

OBSERVATIONS OF INTERSTELLAR CHLORINE AND PHOSPHORUS

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Received 1977 April 18; accepted 1977 June 23

ABSTRACT

Observations of interstellar Cl I and Cl II and upper limits for HCl have been obtained toward 10 stars with the *Copernicus* satellite. Since the cosmic abundance of chlorine is not well established and the f -values of the weak Cl I lines are not well known, we can show only that the average chlorine depletion is not greater than a factor of 3; chlorine may very well be generally undepleted. Even for clouds of widely different densities, we find that the chlorine abundance is uniform to within a factor of 3, and our results are consistent with the view that the interstellar medium within 1000 pc of the Sun is well mixed. Qualitatively, our observations support models of interstellar chlorine chemistry, and our results can be used to constrain models of interstellar clouds. We have also obtained estimates of the phosphorus gas-phase abundance. Because phosphorus and iron have nearly the same condensation temperature, yet very different depletions, our results cast doubts on models that grains are mostly formed in hot regions near 1200 K. Instead, it appears possible that much of the depletion onto grains occurs in the interstellar medium itself.

Subject headings: interstellar: abundances — interstellar: matter — interstellar: molecules

I. INTRODUCTION

The degree of uniformity of gas-phase abundances within the interstellar gas and the exact depletions of different elements onto grains are still uncertain. Previous investigations with the *Copernicus* satellite (see Spitzer and Jenkins 1975) have made substantial progress, but many ultraviolet resonance lines are strongly saturated, and the determination of many column densities is subject to large errors. In this program we have aimed at measuring weak lines that lie on or near the linear portion of the curve of growth; we have therefore observed chlorine and phosphorus.

Another reason to study chlorine is its very simple interstellar chemistry (Jura 1974a; Dalgarno *et al.* 1974). Because of the rapid reaction of Cl⁺ with H₂, we expect that in regions where the hydrogen is primarily atomic, chlorine is ionized; in regions where there is a significant amount of molecular hydrogen, chlorine is neutral. Our observations serve to test this model.

II. OBSERVATIONS

The *Copernicus* telescope and spectrometer have been described by Rogerson *et al.* (1973). In the U1 mode we have measured the equivalent widths of lines of Cl I, Cl II, and HCl listed in Morton (1975) toward stars for which the physical conditions in the lines of sight have been estimated (Jura 1975a, b). Each

chlorine line was scanned four times and the equivalent widths were measured from the usual *Copernicus* stacks; all other lines were scanned twice and stacked. To block the stray light in the spectrometer (York *et al.* 1973), we have used the dipping mirror on the low-resolution carriage as described by Spitzer and Cochran (1973). Also, to be certain that we have properly corrected for stray light, we have obtained profiles for the saturated lines of O I, C II, and N II. To determine the radial velocities of the dense neutral-gas regions, we have measured lines of H₂, and, because of its proximity in wavelength to O I, we have also measured P II 1301. Some of our P II measurements are uncertain because of a lack of short-wavelength continuum. Because some absorption lines are appreciably broader than the instrumental profile (Cohn and York 1977), we have also measured the FWHM of all these lines. Both equivalent widths and our measurements of the FWHM of the lines are listed in Table 1. Using the reduction formula (Shull and York 1977, Appendix B

$$V = c\Delta\lambda/\lambda + 2T + 26 \text{ km s}^{-1},$$

we derived velocities which are listed in Table 2. Systematic errors in V as a function of T and/or λ may exist. In addition, statistical errors may exist, especially for the weaker lines. Relative errors from line to line for a given star are $\pm 2 \text{ km s}^{-1}$ if the value of W_λ is known to better than 20% (Table 1). For less well determined lines, random errors as large as $\pm 4 \text{ km s}^{-1}$ may exist. The combined effects of all errors leaves a typical uncertainty of $\pm 6\%$ in the true values of LSR velocity for any given line.

By accident, we have also measured some other lines listed in Tables 1 and 2. Toward several stars, we have measured a line at 1081.850 Å which Shull

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TABLE 1
 EQUIVALENT WIDTHS AND FWHM IN Å

Line	δ Per	ϵ Per	ξ Per	α Cam
Cl I 1347.240.....	12 ± 5 (0.033)	22 ± 2 (0.057)	52 ± 5 (0.071)	60 ± 7 (0.062)
Cl I 1097.369.....	≤ 3	2.5 ± 0.7 (0.057)*	11 ± 2 (0.064)	11 ± 4 (0.060)
Cl II 1071.050.....	2.4 ± 2.5 (0.065)	3.0 ± 1 (0.049)	6 ± 3 (0.064)	15 ± 6 (0.091)
HCl 1290.257.....	≤ 3	≤ 1.5	≤ 3.4	≤ 6
P II 1301.870.....	≤ 5	10 ± 2 (0.046)	31 ± 9 (0.056)	30 ± 6 (0.050)
C II 1334.532.....	189 ± 29 (0.187)	157 ± 5 (0.159)	203 ± 11 (0.208)	266 ± 15 (0.274)
O I 1302.169.....	171 ± 13 (0.187)	144 ± 3 (0.145)	197 ± 9 (0.188)	263 ± 40 (0.260)
N II 1083.990.....	116 ± 11 (0.115)	101 ± 2 (0.100)	150 ± 3 (0.150)	201 ± 10 (0.200)
H ₂ (2, 0)R(3) 1081.710.....	37 ± 2 (0.056)	46 ± 1 (0.062)	...	...
H ₂ (3, 0)R(4) 1070.898.....	14 ± 2.5 (0.053)	7 ± 0.7 (0.052)	60 ± 3 (0.075)	$77 \pm 6^\dagger$ (0.095)
H ₂ (2, 0)R(4) 1085.144.....	...	...	56 ± 5 (0.065)	$55 \pm 8^\dagger$ (0.107)
Fe II 1081.850(?).....	3.6 ± 3 (0.031)	18 ± 1 (0.060)	...	...
Cl I 1085.303(?).....	...	...	16 ± 5 (0.042)	12 ± 8 (0.044)

and York (1977) have tentatively identified as belonging to Fe II with an f -value between 0.013 and 0.016. Toward ξ Per and α Cam, we have found a line at 1085.303 which is almost certainly Cl I (see Kurucz and Peytremann 1975). Toward these two stars, the equivalent width of 1085 Å is nearly the same as Cl I 1097 Å, and it seems that the f -values for these two lines are nearly equal.

Finally, toward γ Ara and α Cam, we have seen that the $R(4)$ lines of H₂ are asymmetric, as described by Spitzer and Morton (1976) for several other lines of sight.

III. COLUMN DENSITIES

a) Cl II

Except toward α Cam and γ Ara, we find that the equivalent width of Cl II 1071 is appreciably less than 10 mÅ. The absence of hyperfine structure in the Na D lines in the interstellar medium led Hobbs (1969) to conclude that internal b -values less than 1 km s⁻¹ were not common. For gas warmer than that found in the Na I producing clouds, higher b -values would be expected. For $b > 1$ km s⁻¹, 10 mÅ yields $\tau \leq 2$. We assume that the Cl II line lies on the linear portion of the curve of growth and that the f -value for this line is 0.0159 (Morton 1975).

b) Cl I

To determine the Cl I column densities, we have used, whenever possible, the weaker line at 1097 Å (Morton 1975) to avoid possible saturation in the stronger line at 1347 Å. Since the f -value for Cl I 1097 Å is not known, we must estimate it from our data by comparing its strength with that of Cl I 1347, for which the f -value is 0.118 (Morton 1975) or 0.1 ± 0.03 (Clyne and Nip 1977). For several stars (ϵ Per, λ Ori, γ Ara), we find that $W(1347)/W(1097) \geq 8.5$, and this ratio implies that $f(1097) \leq 0.02$. Toward λ Ori, we measure for Cl I 1347 that $W/\lambda = 1.7 \times 10^{-5}$, and there is a strong possibility that this line is saturated. That is, according to Spitzer, Cochran and Hirshfeld (1974), the b -value for H₂ in the $J = 2$ level

is 3.5 km s⁻¹. In this case, $N(\text{Cl I})$ may be underestimated by about a factor of 1.5 if we assume that Cl I 1347 is unsaturated. Correcting for saturation, we find that $f(1097) = 0.014$, which we adopt.

There is other evidence that $f(1097)$ is near 0.014. Toward α Cam, Cl I 1347 Å is saturated because the residual intensity at line center is measured to be only about 0.1 of the continuum. Therefore the optical depth at line center must be at least 2. If the line is not fully resolved by the *Copernicus* spectrometer, the optical depth at line center may be even higher, but the high b -value found by Spitzer, Cochran, and Hirshfeld (1974) of 8.5 km s⁻¹ suggests that we should just resolve the features. For a Gaussian profile, we therefore underestimate $N(\text{Cl I})$ from 1347 by about a factor of 2 (Spitzer 1968) if we assume that this line is unsaturated. Since we observe that $W(1347)/W(1097) = 5.7$, this argument indicates that in the absence of saturation $W(1347)/W(1097)$ would equal 11.4. In this case, $f(1097)$ would equal 0.016. In any case, our adopted value for Cl I 1097 is clearly somewhat uncertain.

To estimate the Cl I column densities, we have usually assumed that Cl I 1097 Å is on the linear portion of the curve of growth. Toward ξ Per, we find that $W(1347)/W(1097) = 4.7 \pm 1.5$, the lowest ratio of any star we observed. Applying doublet ratio type of arguments (e.g., Spitzer 1968), we find that Cl I could be underestimated by 0.1 in the logarithm with the assumption that 1097 Å is unsaturated. This uncertainty for ξ Per is reflected in Table 3, where our Cl I column densities are listed. For stars where we have been unable to detect Cl I 1097 Å, we have used Cl I 1347 to estimate the neutral chlorine column density, or to derive an upper limit.

As a further check on our column densities, we have used the H₂ curves of growth (Spitzer, Cochran, and Hirshfeld 1974) and the equivalent width of Cl I 1347 to estimate $N(\text{Cl I})$. In light of our later discussion on the physical conditions where Cl I is formed, we expect Cl I and H₂ to have similar curves of growth. In general, we find agreement to within 0.1 in the

TABLE 1—Continued

δ Ori A	λ Ori A	ι Ori	15 Mon	γ Vel	γ Ara
≤ 1.3	23 ± 3 (0.056)	1.5 ± 1.6 (0.050)	7 ± 4 : (0.090:)	≤ 1	22 ± 6 (0.065)
≤ 1	3 ± 1 (0.062)	≤ 0.6	≤ 1.3	≤ 0.4	2.5 ± 1.4 (0.040)
3.1 ± 0.8 (0.080)	7 ± 1 (0.064)	1.1 ± 0.7 (0.050)	5.7 ± 1.3 (0.078)	1.4 ± 1.1 (0.040)	9 ± 2 (0.064)
≤ 1	≤ 2.1	≤ 1.1	≤ 2.6	≤ 0.8	≤ 2
$\{1.6 \pm 1.1$ (0.055)† 5.6 ± 1.1 (0.055)†	12 ± 3 (0.052)	$\{1.2 \pm 1.2$ (0.055:) 3.8 ± 1.2 (0.050)	8 ± 3 (0.078)	3.5 ± 0.7 (0.080)	20 ± 4 (0.070)
\dagger	> 350 (70.350)	> 250 (> 0.250)	> 400 (> 0.40)	254 ± 2 (0.230)	215 ± 12 (0.216)
214 ± 2 (0.217)	215 ± 5 (0.211)	214 ± 2 (0.214)	275 ± 4 (0.280)	160 ± 1 (0.164)	207 ± 6 (0.197)
\dagger	> 200 (> 0.200)	> 250 (> 0.250)	\S	159 ± 1 (0.067)	137 ± 4 (0.142)
$\{1.1 \pm 0.7$ (0.056) 4.4 ± 0.7 (0.098)	51 ± 2 (0.067)	1.8 ± 0.9 (0.046)	15.2 ± 9 (0.100)	3.8 ± 0.6 (0.067)	57.5 ± 2 (0.065)
\dagger		2.6 ± 0.9 (0.060)			
2 ± 1 † (0.110)	11 ± 1 (0.049)	≤ 1	≤ 3	1.8 ± 1.3 (0.050)	14 ± 2 (0.059)∥
12 ± 1 (0.106)	43 ± 2 (0.080)	16 ± 1 (0.075)	40 ± 2 (0.086)	14 ± 6 (0.072)	34 ± 2 (0.070)
...

NOTE.—For α Cam, λ Ori, and γ Ara we had incomplete continuum to measure P II 1302. We had half of the feature measurable, and we assumed symmetry to obtain W_λ and ΔW_λ . The velocity is measurable from the available data.

* ϵ Per: Cl I 1097 is asymmetric, apparently a blend with a much wider feature.

† α Cam: asymmetric lines of H₂.

‡ δ Ori A: C II 1334 and N II 1084—detectable high-velocity components discussed in Cohn and York (1977); H₂ (3, 0) 1071 continuum uncertainty included in error estimate for W_λ . The weak component of P II 1301 might be confused with high-velocity O I (cf. Cohn and York 1977).

§ 15 Mon: C II 1334 and N II 1084 detectable high-velocity features.

∥ γ Ara: H₂ 1071 asymmetric.

logarithm with this method compared with using only Cl I 1097.

An exception to this general rule should be noted. We may use these procedures and Morton's (1975) observations of $W(1347)/W(1097)$ to estimate $N(\text{Cl I})$ toward ζ Oph. We find that $\log N(\text{Cl I}) = 14.07$ and $b = 1.5 \text{ km s}^{-1}$. This value of b is significantly less

than the value of 3.8 km s^{-1} derived from H₂ measurements (Spitzer, Cochran, and Hirshfeld 1974) but in moderate agreement with the empirical curve of growth given by Morton (1975) for the neutral species such as Na I, S I, K I, and Cl I. Low-column-density but high-volume-density regions near the velocity of the high-column-density cloud may contribute H₂

TABLE 2
LSR RADIAL VELOCITIES (km s⁻¹)*

Line	δ Per (-10° C)	ϵ Per (-10° C)	ξ Per (-8° C)	α Cam (-9° C)	δ Ori A (-8° C)	λ Ori A (-8° C)	ι Ori (-9° C)	15 Mon (-11° C)	γ Vel (-8° C)	γ Ara (-10° C)
Cl I 1347.240.....	+5	+6	+4	+1	...	+11	-1(?)	+2	...	+4
Cl I 1097.369.....	...	+9	+1	-2	...	+13	...	...	...	+10
Cl II 1071.050.....	+3	+5	+1	-6	$\left\{ \begin{array}{l} +2 \\ -12 \end{array} \right\}$	+8	+3	+1	-11	+1
P II 1301.870.....	...	+3	0	-2	+2	+8	+5	+2	-4	0
C II 1334.532.....	+6	+10	+2	-6	†	†	†	†	-12	-7
O I 1302.169.....	+5	+7	+1	-6	-2	+1	-21	-7	-8	-9
N II 1083.990.....	+11	+11	+2	-4	$\left\{ \begin{array}{l} \dagger \\ -25 \end{array} \right\}$	-6	†	†	-10	-6
H ₂ (2, 0)R(3) 1081.710.....	+7	+7	...	...	-4:	+9	$\left\{ \begin{array}{l} -31 \\ -11 \end{array} \right\}$	+1	-10	+4
H ₂ (3, 0)R(4) 1070.898.....	+10	+7	+1	-2	-6	+11	...	...	-9	+4
H ₂ (2, 0)R(4) 1085.144.....	...	...	+1	-8	...	...	...	...	...	...
Fe II 1081.850(?).....	+17:	+6	...	...	+11	+11	-3	+4	+1	+9
Cl I 1085.303(?).....	...	...	+3	+2	...	...	...	...	...	...

* Derived by using the equation $V = C\Delta\lambda/\lambda + 2T + 26 \text{ km s}^{-1}$ (Shull and York 1977, Appendix B). The equation $V = c\Delta\lambda/\lambda + 2(T + 9.5) + 14.5 \text{ km s}^{-1}$ ($V = c\Delta\lambda/\lambda + 2T + 33.5 \text{ km s}^{-1}$) implied by Spitzer and Morton (1976) requires a temperature measured at the front of the spectrometer. Owing to telemetry failures, this temperature is no longer available on a routine basis. The equation used here requires a temperature reading made about 9 inches (22.5 cm) from the grating at the back of the spectrometer. This temperature is generally warmer than the temperature at the front of the spectrometer. This value is measured at least twice a day and is routinely available for all *Copernicus* observations. See Shull and York 1977, Appendix B, for a discussion of errors. The temperature used to derive the velocities for a given observation is listed under the star name.

† Velocity not measured because of wide, asymmetric component (cf. Cohn and York 1977).

TABLE 3
 COLUMN DENSITIES

Star	$\log N(\text{Cl I})$	$\log N(\text{Cl II})$	$\log N(\text{HCl})$	$\log N(\text{Cl})$	$\log N(\text{P II})$
δ Per	12.80 ± 0.2	≤ 13.17	≤ 12.61	$12.80 (+0.5, -0.2)$	≤ 13.29
ϵ Per	13.06 ± 0.2	$13.27 (+0.1, -0.2)$	≤ 12.30	$13.48 (+0.1, -0.2)$	13.59 ± 0.1
ξ Per	$13.87 (+0.2, -0.1)$	$13.57 (+0.2, -0.3)$	≤ 12.66	14.04 ± 0.2	14.08 ± 0.1
α Cam	13.87 ± 0.2	$13.97 (+0.1, -0.2)$	≤ 12.91	14.22 ± 0.2	14.07 ± 0.1
δ Ori A	≤ 11.84	13.28 ± 0.1	≤ 12.13	13.28 ± 0.1	13.34 ± 0.1
λ Ori A	$13.30 (+0.1, -0.2)$	13.64 ± 0.1	≤ 12.45	13.80 ± 0.1	13.67 ± 0.1
ι Ori	≤ 11.90	$12.83 (+0.2, -0.4)$	≤ 12.17	$12.83 (+0.2, -0.4)$	$13.17 (0.1, -0.2)$
15 Mon	$12.6 (+0.2, -0.4)$	13.55 ± 0.1	≤ 12.54	13.55 ± 0.1	$13.50 (+0.1, -0.2)$
γ Vel	≤ 11.72	$12.94 (+0.3, -0.6)$	≤ 12.03	$12.94 (+0.3, -0.6)$	13.14 ± 0.1
γ Ara	$13.22 (+0.2, -0.3)$	13.75 ± 0.1	≤ 12.43	13.86 ± 0.1	13.89 ± 0.1

but no Cl I to the observed equivalent widths. Velocity differences of 4 km s^{-1} have been noted for several density-dependent species by Hobbs (1973).

c) HCl

We have not detected HCl in any line of sight. The f -value for HCl is not known, but following Morton (1975) we tentatively adopt $f = 0.05$, and we compute upper limits to the HCl column density listed in Table 3 with this estimate.

d) P II

The P II 1301 f -value has been measured to equal 0.017 (see Morton 1975), but this result has been questioned (Shull and York 1977). Because we have measured only one line, we have no way to determine the amount of saturation. Our determinations of $N(\text{P II})$ shown in Table 3 are uncertain, and for some lines of sight they may be too low for cases with $W_\lambda > 10 \text{ m}\text{\AA}$.

IV. ABUNDANCES AND DEPLETIONS

Using the column densities listed in Table 3 and the results for hydrogen nuclei in Bohlin (1975) and Savage *et al.* (1977), we may derive gas-phase abundances for chlorine and phosphorus; the results are shown in Table 4. Although there is some uncertainty, it appears that the averages of both the chlorine and phosphorus abundances are between 5.0 and 5.1 on the usual logarithmic scale where hydrogen is 12.0. At the

moment our measurement errors are sufficiently large that it is not clear whether there are real gas-phase abundance variations, or whether it is appropriate to use an average value of our measures to obtain the interstellar abundance.

Using equivalent widths obtained with other observing programs that have used *Copernicus*, but our own analysis, we list in Table 5 gas-phase abundances for chlorine and phosphorus for several stars. These results are in essential agreement with ours. Toward α Vir, higher values of the gas-phase phosphorus and chlorine abundances are found, but this probably results from a significant amount of ionized hydrogen being in the line of sight (York and Kinahan 1978). That is, a comparison of the amount of chlorine or phosphorus with the amount of neutral hydrogen may be misleading.

The cosmic chlorine abundance is uncertain. Lambert, Mallia, and Brault (1971) have suggested that in the solar photosphere an upper limit of 5.5 is appropriate. From sunspot spectra of HCl, Hall and Noyes (1972) suggest a value of 5.4 ± 0.3 . Recently, Bruhweiler (1976) has suggested that in several early-type stars a non-LTE analysis indicates an abundance near 5.1. In planetary nebulae, Buerger (1973) has derived abundances between 5.0 and 5.5, while Boeshaar (1975) has found values between 6.1 and 6.5. In a region of the Orion Nebula where depletion is apparently not important, Peimbert and Torres-Peimbert (1977) have derived a chlorine abundance of 5.15. If the solar abundance is 5.5, chlorine is generally depleted by about a factor of 3. How-

 TABLE 4
 ABUNDANCES

Star	$\text{Log } N_{\text{H}}$	$a(\text{Cl})$	$a(\text{P})$
δ Per	20.30?	$4.5 (+0.5, -0.2)?$	4.99?
ϵ Per	20.50	$4.98 (+0.2, -0.3)$	5.09 ± 0.2
ξ Per	21.30	4.74 ± 0.3	4.78 ± 0.2
α Cam	21.09	5.13 ± 0.3	4.98 ± 0.2
δ Ori A	20.23	5.05 ± 0.2	5.11 ± 0.2
λ Ori A	20.80	5.00 ± 0.2	4.87 ± 0.2
ι Ori	20.15	$4.68 (+0.3, -0.5)$	$5.02 (+0.1, -0.2)$
15 Mon	20.40	5.15 ± 0.2	$5.10 (+0.2, -0.3)$
γ Vel	19.78	$5.16 (+0.4, -0.7)$	5.36 ± 0.2
γ Ara	20.71	5.15 ± 0.2	5.18 ± 0.2

TABLE 5
OTHER LINES OF SIGHT OBSERVED WITH *COPERNICUS*

Star	Log N_{H}	$a(\text{Cl})$	$a(\text{P})$	Reference
HD 50896.....	20.6 (+0.4, -0.2)	5.34 (+0.5 - 0.3)	...	(1)
μ Col.....	19.85	5.65	5.6 ± 0.3	(2)
HD 28497.....	20.2	5.	4.8 ± 0.2	(2)
\circ Per.....	21.2 ± 0.06	4.5 ± 0.3	4.7 ± 0.3	(3)
λ Sco.....	19.4 ± 0.1	5.4:	5.1 ± 0.2	(4)
α Vir.....	19.0 ± 0.1	$5.75 (+0.2, -0.3)$	$5.4 (+0.1, -0.2)$	(5)
ζ Oph.....	21.13	4.9 ± 0.1	4.7 ± 0.1	(6)

REFERENCES.—(1) Shull 1977, neutral chlorine not observed; (2) Shull and York 1977; (3) Snow 1976; (4) York 1975; (5) York and Kinahan 1978; (6) Morton 1975.

ever, because of the large uncertainty in the cosmic chlorine abundance, chlorine could well be generally undepleted.

Morton (1974) has suggested a cosmic phosphorus abundance of 5.43, which agrees with 5.50 ± 0.15 as suggested by Ross and Aller (1976). Within the uncertainties of our analysis, it appears that the phosphorus abundance in the gas phase is relatively uniform and that the depletion is generally between a factor of 2 and 3 below the solar value.

V. CHLORINE CHEMISTRY

Because of the rapid reaction between Cl^+ and H_2 (see Jura 1974a; Fehsenfeld and Ferguson 1974), we expect chlorine to be ionized in regions where hydrogen is primarily atomic and neutral in regions where there is a significant amount of H_2 . (This reaction is unique among species that may be ionized by photons with $E < 13.6$ eV; for example, P^+ does not react with H_2 .) Our results support this prediction. In clouds where H_2 is optically thin, we have been unable to detect neutral chlorine except, possibly, toward ι Ori. In clouds where H_2 is optically thick, there is a reasonably good correlation between $N(\text{Cl I})/N(\text{Cl II})$ compared with $2N(\text{H}_2)/N(\text{H})$. In the case with an intermediate amount of H_2 , 15 Mon, we have found a small amount of neutral chlorine. In the Appendix, we discuss quantitative models for interstellar clouds to reproduce the observed amounts of neutral and ionized chlorine.

In clouds where the density is sufficiently high and H_2 is optically thick, we expect (Jura 1974a; Dalgarno *et al.* 1974) that

$$N(\text{HCl})/N(\text{Cl I}) = \Gamma(\text{Cl I})/\Gamma(\text{HCl}), \quad (1)$$

where $\Gamma(\text{Cl I})$ and $\Gamma(\text{HCl})$ denote the photoionization and photodestruction rates of Cl I and HCl . Jura (1974a) estimated $\Gamma(\text{Cl I}) = 2 \Gamma(\text{HCl})$ and predicted that $N(\text{HCl}) = 0.5 N(\text{Cl I})$. Instead we generally observe that $N(\text{HCl}) < 0.1 N(\text{Cl I})$, as has been found toward ζ Oph by Wright and Morton (1978). We now argue that $\Gamma(\text{Cl I})$ may have a considerably lower value than proposed by Jura (1974a), so that in fact our new result is not inconsistent with theoretical expectations.

Photoionization of Cl I in interstellar clouds is produced only by photons in the wavelength interval

between 956 and 912 Å. The general interstellar radiation field between 1100 and 912 Å is probably known to within a factor of 1.5 because of the agreement between observations of the populations of H_2 rotational levels with optical pumping models (Jura 1975a). However, the radiation field between 956 and 912 Å is probably quite small (Jura 1974b) and could be nearly zero without appreciably altering the inferred H_2 pumping rate. The radiation field in this spectral range is uncertain because the appropriate corrections for blanketed model atmospheres are uncertain. Also, the chlorine photoionization cross section used by Jura (1974a) from the theoretical calculations by McGuire (1968) is much larger than other photoionization cross sections, and a much lower cross section might be more accurate.

We can use our observations to estimate $\Gamma(\text{Cl I})$. Toward 15 Mon, in the cloud with the largest amount of H_2 (Spitzer and Morton component 2 at $+8 \text{ km s}^{-1}$ in the LSR) where we observe the neutral chlorine to be present (at $+2 \text{ km s}^{-1}$ in the LSR), the atomic hydrogen column density may be as high as $2.5 \times 10^{20} \text{ cm}^{-2}$ (Bohlin 1975). With the observed H_2 column density in $J = 5$ (Spitzer and Morton 1976), we may use equation (3b) of Jura (1976b) to estimate that $n = 20 \text{ cm}^{-3}$. Ignoring radiative recombination of Cl^+ , we may write approximately that

$$\Gamma(\text{Cl I})n(\text{Cl I}) = n(\text{Cl II})n(\text{H}_2)k, \quad (2)$$

where k is the rate for the ion molecule reaction between Cl^+ and H_2 . We therefore estimate that

$$\Gamma(\text{Cl I}) = N(\text{H}_2)kn(\text{Cl II})/N(\text{Cl I}). \quad (3)$$

With $n = 20 \text{ cm}^{-3}$, we may take our observed gas-phase abundance to give $n(\text{Cl}^+) = 3 \times 10^{-6} \text{ cm}^{-3}$. With $N(\text{H}_2) = 4 \times 10^{15} \text{ cm}^{-2}$ (Spitzer and Morton 1976), $k = 7 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$ (Fehsenfeld and Ferguson 1974) and $N(\text{Cl I}) = 4 \times 10^{12} \text{ cm}^{-2}$ (this paper), we find that $\Gamma(\text{Cl I}) = 2 \times 10^{-12} \text{ s}^{-1}$. By ignoring radiative recombination of Cl^+ , we may have underestimated $\Gamma(\text{Cl I})$ in this procedure. Also, if not all the atomic hydrogen in the line of sight is associated with this cloud, we may have underestimated n and $n(\text{Cl}^+)$, and therefore we may have underestimated $\Gamma(\text{Cl I})$.

We can place a lower limit of $\Gamma(\text{Cl I})$ by considering

a region where Cl I is formed only by radiative recombination. That is, we may consider a region where the amount of H_2 is very small. The best line of sight to apply this test is toward δ Ori. Here it appears that abundances are normal (Jura 1975c; this paper) and with $n = 30 \text{ cm}^{-3}$ in the main component (Jura 1975a; Spitzer and Morton 1976), we may take $n_e \sim 0.01 \text{ cm}^{-3}$ (e.g., Spitzer and Jenkins 1975). Therefore, the Cl^+ recombination rate is about 10^{-13} s^{-1} . Since we observe that $N(Cl I)/N(Cl II) \leq 0.03$, we expect that the $\Gamma(Cl I) \geq 3 \times 10^{-12} \text{ s}^{-1}$.

If $\Gamma(Cl I) = 3 \times 10^{12} \text{ s}^{-1}$ for a radiation field in the solar neighborhood, we expect $N(HCl)/N(Cl I) = 0.01$ in clouds where $n(H_2)$ is high—which is consistent with our observed upper limits. Therefore there is no disagreement between our observations and models for interstellar chlorine chemistry. The oscillator strength of the HCl transition at 1290 \AA is uncertain. A precise measurement of this f -value would allow us to confirm our suspicion that $\Gamma(Cl I) = 3 \times 10^{-12} \text{ s}^{-1}$.

VI. DISCUSSION

Field (1974) has noted a systematic tendency for refractory elements to be substantially depleted relative to volatile elements in the interstellar gas, and our result that chlorine is at most only moderately depleted is in accord with this correlation. That is, although condensation temperature calculations for chlorine are unavailable, it is generally thought that chlorine is volatile (e.g., Larimer 1973). For example, although the scatter is large, there is an apparent tendency for chlorine to be most abundant in the C1 (or C I) carbonaceous chondrites compared with the C3 carbonaceous chondrites (see Mason 1971). This pattern is in agreement with the results of volatile elements such as sulfur and in disagreement with refractory elements such as iron or titanium (see Mason 1971). Also, we might expect that chlorine behaves very roughly as fluorine, which is relatively volatile (e.g., Wai and Wasson 1977). Sulfur is generally undepleted in the interstellar gas (e.g., Spitzer and Jenkins 1975), and this agrees with our result that chlorine is at most only moderately depleted in the gas phase.

It has long been suspected that the calcium gas-phase abundance is variable (e.g., Spitzer 1968; Jura 1976a). Our results for chlorine and phosphorus are in marked contrast with the variability in depletion shown by refractory elements such as calcium. De Boer *et al.* (1974) have shown that the iron depletion ranges from factors between 8 and 150 below the solar value. York (1978) has suggested an even wider range, based on the weakness of visible Fe I lines compared with the relatively strong ultraviolet S I lines seen in reddened stars.

There is now direct evidence that the refractory elements iron, titanium, and silicon also have widely variable gas-phase abundances in clouds of different velocities (Shull, York, and Hobbs 1977; Shull and York 1977; Shull 1977; Jenkins, Silk, and Wallerstein 1976; Stokes 1977; Stokes and Hobbs 1976). Since these elements are mostly contained within grains,

we may understand their large gas-phase abundance variations, most notably in high-velocity clouds, as resulting from grain destruction processes (Spitzer 1954, 1976).

The lack of any significant variation of the gas-phase abundance of chlorine among a set of interstellar clouds which apparently show variations of over a factor of 10 in the abundances of refractory elements is consistent with the idea that most chlorine is contained within the gas phase. That is, chlorine apparently does not strongly adhere to grains.

In addition to the lack of variation in the abundances of chlorine and phosphorus where variations in refractory elements do occur, we note that the depletions of Cl and P show no density dependence. Elements which do stick to grains would be expected to be more depleted at higher densities. From analysis of the H_2 observation of Spitzer, Cochran, and Hirshfeld (1974), it may be shown (Jura 1975a, b; our Appendix) that the clouds we have observed have densities that range from 30 cm^{-3} to 1000 cm^{-3} . Despite the wide variation in density, the Cl and P depletions do not vary by more than a factor of 3. Again, it appears that Cl and P do not strongly adhere to grains.

We have found that, for clouds toward stars as distant as 1000 pc, the chlorine abundance is constant to within a factor of 3. This agrees with the result for deuterium of York and Rogerson (1976) and Vidal-Majdar *et al.* (1977). We conclude that the region within 1 kpc of the Sun is probably well mixed. Smith (1975) has argued that there is a factor of 10 variation from the center to the outer observed region in spiral galaxies in the abundances of Ne, S, and O. Although the local interstellar medium may be well mixed, it is entirely possible that the Galaxy as a whole is not.

Using indirect arguments, Crutcher (1975) has found that sodium is generally depleted by about a factor of 6, but there are very large variations in this depletion. This is in contrast to other estimates for the sodium depletion (Jura 1975c; Hobbs 1974). It will be of interest to extend our observations of chlorine and phosphorus to the same stars observed by Crutcher.

Morris *et al.* (1973) have searched for PN in molecular clouds, and they have placed a strong upper limit on its abundance. It is quite possible that an appreciable fraction of phosphorus in dark clouds is contained within PN (Dalgarno 1977), and with a more quantitative understanding of the appropriate chemical reactions, it may be possible to show that phosphorus is more depleted in dark clouds than in diffuse clouds.

We have found that phosphorus is generally depleted by about a factor of 2 or 3. This depletion is between a factor of 10 and 100 less than is generally found for iron (de Boer *et al.* 1974; Morton 1974; Morton and Hu 1975; York 1975; York and Kinahan 1978; Snow 1975). However, theoretical calculations (Grossman and Olsen 1974; Wai and Wasson 1977) show that phosphorus and iron have nearly the same condensation temperature. For example, at 10^{-4} atm

Wai and Wasson (1977) have shown that 0.5 of the iron condenses at 1336 K, while 0.5 of the phosphorus condenses at 1290 K. Meteoritic evidence supports the calculations that phosphorus and iron deplete together (Wai and Wasson 1977). The result that iron and phosphorus are observed to have such different depletion characteristics must cast doubt on models such as those by Field (1974) or Burke and Silk (1976) that propose that much of the depletion of refractory elements occurs in a high-temperature medium (at 1200 K) where thermodynamic calculations of condensation are appropriate. Instead, a model

for grain growth in the interstellar medium (e.g., Snow 1975; Barlow and Silk 1977; Duley and Millar 1977) based on a detailed understanding of the processes on grain surfaces seems required if we are to understand the composition of interstellar grains and interstellar gas-phase abundances.

This work, including a summer visit by M. J., has been supported at Princeton by NASA contract NAS 5-1810. M. J. has also been partly supported by the National Science Foundation. We thank Dr. J. Wasson for discussions about meteorites.

APPENDIX

In the text we noted that the relative amounts of neutral and ionized chlorine are comparable with the relative amounts of molecular and atomic hydrogen. Qualitatively, we understand this result in terms of the rapid reaction between Cl^+ and H_2 . Here we discuss the implications of our observations for constraining models of interstellar clouds.

Let $I(\text{H}_2)$ denote the photodestruction rate of H_2 . When H_2 becomes optically thick, but before it lies on the damping portion of the curve of growth, it is straightforward to show that, very approximately, $I(\text{H}_2) \propto N(\text{H}_2)^{-1}$ (e.g., Hollenbach, Werner, and Salpeter 1971). As a first approximation, we may write

$$I(\text{H}_2) = I_0(\text{H}_2)/[1 + N(\text{H}_2)/N_0], \quad (\text{A1})$$

where N_0 is a scale parameter discussed below. In a steady state when $n(\text{H}_2) \ll n(\text{H})$, we may write that (e.g., Jura 1974*b*)

$$n(\text{H}_2) = Rn(\text{H})^2/I(\text{H}_2). \quad (\text{A2})$$

Taking the derivative of equation (A2) with $n(\text{H})$ constant and using $\partial N(\text{H}_2)/\partial x = n(\text{H}_2)$ and equation (A1), we may write

$$I_0(\text{H}_2)\partial n(\text{H}_2)/\partial x = [n(\text{H}_2)/N_0][n(\text{H})^2R]. \quad (\text{A3})$$

The solution to equation (A3) is

$$n(\text{H}_2) = n(\text{H}_2)_0 \exp [n(\text{H}_2)_0 x/N_0], \quad (\text{A4})$$

where $n(\text{H}_2)_0 = Rn(\text{H})^2/I_0$. From equation (A4), we may write that

$$N(\text{H}_2) = N_0\{\exp [n(\text{H}_2)_0 x/N_0] - 1\}. \quad (\text{A5})$$

In the usual notation, we may write that

$$\tau = Nf \frac{\lambda}{b} \frac{e^2}{mc} \sqrt{\pi}. \quad (\text{A6})$$

The lines begin to saturate when $\tau \sim 1$. For typical H_2 lines that lead to dissociation, $\lambda = 1000 \text{ \AA}$ and $f \sim 0.005$ (Morton and Dinerstein 1976) and $\tau = 1$ when $N = 4 \times 10^{14} \text{ cm}^{-2}$ ($b/3 \text{ km s}^{-1}$). Comparison with detailed numerical results shows that an appropriate value for N_0 is about $2.5 \times 10^{14} (b/3 \text{ km s}^{-1}) \text{ cm}^{-2}$. Some observational evidence supports this simple model. Spitzer, Cochran, and Hirshfeld (1974) have found that, in clouds where the column density of H_2 in $J = 0$ and $J = 1$ is on the order of 10^{15} cm^{-2} , the ratios of $N(4)/N(0)$ and $N(5)/N(1)$, which are mainly controlled by the pumping rate of molecules from $J = 0$ and $J = 1$ levels of the ground state of H_2 by the absorption of ultraviolet photons, are lower by factors of from 5 to 10 than in clouds where there is less H_2 and self-shielding in the H_2 lines can be ignored. A fraction of the pumping transitions lead to dissociation, so for the lines of sight with lower pumping rates, the photodissociation rate must also be lower by about the same amount as the pumping.

We expect that chlorine will be mostly neutral when the reaction of Cl^+ with H_2 is more rapid than photoionization of Cl. This occurs when $n(\text{H}_2) = 0.003 \text{ cm}^{-3}$ if $\Gamma(\text{Cl}) = 3 \times 10^{-12} \text{ s}^{-1}$ (see the text).

Consider now the clouds where $2N(\text{H}_2)$, $N(\text{H})$, $N(\text{Cl I})$, and $N(\text{Cl II})$ are known. If we assume that the depletions of chlorine is the same in regions where $N(\text{Cl}) \sim N(\text{Cl II})$ as in regions where $N(\text{Cl}) \sim N(\text{Cl I})$, and that the amount of ionized hydrogen in the line of sight is negligible, we may use $N(\text{Cl I})/N(\text{Cl II})$ to estimate the amount of atomic

hydrogen in the cloud where the molecular hydrogen is found. We may then use equation (3a) of Jura (1975*b*) to estimate the cloud density from the comparison of $N(4)$ (the column density of H_2 in $J = 4$) with $N(H)$, the column of atomic hydrogen.

Let N_H denote the total column density of hydrogen nuclei in the line of sight so that $N_H = N(H) + 2N(H_2)$. Let $f(Cl\ I)$ denote the fraction of chlorine along the line of sight that is neutral. Let $N(H)_{at}$ denote the column density of atomic hydrogen at the boundary of the cloud where there is a large amount of H_2 , as discussed above. With these definitions, it is straightforward to show that $N(H)_{mol}$, the amount of atomic hydrogen in the cloud with a large amount of H_2 , can be written as

$$N(H)_{mol} = N(H)_{at} + [f(Cl\ I)N_H - 2N(H_2)]. \quad (A7)$$

With $N(H)_{mol}$ and $N(4)$ or $N(5)$, we can use equation (3a) or (3b) of Jura (1975*b*) to estimate the density within a cloud.

For example, toward γ Ara, in the model of Jura (1975*b*) with $n = 30\text{ cm}^{-3}$, we would expect $n_0 = 5 \times 10^{-4}\text{ cm}^{-3}$. With $b = 4.8\text{ km s}^{-1}$ (Spitzer, Cochran, and Hirshfeld 1974), we would find $n(H_2) = 0.003\text{ cm}^{-3}$ when $x = 1.5 \times 10^{18}\text{ cm}^{-2}$ or when $N(H)$ equals $5 \times 10^{19}\text{ cm}^{-2}$. Toward γ Ara, N_H equals $5 \times 10^{20}\text{ cm}^{-2}$. If there were only one cloud in the line of sight, we would expect that, since chlorine could be ionized only in the zone where $N_H = 5 \times 10^{19}\text{ cm}^{-2}$, that most of the chlorine would be neutral. In contrast, we have observed that most of the chlorine in the line of sight is ionized. This discrepancy can be resolved if we assume that there is more than one cloud in the line of sight: at least one cloud, containing most of the hydrogen nuclei with $n(H_2) < 0.003$, and another lower-column-density cloud with $n(H_2) > 0.003$ at the center.

From our measurements, we know that the fraction of chlorine that is neutral is between 0.11 and 0.44. With $2N(H_2) = 3.4 \times 10^{19}\text{ cm}^{-2}$ (Savage *et al.* 1977) and $N(H) = 4.8 \times 10^{20}\text{ cm}^{-2}$ (Bohlin 1975), the fraction of hydrogen in the line of sight that is molecular is 0.066. Perhaps 0.44 of the chlorine along the line of sight is neutral. In this case, in the region where chlorine is neutral, we expect that $N(H) = 1.9 \times 10^{20}\text{ cm}^{-2}$. As a first approximation (in this same cloud), we might expect that, in the outer region where chlorine is ionized, $N(H) = 5 \times 10^{19}\text{ cm}^{-2}$. Therefore the total amount of atomic hydrogen in this cloud could be $2.4 \times 10^{20}\text{ cm}^{-2}$. With $N(4) = 1.4 \times 10^{14}\text{ cm}^{-2}$ and $R = 3 \times 10^{-17}\text{ cm}^3\text{ s}^{-1}$, we find from equation (3a) of Jura (1975*b*) that $n = 50\text{ cm}^{-3}$, in contrast to the previous estimate of $n = 30\text{ cm}^{-3}$. However, since we have observed that the $R(4)$ lines toward γ Ara are asymmetric, we suspect that some of the H_2 in the $J = 4$ level is not associated with the H_2 in the $J = 0$ and $J = 1$ levels. If 0.5 of the H_2 in $J = 4$ is associated with the H_2 ground state, we would find a cloud density of 25 cm^{-3} . On the other hand, it is also possible that the fraction of chlorine in the line of sight that is neutral is only 0.11. In this case, the density could be as high as 500 cm^{-3} .

Toward ϵ Per, we find that the amount of neutral chlorine compared with the amount of neutral and ionized chlorine may range from 0.20 to 0.61. With $2N(H_2) = 6.8 \times 10^{19}\text{ cm}^{-2}$ and $N(H) = 2.5 \times 10^{20}\text{ cm}^{-2}$, in the region where chlorine is neutral, $N(H)$ may range from 0 to $1.3 \times 10^{20}\text{ cm}^{-2}$. In the zone where H_2 is optically thin, $N(H)$ may be as high as $5 \times 10^{19}\text{ cm}^{-2}$, so that, in the cloud where hydrogen is atomic, it is possible that $N(H) = 1.8 \times 10^{20}\text{ cm}^{-2}$. With $N(4) = 7.9 \times 10^{13}\text{ cm}^{-2}$, the density in the cloud may range from infinite to 30 cm^{-3} , in contrast to the estimate of Jura (1975*b*) of 15 cm^{-3} . A similar analysis toward ξ Per indicates that the density may range upward from 280 cm^{-3} (to much larger values). Toward α Cam, the density is greater than 180 cm^{-3} in the cloud where there is a large amount of H_2 in $J = 0$ and $J = 1$. Again, however, in all these clouds and especially α Cam (where the b -value derived by Spitzer, Cochran, and Hirshfeld 1974 is very high), there is the possibility that there are several clouds in the line of sight that contain rotationally excited H_2 , and these estimates for the density may be somewhat too high.

That cloud densities are often greater than 30 cm^{-3} places severe constraints on models for cloud heating (e.g., Jura 1976*b*). It also seems very improbable that the pressure in most interstellar clouds can be much below a value where $nT = 3000\text{ cm}^{-3}\text{ K}$, and this is an important measure for dynamical models of the interstellar gas (e.g., McKee and Ostriker 1977).

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