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

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ABSTRACT

Interstellar spectra toward ζ Oph acquired with the Goddard High-Resolution Spectrograph were used to obtain oscillator strengths for approximately two dozen S I lines. This analysis was possible because precisely determined experimental oscillator strengths are available for several multiplets, including one with a weak interstellar line. The self-consistent set of oscillator strengths then was obtained from a curve of growth based on line strengths spanning a range of a factor of 100. The derived *f*-values for a number of multiplets differ from values quoted by Morton (1991) but are generally consistent with the suite of available experimental and theoretical results.

Subject headings: atomic data — ISM: abundances — stars: individual (ζ Ophiuchi)

1. INTRODUCTION

The Goddard High-Resolution Spectrograph (GHRS) is yielding spectra of unprecedented quality. Signal-to-noise ratios exceeding 100–200 are routinely achieved (Cardelli & Ebbets 1994; Fitzpatrick & Spitzer 1994; Lambert et al. 1994). The resulting analyses on absorption lines are challenging the available atomic and molecular data from experimental and theoretical sources. In particular, the astronomical measurements are now requiring accuracies of 10% in more and more instances. The atomic data on weak intercombination lines of C II, N I, O I, and Si II (Cardelli et al. 1993, 1994) are consistent with the amount of interstellar absorption seen toward ζ Oph when the comparisons include results from the damping wings of strong, highly saturated lines (Sofia, Cardelli, & Savage 1994). The comparison involving strong and weak Mg II lines (Cardelli et al. 1991; Sofia et al. 1994), however, suggests the need for revised oscillator strengths for the doublet near 1240 Å. In the area of molecular *f*-values, several intersystem bands of CO detected toward ζ Oph (Federman et al. 1994) indicate the need for revisions to the values obtained through laboratory spectroscopic analyses (see Morton & Noreau 1994), and the observed F–X (0, 0), D–X (0, 0), and A–X (2, 0) bands of C_2 yield relative *f*-values that are more consistent with theoretical determinations than with available experimental results (Lambert, Sheffer, & Federman 1995). Here, data on a series of multiplets in S I acquired with the GHRS are analyzed so that a consistent set of oscillator strengths is available for future studies.

Neutral sulfur has been the focus of several studies recently. Large-scale computations that include configuration interaction (Ho & Henry 1985; Mendoza & Zeippen 1988) have yielded estimates of oscillator strengths for a number of multiplets. Experimental measurements have been performed on the relative strengths of the multiplets at 1814 Å, 1479 Å, and 1429 Å (Doering 1990) and on individual line *f*-values for the multiplets λλ1814, 1299 (Beideck et al. 1994). Emission from neutral sulfur has been reported for the Io torus (Durrance, Feldman, & Weaver 1983), for the vicinity of Io (Ballester et al. 1987), and for cometary comae (Roettger et al. 1989). Absorption from interstellar gas toward ζ Oph has been analyzed by Federman et al. (1993). The astronomical data on S I are not always consistent with the laboratory and theoretical results, as discussed in the above references.

The spectral range covered by recent observations toward ζ Oph with the GHRS span most of the multiplets for S I listed by Morton (1991). In this paper, 14 multiplets are analyzed in a self-consistent manner in order to extract a suite of oscillator strengths accurate to about 20% in all cases and approaching 10% in many instances. For some, the improvement over previous values exceeds a factor of 10. The data considered here include those previously discussed by Federman et al. (1993). The basic approach is to use the column density deduced from a weak line with a precise, experimentally determined *f*-value and the *b*-value from analysis of the stronger lines of the multiplet as a starting point for a theoretical curve-of-growth analysis on all the observed lines. Such an approach is possible because the neutral species predominantly reside in a single velocity component, the main component at $v_{\rm helio} = -15$ km s^{-1}, with a well-defined *b*-value (see Savage, Cardelli, & Sofia 1992; Federman et al. 1993). This point is further highlighted in Figure 1, where the strong S I line at 1807 Å and the Si II line at 1808 Å are plotted on a common velocity scale. The substructure apparent in ultra-high-resolution observations of CH and CN (Lambert, Sheffer, & Crane 1990; Crawford et al. 1994) may not be consistent with the curve-of-growth analyses for the atoms (Federman et al. 1993) because the two narrow molecular components have different strengths. From data on

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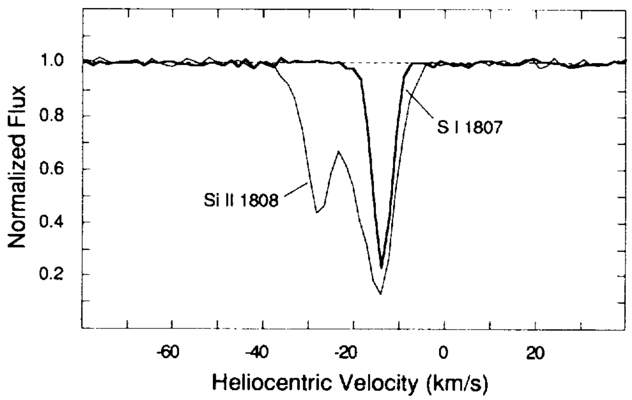

FIG. 1.—Echelle spectra for S I λ1807 and Si II λ1808. The strong S I line is only seen in the main component at -15 km s^{-1}.

K I absorption acquired at ultra-high resolution, D. Welty & L. Hobbs (1994, private communication) obtain results for the b-value consistent with those for CN and CH, but with two components of *comparable* strength. Because the K I components have comparable strength, a single curve of growth for a potentially unresolved blend should not introduce any significant systematic error. The reliability of our analysis also is a result of detections of very weak lines that lie on the linear portion of a theoretical curve of growth.

2. OBSERVATIONAL DATA

The data were acquired with the GHRS for other programs in which we participated. Most of the data were taken with the moderate-resolution grating G160M, consisting of the wavelength intervals 1221–1258 Å, 1252–1293 Å, 1296–1333 Å, 1334–1375 Å, 1403–1440 Å, and 1442–1488 Å. Spectra in the vicinity of 1400 and 1807 Å were obtained with the echelle gratings. Procedures were applied to the data to correct for fixed pattern noise/granularity, etc. (see Cardelli et al. 1993, 1994; Cardelli & Ebbets 1994; Fitzpatrick & Spitzer 1994; Lambert et al. 1994 for details). The signal-to-noise ratios that were achieved in the final merged spectra (from individual FP-SPLITs) were between 100 and 1000. The spectra in the vicinity of each of the S I lines not already displayed by Federman et al. (1993) are shown in Figure 2.

3. ANALYSIS AND RESULTS

The standard way of analyzing data via a curve of growth was followed by Federman et al. (1993): weak lines set the column density, and stronger ones set the b-value. The optical depth at line center for our data spanned a range from 0.10 to 15. The method was applied to the data for the multiplet λ1479 and was based on f-values recently measured in the laboratory. Doering (1990) obtained relative values between the multiplets at 1814, 1479, and 1429 Å. When his ratio for $f(1479)/f(1814)$ of 1.12 ± 0.06 is combined with the f-value for λ1814 of 0.088 ± 0.005 reported by Beideck et al. (1994), a multiplet value of 0.099 ± 0.008 is obtained. With the assumption that LS coupling applies, the line oscillator strengths are 1.33×10^{-3}, 1.79×10^{-2}, and 8.03×10^{-2} for λλ1474.6, 1474.4, and 1474.0, respectively. The interstellar line at 1474.6 Å, with $W_\lambda = 1.56 \pm 0.15$ mÅ (Federman et al. 1993), indicates a column density, N(S I), of $(6.46 \pm 0.67) \times 10^{13}$ cm^{-2}, in which the uncertainty in column density does not include uncertainties in oscillator strength. The optical depth at line center obtained from the analysis is 0.17, revealing that absorption from λ1474.6 is indeed optically thin. The b-value of 1.1–1.2 km s^{-1} was constrained by the stronger lines in the multiplet. The derived b-value is similar to the one obtained by Savage et al. (1992) for Mg I. [For comparison, Federman et al. 1993 used the multiplet oscillator strength of 0.090 quoted by Morton 1991 for λ1479, and from lines in three multiplets they obtained a weighted average of $N(\mathrm{S\ I}) = (6.95 \pm 0.18) \times 10^{13}$ cm^{-2} and $b = 1.2 \pm 0.1$ km s^{-1}.]

The value for N(S I) of 6.46×10^{13} cm^{-2} and a b-value of 1.15 km s^{-1} are utilized in the present analysis for all the other transitions. Including the six lines (in four multiplets) studied by Federman et al. (1993), the present investigation is based on 27 lines from 14 multiplets. The multiplet at 1236 Å is not included because its lines appear on the steeply varying wing of a stellar feature. The results of our curve-of-growth analysis appear in Table 1, where the columns correspond to multiplet wavelength, line wavelength, the upper state designation for the transition ($3p^4\ ^3P$ for the ground state), observed equivalent width (W_λ) with 1 σ measurement uncertainties, the f-value quoted by Morton (1991) or by Beideck et al. (1994) for the multiplets λλ1814, 1299 (f_M), the f-values required to place the observations on a single curve of growth (f_{ISM}), and $\log f_{ISM}\lambda$. In all cases in which the spin did not change, line oscillator strengths were converted into multiplet values under the assumption that LS coupling applies; this assumption was considered by Morton (1991) also and appears to be valid for the data obtained by Beideck et al. (1994). A visual presentation of the resulting empirical curve of growth appears in Figure 3. The variation about a smooth curve of growth for $\log f_{ISM}\lambda \geq 1.5$ in the bottom panel provides a measure of the uncertainty in b-value from the observations. Some of the scatter for these values of $\log f_{ISM}\lambda$ arises from the estimates in W_λ for blended lines. Note that observational limitations with the *IUE* satellite prevented other empirical curve-of-growth analyses from including lines with optical depth at line center of ≤ 0.5, which is indicated in this figure. For larger optical depths, line saturation becomes important.

Several points deserve mention. First, the precise experimental f-values of Beideck et al. (1994) for lines in the multiplets at 1814 and 1299 Å also indicate b-values of 1.1–1.2 km s^{-1}. Second, the revised oscillator strengths for the lines of the multiplet at 1429 Å yield a multiplet f-value that agrees reasonably well with the experimental results of Doering (1990) and Beideck et al. (1994): $f_{ISM} = 0.168$ versus 0.149 ± 0.011 from $f(1429)/f(1814) = 1.69 \pm 0.08$ and $f(1814)$ given above. The line oscillator strengths for λλ1425.19, 1425.03 are consistent with this assessment even though a correction to $W_\lambda(1425.19)$ of 1.90 mÅ was made to take into account the contribution from the blended weak line of the multiplet at 1425.22 Å. Here, the equivalent width for λ1425.22 was estimated from N(S I) and b with the revised line oscillator strength from our analysis. This multiplet could be used in conjunction with the multiplet at 1479 Å in future analyses if high-resolution (echelle) observations are available. Third, in a similar vein, the blended lines in the multiplet λ1320 were analyzed through estimates of the equivalent widths for the two weakest lines. Fourth, our data for the lines λλ1296.17, 1295.65 had comparable errors to those reported by Morton (1975) from spectra obtained with the *Copernicus* satellite, and so our analysis was based on equivalent widths derived from taking weighted means. Fifth, slight changes in f-values for transitions studied by Federman et al. (1993) are the result of setting N(S I) and b.

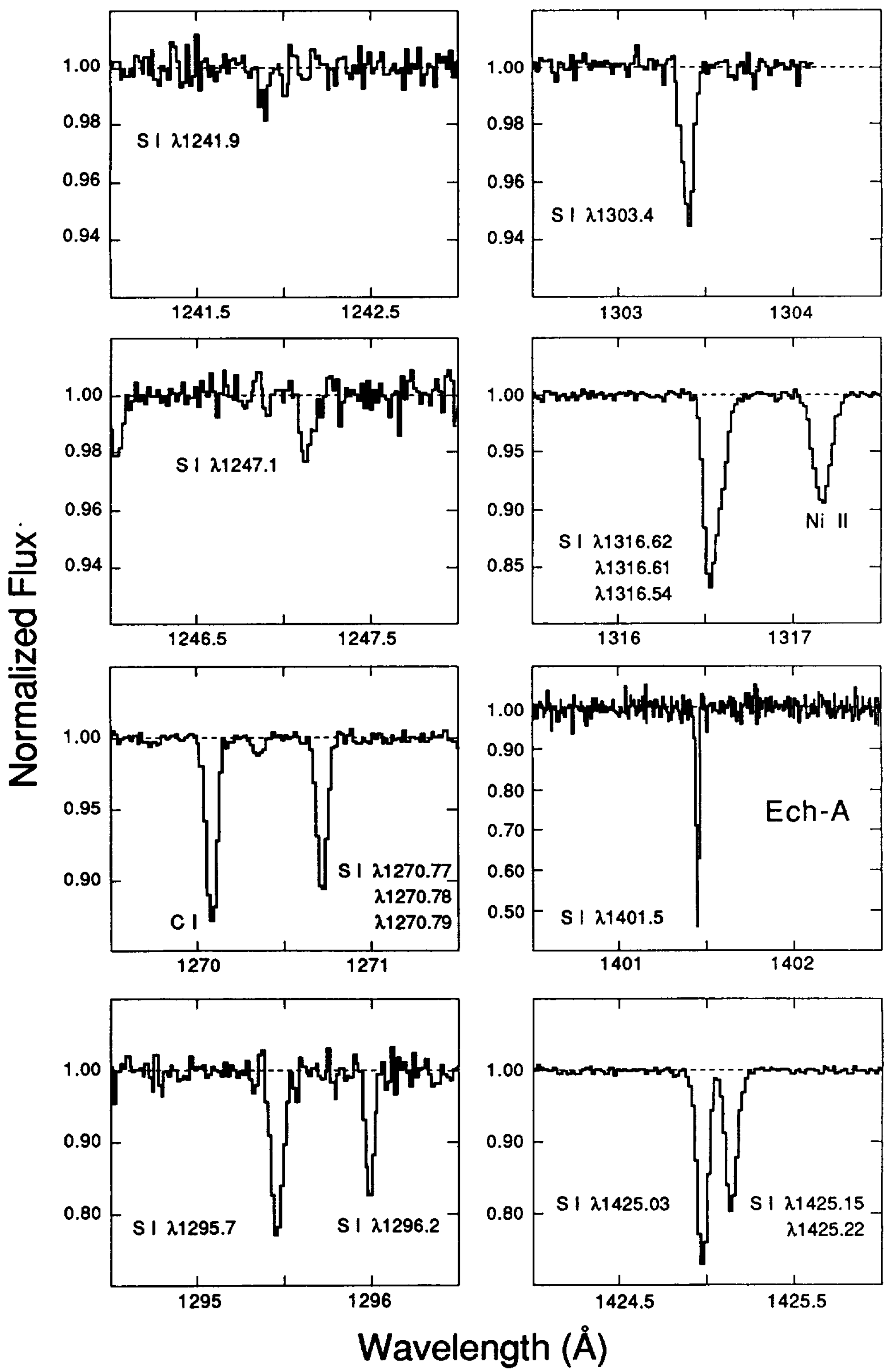

FIG. 2.—Newly analyzed S I lines. The line at 1401.5 Å comes from echelle data; the others are from spectra acquired with G160M. Features ascribed to multiple lines are blends. The lines of C I and Ni II in these spectral ranges are also noted.

TABLE 1

RESULTS OF CURVE-OF-GROWTH ANALYSIS

λ_M (Å)	λ (Å)	Designation	W_λ (mÅ)	f_M[a]	f_{ISM}[b]	$\log f_{ISM}\lambda$
1814	1807.311	$4s\,^3S^o$	23.97 ± 0.55	9.6×10^{-2}	9.6×10^{-2}	2.239
1479	1474.571	$4s'\,^3D^o$	1.56 ± 0.15	1.21×10^{-3}	1.33×10^{-3}	0.293
...	1474.379	...	11.85 ± 0.20	1.63×10^{-2}	1.79×10^{-2}	1.421
...	1473.994	...	18.78 ± 0.20	7.30×10^{-2}	8.03×10^{-2}	2.073
...[c]	1472.971	$3d\,^5D^o$	12.88 ± 0.27	1.91×10^{-2}	2.18×10^{-2}	1.507
...[c]	1444.296	$4s'\,^1D^o$	1.40 ± 0.40	8.13×10^{-4}	1.24×10^{-3}	0.253
1429	1425.219	$3d\,^3D^o$	(1.90)[d]	2.38×10^{-3}	1.75×10^{-3}	0.397
...	1425.188	...	14.46 ± 0.31	3.65×10^{-2}	2.69×10^{-2}	1.584
...	1425.030	...	20.54 ± 0.28	1.92×10^{-1}	1.41×10^{-1}	2.303
1405	1401.514	$5s\,^3S^o$	9.87 ± 0.51	1.61×10^{-2}	1.49×10^{-2}	1.320
1320	1316.622	$4d\,^3D^o$	(0.44)[d]	4.11×10^{-4}	4.54×10^{-4}	−0.223
...	1316.615	...	(5.26)[d]	6.15×10^{-3}	6.79×10^{-3}	0.951
...	1316.543	...	13.57 ± 0.30	3.45×10^{-2}	3.81×10^{-2}	1.700
1307	1303.430	$6s\,^3S^o$	4.08 ± 0.31	2.91×10^{-2}	5.06×10^{-3}	0.819
1299	1296.174	$4s''\,^3P^o$	11.42 ± 0.95[e]	2.2×10^{-2}	2.2×10^{-2}	1.455
...	1295.653	...	16.99 ± 0.88[e]	8.7×10^{-2}	8.7×10^{-2}	2.052
1274	1270.787	$5d\,^3D^o$	(1.42)[d]	1.00×10^{-2}	1.64×10^{-3}	0.319
...	1270.780	...	6.08 ± 0.21	5.51×10^{-2}	9.02×10^{-3}	1.059
...	1270.769	...	...	6.62×10^{-4}	1.09×10^{-4}	−0.859
1266	1262.860	$7s\,^3S^o$	2.15 ± 0.29	...	2.59×10^{-3}	0.515
1256	1247.160	$6d\,^3D^o$	1.37 ± 0.31	3.24×10^{-2}	1.64×10^{-3}	0.311
...	1247.134	...	...	5.77×10^{-3}	2.90×10^{-4}	−0.442
...	1247.107	...	...	3.81×10^{-4}	1.92×10^{-5}	−1.621
1245.	1241.905	$8s\,^3S^o$	0.90 ± 0.27	...	1.06×10^{-3}	0.119
1227	1224.544	$8d\,^3D^o$	≤ 0.80	1.23×10^{-2}	$\leq 9.6 \times 10^{-4}$	≤ 0.070
...	1224.506	...	...	2.19×10^{-3}	...	...
...	1224.471	...	...	1.48×10^{-4}	...	...

[a] The results for the multiplets at 1814 and 1299 Å are from Beideck et al. 1994.

[b] The column density and b-value were derived by fitting a curve of growth to the lines of the multiplet at 1479 Å. Beideck et al's. 1994 results for the multiplets $\lambda\lambda$1814, 1299 are consistent with this curve of growth. The analysis resulted in refined f-values for the multiplets $\lambda\lambda$1429, 1320, 1274, 1256 under the assumption that LS coupling applies for line oscillator strengths.

[c] Morton 1991 does not give a multiplet wavelength for the spin-changing transitions.

[d] The number in parenthesis is the estimate removed from the blended feature.

[e] Average of the results from *Copernicus* and GHRS.

Last, the structure seen in K I absorption (D. Welty & L. Hobbs 1994, private communication) does not affect our conclusions, in large measure because very weak lines were analyzed here. There is also the possibility that S I, which has a larger ionization potential than K I, is more widely distributed along the line of sight and consequently has a larger intrinsic b-value. The b-value of 1.5 km s^{-1} obtained by Federman et al. (1993) for the dominant ion Ni II suggests that dominant ions are even more widely dispersed in this picture.

4. DISCUSSION

As revealed in Table 1, our analysis yields significant revisions in f-values for 12 lines in six multiplets and two new determinations when comparison is made with the compilation of Morton (1991), updated to include the results of Beideck et al. (1994). These f_{ISM}-values, as well as those for the multiplets $\lambda\lambda$1405, 1320, and 1227, are listed in Table 2 with available experimental and theoretical results. Line oscillator strengths are only displayed when such were reported. The comparisons for $\lambda\lambda$1814, 1299 are discussed in Beideck et al. (1994) and are not repeated here.

There is general agreement among the results shown in Table 2. As noted above, the experimental oscillator strengths of Beideck et al. (1994) form the basis for our analysis, and when combined with the relative f-values measured by Doering (1990), they provide an additional check on the value used for the multiplet λ1429. Furthermore, the experimental results earlier than 1990 are consistent with the more accurate values reported here, except for Müller's (1968) result for the line at 1303 Å.

For the most part, there is also agreement involving the theoretical determinations. The correspondence between f_{ISM} and the values obtained from the large-scale computations of Ho & Henry (1985) and Mendoza & Zeippen (1988) is reasonable although not quite as good as that discussed by Beideck et al. The one exception is the theoretical result of Mendoza & Zeippen for the multiplet at 1274 Å. It appears that cancellation in the dipole transition integral occurs for λ1274, a result reminiscent of that for λ1479 (see Beideck et al. 1994). For λ1274, the admixture of upper states involves $3p^3(^4S^o)5d\,^3D^o$ and $3p^3(^2D^o)3d\,^3D^o$ (Martin, Zalubas, & Musgrove 1990). The results from the Opacity Project (Butler, Mendoza, & Zeippen 1995) agree with the results derived here from interstellar absorption remarkably well, being somewhat more consistent than those of Mendoza & Zeippen (1988). Discrepancies at the 50% level still persist, however, for the multiplets $\lambda\lambda$1479, 1274, as well as a significant difference for λ1256. Martin et al. (1990) also note an admixture involving $3p^3(^2D^o)3d\,^3D^o$ for λ1256. We remark that the results of Ganas (1982) for transitions into nd $^3D^o$ states differ significantly from the interstellar ones, possibly because configuration interaction was not taken into account. Moreover, the results of Kurucz and Peytremann for $\lambda\lambda$1274, 1256, and 1227 quoted by Morton (1991) do not appear to be

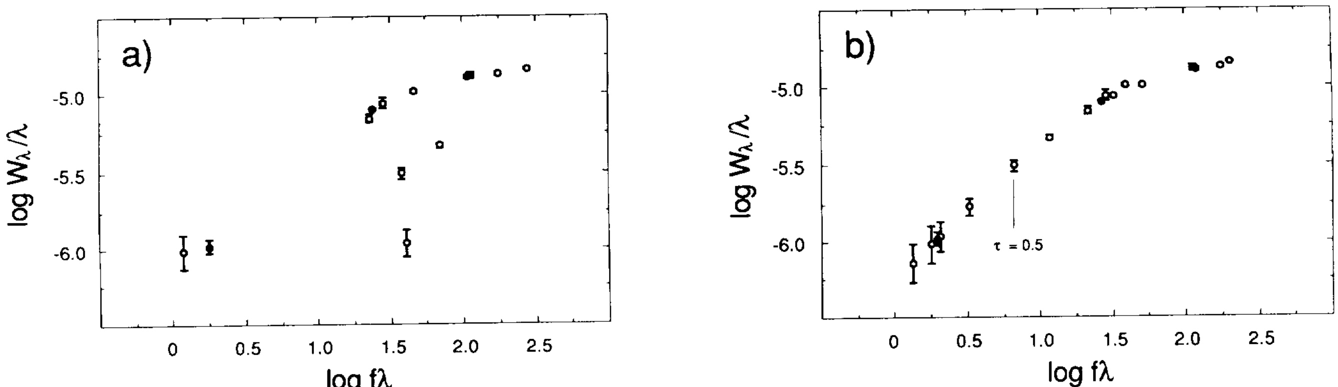

FIG. 3.—Curves of growth (*a*) based on the *f*-values quoted by Morton (1991) and (*b*) based on the revised *f*-values presented here. The lines in the multiplet at 1479 Å, on which the present analysis is based, are indicated by solid circles. The open circles represent lines whose oscillator strength either was based on the experiments of Beideck et al. (1994) or was refined to be consistent with the curve of growth defined by λ1479. The bottom panel also shows where the optical depth at line center is 0.5, when saturation begins to play an important role in the analysis.

reliable; their *f*-values differ by factors of 5 to 20 when compared with f_{ISM}.

In conclusion, a curve-of-growth analysis yielded a self-consistent set of oscillator strengths for 14 multiplets of S I. The analysis, which was based on recently obtained precise experimental values (Doering 1990; Beideck et al. 1994) for the multiplet λ1479, is consistent with these experimental results for three other multiplets, λλ1814, 1429, and 1299. The four multiplets are also seen in emission from solar system objects (Durrance et al. 1983; Ballester et al. 1987; Roettger et al. 1989). Our analysis highlights the interplay among precise laboratory measurements on selected lines, high-quality

TABLE 2

COMPARISON OF RESULTS FOR OSCILLATOR STRENGTHS

References	λ1444	λ1425.22	λ1425.19	λ1425.03	λ1429M[a]
ISM	1.24×10^{-3}	1.75×10^{-3}	2.69×10^{-2}	1.41×10^{-1}	1.68×10^{-1}
Savage & Lawrence 1966[b]	...	...	...	...	$(2.4 \pm 0.4) \times 10^{-1}$
Müller 1968[b]	8.1×10^{-4}	...	...	...	1.8×10^{-1}
Doering 1990/Beideck et al. 1994[b]	...	...	...	...	$(1.49 \pm 0.11) \times 10^{-1}$
Lawrence 1967[c]	7.0×10^{-4}	...	...	...	...
Gruzdev 1969[c]	3.0×10^{-4}	...	...	...	...
Aymar 1973 (CI)[c]	9.4×10^{-4}	2.47×10^{-3}	3.56×10^{-2}	1.94×10^{-1}	2.30×10^{-1}
Ganas 1982[c]	...	...	...	...	2.56×10^{-1}
Ho & Henry 1985 (L)[c]	...	...	...	...	2.18×10^{-1}
Ho & Henry 1985 (V)[c]	...	...	...	...	1.40×10^{-1}
Fawcett 1986[c]	...	...	1.62×10^{-2}	9.66×10^{-2}	...
Mendoza & Zeippen 1988[c]	...	...	...	...	1.72×10^{-1}
Butler et al. 1995[c]	...	...	...	...	1.51×10^{-1}

Reference	λ1402	λ1405M[a]	λ1320M[a]	λ1303	λ1307M[a]
ISM	1.49×10^{-2}	1.43×10^{-2}	4.52×10^{-2}	5.06×10^{-3}	5.04×10^{-3}
Müller 1968[b]	1.6×10^{-2}	...	4.2×10^{-2}	2.9×10^{-2}	...
Smith 1978[b]	...	...	$(3.8 \pm 0.5) \times 10^{-2}$	...	...
Aymar 1973 (CI)[c]	1.8×10^{-2}	1.8×10^{-2}	...	...	...
Ganas 1982[c]	...	1.5×10^{-2}	1.15×10^{-1}	...	5.4×10^{-3}
Ho & Henry 1985 (L)[c]	...	1.1×10^{-2}	3.3×10^{-2}	...	...
Ho & Henry 1985 (V)[c]	...	1.4×10^{-2}	2.6×10^{-2}	...	...
Mendoza & Zeippen 1988[c]	...	1.2×10^{-2}	2.6×10^{-2}	...	4.0×10^{-3}
Butler et al. 1995[c]	...	1.5×10^{-2}	2.8×10^{-2}	...	4.8×10^{-3}

Reference	λ1274M[a]	λ1266M[a]	λ1256M[a]	λ1245M[a]	λ1227M[a]
ISM	1.08×10^{-2}	2.59×10^{-3}	1.92×10^{-3}	1.06×10^{-3}	$\leq 1.2 \times 10^{-3}$
Müller 1968[b]	7.3×10^{-3}	...	...	...	...
Ganas 1982[c]	5.68×10^{-2}	2.6×10^{-3}	3.17×10^{-2}	...	...
Mendoza & Zeippen 1988[c]	2.0×10^{-3}	2.0×10^{-3}	...	...	...
Butler et al. 1995[c]	4.3×10^{-3}	2.1×10^{-3}	9.2×10^{-5}	1.1×10^{-3}	1.3×10^{-3}

[a] M indicates multiplet wavelength.

[b] Experimental results.

[c] Theoretical results in which for Aymar 1973 the results based on configuration interaction are shown, and for Ho & Henry 1985 both the length (L) and velocity (V) results are given.

astronomical data for a suite of lines of varying strength, and large-scale theoretical computations for a large number of multiplets. Overall, the suite of oscillator strengths derived here have an accuracy of some 20%, with those for the multiplets with precise experimental data approaching 10%. Therefore, future analyses involving lines of neutral sulfur are now more secure. Of particular note are those analyses of emission from Io and its plasma torus and cometary comae where uncertainties in the atomic data are no longer the limiting factor.

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