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CHANGES IN INTERSTELLAR ATOMIC ABUNDANCES FROM THE GALACTIC PLANE TO THE HALO

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ABSTRACT

A few, specially selected interstellar absorption lines have been measured in the high resolution, far-ultraviolet spectra of some 200 O and B type stars observed by the *International Ultraviolet Explorer* (IUE). This study indicates that for lines of sight extending beyond about 500 pc from the galactic plane, the abundance of singly-ionized iron atoms increases relative to singly-ionized sulfur. However, the relative abundances of singly-ionized sulfur, silicon and aluminum do not seem to change appreciably. A likely explanation for the apparent increase of iron is the partial sputtering of material off the surfaces of dust grains by interstellar shocks. Another possibility might be that the ejecta from type I supernovae enrich the low density medium in the halo with iron.

I. INTRODUCTION

Many absorption lines which appear in ultraviolet stellar spectra reveal the gas-phase abundances of elements in the interstellar medium (Spitzer and Jenkins 1975). In past years, the spectrometer on the *Copernicus* satellite provided much information in this regard, but the limited sensitivity of this instrument has restricted surveys of the interstellar gas to within a few kpc of the sun. The *International Ultraviolet Explorer* (IUE) can, in its high resolution mode, observe the spectra of early-type stars as faint as 10th magnitude, thus greatly extending our distance range. Early in the life of this satellite, Savage and de Boer (1979) capitalized on IUE's high sensitivity by observing lines of sight through our galactic halo toward stars in the Large Magellanic Cloud. This paper will report on the material in front of a large selection of stars widely scattered about the galactic halo. The result for these stars will be compared with those from other stars in the plane of the galaxy. For reasons discussed below, however, the analysis of each spectrum will be restricted to a few, specially selected absorption lines.

Under most circumstances, interstellar lines recorded by IUE are not suitable for deriving column densities. As a rule, a line which is strong enough to measure reliably in a single exposure is, with the usually found velocity dispersion $b < 10$ km s^{-1}, badly saturated and on the flat portion of the curve of growth. Only when many exposures are co-added or special, noise-suppressing reduction procedures are invoked can one hope to obtain a believable measurement (see, e.g. York and Jura (1982)). The survey being considered here makes use of single exposures which were analyzed only with the standard spectrum reduction procedure (IUESIPS). As a consequence, we must adopt a conservative viewpoint in the data interpretation and concentrate on a restricted set of conclusions which have the least sensitivity to the unknown behavior of the radial velocity profiles.

If absorption lines from two atomic species have the same equivalent width divided by wavelength W_λ/λ, we may infer that the ratio of their column densities is inversely proportional to the ratio of the respective products of transition f-values and wavelengths, provided the two velocity profiles are identical. The requirement for profile similarity becomes more critical if the lines are highly saturated. In general, the profiles *can* be somewhat different, but we may still cope with saturated lines if we add a qualification to the conclusion on column density ratios: that the results apply only to gases at velocities displaced from the line core, at approximately unit optical depth in each case. Since we will be considering moderately strong and probably badly saturated lines in this study, the column density comparisons will apply only to *disturbed* gases, at a velocity displacement on either side of the line core of roughly one-half of the equivalent width (see Figure 1). Such restricted conclusions are of use in qualitative comparisons between disk and halo gas, and they should be valid as long as the profile differences are not as extreme as the hypothetical, pathological situation illustrated in Figure 2.

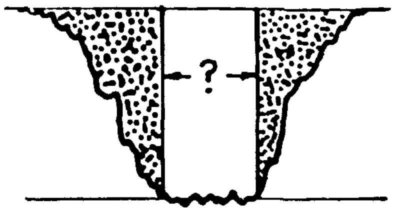

Figure 1. Parts of a saturated profile, displaced from the core, for which abundance comparisons can be made.

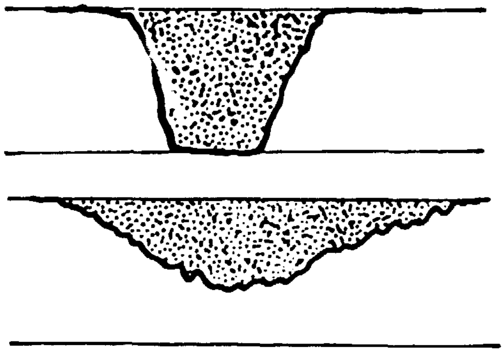

Figure 2. Two profiles with identical equivalent widths which have such a large difference in velocity behavior that the comparisons discussed here lose their meaning.

If the two lines have unequal equivalent widths, we can, strictly speaking, only state the column density ratio in terms of an inequality, i.e., the ratio is greater or less than the amount corresponding to lines of equal strength. However, information on the slope of the curve of growth may be available from two or more lines of differing strength from a given atom or ion. In this case, one can deduce an approximate column density ratio for unequal lines, provided the slope is not very small.

II. DATA

For this survey we make use of IUE high-resolution spectra of approximately 200 stars, 41 of which are more than 500 pc from the galactic plane. About half of the stars at large z distances and a few of the low-z stars were observed by the author in 1978 and 1979. The remaining spectra, and by far the largest portion, were furnished by the National Space Science Data Center (i.e., results from other observing programs now released to the public domain).

Distances to the stars are inferred from the MK classifications, their corresponding absolute magnitudes and the stars' apparent magnitudes. Since the scale height of O and B type stars is less than a hundred pc, stars at z distances greater than a kpc or so are very rare. Hence, we must consider the danger that in the necessarily selective process of finding suitable target stars at large z, our sample may be badly contaminated by underluminous, nearby stars whose distances are greatly overestimated. Our concern is aggravated by a nagging theoretical question: if such stars are normal and were born in the galactic plane, how do we reconcile their long time in transit away from the plane with their relatively short main-sequence lifetimes(1) (Greenstein and Sargent 1974)? Pettini and West (1982) have given a rather complete overview of the observational evidence and the controversies in the literature bearing on the stars' distances and present a fairly optimistic viewpoint that the inferred distances are not significantly overestimated in a systematic fashion. Of course, if our investigation of interstellar lines shows that the apparently high-z stars seem to differ from ones at low z, that evidence alone would confirm independently that the high latitude stars are not nearby interlopers.

After a perusal of the many absorption lines within the coverage of IUE's short-wavelength camera, the following three pairs of lines were found, empirically, to have nearly similar equivalent widths.

Pair	Typical W_λ/λ (km s^{-1})	ion	λ(Å)	f-value(2)	ion	λ(Å)	f-value(2)
1	15-75	FeII	1608	0.062	SII	1253	0.0107
2	10-60	SiII	1808	0.0055	SII	1250	0.0053
3	20-100	AlII	1670	1.88	SiII	1304	0.147

All of these ions are in the dominant stage of ionization expected within HI regions; i.e., each is at the lowest stage which has an ionization potential greater than that of hydrogen. Moreover, the ionization potentials of FeII, SiII and AlII are very similar to each other (~ 17 eV), but that of SII is somewhat larger (~ 23 eV).

Figures 3, 4 and 5 show how the ratios of the equivalent widths of the three pairs of lines vary with the z distances of the target stars. A significant increasing trend can be seen for the ratio of FeII and SII as lines of sight go beyond |z| > 500 pc. This enchancement of the Fe feature

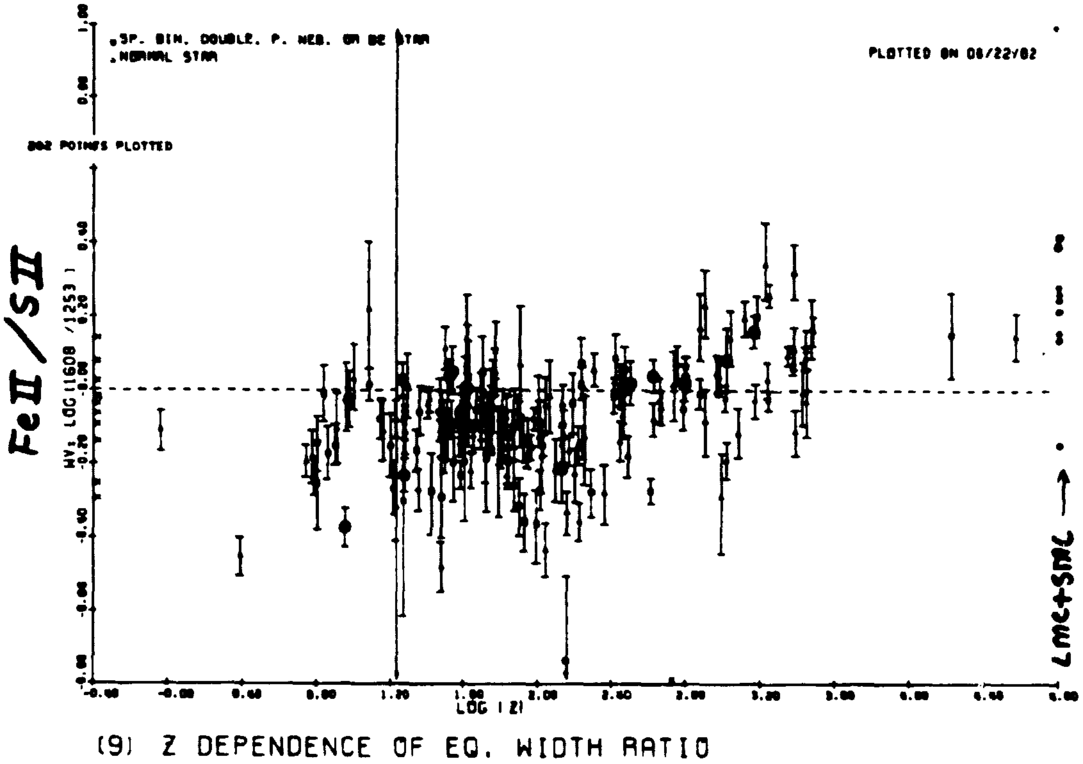

Figure 3. Logarithm of the ratio of the W_λ/λ of FeII (λ1608) and SII (λ1253) absorptions vs. the logarithm of the star's distance away from the galactic plane (in pc). The horizontal dashed line representing equal strengths corresponds to log [N(FeII)/N(SII)] = -0.87. Measurements toward the Large and Small Magellanic Clouds taken by Savage and de Boer (1981) are plotted at the far right (without error bars). Errors in the equivalent widths due to noise were estimated from the amplitudes of fluctuations in the continuum levels near the respective lines; the resulting $\pm 1\sigma$ errors in the ratios are shown. In practice, comparisons of multiple measurements of some lines show that the true errors are about 1.5 times the calculated errors, indicating other sources of uncertainty of undetermined origin. Hence, error bars should be interpreted only as an indication of relative reliability from one measurement to another. Circled points are for absorption lines having $|v_{LSR}|$ > 20 km s^{-1}.

over hat of S is also seen in the Magellanic Cloud stars. The SiII/SII and AlII/SiII plots seem to show virtually no change for the high-z stars, although the LMC + SMC data show some increase in the ratios. Typically, the strengths of the two SII lines (at 1250 and 1253 Å) differ by less than $2^1/^2$, which means that the changes in relative abundances are somewhat more than twice the variations (in the logarithm) of the plotted line strength ratios.

The AlII and SiII lines shown in Figure 5 are generally stronger than those which are compared in Figures 3 and 4. If, in general, the wings of the velocity profiles converge to zero rapidly (i.e., as does a gaussian distribution, for instance), the sides of the strong absorption lines will be steep, making the curves of growth flat and the points in Figure 5 less sensitive to changes in relative abundance.

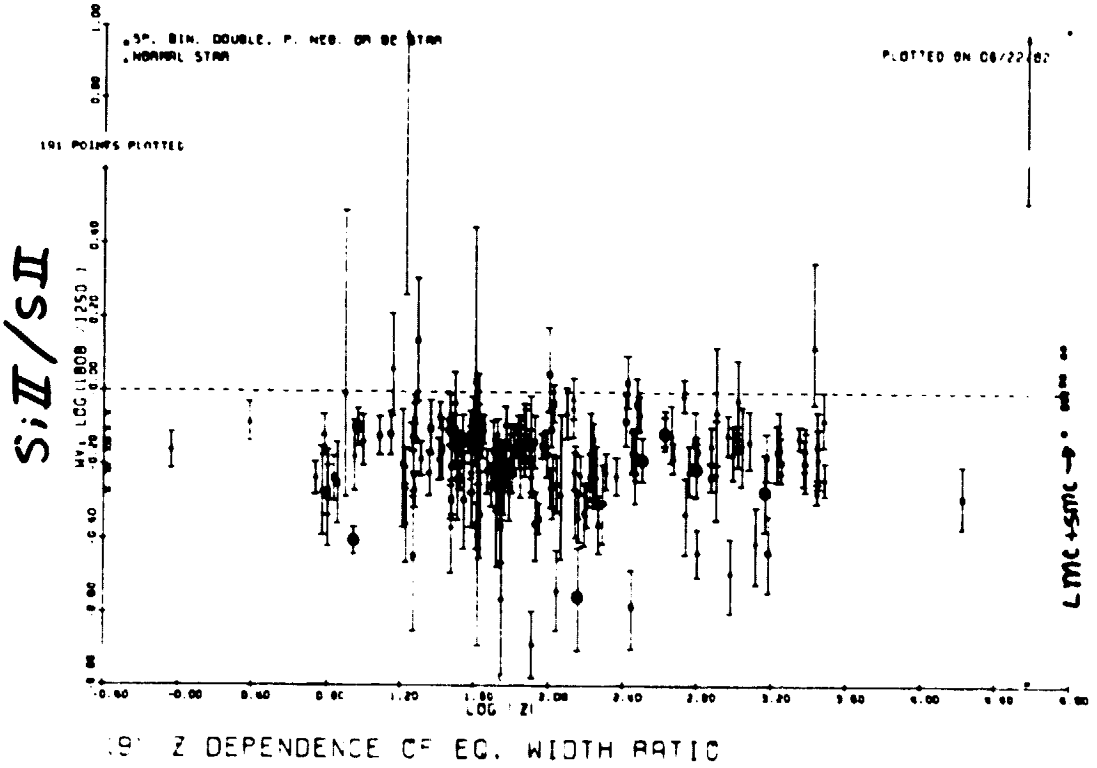

Figure 4. Same as Figure 3, but for the ratio of SiII (λ1808) to SII (λ1250). The dashed line of equality corresponds to log [N(SiII)/N(SII)] = -0.18.

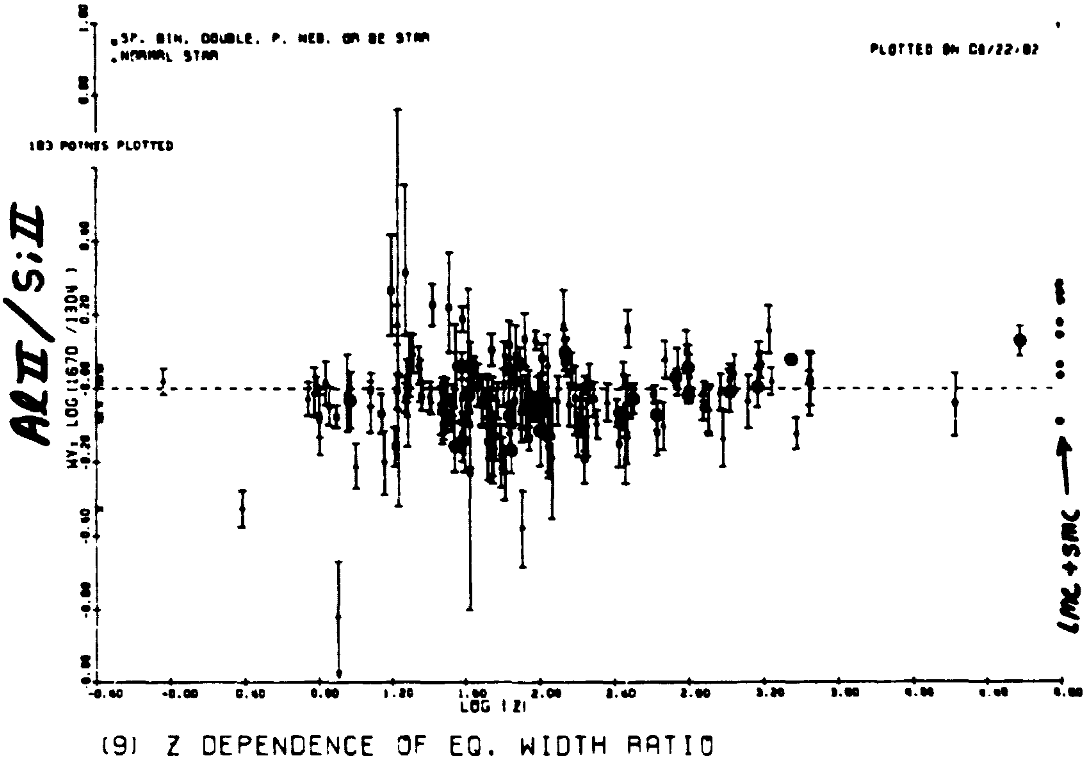

Figure 5. Same as Figure 3, but for the ratio of AlII (λ1670) to SiII (λ1304). The dashed line of equality corresponds to log [N(AlII)/N(SiII)] = -1.21.

As a rule, the absorption lines toward the high latitude stars are not systematically weaker or stronger than those toward stars near the plane. This is because there is a mix of nearby and distant stars in the low-z set. Thus, the change in FeII/SII is not due to there being systematically stronger or weaker lines in either set. Moreover, the ratios of the strengths of the two SII lines (λ1250 and λ1253) do not seem to change with z, which suggests that there is no strange behavior in the velocity profiles.

III. DISCUSSION

From earlier studies with the Copernicus satellite, we know that interstellar abundances of most free atoms and ions, relative to hydrogen, are below the respective amounts corresponding to the cosmic abundance ratios. It is generally accepted that these depletions are caused by condensation onto grains, and the amounts vary strongly from one element to the next. Those atoms which easily form refractory compounds are highly depleted (some by a factor of at least 1000), while others which are left over to form volatile substances are only slightly below their cosmic abundances (to within a factor of less than 3). Dense interstellar clouds exhibit the strongest depletions (Morton 1974; Snow 1976, 1977; Snow and Jenkins 1980). Stars which have relatively little reddening, i.e. lines of sight dominated by intercloud material, show smaller depletions (Morton 1978, York and Kinahan 1979, Morton and Bhavsar 1979). It is reasonable to presume that the intercloud material is frequently exposed to shocks which partially destroy the grains by sputtering and grain-grain collisions (Shull 1978, Draine and Salpeter 1979, Spitzer 1976) and return atoms to the gas phase.

Generally, the previous studies have shown that depletions of S are very much less than those of Fe, Si or Al. For the purpose of discussion here, we may adopt the SII lines as indicators of virtually undepleted material, against which we compare the abundances of the more highly depleted species. The three plots indicate that the logarithms of the Fe, Si and Al abundances relative to that of S seem to be midway between the solar values +0.19, +0.34 and -0.81, respectively, and the numbers -1.70, -1.17 and -3.80 observed toward ζ Oph (Morton 1974; Shull, Snow and York 1981; Snow and Meyers 1979), with its classic line of sight through a dense cloud. This statement is only approximate, however, for the reasons given earlier. The lower depletions indicated for gas even in the galactic plane is probably a consequence of our preferentially sampling the intercloud material, which dominates over the cloud gas in the wings of the strong absorption lines.

The decline in the depletion of Fe away from the plane mimics the effect seen in high-z stars for Ca by Cohen and Meloy (1975) and Ti by Albert (1982). (See also Phillips, Gondhalekar and Pettini 1982). It is surprising that a similar behavior is not seen for Al and Si. A uniform, partial destruction of grains having a homogenious composition seems to be ruled out here. Otherwise, we would expect Al, the most highly depleted element, to show the strongest change, which is not the case. Barlow and Silk (1977) have proposed that thin monolayers of metals may physically adsorb to the surfaces of silicates or the ice mantles of grains. These layers would be easily disrupted by low velocity shocks, which could explain the variability of depletion. In contrast to the situation for Fe, Barlow and Silk point out that silicon is unlikely to coat grain surfaces because the energy liberated in forming a hydride is sufficient to overcome the binding.

In their survey of weak interstellar iron lines recorded by Copernicus, Savage and Bohlin (1979) found that the Fe depletion was highly correlated with the average density of gas along the various lines of sight. One could argue that the dependence with z seen here is a manifestation of the same effect, inasmuch as the high latitude lines of sight have less average density than those in the plane. Indeed, one might question whether or not there is any fundamental difference between intercloud material at $z = 0$ and the gases geographically removed from the layer of clouds centered on the plane.

While not too common in this survey, there are a few lines of sight in the plane which have color excesses per unit distance which are as low as many of the high latitude cases. Twenty-five stars with $|z| < 500$ pc and $E(B-V)/r < 0.1$ mag/kpc were found to have an average value of -0.10 for the logarithms of the ratios of FeII to SII W_λ/λ. Thus, we may conclude that low average densities alone do not explain the trend that is seen for stars at high z.

If, for some reason, the moderately stirred up gas in each case is dominated by circumstellar material, it would be conceivable that the FeII we measure could, to varying extents, be further ionized by stellar radiation from the target stars. Such an effect could alter the apparent ratio of Fe to S, since SII is harder to ionize. One might then propose that we are misled into thinking the variation in FeII/SII is a z effect, when indeed it results only from the fact that low-z stars are generally hotter and more able to doubly ionize the nearby Fe. Figure 6 addresses this possibility by showing the relationship between the target stars' effective temperatures and the ratios of the line widths. No correlation is evident; hence the prospects of circumstellar ionization influencing the results seems remote.

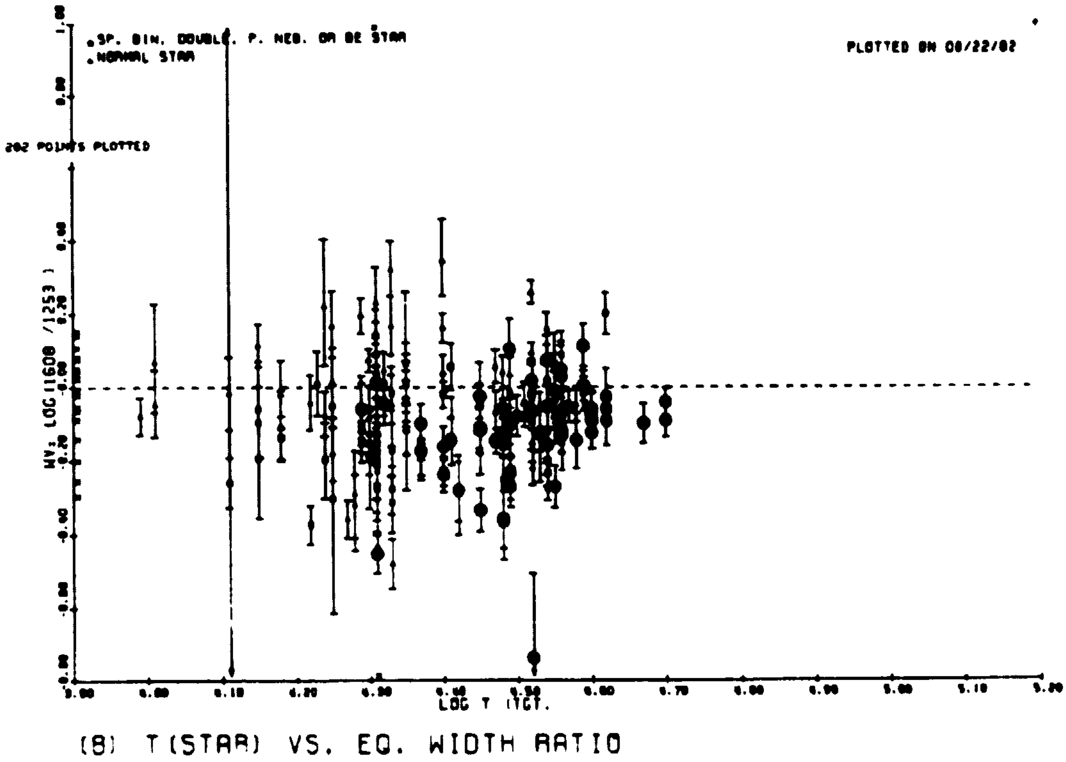

Figure 6. Logarithm of the FeII to SII W_λ/λ ratios (as in Fig. 3) vs. the logarithm of the effective temperature of the respective target stars. Circled points are for stars identified to exist within prominent O-B associations (Humphries 1978).

So far, the discussion here has emphasized the possibility that the extra Fe in the halo is caused by a more efficient destruction of grains. Perhaps it is worthwhile to consider an alternate origin, however, such as enrichment of the low-density gas away from the plane by the ejecta of type I supernovae. Such ejecta are believed to be especially rich in iron, and the importance of such injection could be far greater in the halo than in the disk of our galaxy. From a theoretical standpoint, it is probably very difficult to estimate quantitatively the contributions from direct element enrichment by supernovae in the halo, because we can draw only upon rough estimates on the composition and amount of the ejecta, along with a very crude picture on the rate (and even the overall nature) of the cycling of high-z gaseous material.

An insight on whether the extra Fe comes from grains or supernovae may evolve from further observational studies. For instance, the methods used here could be applied to shocked, high-velocity gas components seen in the galactic plane. For these absorptions, which occur near known supernovae or active stellar associations (Jenkins, Silk and Wallerstein 1976, Cowie, Songaila and York 1979), grains are probably being destroyed. If the differential changes in depletion from one element to another are the same as in the halo gas, one would favor the grain destruction as the proper explanation for the enrichment in the halo.

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NOTES:

(1) One way out of this problem, suggested by R. Polidan (private communication), is to propose that these stars have been rejuvenated recently by mass deposition from (as yet unrecognized) close companion stars which are relatively long lived but which have just recently evolved off the main sequence.

(2) Sources for f-values of atomic transitions:
FeII from Shull, Van Steenberg and Seab (1982)
SiII from Shull, Snow and York (1981)
AlII and SII from Morton and Smith (1973)