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THE CORRELATION OF INTERSTELLAR ELEMENT DEPLETIONS WITH MEAN GAS DENSITY

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ABSTRACT

The dependence of interstellar element depletion on line-of-sight mean hydrogen space density $\bar{n}$(H) is investigated for 14 elements using mainly published gas-phase abundances. For six elements the correlation with $\bar{n}$(H) is clearly stronger than with column density, N(H), whereas for Zn, O, N, and D there is virtually no correlation with $\bar{n}$(H). The results clearly demonstrate that depletion is mainly governed by density-dependent processes, emphasize that $\bar{n}$(H) is a more useful sight-line parameter than N(H), and suggest that significant depletion occurs in relatively low density gas as well as in dense clouds. In addition it is shown that chlorine, which is volatile and was previously thought undepleted, can in fact be depleted by a factor 5 or more. No evidence is found for any significant depletion of interstellar deuterium.

Subject heading: interstellar: abundances

I. INTRODUCTION

Investigations of absorption by interstellar gas in the sight-lines to many stars have been carried out with the *Copernicus* satellite (see, for example, Morton 1975, 1978; Snow 1977; York 1983). The total number of published data is such that it has become possible to survey the absorption by particular elements in a large number of sight-lines with a wide distribution of galactic coordinates. In addition, the large body of spectra in the *IUE* data banks now constitutes a valuable source of data for such studies. Large-scale surveys of interstellar absorption allow the dependence of gas-phase abundances on sight-line parameters such as H column density and E_{B-V} to be investigated. In a small investigation it may not be clear whether observed variations from star to star in the abundance of an element are real or simply a result of the limited accuracy of the measurements. The establishing of any correlations between abundances and sight-line parameters in a large-scale survey obviously indicates the reality of abundance variations, provided selection effects are taken into account.

A survey based on 24 sight-lines has been completed for the volatile element *zinc* by Harris, Bromage, and Blades (1983). No significant variation in abundance was found, and it appears that this element is virtually undepleted. In contrast, Savage and Bohlin (1979) found a particularly strong dependence of *iron* depletion on the mean line-of-sight hydrogen space density $\bar{n}(H) = N(H)/r$, where N(H) is the total H column density $[N(H) = 2N(H_2) + N(\text{H I})]$ and r is the sight-line length. Phillips, Gondhalekar, and Pettini (1982) and Murray *et al.* (1984) found some evidence of similar correlations for Mg, Al, and Mn.

The present paper adds an extra dimension by investigating the depletion-density relationship for *many* elements, with a very wide range of mean depletions and other properties. The results confirm that grain formation and/or destruction processes are density dependent and reveal that in general $\bar{n}$(H), rather than N(H), is the more appropriate and physically meaningful measure of density for these studies.

II. DATA BASE AND ANALYSIS PROCEDURE

The element column densities were obtained from the following sources:

Ca II: Compilation by Stokes 1978
D I: Vidal-Madjar 1982
Fe II: Savage and Bohlin 1979
N I, O I: York *et al.* 1983
Ti II: Stokes 1978
Zn II: Harris, Bromage, and Blades 1983
Cl I, II: Newly derived (see below)
H I, + H_2: Bohlin, Savage, and Drake 1978; Bohlin *et al.* 1983
Other Data: Compilation by Tarafdar, Prasad, and Huntress 1983

Measurements on sight-lines for which the total hydrogen column density is uncertain or which give only an upper limit for an element column density have been excluded.

The relative abundance defined as $a(X) = \log\,[N(X)/N(H)] + 12$ was plotted against N(H) and $\bar{n}$(H), and linear regression analyses were performed. Examples are shown in Figure 1 (heavily depleted Ti) and Figure 2 (moderately depleted Cl). Table 1 gives the gradients of the fitted lines and the correlation coefficients $r_{N(H)}$ and $r_{n(H)}$ for all the elements in the study. In four cases the correlation coefficients were also calculated for a subset of the data (taking every other measurement from the original list): the results showed that differences from element to element in the number of data points used would not significantly affect the conclusions of this paper. The mean abundance was calculated from the data for each element and subtracted from the relevant cosmic (solar) abundance to give a "mean depletion." The adopted solar abundances are listed in Table 1, where references to the sources are also given. In each case the ion species quoted is the dominant one in most H I regions, but of course the Ca mean depletion is a lower limit since ionization corrections for the unobserved Ca III have not been applied. For Cl, both Cl I and II were included.

III. RESULTS AND DISCUSSION

It is immediately clear from Table 1 that many elements show a significantly better correlation of gas-phase abundance with $\bar{n}$(H) than with N(H). The fact that this is true also for Cl

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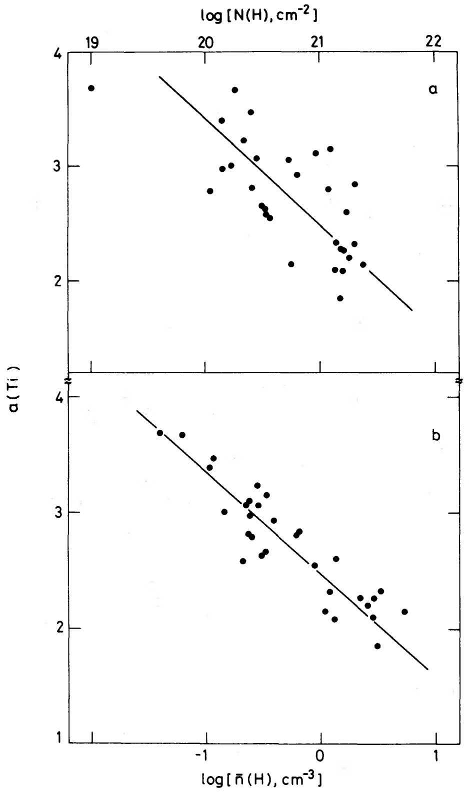

FIG. 1.—Plot of titanium (Ti II) gas-phase abundance against (*a*) log N(H) and (*b*) log $\bar{n}$(H). The Ti II column densities were taken from Stokes (1978). The gradients of the best-fit straight lines are −0.93 and −0.89 with correlation coefficients −0.70 and −0.91, respectively.

(Fig. 2) is perhaps somewhat surprising in the light of the earlier results of Jura and York (1978), who concluded (albeit from a smaller data base) that Cl abundance shows no density dependence and is constant to within a factor of 3.

a) Possible Effects of Line Saturation on Abundance Determinations

Before discussing the implications of Table 1, we consider the extent to which correlations might be distorted by any spurious saturation effects.

Consider first the case of chlorine. The Cl data in the present study were based on the Bohlin *et al.* (1983) compilation of equivalent widths. Sight-lines were chosen for which the measured equivalent widths W_λ of the Cl II λ1071 and Cl I λ1097 (*or* Cl I λ1347 in five cases) lines were small enough for the assumption of optical thinness to be reasonable in the estimation of total Cl abundances. Even for the largest W_λ values used ($\sim$16 mÅ) this assumption is valid for *b*-values as low as 3 km s^{-1}. In general, several velocity components may contribute to total absorption, hence for most sight-lines *effective* *b*-values of comparable species are above this figure (see, for example, the studies of Morton and Hu 1975; Snow 1976; Shull and York 1977; Murray *et al.* 1984). However, in some cases a weak line may be dominated by a single saturated component with a very low *b*-value, and the assumption of optical thinness would then lead to underestimates of column densities. Indeed, York *et al.* (1983) have found single-component *b*-values for N I of the order of 1 km s^{-1} or less. Such saturation errors would be expected to be greater for sight-lines with large $\bar{n}$(H) and hence could account, at least in part, for the observed correlations.

To test this possibility, the *b*-values which would be required to increase *a*(Cl) to 5.2 were calculated for the sight-lines with $\bar{n}$(H) $\gtrsim$ 1 cm^{-3}. It is clear from Figure 2*b* that a revision of the *a*(Cl) values of at least this order would be required for the correlation to be explicable mainly in terms of saturation errors. In general, both Cl I and Cl II contribute to the total chlorine abundance; but in cool, dense H I clouds with *b*(Cl) < 3 km s^{-1}, Cl would be predominantly neutral since its ionization potential is only 0.6 eV below that of hydrogen. Hence any serious saturation errors will occur in the Cl I contribution only. The required maximum *b*(Cl I) values are given in Table 2, together with comparison values actually derived for N I by York *et al.* (1983) for the same sight-lines. These results demonstrate that unrealistically low *b*-values would have to apply to the majority of sight-lines if the correlation of Cl depletion with $\bar{n}$(H) were to be attributable to saturation errors. We believe, therefore, that although such errors could contribute to the correlation, the dominant effect is that of real density-dependent depletion. A large-scale survey of interstellar Cl abundances, based on *Copernicus* and *IUE* data, has been completed recently (Harris and Bromage 1984) which confirms that Cl can be depleted by a factor 5 or more.

Abundance data for most of the other elements considered here are based on column density estimates from more detailed analyses which allow for saturation, including curve-of-growth analyses. Although such analyses may still lead to underestimates of column densities when absorption lines have very

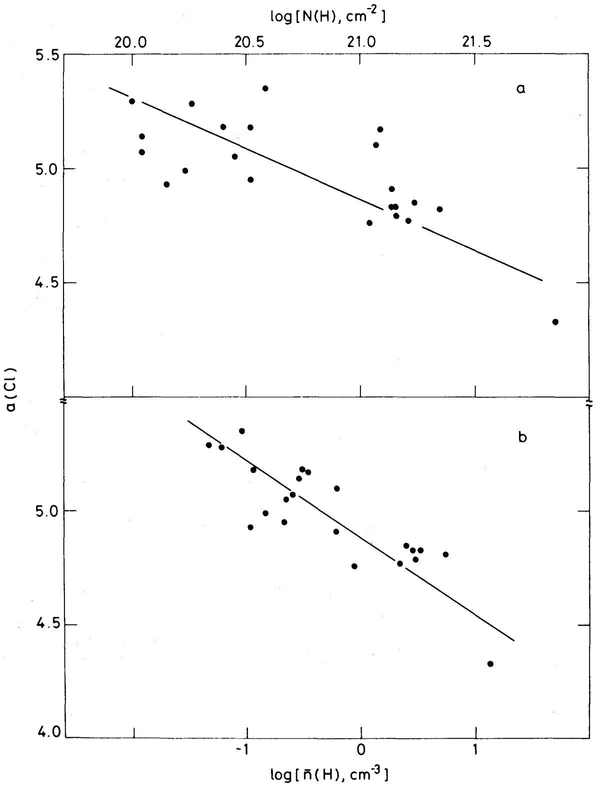

FIG. 2.—Plot of chlorine (Cl I + II) gas-phase abundance against (*a*) log N(H) and (*b*) log $\bar{n}$(H). The best-fit gradients are −0.45 and −0.34, and the linear correlation coefficients are −0.73 and −0.85, respectively. The clear correlation of decreasing abundance with increasing $\bar{n}$(H) confirms that variations in Cl abundance are real and that Cl is significantly depleted. The data were derived from equivalent widths given by Bohlin *et al.* (18 stars with well-determined W_λ), Morton (1975, 1978), Shull (1977), and Jura and York (1978).

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TABLE 1

SLOPES OF LEAST-SQUARES STRAIGHT-LINE FITS AND LINEAR CORRELATION COEFFICIENTS FOR PLOTS OF GAS-PHASE ABUNDANCE AGAINST LOG $N(\mathrm{H})$ AND LOG $\bar{n}(\mathrm{H})$[a]

Species	No. of Data Points	Slope $N(\mathrm{H})$	Slope $\bar{n}(\mathrm{H})$	$\lvert r_{N(\mathrm{H})}\rvert$	$\lvert r_{n(\mathrm{H})}\rvert$	$\lvert r_{n(\mathrm{H})}/r_{N(\mathrm{H})}\rvert$	Mean Element Abundance	Solar Abundance	Mean Element Depletion
D I	16	(−0.06)	(−0.05)	0.23	0.09	0.4:	7.1	...	...
C II	14	−0.47	−0.33	0.50	0.44	0.9	>8.1	8.4	<0.3
N I	24	(+0.12)	(−0.06)	0.26	0.12	0.5:	7.8	7.9	0.1
O I	13	(+0.09)	(+0.05)	0.35	0.15	0.4:	8.1	8.8	0.1
Mg II	13	−0.53	−0.45	0.79	0.88	1.1	6.6	7.6	1.0
Si II	15	(−0.44)	−0.40	0.36	0.43	1.2	6.5	7.5	1.0
P II	16	−0.55	−0.49	0.78	0.81	1.0	5.0	5.5	0.5
S II	15	−0.49	−0.35	0.68	0.64	0.9	7.0	7.2	0.2
Cl I + II	22	−0.45	−0.34	0.73	0.85	1.2	5.0	5.5	0.5
Ar I	16	−0.56	−0.44	0.71	0.71	1.0	6.0	6.3	0.3
Ca II	24	−0.67	−0.74	0.60	0.87	1.5	>3.1	6.3	<3.2
Ti II	31	−0.93	−0.89	0.70	0.91	1.3	2.7	4.8	2.1
Fe II	27	−0.43	−0.38	0.48	0.75	1.6	5.7	7.6	1.9
Zn II	17	(−0.18)	(−0.08)	0.37	0.24	0.7:	4.4	4.6	0.2

[a] Values of slopes placed in brackets are of low significance, corresponding to correlation coefficients below 0.4. Mean abundance and depletion data are also given on the usual logarithmic scales. The solar abundances were taken from the detailed compilation by Hauge and Engvold 1977, adopting their recommended values except for Zn and Ar. For Zn the value derived recently by Biémont and Godefroid 1980 was adopted, whereas for Ar the mean of the coronal and meteoritic abundances has been used since these are somewhat discrepant.

heavily saturated components, it is difficult to see how this could account, for instance, for the very pronounced trend of decreasing Fe abundance with $\bar{n}(\mathrm{H})$ (Savage and Bohlin 1979, Fig. 3*a*) which is apparent even in those data points with $\bar{n}(\mathrm{H}) < 0.1$. Furthermore, the Ti data (Fig. 1) show an even better correlation with $\bar{n}(\mathrm{H})$, and these are based on high-resolution ground-based measurements of individual kinematic components (Stokes 1978).

Finally, we point out that if saturation errors were in fact the primary cause of the correlations, the mean abundances of many of the elements concerned must have been grossly underestimated in the past. We maintain that this is highly unlikely and that the results of the present study, which is based on a large number of abundance determinations of different elements for many different sight-lines, are not significantly affected by saturation errors.

b) *Dependence of Element Depletion on Density*

The dependence of depletion on hydrogen *column* density $N(\mathrm{H})$ has been studied by Tarafdar, Prasad, and Huntress (1983) for a number of elements. They conclude that in general depletion increases with $N(\mathrm{H})$, although observational selection effects [such as insufficient representation in the data sets of sight-lines with high depletion and low $N(\mathrm{H})$] may enhance the trends. In the present study we investigate the dependence of depletion on $\bar{n}(\mathrm{H})$, in addition to $N(\mathrm{H})$, and compare the correlations with these two different measures of matter density.

If the correlations were due largely to selection effects, the ratio $r_{n(\mathrm{H})}/r_{N(\mathrm{H})}$ would not be expected to vary greatly from element to element. This is clearly not the case, for not only does it vary from element to element but there is a very clear trend of increasing relative importance of $\bar{n}(\mathrm{H})$ with increasing mean depletion (Fig. 3). Therefore, our results not only confirm that the depletion of many elements is density dependent but demonstrate in addition that the dependence is stronger if the parameter $\bar{n}(\mathrm{H})$, rather than $N(\mathrm{H})$, is used as the measure of density. Hence for depletion processes at least, $\bar{n}(\mathrm{H})$ appears to be the more relevant measure of particle density in a sight-line.

This result is surprising if depletion takes place only in dense clouds, since $\bar{n}(\mathrm{H})$ is proportional to the *mean* density of matter along a sight-line: one can image two sight-lines with back-

TABLE 2

COMPARISON OF *b*-VALUES NEEDED FOR Cl I TO FORCE-FIT TO $a(\mathrm{Cl}) = 5.2$[a] WITH ACTUAL *b*-VALUES FOR N I DETERMINED OBSERVATIONALLY BY YORK *et al.* 1983, FOR ALL COMMON SIGHT-LINES WITH $\bar{n}(\mathrm{H}) \gtrsim 1\ \mathrm{cm}^{-3}$

HD	Name	log $\bar{n}_{\mathrm{H}}$	Hypothetical Values of b(Cl I) [km s^{-1}] Needed to Force $a(\mathrm{Cl}) = 5.2$	Observationally Determined b(N I) [km s^{-1}] (York *et al.* 1983)
23180	o Per	0.34	0.8	>4
143275	δ Sco	0.48	0.2	>1.1
144217	β' Sco	0.45	0.4	1.0–1.6
144470	ω' Sco	0.40	0.2	>1.0
147933	ρ Oph	1.13	0.5	>0.7
148184	χ Oph	0.74	1.4	>0.8
224572	σ Cas	−0.03	0.5	0.4–1.4

[a] That is, the maximum values which would allow the apparent correlation in Fig. 2*b* to be explained solely by spurious saturation effects.

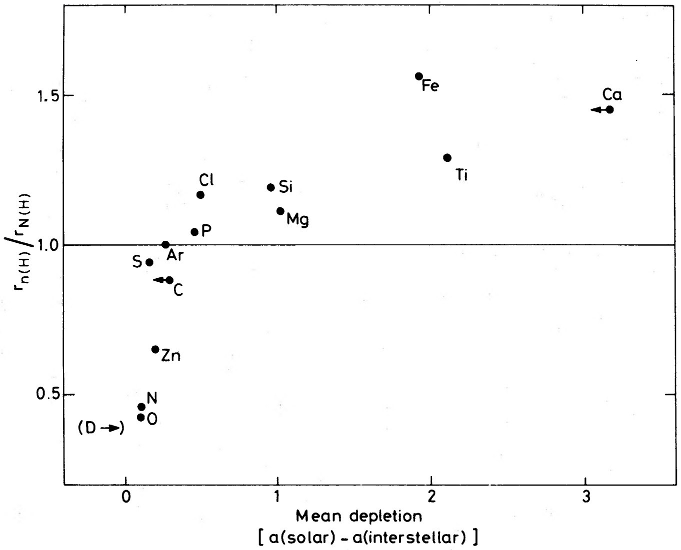

FIG. 3.—Empirical dependence of depletion-correlation index $[r_{n(H)}/r_{N(H)}]$ on mean depletion of an element. Here, $r_{n(H)}$ and $r_{N(H)}$ are the coefficients of the linear correlations of element depletion with log $\bar{n}$(H) (mean H *space* density) and log N(H) (*column* density), respectively.

ground stars at different distances passing through similar clouds, but having very different $\bar{n}$(H) values. The more realistic measure of density in this case would seem to be N(H). In general, therefore, our present results are consistent with a more homogeneous distribution of depleted gas. Since the correlations persist over more than two orders of magnitude in $\bar{n}$(H), they indicate that significant depletion occurs in relatively diffuse, low-density gas. Plots of depletion against log N(H), on the other hand, do not reveal this since there is virtually no correlation apparent at the lower end of the log N(H) scale (see Figs. 1*a*, 2*a*, and the plots of Tarafdar, Prasad, and Huntress 1983, Fig. 2).

In this connection we note that the ratio of molecular to atomic hydrogen, which is a tracer of the densest clouds, shows a better correlation with N(H) than with $\bar{n}$(H): for 28 of the sight-lines used in Figure 1 [excluding three for which $N(H_2)$ is not well determined] the coefficients of correlation of log $[N(H_2)/N(\text{H I})]$ with log $\bar{n}$(H) and log N(H) are 0.71 and 0.82, respectively.

The fact that the five lightly depleted elements S, C, N, O, and Zn *all* have $|r_{n(H)}/r_{N(H)}| < 1$ seems to be significant. On the basis of the above argument this suggests that any depletion of these elements might be associated only with dense clouds. However, for N, O, and Zn the *individual* correlations are of such low significance (cf. York *et al.* 1983; Harris, Bromage, and Blades 1983) that any such conclusions must be considered to be very tentative at this stage.

c) Deuterium

Deuterium is a special case in our study due to its crucial bearing on cosmological models. It is normally assumed that D, like H, is essentially undepleted. However, the abundance of D in the nearby interstellar medium shows a large scatter, and Jura (1982) has discussed the possibility that on the surface of grains D behaves not like hydrogen but more like a heavy element and may be more tightly bound to grains than H. If this is the case, then the interstellar abundance of D derived from *Copernicus* observations has been underestimated, implying that the universe is even more open than has been suggested on the basis of these observations. However, for deuterium we find the lowest correlation coefficients of all 14 elements in our study, and although the density range covered is somewhat restricted, there is certainly no evidence that would point to $r_{n(H)}$ exceeding $r_{N(H)}$ (cf. Fig. 3). Therefore our results lend no support to the proposal of Jura (1982) that D depletion may be substantial.

IV. CONCLUSIONS

We have demonstrated that many elements show a stronger correlation of depletion with density if the mean space density of hydrogen, $\bar{n}$(H), rather than the more widely used parameter N(H), is taken as the measure of density in a sight-line. Furthermore, a study of the correlation coefficients of straight-line fits to depletion/density data for 14 elements has shown a remarkable trend of increasing importance of $\bar{n}$(H) over N(H) with increasing mean element depletion. These results imply that in general depleted gas is not confined to dense clouds but is more uniformly distributed in space.

A plot of chlorine abundance against log $\bar{n}$(H) reveals a strong correlation of depletion with density and shows convincingly that this element can be depleted by a factor 5 or more. However, we find no evidence to support a recent proposal that deuterium may be substantially depleted.

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