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THE DEPLETION OF CALCIUM IN THE INTERSTELLAR MEDIUM

Greg Crinklaw[1] and S. R. Federman
Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606
and
Charles L. Joseph
Space Astronomy Laboratory, University of Wisconsin, Madison, WI 53706
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ABSTRACT

Calcium is always found to be highly depleted in the interstellar medium. New observations of the interstellar Ca II H and K lines toward 10 stars along varied lines of sight are combined with existing data in order to study the nature of its depletion. The depletion of Ca along with that of Ti is found to be a stronger function of mean line-of-sight density than P, Mg, Mn, and Fe. This result indicates that both Ca and Ti are so highly depleted in cold diffuse clouds that Ca II and Ti II essentially trace only the warm intercloud medium. This conclusion is based on the fact that the Ca II/Ti II abundance ratio remains constant rather than exhibiting the systematic differences which would be expected from relative changes in the Ca III/Ca II ionization balance. Furthermore, the present results place strong constraints on the efficiency of grain destruction by shocks; the data indicate efficiencies of $\leq 5\%$.

Subject headings: dust, extinction — ISM: abundances

1. INTRODUCTION

The gas-phase abundances of many heavy elements in the interstellar medium are found to be significantly lower, relative to hydrogen, than in the solar system. It is generally assumed that most of the interstellar medium has the same intrinsic relative elemental abundances as that of normal Population I stars such as the Sun, since these stars formed from this very medium on timescales that are short compared to those for Galactic chemical evolution. From the presence of the interstellar extinction of starlight, dust grains are known to pervade the regions between stars. Thus, the most likely explanation for the observed elemental depletions is that the atoms missing from the gas phase are incorporated into grains. The study of calcium is of particular interest because calcium is always found to be highly depleted.

Snow (1975) was the first to introduce an in situ grain processing model which focuses on the ongoing processes in the interstellar medium (grain accretion and destruction). In later models developed by Barlow & Silk (1977), as well as Duley & Millar (1978), the growth of grains is controlled by the probability of a gas-phase ion sticking to a grain or being removed. Interstellar grains are destroyed by shocks produced by supernovae. These shocks propagate in the low-density intercloud regions, but in regions of higher density the shocks should be attenuated. The evidence for this picture is that depletions are universally found to be diminished in high-velocity gas (e.g. Frisch 1980; Vallerga et al. 1993). All of the in situ grain processing models predict density dependent depletions, with some elements depleted preferentially with increasing density. The observational evidence does show a clear dependence of depletion on mean line-of-sight density (Stokes 1978; Savage & Bohlin 1979; Snow & Jenkins 1980; Jenkins, Savage & Spitzer 1986), but there is little evidence for the preferential depletion of one element over another (Snow & Jenkins 1980; York 1983; Snow 1984; Joseph, Snow, & Morrow 1985; Jenkins 1987; Joseph 1988). In contrast, studies of lines of sight that are rich in molecules (Joseph et al. 1986, 1989; Savage, Cardelli, & Sofia 1992; Federman et al. 1993) reveal some preferential depletion between volatile and refractory elements.

Joseph (1988) found that the depletions of Fe, P, Mg, and Mn in diffuse lines of sight are linearly correlated and show no evidence for different (preferential) rates of depletion from one element to another. This result probably indicates that the relative abundances of these elements are determined early in the lifetime of the grain and are not significantly altered by subsequent processing which must occur. The winds from hot stars must have contributed at least 10% of the total mass of the ISM in an undepleted form, yet we seldom find certain elements with 10% gas-phase abundance (Jura 1987). In addition, subsequent processing in the interstellar medium explains the range in depletions found for various lines of sight.

Joseph also points out that the constant element-to-element differences in depletion constrain the number of grains completely disrupted by shocks since less than 10% of the iron is rarely observed in the gas phase. Differences in depletion between some elements are easily altered when even a small percentage of the grains are completely vaporized. Alternatively, iron could be contained in robust grains which are too small to be destroyed efficiently by grain-grain collisions.

The present study presents a survey of the depletion of interstellar calcium for 10 different lines of sight, providing additional constraints on grain processing beyond those of Fe in Joseph (1988). A better understanding of calcium depletion is particularly important because this element is so severely depleted in cold clouds. The lines of sight sample a wide range

[1] Presently at Malin Space Science Systems

of conditions in the disk, including the intercloud medium and diffuse clouds, out to a distance of 600 pc. The intent of this study is to investigate the correlations between the depletion of calcium and that of other elements found in the interstellar medium so that new observational constraints may be placed upon the models for grain processing. Particular emphasis is given to the comparison of the depletions of calcium and titanium, which have similar properties such as large correlated depletions and high condensation temperatures, but different ionization potentials. The implications of the model proposed by Spitzer (1985), where depletion is considered to be constant within gas of similar density, will also be explored.

2. OBSERVATIONS

The interstellar Ca II H and K lines (3968 and 3934 Å, respectively) were observed toward 12 lines of sight with the Ritter 1 m telescope between 1990 January and 1991 June. The properties of the stars observed are detailed in Table 1. Several bright stars that had been previously observed by others were included in the program as a check for systematic errors. An échelle spectrograph was employed, fed by a fiber-optic cable from the Cassegrain focus and imaged on a 385X576 GEC P8603 CCD (Bopp et al. 1989). With a dispersion of 0.033 Å pixel^{-1}, the nominal resolving power was 12,000. The S/N ranged from 8–50 for the combined spectra (individual spectra ranged from 3 to 40). Integration times were 60 minutes except for bright standard stars (30 minutes) and when weather interfered.

The spectra, which were reduced with the Image Reduction and Analysis Facility (IRAF) of the National Optical Astronomy Observatories, contained a substantial component of scattered light that could not be easily modeled for the entire image due to the small spacing between the orders. Instead, the scattered light component was measured in the vicinity of the line of interest and subtracted as a constant from the entire image. In all other respects, the spectra were reduced in the manner suggested by IRAF documentation. The spectra of three representative stars are displayed in Figure 1. Finally, the measured equivalent widths were converted into column densities via the doublet-ratio method (Strömgren 1948; Münch 1968).

3. ANALYSIS AND DISCUSSION

The depletion of calcium relative to the depletion of other elements will be analyzed here in a manner similar to that of Joseph (1988). If the preferential depletion predicted by the in situ grain processing models is taking place in the interstellar medium, then Ca should be a stronger indicator of this effect, since it is always highly depleted. An investigation of the correlations between Ca and Ti depletions will be emphasized, due to their similar properties (high depletions, high condensation temperatures, and low ionization potentials for the neutral atom).

The lines of sight employed in this study are a compilation of Ca II data from the present survey and that of Hobbs (1978, 1984). The Ti II column densities are from Hobbs (1984) and Stokes (1978); those of Fe II are from Jenkins et al. (1986). The compilation of data is found in Table 2. The logarithmic depletions, D, listed in the Table are based on the solar abundances given by Grevesse & Anders (1989). The values for D(Ca) in Table 2 do not take into account the contribution from Ca III, which as described below would make D(Ca) more positive by an amount equal to ~ 1.0 dex. The combined sightlines sample a wide range of interstellar conditions as can be readily seen in Figure 2, where the stars are overlaid upon the contours of neutral hydrogen density derived from *IUE* observations (Frisch & York 1983).

In Figure 3, the depletion of Ti and the relative amount of Ca II, $\log [N(\text{Ca II})/N(\text{H})] - \log[\text{Ca/H}]_\odot$, are plotted versus $\langle n_\text{H} \rangle$, the mean line-of-sight hydrogen density, which is computed as the column density $N(\text{H}) = N(\text{H I}) + 2\,N(\text{H}_2)$ divided by r, the distance to the star. The relative amount of Ca II, instead of Ca depletion, is used here because an estimate for depletion must include the important contribution from Ca III. The values for N(H) come from Savage et al. (1977), Bohlin, Savage, & Drake (1978), and Bohlin et al. (1983); the few limiting values from these studies are not considered in our analysis. Figure 3 shows quite dramatically how similar the slopes are for the relative amount of Ca II and the depletion of Ti (-0.84 ± 0.09 and -0.82 ± 0.06, respectively), perhaps signifying a similar pattern of depletion under various physical conditions. This is also evident from a comparison of the analyses of Ti depletion by Jenkins (1987) and Ca depletion by Phillips, Pettini, & Gondhalekar (1984); the sample of Phillips et al., however, is much smaller than ours. In contrast, the slopes for Mg, Mn, P, and Fe are much smaller at -0.28 ± 0.05, -0.22 ± 0.02, -0.32 ± 0.06, and -0.38 ± 0.05, respectively (Hibbert, Dufton, & Keenan 1985). (Hereafter, Mg, Mn, P, and Fe shall be referred to as iron-like elements.) On the basis of Figure 3 alone, both Ca and Ti appear to be preferentially depleted as a function of density, compared to the iron-like elements.

TABLE 1

PROPERTIES OF STARS OBSERVED

HD	Name	R.A.	Decl.	l	b	r (pc)	Spectral Type	V	$B-V$	$E(B-V)$	log N(H)
21856......	...	$03^h32^m40^s$	35°27′	156°	−17°	581	B1V	5.89	−0.07	0.19	21.12
23180......	o Per	03 41 11	32 08	160	−18	239	B1III	3.82	0.05	0.32	20.21
35149......	23 Ori	05 22 50	03 33	199	−18	429	B1V	4.99	−0.15	0.11	20.74
35439......	25 Ori	05 24 44	01 50	201	−18	315	B1Vpe	4.94	−0.21	0.05	20.46
35715......	ψ Ori	05 26 50	03 06	200	−17	273	B2IV	4.58	−0.22	0.04	20.62
36166......	...	05 29 54	01 48	202	−17	378	B1V	5.79	−0.20	0.03	20.32
36822......	ϕ^1 Ori	05 34 49	09 29	195	−13	413	B0IV	4.41	−0.17	0.11	20.84
52918......	19 Mon	07 02 55	−04 15	218	1	459	B1V	4.89	−0.21	0.06	20.34
149757......	ζ Oph	16 37 09	−10 34	6	24	138	O9.5V	2.56	0.02	0.32	21.15
184915......	κ Aql	19 36 54	−07 12	32	−13	630	B0.5III	4.96	−0.01	0.26	21.08
193322......	...	20 18 17	40 44	78	3	608	O8	5.84	0.11	0.40	21.16
224572......	σ Cas	23 59 00	55 45	116	−6	337	B1V	4.95	−0.08	0.17	21.04

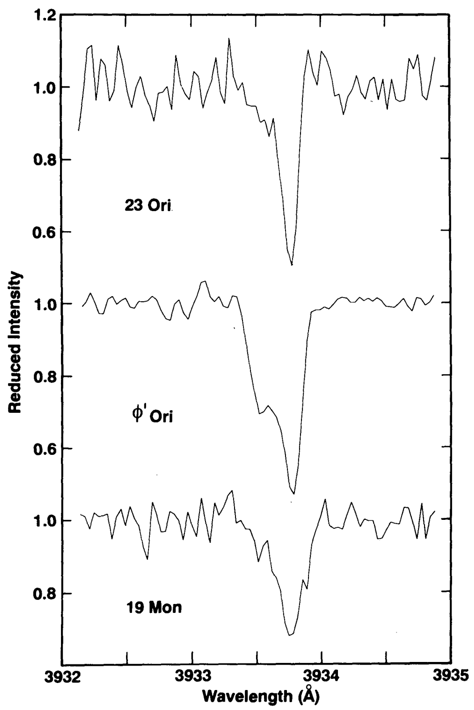

FIG. 1*a*

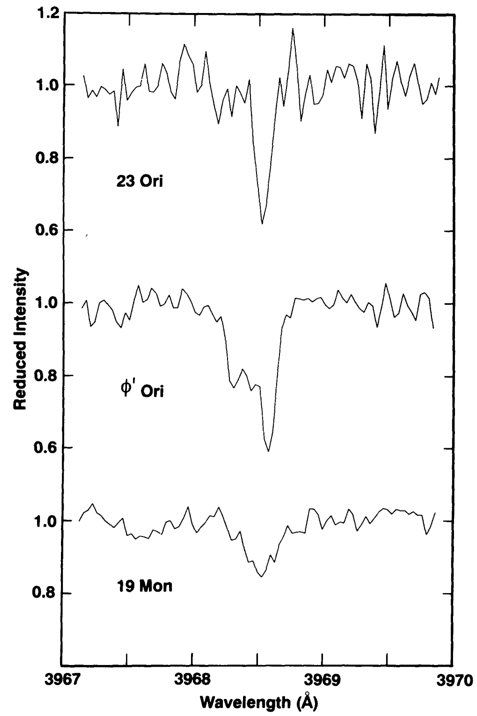

FIG. 1*b*

FIG. 1.—Representative spectra of the interstellar Ca II H and K lines toward 23 Ori, ϕ^1 Ori, and 19 Mon. The wavelength scale is in the frame of the local standard of rest. (*a*) K line at λ3933; (*b*) H line at λ3968.

The variations in abundance of Ca II and Ti II are quite similar, as exemplified in Figure 4 where Ti depletion is plotted against the relative amount of Ca II. The slope is essentially unity (0.90 ± 0.09), implying a constant depletion difference between these two elements. In contrast, a plot of Ti depletion versus Fe depletion (Fig. 5) has a slope of 1.8 ± 0.4 (including measures of upper limits by the method of La Valley, Isobe, & Feigelson 1992), a slope which is larger than those from similar plots among the iron-like elements (Joseph 1988). The slope for the relative amount of Ca II versus the depletion of Fe also reveals a slope significantly greater than unity, although of lower accuracy than the one found in Figure 5. The results of Figures 4 and 5 taken together indicate that the slope for *D*(Ca) versus *D*(Fe) is indeed greater than 1.

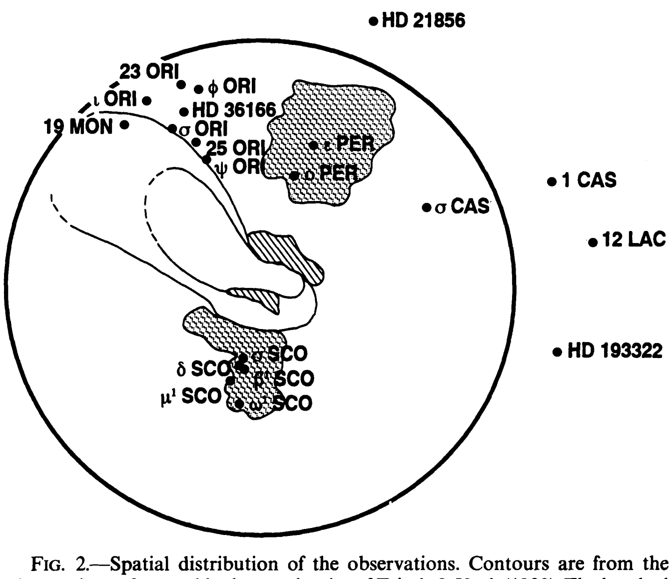

FIG. 2.—Spatial distribution of the observations. Contours are from the observations of neutral hydrogen density of Frisch & York (1983). The hatched areas are diffuse clouds. The circle has a radius of 500 pc.

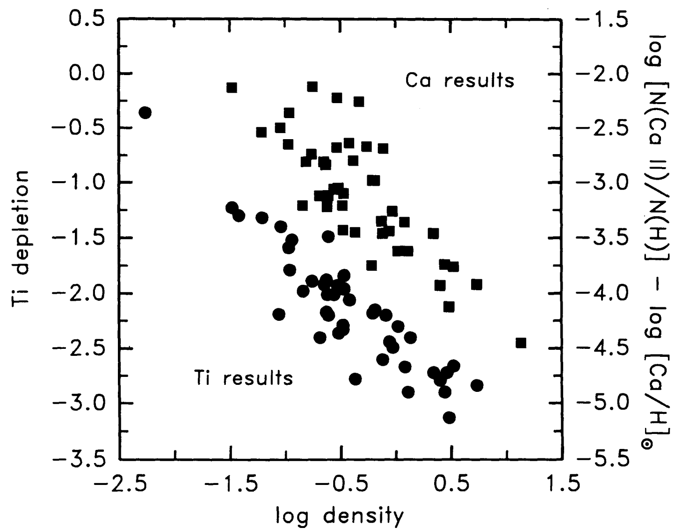

FIG. 3.—Ti depletion and the relative amount of Ca II–log $[N(\text{Ca II})/N(\text{H})] - \log\,[\text{Ca/H}]_\odot$–vs. $\langle n_\text{H} \rangle$, the average line-of-sight density. The results for Ca are indicated by squares and the right-hand scale, while the Ti results are indicated by the circles and the left-hand scale. The comparable slopes suggest that the depletions of Ti and Ca vary with density in a similar manner. Note: Ca III is expected to be $\sim$10 times more abundant than Ca II for all of these data points (see text).

TABLE 2

COMPILATION OF DATA

Star	log *N*(Ca)	*D*(Ca)	log *N*(Ti)	*D*(Ti)	log *N*(Fe)	*D*(Fe)	log *N*(H)
γ Peg	...	...	10.83	−2.20	...	...	20.04
κ Cas	12.68	−2.98	12.14	−2.15	...	...	21.30
γ Cas	11.30	−3.22	11.14	−2.01	...	...	20.16
φ Per	11.49	−3.44	11.12	−2.44	...	...	20.57
HD 21856	12.13	−3.35	...	...	15.05	−1.74	21.12
δ Per	11.18	−3.46	10.67	−2.60	...	...	20.28
40 Per	...	...	11.82	−2.40	...	...	21.23
o Per	12.11	−3.46	11.48	−2.72	14.75	−2.13	21.21
ζ Per	11.94	−3.62	11.29	−2.90	...	...	21.20
ε Per	11.65	−3.21	11.16	−2.33	14.30	−1.87	20.50
ξ Per	12.30	−3.36	11.62	−2.67	...	...	21.30
HD 28497	12.20	−2.36	11.40	−1.79	...	...	20.20
ν Eri	11.38	−3.43	11.15	−2.29	...	...	20.45
α Cam	...	...	12.24	−1.84	...	...	21.09
23 Ori	12.30	−2.80	...	...	14.60	−1.81	20.74
25 Ori	12.60	−2.22	...	...	13.80	−2.33	20.46
ψ Ori	12.70	−2.26	...	...	14.20	−2.07	20.60
HD 36166	12.56	−2.12	...	...	14.45	−1.54	20.32
δ Ori	11.38	−3.21	11.24	−1.98	...	...	20.23
ϕ^1 Ori	12.53	−2.67	...	...	14.45	−2.06	20.84
λ Ori	12.52	−2.64	11.73	−2.06	...	...	20.80
ι Ori	11.86	−2.65	11.55	−1.59	14.20	−1.62	20.15
ε Ori	12.00	−2.81	11.52	−1.92	...	...	20.45
ς Tau	11.28	−3.12	11.54	−1.49	...	...	20.04
σ Ori	11.83	−3.05	11.15	−2.36	14.55	−1.64	20.52
ζ Ori	11.93	−2.84	11.23	−2.17	...	...	20.41
μ Col	12.08	−2.13	11.61	−1.23	...	...	19.85
κ Ori	11.76	−3.12	11.11	−2.40	...	...	20.52
139 Tau	...	...	12.07	−1.88	...	...	20.96
15 Mon	...	...	11.87	−1.52	...	...	20.40
HD 50896	12.45	−2.50	12.18	−1.40	...	...	20.59
19 Mon	11.89	−2.81	...	...	14.10	−1.91	20.34
29 CMa	...	...	11.50	−2.19	...	...	20.70
τ CMa	12.32	−2.74	11.80	−1.89	...	...	20.70
ρ Leo	12.08	−2.54	11.93	−1.32	...	...	20.26
α Vir	...	...	10.69	−1.30	...	...	19.00
η UMa	...	...	10.48	−0.36	...	...	17.85
δ Sco	11.40	−4.12	11.02	−3.13	14.75	−2.08	21.16
β^1 Sco	11.76	−3.74	11.23	−2.90	14.80	−2.01	21.14
ω^1 sco	11.67	−3.93	11.44	−2.79	14.75	−2.16	21.24
ν Sco	...	...	11.46	−2.72	...	...	21.19
σ Sco	11.81	−3.92	11.52	−2.84	15.10	−1.94	21.37
τ Sco	11.40	−3.45	10.70	−2.78	...	...	20.49
ζ Oph	11.75	−3.76	11.48	−2.66	...	...	21.15
ρ Oph	11.77	−4.45	...	...	14.90	−2.63	21.86
μ^1 Sco	11.15	−3.75	<10.73	< −2.80	14.30	−1.91	20.54
κ Aql	12.46	−2.98	...	...	14.85	−1.90	21.08
HD 193322	12.83	−2.69	...	...	14.85	−1.98	21.16
59 Cyg	11.64	−3.06	11.32	−2.01	...	...	20.34
ν Cyg	11.45	−3.62	11.40	−2.30	...	...	20.71
λ Cep	...	...	12.19	−2.20	...	...	21.40
10 Lac	12.41	−2.68	11.79	−1.93	...	...	20.73
12 Lac	12.11	−3.10	11.88	−1.96	15.00	−1.52	20.85
1 Cas	...	...	11.88	−2.18	15.00	−1.74	21.07
σ Cas	12.14	−3.26	11.54	−2.49	14.75	−1.96	21.04

The systematic differences in depletion between the iron-like elements and those of Ca and Ti could be explained by a preferential depletion of Ca and Ti in regions of higher density. The preferential depletions expected from theory, however, should occur for elements such as Fe as well. A different, and more subtle, interpretation involves the relative densities of these gases in clouds of differing hydrogen density. If an element is observed primarily in the intercloud region, its measured depletion will be more sensitive to the inclusion of dense clouds in the line of sight than those elements sampling both regions. This would result in an apparent increase in *N*(H) observed in lines of sight that include dense clouds without a corresponding increase in *N*(Ca) or *N*(Ti), for instance. This idea is consistent with our results and indicates that Ca and Ti are associated primarily with the warm intercloud region.

A considerable body of evidence is building in support of this hypothesis. First, Joseph & Jenkins (1991) analyzed high-resolution spectra in the direction of π Sco. Their absorption-line profile of Fe II is resolved into several components which can be ascribed to either diffuse clouds or to the intercloud medium. A comparison of their Fe II line profile to the Ti II spectrum of Stokes (1978) reveals that the Ti II profile traces only the weak high-velocity Fe II component attributed to the intercloud region. This is strong evidence that Ti II is a tracer of

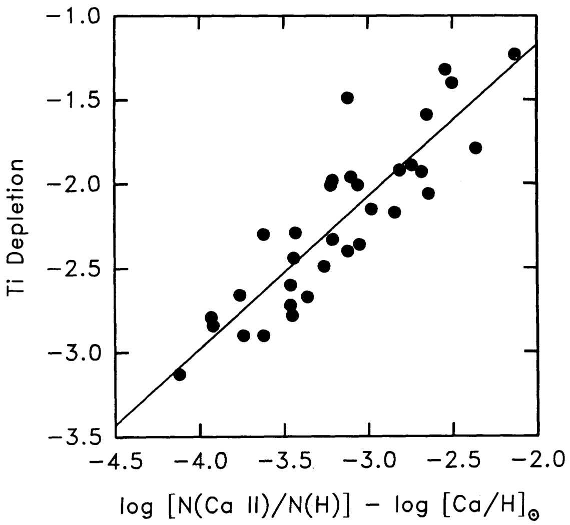

FIG. 4.—Ti depletion vs. the relative amount of Ca II. A slope of essentially unity implies a constant depletion difference for these elements.

the intercloud gas, unlike Fe II. Second, Cardelli, Federman, & Smith (1991) found that Ca is so severely depleted in dense clouds that Ca I is probably below the limits of detection. Crawford (1992) also found severe Ca depletions in dense gas. Third, Welsh et al. (1991) and Vallerga et al. (1993) suggested that Na D observations may be probing a different environment than observations of Ca and Ti. In particular, they noted that the line widths and profiles for Na D often differ significantly from those of Ca II and Ti II. Fourth, in a study of Ca II and Ti II column densities toward lines of sight sampling Galactic halo gas, Edgar & Savage (1989) found that these elements are considerably more extended in $|z|$ than H I and Fe II ($h_{\rm Ca\,II} = 1$ kpc, $h_{\rm Ti\,II} \geq 2$ kpc, $h_{\rm Fe\,II} = 0.5$ kpc, and $h_{\rm H\,I} = 0.3$ kpc). They also found that Ca II and Ti II are much more smoothly distributed than the hydrogen or dust. They concluded that both Ca II and Ti II trace the smoothly distributed medium in the halo, a conclusion which complements the result of this study—that these elements are tracing the intercloud disk gas as well. A consistent picture concerning the depletions of Ca and Ti seems to be emerging—one that can be explained if these elements are primarily tracing the warm low-density intercloud gas, and not the diffuse clouds as once assumed.

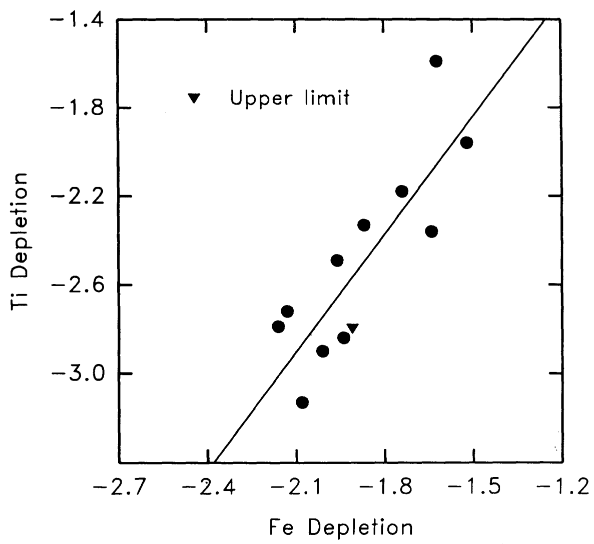

FIG. 5.—Ti depletion vs. Fe depletion. The slope of 1.8 indicates that Ti is depleted preferentially relative to Fe in denser gas.

Analysis of the ionization balances for Ca and Ti is also consistent with the premise that the observed Ca II is more exclusively associated with warmer gas of lower density than had been previously thought. Our calculations, consistent with other published models (e.g., Phillips et al. 1984; Joseph & Jenkins 1991), indicate that most of the available Ca is in Ca III for the warm intercloud gas, but is in Ca II for lines of sight dominated by cold clouds. Then why does N(Ca II) trace N(Ti II) when Ti II is the dominant ionization stage for all of these sight lines? Ca II and Ti II in most lines of sight only sample the warm intercloud gas, and as such the Ca III/Ca II remains relatively constant.

In the highly simplified model of Spitzer (1985), the observed depletion of an element in a line of sight is determined solely by the relative percentage of three types of gas present, each having a particular fixed-level of depletion for that element. The data presented in Figure 3, however, show no indication of the types of curves used by Jenkins et al. (1986) to fit the Spitzer model. These data, therefore, are only consistent with that model if the Ca and Ti abundances in the cold component are at least 100 times more depleted than these elements are in the warm intercloud medium.

The high degree of Ca and Ti depletion in every sight line leads to an elevated sensitivity to regions of relatively high overall density—no matter where we look, the Ca II and Ti II gas we observe is a constituent of the intercloud region. If this is true, then comparisons of elemental depletion are sensitive to the physical conditions associated with the gas we observe, as well as to the depletion rate. In addition if Ca, is primarily found in the warm intercloud gas, then its high degree of depletion places strong constraints upon the efficiency of grain destruction. After all, it is the shocks passing through the gas that are believed to be the dominant method of grain destruction; these shocks should be most effective at freeing atoms from grains in the intercloud medium, and yet less than $\sim 10\%$ of Ca is ever found in the gas phase, assuming a Ca III/Ca II ratio of ~ 10.

An interstellar grain inside a diffuse cloud is expected to be hit by a 100 km s^{-1} shock approximately once every 10^8 yr assuming the galactic magnetic field is ~ 3 μG (e.g., Dwek & Scalo 1980; McKee et al. 1987; McKee 1989). A grain should experience ~ 10 such shocks in its lifetime, assuming the mean lifetime between subsequent incorporations of the material into stars is $\sim 10^9$ yr. Thus if one could select at random an individual parcel of dust and gas having a mean age between asterations, that parcel would have only a 0.7% chance of never having been shocked and a 74% chance of having been shocked 4 or more times for a Poisson distribution of shock arrival times. In this scenario, most of the gas along most lines of sight must have been shocked. The lowest level of depletion observed in more than say 20 sight lines must reflect the degree of grain destruction in a typical shock if accretion and destruction processes are in equilibrium. Furthermore, shocks propagating through the intercloud medium should be 10 times faster and 10 times more frequent than in diffuse clouds.

The present data, for which we have shown only trace the warm intercloud medium, indicate mean depletions for Ca and Ti that are comparable to or slightly more than that of Fe

(Joseph 1988, 1993). Similarly, the scatter in depletions from one sight line to another, a measure of the magnitude of the balance between accretion and destruction, is comparable to that of Fe. These results suggest the destruction and subsequent accretion must be no greater in the warm intercloud medium than it is inside cold clouds, which Joseph (1988, 1993) argues is typically 5% or less. The Ca II and Ti II data along with Fe II imply destruction rates that are lower by factors of 5–8 than predicted by theoretical models. These theoretical models, however, all assume that each grain population has a single chemical composition, a critical assumption that may not be valid (Duley 1980; Mathis 1986; Joseph 1988; Mathis & Whiffen 1989).

Another contributing factor for lower destruction rates than predicted by popular models is recent evidence suggesting the Galactic magnetic field may be much larger than originally thought (Boulares & Cox 1990). If the field strength is 5 rather than 3 μG, supernova remnants would produce strong, destructive shocks for radii of 50 rather than 100 pc. The shocks ultimately propagate as far, but are relatively slow and rather benign for most of volume swept up (Slavin & Cox 1992). The volume where grain destruction is important is reduced by a factor of 8 in this case. This conclusion is supported by the fact that high-velocity gas is not observed as commonly as originally supposed (Cowie et al. 1979; Nichols-Bohlin 1992; Nichols-Bohlin & Fesen 1994).

4. SUMMARY

The observed Ca II, along with Ti II, is found to be associated primarily with the warm intercloud medium. Consequently, the observed depletions of these elements are more sensitive to the presence of dense clouds in the line of sight. Thus, it is important to consider the regions in which the bulk of the absorption arises when comparing depletions of different elements. Furthermore, under the conditions found in the intercloud region, most of the gaseous calcium will be in the form of Ca III, so that depletions determined from N(Ca II) alone will be overestimated. Another consequence of the association of Ca II with the intercloud region is that the efficiency of grain destruction by shocks from supernovae is constrained to be $\leq 5\%$ because such shocks should be most efficient at destroying grains in this region, but very little of the available calcium or titanium is found in the gas phase.

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