The Most Metal-poor Stars. V. The CEMP-no Stars in 3D and Non-LTE

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Abstract

We explore the nature of carbon-rich ([C/Fe] 1D,LTE > +0.7), metal-poor ([Fe/H] 1D,LTE < -2.0) stars in the light of post 1D,LTE literature analyses, which provide 3D-1D and NLTE-LTE corrections for iron, and 3D-1D corrections for carbon (from the CH G-band, the only indicator at lowest [Fe/H]). High-excitation C I lines are used to constrain 3D,NLTE corrections of G-band analyses. Corrections to the 1D,LTE compilations of Yoon et al. and Yong et al. yield 3D,LTE and 3D,NLTE Fe and C abundances. The number of CEMP-no stars in the Yoon et al. compilation (plus eight others) decreases from 130 (1D,LTE) to 68 (3D,LTE) and 35 (3D,NLTE). For stars with $-4.5 < [\text{Fe/H}] < -3.0$ in the compilation of Yong et al., the corresponding CEMP-no fractions change from 0.30 to 0.15 and 0.12, respectively. We present a toy model of the coalescence of pre-stellar clouds of the two populations that followed chemical enrichment by the first zero-heavy-element stars: the C-rich, hyper-metal-poor and the C-normal, very-metal-poor populations. The model provides a reasonable first-order explanation of the distribution of the 1D,LTE abundances of CEMP-no stars in the $A(C)$ and [C/Fe] versus [Fe/H] planes, in the range $-4.0 < [\text{Fe/H}] < -2.0$. The Yoon et al. CEMP Group I contains a subset of 19 CEMP-no stars (14% of the group), four out of nine of which are binary, and which have large [Sr/Ba] 1D,LTE values. The data support the conjectures of Hansen et al. and Arendsen et al. that these stars may have experienced enrichment from asymptotic giant branch stars and/or “spinstars.”

Key words: early universe – Galaxy: formation – Galaxy: halo – nuclear reactions, nucleosynthesis, abundances – stars: abundances

1. Introduction

The CEMP-no sub-population of carbon-enhanced metal-poor (CEMP) stars, with [C/Fe] > +0.7 but no enhancement of heavy neutron-capture elements, arguably contains the most chemically primitive objects currently known. Indeed, among the 12 of the 14 metal-poor stars that have [Fe/H] < −4.5 and [C/Fe] > +1.0, 11 have [C/Fe] > +3.0, while three have values +1.6, <+0.9, and <+1.8 dex (see Tables 1 and 6 for details). At least 12 of the 14 belong to the CEMP-no group. It has been argued that the latter formed the objects which later became the rich heavy element abundances found in some very metal-poor stars...Similarly, the fraction of strongly C-enhanced ([C/Fe] > ~ +1.0) metal-poor stars is likely substantially less than the claimed >20% for [Fe/H] < ~2.0.” One should be alive to the possibility that the apparent characteristics of the CEMP-no stars might result from the 1D,LTE assumptions made in the analysis, rather than the potentially more realistic 3D and non-LTE (hereafter 3D,NLTE) ones. More generally, while 1D, LTE is currently a more precise formalism than 3D,NLTE (which is a much more challenging endeavor) it is the latter that will result in more accurate results.

The aim of the present work is to use literature-based corrections determined by adopting the assumptions of 3D, NLTE to correct carbon and iron abundances based on those of 1D,LTE. The outline of the paper is as follows. In Section 2 we address semantics of carbon richness relevant to the present work. Section 3 summarizes results from the literature for 3D–1D,LTE corrections for the analysis of both the G-band and Fe I lines and 3D–1D,NLTE corrections for Fe I lines. In order to address the problem that determination of NLTE corrections is not currently possible for the CH molecule, we also use abundances from infrared high-excitation C I lines to constrain the CH NLTE corrections in the range $-3.3 < [\text{Fe/H}] < -2.0$. In Section 4 we use these corrections to update the 1D,
**Table 1**

Major Milestones in the Study of CEMP-no Stars

| Milestone                                                                 | References |
|---------------------------------------------------------------------------|------------|
| Discovery of very metal-poor stars ([Fe/H] < −2.0) with anomalously strong CH λ4300 features | 1          |
| High dispersion abundance analyses reveal distinct C-rich subclassees      | 2, 3, 4, 5, 6 |
| Taxonomy: [C/Fe]_{CEMP} > +0.7; and subclassees CEMP-F, CEMP-s, CEMP-c/s, and CEMP-no  | 7, 8, 9     |
| Taxonomy: many CEMP-no stars have large supersolar abundances of N, O, Na, Mg, and Al relative to Fe, but not of the heavy neutron-capture elements (in particular, [Ba/Fe] < 0.1) | 10, 11     |
| Taxonomy: two distinct peaks in the [Fe/H] and A(C) histograms, populated principally by CEMP-no and CEMP-s stars | 10, 12, 13, 14, 15 |
| Taxonomy: essentially all CEMP-no stars with [Fe/H] ≤ −3.3 belong to the CEMP-no subclass | 10, 12      |
| Taxonomy: two subgroups of CEMP-no stars exist in A(C)-[Fe/H] space        | 16         |
| For CEMP-no stars, [C/Fe] increases strongly as [Fe/H] decreases           | 17         |
| Discovery of C-rich stars having [Fe/H] < −5.5 (assumed to be CEMP-no stars) | 18, 19, 20 |
| 14 halo stars currently known to have [Fe/H] < −4.5. At least 11 of them are C-rich | 11, 21, 22, 23, 24, 25, 26 |
| CEMP-no main-sequence turn-off stars with [Fe/H] < −4.0 have A(Li) < 2.0    | 14, 27     |
| The earliest two observed stellar populations formed by cooling of C-rich and C-normal clouds | 10, 28, 29, 30 |
| Suggested origin of CEMP-no enrichment: mixing and fallback stellar models (in minihalos) | 31, 32, 33, 34 |
| Suggested origin of CEMP-no enrichment: spinstars                          | 35, 36, 37 |
| Suggested origin of CEMP-no enrichment: mixing and fallback + spinstars    | 38         |
| Suggested origin of CEMP-no enrichment: binarity                           | 39         |
| Radial velocity monitoring supports CEMP-no binary fraction similar to that of C-normal halo stars | 10, 40, 41 |
| Most recent radial velocity monitoring reports that CEMP-no binary fraction is larger than C-normal halo star value | 42         |
| The fraction of CEMP-no stars increases as [Fe/H] decreases, and as Galactocentric distance increases | 43, 44, 45 |
| The ratio of CEMP-no to CEMP-s stars reported to increase with increasing Galactocentric distance | 46, 47, 48 |
| CEMP-no stars exist in the Milky Way’s dwarf ultra-faint galaxy satellites Bootes I and Segue 1 | 49, 50     |
| Discovery of Damped Lyα Systems with enhanced [C/Fe] in quasar Lyα forests | 51, 52, 53 |
| Discussion of CEMP-no stars within the framework of the formation of the first galaxies | 54, 55, 56 |

**References.** (1) Beers et al. (1992), (2) Sneden et al. (1994), (3) McWilliam et al. (1995), (4) Barbey et al. (1997), (5) Norris et al. (1997a, 1997b), (6) Bonifacio et al. (1998), (7) Aoki et al. (2002, 2007), (8) Beers & Christlieb (2005), (9) Ryan et al. (2005), (10) Norris et al. (2013), (11) Frebel & Norris (2015), (12) Aoki (2010), (13) Spite et al. (2013), (14) Bonifacio et al. (2018), (15) Caffau et al. (2018), (16) Yoon et al. (2016), (17) Rossi et al. (1999), (18) Christlieb et al. (2002), (19) Frebel et al. (2005), (20) Keller et al. (2014), (21) Frebel et al. (2015), (22) Caffau et al. (2016), (23) Aguado et al. (2018), (24) Aguado et al. (2018b), (25) Starkenburg et al. (2018), (26) Nordlander et al. (2019), (27) Frebel et al. (2008), (28) Frebel et al. (2007), (29) Schneider et al. (2012), (30) Chiaki et al. (2017), (31) Umeda & Nomoto (2003), (32) Iwamoto et al. (2005), (33) Nomoto et al. (2013), (34) Cooke & Madau (2014), (35) Meynet et al. (2006), (36) Maeder et al. (2015), (37) Maeder & Meynet (2015), (38) Takahashi et al. (2014), (39) Suda et al. (2004), (40) Starkenburg et al. (2014), (41) Hansen et al. (2016), (42) Arensen et al. (2018), (43) Frebel et al. (2006), (44) Carollo et al. (2012), (45) Lee et al. (2013), (46) Carollo et al. (2014), (47) Lee et al. (2017), (48) Hansen et al. (2019), (49) Gilmore et al. (2013), (50) Norris et al. (2010), (51) Cooke et al. (2011), (52) Cooke et al. (2012), (53) Carswell et al. (2012), (54) Becker et al. (2012), (55) Sarmento et al. (2017), (56) Sharma et al. (2018).

LTE Fe and C abundances of Yoon et al. (2016), Yong et al. (2013a), and a few more recent values, to place them within the 3D,LTE and 3D,NLTE frameworks. As foreshadowed by Asplund (2005) the changes are large, and in Section 5, following Yong et al. (2013b), we address their effect on the metallicity distribution function (MDF) and the fraction of CEMP (principally CEMP-no) stars in the range [Fe/H] < −3.0. For completeness, Section 6 discusses some uncertainties of the present work, while Section 7 addresses 1D,LTE abundances of the light elements Na, Mg, Al, and Ca, together with the heavy neutron-capture elements Sr and Ba, and their implications for the nature of the CEMP-no stars. In Section 8 we present a toy model that seeks to explain the CEMP-no stars in the abundance range −4.0 < [Fe/H] < −2.0 in terms of the coalescence of gas clouds of C-rich material of the second generation ([Fe/H] < −5.0, [C/Fe] ≥ +1.0), and those of the C-normal stars of the canonical halo population ([Fe/H] > −4.0, [C/Fe] = 0.0). Section 9 summarizes our results.

### 2. The Semantics of Carbon Richness

Just what does one mean by carbon richness? In almost all discussions based on the analysis of the G-band strength in the spectra of metal-poor stars with [Fe/H] ≲ −3.0, the framework is based on 1D,LTE assumptions, and a star is C-rich if it has an abundance [C/Fe]_{1D,LTE} > +0.7 (following Beers & Christlieb 2005 and Aoki et al. 2007). If, however, 1D,LTE-based results were to overestimate carbon abundances by, say, 0.7 dex, stars “observed” at this limit would in reality have the solar relative carbon abundance. If one is interested in abundances relative to the Sun, it thus follows there is a problem in defining an abundance limit based on a formalism containing systematic errors that are a function of chemical abundance. It would be better to choose an independent limit relative to the solar abundance that would be useful when seeking to compare stellar overabundances with, for example, overabundances that might be observed in other fields, such as gaseous nebulae and far-field cosmology, and also theoretical models of stellar, galactic, and cosmological formation and evolution.

Insofar as we shall be discussing carbon and iron abundances determined using different assumptions we adopt the following definitions. As noted above, [Fe/H]_{1D,LTE} and [C/Fe]_{1D,LTE} refer to values determined assuming 1D,LTE, [Fe/H]_{3D,LTE} and [C/Fe]_{3D,LTE} assume 3D,LTE, and [Fe/H]_{1D,NLTE} and [C/Fe]_{3D,NLTE} adopt 3D,NLTE. [Fe/H] and [C/Fe] are used generically. Finally, we adopt a generic carbon overabundance limit for all of these cases that somewhat arbitrarily defines carbon richness as [C/Fe] > +0.7 as the independent limit.
In order to convert the available 1D,LTE carbon and iron abundances of very metal-poor stars to include 3D and NLTE effects, we seek corrections of the form \( \Delta A(X)_{3D,\text{NLTE}} - A(X)_{1D,\text{LTE}} = A(X)_{1D,\text{NLTE}} - A(X)_{1D,\text{LTE}} \) for analyses of the CH G-band \((X = C)\) and Fe lines \((X = Fe)\).\(^4\) The enormous computational challenge to this requirement is highlighted by the very small number of relevant papers available in the literature. Further, in most cases, one finds partial solutions involving changes between only 3D and 1D, assuming LTE \((\Delta A(X)_{3D,\text{LTE}} = A(X)_{3D,\text{LTE}} - A(X)_{1D,\text{LTE}})\), or between only NLTE and LTE, assuming 1D \((\Delta A(X)_{1D,\text{NLTE}} = A(X)_{1D,\text{NLTE}} - A(X)_{1D,\text{LTE}})\). As noted above, in the case of carbon abundances determined from analysis of the CH G-band, NLTE corrections are not currently possible. To cite Gallagher et al. (2016) “computing full 3D ... NLTE ... departures for molecular data ... has not been attempted in great detail because of the complexities involved.”

With this in mind we first discuss what is currently possible in the analysis of the G-band, together with results for Fe I lines. Following this, we consider the analysis of near-infrared high-excitation C I lines in metal-poor stars, in order to place constraints on the role of NLTE in determining \(A(C)_{3D,\text{NLTE}}\) values based on analysis of the G-band.

### 3.3D and NLTE Corrections for the G-band and Fe I lines

Literature information that we shall use is presented in Table 2, where Columns (1)–(3) contain the star or model name, \(T_{\text{eff}}\), and \(\log g\), respectively, while Columns (4)–(9) present \([Fe/H]_{3D,\text{LTE}}\), \([Fe/H]_{1D,\text{LTE}}\), \([Fe/H]_{3D,\text{NLTE}}\), \([Fe/H]_{1D,\text{NLTE}}\), \([C/H]_{3D,\text{LTE}}\), and \([C/H]_{1D,\text{LTE}}\). The final column contains source information.

There are nine cases for which CH corrections are available, from the work of Collet et al. (2006, 2007, 2018), Frebel et al. (2008), Spite et al. (2013), and Gallagher et al. (2016). Six of the nine cases are based on analysis of stars, while three are determined entirely from model atmosphere comparisons. The data are also plotted in Figure 2, where the upper panel (a) presents \(\Delta A(C)_{3D,\text{LTE}} = A(C)_{3D,\text{LTE}} - A(C)_{1D,\text{LTE}}\) versus \([Fe/H]_{1D,\text{LTE}}\). Red and green symbols refer to dwarfs and giants (defined here to have log g larger or smaller than 3.35), respectively. The full line in the figure represents the linear least-squares best fit to the data, which is given by: \(\Delta A(C)_{3D,\text{LTE}} = 0.087 + 0.170 [Fe/H] (9 \text{ points, with } \text{rms} = 0.24)\).

Further literature data are available that provide 1D,LTE corrections of Fe I. Results from the work of Amarsi et al. (2016), Collet et al. (2006, 2007, 2018), Ezzeddine et al. (2017), and Frebel et al. (2008) are presented in Columns (4)–(7) of Table 2, where there are 22 stars, all having 1D,NLTE–corrections; seven have 3D,LTE information and four have 3D,NLTE data.

The 3D–1D,LTE and 1D,NLTE–LTE corrections for Fe are plotted in Figure 2, panel (b) as a function of \([Fe/H]_{1D,\text{LTE}}\). The panel also presents linear and quadratic least-squares lines of best fit, the equations for which are: \(\Delta [Fe/H]_{1D,\text{LTE}} = [Fe/H]_{1D,\text{LTE}} - [Fe/H]_{1D,\text{LTE}} = 0.013 - 0.011 [Fe/H]_{1D,\text{LTE}} + 0.019 [Fe/H]_{1D,\text{LTE}}^2\) (22 points, with \(\text{rms} = 0.09\)) and \(\Delta [Fe/H]_{1D,\text{LTE}} = [Fe/H]_{1D,\text{LTE}} - [Fe/H]_{1D,\text{LTE}} = 0.061 + 0.053 [Fe/H]_{1D,\text{LTE}}\) (7 points, with \(\text{rms} = 0.02\)). We conclude this section with two comments. First, as the reader can confirm from inspection of panel (b) of Figure 2, the (3D–1D,LTE) corrections are in the opposite sense to those for the 1D, (NLTE–LTE) case. Second, inspection of panels (a) and (b) of Figure 2 reveals that there appears to be no significant difference between the distributions of the dwarf and giant stars. In what follows, we shall assume that this is the case.
Table 2

| Star          | T_{eff} (K) | log g | \[Fe/H]_{1D,LTE} | \[Fe/H]_{1D,NLTE} | \[Fe/H]_{3D,LTE} | \[Fe/H]_{3D,NLTE} | A(C) | A(C) | Source |
|---------------|-------------|-------|------------------|-------------------|----------------|------------------|------|------|--------|
| HD 84937      | 6356        | 4.1   | −2.19            | −2.02             | −2.24          | −1.90            | ...  | ...  | 1      |
| HD 122563     | 4587        | 1.6   | −2.87            | −2.78             | −2.94          | −2.70            | ...  | ...  | 1      |
| HD 122563     | 4600        | 1.6   | −2.75            | ...               | −2.83          | ...              | 5.28 | 5.33 | 2      |
| HD 140283     | 5591        | 3.6   | −2.68            | −2.49             | −2.79          | −2.34            | ...  | ...  | 1      |
| G 64-12       | 6435        | 4.3   | −3.21            | −2.98             | −3.32          | −2.87            | ...  | ...  | 1      |
| CD −38° 245   | 4700        | 2.0   | −4.28            | −4.03             | ...            | ...              | ...  | ...  | 3      |
| CS 22940-037  | 4800        | 1.9   | −3.99            | −3.48             | ...            | ...              | ...  | ...  | 3      |
| CS 30336-049  | 4685        | 1.4   | −4.21            | −3.91             | ...            | ...              | ...  | ...  | 3      |
| HE 0057−5959  | 5200        | 2.8   | −4.28            | −3.83             | ...            | ...              | ...  | ...  | 3      |
| HE 0107−5240  | 5130        | 2.2   | −5.44            | ...               | −5.67          | 6.81             | 5.81 | 4     |
| HE 0127−5240  | 5050        | 2.3   | −5.47            | −4.72             | ...            | ...              | ...  | ...  | 3      |
| HE 0233−3043  | 6020        | 3.4   | −4.44            | −3.99             | ...            | ...              | ...  | ...  | 3      |
| HE 0557−4840  | 4800        | 2.4   | −4.86            | −4.48             | ...            | ...              | ...  | ...  | 3      |
| HE 1310−0536  | 5000        | 1.9   | −4.25            | −3.77             | ...            | ...              | ...  | ...  | 3      |
| HD 1327−2326  | 6190        | 3.9   | −5.78            | ...               | −5.95          | 6.84             | 6.13 | 4.5   |
| HE 1327−2326  | 6130        | 3.7   | −5.82            | −5.16             | ...            | ...              | ...  | ...  | 3      |
| HE 1424−0241  | 5140        | 2.8   | −4.19            | −3.73             | ...            | ...              | ...  | ...  | 3      |
| HE 2139−5432  | 5270        | 3.2   | −4.00            | −3.52             | ...            | ...              | ...  | ...  | 3      |
| HE 2239−5019  | 6000        | 3.5   | −4.18            | −3.76             | ...            | ...              | ...  | ...  | 3      |
| SD 0140+2344  | 5600        | 4.6   | −4.09            | −3.83             | ...            | ...              | ...  | ...  | 3      |
| SD 0109+1729  | 5811        | 4.0   | −4.63            | −4.23             | ...            | ...              | ...  | ...  | 3      |
| SD 1143+2020  | 6240        | 4.0   | −3.15            | ...               | ...            | 8.10             | 7.40 | 6     |
| SD 1204+1201  | 5350        | 3.3   | −4.39            | −3.91             | ...            | ...              | ...  | ...  | 3      |
| SD 1313−0019  | 5100        | 2.7   | −5.02            | −4.41             | ...            | ...              | ...  | ...  | 3      |
| SD 1742+2531  | 6345        | 4.0   | −4.82            | −4.34             | ...            | ...              | ...  | ...  | 3      |
| SD 2209−0028  | 6440        | 4.0   | −3.97            | −3.65             | ...            | ...              | ...  | ...  | 3      |
| 5131/2.2/−1.0 | 5131        | 2.2   | −1.00            | ...               | 7.52           | 7.40             | ...  | ...  | 7      |
| 5035/2.2/−2.0 | 5035        | 2.2   | −2.00            | ...               | 6.52           | 6.30             | ...  | ...  | 7      |
| 5128/2.2/−3.0 | 5128        | 2.2   | −3.00            | ...               | 5.52           | 4.80             | ...  | ...  | 7      |
| C-normal dwarfs | 5090−6500 | 4.0−4.5 | −3.00          | ...               | 5.95           | 5.55             | ...  | ...  | 8      |
| CEMP-no dwarfs | 5090−6500 | 4.0−4.5 | −3.00          | ...               | 6.80           | 6.50             | ...  | ...  | 8      |

Notes.

a Source: (1) Amarsi et al. (2016), (2) Collet et al. (2018), (3) Ezeddine et al. (2017), (4) Collet et al. (2006), (5) Frebel et al. (2008), (6) Spite et al. (2013), (7) Collet et al. (2007), (8) Gallagher et al. (2016, Section 4.2).

b SD 0140+2344 = SDSS J0140+2344, SD 1029+1729 = SDSS J1029+1729, SD 1143+2020 = SDSS J1143+2020, SD 1204+1201 = SDSS J1204+1201, SD 1313−0019 = SDSS J1313−0019, SD 1742+2531 = SDSS J1742+2531, SD 2209−0028 = SDSS J2209−0028.

c We adopt the Gallagher et al. (2016) result for low A(C) ~ 6.8, which is more pertinent to CEMP-no stars.

3.2. \([Fe/H]\) 3D,NLTE Corrections

The previous section presents \([Fe/H]_{1D,LTE}\) and \([Fe/H]_{1D,NLTE}\) corrections (relative to \([Fe/H]_{1D,LTE}\) abundances. What we would really like, however, are \([Fe/H]_{3D,NLTE}\) corrections. The very limited available data in Table 2 are from Amarsi et al. (2016) and are shown in panel (c) of Figure 2. The gray symbols are the \([Fe/H]\) (3D−1D),LTE and 1D, (NLTE-LTE) corrections from panel (b) of the figure, while the square symbols above them are the \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,LTE}\) corrections. A very significant result of panel (c) is that while the \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,LTE}\) corrections in (b) are positive and the \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,LTE}\) values, also in (b), are negative, the \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,LTE}\) corrections in (c) are positive and larger than \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,LTE}\) (from (b)), by 0.08−0.15 dex (with a mean value 0.12). This suggests that when 3D and NLTE effects are treated in a self-consistent manner the NLTE corrections dominate. In the absence of other information, in the following we shall assume that \([Fe/H]_{3D,NLTE}−[Fe/H]_{1D,NLTE} = 0.12.\)

3.3. High-excitation C1 Lines and 3D,NLTE Corrections for CH

As emphasized above, 3D,NLTE carbon abundances based on the analysis of the G-band are currently unavailable due to the intractability of the CH molecule to NLTE analysis. The near-infrared high-excitation C1 lines, however, are not affected by this problem. With excitation potentials \(\sim 7\) eV, these lines form deep in the stellar atmosphere, well below the outer layers where the 3D effects are significant. We now use literature C1 abundance analyses to obtain estimates of 3D,
NLTE corrections for CH-based values. By comparing the results for stars for which carbon abundances have been obtained from analyses of both the CH G-band and near-infrared C I lines, we then estimate the sense and size of the 3D, NLTE corrections for the CH-based carbon abundances discussed in the previous section.

3.3.1. Carbon Abundances from the Near-infrared C I Lines

Fabbian et al. (2009) present A(C)_{1D,NLTE} abundances for 43 metal-poor dwarfs and subgiants in the abundance range $-3.2 < [\text{Fe/H}] < -1.3$, based on analysis of the high-excitation C I 9094.8 and 9111.8 Å lines (EP = 7.49 eV). They also provide atmospheric parameters $T_{\text{eff}}$, log g, and [Fe/H]_{1D,LTE}, together with [C/H]_{1D,LTE} and [C/H]_{1D,NLTE} for two values of the Drawin scaling factor $\Delta T_{\text{eff}} = (0.0$ and 1.0). In what follows we shall adopt the average of these two values of [C/H]_{1D,NLTE}. Fabbian et al. (2009) also noted that the high-excitation potential of the C I lines would very likely lead to only small (3D–1D),NLTE corrections, given that these lines are formed sufficiently deep in the atmospheres of the stars to be insensitive to the 3D effects, which are significant principally in the outermost layers. This expectation is supported by the work of Dobrovolskas et al. (2013) from their comprehensive analysis of (3D–1D),LTE corrections for a large number of atomic species as a function of excitation potential, among other parameters. In particular their Figure 4 shows that for neutral carbon lines having EP = 6 eV, $\Delta$ (3D–1D),LTE = 0.04 dex. That is, effectively, $A(C)_{1D,NLTE} = A(C)_{1D,LTE}$. (For convenience, in this sub-section we shall refer to abundances based on C I lines as $A(C)$ and those on the CH features as $A(CH)$.)

To proceed further we also require CH-based carbon abundances for these stars. For 23 of the Fabbian et al. sample we obtained high-resolution, high signal-to-noise spectra from astronomical archives. Details of this sub-sample are presented in Table 3. Columns (1)–(4) contain the star name, $T_{\text{eff}}$, log g, and [Fe/H] from Fabbian et al. (2009), while Columns (5) and (6) present their values of $A(C)_{1D,LTE}$ and $A(CH)_{1D,LTE}$. Columns (10) and (11) of the table contain the signal-to-noise ratio (S/N) of the spectra and the archives from which the CH data were obtained.

To obtain $A(CH)$ we proceeded as follows. For each star we co-added multiple spectra as available, followed by continuum normalization. Using the atmospheric parameters of Fabbian et al. (2009), model-atmospheric spectra of each star were computed for several carbon abundances over the range 4305–4330 Å. We refer the reader to Yong et al. (2013a) for details of the technique. In brief, we used the code MOOG (Sneden 1973), as modified by Sobeck et al. (2011), together with the model atmospheres of Castelli & Kurucz (2003). In the lineist, the data for CH lines were provided by B. Plez et al. (2009, private communication; see MASSeron et al. 2014). Other pertinent data are: we adopted microturbulence $= 1.5 \text{ km s}^{-1}$ and [O/Fe] = 0.40, and note that the results are insensitive to the latter, given the relatively high effective temperatures of these dwarfs. The resulting abundances are presented in Table 3, where columns (7)–(9) contain $A(CH)_{1D,LTE}$, $A(CH)_{1D,NLTE}$, and $A(CH)_{3D,LTE}$, respectively. $A(CH)_{3D,LTE}$ was computed using the (3D–1D),LTE corrections presented in Section 3.1 above. For comparison purposes, we also present in Table 3 the CH-based literature abundances for CD $= 24^{h} \text{ 17504}$ from Jacobson & Frebel (2015), and G64-12 and G64-37 from Placco et al. (2016a). We note that the mean difference between our results and those of Jacobson & Frebel (2015) and Placco et al. (2016a) is $A(CH)_{1D,LTE} = 0.06$.

3.3.2. Estimating the 3D,NLTE Corrections Appropriate for the CH G-band

We now estimate the sense and size of 3D,NLTE corrections appropriate for the CH G-band analysis. In Figure 3 the top two
panels (a) and (b) present \( A(C)_{1D,LTE} \) versus \( A(CH)_{1D,LTE} \) and \( A(C)_{3D,LTE} \) versus \( A(CH)_{3D,LTE} \), respectively, for heuristic purposes, to give the reader a feeling for the changes brought about by 3D and NLTE effects. Panel (c) of the figure shows \( \Delta A(C) = A(C)_{3D,NLTE} - A(CH)_{3D,LTE} \) as a function of \( \text{[Fe/H]}_{1D,LTE} \). If the C1 and CH estimates of carbon abundances accurately and self-consistently include all 3D and NLTE effects, \( \Delta A(C) \) should be zero. Given (as discussed above) that \( A(C)_{1D,LTE} = A(C)_{1D,NLTE} \), any departure of \( \Delta A(C) \) from zero represents an estimate of the 3D NLTE corrections needed for these stars. The negative values of \( \Delta A(C) \) for G64-12 and G64-37 in Figure 3 indicate that their \( A(CH)_{3D,LTE} \) values are larger than \( A(CH)_{3D,NLTE} \). That is, a further negative correction is required to produce more accurate \( A(CH)_{3D,NLTE} \) values. The full red line in Figure 3 is the linear least-squares fit to the data (excluding stars BD \(-13\,3442\) and G48-29, for which only limits are available) which is given by \( A(C)_{3D,NLTE} - A(CH)_{3D,LTE} = 0.483 + 0.240 \text{[Fe/H]}_{1D,LTE} \) (24 points, with rms = 0.17) and which we take as the in-principal improvement necessary to \( A(CH)_{3D,LTE} \) to correct it to \( A(CH)_{3D,NLTE} \).

That said, given the weakness of the CH features and C1 lines in metal-poor dwarfs with \( \text{[Fe/H]} < -3.0 \) (see Fabbian et al. 2009; Jacobson & Frebel 2015; Placco et al. 2016a), in what follows we shall assume that this correction is not well-determined below \( \text{[Fe/H]} \lesssim -3.0 \), and make the conservative assumption that \( A(CH)_{3D,NLTE} - A(CH)_{3D,LTE} = 0.0 \), for all \( \text{[Fe/H]} \), and hence \( A(CH)_{3D,NLTE} = A(CH)_{3D,LTE} \). The reader should bear in mind that the 3D NLTE corrections we shall present in what follows are most likely less extreme than would be obtained by adoption of the equation in the previous paragraph.

4. Revised \( A(C) \) versus \( \text{[Fe/H]} \) and \( [\text{C/Fe}] \) versus \( \text{[Fe/H]} \) Diagrams

4.1. The Yoon et al. (2016) Sample of CEMP Stars

With the 3D–1D and NLTE–LTE corrections in hand, we now investigate their effect on the distribution of the CEMP-no stars in the \( (A(C), \text{[Fe/H]} \) and \( ([C/Fe], \text{[Fe/H]} \) planes. Figure 4 presents the data for the CEMP-no and CEMP-s objects compiled by Yoon et al. (2016),\(^7\) together with those for an additional recently reported eight CEMP-no stars presented in Table 4, and four stars identified in Table 6. The effects of the corrections to \( A(C), [\text{C/Fe}], \) and \( \text{[Fe/H]} \) are presented in the three rows of the figure. The uppermost row,

\(^{a}\) Here and in Section 3.3, \( A(C) \) and \( A(CH) \) refer to \( A(C) \) abundances determined from C1 lines and the CH G-band, respectively.

\(^{b}\) Source: (1) UVES, 266.D-5655(A), (2) UVES, 165.N-0276(A), (3) UVES, 95.D-0504(A), (4) UVES, 73.D-0024(A), (5) Results from Jacobson & Frebel (2015), (6) UVES, 86.D-0871(A), (7) UVES, 67.D-0806(A), (8) UVES, 71.B-0529(A), (9) UVES,170.D-0010(G), (10) HIRES,PI Melendez, (11) Results from Placco et al. (2016a).
panels (a) and (b), show data obtained using 1D,LTE for $A(C)_{1D,LTE}$ and $[C/Fe]_{1D,LTE}$ versus $[Fe/H]_{1D,LTE}$, respectively. Also shown in the top left panel (a) are the the ellipses containing the Groups I, II, and III of Yoon et al. (2016), together with the “high-carbon band” (horizontal orange line) and the “low-carbon band” (horizontal light blue line) of Spite et al. (2013), Bonifacio et al. (2015, 2018), and Caffau et al. (2018) (truncated on the right by the $[C/Fe] = +1.0$ locus). In these panels, (a) and (b), red and gray symbols refer to CEMP-no stars on the one hand, and CEMP-s stars on the other, and in what follows in the middle and bottom rows the symbol for each star will retain the same color as adopted in these uppermost panels. The full and dotted lines in all panels represent the loci of the $[C/Fe] > +0.7$ divide between C-normal and CEMP stars, and $[C/Fe] = 0.0$, respectively.

In the middle row, panels (c) and (d), we show the effect of (3D–1D),LTE corrections. In the left panel (c), the $A(C)$ distribution lies well below that of the 1D,LTE data, and at lower $[Fe/H]$, than in panel (a). Here the abscissa becomes $[Fe/H]_{3D,LTE}$ in both panels, while the ordinate is $A(C)_{3D,LTE}$ on the left and becomes $[C/Fe]_{3D,LTE} = [C/H]_{3D,LTE} - [Fe/H]_{3D,LTE}$ on the right. In both panels one sees that the distribution moves to lower values of $[Fe/H]$, while the carbon abundances also decrease. With these corrections, a significant number of stars now fall below the CEMP limit of $[C/Fe] > +0.7$: the number of CEMP-no stars has reduced from 130 in the top row to 68 in the middle row, a decrease of 48%.

The bottom row of Figure 4, panels (e) and (f), presents the changes when 3D,NLTE corrections are applied to the 1D,LTE data in the top row. To produce $[Fe/H]_{3D,NLTE}$ we use the 3D, NLTE corrections of Section 3.2, and for $A(C)_{3D,NLTE}$ and $[C/Fe]_{3D,NLTE}$ adopt corrections following the discussion in Section 3.3. In the context of carbon 3D,NLTE effects, we recall that in Section 3.3 a comparison of carbon abundances derived from the CH G band and from high-excitation C I lines leads to the conclusion that the (currently unknowable) NLTE effects on the G band appear not to increase CH-based abundances (and indeed hint that they will further decrease them; see Figure 3). Given the the extreme weakness of the CH and C I features and the sparseness of data for stars with $[Fe/H] < -3.0$, we choose to assume $A(C)_{3D,NLTE} = A(C)_{3D,LTE}$ for the purposes of the present discussion.

Inspection of the bottom panels (e) and (f) of Figure 4 shows that 3D,NLTE considerations have an enormous effect on the number of putative C-rich stars (exclusively on those in the Yoon Group II, which have lower $A(C)_{1D,LTE}$). The number of CEMP-no stars having $[C/Fe] > +0.7$ and $[Fe/H] < -2.0$ in the upper left panel (a) has decreased from 130 to 35 in the bottom left panel (e)—a reduction of 73%. Against this background it is worth noting that it is the number of CEMP-no, Group II stars that has decreased; the number of CEMP-no, Group III stars, which are considerably more carbon rich, is not affected.

Said differently, 3D,NLTE effects constitute the perfect storm for those who might wish to understand the carbon abundances of metal-poor stars by adopting results based on the 1D,LTE assumptions. First, 1D,LTE overestimates CH-based carbon abundances and, second, it underestimates iron effects on the stellar distribution? We shall discuss this further in Sections 7.1 and 8.

Figure 3. Comparison between the 3D and 1D carbon abundances determined from analysis of the CH G-band and C I high-excitation lines: (a) $A(C)_{1D,LTE}$ vs. $A(C)_{3D,LTE}$, (b) $A(C)_{1D,LTE}$ vs. $A(C)_{3D,LTE}$, and (c) $\Delta A(C) = A(C)_{3D,NLTE} - A(C)_{3D,LTE}$ as a function of $[Fe/H]_{1D,LTE}$. The red and green symbols represent stars for which CH-based abundances come from the present work and the literature, respectively. In (a) and (b) the full line represents the 1–1 relation, while in (c) the wide red line is the linear least-squares best fit to the data. See the text for a discussion.

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8 We draw the reader’s attention to the fact that the Yoon et al. (2016) model contains three components, while that of Caffau et al. (2018) has only two. The question one might ask is: how many components are required to best describe the stellar distribution? We shall discuss this further in Sections 7.1 and 8.
abundances (determined from Fe I lines) relative to those determined using 3D, NLTE. Both effects inflate [C/Fe], and in both the [C/Fe] versus [Fe/H] and the A(C) versus [Fe/H] planes the effects of the transformations are huge. A third effect is that in these planes the C-rich stars are seen against a considerably larger C-normal population, in which errors of measurement in both estimates of, say, 0.2–0.3 dex have the potential to move C-normal stars into the sparse [C/Fe]-rich region (i.e., into that of the Group II stars).

It has been suggested to the authors that the above results may be affected by the strong log \( g \) sensitivity of the Placco [C/Fe] corrections present in the Yoon et al. (2016) data compilation. That is, while the corrections are negligible for main-sequence stars, they are large (\( \sim +0.5 \) dex for objects toward the top of the giant branch). Examination of the Placco corrections for [Fe/H] = −3.0 (a representative value for the present discussion) against the [Fe/H] = −3.0, age = 12 Gyr isochrone of Demarque et al. (2004) shows that only above...
log $g = 2.0$ do they become larger than $\sim 0.05$. When we then replot our Figure 4 including only stars having $log g < 2.0$, we find that the areas covered by the stars are not significantly changed from the point of view of the present discussion of the 3D and NLTE predictions. In particular, the number of CEMP-no stars on the 1D,LTE panel is 66, which reduces to 40 for 3D,LTE, and 24 for 3D,NLTE—reductions of 39% and 64%, respectively (compared with 48% and 73% for the complete sample).

4.2. The Yong et al. (2013a) Sample of CEMP and C-normal Stars

We have also applied the above formalism to the literature sample of 190 extremely metal-poor stars of Yong et al. (2013a). An advantage of this sample is that it is not limited to only CEMP stars as is that of Yoon et al. (2016). It was used by Yong et al. (2013b) to place constraints on the MDF of metal-poor stars, and on the fraction of C-rich stars as a function of metallicity ([Fe/H]). Re-examination of the Yong et al. (2013a) sample has the potential to highlight the effects that the correction of abundances from 1D,LTE to 3D,LTE and 3D,NLTE has on these important relationships, not only on the C-rich stars but also on those that are C-normal.

Figure 5 presents $A(C)$ and [C/Fe] as a function of [Fe/H], where the layout in the figure is the same as that of Figure 4 and we have adopted the same 3D,LTE and 3D,NLTE corrections. The red symbols refer to CEMP-no stars that have carbon abundances based on detections yielding [C/Fe]_{1D,LTE} > +0.7 and [Ba/Fe]_{1D,LTE} < 0.0, the green symbols represent C-normal stars with either carbon detections or limits having [C/Fe]_{1D,LTE} < +0.7, and the gray circles stand for CEMP-s stars. As in our discussion of Figure 4, in the middle and bottom rows the symbol for each star retains the same color as adopted in the upper, 1D,LTE panels. For 1D,LTE-based abundances and [Fe/H]_{1D,LTE} < −2.0, there are some 88 C-normal and 28 CEMP-no stars. The latter represent a fraction of 24% of the total of CEMP-no plus C-normal stars.

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| Star | $T_{eff}$ | $log g$ | [Fe/H]_{1D,LTE} | [C/Fe]_{1D,LTE} | A(C) | [Ba/Fe] | Source
|------|-----------|---------|----------------|----------------|------|---------|--------|
| G 64-12 | 6463 | 4.26 | −3.29 | +1.07 | 6.21 | −0.06 | 1 |
| G 64-37 | 6570 | 4.40 | −3.11 | +1.22 | 6.45 | −0.36 | 1 |
| SD 1341+4741\a | 5450 | 2.50 | −3.20 | +1.00 | 6.23 | −0.73 | 2 |
| Bootes I-119 | 4770 | 1.40 | −3.33 | −2.42 | 7.52 | −1.00 | 3, 4 |
| Pisces II-10694 | 4130 | 0.80 | −2.60 | +1.58 | 7.48 | −1.10 | 5 |
| Segue I-7 | 4960 | 1.90 | −3.52 | −2.38 | 7.29 | <−0.96 | 6 |
| Segue 1 SD 1006+1602\b | 5484 | 3.30 | −3.60 | +1.20 | 6.03 | <−1.87 | 7 |
| Segue 1 SD 1006+1600\b | 5170 | 2.50 | −3.78 | −0.91 | 5.54 | <−2.25 | 7 |

Notes.
\a Corrected for stellar evolutionary effects following Placco et al. (2014) (http://www.nd.edu/~vplacco/carbon-cor.html).
\b Source: (1) Placco et al. (2016b), (2) Bandyopadhyay et al. (2018), (3) Gilmore et al. (2013), (4) Lai et al. (2011), (5) Spite et al. (2018), (6) Norris et al. (2010), (7) Frebel et al. (2014).
\c SD 1341+4741 = J134144+474128, SD 1006+1602 = SDSS J100652+160235, SD 1006+1600 = SDSS J100639+160008.

Figure 5 also permits an estimate of the 3D and NLTE effects on the fraction of CEMP-no stars in a sample containing both C-normal and CEMP-no stars. As in Figure 4, the middle and bottom rows refer to abundances determined assuming 3D, LTE and 3D,NLTE, respectively, and here too large fractions of 1D,LTE CEMP-no stars become C-normal when investigated in 3D and NLTE. For stars with [Fe/H]_{1D,LTE} < −2.0 in the bottom row, A(C)_{3D,LTE} versus [Fe/H]_{3D,LTE} there are some 108 C-normal and nine CEMP-no stars, leading to a fraction of CEMP-no stars of 8%, a very significant decrease compared with the 1D,LTE fraction of 24%. (As noted in the previous section, it is the number of Group II stars that is decreasing, while that of their Group III counterparts remains unchanged.)

A somewhat surprising result evident in the bottom panels is the number of stars well below [C/Fe]_{3D,NLTE} ≲ 0.0. For these stars, and ignoring those having only carbon abundance limits, [C/Fe]_{3D,NLTE} = −0.42 ± 0.03, with dispersion $\sigma = 0.27$ (82 objects). In comparison, for dwarfs with $−3.2 < [Fe/H] < −2.0$, Amarsi et al. (2019), see their Figure 1), from analysis of the infrared high-excitation C1 lines, report [C/Fe]_{3D,NLTE} values $\sim +0.1$ dex. While a full explanation of the present G-band abundances lies outside the scope of the present work, we make two comments. The first is that the effect appears to be gravity dependent, insofar as giants (log $g < 3.35$) in the present sample we find [C/Fe]_{3D,NLTE} = −0.49 ± 0.04 (61 stars) and for dwarfs (log $g > 3.35$) [C/Fe]_{3D,NLTE} = −0.24 ± 0.03 (21 stars). Further support for the higher value obtained for dwarfs is provided by the data for those in our Table 3. For the stars in the table with CH-based carbon abundances determined in the present work, and excluding stars with only limits, we find [C/Fe]_{3D,NLTE} = −0.18 ± 0.03. A possible explanation of the effect is that the giant abundances have been underestimated. The second point is that Gallagher et al. (2016) have reported that the A(C) 3D,LTE corrections are a function of A(C) (see our Section 6).

4.3. A Comment on the CEMP-no Status of CD −24° 17504, G 64-12, and G 64-37

CD −24° 17504, G 64-12, and G 64-37 were recently reclassified as CEMP-no stars by Jacobson & Frebel (2015) and

9 The carbon abundances have been corrected for evolutionary effects following Placco et al. (2014).
10 As in Section 4.1 we have excluded from our analysis stars having carbon abundances based on the C2 molecule.
Placco et al. (2016a). They are all extremely metal-poor, near-main-sequence turn-off stars with similar $T_{\text{eff}}$, log $g$, $[\text{Fe/H}]_{1\text{D,LTE}} (-3.41, -3.29, -3.11)$, and $[\text{C}/\text{Fe}]_{1\text{D,LTE}} (1.10, 1.07, \text{and } 1.12)$, together with $[\text{Ba}/\text{Fe}] = < -1.05, -0.36,$ and $-0.06$, respectively. The 3D,LTE and 3D,NLTE iron and carbon abundances of these objects, however, argue that all of them are C-normal, with an average carbon abundance of $\langle [\text{C}/\text{Fe}]_{3\text{D,LTE}} \rangle = 0.74$ and $\langle [\text{C}/\text{Fe}]_{3\text{D,NLTE}} \rangle = 0.26$. Some support for this conclusion is suggested by the fact that their discovery as metal-poor stars is based on their halo kinematics (Carney & Peterson 1981; Ryan et al. 1991), without knowledge concerning their abundance characteristics, i.e., they are an unbiased sample with respect to abundance.\textsuperscript{11} If one accepts that the CEMP fraction at $[\text{Fe/H}] = -3.2$ is $\sim 0.30$, based on 1D,LTE analyses (Lee et al. 2013; Yong et al. 2013b), the probability that all three of them should be CEMP stars is only $\sim 3\%$.

\textsuperscript{11} We implicitly assume that halo stars chosen by their extreme kinematics are drawn without bias from the same population as halo stars selected by their extreme metal deficiency.

\textbf{Figure 5.} Carbon vs. iron abundances for the data sample of Yong et al. (2013a), where the format is the same as that of Figure 4, with the exception that the green symbols represent 1D,LTE C-normal stars. The color for each individual star is as determined in the 1D,LTE uppermost panels. The thin full and dotted lines refer to the $[\text{C}/\text{Fe}]_{1\text{D,LTE}} = +0.7$ and 0.0 loci. See the text for a discussion.
One of the most intriguing aspects of the Yoon et al. (2016) \( A(C) \) versus \([\text{Fe/H}]\) diagram is that, while all of the CEMP-s stars belong to Group I and their Groups II and III contain only CEMP-no stars, there is a non-negligible fraction of CEMP-no stars within the Group I boundary. Inspection of our Figure 4 shows there are 19 such CEMP-I Group I stars,\(^4\) which represent 14% of the group. The obvious question is: why is the abundance of carbon relative to hydrogen higher by some \( \sim 1 \) dex in the CEMP-no, Group I stars compared with that of the majority of their counterparts in Groups II and III? For future reference, Table 5 presents details of the 19 CEMP-no, Group I stars.

To our knowledge, the significance of this subset of CEMP-no stars was first appreciated by Hansen et al. (2016b), who reported that five of their sample of 24 CEMP-no stars (HE 2019−1739, HE 1133−0555, HE 1410+0213, HE 1150−0428, and CS 22957−027) lie in or close to the “high-carbon band” first reported by Spitak et al. (2013) (in large part their “high-carbon band” is related to the Yoon et al. (2016) Group I). Hansen et al. (2016b) noted that three of these are binaries. They commented: “Should the majority (of this subset of CEMP-no stars) turn out to be members of binary systems ... and in particular if there are signs that mass transfer has occurred, this would lend support to the existence of AGB (asymptotic giant branch) stars that produce little if any s-process elements.” Arentsen et al. (2018) have further addressed the issue and reported that this CEMP-no subset has a “binary fraction ... of \( 47^{+15}_{-14} \)% for stars with higher absolute carbon abundance.” Inspection of our Table 5 shows that four out of nine CEMP-no, Group I (i.e., \( \sim 45\% \)) stars for which data are available are binary.

A further related conjecture is that the putative AGB stars of Hansen et al. may have been the 7 \( M_\odot \), initial rotational velocity 800 km s\(^{-1}\) spinstars of Meynet et al. (2006), which very nicely reproduce the light-element abundance patterns of the CEMP-no stars. Taking the potential binary-with-mass-transfer hypothesis further, if one assumes that the number of Group I CEMP-s stars is proportional to the number of putative polluting stars in the mass range (say) 2−6 \( M_\odot \) (see Lugaro et al. 2005), while the number of CEMP-no, Group I is proportional to that of those in the mass range (say) 6−8 \( M_\odot \) (e.g., Meynet et al. 2006), and further assumes that star formation followed the Salpeter initial mass function, one finds that the ratio of AGB stars in the 6−8 \( M_\odot \) range to those in the two mass ranges together is 0.09,\(^\text{13}\) similar to the observed fraction of 0.14 noted above, which CEMP-no, Group I stars contribute to the total Group I sample.

### 5. The MDF and the CEMP-no Fraction

The MDF of the Galaxy’s very metal-poor stars (VMP, \([\text{Fe/H}] < −2.0\)) is complicated by the fact that the sample is inhomogeneous, comprising several sub-populations. A topic closely related to the MDF is the size of the CEMP-no fraction, and its dependence on metal abundance. Any understanding of these will ultimately turn on a closer knowledge of the metallicity distribution functions of the halo’s several

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\(^{12}\) Guided by Figure 4, we required the CEMP-no stars to have \( A(C) > 7.1 \) and \( −3.9 < [\text{Fe/H}] < −2.0 \).

\(^{13}\) The fraction is somewhat sensitive to the lower-mass limit of the low-mass range. Had we chosen 1−6 \( M_\odot \), or 3−6 \( M_\odot \), the fraction would have changed from 0.09 to 0.03, or 0.17, respectively.
components. In this context, the two major C-rich groups, of CEMP-s and CEMP-no stars, provide an interesting challenge. We refer the reader to Papers III and IV of this series (Norris et al. 2013; Yong et al. 2013b), and references therein, for an effort to better understand the role of these sub-populations. Other important investigations include those of Carollo et al. (2012, 2014) and Lee et al. (2013, 2017). The question we shall address here is the role that 3D,NLTE corrections to 1D,LTE carbon and iron abundances play in our understanding of these matters.

5.1. MDFs

We use the formalism of Yong et al. (2013b) to examine the MDF of the Yong et al. (2013a) sample discussed in the previous section. C-rich stars ([C/Fe] > +0.7) were included only if an abundance was available in Yong et al. (2013a) (i.e., those with an abundance limit were excluded), while both detections and limits were included in the C-normal regime ([C/Fe] < +0.7). In the left panel of Figure 6, the logarithm (base 10) of the generalized histogram (adopting a Gaussian kernel having $\sigma = 0.30$ dex) is presented as a function of [Fe/H]$_{1D,LTE}$, while both detections and limits were included in the C-normal regime ([C/Fe] < +0.7). In the left panel of Figure 6, the logarithm (base 10) of the generalized histogram (adopting a Gaussian kernel having $\sigma = 0.30$ dex) is presented as a function of [Fe/H]$_{1D,LTE}$, where [Fe/H] is adopted as proxy for the total heavy-element abundance. As in our earlier work, we investigate the MDF for stars with [Fe/H] < −3.0, and to which we have applied sample completeness corrections. In the figure, the green-shaded areas pertain to the combination of the CEMP-no and CEMP-s subgroups, the gray-shaded areas refer to C-normal stars, and the small unshaded (upper) areas stand for stars for which the carbon abundance was not measured.

The top panel of the figure is based on 1D,LTE abundances, while the middle and bottom panels present 3D,LTE and 3D,NLTE results, respectively. The outstanding feature of the MDFs is the decreasing role of the C-rich stars ([C/Fe] > +0.7) when 3D and NLTE corrections are applied, as would be expected from inspection of Figure 5.

5.2. CEMP-no Fraction

In the right panel of Figure 6 we present the manner in which the fraction of CEMP-no stars increases as [Fe/H] decreases when one changes from 1D,LTE to 3D,LTE, to 3D,NLTE. Here we define the CEMP-no fraction as $N_{CEMP-no} / (N_{C-normal} + N_{CEMP-no} + N_{CEMP-s})$, where we include the CEMP-s stars in the equation on the assumption they were once C-normal stars, in order to obtain a more complete fraction. In practice, this has only a small effect in the present discussion, given there are relatively few CEMP-s stars with [Fe/H] < −3.0.

In this panel, the full lines represent the fraction of CEMP-no stars, while for comparison purposes the dashed line in each of the lower two subpanels is the 1D,LTE fraction presented in the topmost subpanel. In the top, middle, and bottom panels the fraction of CEMP-no stars with $-4.5 < \text{Fe/H} < -3.0$ are 0.30, 0.15, and 0.12, respectively. We also note that, while in
this figure all stars with $[\text{Fe/H}] < -4.5$ are C-rich, the relatively complete sample upon which this basis is based contains only three such objects. We recall from our Tables 1 and 6 that, at time of writing, some 14 stars are now known with $[\text{Fe/H}] < -4.5$, a large majority of which are C-rich (see Frebel & Norris 2015; Frebel et al. 2015; Caffau et al. 2016; Aguado et al. 2018a, 2018b; Starkenburg et al. 2018). In the present context, perhaps the most significant result one might take from the panel is that, when one includes 3D and NLTE corrections, a separation between the population of C-rich stars with $[\text{Fe/H}] < -4.5$ and that with $[\text{Fe/H}] > -4.5$ becomes clearer, and more significant.

6. Uncertainties

We alert the reader to some uncertainties implicit in the present work.

6.1. The CH 3D,LTE Corrections Are a Function of A(C)

Gallagher et al. (2016) report that G-band 3D,LTE corrections are a function not only of $[\text{Fe/H}]$, but also of A(C), and present a comprehensive investigation of 3D corrections for CEMP dwarfs on the ranges $-3.0 < [\text{Fe/H}] < -1.0$, 5900 K $< T_{\text{eff}} < 6500$ K, 4.0 $< \log g < 4.5$, $6.0 < A(C)_{\text{3D}} < 8.5$, and for two values of $C/O = 0.21$ and 3.98. They emphasize that the corrections are sensitive to the C/O ratio, and adopt the value of $C/O = 0.21$ as most appropriate for the CEMP-no stars. We note here that for CEMP-no stars the available abundance data suggest that $[\text{O/Fe}]$ increases linearly with $[\text{C/Fe}]$ (e.g., Norris et al. 2013, Figure 2), and therefore a constant value of C/O.

6.2. How Trustworthy Is the Drawin Scaling Factor $S_H$ Treatment of the Neutral Hydrogen?

In Section 3.3, the carbon abundances based on the analysis of high-excitation C1 lines adopted the formalism of Drawin to describe the influence of inelastic hydrogen atom collisions. Barklem et al. (2011), however, report that “Quantitatively, the Drawin formula compares poorly with the results of the available quantum mechanical calculations, usually significantly overestimating the collision rates by amounts that vary markedly between transitions.” That said, we recall here, from Section 3.3, the excellent agreement between the analyses of Fabbian et al. (2009) and Amarsi et al. (2019), the latter of which adopts “modern descriptions of the inelastic collisions with neutral hydrogen.”

6.3. Are Differences between Photometric and Spectroscopic $T_{\text{eff}}$ Values a Problem?

An evergreen uncertainty in the determination of chemical abundances based on 1D,LTE analyses is the differences that result when $T_{\text{eff}}$ values are based on different assumptions. Suffice it here to say that $[\text{Fe}/H]_{\text{1D,LTE}}$ values can differ systematically by values of order 0.3–0.4 dex between analyses that adopt photometric $T_{\text{eff}}$ values and those that use spectroscopically determined ones (see, e.g., Roederer et al. 2014, Table 17). This could be important in determining Group II, CEMP-no status, for example, in Figures 4 and 5.

7. The Abundances of Other Elements in the CEMP-no Stars

7.1. The Light Elements Na, Mg, and Al

A distinctive feature of the CEMP-no stars is that they also exhibit overabundances of Na, Mg, and Al, to varying degrees in size and from element to element, while only small (if any) differences are found in the relative abundances, $[X/\text{Fe}]$, on the range Si through to the heavy neutron-capture elements (see Frebel & Norris 2015 and references therein). Indeed, the interpretation of $[X/\text{Fe}]$ as a function of atomic number is key to an understanding of the origin of these stars (see Umeda & Nomoto 2003; Meynet et al. 2006; Heger & Woosley 2010; Nomoto et al. 2013; Takahashi et al. 2014; Maeder & Meynet 2015, and references therein). That said, insofar as discussed in Section 4 that many stars which under the 1D,LTE assumption were designated CEMP-no become C-normal when interpreted using 3D,NLTE, it is probably fair to say that we may not yet have a complete understanding of these abundance patterns. A potential example of this problem is the report by Yoon et al. (2016) that their Group II and Group III, CEMP-no stars have different Na and Mg distributions. A second interesting phenomenon, described in Section 4.4, is the existence of a ~15% subgroup of CEMP-no stars in their Group I, which principally comprises only CEMP-s stars. What is the light-element signature of these stars?

Figure 7 shows generalized histograms of 1D,LTE abundances for $[\text{Na/Fe}]$, $[\text{Mg/Fe}]$, and $[\text{Al/Fe}]$14 (which exhibits small if any variation, and is shown here only for comparison purposes). In each sub-panel the thicker red line pertains to CEMP-no stars, the thinner black one to C-normal objects, and the areas under both curves have been normalized to be the same. In the top three rows of the figure, results are presented for the Group I and III, CEMP-no stars, where from top toward bottom we consider Group III, Group I, and Group II + Group I, CEMP-no stars, respectively. (For the C-normal stars the same histogram is presented in all sub-panels of the same element.) The numbers of CEMP-no stars involved are presented in each sub-panel and, while they are small, one’s first impression is that the Na, Mg, and Al distributions are similar in both Groups I and III, at least insofar as significant overabundances are evident in all panels and, while more data are required, the figure suggests that Group I and Group III, CEMP-no stars have experienced similar enrichment pathways.

The bottom two rows present abundances for CEMP-no, Group II stars. The upper of the two rows is for $[\text{C/Fe}]_{\text{1D,LTE}} > +1.0$, while the lower is the result for $+0.7 < [\text{C/Fe}]_{\text{1D,LTE}} < +1.0$. Inspection of the two panels suggests a broader distribution of each of Na, Mg, and Al abundances (but not of Ca) in the upper row than in the lower one. The simplest interpretation of this difference is that the majority of the stars in the range $+0.7 < [\text{C/Fe}]_{\text{1D,LTE}} < +1.0$ does not have overabundances of Na, Mg, and Al, or that their carbon abundances have been underestimated. This could also explain, at least in part, the report by Yoon et al. (2016) that

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14 Figures 7 and 8 are based on data from Aoki et al. (2013), Bonifacio et al. (2015), Barklem et al. (2005), Christlieb et al. (2004), Cohen et al. (2008, 2013), Frebel et al. (2014, 2015), Hansen et al. (2015, 2016a), Hollek et al. (2011), Ito et al. (2013), Jacobson & Frebel (2015), Norris et al. (2010, 2013), Placco et al. (2014, 2016a), Plez & Cohen (2005), Roederer et al. (2014), Spite et al. (2018), Yong et al. (2013a), and Yoon et al. (2016).
the Group II and III CEMP-no stars have experienced different Na and Mg enrichment pathways.

It has been suggested to us that the Yoon et al. (2016) Group II stars are not CEMP-no stars, and have apparently large carbon abundances due to errors of measurement, and/or of the Placco et al. (2014) corrections. This is not obvious to us, given that the Group II stars with $[\text{C}/\text{Fe}] > +1.0$ are identified as CEMP-no by both Yoon et al. (2016) and Caffau et al. (2018) (see Figure 4), and that some of them have Na, Mg, and Al overabundances. Further work is needed to address this issue. The outstanding question for us is: why is the distribution of CEMP-no stars in Figure 4 so obviously non-uniform, leading Yoon et al. (2016) to identify two groups? We shall return to this in Section 8.

We conclude our discussion by noting the enigmatic result that, while overabundances of Na and Mg in the CEMP-no stars are clear in all panels that present these elements in Figure 7 (except for Mg in the bottom row), the histograms also

**Figure 7.** Generalized histograms for (1D,LTE) $[\text{Na}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Ca}/\text{Fe}]$ abundances (with Gaussian kernels of 0.30 dex). The red thicker lines are for the CEMP-no stars of Yoon et al. (2016) and Table 4 of the present work, while the thinner black lines represent the C-normal stars of Yong et al. (2013a). The legends contain the Group memberships of the samples, where the details in the leftmost panels apply to all of the panels in that row. In the legends in the bottom two rows, $[\text{C}/\text{Fe}]$ is the 1D,LTE value. The number in each panel indicates the number of stars included in the histogram.
appear to have a component that has close to the solar abundance ratio. More data are clearly required to confirm and address the reality and implications of this effect.

7.2. \([\text{Sr/Ba}]\) and the Nature of the CEMP-no, Group I Stars

How may one understand the CEMP-no, Group I stars? In Section 4.4 we noted the suggestion of Hansen et al. (2016b), supported by further work of Arentsen et al. (2018), that the binarity of a significant fraction of these stars might signal mass transfer in a system in which the AGB star did not experience s-process enhancement. We also pointed out that the ratio of Group I, CEMP-no to CEMP-s stars is consistent with higher masses for the putative AGB star enrichment of the CEMP-no, Group I stars than exists for their CEMP-s, Group I counterparts.

The question then is: do descriptions of massive AGB stars that produce primary carbon, but little or no s-process enhanced material, exist in the literature? The obvious answer is the extremely metal-poor spinstars of Meynet et al. (2006) and Frischknecht et al. (2010, 2012), which do not produce the s-process pattern, but rather overproduce Sr relative to Ba. In this context, Hansen et al. (2019) have proposed [Sr/Ba] as a parameter to distinguish between the various CEMP subclasses, based in part on the result of Frischknecht et al. that Sr is overproduced more relative to Ba than is observed in the CEMP-no and C-normal stars.

Against this background, Figure 8 presents [Sr/Ba] vs. Fe/H for CEMP-no stars of Group I (red star symbols) and III (red circles), together with CEMP-s stars (gray circles), based on data from the literature. The important result here is that, taken as a whole, the [Sr/Ba] values of the CEMP-no, Group I objects are larger than those of the CEMP-s stars. We also note that most of the [Sr/Ba] values for the Group III, CEMP-no stars are lower limits, and that their values could be as large as those of the Group I, CEMP-no stars. One might envisage scenarios involving spinstars and/or binarity.

8. A Toy Model for the CEMP-no Stars in the A(C), [C/Fe] versus [Fe/H] Planes

A fundamental problem in understanding the formation of the first stellar populations is the manner in which the initial gas clouds cooled to form stars. We refer the reader to Frebel et al. (2007), Schneider et al. (2012), Chiaki et al. (2017), and references therein, for details on the role of the various cooling mechanisms and pathways in which this may have proceeded. We present here a very simple toy model that seeks to explain the distribution of CEMP-no stars in the A(C), [C/Fe] versus [Fe/H] planes in the first few hundred Myr.

We proceed with the following set of assumptions.

1. The first generation of stars produced an initially carbon-rich environment in which further star formation proceeded along two principal pathways, one forming extremely carbon-rich objects (seen today as the C-rich stars with [Fe/H] $\lesssim -4.5$—the minority population), the other (later) one comprising C-normal stars (seen today as the bulk of stars with [Fe/H] $\gtrsim -4.0$—the majority population).

2. CEMP-no stars with [Fe/H] $\gtrsim -4.0$ formed following the coalescence of gas clouds of these C-rich and C-normal populations.

3. Our basic toy model assumption is that in each coalescence of C-rich and C-normal gas clouds their individual masses are determined by the mass function of the respective populations, which we shall assume to be the Salpeter mass function. This mass function is, of course, determined from the observation of stars, rather than of gas clouds but, that said, support for adopting a power-law mass function for the clouds has been reported by Elmegreen (2002). We further assume that the mass of the putative composite star is the sum of those of the two gas clouds. In order to proceed, we draw masses at random from the Salpeter mass function on the range $0.10 \lesssim M/M_\odot \lesssim 0.75$ for each of the carbon classes and accept a composite star if the sum of masses lies in the range $0.65 \lesssim M/M_\odot \lesssim 0.75$, which approximately covers that observed for the metal-poor stars with [Fe/H] $< -2.0$ discussed here.

4. We determine chemical abundances ([Fe/H], A(C), and [C/Fe]), on the range [Fe/H] $< -2.0$, as follows. For C-normal stars we adopt the MDF of Yong et al. (2013b) (transformed to the [Fe/H]$_{\text{3D,NLTE}}$ scale), and draw [Fe/H] at random from that distribution, and assume [C/Fe] = 0.0 (close to the 3D,NLTE values obtained by Fabbian et al. 2009 and Amarsi et al. 2019). For the C-rich population, here defined to lie in the range [Fe/H] $< -4.5$, and for which we have little information on the MDF, we assume individual values of [Fe/H] and [C/Fe] suggested by the observed values of the 10 C-rich stars for which we have information (i.e., in the ranges $-6.0 \lesssim [\text{Fe/H}] \lesssim -4.5$, and $+1.0 \lesssim [\text{C/Fe}] \lesssim +5.0$).

Using these concepts we attempt to learn only about the regions of the A(C) and [C/Fe] versus [Fe/H] planes that are occupied by the putative composite stars, and emphasize that these results should be seen as a zeroth-order approximation. The first assumption is that merging occurs between clouds of random mass (say $M_{\text{C,rich}}$ and $M_{\text{C,normal}}$) adopting a Salpeter mass function, one from each of the two parent populations, to form a composite CEMP-no star in the currently

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15 An exception to this rule, not included in the Yoon et al. (2016) compilation, is SDSS J0222-0313, which has [Fe/H] $= -2.65$ and [Sr/ Ba] = 1.02 (Caffau et al. 2018).
observable mass range $0.65-0.75 \, M_{\odot}$. We implicitly assume that there are reservoirs of gas having the required masses in the two parent populations, and that all of the merging is used to produce a well-mixed composite star, without mass loss. We then determine the chemical abundances of carbon and iron of each of the coalescing gas clouds. For the C-rich component we adopt a representative pair of values (e.g., $[\text{Fe/H}]_{3D,\text{NLTE}} = -5.0$, and $[\text{C/Fe}]_{3D,\text{NLTE}} = +3.0$). For the cloud from the C-normal population we determine $[\text{Fe/H}]_{3D,\text{NLTE}}$ at random from the modified Yong et al. (2013b) MDF over the range $-4.0 < [\text{Fe/H}]_{3D,\text{NLTE}} < -2.0$, and assume $[\text{C/Fe}]_{3D,\text{NLTE}} = 0.0$. Given $M_{\text{C-rich}}$ and $M_{\text{C-normal}}$, and these chemical abundances for the two clouds, the abundances of the composite star follow. We emphasize that with this approach we seek only to reproduce the observations of the CEMP-no stars with $[\text{Fe/H}] > -4.0$ in Figure 4. The results of a number of simulations are shown in Figures 9–11.

Figure 9 pertains to a C-rich parent population having $[\text{Fe/H}] = -5.0$ and $[\text{C/Fe}] = +3.5$, which coalesces with C-normal halo clouds as postulated above. On the left are the computed model results, labeled 3D,NLTE on the assumption that 3D,NLTE observational data would reproduce these results. On the right, labeled 1D,LTE, are the results when the model values are reverse engineered to produce values that would be obtained by a 1D,LTE analysis. The star symbols refer to the adopted values of the C-rich population, while the small symbols represent the composite model results. Figure 10 presents a considerably smaller carbon abundance of the C-rich parent population, with $[\text{Fe/H}] = -5.0$ and $[\text{C/Fe}] = +1.5$, which lead to considerably different abundance distributions compared with the simulation in Figure 9.

In Section 7.1, we noted that the distribution of CEMP-no stars in Figure 4 is obviously non-uniform, leading Yoon et al. (2016) to identify two groups of CEMP-no stars. In Figure 11, we present a comparison of our model results, which contains three simulations and their coaddition, with the Yoon et al. (2016) Groups I, II, and III boundaries—which we recall were defined in this plane. In the figure, simulated $A(C)_{1D,\text{LTE}}$ (left) and $[\text{C/Fe}]_{1D,\text{LTE}}$ (right) values are plotted as a function of $[\text{Fe/H}]_{3D,\text{NLTE}}$, where the format is similar to that of our Figure 4. In the upper left of each of the uppermost three rows in the figure are the assumed $[\text{Fe/H}]/[\text{C/Fe}]$ parameters of the C-rich population, and assuming these are also the 3D,NLTE values of that population, the large red stars represent the corresponding 1D,LTE values. The results of the coalescence model are presented as small red circles, the number of which is given by the isolated number in each of these panels.

Only one parameter, $[\text{C/Fe}]$ of the C-rich population, changes among the top three rows of the figure—from $+4.5$ to $+3.0$, to $+1.5$, and, at least to a first approximation, one can see a reasonable reproduction of the Yoon et al. Groups I, III, and II, respectively, in our Figure 4, proceeding from top toward bottom. Finally, the bottom row of the figure presents the simple co-addition of the data in the upper three rows, and should be compared with the uppermost row of Figure 4.

Perhaps the most interesting feature of the figure is that in the left column ($A(C)\,$ versus $[\text{Fe/H}]$) the morphology of the distribution of coalesced stars in the top panel ($[\text{C/Fe}]_{\text{C-rich}} = +4.5$), which is
similar to that of Yoon et al. (2016) Group III, has changed in the second panel from the bottom ([C/Fe]_{C-\text{rich}} = 1.5) to that of Yoon et al. (2016) Group II. This suggests that the morphology of the CEMP-no stars in this plane is determined by the distribution of carbon in the C-rich cloud population.

We regard the agreement between the model and the observational data as encouraging, given the ad hoc nature and simplicity of the assumptions of the model.

9. Summary and Desiderata

In Sections 3–6 we applied literature-based 3D,NLTE corrections to 1D,LTE Fe i iron and CH-based carbon abundances for stars with [Fe/H]_{1D,LTE} < −2.0, with a view to obtaining a better understanding of the nature and origin of the CEMP-no stars and what they have to tell us about the most iron-poor ([Fe/H] < −4.5) C-rich stars and their relationship to and interaction with the majority iron-poor ([Fe/H] > −4.0), carbon-normal halo population. Bootstrapping from carbon abundances based on 3D,NLTE analysis of the infrared high-excitation C II lines in the range −3.3 < [Fe/H] < −2.0, we showed that, although it is not currently possible to theoretically determine NLTE corrections for the CH molecule, the 3D,NLTE corrections are very likely not smaller (absolutely) than the 3D,LTE values. As emphasized by Asplund (2005), the resulting corrections are very large. For example, for the Yoon et al. (2016) compilation of C-rich stars, if one adopts [C/Fe] > +0.7 as a basic requirement of a CEMP-no star, the fraction of CEMP-no stars in the range −4.5 < [Fe/H] < −3.0 drops from the 1D,LTE result of 0.30 to the 3D,NLTE value of 0.12.

1. In Section 4.2, we found a large number of C-normal stars below [C/Fe]_{3D,NLTE} ≤ 0.0 for which the (CH-based) mean [C/Fe]_{3D,NLTE} abundance is ⟨[C/Fe]_{3D,NLTE}⟩ = −0.42 (82 objects), surprisingly low compared with the result of [C/Fe]_{3D,NLTE} ≈ +0.1 based on high-excitation C I lines in metal-poor dwarfs reported by Amarsi et al. (2019). This might be attributed to the fact that the present sample is dominated by giants. That is, for giants in the present sample we find ⟨[C/Fe]_{3D,NLTE}⟩ = −0.49 (61 stars) and for dwarfs ⟨[C/Fe]_{3D,NLTE}⟩ = −0.24 (21 stars). Also, analysis of C-normal dwarfs in our Table 3 finds ⟨[C/Fe]_{3D,NLTE}⟩ = −0.18 (21 stars).

Perhaps the 1D,LTE values for the giants have been underestimated. Alternatively, we noted that Gallagher et al. (2016) have reported that 3D CH-based carbon abundances are a function of At(C). While it could be a massive undertaking, it would be interesting to further investigate parameter space to better understand this effect.

1. It may be suggested that 1D,LTE [C/Fe] abundances are no longer of use. We would counter that this would be premature, and are of the view that, while comprehensive 3D,NLTE investigations of parameter space are required, further 1D,LTE surveys are important to discover further objects in order to constrain and calibrate the 3D,NLTE predictions.
Figure 11. Toy model simulations for $A(C)_{1D,LTE}$ (left) and $[C/Fe]_{1D,LTE}$ (right) vs. $[Fe/H]_{1D,LTE}$, respectively. The upper three rows present results obtained with the adopted $[Fe/H]/[C/Fe]$ pairs for the C-rich population shown in each row, while the bottom row contains the superset of the above upper three panels. The isolated number indicates the number of stars plotted in each panel.
It was noted in Section 4 that the change of CEMP-no status applies to the Yoon et al. Group II, CEMP-no stars, and not to their C-richer Group III counterparts. An important example of the Group II effect of the corrections on 1D, LTE CH-based carbon abundances is the status change of the three Group II classic metal-poor ([Fe/H] \sim -3.0) stars CD -24° 17504, G64-12, and G64-37, for which \(|[C/Fe]|_{1D,LTE} = 1.1| and \(|[C/Fe]|_{1D,LTE} = 0.3|\) (Section 4.3). In Section 7.1, a second enigmatic result for Group II objects arose in the discussion of 1D, LTE abundances of Na, Mg, and Al (which show large overabundances in the CEMP-no stars) where we found for the Group II stars that, while variations in the abundance histograms of these elements were seen in the abundance range \(|C/Fe|_{1D,LTE} > +1.0|, the effect is not so evident for stars with \(+0.7 < [C/Fe]_{1D,LTE} < +1.0|.

We also discussed the existence of a \(\sim15\%\) component of CEMP-no stars in the Yoon et al. Group I of CEMP stars, which is comprised principally of CEMP-s stars. In this subgroup of CEMP-no stars we found that the \([Sr/Ba]_{1D,LTE}\) values are larger than those of the majority of the CEMP-s stars.

1. Further work is needed to investigate to what extent the stars in this CEMP-no subgroup may be binary and/or the progeny of spinstars.

Finally, we presented a toy model that seeks to describe the formation of CEMP-no stars in the abundance range \(-4.0 \lesssim [Fe/H] \lesssim -2.0|\ in terms of the coalescence of pre-stellar clouds of the two populations that followed the chemical enrichment by the first zero-heavy-element stars, that is, the C-rich, hyper-metal-poor population and the C-normal, extremely metal-poor, halo stars having \([Fe/H] \gtrsim -4.0|.

The simplicity of the model, and the uncertainty of the Fe and C abundance distributions and mass function of the hyper-metal-poor population notwithstanding, the model produces abundance behavior in the \(A(C)_{1D,LTE}\) and \([C/Fe]_{1D,LTE}\) versus \([Fe/H]_{1D,LTE}\) planes not unlike that seen in the Yoon et al. (2016) Groups I, II, and III.

1. A more rigorous approach to this simple coalescence model would seem worthwhile.

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Appendix

The 14 Most Iron-Poor Stars

In Table 6, we present details for the 14 iron-poor stars currently known to have \([Fe/H] < -4.5|\ Columns (1)-(3) contain starname and coordinates, Columns (4)-(6) present atmospheric parameters \(T_{\text{eff}}\), log g, and \([Fe/H]\), Column (7) contains \([C/Fe]\), and source information is presented in the final Column. In this table the abundances assume 1D,LTE.

| Star, Source | RA (2000) | Dec (2000) | Teff (K) | log g (cgs) | [Fe/H] | [C/Fe] | Source |
|-------------|-----------|------------|----------|-------------|--------|--------|--------|
| SMSS J0313−6708 | 03 13 00.4 | −67 08 39.3 | 5125 | 2.3 | <−7.30 | >+4.90 | 1 |
| SMSS J1605−1443 | 16 05 40.2 | −14 43 23.1 | 4850 | 2.0 | −6.20 | +3.90 | 2 |
| SDSS J0815+4729 | 08 15 54.2 | +47 29 47.8 | 6215 | 4.7 | <−5.80 | >+5.00 | 3 |
| HE 1327−2326 | 13 30 06.0 | −23 41 49.7 | 6180 | 3.7 | −5.66 | +4.30 | 4 |
| SDSS J0023+0307 | 00 23 14.0 | +03 07 58.1 | 6224 | 4.8 | <−5.07 | >+3.20 | 5 |
| HE 0107−5240 | 01 09 29.2 | −52 24 34.2 | 5100 | 2.2 | −5.39 | +3.70 | 6 |
| SDSS J1035+0641 | 10 35 56.1 | +06 41 44.0 | 6262 | 4.0 | <−5.07 | >+3.50 | 7 |
| SDSS J1313−0019 | 13 13 26.9 | −01 19 41.4 | 5200 | 2.6 | −5.00 | ~<−3.00 | 8 |
| SDSS J0929+0238 | 09 29 12.3 | +02 38 17.0 | 5894 | 3.7 | −4.97 | +3.90 | 9 |
| SDSS J1742+2531 | 17 42 59.7 | +25 31 35.9 | 6345 | 4.0 | −4.80 | +3.60 | 10 |
| HE 0557−4840 | 05 58 39.3 | −48 39 56.8 | 4900 | 2.0 | −4.75 | +1.60 | 11 |
| SDSS J1109+1729 | 10 29 15.2 | +17 29 28.0 | 5811 | 4.0 | −4.73 | <−0.09 | 12 |
| HE 0233−0343 | 02 36 29.7 | −03 30 06.0 | 6100 | 3.4 | −4.68 | +3.50 | 13 |
| Pristine, 221.8781+9.7844 | 14 47 30.7 | +09 04 03.7 | 5792 | 3.5 | −4.66 | <+1.80 | 14 |

Notes.

1. Keller et al. (2014), 2. Nordlander et al. (2019), 3. Aguado et al. (2018b), 4. Frebel et al. (2005), 5. Aoki et al. (2006), 6. Aguado et al. (2019), Frebel et al. (2019), 7. Christlieb et al. (2004), 8. Bonifacio et al. (2015), 9. Frebel et al. (2015), 10. Caffau et al. (2016), 11. Norris et al. (2007), 12. Caffau et al. (2012), 13. Hansen et al. (2014), 14. Starkenburg et al. (2018).

b This star is included in the analysis in Section 4.1.
