THE ASTROPHYSICAL JOURNAL, 484:820–827, 1997 August 1

ATOMIC PHYSICS WITH THE GODDARD HIGH RESOLUTION SPECTROGRAPH ON THE *HUBBLE SPACE TELESCOPE*. III. OSCILLATOR STRENGTHS FOR NEUTRAL CARBON[1]

J. ZSARGÓ AND S. R. FEDERMAN
Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606
AND
JASON A. CARDELLI[2]
Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085
Received 1996 November 25; accepted 1997 February 28

ABSTRACT

High quality spectra of interstellar absorption from C I toward β^1 Sco, ρ Oph A, and χ Oph were obtained with the Goddard High Resolution Spectrograph on *HST*. Many weak lines were detected within the observed wavelength intervals: 1150–1200 Å for β^1 Sco and 1250–1290 Å for ρ Oph A and χ Oph. Curve-of-growth analyses were performed in order to extract accurate column densities and Doppler parameters from lines with precise laboratory-based *f*-values. These column densities and *b*-values were used to obtain a self-consistent set of *f*-values for all the observed C I lines. A particularly important constraint was the need to reproduce data for more than one line of sight. For about 50% of the lines, the derived *f*-values differ appreciably from the values quoted by Morton.

Subject headings: atomic data — ISM: abundances — ultraviolet: ISM

1. INTRODUCTION

Carbon is one of the most important constituents of the interstellar medium. Its cosmic abundance is comparable to that of nitrogen and oxygen. Carbon provides the majority of the free electrons in diffuse clouds since it is the most abundant element with an ionization potential below the Lyman limit. Carbon ions are an important coolant in this environment. Carbon in its various forms (C I, C II, CO) acts as a diagnostic for physical conditions such as gas density and temperature. For example, each of the fine structure levels of the C I ground state can be populated in diffuse gas. Analysis of the distribution of levels yields estimates for density and temperature (Jenkins & Shaya 1979; Jenkins, Jura, & Loewenstein 1983). The first step in such an analysis is the derivation of column densities, but the derivation from data acquired with the Goddard High Resolution Spectrograph (GHRS) is compromised by the quality of available oscillator strengths. Here we improve the situation for C I by presenting a self-consistent set of *f*-values based on precise laboratory oscillator strengths for specific lines.

There are a large number of C I lines accessible at ultraviolet wavelengths. Since the GHRS provides spectra of high quality with signal-to-noise ratios greater than 100–200 (Cardelli & Ebbets 1994; Fitzpatrick & Spitzer 1994; Lambert et al. 1994), relatively weak, optically thin lines are readily seen in these spectra. We use C I lines of varying strengths from GHRS spectra of β^1 Sco, ρ Oph A, and χ Oph (§ 2) to produce curves-of-growth (COGs) for each fine structure level (§ 3). As was done for S I (Federman & Cardelli 1995), the column density and *b*-value are set from lines with precisely known laboratory-based *f*-values. Comparison of our set of *f*-values with other available data is made in § 4, where directions for further improvement are suggested.

2. MEASUREMENTS

Our *HST* observations of ρ Oph A and χ Oph with grating G160M covered the range 1250–1290 Å and included several C I multiplets and spin-forbidden lines. The data were reduced with procedures to minimize systematic noise (Cardelli & Ebbets 1994), and the IRAF package from NOAO was used to measure the W_λ of each line. In all, 27 C I lines were detected in this range, and the extraction of W_λ for the lines was straightforward apart from some minor problems. In the vicinity of multiplet λ1261, there were strongly saturated Si II and Fe II lines which affected the continuum placement. Moreover, C I λ1277.245 and C I* λ1277.282 [3] were blended and quite optically thick, making these measurements unreliable. We decided not to use them in our analysis. There were two main sources of error in our measurements of W_λ; one was noise and the other was placement of the continuum level. The order of magnitude of these errors was generally similar. As for β^1 Sco, the data on 14 C I lines were based on observations taken with G160M that covered the ranges 1155–1160 Å and 1185–1200 Å. These data were described in detail by Cardelli & Savage (1995), but in essence were processed in a manner identical to those above.

Our results appear in Tables 1 and 2, together with *Copernicus* data (Frisch 1980; Snow & Jenkins 1980; Jenkins et al. 1983). Only nine of our 27 lines for ρ Oph A and χ Oph were observed with the *Copernicus* satellite. For three lines only upper limits of W_λ were available, indicating the level of uncertainty for the *Copernicus* data. Where specific values were provided, the quoted errors are much greater than the ones from *HST* spectra. There was a dis-

[1] Based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

[2] Deceased.

[3] C I, C I*, and C I** correspond to lines originating from $^3P_0$, $^3P_1$, and $^3P_2$ respectively.

TABLE 1

C I Equivalent Widths for ρ Oph A and χ Oph

Wavelength (Å)	W_λ (mÅ)			
	ρ Oph A		χ Oph	
	This Paper	Other Papers	This Paper	Other Papers
		C I $J = 0$		
1280.135	35.24 ± 0.24	...	38.26 ± 0.25	...
1277.245[c]	56.34 ± 0.57	...	...	...
1276.483	21.82 ± 0.39	40.0 ± 4.4[a]	21.91 ± 0.19	29.5 ± 5.0[a]
1270.143	9.20 ± 0.30	...	9.39 ± 0.16	...
1260.736	36.39 ± 0.42	24 ± 6[a]	43.97 ± 0.37	43 ± 4[a], 33 ± 3[b]
		C I $J = 1$		
1287.608	2.15 ± 0.28	...	1.69 ± 0.23	...
1280.597	20.95 ± 0.23	...	19.59 ± 0.23	...
1280.404	18.29 ± 0.23	...	15.41 ± 0.22	...
1279.890	25.58 ± 0.24	...	24.30 ± 0.24	...
1279.056	14.57 ± 0.30	...	12.77 ± 0.24	...
1277.513	29.99 ± 0.46	...	26.58 ± 0.18	...
1277.282[c]	27.59 ± 0.47	...	...	...
1276.750	17.36 ± 0.40	40 ± 10[a]	13.15 ± 0.19	≤ 8.0[a]
1270.408	2.02 ± 0.28	...	2.11 ± 0.15	...
1261.122	25.45 ± 0.44	42 ± 6[a]	23.11 ± 0.32	32 ± 5[a], 23 ± 3[b]
1260.996	22.27 ± 0.42	21 ± 5[a]	15.83 ± 0.29	23 ± 4[a], 18 ± 3[b]
1260.927	24.57 ± 0.42	27 ± 5[a]	28.41 ± 0.37	24 ± 3[a], 21 ± 3[b]
		C I $J = 2$		
1280.847	14.75 ± 0.24	...	10.29 ± 0.22	...
1280.333	18.73 ± 0.24	...	14.44 ± 0.22	...
1279.498	5.09 ± 0.26	...	4.32 ± 0.24	...
1279.229	11.40 ± 0.28	...	10.05 ± 0.23	...
1277.954	5.67 ± 0.37	≤12[a]	4.94 ± 0.18	≤7.8[a]
1277.723	19.96 ± 0.41	...	14.20 ± 0.18	...
1277.550	25.01 ± 0.44	...	25.55 ± 0.18	...
1274.109	3.63 ± 0.31	...	2.62 ± 0.15	...
1261.552	21.12 ± 0.41	≤12[a]	19.65 ± 0.32	≤7.8[a], 24 ± 3[b]
1261.426	15.94 ± 0.42	≤12[a]	13.44 ± 0.32	≤6.8[a], 13 ± 3[b]

[a] Jenkins et al. 1983.
[b] Frisch 1980.
[c] Blended lines, measurements were unreliable.

turbing inconsistency between our results and those of Jenkins et al. (1983) around 1261 Å. As mentioned earlier, strong Si II and Fe II lines affected the continuum fit and could account for the inconsistency. Other than this, our *HST* data and the *Copernicus* ones agree reasonably well. Below 1200 Å for β^1 Sco, three lines were measured with *Copernicus*, and these show satisfactory correspondence with our results. The line λ1188 is blended with a pair of neutral chlorine lines. We accounted for the Cl I contribution by estimating the column density from λ1097 (Bohlin et al. 1983) with the *f*-value of Schectman et al. (1993). The difference in our results for the C I line and those from Snow & Jenkins (1980) likely arises from estimating the contribution from Cl I.

3. ANALYSIS

In order to obtain column densities [N(X)] and Doppler parameters (b-values), we performed COG analyses. Since our *HST* spectra could not resolve individual velocity components, we assumed one dominant component for each line of sight. This assumption was justified in light of the results on K I and Na I D (Hobbs 1975; Welty, Hobbs, & Kulkarni 1994). We also assumed simple Maxwellian line profiles to find the theoretical COG because most lines had modest or negligible optical depths at line center. Values for N and b were obtained by least-squares fit where the data for each line was weighted by the relative uncertainty in W_λ [$\sigma(W_\lambda)/W_\lambda$] and in the *f*-value. An iterative procedure was adopted for our analysis. The multiplets $\lambda\lambda$1261, 1277, and 1280 formed the basis for empirical COGs for the C I lines toward ρ Oph A and χ Oph because their oscillator strengths are known from precise laboratory measurements (Bromander 1971; Goldbach & Nollez 1987; Goldbach, Martin, & Nollez 1989; Haar et al. 1991); we utilized the *f*-values compiled by Morton (1991) from these data. Unfortunately these multiplets alone could not be used to set the COGs because they covered a restricted range in log $f\lambda$. Weak lines with poorly known oscillator strengths, such as λ1270.143 for $J = 0$ and $\lambda\lambda$1287.608, 1270.408 for $J = 1$, had to be incorporated into the analysis, but their small weights caused by large uncertainties in *f*-values limited their effect in the final fit. Using Morton's compilation as the zeroth-order approximation for oscillator strengths, we obtained the best fits with $N(0) = (1.98 \pm 0.10) \times 10^{15}$ cm^{-2} ($b = 2.0 \pm 0.2$ km s^{-1}), $N(1) = (8.52 \pm 0.21) \times 10^{14}$ cm^{-2} ($b = 1.6 \pm 0.2$ km s^{-1}), and

TABLE 2

C I EQUIVALENT WIDTHS FOR β^1 SCO

Wavelength (Å)	W_λ (mÅ)	Others
	C I $J = 0$	
1193.996......	12.60 ± 0.80	...
1193.031......	24.64 ± 1.00[a]	34 ± 1[b]
1192.218......	2.18 ± 0.40	...
1188.833......	17.99 ± 1.00	12 ± 1[b]
1158.324......	10.01 ± 0.65	...
1157.910......	11.56 ± 0.60[c]	...
1155.809......	6.12 ± 0.44	...
	C I $J = 1$	
1193.679......	3.66 ± 0.60	...
1193.009......	12.84 ± 1.00[a]	...
1189.065......	1.87 ± 0.60[d]	...
1188.993......	2.49 ± 0.60[d]	2.2 ± 0.7[b]
1156.028......	1.41 ± 0.52[e]	...
1155.979......	1.89 ± 0.52[e]	...
	C I $J = 2$	
1158.019......	1.22 ± 0.40[a]	...

[a] Blended pair of lines.
[b] Snow & Jenkins 1980.
[c] Blended pair of lines.
[d] Blended pair of lines.
[e] Blended pair of lines.

$N(2) = (4.71 \pm 0.15) \times 10^{14}$ cm^{-2} ($b = 1.3 \pm 0.2$ km s^{-1}) for $J = 0$, 1, and 2, respectively, for ρ Oph A. The corresponding values for χ Oph were $N(0) = (1.30 \pm 0.05) \times 10^{15}$ cm^{-2} ($b = 2.3 \pm 0.3$ km s^{-1}), $N(1) = (5.49 \pm 0.12) \times 10^{14}$ cm^{-2} ($b = 1.6 \pm 0.2$ km s^{-1}), and $N(2) = (3.06 \pm 0.08) \times 10^{14}$ cm^{-2} ($b = 1.1 \pm 0.2$ km s^{-1}).

One could pinpoint "suspicious" lines by looking at the data points and COGs for different sight lines. The C I* line λ1287.608, for example, was above the curve for both ρ Oph A and χ Oph, indicating a need to modify its oscillator strength (see Figs. 1 and 2). For such lines or multiplets, a quantity $Q = \sum_{i=1}^{m} [f_i \cdot X \cdot \lambda_i - C_i^{\chi\,\mathrm{Oph}}]^2 + \sum_{i=1}^{m} [f_i \cdot X \cdot \lambda_i - C_i^{\rho\,\mathrm{Oph}\,A}]^2$ was minimized in order to get adjusted f-values. In this expression m was 1 if we adjusted an individual line or m was the number of lines in a multiplet, $C_i^{\cdots}$ was the value of $f_i \cdot \lambda_i$ derived from the theoretical COGs for different species and lines of sight, and X was a scaling factor for the f-values ($f_{\mathrm{new}} = X \cdot f_{\mathrm{old}}$). If LS coupling applied for a multiplet, all line f-values were corrected simultaneously with a single scaling factor, keeping their ratios unaltered ($m \neq 1$). Whenever LS coupling did not apply, each line was adjusted individually ($m = 1$) as for the forbidden lines.

After arriving at a preliminary set of self-consistent oscillator strengths in the 1250–1290 Å range, we could apply them to our COG for β^1 Sco. In particular, we used the *Copernicus* data for the multiplets $\lambda\lambda$1261, 1329 with precise laboratory f-values (Morton 1991, and references therein) and for C I λ1276.483 with our revised f-value to obtain N and b-values from a COG. For the C I* and C I** lines of the multiplet at 1329 Å, as a first approximation we assumed that the W_λ for each line of the blend was equal to the relative oscillator strength for the line. Within the precision of the *Copernicus* data, the results for the two multiplets were quite similar; however, the λ1261 multiplet was weighted more heavily in our analysis because the

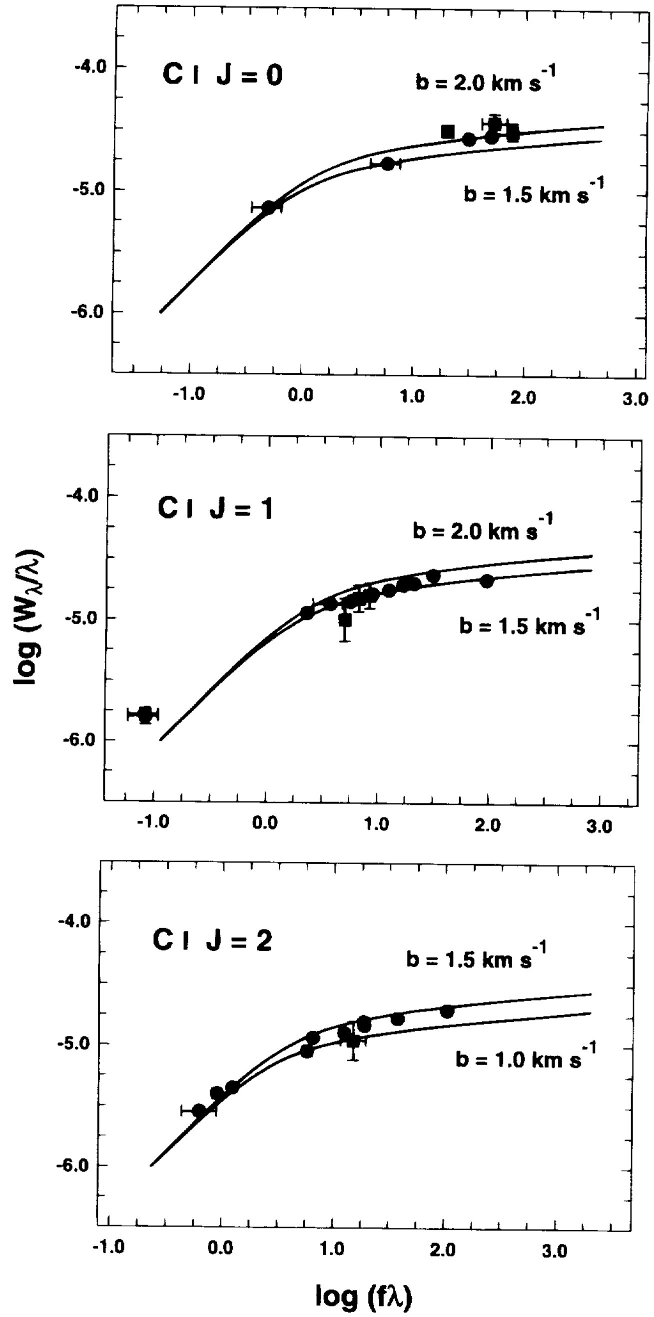

FIG. 1.—Curves of growth for neutral carbon toward ρ Oph A based on f-values in Morton (1991). Filled circles represent our *HST* data, and filled squares are *Copernicus* data (Snow & Jenkins 1980; Jenkins et al. 1983). The solid lines are theoretical curves of growth that best reproduce the data when the refined f-values are used. The initially "suspicious" line at 1287.608 Å noted in the text lies near $\log(W_\lambda/\lambda) = -5.9$ and $\log f\lambda = -1.0$.

lines yielded more tightly constrained column densities. For λ1261, we took a weighted average of the two determinations from *Copernicus* data (Snow & Jenkins 1980; Jenkins et al. 1983), but we note that the results of Jenkins et al. (1983) yielded more consistent column densities. Each set of lines in C I could be fit with a single b-value of 1.8 ± 0.1 km s^{-1} with column densities of $(2.10 \pm 0.32) \times 10^{14}$ cm^{-2}, $(3.61 \pm 0.21) \times 10^{13}$ cm^{-2}, and $(1.66 \pm 0.19) \times 10^{13}$ cm^{-2} for $J = 0$, 1, and 2, respectively. These values were used to obtain a set of self-consistent oscillator strengths from the other lines below 1200 Å seen in *Copernicus* and *HST* spectra.

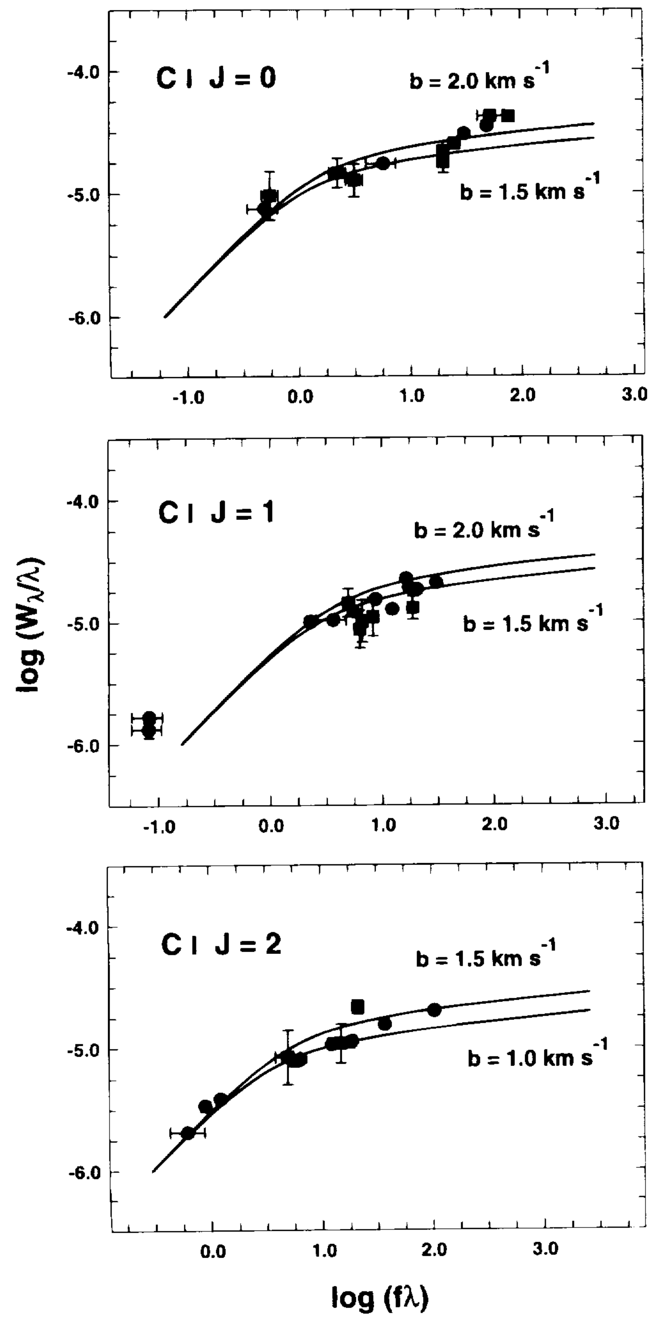

FIG. 2.—Same as Fig. 1 for data toward χ Oph

Two other points should be noted about this portion of the analysis. First, the blended C I* lines $\lambda\lambda$1188.993, 1189.065 of the multiplet at 1189 Å and $\lambda\lambda$1155.979, 1156.028 of the multiplet at 1156 Å were assumed to have an individual W_λ consistent with the relative f-values. Second, blends involving different fine structure levels had the W_λ for the weaker line subtracted from the total W_λ in a self-consistent way, as was done by Federman & Cardelli (1995). Furthermore, the contribution of Cl I to C I λ1188.833 was based on the Cl I column density derived from Cl I λ1097 (Bohlin et al. 1983), as noted above. The empirical COGs before and after modifying oscillator strengths are shown in Figure 3.

The final step in the analysis for ρ Oph A and χ Oph involved incorporating the *Copernicus* measurements, below 1200 Å and above 1300 Å into the empirical COGs with the adjusted oscillator strengths to see if the results for three sight lines were mutually consistent. This is indeed the case, as can be seen by comparing Figures 4 and 5 with Figures 1 and 2. The adjusted oscillator strengths, together with other values, are displayed in Table 3. The columns of this table list the wavelength for the line, the upper level of the transition, our refined f-values, and those of Morton (1991), de Boer & Morton (1979), Goldbach et al. (1989), Nussbaumer & Storey (1984), and Hibbert et al. (1993). A typical uncertainty for our f-values is 10%–20%, with the weakest lines having the greatest uncertainty.

As an additional check on our method, we produced empirical COGs for S I toward ρ Oph A and χ Oph which were based on the f-values derived by Federman & Cardelli (1995). Twelve sulfur lines were detected in the spectrum of each star; Table 4 lists our results for S I. Furthermore, Frisch (1980) measured the absorption from λ1295, and this result was incorporated into the analysis. In all respects, the present analysis mirrored that of Federman & Cardelli (1995): A single velocity component was used, and the contribution from the weaker line or lines of a blend was subtracted from the total W_λ. Figure 6 shows the empirical COGs derived for S I toward the two stars. These COGs show (1) that the f-values suggested by Federman & Cardelli (1995) for gas toward ζ Oph are applicable to other sight lines, and (2) that a b-value of approximately 1.25 km s^{-1} describes the data quite well. The b-value is essentially the value derived from our analysis of absorption from the $J = 2$ level of C I, a result consistent with expectations for the distributions of neutral carbon and sulfur. This analysis indicates column densities for neutral sulfur of $(9.1 \pm 0.8) \times 10^{13}$ cm^{-2} and $(5.8 \pm 0.5) \times 10^{13}$ cm^{-2}, respectively, toward ρ Oph A and χ Oph.

4. DISCUSSION

As revealed in Table 3, our analysis yields significant revisions to f-values for 24 lines when comparison is made with previous work. Above 1200 Å only forbidden lines needed significant adjustments to their oscillator strengths. This result is not surprising since most multiplets in this range had well-defined f-values, and most of the weak lines were forbidden. Below 1200 Å few reliable measures of f-value exist. Therefore, significant changes in multiplet oscillator strengths could be expected. Comparison with the compilation of Morton (1991) shows reasonable agreement (within 3 σ) for about half of the lines. Many of the differences involving dipole-allowed transitions arise because *LS* coupling may not apply. The f-values inferred from *Copernicus* spectra by de Boer & Morton (1979) (and used by Morton 1991 in his compilation) agree with our results reasonably well, considering the large uncertainties associated with their data. Our results for the line λ1279.2 agree with the laboratory results of Goldbach et al. (1989), but the comparison for the other two lines with upper state $2s^2 2p3d$ $^3F^o$ is not very good. For the theoretical results involving spin-forbidden transitions, our results are somewhat more consistent with the predictions of Nussbaumer & Storey (1984) than with those of Hibbert et al. (1993). For the allowed transitions involving the configurations $2s^2 2p5s$ and $2s^2 2p4d$, the predictions of Hibbert et al. (1993) agree with our results in about half of the cases.

Our GHRS results for C I toward β^1 Sco suggest that *LS* coupling does not apply to individual lines within multiplets in a number of instances. We utilized the well-known

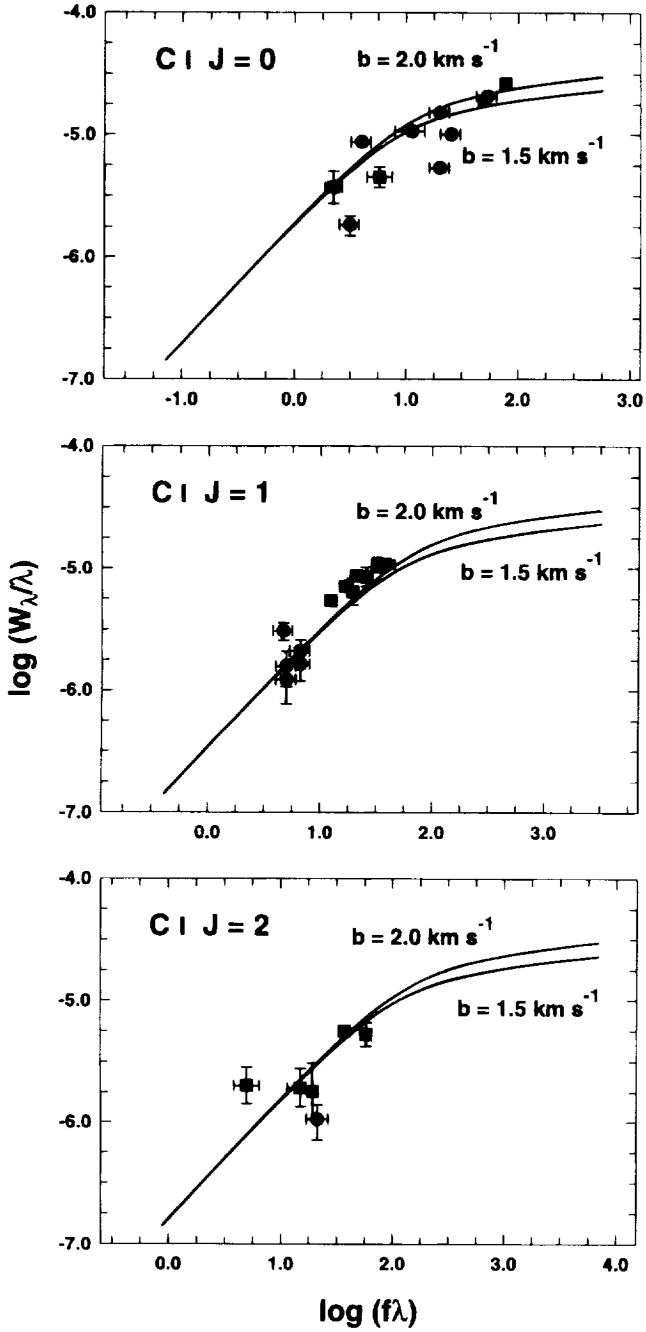

FIG. 3a

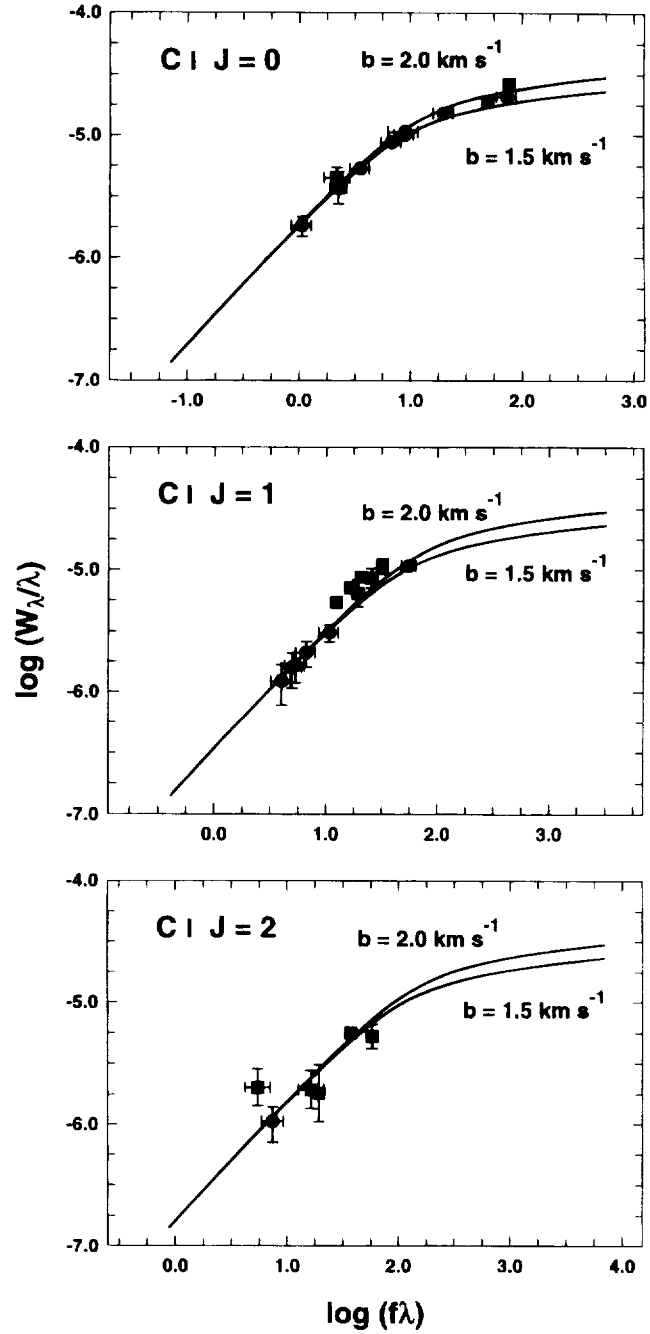

FIG. 3b

FIG. 3.—Same as Fig. 1 for data toward β^1 Sco. (*a*) Curve of growth with Morton's (1991) suggested *f*-values. (*b*) Curve of growth with our adjusted *f*-values. The *Copernicus* data point near $\log (W_\lambda/\lambda) = -5.75$ and $\log f\lambda = 0.75$ in the lowest panel ($J = 2$) is a 3 σ detection, and no attempt was made to adjust its *f*-value.

computer code developed by Cowan (1981) to check the reliability of our astronomical results. The calculation was based on the HFR (Hartree-Fock with lowest order relativistic effects) formalism and took full account of spin-orbit interactions. This program is especially useful in describing mixing among levels, resulting in line ratios that do not obey *LS* coupling rules. Because all excited even-parity states lie at appreciable energies above the ground state, we only considered the configuration $2s^22p^2$. As for odd-parity states, we included the following 16 configurations: $2s^22pns$ ($n = 3$–8), $2s^22pnd$ ($n = 3$–7), $2s2p^3$, $2s2p^2np$ ($n = 3$–5), and $2s2p^24f$. We note that the last 5 configurations involve exciting a core electron.

We have data on at least two lines in the multiplets at 1194, 1193, 1189, 1157, and 1156 Å (see also Brooks, Rohrlich, & Smith 1977). Of these multiplets, our astronomical observations indicate that *LS* coupling is not applicable to the lines λλ1194, 1156, and possibly λ1189, where the difference is slight. For λ1194, *LS* coupling gives a ratio of 1.25 for the transitions $2s^22p^2\ {}^3P_2$–$2s^22p5s\ {}^3P^o_1$ to $2s^22p^2\ {}^3P_1$–$2s^22p5s\ {}^3P^o_2$, while the astronomical ratio is 3.59. The computation yields a ratio of 3.54. Similarly, the *LS* ratios involving lines in the $2s^22p^2$–$2s^22p5d$ multiplet at 1156 Å are 4.99, 0.75, and 1.33 for ${}^3P_{1,2}$–${}^3P^o_2$ to ${}^3P_0$–${}^3P^o_1$, ${}^3P_1$–${}^3P^o_1$ to ${}^3P_0$–${}^3P^o_1$, and ${}^3P_1$–${}^3P^o_0$ to ${}^3P_1$–${}^3P^o_1$, respectively. The respective astronomical ratios are 28.5, 3.42, and 1.34, while

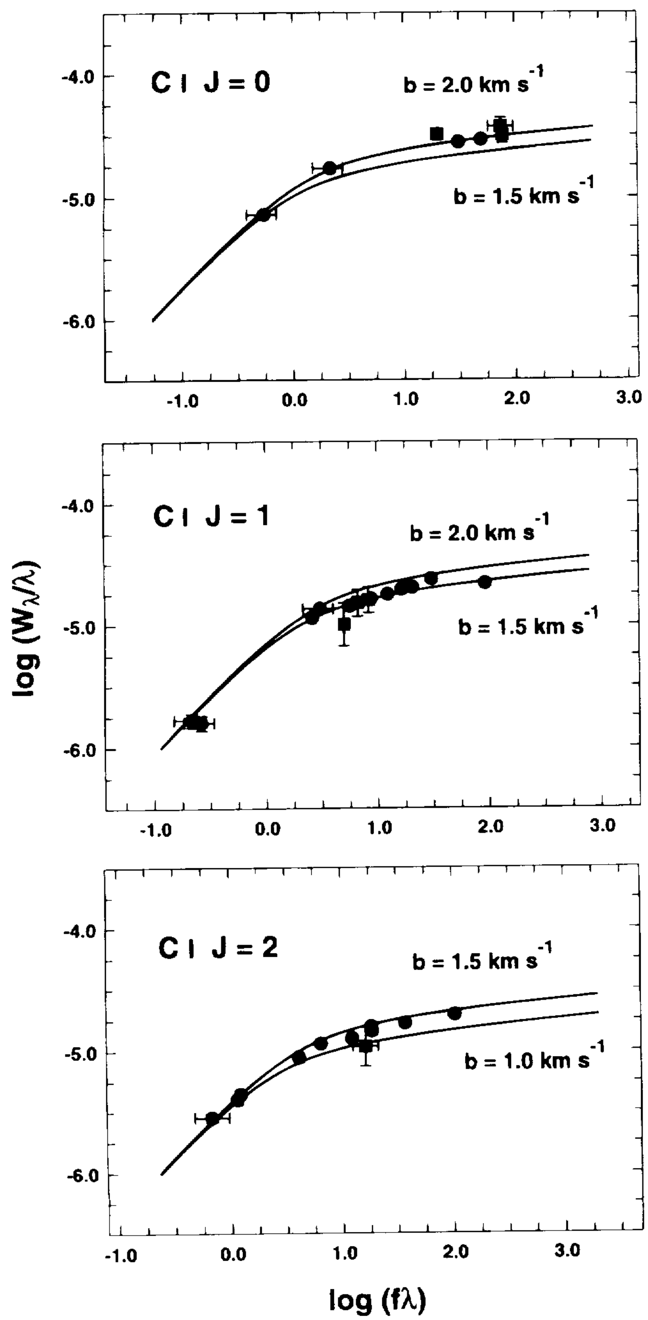

FIG. 4.—Curve of growth for neutral carbon toward ρ Oph A with our refined oscillator strengths. Same symbols as in earlier figures.

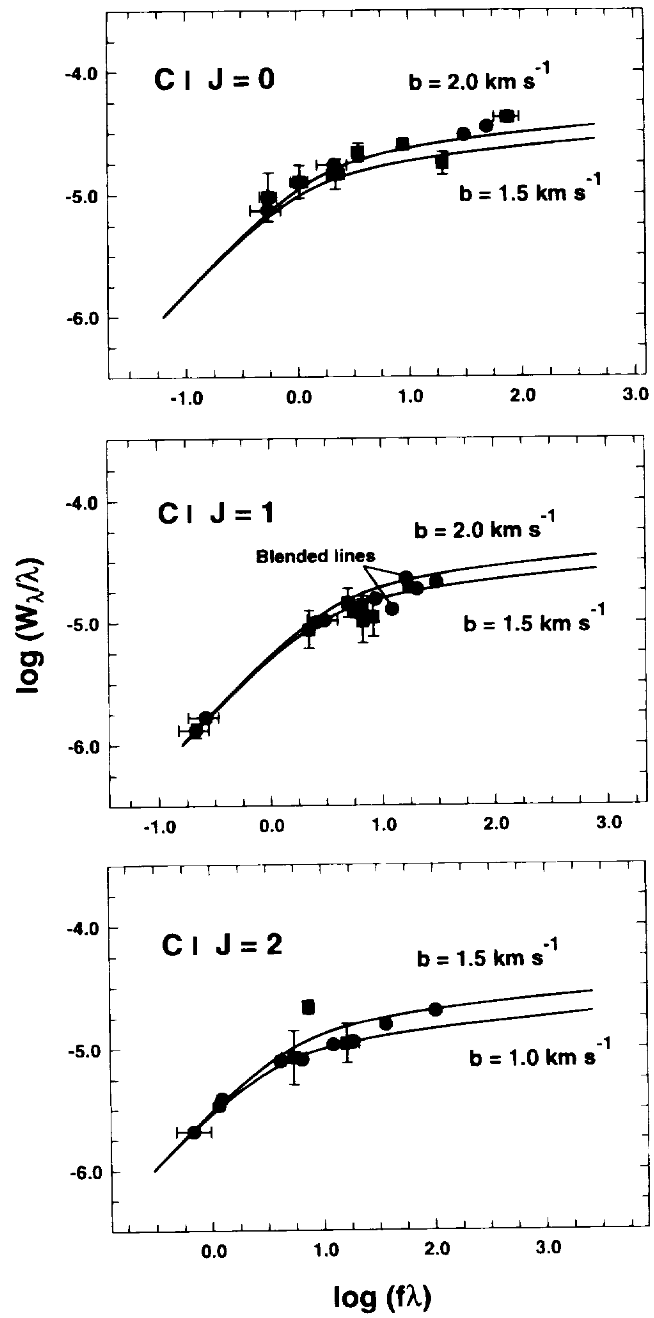

FIG. 5.—Same as Fig. 4 for data toward χ Oph. Note the effect of blending for the lines λλ1260.927, 1260.996 in the middle panel; the center of gravity of the lines is consistent with the curve of growth for the other lines.

the calculation gives 6.39, 1.61, 1.06; although there is no quantitative agreement, the calculated results do suggest that *LS* coupling is not valid for this multiplet.

When *LS* coupling does not apply, there must be substantial configuration interaction and/or spin-orbit mixing among states. Our computations indicate this is the case for the astronomical data on λλ1194, 1189, and 1156. For λλ1194, 1189 configuration interaction occurs between $2s^22p5s\ ^3P_2^o$ and $2s^22p4d\ ^3P_2^o$, but the latter is affected to a lesser extent. As for λ1156, configuration interaction involves $2s^22p5d\ ^3P_1^o$ and $2s^22p6s\ ^3P_1^o$, which is a level in the multiplet at 1158 Å. Furthermore, configuration interaction between $2s^22p5d\ ^3P_2^o$ and $2s^22p6s\ ^3P_2^o$ is expected, but we have no data involving the $2s^22p6s\ ^3P_2^o$ level. More high-quality data on transitions into $2s^22p6s\ ^3P_2^o$ are also necessary to check the computational results which suggest spin-orbit mixing with the level $2s^22p5d\ ^3D_2^o$ of multiplet λ1157. The results of the program for λλ1193, 1157 reveal no significant deviation from *LS* coupling, thereby confirming the inferences made from the GHRS data.

In conclusion, our COG analysis yielded a self-consistent set of oscillator strengths for 41 C I lines in the 1150–1300 Å range. The analysis was based on the precise experimental results for the multiplets λλ1261, 1277, 1280, and 1329, and yielded adjusted oscillator strengths for other lines. Our analysis shows the interplay among precise laboratory measurements on selected lines, high-quality astronomical data

TABLE 3

COMPARISON OF OSCILLATOR STRENGTHS FOR LINES OF NEUTRAL CARBON

Wavelength (Å)	Upper Level[a]	f(ZsFC)[b]	f(M)[c]	f(dB)[d]	f(GMN)[e]	f(NS)[f]	f(H)[g]
1287.608	$3d\ ^1D^o_2$	1.66×10^{-4}	6.38×10^{-5}	...	...	6.38×10^{-5}	5.00×10^{-5}
1279.498	$3d\ ^3F^o_2$	9.03×10^{-4}	$(7.01 \pm 0.61) \times 10^{-4}$	...	$(1.98 \pm 0.50) \times 10^{-4}$	7.01×10^{-4}	4.60×10^{-4}
1279.229	$3d\ ^3F^o_3$	3.24×10^{-3}	$(4.49 \pm 0.39) \times 10^{-3}$	...	$(3.60 \pm 0.90) \times 10^{-3}$	4.49×10^{-3}	3.19×10^{-3}
1279.056	$3d\ ^3F^o_2$	2.02×10^{-3}	$(1.78 \pm 0.15) \times 10^{-3}$	...	$(7.33 \pm 1.83) \times 10^{-4}$	1.78×10^{-3}	1.29×10^{-3}
1276.750	$4s\ ^1P^o_1$	2.39×10^{-3}	2.87×10^{-3}	...	...	2.87×10^{-3}	2.52×10^{-3}
1276.483	$4s\ ^1P^o_1$	1.68×10^{-3}	4.50×10^{-3}	...	...	4.50×10^{-3}	4.49×10^{-3}
1274.109	$3d\ ^1F^o_3$	5.39×10^{-4}	4.90×10^{-4}	...	...	4.90×10^{-4}	3.50×10^{-4}
1270.408	$3d\ ^1P^o_1$	2.06×10^{-4}	6.54×10^{-5}	...	...	6.54×10^{-5}	4.00×10^{-5}
1270.143	$3d\ ^1P^o_1$	4.28×10^{-4}	3.88×10^{-4}	...	...	3.88×10^{-4}	2.80×10^{-4}
1193.996	$5s\ ^3P^o_1$	7.50×10^{-3}	$(9.41 \pm 0.81) \times 10^{-3}$	$(9.41 \pm 2.35) \times 10^{-3}$	...	...	1.33×10^{-2}
1193.679	$5s\ ^3P^o_2$	9.00×10^{-3}	$(3.92 \pm 0.34) \times 10^{-3}$	...	...	...	1.06×10^{-2}
1193.031[h]	$4d\ ^3D^o_1$	6.23×10^{-2}	4.45×10^{-2}	$(5.29 \pm 0.37) \times 10^{-2}$	...	...	4.10×10^{-2}
1193.009[h]	$4d\ ^3D^o_2$	4.68×10^{-2}	3.34×10^{-2}	...	...	...	2.64×10^{-2}
1192.218	$5s\ ^1P^o_1$	8.77×10^{-4}	$(2.63 \pm 0.51) \times 10^{-3}$	...	...	...	...
1189.631	$4d\ ^3P^o_2$	1.38×10^{-2}	$(1.26 \pm 0.11) \times 10^{-2}$	...	...	...	8.99×10^{-3}
1189.447	$4d\ ^3P^o_1$	4.59×10^{-3}	$(4.19 \pm 0.36) \times 10^{-3}$	...	...	...	3.16×10^{-3}
1158.324	$6s\ ^3P^o_1$	5.83×10^{-3}	$(3.42 \pm 0.30) \times 10^{-3}$	$(3.42 \pm 0.86) \times 10^{-3}$	...	...	...
1158.130[i]	$5d\ ^3D^o_1$	1.90×10^{-3}	$(5.44 \pm 0.47) \times 10^{-3}$	...	...	...	...
1158.019[i]	$5d\ ^3D^o_3$	6.41×10^{-3}	$(1.83 \pm 0.16) \times 10^{-2}$	...	...	...	...
1157.910[i]	$5d\ ^3D^o_1$	7.63×10^{-3}	$(2.18 \pm 0.19) \times 10^{-2}$	$(2.18 \pm 0.55) \times 10^{-2}$	...	...	...
1157.770[i]	$5d\ ^3D^o_2$	5.71×10^{-3}	$(1.63 \pm 0.14) \times 10^{-2}$	...	...	...	...
1156.028	$5d\ ^3P^o_1$	3.45×10^{-3}	$(4.31 \pm 0.37) \times 10^{-3}$	...	...	...	...
1155.979	$5d\ ^3P^o_0$	4.60×10^{-3}	$(5.75 \pm 0.50) \times 10^{-3}$	...	...	...	...
1155.809	$5d\ ^3P^o_1$	3.04×10^{-3}	$(1.73 \pm 0.15) \times 10^{-2}$	$(1.73 \pm 0.43) \times 10^{-2}$	...	...	...

[a] Ground state is $2p^2\ ^3P_{0,1,2}$.
[b] Our values. Typical uncertainties range from 10% to 20%; the weakest lines have the greatest uncertainty.
[c] Morton 1991 compilation.
[d] de Boer & Morton 1979.
[e] Goldbach et al. 1989.
[f] Nussbaumer & Storey 1984.
[g] Hibbert et al. 1993.
[h] *LS* coupling seems to apply: f_M(ZsFC) = 6.23×10^{-2}; f_M(M) = 4.45×10^{-2}; f_M(Brooks et al. 1977) = $(4.45 \pm 0.45) \times 10^{-2}$; f_M(Opacity) = 4.87×10^{-2}.
[i] *LS* coupling seems to apply: f_M(ZsFC) = 7.63×10^{-3}; f_M(M) = 2.18×10^{-2}; f_M(Opacity) = 2.50×10^{-2}.

for a suite of lines of varying strength, and large-scale theoretical computations for a large number of multiplets. For instance, additional theoretical work is needed so that our interstellar determinations involving transitions with energy greater than 10 eV can be verified. The new oscillator strengths derived here have an accuracy of 10%–20%, comparable to the available laboratory data on C I. Therefore, future analyses involving lines of neutral carbon are now more secure.

TABLE 4

S I EQUIVALENT WIDTHS

WAVELENGTH (Å)	W_λ (mÅ) ρ Oph A	W_λ (mÅ) χ Oph
1474.571......	2.26 ± 0.26	1.30 ± 0.20
1474.379......	10.98 ± 0.24	11.33 ± 0.19
1473.994......	19.85 ± 0.25	19.52 ± 0.19
1472.971......	12.80 ± 0.28	11.10 ± 0.20
1444.296......	2.02 ± 0.42	1.68 ± 0.30
1425.219......	2.55 ± 0.80[a]	1.65 ± 0.50[a]
1425.188......	15.32 ± 1.07[a]	9.75 ± 1.01[a]
1425.030......	20.17 ± 1.06	20.07 ± 0.96
1401.514......	9.70 ± 0.27	10.43 ± 0.19
1295.653......	...	20.00 ± 2.00[b]
1270.787......	1.94 ± 0.34[c]	1.24 ± 0.16[c]
1270.780......	5.76 ± 0.34[c]	7.43 ± 0.16[c]
1262.860......	2.68 ± 0.31	1.96 ± 0.24

[a] Blended pair of lines.
[b] Frisch 1980.
[c] Blended pair of lines.

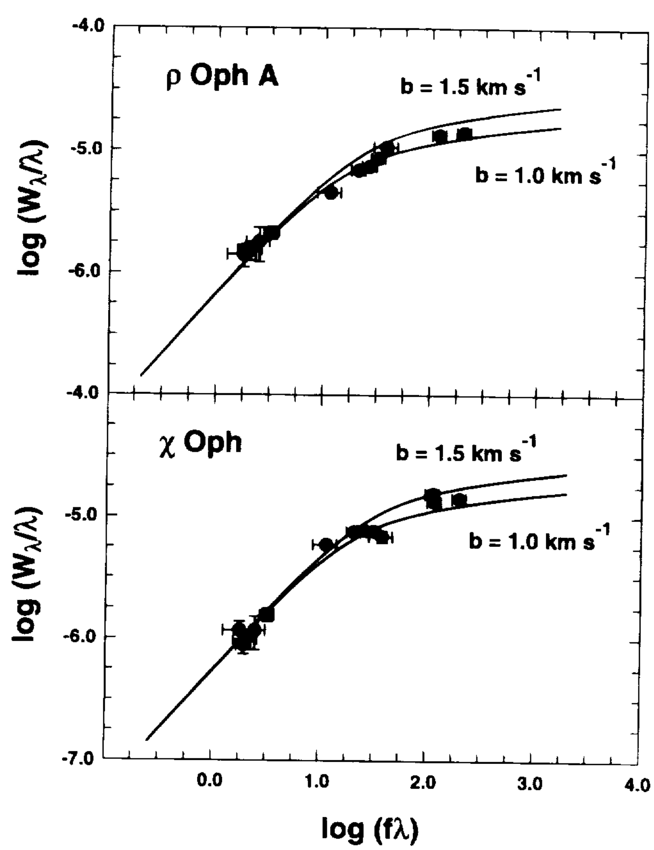

FIG. 6.—Curves of growth for neutral sulfur toward ρ Oph A and χ Oph based on *f*-values of Federman & Cardelli (1995). Same symbols as in earlier figures.

This research was supported by NASA grant NAGW-3840 and STScI grant GO-05389.02-93A. Also, we are grateful to D. G. Ellis for assistance with the Cowan code. S. R. F. acknowledges the hospitality of the Department of Astronomy at the University of Wisconsin-Madison, where initial phases of this work were completed.

REFERENCES

Bohlin, R. C., Jenkins, E. B., Spitzer, L., York, D. G., Hill, J. K., Savage, B. D., & Snow, T.P. 1983, ApJS, 51, 277
Bromander, J. 1971, Phys. Scr., 4, 61
Brooks, N. M., Rohrlich, D., & Smith, W. H. 1977, ApJ, 214, 328
Cardelli, J. A., & Ebbets, D. C. 1994, Calibrating *Hubble Space Telescope*, *HST* Calibration Workshop, ed. J. C. Blades & A. J. Osmer (Baltimore: STScI), 322
Cardelli, J. A., & Savage, B. D. 1995, ApJ, 452, 275
Cowan, R. D. 1981, Theory of Atomic Structure and Spectra (Berkeley: Univ. California Press)
de Boer, K. S., & Morton, D. C. 1979, A&A, 71, 141
Federman, S. R., & Cardelli, J. A. 1995, ApJ, 452, 269
Fitzpatrick, E. L., & Spitzer, L. 1994, ApJ, 427, 232
Frisch, P. C. 1980, ApJ, 241, 697
Goldbach, C., Martin, M., & Nollez, G. 1989, A&A, 221, 155
Goldbach, C., & Nollez, G. 1987, A&A, 181, 203
Haar, R. R., Curtis, L. J., Kvale, T. J., Beideck, D. J., Martinson, I., & Hellborg, R. 1991, A&A, 241, 321
Hibbert, A., Biemont, E., Godefroid, M., & Vaeck, N. 1993, A&AS, 99, 179
Hobbs, L. M. 1975, ApJ, 200, 621
Jenkins, E. B., Jura, M., & Loewenstein, M. 1983, ApJ, 270, 88
Jenkins, E. B., & Shaya, E. J. 1979, ApJ, 231, 55
Lambert, D. L., Sheffer, Y., Gilliland, R. L., & Federman, S. R. 1994, ApJ, 420, 756
Morton, D. C. 1991, ApJS, 77, 119
Nussbaumer, H., & Storey, P. J. 1984, A&A, 140, 383
Schectman, R. M., Federman, S. R., Beideck, D. J., & Ellis, D. G. 1993, ApJ, 406, 735
Snow, T. P., & Jenkins, E. B. 1980, ApJ, 241, 161
Welty, D. E., Hobbs, L. M., & Kulkarni, V. P. 1994, ApJ, 436, 152

Note Added in Proof.—Don Morton brought to our attention two items. In an erratum to his 1991 compilation (1992, ApJS, 81, 883) he suggests the use of the measurements of Goldbach et al. (1989) for multiplet 6 at 1279 Å, and therefore, these experimental values should also appear under the column labeled Morton in Table 3. The second item is mention of the recent compilation of C I oscillator strengths by Wiese et al. (1996, J. Phys. Chem. Ref. Data Monograph 7). Many of the entries in this compilation are based on the theoretical calculations of the Opacity Project. As noted in our paper, differences of factors of 2 or so exist between our empirical multiplet values and these, and line strengths do not obey LS coupling rules in a number of instances. Therefore, care should be taken when applying the compiled results to detailed analyses.