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CARBON ABUNDANCES IN HALO DWARFS

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ABSTRACT

We have made a spectrum synthesis analysis of Digicon observations of CH in 32 halo F and G dwarfs with iron abundances as low as [Fe/H] ≈ -2.5. The results, combined with earlier results, also based on spectrum synthesis of Digicon CH spectra, show that carbon follows iron down to [Fe/H] ≈ -1.8; at lower metallicities there is evidence of a positive trend in [C/Fe]. We suggest that the change in slope of the [C/Fe] versus [Fe/H] relationship at [Fe/H] ≈ -1.8 is due to the appearance of Type I supernovae. The sense of the change of slope is consistent with the prediction that Type I supernovae are inefficient producers of carbon.

More carbon abundances, determined from analysis of CH in even more metal-deficient stars and, also, determined from C I lines, are needed in order to establish the relationship between carbon and iron abundances in extremely metal-deficient ([Fe/H] $\lesssim -2.0$) dwarfs more firmly.

One of the program stars (BD $-0°4470$) is found to be a double-lined spectroscopic binary composed of two nearly identical halo dwarfs.

Subject headings: stars: abundances — stars: Population II

I. INTRODUCTION

Carbon, an abundant element, is the first link in the chain of nucleosynthesis whereby the heavy elements are made from H and He in stellar interiors. Carbon abundances in halo dwarfs are of interest because of what they can tell us about the early phases of the Galaxy's history. Peterson and Sneden's (1978) analysis of CH lines on photographic echelle spectra was the first extensive investigation of carbon abundances in these stars. Their results, combined with those of Clegg, Lambert, and Tomkin (1981) for disk dwarfs, showed that in both the halo and the disk the carbon abundance follows that of iron, i.e., [C/Fe] = 0. A recent investigation (Tomkin and Lambert 1984) of 14 disk and halo dwarfs with [Fe/H] from -2.3 to -0.4, which also determined carbon abundances from CH, suggested the presence of an offset such that in metal-deficient stars carbon tends to be 0.2 dex more deficient than iron, independent of overall metallicity.

The total number of halo stars involved in these studies is quite modest and, in particular, few results are available for very metal-deficient stars. These studies have included only one star (HD 140283) with [Fe/H] less than -2.0, for example. Recently Barbuy, Spite, and Spite (1985) have added a data point for another extremely metal-deficient dwarf, BD $-10°388$ which has [Fe/H] = -2.2 and [C/Fe] = 0.2. Also, Laird (1985) has determined carbon abundances for a large number of disk and halo dwarfs, but the modest resolution (2.5 Å) of his data did not allow him to pursue [C/Fe] beyond [Fe/H] = -2.0.

In order to examine how the carbon abundance depends on iron abundance in more detail, especially for [Fe/H] ≤ -2.0, we have determined carbon abundances in a new sample of field F and G halo dwarfs. The sample of 32 stars is detailed in Table 1. Thirty of the stars were selected from the list of subdwarfs compiled by Carney (1979, Tables 2 and 3), and the remaining two (BD $+23°3912$ and HD 210595) were selected from the list of Bond (1970).

Spectrum synthesis of CH and atomic lines in the neighborhood of 4300 Å provides [C/Fe], with [Fe/H] determined from the atomic lines. Nearly all the stars turn out to have [Fe/H] $\lesssim -1.0$, and about one third of them have [Fe/H] $\lesssim -2.0$. We also find that BD $-0°4470$ is a new double-lined spectroscopic binary.

II. OBSERVATIONS

The McDonald Observatory's 2.7 m telescope, coudé spectrograph, and a 936 diode Digicon (Tull, Choisser, and Snow 1975) were used to observe CH in the 32 program stars. The observations were centered at 4330 Å and covered 120 Å at a resolution of 0.26 Å. This interval was chosen because it includes the two most prominent CH features: the blue degraded (0, 0) and (1, 1) bands with Q-branch band heads at 4314 Å and the red degraded (2, 2) band Q-branch band head at 4323 Å. Most observations had signal-to-noise ratios of between 100 and 150 and all observations in which CH was weak had signal-to-noise ratios in this range.

III. ANALYSIS AND RESULTS

Before describing the spectrum synthesis analysis, we outline the necessary preliminaries of choice of stellar parameters, calculation of the model atmospheres, and sources of data for atomic and molecular lines in the synthesized piece of spectrum.

The effective temperatures are the mean values derived from the $b-y$, $R-I_J$, $R-I_K$, and $V-K$ colors. (The subscripts J and K denote the Johnson and Kron RI systems.) We used the effective temperature-color calibrations of Peterson and Carney (1979), which are valid for the temperature range covered by the program stars. The gravities were calculated from the effective temperatures and Hejlesen's (1980) relations between log g and effective temperature for metal-deficient main-sequence stars. For the purpose of calculating the model atmospheres, preliminary values of [Fe/H] were estimated from the ultra-violet excess, $\delta(U-B)$.

These effective temperatures, gravities, and preliminary metallicity estimates were then used to calculate scaled Holweger-Müller (1974, hereafter HM) solar model atmo-

TABLE 1

PROGRAM STARS

Star	Sp T	V	T_{eff}	log g	[Fe/H]	[C/Fe]
HD 7424	...	10.08	5360	4.7	−0.97	−0.33
BD +72°94	G3 VI	10.20	6200	4.7	−1.62	−0.08
HD 16031	sd F4	9.78	6000	4.7	−1.82	0.02
BD +9°352	...	10.18	5950	4.7	−2.08	0.08
BD +66°268	G8 VI	9.91	5250	4.7	−2.10	−0.20
HD 25329	K1 V	8.50	4750	4.8	−1.90	0.00
BD +21°607	F5 VI	9.23	5940	4.7	−1.85	−0.05
BD +37°1458	...	8.92	5210	4.7	−2.20	−0.10
BD +54°1216	F5 VI	9.69	5940	4.7	−1.55	−0.05
HD 74000	F6 VI	9.62	6090	4.7	−1.98	0.08
HD 84937	F5 VI	8.32	6170	4.7	−2.18	0.20
HD 87140	...	8.98	4940	4.8	−1.87	−0.48
BD +29°2091	sd G0	10.25	5630	4.7	−1.78	−0.32
HD 99383	F5 VI	9.07	5960	4.7	−1.56	−0.05
HD 101063	G5	9.44	4980	4.7	−1.41	−0.50
BD +51°1696	G0 VI	9.92	5600	4.7	−1.31	−0.45
BD −4°3208	sd A7	10.04	6200	4.7	−2.35	≲0.2
HD 108177	F5 VI	9.67	5960	4.7	−1.92	0.12
BD +34°2476	sd G2	10.06	6120	4.7	−2.16	0.20
HD 126681	G2 V	9.31	5500	4.7	−1.43	−0.37
BD +26°2606	sd F4	9.73	5910	4.7	−2.58	0.25
BD +2°3375	sd G0	9.92	5800	4.7	−2.55	0.25
BD +20°3603	sd G1	9.75	6020	4.7	−2.24	0.24
BD +26°3578	sd F8	9.36	6090	4.7	−2.46	0.15
HD 188510	G5 V	8.82	5500	4.7	−1.75	−0.15
BD +23°3912	G0 V	8.89	5630	4.7	−1.60	−0.40
HD 193901	F8 V	8.67	5810	4.7	−1.24	−0.46
HD 194598	F7 V–VI	8.34	5910	4.7	−1.28	−0.12
BD +4°4551	F7 V	9.61	5730	4.7	−1.76	−0.14
HD 210595	F7 V	8.61	6230	4.7	−0.72	−0.38
BD −0°4470[a]	sd G3	9.95	5130	4.7	...	...
BD +2°4651	sd F0	10.20	5880	4.7	−2.17	0.07

[a] BD −0°4470 is a spectroscopic binary; see text.

spheres. A representative microturbulence of 1.0 km s^{-1} (Clegg, Lambert, and Tomkin 1981) was used for all stars.

The equivalent widths of the Fe I lines given in Table 2 were used to determine the stellar iron abundances. Atomic data, including the laboratory oscillator strengths (Fuhr *et al.* 1981), for these lines are given in Table 3. In most cases the preliminary photometric [Fe/H] and the spectroscopic [Fe/H] were in reasonable agreement; for 80% of the stars the difference between the two [Fe/H] estimates was ±0.5 dex, or less. In those cases where the spectroscopic and photometric metal abundance estimates differed by more than 0.5 dex, new scaled HM solar models were calculated with the spectroscopic metal abundance. A second iteration of the Fe abundance analysis then gave the final iron abundances given in Table 1. A solar iron abundance log N(Fe) = 7.67 (Grevesse 1984), on a log N(H) = 12.0 scale, was used to express these abundances relative to the Sun. For a few stars, which do not appear in Table 2 because their crowded spectra did not allow measurement of Fe I line equivalent widths, the iron abundances were determined from the Fe I lines included in the spectrum synthesis; these abundances are also given in Table 1.

We chose to synthesize the interval 4306–4330 Å. It includes the strongest CH features and the window between 4314 Å and 4323 Å which is free of CH lines and therefore useful for the determination of the continuum level. The sources of data for the CH and atomic lines, especially the dissociation energy and band oscillator strengths for CH and the atomic line oscillator strengths, were the same as described in Tomkin and Lambert (1984). An exception was the three lines of Ti II at 4312.86, 4314.98, and 4320.97 Å for which we adopted the accurate laboratory oscillator strengths of Danzmann and Kock (1980) in place of the Wiese and Fuhr (1975) values.

TABLE 2

Fe I LINE EQUIVALENT WIDTHS

Star	Equivalent Width (mÅ)							
	4282.4 Å	4325.8 Å	4337.0 Å	4348.9 Å	4365.9 Å	4369.8 Å	4375.9 Å	4383.5 Å
HD 7424	...	...	...	44	35	...	...	...
BD +72°94	74	139	...	...	...	39	64	172
HD 16031	72	144	64	...	...	31	67	...
BD +9°352	...	130	48	...	...	32	56	174
BD +21°607	73	157	71	...	...	32	...	...
BD +54°1216	...	...	75	...	...	52	90	198
HD 74000	50	140	42	...	...	33	60	144
HD 84937	...	103	38	...	...	...	...	...
HD 87140	...	...	...	18	...	...	...	...
BD +29°2091	...	...	...	9	...	54	82	...
HD 99383	...	...	70	...	...	...	72	...
HD 101063	...	...	...	41	32	...	...	...
BD +51°1696	...	...	115	20:	...	...	...	...
BD −4°3208	...	93	17	...	...	...	...	112
HD 108177	75	144	53	...	...	32	60	...
BD +34°2476	51	104	28	...	...	21	56	133
HD 126681	...	...	120	23:	11:	...	...	...
BD +26°2606	...	109	20	...	...	17	...	127
BD +2°3375	...	109	32	...	...	18	53	127
BD +20°3603	53	106	38	...	...	26	47	123
BD +26°3578	43	102	18	...	...	...	...	120
BD +23°3912	...	...	69	10	11	70	104	...
HD 193901	...	...	94	14	...	...	98	...
HD 194598	...	...	91	7	...	77	91	...
BD +4°4551	...	...	71	...	...	52	81	...
HD 210595	...	...	95	14	18	...	102	...
BD +2°4651	56	133	47	...	...	34	58	168

TABLE 3

Fe I LINE DATA

λ(Å)	χ(eV)	log *gf*
4282.4......	2.176	−0.76
4325.8......	1.608	0.00
4337.0......	1.557	−1.61
4348.9......	2.991	−2.06
4365.9......	2.991	−2.14
4369.8......	3.047	−0.72
4375.9......	0.000	−3.031
4383.5......	1.485	0.16

For each star, three synthetic spectra, with overall metal deficiency equal to the [Fe/H] and three values of [C/Fe] spaced 0.5 dex apart, were calculated and compared with the observed spectrum in order to estimate the [C/Fe]. Table 1 gives the [C/Fe] results, and Figure 1 shows an example of the comparison of observed and synthetic spectra. (In this figure the [C/Fe] of the synthetic spectra are 1.0 dex apart.)

The error of the [Fe/H] due to the scatter of the abundances from individual Fe I lines is typically 0.15 dex. We estimate the uncertainty of [C/Fe] associated with the matching of the synthetic and observed spectra at ±0.1 dex. This includes the uncertainty of continuum location. For the coolest stars in the program, whose continua are less well defined because of their more crowded spectra, our estimate of this abundance error is increased to ±0.2 dex. Also, in one or two of the hottest, most metal-deficient stars, the [C/Fe] error estimate must be increased to ±0.2 dex, because, although the continuum is clearly defined, the CH is weak and not very well defined. The random error in the effective temperatures, estimated from comparison of individual temperatures derived from the different photometric indices of the same star, is about ±100 K. Table 4 gives the corresponding uncertainties in [Fe/H] and [C/H], which are ±0.07 and ±0.09 dex, respectively. This source of error largely cancels in [C/Fe]. Both the CH and neutral atomic line strengths are insensitive to the gravity—see Table 4—with the result that the errors due to uncertainties in the adopted log g are negligible. In the typical program star, a departure of 0.3 km s^{-1} of the microturbulence from the 1.0 km s^{-1} adopted value caused a 0.07 dex change of [Fe/H] and an insignificant change of [C/H]. The insensitivity of the carbon abundance to microturbulence is due to the high thermal velocity of CH and the fact that in most stars the CH is unsaturated. Thus a 0.3 km s^{-1} microturbulence error causes errors of ∓0.07 and ±0.07 dex in [Fe/H] and [C/Fe], respectively, and a negligible error in [C/H]. The actual errors of [C/Fe] and [Fe/H], due to the combination of these sources of error, are estimated to be ±0.15 and ±0.2 dex, respectively, for most stars.

TABLE 4

DEPENDENCE OF ABUNDANCES ON T_{eff} AND LOG g

	CHANGE OF ABUNDANCE (dex)	
SPECIES	$\Delta T_{eff} = 100$ K	$\Delta \log g = 0.2$
CH	0.09	−0.01
Fe I	0.07	0.00

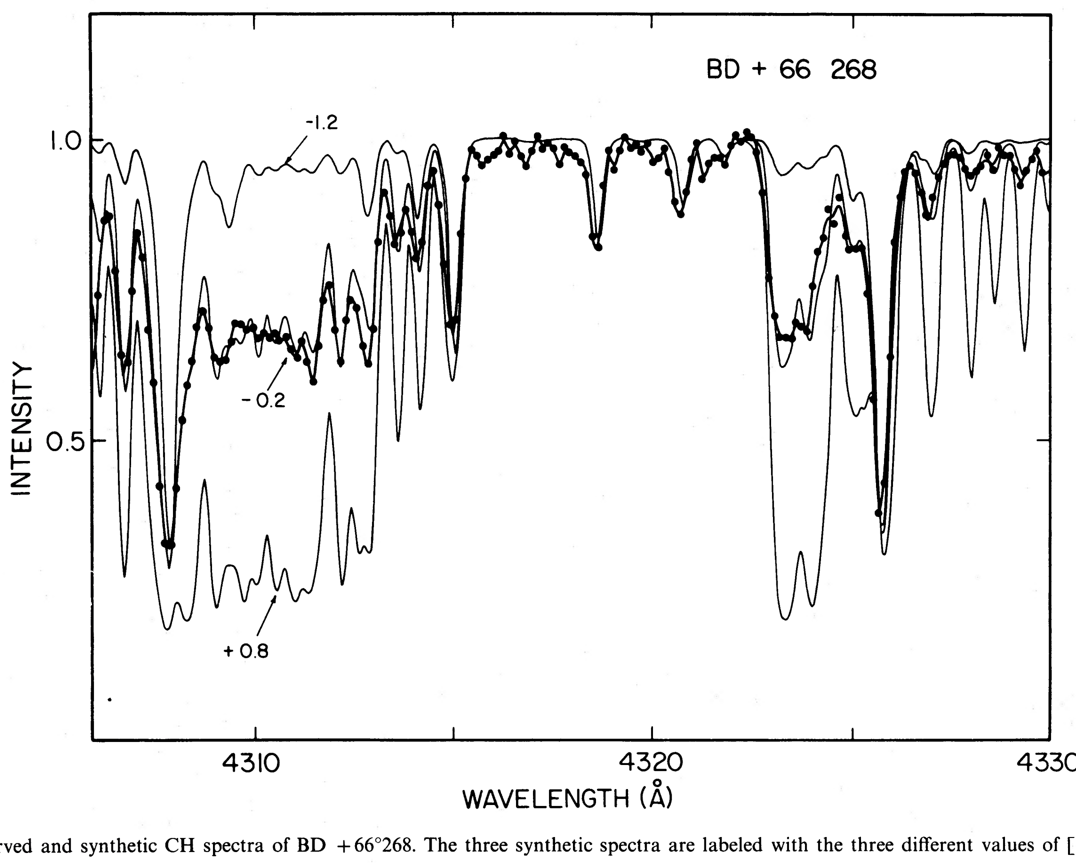

FIG. 1.—Observed and synthetic CH spectra of BD +66°268. The three synthetic spectra are labeled with the three different values of [C/Fe] used in their calculation.

We note that in the neighborhood of 4300 Å used in this analysis, the synthetic solar CH spectrum, computed with Lambert's (1978) carbon abundance [log $N(C) = 8.67$, on a log $N(H) = 12.0$ scale], is in good agreement with the observed solar spectrum; see Tomkin and Lambert (1984). This observed solar spectrum was a Moon, i.e., flux, spectrum observed with the same combination of telescope and instrumentation as that used to secure the program star observations. Therefore, in spite of evidence (Chmielewski 1984) that the solar carbon abundance obtained from analysis of high-resolution center-of-disk CH spectra is 0.1 dex lower than Lambert's (1978) value, we have adopted this solar carbon abundance because it is more consistent with our observed solar spectrum and so should provide more reliable differential carbon abundances with respect to the Sun as standard.

To see how the results depend on the choice of the model atmospheres, we computed CH synthetic spectra for a Kurucz (1979) theoretical model with 5500 K effective temperature, log g of 4.5, and a metal deficiency of 2.0 dex and a scaled HM solar model of the same parameters. Comparison of the synthetic spectra showed that the Kurucz model gives 0.25 dex lower carbon abundances than the scaled HM solar model. A similar comparison for the Fe I lines showed that [Fe/H] decreases 0.05 dex when this Kurucz model is used instead of the corresponding scaled HM solar model. These differences arise because, in the line-forming layers, the Kurucz model is cooler than its scaled HM solar model counterpart. Which type of model—the theoretical Kurucz solar model or the observationally based HM solar model—should be used for the solar analysis in order to obtain the most reliable differential abundances with respect to the Sun as standard? For the Sun the dependence of the C and Fe abundances (from CH and Fe I) on choice of model is very similar to that of the 5500 K, metal-deficient dwarf so in an analysis which uses Kurucz models instead of HM models for both the program stars and the Sun there is little change of [C/Fe] and [Fe/H]. But theoretical solar models, such as the Kurucz model, are known to be too cool at line-forming optical depths. (At $\tau_{5000} = 0.1$ the Kurucz model is 150 K cooler than the HM model, for example.) Failure of the theoretical models to account properly for backwarming is a possible explanation. If so, then in the extremely metal-deficient dwarfs, in which backwarming must be relatively insignificant, the Kurucz models may represent the actual atmospheres better than the scaled HM solar models. Thus it might be appropriate to use Kurucz models for analysis of the extremely metal-deficient stars while retaining the HM solar model for the Sun. This would cause a 0.20 dex decrease of [C/Fe] and a marginal 0.05 dex decrease of [Fe/H] for the most metal-deficient stars.

Figure 2 shows a plot of [C/Fe] as a function of [Fe/H]. Also included, are results for 14 additional metal-deficient dwarfs (Tomkin and Lambert 1984) derived from an identical spectrum synthesis analysis of CH and results for four metal-normal dwarfs (Clegg, Lambert, and Tomkin 1981) also derived from CH. From solar metallicity down to $[Fe/H] \approx -1.8$, carbon is slightly more deficient than iron, independent of metal abundance; the average [C/Fe] for the stars with $[Fe/H] \geq -1.8$ is -0.23 ± 0.15 (standard deviation). Below $[Fe/H] \approx -1.8$, carbon becomes less deficient than iron as [Fe/H] decreases so that for the most metal-deficient stars, $[Fe/H] \approx -2.6$, [C/Fe] is about +0.2.

Laird (1985) has also determined carbon abundances in disk and halo dwarfs via CH. We will compare results for the stars in common to our sample and his and then compare the above [C/Fe] versus [Fe/H] relationship with his.

Our sample and Laird's have nine stars in common. In all cases, except HD 101063,[1] the differences between the adopted temperatures and gravities are so small that they play an insignificant role in the comparison of the [Fe/H] and [C/Fe] results. The [Fe/H] results are in excellent agreement; the average of the absolute differences of [Fe/H] is 0.10 dex, and the largest difference is 0.19 dex. For [C/Fe] the average of the absolute differences is 0.31 dex for six of the stars in common, and our results are consistent with Laird's upper limits on [C/Fe] for the other two stars. (The [Fe/H] and [C/Fe] comparisons exclude HD 101063.) The agreement is not as good as for the [Fe/H] results, but this is not unexpected in view of the modest resolution of Laird's spectra and weakness of CH in many of the stars.

From solar metallicity down to $[Fe/H] = -1.8$, Laird also finds [C/Fe] is essentially constant such that $[C/Fe] \approx -0.2$ (his Fig. 5). Laird's analysis of his lunar CH spectrum provides a [C/H] of -0.15 for the Sun, so a normalization of his results to satisfy the condition that the solar $[C/H] = 0.0$ changes this offset from -0.2 to -0.05 dex. Thus we confirm Laird's results over this metallicity range, except for a small difference between the average [C/Fe] values of -0.23 and -0.05 determined in this investigation and Laird's respectively. Below $[Fe/H] = -1.8$, Laird's results are too sparse to reveal the positive trend of [C/Fe].

There is a correlation between [C/Fe] and effective temperature in the sense that the hotter stars tend to have more positive [C/Fe]. Although this might be the result of a systematic error in the [C/Fe] it is more likely to be a consequence of the fact that the hotter program stars also tend to be the more metal deficient. (The reason for this is not clear; a number of different observational selection effects might be responsible.) This, combined with the increase of [C/Fe] below $[Fe/H] \approx -1.8$, probably causes the correlation between [C/Fe] and temperature.

We note that in recent determinations of carbon abundances in F and G dwarfs, the C I–based carbon abundances are systematically higher than those derived from the CH lines. For nine stars, with iron abundances over the range $-0.9 \leq [Fe/H] \leq 0.0$, with both C I–based (Clegg, Lambert, and Tomkin 1981) and CH-based (Clegg, Lambert, and Tomkin 1981; Tomkin and Lambert 1984) carbon abundances, the carbon abundance from C I lines is 0.30 dex greater than that from CH, on average. The temperature dependences of the C I– and CH-based carbon abundances have opposite senses so a temperature error is a possible cause of the discrepancy. A 175 K increase of effective temperature would reconcile the C I– and CH-based carbon abundances of the case above. Such a systematic error of the adopted effective temperatures would be a surprise, but is not completely out of the question.

[1] The adopted temperatures of HD 101063 are almost identical but, whereas we adopt log $g = 4.7$, Laird adopts log $g = 2.77$. The star does not have a spectral type luminosity classification. Our gravity follows Carney's (1979) color-based identification of HD 101063 as a dwarf; Laird's gravity comes from a color-based indicator and the relative strengths of Sr II λ4077 and Fe I lines on his spectra. We note that although a luminosity ($M_v \approx 1.0$) consistent with Laird's gravity would demand a very large space velocity ($U = 582$, $V = -432$, $W = -98$ km s^{-1} relative to Sun), the local escape velocity is not well known, so this is not a decisive argument against possible giant status. We conclude that the gravity of this star is uncertain and the [C/Fe] should be treated with caution.

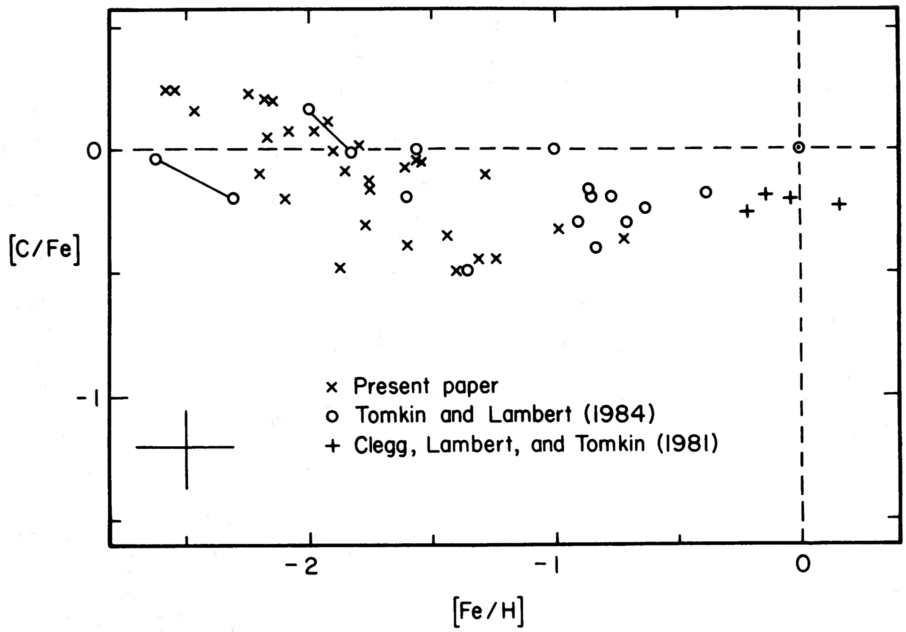

FIG. 2.—[C/Fe] vs. [Fe/H] for the stars of this investigation. Results for additional dwarfs, also based on analysis of Digicon or Reticon CH spectra, are also shown. HD 19445 and HD 140283 are shown as pairs of points connected by lines. For each star, the second more metal-deficient point corresponds to the [C/Fe] and [Fe/H] derived with the parameters suggested by Magain (1984).

Because the CH-based carbon abundance and Fe I–based iron abundance have similar temperature dependences—see Table 4—[C/Fe] changes only slowly with temperature; a 175 K temperature increase would increase [C/Fe] an insignificant 0.04 dex.

The existence of the discrepancy between the CH- and C I–based carbon abundances indicates that the tendency of [C/Fe] to increase below [Fe/H] ≈ -1.8 needs to be more firmly established. This, coupled with the possibility, discussed above, that theoretical models may be more appropriate for the most metal-deficient stars of our sample, in which case the tendency of [C/Fe] to increase in the stars with [Fe/H] $\lesssim -1.8$ would be much less marked, means that it would be worthwhile to try and determine C I–based abundances. Abundances from C I would allow a useful check because their temperature dependence is opposite to that of the CH-based abundances. Calculations show that in a metal-deficient late F dwarf with $T_{\rm eff} = 6000$ K and [C/H] $= -2.0$ the equivalent width of the strongest of the C I lines near 10,700 Å is 50 mÅ; so, with a modest improvement in detectors, this line should be accessible in metal-poor stars. Determination of oxygen abundances from OH at 3000 Å in order to obtain reliable molecule-based [C/O] results would also be worthwhile.

The spectrum of BD $-0°4470$ reveals it as a double-lined spectroscopic binary whose components have very similar spectra. Our observation, which was made 1983 July 30 at 0835 UT (midobservation), has the spectra separated by 40 km s^{-1} with the weaker spectrum to the blue of the stronger spectrum. Although the double-lined nature of the spectrum prevents derivation of carbon and iron abundances in this analysis, it is clear that the components of BD $-0°4470$ are of nearly identical spectral type and have the large metal deficiency characteristic of halo stars.

Carney (1983), after a photometric search for binaries in halo dwarfs, suggested that BD $-0°4470$ may be a binary. But Stryker *et al.* (1985), who made a spectroscopic search for binaries in halo dwarfs which also included BD $-0°4470$, did not identify it as a spectroscopic binary and rejected Carney's suggestion. Perhaps the resolutions of their spectra (78 and 30 Å mm^{-1}) were insufficient to reveal its double-lined nature and, because of the nearly identical line strengths, the radial velocity variations of the blended lines were so small as to escape detection.

IV. DISCUSSION

Luck and Bond's (1983) study of Ni and Fe in extremely metal-poor field red giants revealed a [Ni/Fe] versus [Fe/H] relationship very similar to the one we find for C and Fe. From solar abundances down to [Fe/H] $= -1.8$ Ni follows Fe, but as [Fe/H] decreases below -1.8 Ni becomes overabundant with respect to Fe. They point out that the *s*-process/Fe ratios show a slope change (of the opposite sense) at the same [Fe/H] (Luck and Bond 1981) and remark "that a new source of nucleosynthesis appeared at the time (still during galactic halo evolution) when [Fe/H] had risen to -1.8. We are tempted to identify this new source either with the first appearance of the longer lived Type I supernovae, or with a change in the stellar mass function such that very massive stars were no longer favored."

The evidence we find of a change of slope, also at [Fe/H] $= -1.8$, in the [C/Fe] versus [Fe/H] relation is another indication of the appearance of this new source. The sense of the change of slope in the [C/Fe] versus [Fe/H] relation is consistent with model predictions (Nomoto, Thielemann, and Wheeler 1984) that Type I supernovae are relatively inefficient C producers. This suggests that the new source of nucleosynthesis may be the first appearance of Type I supernovae, rather than a change of the stellar mass function.

More results are needed in order to better establish the relation between C and Fe in extremely metal-deficient dwarfs. Determination of C abundances for even more metal-deficient stars will be one way to do this; in cool dwarfs ($T_{eff} = 5000$ K) CH can be used to pursue C down to [Fe/H] = −3. Determination of C abundances from C I lines, so as to check the CH-based results, will also be worthwhile.

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