Self-Consistent Sets of Oscillator Strength for Ultraviolet Lines in C I, S I, and Ni II

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1 Introduction

High quality spectra of interstellar absorption from C I, S I and Ni II toward several lines of sight[1] were obtained with the Goddard High Resolution Spectrograph on *HST*. A curve-of-growth analysis yields adjusted sets of oscillator strengths (Federman & Cardelli 1995; Zsargó, Federman, & Cardelli 1997; Zsargó & Federman 1998) if the uncertainties are dominated by the errors in the atomic properties. Our GHRS spectra with signal-to-noise ratios greater than 100-200 were used to perform such an analysis. Our astronomically derived oscillator strengths were compared with available information in our papers noted above. Here comparisons with the compilations of Morton (1991) and Verner et al. (1996) are presented.

2 Analysis

We assumed simple Maxwellian line profiles to find the theoretical curves of growth, and the values for column densities and Doppler parameters 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. The oscillator strengths for the lines of a given species then were adjusted to have the best overall fit to the corresponding curves of growth. For C I and S I, precise laboratory data for several multiplets allowed us to place the results on an absolute scale; such was not the case for Ni II.

3 Discussion

3.1 Neutral Carbon

As revealed in Table 1, 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 3σ) for about half the lines. Many of the differences involving dipole-allowed transitions arise because

[1] β^1 Sco, ρ Oph A, and χ Oph for C I; ζ Oph for S I; χ Oph, ζ Oph and ρ Oph A for Ni II

LS coupling may not apply. Our astronomical observations indicate that LS coupling is not applicable to the lines at $\lambda\lambda$1194, 1156, and possibly λ1189. Verner et al. (1996) corrected the tabulated results from the Opacity Project by using laboratory wavelengths in converting A-values into f-values. Their f-values are similar to those listed by Morton (1991), except for λ1156.

Table 1
Comparison of Oscillator Strengths for Lines of Neutral Carbon

Wavelength (Å)	Transition	f(ZsFC)[a]	f(M)[b]	f(VVF)[c]
1287.608	$2p^2\ ^3P_1 - 3d\ ^1D^o_2$	1.66×10^{-4}	6.38×10^{-5}	...
1279.498	$2p^2\ ^3P_2 - 3d\ ^3F^o_2$	9.03×10^{-4}	$(1.98 \pm 0.50) \times 10^{-4}$	...
1279.229	$2p^2\ ^3P_2 - 3d\ ^3F^o_3$	3.24×10^{-3}	$(3.60 \pm 0.90) \times 10^{-3}$	...
1279.056	$2p^2\ ^3P_1 - 3d\ ^3F^o_2$	2.02×10^{-3}	$(7.33 \pm 1.83) \times 10^{-4}$	...
1276.750	$2p^2\ ^3P_1 - 4s\ ^1P^o_1$	2.39×10^{-3}	2.87×10^{-3}	...
1276.483	$2p^2\ ^3P_0 - 4s\ ^1P^o_1$	1.68×10^{-3}	4.50×10^{-3}	...
1274.109	$2p^2\ ^3P_2 - 3d\ ^1F^o_3$	5.39×10^{-4}	4.90×10^{-4}	...
1270.408	$2p^2\ ^3P_1 - 3d\ ^1P^o_1$	2.06×10^{-4}	6.54×10^{-5}	...
1270.143	$2p^2\ ^3P_0 - 3d\ ^1P^o_1$	4.28×10^{-4}	3.88×10^{-4}	...
1193.996	$2p^2\ ^3P_0 - 5s\ ^3P^o_1$	7.50×10^{-3}	$(9.41 \pm 0.81) \times 10^{-3}$	1.05×10^{-2}
1193.679	$2p^2\ ^3P_1 - 5s\ ^3P^o_2$	9.00×10^{-3}	$(3.92 \pm 0.34) \times 10^{-3}$	4.40×10^{-3}
1193.031[d]	$2p^2\ ^3P_0 - 4d\ ^3D^o_1$	6.23×10^{-2}	4.45×10^{-2}	4.76×10^{-2}
1193.009[d]	$2p^2\ ^3P_1 - 4d\ ^3D^o_2$	4.68×10^{-2}	3.34×10^{-2}	3.56×10^{-2}
1192.218	$2p^2\ ^3P_0 - 5s\ ^1P^o_1$	8.77×10^{-4}	$(2.63 \pm 0.51) \times 10^{-3}$	...
1189.631	$2p^2\ ^3P_2 - 4d\ ^3P^o_2$	1.38×10^{-2}	$(1.26 \pm 0.11) \times 10^{-2}$	9.69×10^{-3}
1189.447	$2p^2\ ^3P_2 - 4d\ ^3P^o_1$	4.59×10^{-3}	$(4.19 \pm 0.36) \times 10^{-3}$	3.23×10^{-3}
1158.324	$2p^2\ ^3P_0 - 6s\ ^3P^o_1$	5.83×10^{-3}	$(3.42 \pm 0.30) \times 10^{-3}$	5.57×10^{-3}
1158.130[d]	$2p^2\ ^3P_1 - 5d\ ^3D^o_1$	1.90×10^{-3}	$(5.44 \pm 0.47) \times 10^{-3}$	6.10×10^{-3}
1158.019[d]	$2p^2\ ^3P_2 - 5d\ ^3D^o_3$	6.41×10^{-3}	$(1.83 \pm 0.16) \times 10^{-2}$	2.05×10^{-2}
1157.910[d]	$2p^2\ ^3P_0 - 5d\ ^3D^o_1$	7.63×10^{-3}	$(2.18 \pm 0.19) \times 10^{-2}$	2.44×10^{-2}
1157.770[d]	$2p^2\ ^3P_1 - 5d\ ^3D^o_2$	5.71×10^{-3}	$(1.63 \pm 0.14) \times 10^{-2}$	1.83×10^{-2}
1156.028	$2p^2\ ^3P_1 - 5d\ ^3P^o_1$	3.45×10^{-3}	$(4.31 \pm 0.37) \times 10^{-3}$	1.52×10^{-3}
1155.979	$2p^2\ ^3P_1 - 5d\ ^3P^o_0$	4.60×10^{-3}	$(5.75 \pm 0.50) \times 10^{-3}$	2.01×10^{-3}
1155.809	$2p^2\ ^3P_0 - 5d\ ^3P^o_1$	3.04×10^{-3}	$(1.73 \pm 0.15) \times 10^{-2}$	6.05×10^{-3}

Notes:
[a] Our values (Zsargó et al. 1997). Typical uncertainties range from 10% to 20%; the weakest lines have the greatest uncertainty.
[b] Morton (1991) compilation.
[c] Verner et al. (1996).
[d] LS coupling seems to apply.

3.2 Neutral Sulfur

The comparison for the 25 S I lines appears in Table 2. Unlike the situation for C I, LS coupling adequately describes line strengths within a multiplet. In about 1/3 of the cases, substantial differences exist with the values quoted by Morton (1991). There is good agreement with most of

the results of Verner et al. (1996), except for several multiplets with ^{3}D^o upper states ($\lambda\lambda$1479, 1274, 1256).

Table 2
Comparison of Oscillator Strengths for Lines of Neutral Sulfur

Wavelength (Å)	Transition	f(FC)[a]	f(M)[b]	f(VVF)[c]
1807.311	$3p^4\ ^3P_2 - 4s\ ^3S^o_1$	9.6×10^{-2} [d]	$(1.11 \pm 0.10) \times 10^{-1}$	8.45×10^{-2}
1474.571	$3p^4\ ^3P_2 - 4s'\ ^3D^o_1$	1.33×10^{-3}	$(1.21 \pm 0.24) \times 10^{-3}$	4.09×10^{-4}
1474.379	$3p^4\ ^3P_2 - 4s'\ ^3D^o_2$	1.79×10^{-2}	$(1.63 \pm 0.32) \times 10^{-2}$	6.14×10^{-3}
1473.994	$3p^4\ ^3P_2 - 4s'\ ^3D^o_3$	8.03×10^{-2}	$(7.30 \pm 1.42) \times 10^{-2}$	3.44×10^{-2}
1472.971	$3p^4\ ^3P_2 - 3d\ ^5D^o_3$	2.18×10^{-2}	$(1.91 \pm 0.37) \times 10^{-2}$	...
1444.296	$3p^4\ ^3P_2 - 4s'\ ^1D^o_2$	1.24×10^{-3}	$(8.13 \pm 1.59) \times 10^{-4}$	...
1425.219	$3p^4\ ^3P_2 - 3d\ ^3D^o_1$	1.75×10^{-3}	$(2.38 \pm 0.46) \times 10^{-3}$	1.44×10^{-3}
1425.188	$3p^4\ ^3P_2 - 3d\ ^3D^o_2$	2.69×10^{-2}	$(3.65 \pm 0.71) \times 10^{-2}$	2.16×10^{-2}
1425.030	$3p^4\ ^3P_2 - 3d\ ^3D^o_3$	1.41×10^{-1}	$(1.92 \pm 0.37) \times 10^{-1}$	1.21×10^{-1}
1401.514	$3p^4\ ^3P_2 - 5s\ ^3S^o_1$	1.49×10^{-2}	$(1.61 \pm 0.31) \times 10^{-2}$	1.42×10^{-2}
1316.622	$3p^4\ ^3P_2 - 4d\ ^3D^o_1$	4.54×10^{-4}	$(4.11 \pm 0.80) \times 10^{-4}$	2.69×10^{-4}
1316.615	$3p^4\ ^3P_2 - 4d\ ^3D^o_2$	6.79×10^{-3}	$(6.15 \pm 1.20) \times 10^{-3}$	4.03×10^{-3}
1316.543	$3p^4\ ^3P_2 - 4d\ ^3D^o_3$	3.81×10^{-2}	$(3.45 \pm 0.67) \times 10^{-2}$	2.26×10^{-2}
1303.430	$3p^4\ ^3P_2 - 6s\ ^3S^o_1$	5.06×10^{-3}	$(2.91 \pm 0.57) \times 10^{-2}$	4.60×10^{-3}
1296.174	$3p^4\ ^3P_2 - 4s''\ ^3P^o_1$	2.2×10^{-2} [d]	$(4.08 \pm 0.80) \times 10^{-2}$	2.78×10^{-2}
1295.653	$3p^4\ ^3P_2 - 4s''\ ^3P^o_2$	8.7×10^{-2} [d]	$(1.23 \pm 0.24) \times 10^{-1}$	8.36×10^{-2}
1270.787	$3p^4\ ^3P_2 - 5d\ ^3D^o_2$	1.64×10^{-3}	1.00×10^{-2}	6.21×10^{-4}
1270.780	$3p^4\ ^3P_2 - 5d\ ^3D^o_3$	9.02×10^{-3}	5.51×10^{-2}	3.47×10^{-3}
1270.769	$3p^4\ ^3P_2 - 5d\ ^3D^o_1$	1.09×10^{-4}	6.62×10^{-4}	4.14×10^{-5}
1262.860	$3p^4\ ^3P_2 - 7s\ ^3S^o_1$	2.59×10^{-3}	...	2.00×10^{-3}
1247.160	$3p^4\ ^3P_2 - 6d\ ^3D^o_3$	1.64×10^{-3}	3.24×10^{-2}	7.44×10^{-5}
1247.134	$3p^4\ ^3P_2 - 6d\ ^3D^o_2$	2.90×10^{-4}	5.77×10^{-3}	1.33×10^{-5}
1247.107	$3p^4\ ^3P_2 - 6d\ ^3D^o_1$	1.92×10^{-5}	3.81×10^{-4}	8.86×10^{-7}
1241.905	$3p^4\ ^3P_2 - 8s\ ^3S^o_1$	1.06×10^{-3}	...	1.02×10^{-3}
1224.544	$3p^4\ ^3P_2 - 8d\ ^3D^o_3$	$\leq 9.6 \times 10^{-4}$	1.23×10^{-2}	1.07×10^{-3}

Notes:
[a] Our values (Federman & Cardelli 1995). Typical uncertainties range from 10% to 20%; the weakest lines have the greatest uncertainty.
[b] Morton (1991) compilation.
[c] Verner et al. (1996).
[d] Experimental results of Beideck et al. (1994).

3.3 Singly-ionized Nickel

Table 3 shows the adjusted oscillator strengths together with Morton's (1991) values. The adjusted and the original f-values differ by less than 30% in most cases, implying that the theoretical calculations of Kurucz (1989) are reliable (in a relative sense). There are several lines with considerable differences, those for $\lambda\lambda$1477, 1415 and 1345. Since we measured these lines in only one direction,

higher than average uncertainties could arise. These three lines are among the weakest observed by us, and it is not unreasonable to find the largest discrepancies here between our results and the predictions of Kurucz (1989) from intermediate coupling calculations. Work is in progress to place these results on an absolute scale.

Table 3
Comparison of Oscillator Strengths for Lines of Singly-ionized Nickel

Wavelength (Å)	Transition	f(ZsF)[a]	f(M)[b]
1741.549	$3d^9\ ^2D_{5/2} - 4p\ ^2D^o_{5/2}$	7.76×10^{-2}	1.04×10^{-1}
1709.600	$3d^9\ ^2D_{5/2} - 4p\ ^2F^o_{5/2}$	6.66×10^{-2}	6.88×10^{-2}
1477.222	$3d^9\ ^2D_{5/2} - 4p''\ ^2F^o_{5/2}$	1.82×10^{-3}	1.06×10^{-3}
1467.756	$3d^9\ ^2D_{5/2} - 4p''\ ^2F^o_{7/2}$	1.81×10^{-2}	2.27×10^{-2}
1467.259	$3d^9\ ^2D_{5/2} - 4p''\ ^2D^o_{3/2}$	1.13×10^{-2}	1.11×10^{-2}
1454.842	$3d^9\ ^2D_{5/2} - 4p''\ ^2D^o_{5/2}$	5.16×10^{-2}	5.95×10^{-2}
1449.997	$3d^9\ ^2D_{5/2} - 4p''\ ^2P^o_{3/2}$	3.27×10^{-3}	3.53×10^{-3}
1415.720	$3d^9\ ^2D_{5/2} - 4p'\ ^4D^o_{5/2}$	5.97×10^{-3}	4.13×10^{-3}
1412.886	$3d^9\ ^2D_{5/2} - 4p'\ ^4D^o_{7/2}$	6.65×10^{-3}	6.65×10^{-3}
1393.324	$3d^9\ ^2D_{5/2} - 4p'\ ^2D^o_{5/2}$	1.89×10^{-2}	2.22×10^{-2}
1370.132	$3d^9\ ^2D_{5/2} - 4p'\ ^2P^o_{3/2}$	1.44×10^{-1}	1.31×10^{-1}
1345.878	$3d^9\ ^2D_{5/2} - 4p'\ ^4S^o_{3/2}$	1.44×10^{-2}	6.43×10^{-3}

Notes:
[a] Our values (Zsargó and Federman 1998). Typical uncertainties 30%.
[b] Morton (1991) compilation.

References

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