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SINGLE GAUSSIAN CURVE OF GROWTH ABUNDANCE DETERMINATIONS FROM ULTRAVIOLET INTERSTELLAR ABSORPTION-LINE DATA

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ABSTRACT

In recent years a number of investigations based on *Copernicus* and *IUE* absorption-line data have revealed apparent correlations between interstellar element depletion and mean line-of-sight hydrogen density, $\bar{n}_H$. These correlations, if real, have important implications for models of the physical processes involved in depletion and the large-scale distribution of depleted gas in the interstellar medium. However, the majority of these investigations have used the rather crude assumption of a single component Gaussian curve of growth to correct for line saturation in the calculation of column densities. Here, the possibility is investigated that these correlations arise as a result of saturation errors in the column density determinations.

Published absorption-line data for the elements Fe, P, and S have been studied for evidence of correlations between gas-phase abundances, derived using the single Gaussian curve of growth method, and parameters indicative of line saturation. No evidence is found for correlations with these parameters, in contrast to the strong dependence of abundance on log $\bar{n}_H$ exhibited by all three elements. The possibility that an apparent discrepancy between Doppler widths (*b*-values) derived from the relatively strong S II lines and those derived from the P II lines is indicative of saturation errors in the S II abundance determinations is investigated. Results indicate, however, that the discrepancy is essentially independent of S II line strength, degree of saturation, and $\bar{n}_H$ and does not imply erroneous S II column densities. Possible explanations for the discrepancy are briefly discussed. It is concluded that the single Gaussian curve of growth method gives reasonable results, in general, even with lines as strong as those used for S II.

Subject headings: interstellar: abundances

I. INTRODUCTION

In recent years a number of surveys of gas-phase interstellar element abundances have been carried out based on UV absorption-line data obtained with the *Copernicus* and *IUE* satellites. In particular, the extensive body of *Copernicus* equivalent width data for 88 early-type stars published by Bohlin *et al.* (1983) has provided the basis for abundance surveys of several elements, including N and O (York *et al.* 1983), Mg (Murray *et al.* 1984; Jenkins, Savage, and Spitzer 1986), Cl (Harris and Bromage 1984; Jenkins, Savage, and Spitzer 1986), P (Jenkins, Savage, and Spitzer 1986; Dufton, Keenan, and Hibbert 1986) and S (Harris and Mas Hesse 1986*b*). A serious problem with the UV data used in these surveys is the relatively coarse resolution of ~ 15 km s^{-1} and ~ 25 km s^{-1} afforded by the *Copernicus* and *IUE* instruments, respectively. This is insufficient to resolve the complex velocity structure of absorbing components along the sight lines which is known to exist from high-resolution ground-based investigations (e.g., Hobbs 1969). Consequently, in order to derive column densities from *Copernicus* or *IUE* equivalent width measurements, it has become customary to make the assumption that saturation of the absorption lines can be accounted for using a simple theoretical curve of growth valid for a single component with a Gaussian distribution of absorber radial velocities. If measurements of at least two lines are available, column densities can then be calculated using a procedure similar to that of the doublet ratio method discussed by Strömgren (1948).

It is clear, however, that this simplistic approach lacks sound justification, and a number of authors have pointed out that element abundances thus derived may be subject to very large errors. Nachman and Hobbs (1973) have demonstrated that the doublet ratio method may underestimate column densities by up to a factor of 10 if narrow, saturated absorption components are blended with broad, unsaturated components, so that much of the absorbing material does not contribute to the observed equivalent widths. Furthermore, it is clear from their results that the error would increase with decreasing doublet ratio (increasing optical depth) and hence could mimic the apparent correlations of element depletion with mean line-of-sight density demonstrated by a number of authors (e.g., Savage and Bohlin 1979; Phillips, Gondhalekar, and Pettini 1982; Murray *et al.* 1984; Harris and Bromage 1984; Harris, Gry, and Bromage 1984; Jenkins, Savage, and Spitzer 1986; Harris and Mas Hesse 1986*a*, *b*).

Another effect which could lead to underestimates of column densities is the broadening of absorption lines by relatively weak, but numerous, moderate-velocity components of the type discussed by Routly and Spitzer (1952). Such components may increase the ratio of stronger/weaker line equivalent widths, thereby causing distortion of the curve of growth in the sense of increasing the *b*-value (York 1985; Shull 1986). Column densities may then be significantly underestimated. This effect might be expected to be most serious for heavily depleted elements such as Fe, Mn, and Si, which are thought to have relatively large gas-phase abundances in high-velocity material due to grain destruction. Again, if the effect is significant and systematic, spurious correlations of depletion with density may be expected since the errors would increase with optical depth.

It should be noted that in the case of Ti II, at least, the evidence for a real correlation between depletion and $\bar{n}_H$ is rather more convincing (see, for example, Harris, Gry, and

Bromage 1984) since abundances can be derived from high-resolution ground-based measurements of individual kinematic components (Stokes 1978). However, interstellar abundance data published to date for most other elements derive from relatively coarse resolution UV measurements and are unavoidably less reliable.

Given the importance of establishing the reality of depletion variations between sight lines with different physical parameters, it is crucial to attempt some assessment of the significance of saturation related errors in gas-phase abundance data sets. In the study described here, equivalent width data sets used in published studies of element abundances in many sight lines have been examined for evidence of saturation related errors.

II. GAS-PHASE ABUNDANCE DATA SETS

Equivalent widths of the Fe II $\lambda\lambda1097$, 1134, P II $\lambda\lambda1153$, 1302, and S II $\lambda\lambda1251$, 1260 lines from Bohlin *et al.* (1983) formed the basis of the study. For each element, optical depths, *b*-values, and column densities were derived using the single Gaussian curve of growth assumption. Oscillator strengths used are as quoted by Bohlin *et al.* (1983). Abundance values are defined as $a(\mathrm{el}) = \log\ [N(\mathrm{el})/N(\mathrm{H_{tot}})] + 12$, where the hydrogen data were taken from Savage *et al.* (1977), Bohlin, Savage, and Drake (1978), and Bohlin *et al.* (1983).

III. RESULTS AND DISCUSSION

The saturation effects discussed in § I have been invoked as possible causes of the correlations of depletion with log $\bar{n}_{\mathrm{H}}$ apparent in abundance surveys of various elements (Jenkins, Savage, and Spitzer 1986; York 1985; Jenkins 1987; Shull 1986). However, the primary effect of these saturation errors would be to produce apparent negative correlations between abundance and *optical depth.* It is normally assumed that sight lines with high optical depths are, in general, those having large values of $\bar{n}_{\mathrm{H}}$. It follows that spurious negative correlations might be expected between gas-phase abundances and $\bar{n}_{\mathrm{H}}$. However, for the elements S, Fe, and P (Fig. 1), it is seen that while the trend between abundance and $\bar{n}_{\mathrm{H}}$ is quite marked, there is no evidence whatsoever for similar negative correlations of abundance with central optical depth or strength of the weaker line. It is particularly noteworthy that this result holds for S, despite the fact that the lines used to derive the S abundance data are relatively strong. It should be noted that the optical depth values derived using the single Gaussian curve of growth method would themselves be affected by saturation errors. However, the sense of such errors would be to *reduce* optical depth, since *b*-values would effectively be increased by the errors. It follows that points to the right of the abundance/τ_0 plots in Figure 1 would have been moved downward *and to the left* by saturation related effects, implying that these plots should be particularly sensitive to such effects. The absence of negative slopes in these plots is therefore a strong indication that significant saturation errors are not *systematic* in the data sets used in this study, although their presence in any individual case cannot be excluded.

The primary effect of unresolved moderate-velocity components on doublets, or line pairs, used in abundance determinations would be to broaden the lines and possibly to increase significantly the ratio of stronger/weaker line equivalent widths thus leading to overestimation of the corresponding *b*-value and underestimation of column density. Such components offer a tempting explanation for the discrepancy between *b*-values derived from the S II $\lambda\lambda1251$, 1260 lines (Harris and Mas Hesse 1986*b*) and those derived from P II and Fe II lines in the survey of Jenkins, Savage, and Spitzer (1986) for the same sight lines. Harris and Mas Hesse (1986*b*) noted that *b*(S II) is higher than *b*(P II) by a factor of 1.7 on average and discussed the discrepancy in terms of possible errors in the normally adopted oscillator strengths of the P II $\lambda\lambda1153$, 1302 lines. On the other hand, there is good agreement between *b*(P II) and *b*(Fe II) (Jenkins, Savage, and Spitzer 1986). Given the very similar atomic properties of S and P, and the fact that these elements both exhibit relatively mild depletion, a large discrepancy between *b*(S II) and *b*(P II) is unexpected.

Curve of growth anomalies for S II have been discussed by Smith (1972) in a study of the sight line to ζ Oph. He found that curves of growth which produced reasonable results when applied to C II, O I and Si II gave excessive abundance values when used on the S II equivalent widths. He concluded that there was probably some structure in the S II lines, related to the wider spatial distribution of S II, which was causing broadening of the lines. Indeed, there is evidence in the Bohlin *et al.* (1983) S II equivalent widths that multicomponent broadening of the S II lines is significant in a number of cases: some sight lines, such as those to HD 21278, 23630, and 219188, have relatively small S II equivalent widths, with the S II line ratio indicating heavy saturation; on the other hand, sight lines such as those to HD 36486, 38771, and 64760 have much stronger S II lines, but the line ratios indicate rather large *b*-values (Harris and Mas Hesse 1986*b*) and only moderate optical depths.

The question is whether the probable multicomponent nature of the S II lines is causing the single Gaussian curve of growth method to give erroneous column densities. This is not necessarily the case, as shown by Jenkins (1986). He has demonstrated that if the equivalent widths are composed of a large number of components whose distribution in optical depth and *b*-value is broad but not irregular, the simplistic single Gaussian curve of growth approach does, in fact, give results which are surprisingly accurate. However, Jenkins stresses that any departure from a smooth distribution of optical depth and *b*-value, such as the bimodal situation discussed by Nachman and Hobbs (1973), will inevitably give rise to large errors.

For the majority of the Bohlin *et al.* (1983) sight lines, the central optical depth of the weaker ($\lambda1302$) P II line, τ_0, is in the range 0–2 (as derived on the basis of the single Gaussian curve of growth assumption). These data, therefore, should be relatively free of saturation related errors. In contrast, the S II data have τ_0 ranging from ~ 1 to 12, and one might expect those results for which $\tau_0 > 2$ to be susceptible, in general, to significant errors, and those with $\tau_0 < 2$ to be relatively trustworthy (cf. the criterion adopted by Jenkins 1987). Indeed, it is clear that many of the S II abundance values for low mean-density sight lines cannot be grossly in error because they come close to the solar value of 7.2 (see Fig. 1). Hence, one might expect reasonable agreement between the S II and P II *b*-values in sight lines with relatively weak S II absorption, or low $\bar{n}_{\mathrm{H}}$, while the ratio *b*(S II)/*b*(P II) should increase with increasing S II line strength if saturation errors are the cause of the discrepancy. Figures 2*a* and 2*b* show *b*(S II)/*b*(P II) plotted against the equivalent width, W_λ, of the weaker ($\lambda1251$) S II line and log $\bar{n}_{\mathrm{H}}$, respectively. It is clear that there is no obvious relation between *b*(S II)/*b*(P II) and line strength (Fig. 2*a*): the discrepancy is significant even at low values of W_λ ($\lambda1251$) and shows

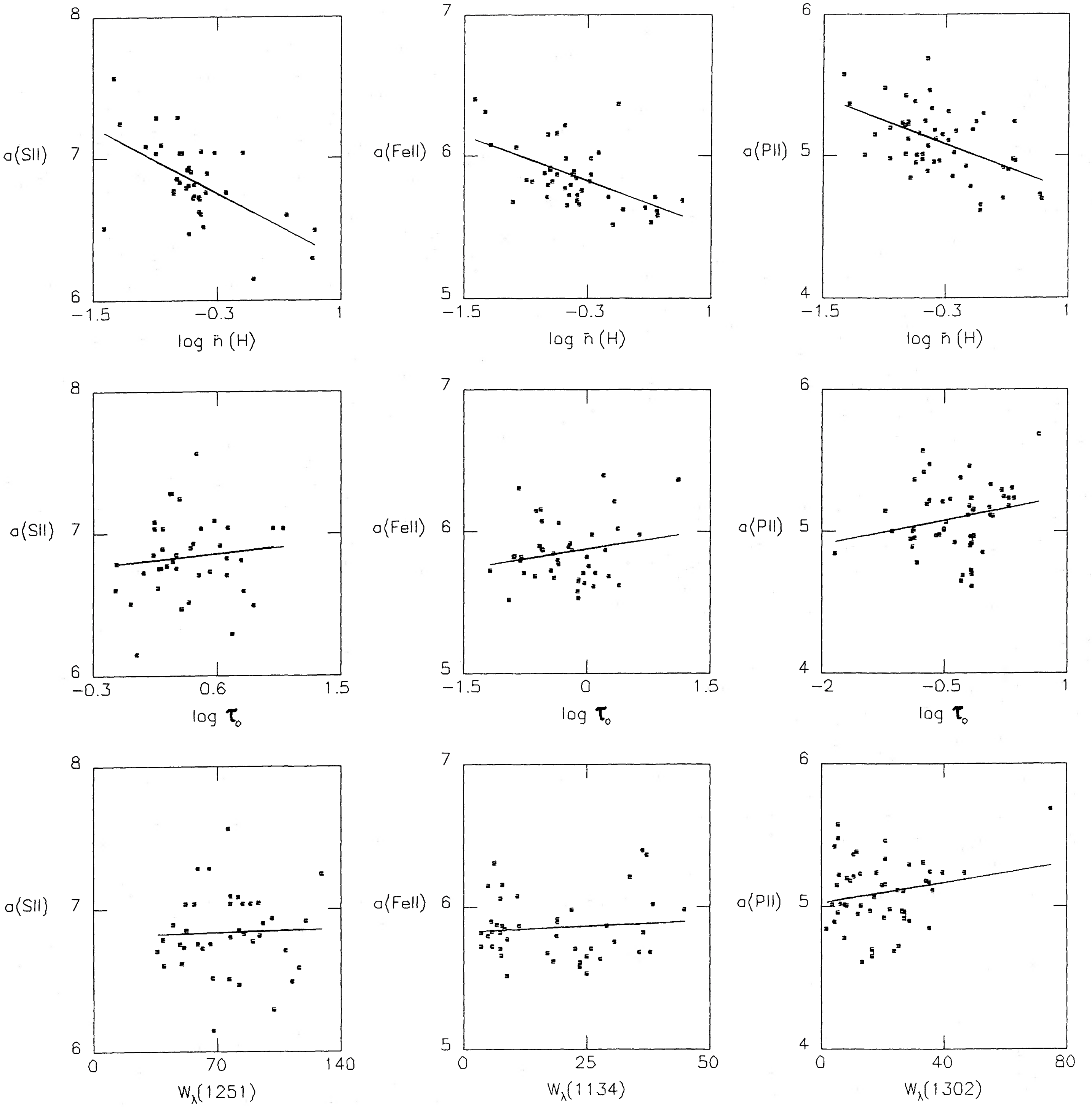

FIG. 1.—Plots of gas-phase abundance vs. log mean hydrogen volume density, log optical depth, and equivalent width for S II, Fe II, and P II. Latter two parameters refer to weaker line used in abundance determinations in each case. For S II, data set of Harris and Mas Hesse (1986*b*) was used. Fe II and P II data sets exclude sight lines for which $W_\lambda < 2\,\sigma$ for either line (or is flagged as otherwise uncertain by Bohlin *et al.* 1983), hydrogen data were not available, or Bohlin *et al.* line ratio is close to unity. Abundance values and their uncertainties are, in general, very similar to those of Jenkins, Savage, and Spitzer (1986). Uncertainties in *a*(el) values corresponding to 1 σ uncertainties in W_λ given by Bohlin *et al.* and uncertainties in hydrogen data are typically ± 0.2. Superposed lines are unweighted least-squares linear fits. Only parameter on which abundance shows any significant dependence is $\bar{n}_H$.

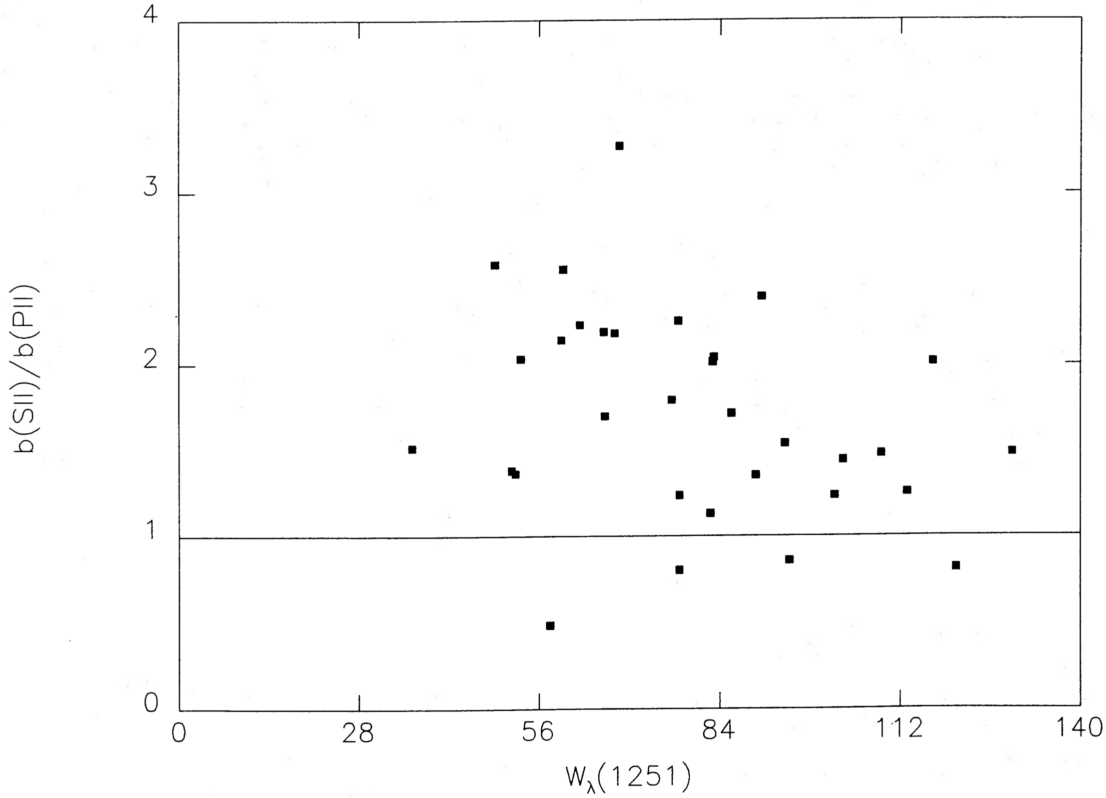

FIG. 2*a*

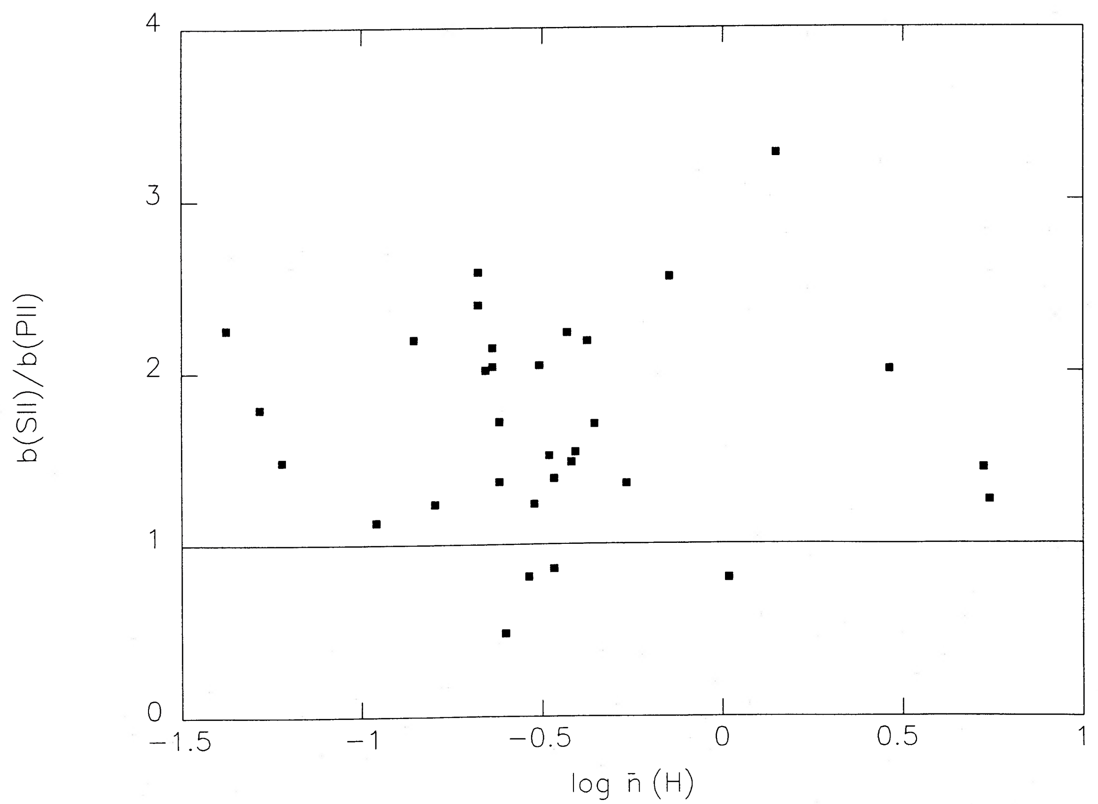

FIG. 2*b*

FIG. 2.—S II/P II *b*-value discrepancy vs. (*a*) equivalent width of weaker (λ1251) S II line and (*b*) log $\bar{n}_H$. Ratio *b*(S II)/*b*(P II) shows no dependence on either parameter.

TABLE 1

THE b(S II)/b(P II) DISCREPANCY AND S II ABUNDANCES FOR SIGHT LINES WITH τ_0(S II λ1251) < 2

HD (1)	$W_\lambda(\lambda1251)$ (mÅ) (2)	$\tau_0(\lambda1251)$ (3)	b(S II) (km s^{-1}) (4)	b(P II) (km s^{-1}) (5)	b(S II)/b(P II) (6)	a(S II) Derived Using b(S II) (7)	a(S II) Derived Using b(P II) (8)
138690......	40.3	0.74	9.5	1.2	7.9	6.6	>8.0
214080......	77.5	0.96	14.9	6.6	2.3	6.5	6.9
148605......	68.4	1.06	12.3	3.7	3.3	6.2	7.5
160578......	62.3	1.19	10.3	4.6	2.2	6.7	7.3
22928......	40.1	1.21	6.6	2.1	3.1	<7.3	<8.8
121263......	35.8	1.24	5.8	2.3	2.5	>6.8	>7.7
136298......	53.1	1.39	8.0	3.9	2.1	6.9	7.4
37043......	82.5	1.43	12.1	10.7	1.1	7.1	7.2
64740......	49.1	1.53	6.9	2.7	2.6	6.8	8.1
151890......	66.2	1.58	9.2	5.4	1.7	6.8	7.2
38771......	90.4	1.76	11.8	4.9	2.4	6.8	8.1
108248......	59.4	1.87	7.5	3.5	2.1	7.3	8.3
118716......	66.0	1.88	8.3	3.8	2.2	7.3	8.4

no sign of increasing with line strength. Similarly, in Figure 2*b*, the discrepancy persists to the lowest values of log $\bar{n}_H$.

The fact that the b(S II)/b(P II) discrepancy is evident even in low τ_0(S II λ1251) sight lines is also illustrated in Table 1, which lists equivalent widths of the S II λ1251 line, S II abundances, and the b-values derived from the S II and P II lines, for the sight lines with τ_0(S II λ1251) < 2. Column (6) shows that even when τ_0 is as low as 1, b(S II) is generally a factor of 2 or 3 greater than b(P II). Furthermore, it is interesting to note the values of a(S II) obtained by applying the b-values obtained from the P II lines to the S II λ1251 equivalent widths in these low S II optical depth sight lines (col. [8]); in a number of cases the resulting S II abundance is well above the cosmic value of 7.2 and therefore apparently erroneous, while the highest S II abundances obtained with the b(S II) values (col. [7]) are comparable to the cosmic value as would be expected. Hence it appears that the P II b-values cannot realistically be applied to the S II data, even in low τ_0 cases which should be free of saturation errors.

These results show that apparently reasonable S II abundances are obtained for many sight lines with the single Gaussian curve of growth method, despite the fact that the S II b-values appear to be anomalously high. Furthermore, the b(S II)/b(P II) discrepancy is systematic and present throughout the data set and appears to be unrelated to S II line strength or $\bar{n}_H$. The S II abundances, on the other hand, show a strong dependence on log $\bar{n}_H$ (Fig. 1).

While the optical depth of the weaker P II line (λ1302) is generally much less than that of S II λ1251, the P II τ_0 range in the Bohlin *et al.* (1983) data extends as far as $\sim$5. Moreover, the ratio of P II optical depths, $\tau_0(\lambda1153)/\tau_0(\lambda1302)$, is 12, whereas that of the S II lines, $\tau_0(\lambda1260)/\tau_0(\lambda1251)$, is only 3. Consequently, given the same optical depth of the weaker line for each species, the stronger P II line will be far more susceptible to saturation effects than the stronger S II line. The possibility of multicomponent line broadening affecting the high optical depth P II data was checked by comparing b-values for P II with the b-values derived for Fe II (Jenkins, Savage, and Spitzer 1986) for sight lines with τ_0(P II λ1302) > 1. The results are shown in Table 2, from which it is clear that there is no significant tendency for the ratio b(P II)/b(Fe II) to increase above unity with increasing $\tau_0(\lambda1302)$, even over a range of τ_0 extending well above 2 [compare the values of this ratio with the values of b(S II)/b(P II) for sight lines with τ_0(S II λ1251) < 2 in Table 1].

Why do the S II lines apparently suffer considerable multicomponent broadening, including the weakest, while even the strongest P II lines do not? A possible explanation is that the abundance of S II relative to that of P II in moderate-velocity components is abnormally large. This might be the case if the moderate-velocity components were primarily H II regions, since the ionization potential of S II (23.3 eV) is higher than that of P II (19.7 eV) and a greater proportion of P would therefore be doubly ionized in such components. The proportion of H II/H I gas in a sight line should decrease with increasing $\bar{n}_H$ since high $\bar{n}_H$ sight lines are likely to be dominated by cool, relatively dense clouds (Spitzer 1985). Therefore, b(S II)/b(P II) would be expected to decrease with increasing $\bar{n}_H$ if H II regions were the dominant cause of the discrepancy. However, as Figure 2*b* shows, there is no obvious relation between b(S II)/b(P II) and $\bar{n}_H$.

Another possibility has been discussed by Routly and Spitzer (1952) who argued that anomalous relative abundances in moderate-velocity components could account for the

TABLE 2

THE RATIO b(P II)/b(Fe II) FOR SIGHT LINES WITH THE HIGHEST VALUES OF τ_0(P II λ1302)

HD (1)	$W_\lambda(\lambda1302)$ (mÅ) (2)	$\tau_0(\lambda1302)$ (3)	b(P II) (km s^{-1}) (4)	b(Fe II) (km s^{-1}) (5)	b(P II)/b(Fe II) (6)
54662......	35.6	0.96	6.6	7.9	0.84
21856......	35.5	1.17	5.7	6.3	0.90
35149......	21.4	1.20	3.4	5.0	0.68
209975......	36.7	1.21	5.8	3.2	1.81
184915......	27.2	1.28	4.1	3.2	1.28
148605......	28.9	1.65	3.8	5.0	0.76
135591......	35.9	1.74	4.5	6.3	0.71
2905......	65.8	1.85	8.0	7.9	1.01
145502......	39.7	1.98	4.7	3.2	1.47
149038......	34.5	2.00	4.0	6.3	0.63
218376......	33.6	2.16	3.8	4.0	0.95
24912......	47.1	2.31	5.1	4.0	1.28
167264......	75.1	4.69	6.2	4.0	1.55
55879......	23.2	5.39	1.9	13.0	0.15

NOTE.—For the purposes of this table the Fe II b-value data were taken from the detailed study of Jenkins, Savage, and Spitzer 1986.

enhanced b(Ca II)/b(Na I) ratio for sight lines with strong Na I and Ca II absorption. They proposed that the destruction, or inhibited formation, of grains in the higher velocity clouds may lead to enhanced gas-phase abundances of certain elements (which are normally depleted) in this material. The results of Harris and Mas Hesse (1986*b*) and Jenkins, Savage, and Spitzer (1986) indicate that S and P are, in general, depleted in the interstellar gas. Moreover, S is a much more volatile element than P or Fe. This suggests that the gas-phase abundance of S may be preferentially enhanced in the moderate-velocity clouds (due to inhibited adherence to grains and/or increased return to the gas phase of S) giving rise to relatively broad S II lines.

A further contributory factor to, or indeed an alternative explanation for, the b(S II)/b(P II) discrepancy may be errors in the normally adopted oscillator strengths of the P II $\lambda\lambda$1153, 1302 lines. The ratio $f(\lambda 1153)/f(\lambda 1302)$ is very uncertain: values given in the literature range from 4.7 (Morton and Smith 1973) to 22.0 (Dufton, Keenan, and Hibbert 1986). The experimental results of Livingston *et al.* (1975) give 13.6, the range allowed by their quoted errors being 9.1–21.7. In order to completely resolve the b-value discrepancy in this way, the $f(\lambda 1153)/f(\lambda 1302)$ ratio must be about 9.2 (Harris and Mas Hesse 1986*b*). Alternatively, the S II oscillator strengths may be in error, although there is no indication in the literature that the normally adopted values for the S II lines (Morton and Smith 1973) may be inaccurate.

IV. CONCLUSIONS

Data sets used in gas-phase abundance determinations of the elements Fe, P, and S, based on the single Gaussian curve of growth method, have been examined for evidence that saturation related errors give rise to, or enhance, the apparent correlations of depletion with mean hydrogen volume density, $\bar{n}_H$. It has been shown that the same abundance data which exhibit a strong dependence on $\bar{n}_H$ show no tendency to correlate similarly with the strength or optical depth of the absorption lines, in contrast to the behavior expected if the apparent density dependence were due primarily to effects arising from line saturation. Furthermore, it has been demonstrated that the discrepancy between S II and P II b-values (Harris and Mas Hesse 1986*b*) is essentially independent of the strength of the S II lines and $\bar{n}_H$ and is evident even in low $\bar{n}_H$ sight lines in which the derived S II abundance is comparable to the cosmic value and therefore cannot have been seriously underestimated. It appears that this discrepancy is not indicative of errors in S II abundance determinations and that the single Gaussian curve of growth method still gives reasonable results, in general, for S II abundances, despite the probable multi component nature of the S II lines. This can be understood on the basis of Jenkins's (1986) study, which indicates that, provided the probability distributions of the optical depths and b-values of the component lines are not abnormal, the single Gaussian method gives reasonably accurate results even when many different velocity components are present.

The b(S II)/b(P II) discrepancy may be explicable in terms of broadening of the S II lines by moderate velocity components and/or inaccuracy of the P II or S II oscillator strengths adopted for the abundance determinations.

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Note added in proof.—After submission of this paper preprints were received (M. E. Van Steenberg and J. M. Shull, *Ap. J.*, submitted) describing surveys of interstellar abundances based on *IUE* data and the single component curve of growth method. The results presented support the conclusions reached by Harris and Mas Hesse (1986*a*, *b*) on the density dependence of S and Zn depletion and the argument in the present work that multiple components in the S II lines could at least partially account for the b(S II)/b(P II) discrepancy. It should be emphasized, however, that the lack of dependence of the b-value discrepancy on S II line strength and, in particular, its persistence right down to the lowest S II equivalent widths and optical depths (*see text*) indicate that the discrepancy is not explicable simply in terms of saturation effects. It appears that a complete explanation requires further contributory factors, such as inaccurate oscillator strengths or anomalous S II/P II gas-phase abundance ratios in moderate-velocity clouds, as discussed in the present work.

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