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COPPER AND ZINC IN VERY METAL-POOR STARS

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ABSTRACT

New high-resolution, low-noise spectroscopic observations have been made of Cu I and Zn I transitions in five bright very metal deficient Population II stars. The Cu I lines are anomalously very weak in all five stars, while the Zn I lines retain reasonable strengths even in the most metal-poor example. A full model atmosphere LTE analysis of Cu and Zn in the program stars, and the inclusion of some results from earlier studies, demonstrate that regular trends exist in the abundances of these elements. First, Zn/Fe retains its solar ratio down to an overall stellar metallicity of [Fe/H] ≈ -2.5 and even may begin to increase in more extremely metal-poor stars. Second, Cu/Fe declines steadily below [Fe/H] ≈ -1, reaching less than $\frac{1}{5}$ solar by [Fe/H] ≈ -2.7. The different nucleosynthesis events which may account for the apparent primary origin for Zn and secondary origin for Cu are discussed.

Subject headings: nucleosynthesis — stars: abundances — stars: Population II — stars: weak-line

I. INTRODUCTION

Recent years have seen great advances in our knowledge of the detailed abundance patterns of extremely metal-poor halo stars, due largely to the increased use of low-noise silicon-based detectors in high-resolution spectroscopy. Typically the most noteworthy new results have been obtained for the lighter elements ($Z \leq 20$) or the very heavy elements ($Z \geq 38$). Observations of the iron-peak elements in metal-poor stars generally have proved to be of less interest, simply because most studies have confirmed that these elements occur in their solar ratios throughout the metallicity range $+0.5 \geq$ [Fe/H] ≥ -3.0 {we adopt the usual spectroscopic notation that $[X] = \log_{10}(X)_{\rm star} - \log_{10}(X)_{\odot}$}.

Most spectroscopists today would agree with the conclusion of the review by Spite and Spite (1985) that variations in the abundances of the elements V through Zn are "virtually insignificant" in metal-poor stars, and at least are less than the observational errors. However, an interesting dissent to this view has been lodged by Luck and Bond (1983, 1985), who suggest that Ni may be overabundant in the most extremely metal-deficient stars. Although values of [Ni/Fe] > 0 first appear in the data at [Fe/H] ≈ -2, the effect becomes significant only at lower metallicities: [Ni/Fe] $= +0.4 \pm 0.2$ for five stars at [Fe/H] ≈ -2.7 (Luck and Bond 1985). So far, other investigators either have not been able to confirm that Ni is overabundant in stars of similar metallicity (see, for example, the references cited by Spite and Spite 1985), or have suggested that the effect may be present but at a much lower level (Gratton and Sneden 1988). Bond and Luck (1987) summarize the current status of this question and assert that no firm conclusions may be drawn about the reality of the Ni overabundances at the present time.

Spite and Spite's (1985) review also makes it clear that among the iron-peak elements the data are the most sparse for Cu and Zn. Indeed, they cite just one reference for Cu abundances in metal-poor stars (Peterson 1981), and point to no specific reference for Zn abundances. The reason for the poor representation of these two elements in the spectroscopic literature is simple: Cu and Zn do not have many suitable transitions in commonly observed wavelength regions. Zn I possesses only two useful lines, at 4722 Å and 4810 Å. There are few more available lines of Cu I, but usually only two of them (at 5105 Å and 5782 Å) can be detected in the spectra of very metal-poor stars. No suitable ionized lines of either element exist in spectroscopically accessible wavelength regions.

In this paper we attempt to bring some belated attention to these two elements. We report here the analysis of new high-resolution, low-noise spectra of Cu I and Zn I lines in five well-known, bright, metal-poor stars. We will show that our data, and some data obtained by previous investigators, indicate some interesting trends in these elements. In particular, we will suggest a stronger reason for the lack of Cu abundances in the literature: this element is quite overdeficient in extremely metal-poor stars.

II. OBSERVATIONS AND REDUCTIONS

The stars HD 19445, HD 103095 (Groombridge 1830), HD 122563, HD 165195, and HD 175305 were chosen for our initial exploration of Cu and Zn. Abundances in these stars have been determined by various authors (see the long list of references in Cayrel de Strobel *et al.* 1984), and thus their physical parameters generally are well known and are not controversial. In Table 1 we summarize the overall characteristics of these stars and reference the sources of the parameters.

The observational data consisted of high-resolution, low-noise digital spectra covering short-wavelength regions around the individual Cu and Zn lines for each star. A few additional spectra were obtained of wavelength regions which contained useful Fe and Ni Features. The instruments employed were the coudé spectrographs of the McDonald Observatory 2.1 m and 2.7 m telescopes. The detector for most observations was a TI 800 × 800 thinned CCD, while for a few observations we used an RCA 320 × 512 thinned chip or an 1872 diode Reticon array. Detailed information on the observations is given in Table 2.

The reduction of the CCD frames was accomplished with the IRAF reduction package implemented at Texas on a Micro VAX computer. The reduction procedure included bias subtraction and trimming of the frames, dark current subtraction,

TABLE 1

ATMOSPHERE PARAMETERS OF THE PROGRAM STARS

Star	V	$B-V$	M_v	$T_{\rm eff}$ (K)	$\log g$	$v_{\rm micro}$ (km s^{-1})	[Fe/H]	References
HD 19445...........	8.06	0.46	+5.0	5900	4.0	1.4	−2.1	1, 2, 3, 4
HD 103095..........	6.42	0.75	+6.5	5000	4.5	1.5	−1.4	2, 3, 4
HD 122563..........	6.21	1.00	−1.5	4600	1.2	2.3	−2.7	5, 6, 7
HD 165195..........	7.90	1.20	−1.8	4500	1.5	2.8	−2.2	5, 6, 7
HD 175305..........	7.30	1.00	+1.2	5200	2.7	2.0	−1.5	5, 7

REFERENCES.—(1) Magain 1985; (2) Peterson 1981; (3) Tomkin and Lambert 1984; (4) Carney 1979; (5) Bond 1980; (6) Gilroy *et al.* 1988; (7) Sneden, Pilachowski, and VandenBerg 1986.

flat-fielding by division of quartz lamp frames, preliminary radiation event excision, and extraction of single-dimension spectra.

The final reduction and measurement of the extracted CCD spectra and of the Reticon spectra was done with SPECTRE, a spectrum reduction package for high-resolution spectra (Fitzpatrick and Sneden 1987) implemented on an IBM PC-AT microcomputer. The tasks accomplished with this package included the wavelength calibration, Fourier transform smoothing, final radiation event fixing, and continuum flattening. An interactive routine based on Gaussian curve fitting was employed in the measurement of equivalent widths.

In Figure 1 we show a 5 Å region of the spectra around the 5105 Å Cu I lines in the program stars. Similar spectra of the 4810 Å Zn I lines are shown in Figure 2. The Cu and Zn lines are seen clearly in all stars with the exception that neither of the Cu I lines could be detected in HD 19445. The equivalent-width measurements of Cu I, Zn I, and Ni I lines are given in Table 3, and the measurements of Fe I are given in Table 4.

A comparison of our equivalent-width scales with those of other investigators is not very informative since the spectral regions studied here are small; few lines that we measured are tabulated in other publications. The classical study of HD 122563 and HD 165195 by Wallerstein *et al.* (1963) included the Zn I lines. For the 4722 Å and 4810 Å lines they quote 8 mÅ and 26 mÅ for HD 122563, and 26 mÅ and 41 mÅ for HD

TABLE 2

THE OBSERVATIONS

Star	λc[a] (Å)	$\Delta\lambda$[b] (Å)	$\delta\lambda$[c] (Å)	Telescope (m)	Detector	δt (minutes)	S/N[d]
HD 19445...........	4722	22	0.10	2.7	TI CCD	75	400
	4810	22	0.10	2.7	TI CCD	40	300
	5105	22	0.10	2.7	TI CCD	40	300
	5105	22	0.10	2.7	TI CCD	40	250
	5782	48	0.16	2.7	TI CCD	20	250
	5782	65	0.30	2.1	RCA CCD	90	200
	6120	48	0.16	2.7	TI CCD	45	300
HD 103095..........	4722	22	0.10	2.7	TI CCD	15	150
	4810	22	0.10	2.7	TI CCD	25	200
	5105	22	0.10	2.7	TI CCD	30	200
	5782	22	0.15	2.7	TI CCD	8	300
HD 122563..........	4722	11	0.12	2.7	TI CCD	90	300
	4810	11	0.12	2.7	TI CCD	90	300
	5105	11	0.12	2.7	TI CCD	90	500
	6140	105	0.21	2.7	Reticon	90	400
	6190	11	0.12	2.7	TI CCD	60	350
	6615	105	0.21	2.7	Reticon	45	350
HD 165195..........	4722	11	0.12	2.7	TI CCD	90	300
	4810	22	0.10	2.7	TI CCD	45	250
	5105	22	0.10	2.7	TI CCD	40	300
	5782	65	0.30	2.1	RCA CCD	30	100
	6190	11	0.12	2.7	TI CCD	90	450
	6615	105	0.21	2.7	Reticon	90	200
HD 175305..........	4722	11	0.12	2.7	TI CCD	90	400
	4810	22	0.10	2.7	TI CCD	30	150
	5105	22	0.10	2.7	TI CCD	40	200
	5782	11	0.12	2.7	TI CCD	90	500
	5782	65	0.30	2.1	RCA CCD	45	300
	6190	11	0.12	2.7	TI CCD	90	250
	6615	105	0.21	2.7	Reticon	90	200

[a] Approximate central wavelength.
[b] Approximate spectral coverage.
[c] Spectral resolution.
[d] The signal-to-noise after completion of all reduction procedures.

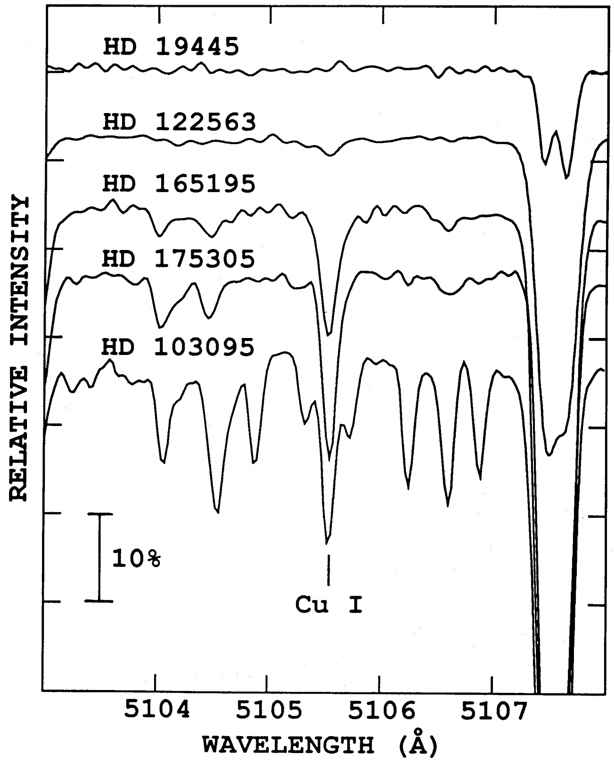

FIG. 1

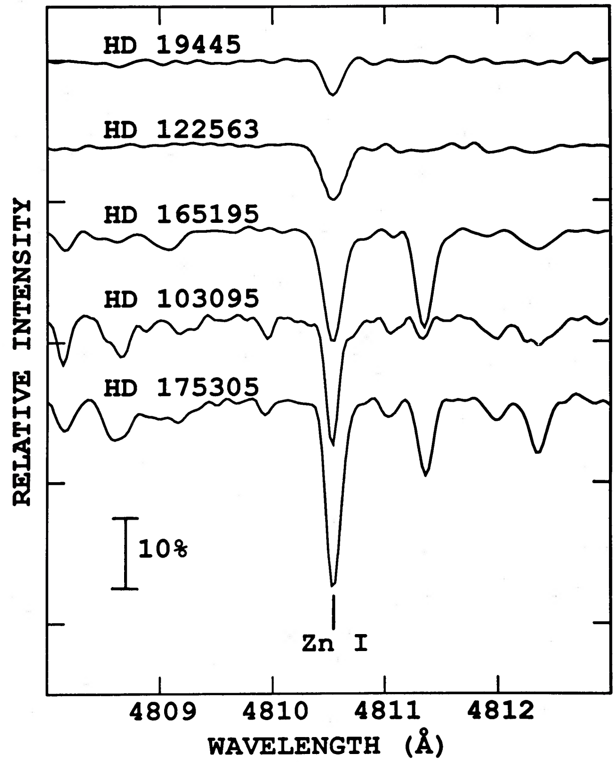

FIG. 2

FIG. 1.—The 5105 Å line of Cu I in the program stars. The relative intensity scale is correct for the top spectrum, and all other spectra have been shifted from this spectrum by constant additive amounts. The order of the spectra is only for convenience of presentation.

FIG. 2.—The 4810 Å line of Zn I in the program stars. The scaling of the spectra are the same as in Fig. 1.

165195. The agreement is satisfactory considering that ~20 mÅ would be the limit of reliable equivalent-width measures with their photographic coudé spectra. Luck and Bond (1981) give HD 122563 Zn I line equivalent widths as 17 mÅ and 31 mÅ, somewhat higher than our values, but those are the only two lines in common between our studies. Sneden and Parthasarathy's (1983) line list for HD 122563 has three Fe and Ni lines covered in the present study. The equivalent-width agreement is good for two strong (~55 mÅ) lines, but we measure a very weak Ni I 6108 Å line at 3 mÅ, while Sneden and Parthasarathy, from a lower resolution spectrum, measured 9 mÅ for this line. Finally, Peterson's (1980) equivalent width of 12.7 mÅ for the Cu I 5782 Å line for HD 103095 is in excellent agreement with our measurement of 11.7 mÅ.

TABLE 3

Cu, Zn, AND Ni EQUIVALENT WIDTHS

λ (Å)	EP (eV)	log *gf*	E.W. 19445 (mÅ)	103095 (mÅ)	122563 (mÅ)	165195 (mÅ)	175305 (mÅ)
			Cu I				
5105.55......	1.39	−1.52	<0.8	35.0	4.0	27.0	33.0
5782.15......	1.64	−1.72	<1.5	11.7	<1.0	...	16.7
			Zn I				
4722.20......	4.03	−0.39	6.0	20.0	14.0	26.0	36.0
4810.55......	4.08	−0.17	9.9	26.0	20.0	34.0	45.0
			Ni I				
4715.77......	3.54	−0.55	4.7	29.0	...	...	...
4806.99......	3.68	−0.50	2.4	15.1	...	...	21.0
4811.99......	3.66	−1.39	...	...	3.1	...	5.5
5094.42......	3.83	−1.11	...	...	...	2.2	5.9
5099.94......	3.68	−0.27	3.3	34.0	10.0	20.0	38.0
5102.97......	1.68	−2.81	...	17.1	5.9	20.0	22.0
6108.13......	1.68	−2.47	2.6	...	11.6	...	...
6176.82......	4.09	−0.21	...	...	2.7	...	...
6191.19......	1.68	−2.23	...	...	19.0	55.0	48.0
6586.32......	1.95	−2.69	...	...	4.1	16.5	14.5
6643.64......	1.68	−1.94	...	...	26.0	66.0	59.0

III. THE ABUNDANCE ANALYSES

The abundance computations were carried out with a standard LTE line analysis and spectrum synthesis code (Sneden 1973). The model atmosphere parameters adopted are given in Table 1. Model atmospheres for the giant stars were determined by interpolation in the grid of Bell *et al.* (1976). For the dwarf star HD 19445 we interpolated an appropriate model from those given by Kurucz (1980), and for HD 103095 we used a model from an unpublished grid of cool dwarf metal-poor stellar models that were obtained from R. A. Bell; these models were generated with the same code that produced the giant star models employed here.

We employed theoretical or laboratory oscillator strengths for our principal elements Cu and Zn. Biemont and Godefroid (1980) used their earlier set of theoretical calculations of Zn I oscillator strengths to redetermine the abundance of Zn in the Sun. They derived log ϵ(Zn) = 4.60 ± 0.03 [on the usual scale in which log ϵ(H) = 12.0] from six Zn I lines which included our transitions. This abundance agrees well with the meteoritic

TABLE 4

Fe Equivalent Widths

λ (Å)	EP (eV)	log *gf*	E.W. 19445 (mÅ)	103095 (mÅ)	122563 (mÅ)	165195 (mÅ)	175305 (mÅ)
4707.29......	3.24	−1.14	13.3	...	...	...	...
4728.55......	3.65	−1.35	4.5	40.0	...	...	50.0
4800.65......	4.14	−1.08	...	19.0	...	8.8	...
4802.89......	3.66	−1.49	1.9	23.0	...	12.9	25.0
4804.52......	3.57	−2.42	...	...	...	4.4	10.8
4807.72......	3.37	−1.95	...	14.4	...	11.3	18.0
4808.16......	3.25	−2.64	...	8.5	...	4.5	6.8
4809.94......	3.57	−2.62	...	3.8	...	...	2.4
4813.12......	3.27	−2.75	...	4.9	...	3.0	4.7
5090.78......	4.26	−0.55	6.5	...	...	22.0	...
5097.01......	4.28	−0.61	7.0	55.0	...	26.0	51.0
5104.44......	4.28	−1.64	...	...	...	5.4	8.8
5109.66......	4.30	−0.68	4.5	36.0	7.9	...	27.0
5763.00......	4.21	−0.60	...	...	...	28.0	...
5775.09......	4.22	−1.20	...	19.0	...	...	17.3
5778.46......	2.59	−3.51	...	6.7	...	...	6.0
5793.92......	4.22	−1.70	...	6.3	...	5.7	...
5806.73......	4.61	−1.00	...	11.6	...	...	15.8
5809.22......	3.88	−1.70	...	10.6	...	...	12.2
6102.18......	4.83	−0.34	2.6	...	...	...	...
6113.33......	3.22	−3.40	...	1.1	...	...	...
6136.62......	2.45	−1.57	27.0	...	62.8	...	...
6137.70......	2.59	−1.66	23.0	...	53.3	...	...
6151.62......	2.18	−3.35	...	...	5.2	...	...
6157.73......	4.07	−1.33	...	...	2.2	...	...
6173.34......	2.22	−2.89	...	...	10.4	...	...
6180.21......	2.73	−2.70	...	...	3.8	...	...
6187.99......	3.94	−1.64	...	...	2.5	6.2	11.5
6191.57......	2.43	−1.63	...	...	61.0	112.0	87.6
6574.25......	0.99	−5.00	...	...	6.1	23.0	15.5
6575.04......	2.59	−2.75	...	...	...	21.0	32.0
6581.22......	1.48	−4.83	...	...	...	8.3	5.4
6593.88......	2.43	−2.35	...	...	17.0	59.0	58.0
6609.12......	2.56	−2.56	...	...	6.3	30.0	31.0
6633.76......	4.56	−0.73	...	...	...	...	24.0

value for Zn of 4.65 ± 0.02 quoted by Grevesse (1984) from the compilation of Anders and Ebihara (1982). Therefore the Zn I *gf*-values given in Table 3 are those of Biemont and Godefroid (1980).

The laboratory determinations of *gf*-values for Cu I by Kock and Richter (1968) generally have been confirmed in the more recent review by Bielski (1975) and in the laboratory work of Hannaford and Lowe (1983). We adopted their *gf*-values for our Cu I lines (see Table 3). Kock and Richter (1968) also redetermined the solar Cu abundance, obtaining log ϵ(Cu) = 4.16 ± 0.08, in satisfactory agreement with the meteoritic value given by Grevesse (1984) of 4.26 ± 0.05 (Grevesse notes also that a new calculation of the solar Cu abundance using the Kock and Richter *gf*'s yields an abundance of 4.21 ± 0.04).

We first employed these oscillator strengths to predict the solar Cu and Zn abundances with our spectrum synthesis code, adopting the Holweger and Muller (1974) model solar atmosphere and a constant microturbulent velocity of 0.8 km s^{-1}. The Cu I and Zn I lines in the Sun are strong enough so that the hyperfine structure effects must be considered. We accounted explicitly for the hyperfine splitting of the Cu I lines, using the experimental hyperfine structure values of Ritschl (1932). Solar Cu abundances then were determined to match the equivalent width measures of 91 mÅ (5105 Å line) and 71 mÅ (5782 Å) given by Mackel *et al.* (1975). Our calculated Cu abundance, log ϵ(Cu) = 4.12 ± 0.01, is in excellent agreement with that of Kock and Richter (1968). Hyperfine structure calculations were not done for the Zn I lines. Although ^{67}Zn possesses large hyperfine structure splitting (Lyshede and Rasmussen 1937), it is not a large contributor to the total solar Zn abundance. The relative proportions of the various Zn isotopes in metal-poor stars are, of course, unknown, but the Zn I lines in most of these stars are sufficiently weak that hyperfine splitting does not change the equivalent widths. Then, adopting the solar equivalent widths of 67.5 mÅ (4722 Å) and 78.3 mÅ (4810 Å) measured by Biemont and Godefroid (1980), we derived a solar Zn abundance of log ϵ(Zn) = 4.62, in very close agreement with Biemont and Godefroid's (1980) recommended value.

Reliable oscillator strengths do not exist in the literature for most of the transitions of Fe I and Ni I used here. Therefore traditional "solar" *gf*-values were determined by forcing the computed and observed solar equivalent widths to match. For this we used a combination of the solar equivalent widths of Mackle *et al.* (1975) and those measured directly from the solar spectrum atlas of Delbouille *et al.* (1973). The assumed solar abundances for these calculations were log ϵ(Fe) = 7.60 and log ϵ(Ni) = 6.28. The resulting solar oscillator strengths are given in Tables 3 and 4.

The application of the model atmosphere and atomic line parameters to the metal-poor program stars was straightforward. Single-line computations were carried out for Fe, Ni, and Zn, and full syntheses with the hyperfine structures discussed above were employed for Cu. As mentioned above, however, the Cu lines were sufficiently weak in the program stars that abundances derived with and without the introduction of hyperfine splitting yielded the same results to within 0.02 dex. The final abundances, given with respect to the solar abundances, are shown in Table 5.

Uncertainties in the abundances are due to equivalent-width errors, model atmosphere parameter uncertainties, and errors associated with the assumptions about line-formation mechanisms. Equivalent-width uncertainties, caused by continuum placement uncertainties and influence of undetected line blends, were estimated to be ±0.1 dex by noting the typical line-to-line scatter in the abundances of Fe and Ni in the program stars.

TABLE 5

Final Abundances

Star	[Fe/H]	[Ni/H]	[Cu/H]	[Zn/H]	[Ni/Fe]	[Cu/Fe]	[Zn/Fe]
HD 175305...........	−1.40	−1.50	−1.75	−1.60	−0.10	−0.35	−0.20
HD 103095...........	−1.45	−1.50	−1.80	−1.45	−0.05	−0.35	+0.00
HD 19445............	−2.05	−2.05	≤ −2.70	−2.05	+0.00	≤ −0.65	+0.00
HD 165195...........	−2.25	−2.35	−2.75	−2.30	−0.10	−0.50	−0.05
HD 122563...........	−2.70	−2.75	−3.45	−2.60	−0.05	−0.75	+0.10

An assessment of the influence of variations in model atmosphere parameters on the derived abundances is given in Table 6. For the entries which give the dependences of [M/H] on the physical parameters we have noted the different effects on typical low- and high-excitation potential lines of Ni I and Fe I. For the entries describing the effects on [M/Fe] we have estimated the overall dependences when all lines are considered at once. It is clear from the values in Table 6 that the abundance ratios [Cu/Fe] and [Ni/Fe] are very insensitive to atmosphere parameter uncertainties; this result follows simply from the very similar ionization potentials of Cu, Ni, and Fe. Zn, however, does not follow this pattern because its ionization potential (9.39 eV) is substantially larger than those of the other three elements ($\approx$7.7 eV). While the elements with the lower excitation potentials are almost totally ionized throughout the line-forming layers of the atmospheres, a substantial part of Zn is neutral. The derived abundances of Zn therefore are sensitive to the details of the atmosphere structures. These trends were checked for sign and magnitude by means of some single-slab curve-of-growth calculations, using the approximate relationships derived by Pagel (1964). These calculations confirmed the weak dependence of Zn to changes in $T_{\rm eff}$ and the relative insensitivity of all of the abundances to gravity.

Our abundance analysis has assumed LTE throughout. The validity of this assumption is difficult to assess completely, since at the present time not all the relevant atomic data for these complex atoms are known to sufficient accuracy. A couple of tests can be attempted with our data. One indicator of departures from LTE lies in a comparison of abundances from low- and high-excitation potentials. Neutral species low-excitation lines give anomalously low abundances in comparison with those determined from high-excitation lines in metal-rich giants (Ruland *et al.* 1980; Brown, Tomkin, and Lambert 1983). A clean test of this effect is not possible here, for $T_{\rm eff}$ values for our stars usually were chosen both to match photometric indices *and* to force agreement between low- and high-excitation potential lines of Fe I. We can only note that our derived abundances for Fe and Ni do not show any dependences on excitation potential and that similar tests are impossible for Cu and Zn due to the limited excitation ranges available for these two elements.

For our data, a stronger indicator of departures from LTE is in a comparison of abundances determined from dwarfs and giants. The Cu and Zn abundances in the dwarf stars agree well with those of the giants. The agreement in these abundances for stars of extremely different atmosphere conditions lends more confidence to our claim that we are seeing real abundance effects in these two elements. A final test ideally would be a comparison of the abundances from neutral and ionized species, but we have already noted the total absence of available lines of ionized Cu and Zn.

IV. DISCUSSION

a) The Observed Abundance Trends

From the entries in Table 5 we come to the following important conclusions. First, the metallicities, [Fe/H], that we have determined are in excellent agreement with those found in previous studies (Cayrel de Strobel *et al.* 1984); our general abundance scale is reliable. Second, we derive [Ni/Fe] ≈ 0 throughout the metallicity range studied here. We do not see evidence for Ni overabundances even in HD 122563 ([Fe/H] ≈ -2.7). It is possible that the difference between the present result and that of Luck and Bond (1983, 1985) lies in our detection of very weak Ni I and Fe I lines; the Ni overabundances derived by Luck and Bond from stronger lines may depend on their assumptions about microturbulent velocities or the equivalent-width measures from their image-tube photographic spectra. However, analyses of Ni in a larger number of stars with [Fe/H] < -2.5 will be necessary to answer this question completely.

More interesting results are the trends in Cu and Zn. The observed abundances given in Table 5 for these elements are plotted in Figures 3 and 4. We emphasize that the Cu abundance for HD 19445 in Figure 3 is an upper limit; its value is taken from the more reliable abundance limit of the 5105 Å line. It is clear that Cu is underabundant in all the stars of our sample, and the [Cu/Fe] ratio appears to decline with decreasing metallicity. This trend is not repeated for Zn, which at least retains its solar ratio with respect to iron at all metallicities.

To increase the data set for Cu and Zn we have added to Figures 3 and 4 a few results from other investigators. This must be done cautiously for elements like Cu and Zn which often are represented by one or two lines in spectroscopic analyses. The data added to these figures came from Peterson (1981), Luck and Bond (1985), and Cohen (1978, 1979). Gratton and Sneden (1988) reported Cu underabundances in a few of their sample of metal-poor stars. We defer reanalysis of their data to a future paper.

TABLE 6

ABUNDANCE UNCERTAINTIES

			Ni/H		Fe/H				
PARAMETER	Cu/H	Zn/H	Low EP	High EP	Low EP	High EP	Cu/Fe	Zn/Fe	Ni/Fe
				Giants					
$T_{\rm eff} = +150$ K	+0.21	+0.03	+0.21	+0.12	+0.30	+0.15	+0.05	−0.15	−0.04
$\log g = +0.4$	+0.05	−0.04	+0.04	+0.04	+0.06	+0.06	−0.01	−0.10	−0.02
[M/H] = +0.3	−0.03	+0.01	−0.03	−0.02	−0.05	−0.03	+0.00	+0.05	+0.04
$v_{\rm turb} = +0.5$	−0.07	−0.07	−0.07	−0.07	−0.09	−0.09	+0.05	+0.05	+0.05
				Dwarfs					
$T_{\rm eff} = +150$ K	+0.15	+0.01	+0.16	+0.08	+0.20	+0.12	−0.02	−0.17	−0.04
$\log g = +0.4$	+0.07	+0.12	+0.07	+0.05	+0.03	+0.02	+0.04	+0.10	+0.03
[M/H] = +0.3	+0.03	+0.05	+0.04	+0.03	+0.02	+0.02	+0.01	+0.03	+0.02
$v_{\rm turb} = +0.5$	−0.02	−0.02	−0.04	−0.02	−0.05	−0.03	+0.02	+0.02	+0.01

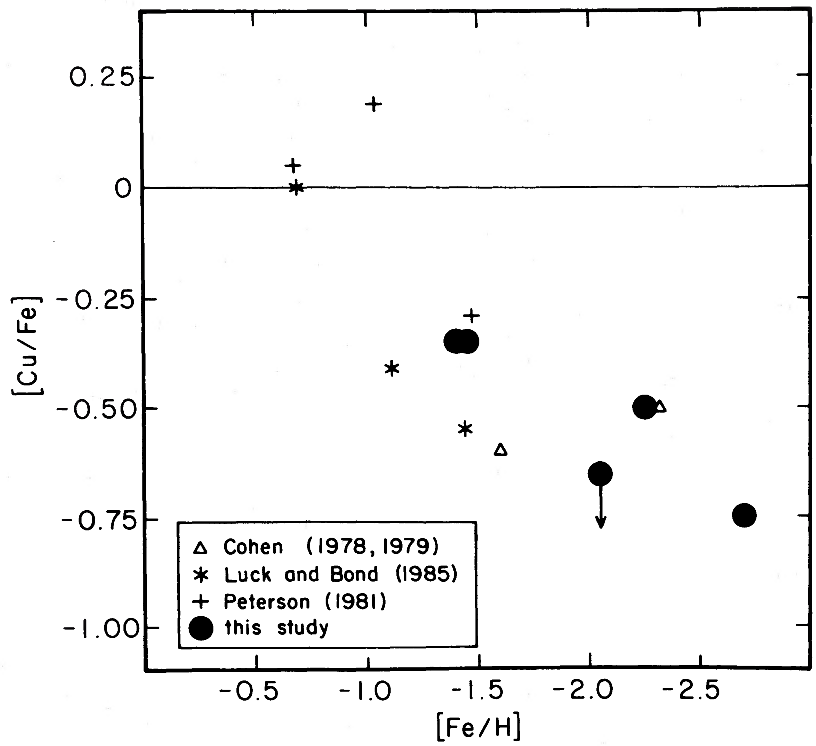

FIG. 3.—Cu abundances in metal-poor stars. Results from different studies are given with the symbols indicated in the figure, and the text gives a discussion of the methods of adding the data from other investigations. The [Cu/Fe] value for HD 19445 is an upper limit.

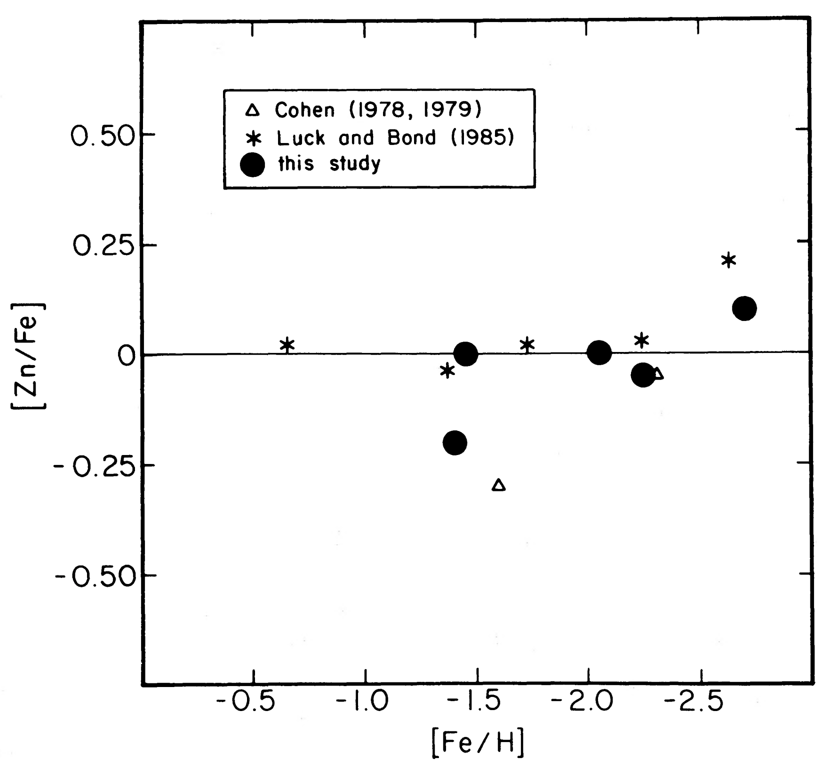

FIG. 4.—Zn abundances in metal-poor stars. Refer to the text for a discussion of the methods of adding data from other investigations.

Peterson's (1981) Cu abundances in 13 field dwarf stars were obtained from one line (the 5782 Å feature) measured from image-tube echelle spectra. While there is not an extremely large scatter in the data set (see Peterson's Fig. 1), overall trends in abundances from star to star are difficult to discern. Therefore, for Figure 3 we chose to average her Cu abundances from individual stars into metallicity bins about 0.4 dex wide, centered at [Fe/H] ≈ -0.7, -1.1, and -1.5 (the Cu I lines become unmeasurably weak in her spectra below [Fe/H] ≈ -1.5, and thus no Cu abundances are given for the more metal-poor stars of her sample).

We performed similar averaging for the Cu and Zn abundances derived by Luck and Bond (1985). Those authors did warn that any of their abundances which were determined from only from one or two lines should be viewed with caution. They gave Cu abundances only for six of their metal-poor field giants and apparently felt strongly that their Cu data were too sparse and unreliable. They did not include Cu either in their Figure 5, which showed overall abundance trends, or in their discussion. They did give many more Zn abundances, and over a much wider metallicity range. For Figure 4 then, we averaged their Zn data for 30 stars into five [Fe/H] metallicity bins of about 0.5 dex width.

Luck and Bond's earlier (1981) discussion of metal-poor star abundance trends did point out that a weak indication of Cu underabundances could be seen in the analyses of globular cluster giants that Cohen had undertaken. Therefore, in Figures 3 and 4 we have added two points which represent average Cu and Zn abundances determined for the very metal-poor globular clusters M92 (Cohen 1979) and M13 (Cohen 1978). Cohen (1980) also determined these abundances in three more metal-rich clusters, but the relevant lines are so strong that their abundances are subject to large uncertainties due to damping and microturbulence in addition to the model atmosphere and line parameter uncertainties discussed in § III. Cohen's choices of oscillator strengths for Cu I and especially for Zn I are somewhat different than those adopted here. Therefore we chose to redetermine the globular cluster abundances in the following way. In order to minimize the star-to-star uncertainties in line measurements and model atmosphere analyses, we averaged appropriate quantities for a few stars in each cluster. These average model atmosphere parameters and line equivalent widths are given in Table 7A. We adopted without revision the overall metallicities [Fe/H] derived by Cohen for these two clusters; these values seem well determined (e.g., Zinn and West 1984). Applying the same abundance determination techniques described above, we obtain the [Cu/Fe] and [Zn/Fe] values indicated in Table 7B. The revised Cu abundances obviously are in excellent agreement with Cohen's original values. The revised Zn abundances are about 0.3 dex larger, and the change is in the direction indicated by the differences in the assumed oscillator strengths.

The inclusion of the work of other investigators confirms the general trends seen in our five program stars. The underabundances of Cu are noticeable in other metal-poor stars, albeit with some scatter. Curiously, there is an extremely weak hint seen in Figure 4 that [Zn/Fe] may be increasing in objects with metallicities [Fe/H] < -2.5. The reader must be warned against overinterpretation of this trend. Its existence depends on the data from just one star in the present study and from six stars from the Luck and Bond (1985) survey. The mean value of [Zn/Fe] for those six stars is $\approx +0.2$, but the abundance ratios for individual stars show a large range: $-0.05 \leq$ [Zn/Fe] $\leq +0.60$.

b) The Origin of Cu *and* Zn *in Metal-Poor Stars*

Cu and Zn may be created in a variety of nucleosynthesis sites since at least some iron-peak element isotopes are manufactured in many of the advanced fusion stages of stars. The observed abundance trends for these two elements in our metal-poor stars do permit the present nucleosynthetic speculations to center on a "secondary" origin for Cu, requiring prior production of seed nuclei, and a "primary" origin for Zn, requiring its contemporaneous production with other Fe-peak elements.

The decline of [Cu/Fe] with decreasing metallicity immediately suggests the investigation of the *s*-process neutron bombardment for the origin of Cu in metal-poor stars. If Cu does prove to be an *s*-process element it would become the lightest element definitely identified with this synthesis chain in metal-poor stars. The proposed attribution of Cu synthesis to the *s*-process is not new. For instance, it was proposed by Burbidge *et al.* (1957), because of the acknowledged inability of the classical *e*-process to produce any element heavier than Ni. There have been many detailed calculations of the abundances expected in an *s*-process nucleosynthesis event (e.g., Clayton *et al.* 1961; Clayton and Ward 1974). Cowley and Downs (1980) provided a convenient tabulation by element of *s*-process products to facilitate comparison with stellar abundances, and Malaney (1987*a*, *b*) has recomputed elemental *s*-process abun-

TABLE 7A

GLOBULAR CLUSTER MODEL ATMOSPHERE PARAMETERS

Cluster	T_{eff} K	log g	[Fe/H]	v_{micro} (km s^{-1})
M92	4450	0.85	−2.3	2.0
M13	4250	0.80	−1.5	1.8

TABLE 7B

GLOBULAR CLUSTER LINE MEASURES AND ABUNDANCES

	E.W.			COHEN		THIS STUDY	
CLUSTER	5105 Å	5782 Å	4810 Å	[Cu/Fe]	[Zn/Fe]	[Cu/Fe]	[Zn/Fe]
M92	18:	14:	34	−0.4	−0.3	−0.5	+0.0
M13	93	57	47	−0.6	−0.6	−0.6	−0.3

dance yields for a large range of neutron exposure densities. A comparison of our observed abundances with these *s*-process theoretical predictions can place some probable limits on the allowed synthesis parameters.

If Cu in metal-poor stars is due solely to the *s*-process, then in addition to the observed correlation of [Cu/Fe] with [Fe/H] one requires simply that the synthesis of Cu in this manner not lead at the same time to overproduction of other heavy elements. For example, an *s*-process event naturally leads to very heavy element abundance mixes which peak at the Sr-Y-Zr and the Ba-La-Ce-Nd element groups. Many abundance studies have shown that [(Sr, Y, or Zr)/Fe] ≈ -0.3 at [Fe/H] ≈ -2.5 (see the results and references in Truran 1981; Luck and Bond 1985; and Gilroy *et al.* 1988), which leads to the observed ratio [Cu/(Sr, Y, or Zr)] ≈ -0.3. With the solar abundances of log ϵ(Cu) ≈ 4.1 and log ϵ(Sr, Y, or Zr) ≈ 2.6, then the observed metal-poor star abundance ratio is log $\{\epsilon(\mathrm{Cu})/\epsilon(\mathrm{Sr, Y, or Zr})\} \approx +1.2$.

A ratio this large is produced only in *s*-process exposures which are weak. Computations by Cowley and Downs (1980) and Malaney (1987*a*, *b*) imply that the neutron exposure parameter must be limited to $\tau < 0.3$ (for a single exposure) or $\tau_0 < 0.2$ (for an exponential distribution of exposures). Apparently no reasonable change in physical conditions of the *s*-process region will alter this conclusion. For example, Malaney (1987*b*) showed that changing the input neutron number density does not significantly alter the ratio of Cu to its neighboring elements. He did note that the assumed initial seed abundances did influence slightly the final abundance distribution for very weak neutron exposure parameters. However, the abundance ratios of interest here are quite similar in the tabulations of Malaney (1987*a*, *b*), which assumed a solar system initial abundance mix, and those of Cowley and Downs (1980), which assumed the prior existence only of ^{56}Fe.

The restrictions on the permitted values of neutron exposures probably are much more severe than we have already estimated. It is not certain that the traditional very heavy "*s*-process" elements such as the Sr-Y-Zr group really are due to the *s*-process in very metal-poor stars. Instead, these elements may be produced wholly or substantially by the *r*-process (Truran 1981; Gilroy *et al.* 1988, and references therein). If the *r*-process manufactured the bulk of the very heavy elements for our stars, then only very weak irradiations by the *s*-process (with smaller values of τ) which avoid production of the Sr-Y-Zr group are allowed. In fact, the existence of just such a weak neutron irradiation for the production of Cu (and other species with $A < 90$) for the solar system already has been proposed (see the detailed discussion in Kappeler *et al.* 1982). This idea may well be the key to understanding Cu abundances throughout the whole observable metallicity range.

As a final comment on the *s*-process synthesis predictions, we note that the theoretical predictions do suggest the production of some Zn as well as Cu. Indeed, some single neutron exposure models with $\tau \approx 0.9$ (Malaney 1987*a*) produce approximately the proper Cu/Zn ratios observed in metal-poor stars. However, with the limits that we have imposed on τ, the *s*-process will produce log $\{\epsilon(\mathrm{Cu})/\epsilon(\mathrm{Zn})\} \approx 0$, underproducing Zn by a large factor. Obviously an attempt to synthesize both Cu and Zn in the *s*-process also would have difficulty in explaining the observed variation of [Cu/Zn] with [Fe/H]. Clearly then it is necessary to find a different nucleosynthetic origin for the bulk of the Zn production in our stars.

Some major primary nuclear fusion stages, such as explosive burning of oxygen, silicon, or neon, can also lead to production of Cu and Zn in various ratios. A good, extensive theoretical survey of expected element production in these fusion chains has been given by Woosley (1986), who summarizes the processes expected to be major contributors to the isotopes of elements C through Zn in the solar system abundance distribution. His review does not deal extensively with the nucleosynthesis expected from progenitors to the very metal-poor stars under investigation here. Woosley and Weaver (1982) did make some preliminary comparisons of the expected element productions between a 25 $M_\odot$ supernova which is metal-rich and one which is metal-poor. They did comment that although the full explosive nucleosynthesis computations had not been carried out for the metal-poor supernova, few differences would be expected in the resulting element mixes for elements heavier than Si. The only exceptions would be for those nuclei attributable to *s*-process syntheses (Cu *might* be one of those nuclei!); they would be underproduced in metal-poor progenitor stars.

Woosley (1986) suggests that the major source for the stable ^{63,65}Cu isotopes is explosive neon burning (Woosley and Weaver 1980). Explosive neon burning is primarily responsible more for the production of Mg, Al, and Si than for Cu. Moreover, the products of this fusion chain have different dependences on prior metallicity in the burning regions: the lighter elements Mg, Al, and Si are "primary" elements manufactured directly by the cumulative effects of all fusion cycles through neon burning, but Cu will be synthesized in this chain only if Fe seed nuclei already exist. Therefore Cu would show the same sort of correlation with Fe that both is predicted by the *s*-process *and* is observed in our stars. Explosive neon burning apparently cannot produce an appreciable amount of Zn. Woosley (1986) has computed abundances for a variety of temperatures and densities, but for almost all burning conditions the resulting abundances from explosive neon burning yield log $\{\epsilon(\mathrm{Cu})/\epsilon(\mathrm{Zn})\} \approx +1$. This is a similar situation to the nonproduction of Zn by the *s*-process. Indeed, it is frustrating to conclude that our observed abundances do not permit us to choose between the *s*-process neutron bombardment synthesis and explosive neon burning for the origin of Cu in metal-poor stars.

If at least two scenarios are available for the production of Cu, it is more of a struggle to find ways to produce Zn at all, much less in the correct abundance ratios to its neighboring elements. Woosley (1986) attributes the solar system abundance of ^{64}Zn to a combination of explosive helium burning and the so-called α-rich freezeout branch of nuclear statistical equilibrium which can occur during explosive silicon burning (Woosley, Arnett, and Clayton 1973). He does not discuss extensively the other stable Zn isotopes (mostly ^{66,67,68}Zn) and does not include them in his summary isotope origin table. The chief problem with most fusion chains for Zn seems to be that in order to produce reasonable amounts of Zn, unreasonably large amounts of Fe, Ni, or Cu also are synthesized. Zn production by explosive helium burning appears to fail for this reason in our metal-poor stars; there is too much Cu produced in most of the models.

Far more attractive is the possibility that an α-rich freezeout from explosive silicon burning is responsible for large amounts of Zn. In this mechanism, the burning region densities are low enough that nuclear statistical equilibrium is not fully attained, and excess α-particles remain to merge with Fe-peak isotopes to produce Zn (after β-decays), and possibly Cu. Only two abundances sets were computed by Woosley (1986) for the relatively high temperatures and low densities which would produce the desired excess numbers of α-particles. However, S. E. Woosley (private communication) cautions that those two cases hardly exhaust the possible abundance results from this process. If we assume for the present that these two computed cases are representative, it is possible to conclude that Zn is produced in far greater quantities than Cu in an α-rich freezeout: $\log \{\epsilon(\mathrm{Cu})/\epsilon(\mathrm{Zn})\} \approx -1.3$. This is allowed by our observations, and the bulk of the Cu synthesis done in one of the ways discussed previously. Unfortunately, Ni also is very much overproduced: $\log \{\epsilon(\mathrm{Ni})/\epsilon(\mathrm{Zn})\} \approx +2.5$, while the observed metal-poor star abundance ratio of these elements is ≈ 1 dex smaller. Our observations do not show a suggestion of Ni overabundances in any of the metal-poor stars. Therefore either the α-rich freeze out mechanism is not at work for the production of Zn in these stars, or a different set of physical conditions during the freezeout, which would lead to smaller Ni/Zn and Ni/Fe ratios, must be imagined.

In summary, then, we conclude that Cu must be built by secondary nucleosynthesis processes due to its behavior with respect to Fe. Either the classical *s*-process or explosive neon burning are capable of synthesizing Cu in this manner. The origin of Zn must be different. The difficulty with the mechanisms we have discussed is that other elements may be overproduced. The most promising explanation is an α-rich freezeout following explosive silicon burning. It would seem, however, that the input physical conditions must be different from those used in current theoretical models. There remain some obvious followup tasks to the present work. Observationally, knowledge of the abundance trends of Cu and Zn must be expanded to include more stars at the lowest metallicities possible. This will show whether: (*a*) the decline of Cu/Fe continues, strengthening the attribution of its production to secondary nucleosynthesis processes; and (*b*) the Zn/Fe ratio begins to rise, increasing the likelihood that the α-rich freezeout is at work for this element (we do not regard the slight rise in [Zn/Fe] seen in Fig. 4 as statistically significant). Theoretically, we hope that a self-consistent set of explosive nucleosynthesis calculations for very metal-poor stars can be generated soon. It is clear that some renewed attention should be given to matching observed and predicted Fe-peak element compositions in metal-poor stars.

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