Neutral Atomic Absorption Lines and Far-UV Extinction: Possible Implications for Depletions and Grain Parameters

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Examination of the equation of ionization equilibrium: n(X I) Γ = n(X II) n_e α(T) suggests that absorption lines from neutral atoms whose first ions are dominant in H I regions are potentially significant diagnostic tools for determining the conditions within the densest portions of diffuse interstellar clouds. Ratios of this equation for different elements can give accurate relative abundances in those densest regions, as the generally poorly known electron density is eliminated and as uncertainties in Γ/α due to lack of specific knowledge of the temperature and radiation field within the cloud core would tend to cancel in the ratios (York 1980). Variations of this technique have been used to explore possible dependences of the depletions of various elements on the local gas density (Snow 1984; Snow, Joseph, and Meyer 1986), to infer characteristics of the grain mantle accretion process (White 1986), and to estimate grain scattering parameters (Jenkins and Shaya 1979). In this paper, we examine nine lines of sight within the Galaxy and one in the LMC for which data on both neutral atomic absorption lines (Snow 1984; White 1986; Welty, Hobbs, and York 1989) and far-UV extinction (Bless and Savage 1972; Jenkins, Savage, and Spitzer 1986) are available, in order to test the assumption that variations in Γ/α will cancel in taking ratios of the ionization balance equation and to try to determine to what extent that assumption has affected the aforementioned studies of depletions and grain properties.

The Galactic lines of sight seem to be naturally segregated into two distinct groups: one characterized by low (and generally shallow) far-UV extinction (LE) and small N(H_2)/N(H) (σ Sco, δ Sco, ρ Oph, β^1 Sco) and one characterized by higher (and generally steeper) far-UV extinction (HE) and larger N(H_2)/N(H) (χ Oph, ξ Per, o Per, ς Per, ς Oph). Average ratios of the column densities of various neutral atoms with respect to N(K I) are presented for the two groups in columns 3 and 4 of Table 1. The ratios for Li I, Ca I, Mg I, and Fe I are all quite similar for both groups, given typical errors of ±0.2 dex in the column densities. The ratios for Na I, S I, and C I, however, seem to be systematically larger by factors of 3 to 4 for the HE lines of sight than for the LE lines of sight. Although this could be indicative of different patterns of depletion in the two groups of clouds, examination of the ionization potentials of the various species suggests instead that the enhanced ratios for S I and C I reflect a substantially reduced far-UV radiation field in the cores of clouds characterized by higher far-UV extinction. This would not be entirely unexpected, as the calculations of Roberge, Dalgarno, and Flannery (1981; RDF) indicate reductions in Γ for S I and C I, relative to K I, by factors of ~2 and ~3 at the center of a cloud with A_V = 1 for their grain models 2 and 1, respectively. For clouds with appreciable N(H_2)/N(H), Γ(C I) will be further reduced due to the many strong absorption lines of H_2 shortward of 1110Å, but probably not by more than a factor of ~1.5. If the results of RDF, who used an average extinction curve, are crudely adjusted for variations in the observed E(9-6.5)†, and also for H_2 (factor 1.5 for the HE lines of sight), we estimate enhancements of N(S I)/N(K I) and N(C I)/N(K I), for the HE lines of sight relative to the LE lines of sight, of factors of ~1.4 and ~2.2 for their grain model 2 and ~1.9 and ~3.0 for their model 1. While much of the observed relative

† Although the available neutral species have ionization potentials corresponding to inverse wavelengths ranging from 3.5 μ^{-1} (K I) to 9.1 μ^{-1} (C I), inspection of their ionization cross sections as functions of energy suggests that the integrated Γ's will be sensitive to radiation fields over restricted ranges near ~5.5 μ^{-1} (Ca I), 6.0 to 7.0 μ^{-1} (K I, Na I, Li I, Mg I, Fe I), ~8.5 μ^{-1} (S I), and ~9.2 μ^{-1} (C I). We thus use E(9-6.5), the difference in extinction between 9 μ^{-1} and 6.5 μ^{-1}, to estimate the effect of the specific line of sight extinction on ratios of S I and C I with respect to K I.

enhancement of S I and C I might be explained by reduced Γ's for the HE lines of sight, however, the enhancement of Na I cannot - so that it still may be possible that much of the enhancement is due to differential depletion.

In principle, one can solve for n_e, assuming the radiation field is known, if data for adjacent ionization states are available for one element (*e.g.* Ca), and then obtain estimates for the absolute depletions of other elements (*e.g.* White 1986): $\delta_X = [N(X\ I)/(N(H)\ A_X)] \times [N(Ca\ II)/N(Ca\ I)] \times [(\Gamma/\alpha)_{X\ I}/(\Gamma/\alpha)_{Ca\ I}]$. The n_e's calculated using Ca I and Ca II, however, seem consistently larger, by factors from ~4 to ~100, than the n_e's calculated from the neutral and first ionized states of Mg, Fe, and S, which typically agree to within a factor ~2. Lower limits on n_e calculated from C, assuming C II dominant and C undepleted, are generally between the values derived from Ca and from Mg, Fe, and S - though if Γ(C I) is "corrected" for extinction the limits are reduced accordingly. Some error is introduced by using total line of sight column densities for the dominant first ions in such calculations, as the neutral species are presumably concentrated in the cloud cores. Analysis of the absorption-line profiles of the first ions, however, suggests that that typically more than ~70% of the column density of the first ions is found at the same velocity as the dominant neutral component for these lines of sight (though see Snow and Meyers 1979 for ς Oph). The absolute errors in n_e will thus be small, and the relative errors in comparing values of n_e determined from different elements will be smaller still. Other possible sources of error are incorrect atomic data, marked differences in the shape of the radiation field from the WJ1 field assumed, and differences in stratification of the various neutral and first ionized species within the clouds.

Since the uncertainties in n_e make estimates of the absolute depletions rather uncertain, we list in columns 6 through 8 of Table 1 the depletions relative to K, which seemed for any choice of n_e to be generally among the least depleted of the elements considered here. The second entries for S and C incorporate the extinction corrections described above, for grain model 1 of RDF. Comparison of these relative depletions with the depletions derived from the dominant first ions (columns 9 through 11 of Table 1) suggests that depletions of Mg, Fe, S, and C could be enhanced in the cloud cores if K is depleted by as much as a factor ~3. The results for Ca, which would seem to imply much reduced depletion in the cloud cores, are puzzling; a substantially reduced Γ(Ca I) could, however, bring both the relative depletions and n_e determined from Ca into better agreement with those determined from the other elements.

The small number of lines of sight represented here makes it difficult to determine the relative importance of differential depletion and of differences in extinction in producing the observed differences in the ratios of various neutral species. Lines of both S I and Fe I should be detectable toward more stars; P I, also having a high ionization potential, may also be detectable. (Two very tentative detections of P I indeed seem to be consistent with behavior similar to that of S I and C I.) In any case, the specific extinction characteristics of individual lines of sight should be considered in attempts to use these trace neutral species to gain insights concerning depletion and/or the scattering and accretion properties of grains (see also Cardelli 1988 and van Dishoeck and Black 1988).

It is also of some interest to compare these Galactic lines of sight with the line of sight to SN 1987A in the LMC. If the dominant cloud in the LMC toward SN 1987A exhibits the steep far-UV extinction derived for the nearby 30 Doradus region (Fitzpatrick 1985), it would nonetheless be different from the Galactic lines of sight with steep far-UV extinction included here; it is likely to have a low $N(H_2)/N(H)$ ratio (from the weak CH line observed by Magain and Gillet (1987) and from the lack of observed CO absorption in the UV (Welty, York, and Frisch 1989)), consistent with its low total extinction. Likewise, the N(C I)/N(K I) and N(Na I)/N(K I) ratios (~1100 and ~20) are similar to those of Galactic lines of sight with low far-UV extinction. The enhanced Mg I may be another indication of the high-pressure component implied by the C I fine structure level populations. In any case, the ambient radiation field is likely to be quite different from the typical Galactic interstellar radiation field.

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Table 1 - Ratios and Relative Depletions

Element	Expected N(X I)/N(K I) (no depletion)[a]	Observed N(X I)/N(K I) (range)			$\log(\delta_X/\delta_K)$[d] (average)			$\log(\delta_{X\ II})$[e]		
		LE[b]	HE[c]	LMC	LE	HE	LMC	LE	HE	LMC[f]
Na	73	25±10	80±30	20	-0.5	0.0	-0.5	-	-	-
Li	.004	.007±.003	.003±.002	<.004	+0.1	-0.2	<-0.1	-	-	-
Ca	2.7	.015±.010	.012±.008	.10	-2.3	-2.5	-1.4	-3.9	-3.6	-3.2
Mg	220	55±25	70±30	525	-0.6	-0.5	+0.4	-0.7	-0.9	-
Fe	100	1.1±0.6	1.2±0.8	<8	-2.0	-2.2	<-1.1	-2.1	-2.1	-1.5
S	17	9±3	35±15	<18	-0.3 -0.7	+0.3 -0.4	<0.0 <-0.1	-	-	-
C	1170	1000±100	4300±300	1070	-0.1 -0.4	+0.5 -0.3	0.0 -0.2	-0.5	-	-

[a] Γ and α(T=100 K) from Pequignot and Aldrovandi 1986, cosmic abundances from Grevesse and Anders 1988

[b] low far-UV extinction: σ Sco, δ Sco, ρ Oph, β^1 Sco

[c] high far-UV extinction: χ Oph, ξ Per, o Per, ς Per, ς Oph

[d] second entry for S and C "corrected" for far-UV extinction using RDF model 1 and E(9-6.5)

[e] omitted where not observed or where so saturated as to be unreliable

[f] assuming log(N(H)) = 21.0