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RELATIVE ABUNDANCES IN METAL-POOR STARS.
II. THE CARBON-TO-IRON RATIO

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ABSTRACT

The abundance of carbon has been determined (or an upper limit established) by spectral synthesis of CH features in a dozen field dwarfs and subgiants of metallicities 1/5 to 1/100 solar. All program stars were selected from the Eggen high-velocity catalog, observed with the SAO echelle–Kron system at Mount Hopkins, Arizona, and analyzed by using model-atmosphere computations of broad-band colors and weak atomic lines. The CH features reveal that all these stars have essentially the solar carbon-to-iron ratio, given the ±0.2 dex uncertainty in the normalization to the solar value, and the ±0.14 dex uncertainty in an individual stellar carbon-abundance determination relative to others. We briefly discuss several implications of this uniformity for studies of the evolution of the Galaxy as a whole.

Subject headings: stars: abundances — stars: high-velocity

I. INTRODUCTION

Metallicities of stars are generally characterized by the value of their iron-to-hydrogen ratios, because the richness of the Fe I absorption spectrum of solar-temperature stars greatly facilitates the determination of the iron abundance. Elements in the adjacent mass range also have rather rich spectra, and so are frequently included in discussions of stellar elemental abundances. Interestingly enough, their proportions with respect to iron are generally rather constant, independent of the overall level of metallicity (see Pagel 1970; Peterson 1978*b*, *d*, and *e*, hereafter Papers I, III, and IV of this series).

However, the iron-peak elements are extremely minor constituents of normal stellar atmospheres. After hydrogen and helium, which account for over 99% of the mass of all but a few stars, the next most abundant elements are carbon, nitrogen, and oxygen. These are the most influential of the "metals" on the detailed course of stellar evolution (Simoda and Iben 1970; Iben 1974), and hence are the ones whose exact abundances are the most pertinent to studies of the age and evolution of the Galaxy (Audouze and Tinsley 1976).

It is not immediately obvious that the CNO elements should be found in constant proportion to the iron-group elements. Synthesis of the iron-peak elements requires high temperatures (Burbidge *et al.* 1957), and is assigned to explosive nucleosynthesis in massive stars (Arnett and Clayton 1970; Arnett 1973), or, less probably (Paper I), in supermassive objects (Wagoner 1968). The CNO group, on the other hand, may be produced under the quiescent conditions found in red giants of a few solar masses (Burbidge *et al.* 1957)—indeed, there are several classes of giants with strikingly anomalous carbon-to-iron ratios (see, e.g., Wallerstein 1973). Carbon may also be produced during hydrostatic phases of evolution of pre-explosive massive stars (Talbot and Arnett 1974)—to name but two of several possibilities (Audouze, Lequeux, and Vigroux 1975).

Because of the variety of plausible sites for CNO nucleosynthesis, CNO enrichment of the interstellar medium per se may have occurred on a variety of time scales. Hydrostatic CNO synthesis, within the very stars which subsequently explode to produce the iron-peak elements, implies the same short time scale for both CNO and iron peak. Because observational evidence favors the assignment of the bulk of iron-peak nucleosynthesis to a brief initial period, concurrent with the collapse of the galactic halo (Eggen, Lynden-Bell, and Sandage 1962), most CNO enrichment by this mechanism would have taken place prior to the formation of the galactic disk. On the other hand, CNO synthesis during the giant-branch evolution of stars $\leq 4\ M_{\odot}$ implies longer time scales, since the main-sequence lifetimes of such stars exceed 200 million years. CNO enhancement by this mechanism would be concurrent with the ongoing formation of stars in the galactic disk.

Therefore, in discussing observations which pertain to CNO enrichment of the interstellar medium, it is desirable to distinguish between stars of the halo and

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disk populations. To avoid the effects of internal evolution on surface carbon abundances, giants should be excluded from consideration.

The majority of determinations of the carbon abundance have been obtained for dwarfs of the disk population. The analysis of Sneden (1974) included three dwarfs of the old disk with metallicities at most 1/10 solar. For the mean value of the logarithm of the carbon-to-iron ratio in these stars with respect to that of the Sun, he obtained [C/Fe] = +0.1. Clegg (1977) found marginal overdeficiencies for nine disk dwarfs, all with metallicities greater than 1/10 solar. On the other hand, Hearnshaw (1974*a*, *b*, 1975), armed with a much larger sample, has argued that a significant change in [C/Fe] is observed in disk stars as a function of their metallicity. His result, that $[\mathrm{C/Fe}] = 0.5 * [\mathrm{Fe/H}] - 0.1$, has been questioned, however. Bell and Branch (1976) cannot reconcile it with their observations of C_2 in a number of disk dwarfs, which point toward a solar carbon-to-iron ratio in all but perhaps the most metal-rich. Peterson (1978*c*) finds evidence that Hearnshaw's [C/Fe] determinations in metal-rich stars are strongly dependent on the degree of formation of the CO molecule, in that when stars in which CO formation introduces large uncertainties are excluded, Hearnshaw's values yield $[\mathrm{C/Fe}] = (0.13 \pm 0.07) * [\mathrm{Fe/H}] - (0.15 \pm 0.02)$ for 44 disk dwarfs with $-0.75 \leq [\mathrm{Fe/H}] \leq 0.35$.

By comparison, carbon-abundance determinations for halo dwarfs are extremely sparse. About half a dozen dwarfs and subgiants with extremely low metallicities, highly eccentric orbits, or large motions out of the galactic plane have been analyzed; several are so cool that CO formation introduces substantial uncertainties (see Cohen 1968). Recent efforts to extend the sample (Sneden 1974; Clegg 1977) have largely been foiled by the faintness of hot halo dwarfs of low metallicity, a very scarce group of stars (Cayrel de Strobel 1976). This recent work is generally in accord with Pagel (1970), who, in summarizing the discordant results of previous studies (Baschek 1962; Cohen and Strom 1968; Cohen 1968), found little evidence for large carbon overdeficiencies.

The carbon-to-iron ratios presented here for a dozen halo stars derive from recent improvements in the speed of high-resolution spectrographic systems (Chaffee and Schroeder 1976). Using the echelle spectrograph (Chaffee 1974) and Kron camera (Kron, Ables, and Hewitt 1969) of the 60 inch (1.5 m) telescope of the Smithsonian Astrophysical Observatory of Mount Hopkins, Arizona, we have recorded photoelectrographic spectra of stars as faint as $B = 10.5$ with a resolution of 170 mÅ at 4300 Å. A total of 15 metal-poor stars whose kinematics (Eggen 1964) indicate that they are members of the halo population were observed in the region of the CH G band near 4300 Å. In accord with the above discussion, several additional considerations entered into the choice of stars. (1) All are either dwarfs or subgiants. (2) Their stellar effective temperatures all exceed 5200 K, so that the effects of CO formation on the free carbon density are negligible. (3) Metallicities of the stars cover a wide range, to enable us to elucidate the dependence of the carbon-to-iron ratio on metallicity.

Section II summarizes the observations and the method of determining stellar effective temperatures T_{eff}, gravities $\log g$, and metallicity values [Fe/H]. Section III describes how the carbon abundance was inferred from the comparison of observed CH spectra with synthetic ones computed from models of appropriate T_{eff}, $\log g$, and [Fe/H]. (Values of [C/Fe] for each star are listed in Table 1, along with these parameters.) In the final section, we discuss the various implications of our carbon results.

II. OBSERVATIONS AND DERIVATION OF STELLAR MODEL PARAMETERS

For all but one of the stars considered here, values of T_{eff}, $\log g$, and [Fe/H] were taken directly from Peterson (1978*a*, hereafter Paper AA I), the first paper of a series on abundance analyses of metal-poor stars, which gives the details of their derivation and the observational material. For HD 140283, not included in Paper AA I, values were taken from Peterson (1976) and Peterson and Carney (1978, hereafter Paper AA II).

The Cassegrain echelle spectra used here extend from 3900 to 4620 Å, with a reciprocal dispersion which varies from 1.36 Å mm^{-1} at the blue end to 1.62 Å mm^{-1} at the red end. The resolution of 2.5×10^4 was set by the slit width of 1″.2. Rapid conversion of the 16 plates to intensity spectra was facilitated by the "on-the-fly" densitometry techniques described by Peterson and Title (1975), at the Lockheed Solar Observatory. A relationship between residual intensity and equivalent width, based on unblended lines, was drawn up for each star (Paper AA II). Equivalent widths were generally measured for 80 or more lines weaker than 210 mÅ, scattered throughout the spectral range. An uncertainty of ±10 mÅ was typical, which corresponds to an error of ±0.20 dex in the abundance deduced from a single measurement of an equivalent width between 20 and 80 mÅ.

The $R - I$ colors of Carney (1978) were used to determine stellar effective temperatures. A comparison presented in Paper AA II, between spectral scan observations and theoretical flux distributions of metal-poor stars, shows that the conversion from $R - I$ to T_{eff} adopted in Paper AA I is in error: T_{eff} increases too rapidly as $R - I$ decreases. The use of the new relationship therefore reduces T_{eff} in the hot stars. For the 14 stars hotter than 5800 K in Paper AA I, the average reduction is 150 K, which in turn reduces $\log g$ by 0.15 dex and [Fe/H] by 0.12 dex. The net effect of all three on [C/Fe] is −0.04 dex (§ III), so no change was made in this paper to the values deduced for T_{eff}, $\log g$, and [Fe/H] in Paper AA I.

In that paper, stellar microturbulent velocities were taken to be 2.0 km s^{-1}, the average value derived from stellar Ti II lines. Surface gravities were determined to about ±0.25 dex from star to star by demanding equality between the abundances derived with respect to the Sun from neutral and ionized lines of iron and titanium.

Abundances were derived by comparing the measured width of each line with a theoretical computation of its strength. The calculations were performed at Kitt Peak National Observatory, using WIDTH, sister program to ATLAS (Kurucz 1970). The Sun was used as the abundance standard. Solar widths of Moore, Minnaert, and Houtgast (1966) were run through the HSRA model (Gingerich *et al.* 1971), assuming a solar microturbulent velocity $v_t = 0.5$ km s^{-1} (see, e.g., Foy 1972; Furenlid and Condal 1976; Blackwell *et al.* 1976). Species abundances relative to the Sun were found by subtracting the logarithm of the stellar abundance for each line from that of the Sun, and performing a straight average.

Fe I lines were excepted from this normalization procedure because of an apparent dependence of the oscillator strengths on lower excitation potential. The solar value of log (Fe/H) appropriate for the normalization of the stellar values of log (Fe/H) was inferred by using HD 106516, a bright dwarf of moderate metal deficiency which is similar to the Sun in temperature and surface gravity.

III. CARBON ABUNDANCES

Using the predetermined values of T_{eff}, log g, and [Fe/H], synthetic spectra of the region from 4290 to 4315 Å were computed for each star. Models from the Kurucz (1978) ATLAS grid were interpolated to the temperature and gravity deduced for each star, except the coolest, where the models of Peytremann (1974) were similarly used. The effect of metallicity on model structure proved to be negligible, because for all the stars considered here, hydrogen (rather than the metals) is the dominant contributor of electrons.

For the atomic lines in the synthesized region, laboratory measurements of oscillator strengths were used wherever possible. For the remainder, adjustments were made to the oscillator strengths of Kurucz and Peytremann (1975) until a good fit was obtained between the theoretical solar spectrum and the observed one (Delbouille, Roland, and Neven 1973).

For the CH parameters, however, no alteration was made to the laboratory values, which were taken from Lambert and Sneden (1977) and Sneden *et al.* (1978). The solar carbon abundance adopted was that of Lambert (1978), log (C/H) = −3.33.

In the stellar syntheses, all elements heavier than carbon were assigned the same deficiency as found for iron in Paper AA I. Since T_{eff} and log g were also taken from that source, the only free parameter in the stellar syntheses was the carbon abundance itself. Two or more syntheses were performed for each star, using various values of [C/Fe] near zero. These were superposed on the observed spectra; Figure 1 shows a typical example. From such a display a visual estimate was made of the value of [C/Fe] which provided the best fit across the entire spectral region. In spectra where the occurrence of CH features was unambiguous, [C/Fe] was readily determined, with an uncertainty of about ±0.10 dex due to the goodness of the fit alone. In several cases, the noise level of the spectra combined with the weakness of the CH lines allowed only an upper limit to be derived. One star with exceptionally poor observational material, +42 2667 (see Paper AA I), was excluded entirely; another, +25 1981, was dropped because of the large uncertainty in T_{eff} resulting from the lack of $R - I$ color. The results for the remaining stars of Paper AA I, plus HD 140283, are to be found in Table 1, where [C/Fe] is given along with T_{eff}, log g, and [Fe/H]. [C/Fe] is plotted versus [Fe/H] in Figure 2.

In addition to the uncertainty of ±0.10 dex arising from the goodness of the CH fit, the effect of errors in T_{eff}, log g, and [Fe/H] must be evaluated. To do this quantitatively, explicit calculations were made of the strength of CH features in ATLAS models with (T_{eff}, log g, [Fe/H], v_t) = (6000, 4.0, −1.0, 1.5), (6000, 4.0, −1.3, 1.5), (6000, 3.8, −1.3, 1.5), (6000, 4.0, −1.3, 2.0), and (5850, 4.0, −1.3, 1.5). These revealed that: (1) lowering T_{eff} alone by 150 K decreases [C/H] by 0.20 dex; (2) lowering log g alone by 0.5 dex increases [C/H] by about 0.12 dex; (3) decreasing model metallicity alone from 1/10 to 1/20

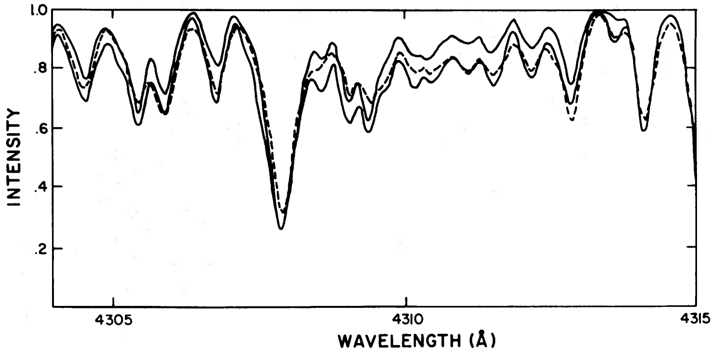

FIG. 1.—Observed and synthetic spectra of HD 94028 in the region of the CH band head. The dashed line is the observed spectrum. The full lines are the synthesized spectra, with [C/Fe] = −0.30 and +0.00 dex, degraded to the resolution of the observed spectrum.

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TABLE 1

CARBON ABUNDANCES IN METAL-POOR STARS

HD/BD	$T_{\rm eff}$*	log *g*	[Fe/H]	[C/Fe]
19445.............	5830	4.0	−1.82	−0.15
64090.............	5250	4.5	−1.60	−0.25
74000.............	6250	4.5	−1.80	< +0.3
84937.............	6250	4.0	−1.84	< +0.3
94028.............	5900	3.75	−1.25	−0.15
97916.............	6130	4.0	−1.15	+0.00
106516............	6250	4.5	−0.65	−0.05
108177............	6000	4.5	−1.55	+0.00
+34 2476.........	6250	4.0	−1.75	< +0.3
140283............	5600	3.3	−2.30	+0.10
+18 3423.........	6250	4.5	−0.80	+0.00
+20 3603.........	6130	4.5	−1.82	< +0.3
+26 3578.........	6000	3.25	−2.20	< +0.6
+17 4708.........	5900	3.75	−1.61	−0.10

* Except for HD 140283, all $T_{\rm eff}$ values were taken from Peterson 1978*a*. According to Peterson and Carney (1978), these values are too high for the hotter stars, by an average of 150 K above 5800 K. The net effect of this error is to reduce [C/Fe] by an average of 0.04 dex in those stars (§ III).

solar changes [C/H] by 0.03 dex at 6000 K; and (4) increasing v_t alone by 0.5 km s^{-1} lowers [C/H] by less than 0.02 dex for CH features weaker than 45 mÅ, by about 0.03 dex at 65 mÅ, and by about 0.10 dex at 100 mÅ.

In Paper AA I we have distinguished between two kinds of errors: random, affecting abundances for one star with respect to the other stars; and systematic, affecting the normalization of all stars uniformly with respect to the Sun at the origin. In Figure 2, the size of random errors is indicated by error bars attached to each point, and normalization errors by the error bars at the origin. The causes of each kind of error are outlined below.

The tendency for all stellar temperatures above 5800 K to be systematically too high by an average of 150 K (§ II) has little effect on [C/Fe] when [Fe/H] and log *g* are treated as free parameters. If all $T_{\rm eff}$ values are lowered by 150 K, all [Fe/H] values drop by 0.12 dex, based on the calculated sensitivity of Fe I abundances (Paper AA I). Simultaneously, the abundances deduced from Fe II and Ti II lines drop by 0.05 dex; the value of log *g* inferred from the ionization equilibrium then drops by about 0.15 dex. (Note that a change in log *g* has no direct effect on [Fe/H], since all the observed elements heavier than carbon are fully ionized; the change in neutral-species number density is exactly offset by the change in H$^-$ opacity.) According to the above, the overall effect of the temperature change is to decrease [C/Fe] by 0.04 dex.

We take ±0.2 dex as an estimate of the uncertainty arising from all sources, solar and stellar, in the normalization of stellar [C/Fe] values. As discussed in Paper AA II, a normalization uncertainty of about 0.15 dex is expected in the revised stellar values of [Fe/H] due to uncertainties in stellar microturbulent velocities and Fe I *gf*-values. This translates directly into an uncertainty in [C/Fe], for the stellar CH fit determines log (C/H). Subtraction of the solar carbon abundance gives [C/H]; subtraction of [Fe/H] then gives [C/Fe].

Similarly, the choice of the solar carbon abundance enters directly. The use of a value which differs from −3.33 by some amount would change all [C/Fe] values by the same amount in the opposite sense. Unlike the stellar syntheses, the solar CH synthesis is rather sensitive to the choice of solar model and the choice of microturbulent velocity, because of the strength of CH features in the solar spectrum. Further discussion may be found in Sneden *et al.* (1978) and references cited therein.

Random errors in [C/Fe] are somewhat smaller. Again, minor error is introduced by the random error in $T_{\rm eff}$ of ±80 K (Paper AA II). Possible variations in v_t from star to star are a significant source of error, however. Because of the weakness of the CH features in the stellar spectra (see Fig. 1), the choice of stellar microturbulent velocity has very little effect on [C/H], but does influence [Fe/H]. A random variation in v_t

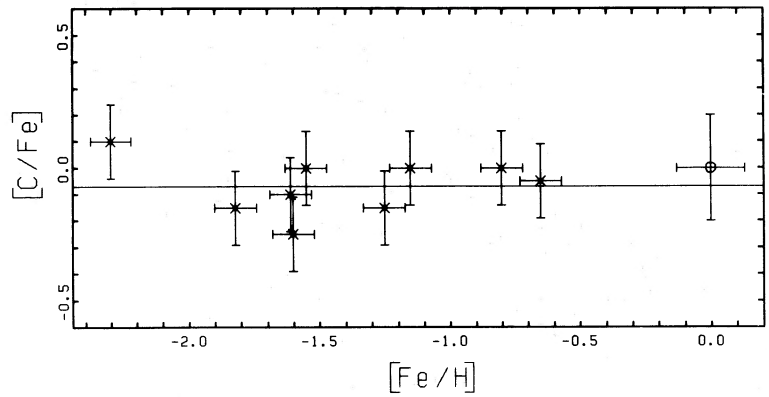

FIG. 2.—A plot of the [C/Fe] determinations of Table 1 versus the corresponding [Fe/H] values. Normalization error is shown by the error bars attached to the origin, which is the solar point by definition. Random errors are indicated by the error bars attached to individual stellar points. The line is drawn through the mean of the nine stellar points, at [C/Fe] = −0.07 dex.

of ± 0.3 km s^{-1} produces a random error of ± 0.06 dex in [Fe/H] and therefore in [C/Fe]. Combined with ± 0.10 dex due to fit uncertainties, and ± 0.07 dex due to random errors of ± 0.05 in log g, this yields ± 0.14 dex for the typical uncertainty of [C/Fe] in one star with respect to others. This value is completely consistent with the value ± 0.13 dex derived from the scatter of the nine [C/Fe] determinations about their mean.

IV. DISCUSSION

Averaging the nine [C/Fe] determinations in Table 1 and Figure 2 gives [C/Fe] = -0.07. When the corrected T_{eff} values of Paper AA II are employed, this average becomes -0.10. The normalization uncertainty of ± 0.2 in this result dominates the random uncertainty of ± 0.04 dex. It appears, then, that the unevolved stars of the halo have a solar carbon-to-iron ratio, as suggested by the previous determinations of [C/Fe] in halo dwarfs (§ I).

Large changes in [C/Fe] as [Fe/H] decreases are ruled out by our results. A least-squares determination of the coefficients of the linear relation [C/Fe] = $a + b *$ [Fe/H] yields $b = -0.01 \pm 0.08$ from the nine values plotted in Figure 2.

The kinematics of these nine stars may be used to rule out large changes in [C/Fe] as radial distance from the galactic center increases or decreases. Orbits of these stars have eccentricities ranging from 0.35 to nearly 1.00, and therefore traverse a considerable range of radial distances: orbits with the largest eccentricities extend from a few kiloparsecs to 20 or more. It is a reasonable assumption that the sample includes stars formed over a range of at least 10 kpc. Yet no star shows a deviation in [C/Fe] greater than 0.25 dex from the solar value.

Judging from this uniformity, it appears likely that the large departures from the solar carbon-to-iron ratio seen in various classes of giants (Wallerstein 1973) and in many planetary nebulae (Torres-Peimbert and Peimbert 1977; Shields 1978) are due to internal nucleosynthesis events during previous stages of evolution, as is generally believed.

The uniformity of the carbon-to-iron ratio in unevolved halo stars also strengthens somewhat the credibility of the majority of calculations of the post–main-sequence evolution of metal-poor stars, in which solar CNO ratios have been assumed. Although nitrogen appears to be overdeficient in some (but not all) metal-poor dwarfs (Pagel 1970; Sneden 1974; Clegg 1977; Sneden and Peterson 1977), it is less abundant than carbon even in the Sun. Oxygen, on the other hand, is more abundant than carbon in the Sun. Its importance as an opacity source is considerable. Moderate departures of the relative oxygen abundance do appear in certain globular-cluster giants, according to recent examinations of CO and forbidden O I spectral features (Wallerstein and Pilachowski 1978; Cohen 1978). Detailed oxygen-abundance analyses of these stars, and especially of unevolved halo stars, are desirable to further clarify the applicability of existing evolutionary calculations.

An additional ramification of the constant carbon-to-iron ratio seen in unevolved halo stars has to do with the cooling rate of the metal-poor interstellar medium, and its effect on the mass of a collapsing protostellar cloud. During certain stages of the collapse of such a cloud, the de-excitation of carbon atoms is the dominant cooling mechanism. Since the carbon-to-iron ratio appears to have been constant in the interstellar medium during the early epochs of Galaxy formation, clouds of low overall metallicity would necessarily have a reduced cooling rate. According to Larson and Starrfield (1971) and Kahn (1974), in clouds where the cooling rate is thus reduced, the critical mass required for a cloud of given density to collapse by self-gravitation is increased, which allows the maximum stellar mass to increase as well. The possibility remains, then, that among the metal-poor stars of the halo, stars existed of larger mass than could be formed at the higher metallicity levels characteristic of disk stars of the solar neighborhood.

The effect of an increased fraction of massive stars on the carbon-to-iron ratio should naturally be considered. Unfortunately, there is some theoretical uncertainty about the carbon-to-iron ratios produced in explosive nucleosynthesis. While iron is a product of the explosive event, carbon is a survivor; the amount of carbon released depends much more strongly on the configuration of the object prior to its explosion than on the exact nature of the explosion itself. Estimates of the abundance of carbon produced with respect to the light elements are obtained from the abundance distribution within the core of a massive star prior to its disruption.

To illustrate the current situation, let us examine the carbon-to-magnesium ratios indicated by two independent investigations of pre-explosive configurations. For the oxygen-to-iron ratio may be variable in metal-poor stars, as noted above, while the magnesium-to-iron ratio appears to be constant, as discussed in Paper III.

Arnett (1978) has followed the evolution of pure helium models through silicon burning, electron captures, and thermal disintegration, to reach generalized approximations to the pre-explosive configurations of cores of stars with a broad range of initial masses. These typically show a carbon-to-magnesium ratio which is within a factor of 2 of that of the Sun. However, Weaver, Zimmerman, and Woosley (1978) have followed the evolution of stars with initial masses 15 and 25 times solar. At the onset of core collapse, the carbon content of these models is deficient with respect to magnesium, by factors of 7 and 3, respectively, compared with the solar proportion. Results for other masses are not yet available.

Since the process of core expansion and mass ejection is poorly understood at present, the effect of the passage of the shock on the abundances of light elements has to be estimated. Theoretical expectations are that this will tend to build up the elements near the iron peak at the expense of the lighter elements, and efforts are under way to examine this in detail.

In spite of the theoretical uncertainties, the observational evidence strongly suggests that carbon was produced in approximately its solar proportion to the iron-peak elements during the collapse of the galactic halo. Given the similarity in [C/Fe] between the Sun and the unevolved halo stars, it appears unlikely that quiescent processes operating after the disk was formed could have contributed more than a factor of 2 to the solar carbon content. Additional carbon-to-iron determinations in young dwarfs of the galactic disk are needed to elucidate the subsequent contribution to the disk medium by such long-term synthesis processes.

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