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HIGH-RESOLUTION ULTRAVIOLET OBSERVATIONS OF INTERSTELLAR LINES TOWARD ζ PERSEI OBSERVED WITH THE BALLOON-BORNE ULTRAVIOLET STELLAR SPECTROMETER

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ABSTRACT

The balloon-borne ultraviolet stellar spectrometer (BUSS) payload has been used to obtain high-resolution ($\lambda/\Delta\lambda = 80{,}000$) data on interstellar absorption lines toward ζ Per. The only lines clearly present in the 2150–2450 region were several Fe II features, which show double structure. The two velocity components were sufficiently well separated ($\Delta v \approx 21$ km s^{-1}) that it was possible to construct separate curves of growth to derive the Fe II column densities for the individual components. These column densities and the component velocity separation were then used to compute a realistic two-component curve of growth for the line of sight to ζ Per, which was then used to reanalyze existing ultraviolet data from *Copernicus*. The results were generally similar to an earlier two-component analysis of the *Copernicus* data, with the important exception that the silicon depletion increased from near zero to about 1 dex. This makes the ζ Per depletion pattern quite similar to those derived for other reddened lines of sight, supporting the viewpoint that the general diffuse interstellar medium has a nearly constant pattern of depletions.

Subject headings: interstellar: abundances — interstellar: matter — stars: individual (ζ Per) — ultraviolet: spectra

I. INTRODUCTION

The determination of interstellar abundances in diffuse clouds, an area opened up with the availability of *Copernicus* ultraviolet spectra and continuing with the use of *IUE* data, has been pursued largely because of intense interest in learning what is *missing* from the gas. The depletion of gas-phase elements onto interstellar grains has great potential for helping us to understand the nature of interstellar dust and the interactions between gas and dust in space.

The data from *Copernicus* have set the standard for depletion studies, because of the relatively high spectral resolution ($\lambda/\Delta\lambda = 20{,}000$) and high signal-to-noise ratio (the detectors were scanning photomultiplier tubes, limited only by photon noise in the wavelength region 1000–1500 Å). Many detailed abundance and depletion studies of individual stars have been based on *Copernicus* data (e.g., Morton 1975, 1978; Snow 1976, 1977; Morton and Hu 1975), and several surveys of specific elements have been carried out as well (e.g., Savage and Bohlin 1979; Jenkins and Shaya 1979; Jenkins, Jura, and Lowenstein 1983; Bohlin *et al.* 1983; York *et al.* 1983; Jenkins, Savage, and Spitzer 1986). These studies have added immeasurably to our knowledge of the diffuse interstellar medium, but have all suffered from one significant drawback: the resolving power of *Copernicus* was insufficient to separate the multiple velocity components found in typical lines of sight. A few studies have attempted to overcome this deficiency through the use of profile-fitting analyses (e.g. Spitzer and Morton 1976; Vidal-Madjar *et al.* 1977; Snow and Meyers 1979), but this is helpful only when the component separation is at least comparable to the 15 km s^{-1} velocity resolution of the instrument.

In some cases, *Copernicus* depletion studies were found inaccurate for elements whose observable lines are saturated, and more recent studies based on very weak lines have forced the revision of previously established depletions (e.g., de Boer 1979; Hobbs, York, and Oegerle 1982; York *et al.* 1983; Luggar *et al.* 1978). In most cases, the abundances of elements were revised upward and the depletions downward as more accurate measurements became available, because saturated lines are capable of concealing blended components with low velocity dispersions; components that, when recognized, add appreciably to the column density that is derived.

In one early *Copernicus* study (Snow 1977), a blending of velocity components was suspected, and the analysis was carried out using a two-component curve of growth. The star was ζ Per, and the adopted curve was based largely on the lines of Fe II, the strongest of which lie in a spectral region ($\lambda > 1800$ Å) where *Copernicus* was beset by serious noise contamination (due to radioactivity in the detector windows). Hence, the two-component curve of growth that was adopted, while it fitted the data well within the errors, was not well established and served only as an example of a possible interpretation of the ζ Per data. Some unusual depletions were found, notably that of silicon, which was found to be nearly undepleted. The silicon result was surprising, because silicates are normally thought to be a major constituent of interstellar grains.

In the present study, higher resolution data on Fe II lines toward ζ Per, obtained by the balloon-borne ultraviolet stellar spectrograph (BUSS) (Kondo *et al.* 1979) are used to separate the formerly suspected velocity components, to establish the Fe II column densities for the separate components, and then to derive a proper two-component curve of growth with which to reanalyze the original *Copernicus* data.

The next section describes the BUSS observational data and is followed by a section describing the measurement of Fe II column densities in the two components (§ III), a rederivation of total column densities and depletions from other elements (§ IV), and a discussion of the results (§ V).

II. THE BUSS OBSERVATIONS

The star ζ Per was observed with the BUSS during flight number XIII on 1984 October 9 from the National Balloon Facility in Palestine, Texas. The essentials of the BUSS payload were described by Kondo *et al.* (1979). It consists of a 40 cm Ritchey-Chretien telescope, an echelle spectrograph and a SEC Vidicon detector. The instrument has a pointing accuracy of 2″. For flights of BUSS XII and XIII on 1984 September 14 and October 9, the payload was equipped with a new echelle spectrograph which operated between 2154 Å (order 263) and 3354 Å (order 170). A movable optical wedge in the light path could shift the echelle spectrum in the vertical direction, i.e., perpendicular to the dispersion direction, so that the required orders were measured by the SEC Vidicon detector. About 50 orders could be measured in one exposure, covering a wavelength range of $\sim$500 Å.

During the flights of BUSS XII and XIII a total of 18 spectra of nine stars with $m_v < 3.5$ mag were obtained. The spectrograph was designed to obtain a wavelength resolution of $\lambda/\Delta\lambda \approx 8 \times 10^4$ FWHM ($\Delta v \approx 3.8$ km s^{-1}). This goal has been achieved, as can be seen from the steep edges of the interstellar Mg II lines in α Cyg (Fig. 1). The wavelength accuracy is $\sim$0.02 Å, i.e., 2.5 km s^{-1}.

The spectrum of ζ Per was observed on 1984 October 9. The exposure started at 4^h54^m UT, and the exposure time was 30 minutes. The recorded spectrum covers the wavelength range from 2154 Å to 2541 Å, with several interorder gaps especially at $\lambda < 2200$ Å and $\lambda > 2400$ Å. The useful (i.e., the well-exposed and well-covered) region of the spectrum is from 2200 Å to $\sim$2400 Å. This allows the measurement of the interstellar lines of Fe II (multiplets 2 and 3). The line of Fe I λ2447.708 (multiplet 9) also happens to occur in the center of a well-exposed order.

III. ANALYSIS OF THE Fe II LINES

Four Fe II lines were included in the wavelength region that was well exposed in the BUSS data (Table 1). Profiles of the three that were detected are shown in Figure 2. In each case, a double structure is seen, most clearly for the 2343 Å line. The velocity separation was measured to be in the range 19–21 km s^{-1}, with a mean of 20.5 km s^{-1}.

In order to establish an absolute velocity scale for the interstellar lines, we identified and measured the velocities of a number of photospheric features. The results (Table 2) show that the photospheric lines are centered at a velocity of $+114 \pm 7$ km s^{-1} with respect to the BUSS wavelength scale. The heliocentric radial velocity of ζ Per is $+22.2$ km s^{-1}, but the star is a spectroscopic binary with a *K*-velocity of 6 km s^{-1} and a period of 1.7 days. Hence the photospheric heliocentric radial velocity is $+22 \pm 6$ km s^{-1}.

TABLE 1

OBSERVATIONAL DATA ON Fe II LINES TOWARD ζ PER

Wavelength[a]	f[a]	W (strong) (mÅ)	W (weak) (mÅ)	Δv[b] (km s^{-1})
2382.034	0.328	185	85	20.2
2373.733	0.0395	95	16	20.8
2366.864	0.00238	12	12	...
2343.495	0.108	106	29	20.5

[a] The wavelengths and oscillator strengths are taken from the compilation of Morton and Smith 1973.

[b] In the last column v is the velocity of the stronger component minus the velocity of the weaker component.

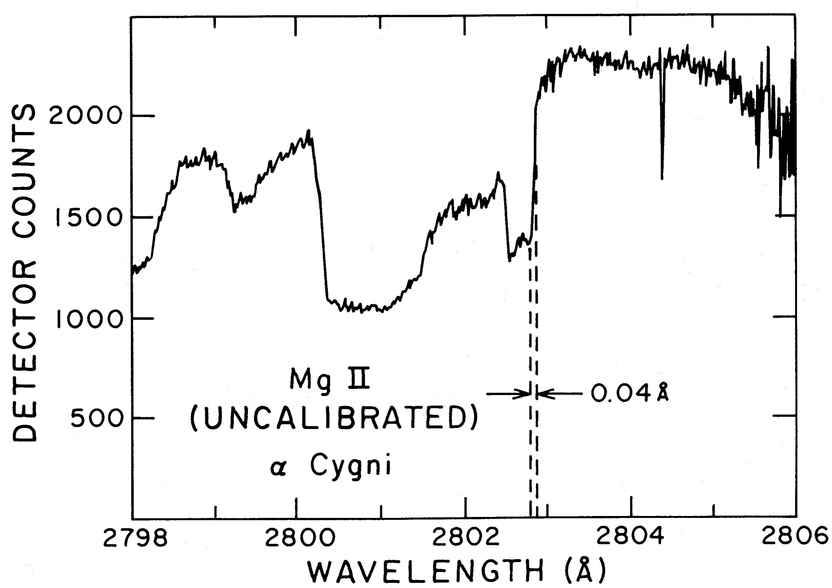

FIG. 1.—Resolving power of BUSS. This shows the interstellar Mg II *h* line (uncalibrated), indicating from the steepness of the line edge that resolution is 0.04 Å at 2800 Å, corresponding to ($\lambda/\Delta\lambda > 7 \times 10^4$). Laboratory measurements show that actual resolving power is $\lambda/\Delta\lambda = 8 \times 10^4$.

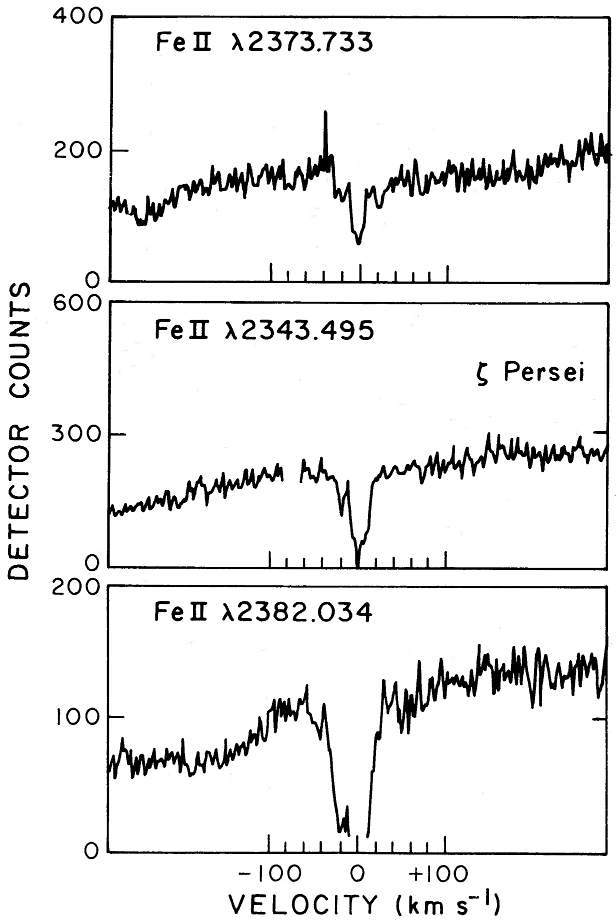

FIG. 2.—Interstellar Fe II lines toward ζ Per. These profiles are plotted on a velocity scale to show the consistent separation between the strongest component and the weaker one at a mean separation of -20.5 km s^{-1}.

The stronger interstellar Fe II component is shifted by -18 ± 5 km s^{-1} with respect to the stellar lines, so the heliocentric velocity of this component is $+4 \pm 8$ km s^{-1}. The weaker component, which is shifted by -20 ± 1 km s^{-1} with respect to the stronger one, has, therefore, a heliocentric velocity of -18 ± 8 km s^{-1}.

We stress that most of the uncertainty of ± 8 km s^{-1} is due to the fact that we have tied our velocity scale to that of the star, which undergoes velocity variations due to its orbital motion. This means that the true velocities of the interstellar components may lie anywhere within the quoted range of uncertainty with almost equal probability. Hence, the strong component lies somewhere between -4 and $+12$ km s^{-1}, and the weak component is roughly -20 km s^{-1} with respect to that.

The high-resolution observations of Ca II and Na I lines toward ζ Per displayed by Hobbs (1974) show only a single velocity component for both ions, centered near $+15$ km s^{-1} (heliocentric) for Ca II and at a point slightly (perhaps 2 km s^{-1}) lower than that for Na I. Unfortunately, Hobbs's interferometric scans do not cover enough velocity range to show any additional components separated from the main one by more than ~ 15 km s^{-1}, so it is impossible to say whether both velocity components seen in the ultraviolet Fe II lines are also present in Ca II or Na I. We cannot clearly identify the Fe II components with the Ca II and Na I velocities observed by Hobbs, but it is possible that the strong Fe II feature coincides with the principal optical lines in the $+13$–$+15$ km s^{-1} range.

Because the two components are resolved in the BUSS data, it was possible to measure their equivalent widths separately. The results are shown in Table 1, which also includes data on line strengths and laboratory wavelengths.

Having separate equivalent-width measurements for the two components allowed the Fe II column densities to be derived separately for the two main velocity components, by fitting each set of equivalent widths to a single-cloud curve of growth. The results were more secure for the weaker component because the lines were weak enough to lie in the transition region on the curve between the linear and flat (saturated) portions. For that component, we find a column density of $N = 8.1 \times 10^{12}$ cm^{-2}, and a velocity dispersion parameter of $b = 6$ km s^{-1}.

For the stronger component, the lines were sufficiently saturated to lie on the flat part of the curve of growth, so the result is more ambiguous. The best fit to the curve of growth yielded $N = 3.1 \times 10^{14}$ cm^{-2} and $b = 3$ km s^{-1} for this component. The width of the Ca II line observed by Hobbs (1974) indicates a b value of 5 km s^{-1}, consistent with our value, if we are seeing the same cloud.

Having adopted column densities and b values for the two components seen in Fe II, we were then able to calculate a new composite curve of growth, taking into account also the observed velocity separation. The result is shown in Figure 3.

TABLE 2

PHOTOSPHERIC LINES IN ζ PER

Observed	Rest	Ion	Multiplet	Notes	λ (Å)	v (km s^{-1})
2181.22	2180.41	Fe III	70		0.81	+111
2209.80	2208.70	Cr III	58		1.10	...
	2208.85	Fe III	110		0.95	...
2218.57:.........	2217.75	Cr III	47		0.82:	+110:
2227.63	2226.68	Cr III	39	1	0.91	+122
2234.70:.........	2233.79	Cr III	45	1	0.89:	+120:
2236.80	2235.91	Cr III	39	1	0.89	+119
2242.45	2241.54	Fe III	109		0.91	+122
2252.33	2251.47	Cr III	39	1	0.88	+117
2309.15	2308.19	Si III	76		1.03:	+134:
2325.80	2324.89	Cr III	44	1	0.92	+118
2339.80	2238.96	Fe III	72		0.84	+108
2347.75	2346.90	Mn III	15		0.85	...
	2346.96	Fe III	72		0.79	...
2388.05	2387.28	Ni III	26		0.86	+108
2411.55:.........	2410.52	Fe II	2?		1.03?	...
	2411.06	Fe II	2?		0.49?	...
2414.72:.........	2413.99	Ti III	9	1	0.75:	+93:
2439.95	2438.70	Zr III	45?		1.25?	...
	2438.76	Co III	74?		1.19?	...
2448.20	2447.37	Fe III	143		0.83	+102
2473.45:.........	2472.87	Cr III	43	1, 2	0.57:	+69:
	...			Mean Velocity		114 ± 7

NOTE.—In the fifth column the numbered notes signify the following: (1) identified in OB subdwarf spectrum HD 149382 as major component, Baschek *et al.* (1982); (2) at edge of detector; unreliable wavelength.

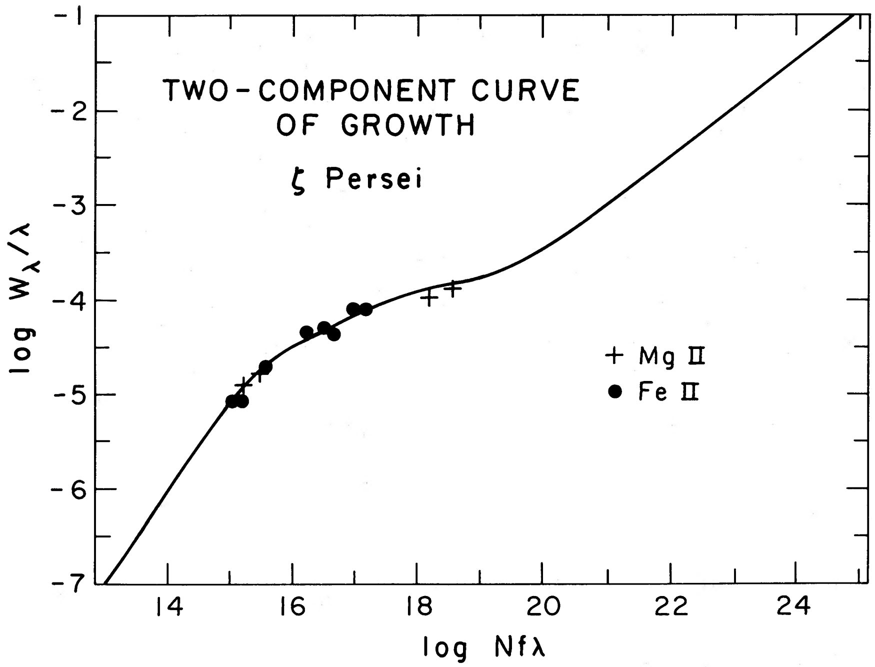

FIG. 3.—Two-component curve of growth based on Fe II lines. This theoretical curve was calculated for relative column densities and velocities of the two Fe II components seen in BUSS data. Points for Fe II and Mg II, representing the total equivalent width for both components, were then added as a check.

This curve represents the *total* equivalent widths of the Fe II lines, so, as a check, we have plotted on the curve the combined measurements for both velocity components. As seen in the figure, the agreement is very good. We have included Fe II lines measured from *Copernicus* data (Snow 1977; Savage and Bohlin 1979; Jenkins, Savage, and Spitzer 1986), as well as measurements from *IUE* data (obtained as part of a program being carried out by two of us). It is particularly noteworthy that the data points adhere closely to the curve of growth through the inflection point where the effect of the secondary velocity component becomes important.

Another species for which lines are available with a very wide spread in oscillator strength is Mg II, which has a weak pair of lines near 1240 Å, and the very strong *h* and *k* lines at 2800 Å. The equivalent widths of these four lines (taken from *Copernicus*) data are also plotted in Figure 3, where it is seen that the agreement with the adopted curve is good. We conclude that this composite curve is an appropriate representation of the distribution of first ions in the line of sight to ζ Per, and can be used to derive the column densities for other species.

IV. COLUMN DENSITIES AND DEPLETIONS

The equivalent widths for all species observed in the original curve of growth based on *Copernicus* data were reanalyzed using the new composite curve of growth. The fit of these species to the new curve is shown in Figure 4, and the results are given in Table 3. The scatter of points about the adopted curve is relatively small, giving us some confidence in the results. If the adopted curve is assumed to be correct, we estimate that the uncertainty in a given column density determination is roughly ± 0.1 dex.

Most of the column densities are similar to those originally derived from the same data (Snow 1977), but a few are quite different, particularly in cases of elements whose lines lie near the inflection point of the curve. This especially affects the derived silicon abundance (this is discussed in the next section). The old column densities are listed in Table 2 for comparison.

The depletions were reanalyzed as well, using the new column densities, along with the cosmic abundances adopted by Cowie and Songaila (1986). The results for most elements are not very different from those found in the original study, again with the outstanding exception of silicon (discussed below). Some minor additional changes in the depletions for several elements were brought about by revisions in the adopted cosmic abundances.

V. DISCUSSION

It is common among researchers in interstellar abundances and depletions to speak of a depletion "pattern," and we do the same here. In order to clarify this discussion, it is helpful for us to say what we mean by a depletion pattern. We use this

TABLE 3

ABUNDANCES AND DEPLETIONS TOWARD ζ PER

		ζ PER (BUSS)		ζ PER (1977)		ζ OPH[b]
SPECIES	COSMIC[a]	log *N*	δ	log *N*	δ	δ
C II	8.69	16.8	−0.95	17.5	−0.25	−0.84
N I	7.99	16.6	−0.45	16.9	−0.15	−0.64
O I	8.91	17.5	−0.47	17.9	−0.07	−0.21
Mg II	7.58	15.3	−1.34	15.5	−1.14	−1.41
Si II	7.55	15.7	−0.91	16.6	−0.01	−1.80
P II	5.51	13.8	−0.77	14.1	−0.47	−0.66
S II	7.24	16.2	−0.10	16.3	−0.00	−0.33
Ar I	6.61	14.9	−0.77	14.8	−0.87	−0.70
Fe II	7.59	14.3	−2.35	14.3	−2.35	−2.39

[a] The cosmic abundances are from Cowie and Songaila 1986.

[b] The depletions listed for ζ Oph have been adjusted for the revised cosmic abundances adopted for the ζ Per analysis. The values given for ζ Oph are from a combination of sources based on *Copernicus* data: Morton 1974; de Boer 1979 (O I); Snow and Meyers 1979 (Mg II, P II, and Fe II); Shull, Snow, and York 1981 (Si II); and Savage and Bohlin 1979 (Fe II).

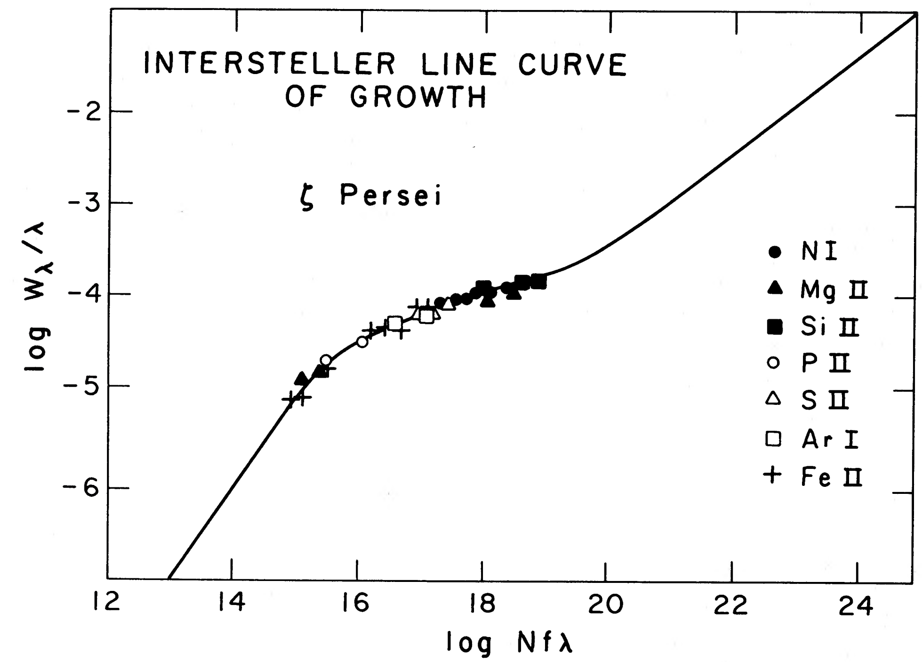

FIG. 4.—Curve of growth for other species. This is the same theoretical two-component curve shown in Fig. 3, illustrating the fit to the curve for all species having at least two observed lines. Most equivalent width data represented here were obtained with *Copernicus*.

term to refer to the *relative* depletions from element to element; we say the pattern is the same for two stars if the relative depletions are constant, even though there may be some difference in the absolute level of depletion.

The new depletion pattern for ζ Per is displayed in Figure 5, where the old pattern from the 1977 study is also shown, as well as the "standard" pattern based on ζ Oph (Morton 1974, as altered by the adoption of the new solar values in Cowie and Songaila 1986, along with the addition of newer measurements for some species). In this figure, we see that the ζ Per pattern is now very similar to that for ζ Oph, and, for certain elements, markedly different from the original ζ Per pattern.

The biggest and most significant contrast between the new and the old ζ Per results is for silicon, which was found to be virtually undepleted in the original study. This was a striking contrast with the result for ζ Oph and other reddened stars, and it is especially difficult to understand in view of the prominent role usually ascribed to silicates as constitutents of interstellar grains. In the original paper (Snow 1977), the comment was made that the silicon abundance may have been overestimated due to blending with stellar lines, a possibility that we could in principle check with high-resolution data such as we have from BUSS, except that no Si II lines were observed. The new results show a substantial depletion (−0.91 dex) for silicon, closer to the normal value (but still less than the depletion for ζ Oph).

It is important to establish whether there truly is a "standard" diffuse cloud depletion pattern, because it may

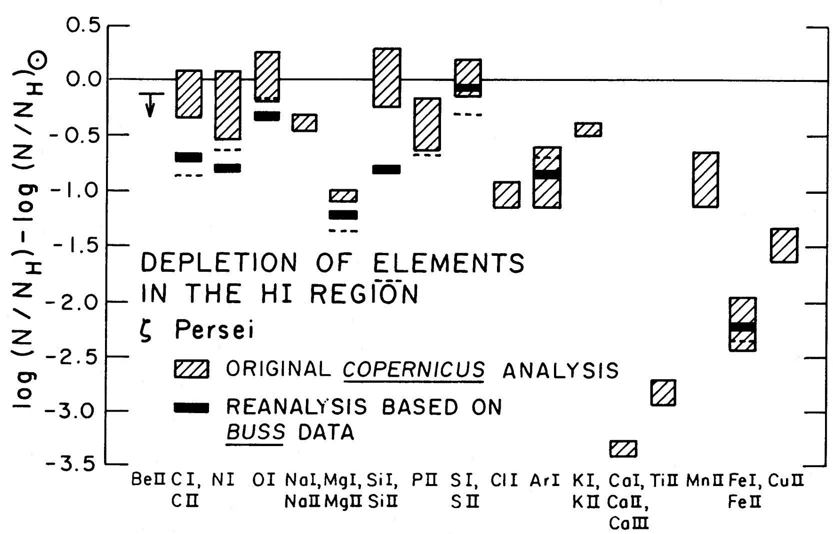

FIG. 5.—Resulting depletion pattern toward ζ Per. The adopted two-component curve indicates greater depletion of some elements, particularly C, N, O, and Si. Short dashed lines indicate the mean depletions for ζ Ophiuchi.

have much to tell us about the depletion process itself. If there are actually significant variations from cloud to cloud, this implies that the depletions are dominated by local processes, whereas if there is a more or less constant pattern, this suggests that the diffuse interstellar medium undergoes some universal processing that results in the observed depletions. Thus, it was important to recheck the original ζ Per results, because there were some outstanding apparent contrasts between that line of sight and others such as ζ Oph. Now it appears that most of these contrasts were not real, but instead were due to ambiguity in the curve of growth analysis.

Our present results support the notion that there is indeed a constant pattern of depletions in diffuse clouds, or at least that the observed pattern is due to a combination of standard processes, as suggested by Spitzer (1985). Spitzer proposes that there are three different types of diffuse material: two represent cold, relatively dense material having substantial depletions; the third is a warm H I gas with little depletion. The observed variation in the absolute level of depletion is then due to the relative proportions of the three types of material in a given line of sight. Variations in the depletion *pattern*, however, would not be consistent with Spitzer's model, so our new results remove a potential counterargument to that interpretation of the depletions.

If we accept that diffuse cloud depletions are indeed due to a combination of materials with different individual depletions, then we still have the problem of determining how the different types of material came about. Here there are several scenarios, ranging from the suggestion (Field 1974) that all depletions arise during the grain formation process, to the idea that the depletions are entirely the result of processing in the interstellar medium, either through accretion of mantles on small grain cores (e.g., Snow 1975) or through the selective evaporation of certain elements from grains subjected to shocks (Savage and Bohlin 1979; Seab and Shull 1985). Some evidence seems to indicate a combination of processes, such that a certain pattern of depletions is established either by grain formation or by a universal type of shock processing and then is enhanced in dense regions by accretion (Joseph 1985; Joseph *et al.* 1986).

There is sufficient uncertainty at present to allow many possible processes or combinations of processes, and a great deal of additional work is needed, particularly in the direction of determining depletions in isolated regions where the physical processes that are occurring are reasonably well known. Meanwhile, it appears that some constraint on the models is required by the presence of a relatively invariant depletion pattern in the diffuse interstellar medium.

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