Merino et al. 2005). The group's grid of models, which cover a large range of temperatures for various surface gravities and metallicities, is computed with the Kurucz (2003) set of model atmospheres by means of the ATLAS9/SYNTHE code (Kurucz 2005). The models are made available through the UVBLUE web site at http://www.inaoep.mx/~modelos/uvblue/uvblue.html.

Because the stellar models are not continuous in parameter space, it is necessary to modify the available synthetic spectra to best fit the observed stellar continuum. The first step in our analysis method identifies the closest-fit model to our data that exists in the UVBLUE sample. We do this by trimming the calibrated STIS data to heliocentric wavelengths of 1332.25–1336.75 Å, which is approximately ±500 km s^{-1} from the transition line center. We adjust the flux level by dividing all values by the average flux in the trimmed wavelength range. This allows us to work with flux numbers that are approximately 0–10 rather than 10^{-10} or smaller, thereby avoiding some computational underflow issues. The uncertainties in the data values, as contained in the calibrated data file delivered by the *HST* archive, are also divided by the average flux value. Next, we interactively flag interstellar lines in the spectrum so that they do not interfere with the continuum determination.

In order to find the best stellar model for our targets, we compare the trimmed and normalized STIS data with each of the solar abundance models in the UVBLUE library. The models, which have lower resolution than the *HST* data, are mapped to the wavelengths of the trimmed STIS observations so that flux values can be compared at each STIS point. The fact that the model data have about one-tenth the spectral resolution of the STIS observations should not affect our results greatly since the stars that we observe generally have high rotation velocities that smear out the stellar spectrum. The UVBLUE library does not have a fine grid of metallicities, so we use only the solar abundance models, plausibly assuming that most of the young, Galactic O and B stars should not deviate drastically from the Sun. However, differences in metallicities must be accounted for. We accomplish this by converting the UVBLUE spectra into line optical depths (using the continuum provided by the UVBLUE library) and apply a single multiplication factor to all of those optical depths to better fit the STIS data. We acknowledge that this method is simplistic in assuming that ratios between all of the elements are solar and that only the gross level differs. However, it would be impractical to try to be more refined than this with the individual elemental abundances.

We allow other modifications to the UVBLUE models in order to better fit the STIS data. The model data are shifted in wavelength in order to account for the radial velocity of the star. The synthetic spectra are also modified to account for the stellar rotation. Finally, the model data are normalized with a third-order polynomial function in order to account for the sight-line reddening and any other sources of large-scale structure in the continuum. The polynomial terms above the zeroth order are always small, as would be expected. The zeroth-order term simply accounts for the continuum level offset between the STIS data and the model.

In order to explore parameter space and find the best fits in our method, we rely on the fitting programs of Markwardt (2009) that are available from http://purl.com/net/mpfit. This suite of IDL programs allows for the simultaneous optimization of multiple fit parameters for a user-supplied function. The seven parameters that are simultaneously fitted during the continuum fitting process are the metallicity multiplier, the radial velocity shift, the four coefficients to the third-order polynomial, and the rotational velocity. The fit is weighted by the data uncertainties, so the regions of the STIS spectrum that were flagged as containing interstellar absorption were effectively ignored in the fitting process. The chi-squared values for the best fit are calculated for each model, and the synthetic spectrum with the lowest χ^2 value is chosen to represent the stellar continuum used for normalization.

Table 1 shows the UVBLUE models and fit parameters that best reproduced the STIS continuum data, and the resulting reduced chi-squared values. As expected, the model fits are not exact but, with the possible exception of HD 152590, they seem to represent the stellar continuum well. Figure 1 shows the range of continuum fits in our sample by displaying the models and normalized spectra for HD 37021 and HD 152590, which have the smallest and largest χ^2 values, respectively. Uncertainties in the fits could be the result of several factors, among which the most likely are the application of the solar abundance pattern to all of the stars, and possible spectral contamination from nearby stars that were in the STIS aperture during the observations (four of the six stars are flagged in the SIMBAD database as being binary or double system). The reduced chi-squared values provide an indication of how well the continuum is fitted, and

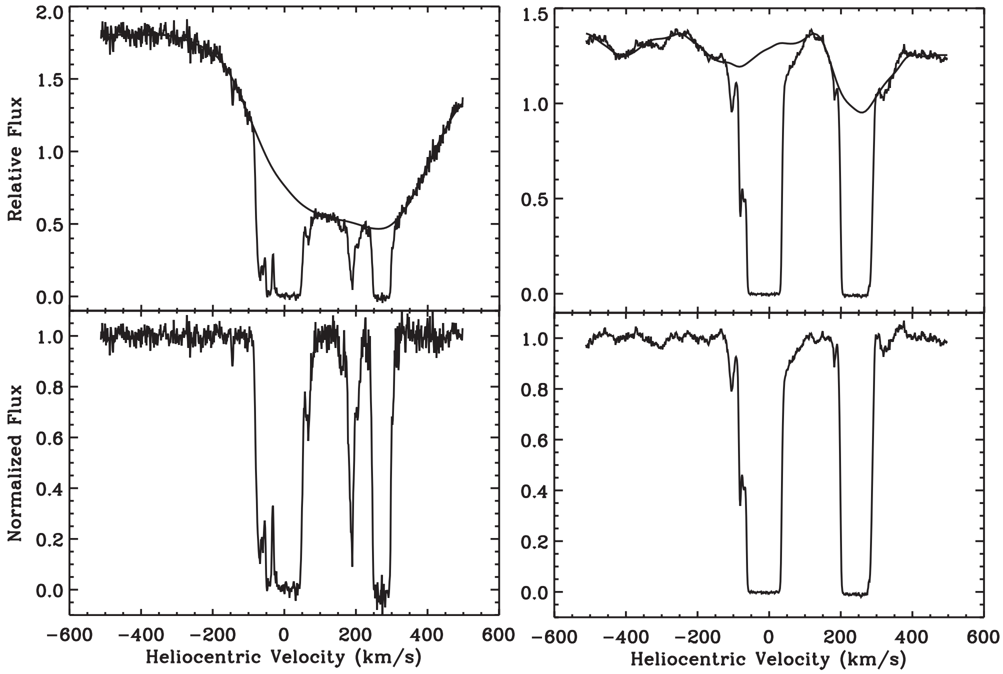

Figure 1. Continuum fits (upper panels) and normalized spectra (lower panels) for the observations of HD 37021 (left) and HD 152590 (right). The feature at 180 km s^{-1} toward HD 37021 is from C II 1334 Å absorption.

Table 1
Continuum Fit

Star	Model Parameters		Spectral[a] Type	Best-fit Parameters			Reduced χ^2
	T (K)	log g		$\tau_{\rm corr}$	$V_{\rm Rot}$	$V_{\rm Rad}$	
HD 27778	18000	3.5	B3 V	0.74	107	14	0.98
HD 37021	22000	4.0	B0 V	1.06	160	24	0.70
HD 37061	18000	4.0	B1 V	0.93	154	31	0.80
HD 147888	19000	3.0	B3 V	0.64	97	−6	1.22
HD 152590	42500	5.0	O7.5 V	1.43	67	−45	2.31
HD 207198	47500	5.0	O9 II	1.09	56	−21	0.75

Note. [a] From the SIMBAD database.

therefore how accurate the final derived carbon abundances are likely to be.

2.3. Carbon Abundances

To determine the carbon abundances in the sight lines, we performed component profile fitting of the strong C II absorption lines. The atomic constants for the transitions were taken from Morton (2003). The strength of the 1334 Å transition makes it difficult to properly identify the absorption component structure along the line of sight, and also requires that we take isotopes and excited states of C II into account.

In order to find the sight-line component structure, we fit weak-to-moderate strength absorption lines of a species that should cohabit with the C II. For this study, we simultaneously fit five transitions of Fe II at 2249, 2260, 2344, 2374, and 2382 Å, which have oscillator strengths that vary by more than two orders of magnitude. This complement of lines has suitable strengths so that the dominant absorbing components, those that contribute significantly to the sight lines' total column densities (and therefore to the damping wings of the strong C II lines), can be identified.

We again make use of the MPFIT fitting routines to optimize the component-fit parameters for the Fe II absorption features. Our routines simultaneously fit column densities, *b*-values, and central velocities for the multiple absorbing components in all five transitions. We fit the iron absorption with the minimum number of components that gives us a reasonable fit to the data. For our purposes, we claim that a fit is sufficient when the reduced χ^2 value is 1.25 or less. From these Fe II component fits, we have the radial velocities and Doppler spread parameters for the major C II absorbing components along the sight lines.

The MPFIT routines are also used to find the C II column densities along the sight lines, in this case using the constraints determined from fitting the iron profiles. For some of the sight lines, we needed to add weak components in the wings to account for absorption features that are visible with the strong carbon transition, but that were not apparent in the weaker iron data. Although these add insignificantly to the total C II abundances, the additional components are necessary for properly fitting the Lorentzian damping wings.

The C II transitions are well separated from other absorption transitions except for a very weak line of each of Ni II and P III (Morton 2003), neither of which should be detectable in the sight lines used here. There are, however, multiple transitions of C II that overlap and must be accounted for, particularly in the higher column density sight lines. Therefore, we fit all of the following transitions simultaneously in our determination of the C II abundances: ^{13}C II 1334.519 Å, ^{12}C II 1334.5323 Å, ^{13}C II* 1335.649 Å, ^{12}C II* 1335.6627 Å, ^{13}C II* 1335.692 Å, and ^{12}C II* 1335.7077 Å. For the fits, we hardwire in the terrestrial ^{12}C/^{13}C ratio of 92.5, but allow the C II/C II* ratio to vary for each absorbing component.

Figure 2 shows the C II and C II* fits toward a simple line of sight, HD 27778, and a complex line of sight, HD 37061. The weak absorption features in the HD 37061 profile, e.g., those around −140 km s^{-1} and +80 km s^{-1}, are examples of components that were not evident in the Fe II absorption lines but were added to the C II profile fit. The absorption components that overlap the damping wings in the HD 37061 sight line increase the uncertainty in the final column density.

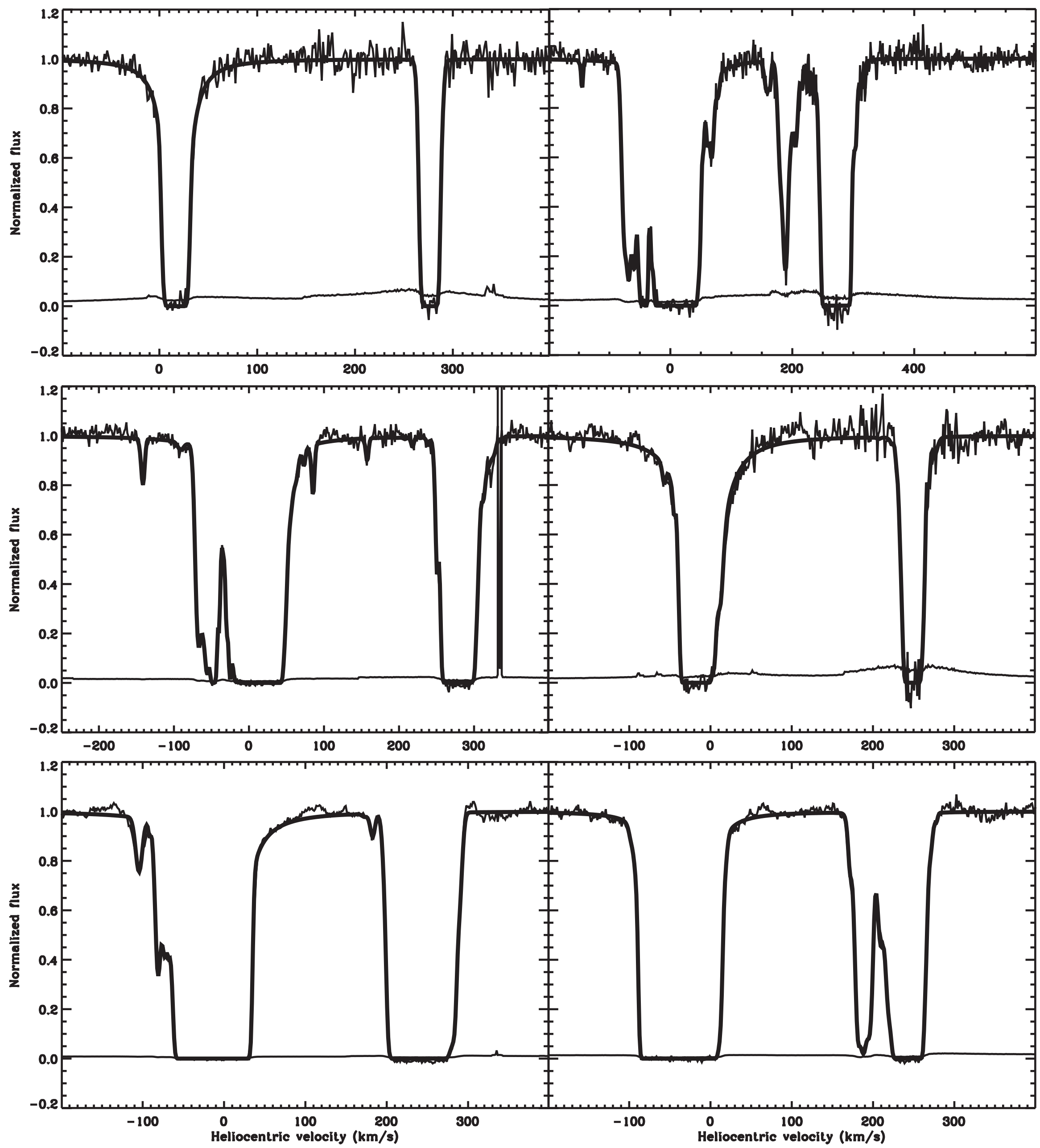

Figure 2. C II component fits to the normalized spectra. The displayed spectra, clockwise from the upper left corner, are for the sight lines toward HD 27778, HD 37021, HD 147888, HD 207198, HD 152590, and HD 37061. The C II features are at the lower velocities and the C II* are at the higher velocities. The uncertainties in the spectral data are shown as a narrow line near the bottom of the graphs.

We calculate a conservative error for the C II column density fits by the following method. We take the optimum component fit to the carbon absorption and its χ^2 as a starting point. We then vary upward the column density of a single carbon absorption component and allow the fitting routines to compensate by varying the strengths of all other carbon absorbing components, and recalculate the χ^2. We continue to raise the single component's column density until the fitting routines can no longer fit the absorption with a χ^2 value that is within 1.0 of the original value. We then repeat the exercise by lowering the component's column density; here we do not reduce the column density below zero. The process is repeated for each individual component of the carbon absorption. We define the uncertainty in our C II fit by the maximum excursion upward or downward for any component in the sight line. Not surprisingly, many of our uncertainties are of the order of 10^{16}–10^{17} cm^{-2}, which is approximately where an absorption line from the C II 1334 Å transition would go from the flat to the square-root portion of the curve of growth. Our method is a conservative approach to defining the C II profile fitting uncertainty, but we note that this error does not take into account any error in the continuum fit. The true uncertainties in the strong-line column densities can therefore be larger than those reported here.

While testing our strong-line method, we found that the exact component structure and the number of absorbers along the sight line have little effect on the abundances determined. Our results generally stayed within the final 1σ error range if we included four or more components along the sight lines (instead of 20 or more that are actually present). If we tried to place all of the column density in fewer than four components, then our fits were

Table 2
Carbon Abundances

Star	Strong N(C II)[a] 10^{17} cm^{-2}	Weak N(C II)[b] 10^{17} cm^{-2}	Strong/Weak Ratio	Strong N(C II*) 10^{15} cm^{-2}	$(C/H)_{Gas}$[c] 10^{-6}	$(C/H)_{Dust}$[d] 10^{-6}
HD 27778	1.99 ± 0.6	$<2.19 \pm 0.73$	$>0.91 \pm 0.41$	0.2	99[e] $\pm$ 31	189[e] $\pm$ 41
HD 37021	4.35 ± 1.2	6.56 ± 2.23	0.66 ± 0.29	2.9	91 ± 33	198 ± 42
HD 37061	5.27 ± 1.5	8.79 ± 1.31	0.60 ± 0.19	4.1	98 ± 34	191 ± 44
HD 147888	5.66 ± 0.8	9.97 ± 1.75	0.57 ± 0.13	3.9	96 ± 20	192 ± 34
HD 152590	6.29 ± 1.4	16.2 ± 3.3	0.39 ± 0.12	3.7	273 ± 71	15 ± 76
HD 207198	3.23 ± 0.7	9.66 ± 2.67	0.33 ± 0.12	1.6	69[f] $\pm$ 21	220[f] $\pm$ 34

Notes.
[a] Values include the measured C II* abundances listed in Column 5.
[b] Values are from Sofia et al. (2004).
[c] H abundances from Sofia et al. (2004) using values from Cartledge et al. (2001, 2003).
[d] Dust abundances assume that the ISM has the proto-Sun abundances reported by Lodders (2003).
[e] C abundances include 0.29×10^{17} cm^{-2} found in CO (Federman et al. 1994) and C I (Sofia et al. 2004).
[f] C abundances include 0.06×10^{17} cm^{-2} found in C I (Sofia et al. 2004).

not likely to represent well the final abundance determinations that we obtained from the full component structure. While this finding bodes well for future uses of the strong-line method, it does bring into question the reliability of H abundances that are often determined by assuming a single absorption component.

3. RESULTS AND DISCUSSION

The column densities that we derive for interstellar C II are listed in Table 2. The value found for each sight line is lower than that determined by Sofia et al. (2004) from the weak transition lines. This could indicate that there is an error in the reported oscillator strength for one of the transitions. If this were the case, one would expect the ratio of strong-to-weak line determinations of the column densities to have the same ratio in all of our sight lines. Alternatively, the difference in abundances could be the result of errors in the continuum fitting, although it would be unlikely that all of the strong-line determinations would be lower than those from the weak lines. We acknowledge, however, that we are dealing with a small sample, so the latter explanation is not implausible.

The uncertainties in the column densities from both the weak-line and strong-line determinations are rather large. If one takes into account the 1σ errors in the ratio of strong-to-weak line abundance determinations, all of the sight lines, except that toward HD 27778, overlap, around a value of 0.43 (see Table 2). The strong-to-weak ratio toward HD 27778 shown in Table 2 is a lower limit, which could well be within 2σ of the overlap value, and therefore consistent with a constant ratio of 0.43. This result could then indicate that there is indeed an inconsistency between the oscillator strengths of the strong and weak transitions. No uncertainty is listed for the C II 1334 Å oscillator strength in Morton (2003), but strong transitions are generally well measured and accurate. The weak-line oscillator strength in Morton (2003) has a small quoted uncertainty of 0.0031 dex. Even so, if the difference between the strong-line and weak-line C II column densities is the result of poorly determined oscillator strengths, then the most plausible source of error is from the weak line.

The column densities from the strong- and weak-line determinations differ quite a bit, but it is not clear which is more accurate. We will therefore explore how the values from each method relate to other results pertaining to the ISM.

With the exception of the sight line toward HD 152590, the strong-line, gas-phase C/H abundances are consistent with $50–100 \times 10^{-6}$ found by Dwek et al. (1997) in the diffuse ISM using *COBE*'s FIRAS observations of the [C II] 158 μm emission line. In contrast, the weak-line determinations generally do not agree with the Dwek et al. range of C II abundances.

As with the weak-line determination, our HD 152590 sight line C II column density remains anomalously high. However, the strong-line measurement does produce a more plausible carbon abundance because, unlike the weak-line determination, it is below the proto-solar C/H reported by Lodders (2003).

If the gas-phase C abundances found through the strong-line analysis are accurate, then this may solve the problem often encountered by grain models: an apparently insufficient dust-phase carbon abundance needed to explain the observed interstellar extinction (Snow & Witt 1995). Assuming that the ISM is reasonably well represented by solar abundances, the strong-line carbon abundance determinations suggest that approximately 190 atoms of C exist in the form of dust for every million H atoms along the sight lines. This is about 50% more carbon in the dust phase than is implied by the weak-line abundance determinations.

As a byproduct of determining the C II abundances, the column densities of the excited states of the ion (C II*) are also found. For all of our sight-line measurements, these abundances are negligible when compared to the unexcited state. However, based on the weak-line transition of the excited state (at 2326.1126 Å), Sofia et al. (2004) found that the C II* column density toward HD 37061 was $4.65 \pm 0.84 \times 10^{17}$ cm^{-2}, implying that about one-third of the sight line's entire C II abundance was in an excited state. Our strong-line determination does not agree with that result and finds that under 1% of C II is in the excited state toward HD 37061.

The small sample of stars with data that have both a sufficiently high resolution and a high enough signal-to-noise ratio from which to measure the C II abundances limits our conclusions about the accuracy of the strong- versus weak-line determinations. We can however say that the carbon column densities determined from the strong lines are compatible with abundances needed to produce observed extinction, and produced results for the C II and C II* abundances toward HD 152590 and HD 37061, respectively, that are more plausible than those determined from the weak lines. The strong-line transition also allowed a C II column density to be determined toward HD 27778 when only an upper limit could be found from the weak line. So, it does appear that the strong-line measurements have some advantages over the weak-line determinations. A large sample of strong-line C II abundance determinations in conjunction with measured extinction curves along the same sight lines could be useful for further assessing the accuracy of this method.

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