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First stars X. The nature of three unevolved Carbon-Enhanced Metal-Poor stars ⋆

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ABSTRACT

Context. Carbon-Enhanced Metal-Poor (CEMP) stars are found in the Galaxy in large numbers at low metallicities. It is important to establish which astrophysical sites, and which processes, are responsible for their observed elemental abundance patterns.
Aims. We seek to understand the nature of the progenitors of three main-sequence turnoff CEMP stars, CS 31080−095 , CS 22958−042 , and CS 29528−041 , based on a detailed abundance analysis.
Methods. High-resolution ($R \sim 43000$) spectra obtained with VLT/UVES are used in order to obtain abundance estimates (or upper limits) for Li, C, N, O, and other important elements, as well as for the ^{12}C/^{13}C isotopic ratio in these stars.
Results. All three stars exhibit very low metallicities ($-3.30 \leq$ [Fe/H] ≤ -2.85) and moderate to high CNO abundances. CS 22958−042 is one of the most carbon-rich CEMP stars known ([C/Fe] = +3.2), while CS 29528−041 is one of the most nitrogen rich ([N/Fe] = +3.0); this star is one of the few known Nitrogen-Enhanced Metal-Poor (NEMP) stars. Oxygen is very high in CS 31080−095 ([O/Fe] = +2.35) and in CS 22958−042 ([O/Fe] = +1.35). All three stars exhibit [Sr/Fe] < 0, however, while CS 22958−042 also has no detectable Ba ([Ba/Fe] < −0.53), the other two stars show a moderate Ba enhancement ([Ba/Fe] ∼ 1). CS 22958−042 displays one of the largest sodium overabundances yet found in CEMP stars ([Na/Fe] = +2.8). CS 22958−042 has a carbon isotope ratio of ^{12}C/^{13}C = 9, similar to most other CEMP stars without enhanced neutron-capture elements. CS 31080−095 does not exhibit a large enhancement in ^{13}C; we estimate a lower limit of 40 for this star. CS 31080−095 and CS 29528−041 both have detectable lithium, with abundances below the Spite Plateau, A(Li) ∼ 1.7, while lithium is not detected in CS 22958−042 .
Conclusions. CS 22958−042 can be classified as a CEMP-no star, while the other two stars do not fall in any of the known classes of CEMP stars, thus either they constitute a new class or they are a link between the CEMP-no and CEMP-s classes. These stars show additional complexity in the chemical pattern of CEMP stars. The interpretation of the abundance patterns found in our stars leads us to conclude that current AGB stellar models are missing an extra-mixing process, similar to extra-mixing processes explored in the past for RGB stars.

Key words. Nucleosynthesis – Stars: abundances – Stars: Mixing – Galaxy: Halo – Galaxy: abundances

1. Introduction

A considerable fraction of very metal-poor stars with [Fe/H] ≤ −2.0, currently estimated to be on the order of 20%-25%,

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⋆ Based on observations made with the ESO Very Large Telescope at Paranal Observatory, Chile (program ID 165.N-0276(A); P.I.: R. Cayrel) exhibit strong enhancements (greater than 10 times the solar ratio) in their carbon (and often, nitrogen) abundances relative to iron (Beers & Christlieb 2005; Lucatello et al., in preparation). It appears that multiple nucleosynthetic pathways must be invoked in order to account for the production of this carbon in low-metallicity stars, almost certainly involving different astrophysical sites. Most of the stars in the range of metallicity $-2.6 \leq$ [Fe/H] ≤ -2.0 appear to be associated with carbon production from Asymptotic Giant Branch (AGB) companions that have transferred material to the star that is now observed (Aoki et al, in preparation). Lower metallicity stars, especially the extremely metal-poor stars with [Fe/H] < -3.0, may have their carbon produced by massive, rapidly-rotating Mega Metal-Poor (MMP; [Fe/H] < -6.0) stars (see, e.g., Hirschi et al. 2006; Karlsson et al. 2006; Piau et al. 2006). In order to better understand details of these various possible mechanisms, detailed investigations of the full array of elemental abundances in Carbon-Enhanced Metal-Poor (CEMP; [C/Fe] $> +1.0$ according to Beers & Christlieb 2005) stars are required.

Recent high-resolution spectroscopic studies of CEMP stars selected from the two large objective-prism surveys for low metallicity stars, the HK survey of Beers and colleagues (Beers et al. 1985, 1992; Beers 1999) and the Hamburg ESO survey of Christlieb and collaborators (Christlieb 2003), have shown them to exhibit a wide variety of elemental abundance patterns (e.g, Norris et al. 1997b,c; Bonifacio et al. 1998; Aoki et al. 2002a,b,c; Barklem et al. 2005; Beers & Christlieb 2005). Many of these stars (roughly 70% - 80% according to Aoki et al. 2003) exhibit strong s-process enhancements (CEMP-s), and are thought to be the result of AGB mass transfer to the presently observed companion (e.g., Aoki et al. 2002c; Lucatello et al. 2003; Sivarani et al. 2004; Barbuy et al. 2005). The observed radial-velocity variations among the CEMP-s stars indicate that most, if not all, are consistent with being members of binary systems (Tsangarides et al. 2004; Lucatello et al. 2005). Even among this homogeneous group of CEMP-s stars, the observed s-process patterns are not identical. For example, at a given metallicity, there exists a large scatter in their observed Sr, Ba, and Pb abundances, as well as in their carbon abundances (e.g., Aoki et al. 2002c; Sivarani et al. 2004; Barbuy et al. 2005) . This diversity presumably arises because of the range in masses of the star that underwent AGB evolution (see Herwig 2005 for a recent review), as well as details of its internal mixing, and possibly, variations in the level of dilution of material it has passed to the now-observed companion.

Other CEMP stars exhibit the presence of r-process enhancements (e.g., CS 22892-052; Sneden et al. 2003); Lucatello (private communication) reports the detection of several additional likely CEMP-r stars from an analysis of the HERES sample of Barklem et al. (2005). Another class of carbon-enhanced metal-poor stars are the CEMP-r/s stars, which exhibit the presence of neutron-capture elements associated with *both* the r- and s-process (e.g., CS 22948-027, CS 29497-034, Hill et al. 2000 and Barbuy et al. 2005; CS 29526-110, CS 22898-027, CS 31062-012, Aoki et al. 2002c; HE 2148-1247, Cohen et al. 2003; CS 29497-030, Ivans et al. 2005); the majority of the CEMP-r/s stars exhibit very high Pb abundances (the so-called "lead stars," see Aoki et al. 2002c and van Eck et al. 2003). The discovery of CS 22957-027 (Norris et al. 1997c; Bonifacio et al. 1998), which exhibits *no* enhancements of neutron-capture elements, followed by a number of other similar stars (Aoki et al. 2002a,b; Depagne et al. 2002; Plez & Cohen 2005; Frebel et al. 2005), led Beers & Christlieb (2005) to introduce the CEMP-no class of stars. As shown below, at least one of the three stars considered in the present paper is classified as a CEMP-no star. The other two stars in our study exhibit intermediate [Ba/Fe] ratios (greater than the solar ratio), but no other strong s-process-element enrichment. Thus, they fail the Beers & Christlieb (2005) criterion for the Ba ratios in CEMP-no stars (which requires [Ba/Fe] < 0.0), but they may well be related to this class. The origin of CEMP-no stars remains unclear at present. They could, for example, be the result of pollution by AGB stars which, for some reason, have been unable to activate the s-process but have still dredged up significant amounts of carbon to their outer atmospheres. Alternatively, the high CNO abundances in these stars could be the products of SNe; such models have been proposed at least in the case of HE 0107-5240 (Christlieb et al. 2002; Bonifacio et al. 2003) and HE 1327-2326 (Frebel et al. 2005; Iwamoto et al. 2005).

Measurements of C, N, and where possible, O abundances, provide crucial information on the nucleosynthetic and mixing history of the progenitors of CEMP stars. The $^{12}C/^{13}C$ ratio is also a sensitive indicator of the mixing processes experienced by carbon-enhanced stars. Lithium provides another valuable diagnotic tool. Lithium is not detected in most CEMP stars, but it is sometimes observed at a level lower than the Spite Plateau (Norris et al. 1997a; Aoki et al. 2002b); both observations suggest that some mechanism that introduced strong mixing (and burning of Li) may have taken place in the past. However, there are at least two known CEMP stars, LP 706-7 (Norris et al. 1997b) and CS 22898-027 (Thorburn & Beers 1992) that exhibit lithium abundances corresponding to the Spite Plateau. Perhaps surprisingly, both of these stars are neutron-capture-element-rich stars (Norris et al. 1997b; Aoki et al. 2002c), although significant radial-velocity variations have yet to be found in either star.

In this paper we present an elemental abundance analysis for three main-sequence turnoff CEMP stars, CS 31080−095 , CS 22958−042 , and CS 29528−041 , based on high-resolution, high signal-to-noise observations obtained with VLT/UVES. The main-sequence turnoff CEMP stars are of particular interest because their present evolutionary stage precludes the significant internal mixing that is expected for cooler CEMP stars, hence their atmospheres better preserve the nucleosynthetic signatures of their progenitors. We describe our observations in Sect. 2. Details of our abundance analysis procedures are reported in Sect. 3. In Sect. 4 we present the results. In Sect. 5 we examine possible scenarios for the nucleosynthesis histories of these objects, and compare them with the properties of previously observed CEMP stars. Conclusions are presented in Sect. 6.

Table 1. Log of observations

Star	Coordinates (2000)	Date y/m/d	MJD-24000.5	Exposure (sec)	Radial Velocity km s^{-1}	S/N at 430 nm
CS 31080-095	04:44:21.8 −45:13:57	2000-10-19	51836.2572450	2400	−43.64	93
		2000-10-19	51836.2864673	2400	−43.30	72
		2001-10-19	52201.3331806	3600	−43.76	82
		2001-10-20	52202.3388291	3000	−43.76	52
		2001-11-06	52219.2454194	3600	−43.66	92
		2001-11-09	52222.2693614	1000	−43.34	48
CS 22958-042	02:01:07.5 −57:17:07	2001-11-05	52218.1900217	3600	+165.21	48
		2001-11-05	52218.2360571	3600	+162.51	35
CS 29528-041	02:29:25.1 −18:13:30	2001-09-06	52158.3486878	5000	−285.1	50
		2001-10-21	52203.2220389	3260	−285.4	33
		2001-11-07	52220.2338976	3600	−285.0	37

2. Observations and data reduction

The spectroscopic data reported herein were obtained at the VLT-Kuyen 8.2m telescope, using the UVES spectrograph (Dekker et al. 2000), with an entrance slit width of 1 arcsec, yielding a resolving power of $R = 43000$. These observations were conducted as a part of the Large Programme 165.N-0276, P.I. R. Cayrel; the coordinates of our program stars and the log of observations are given in Table 1. Non-standard grating settings were used, both with dichroic # 1: 396+573, 396+850; the numbers are the central wavelength in nm in the blue and red arm respectively. The central wavelengths in the red arm were chosen in such a way that both settings would cover the Li doublet, effectively doubling the number of spectra that are suitable for study of this element in each star.

The data were reduced using the UVES context within MIDAS, which includes bias subtraction, flat fielding, wavelength calibration, and the merging of echelle orders. The continuum normalisation was performed with IRAF (using a cubic spline function) for the merged spectra. For a few lines that were either very weak, or of particular interest, we have used the spectra of the individual orders without merging them. Balmer-line profiles were checked using both single-order and merged spectra. Equivalent width measurements for unblended lines were obtained by fitting gaussian profiles, using the genetic algorithm code described by François et al. (2003).

Radial velocities (listed in Table 1) were measured from the positions of unblended lines in the range 380-450 nm. Multiple-epoch observations of CS 31080−095 (over a range of 386 days) and of CS 29528−041 (over a range of 45 days) do not reveal any detectable radial-velocity variations, while quite large (3 km s^{-1}) variations are found in CS 22958−042 over a timespan of only one hour. If this velocity variation is correct, CS 22958−042 may be another example of a very short-period binary similar to HE 0024-2523, as reported previously by Lucatello et al. (2003).

Broadband UBV photometry for CS 29528−041 was previously available from Norris, Ryan, & Beers (1999). For the other two stars, we obtained additional broadband photometry with the Danish 1.5m telescope and DFOSC instrument (Beers et al., in preparation). Near infrared JHK photometry for all three stars was available from the 2MASS catalog (Cutri et al. 2003). Estimates of interstellar reddening along the line of sight to each star were obtained from Schlegel, Finkbeiner, & Davis (1998). We also adopt Table. 6 from Schlegel, Finkbeiner, & Davis (1998), for relative extinctions for various band passes. The photometric information we make use of is listed in Table 2.

All three of our program stars have intermediate-band Strömgren photometry reported by Schuster et al. (2005), who used this information to obtain estimates of metallicity and photometric classifications. The classifications assigned by Schuster et al. for our stars were CS 31080−095: MS (CH), CS 22958−042: TO (CH), and CS 29528−041: TO, respectively; these classifications are consistent with our derived surface gravities, as described below.

3. Analysis

As a first-pass estimate of the effective temperatures for our program stars, we employed the Alonso, Arribas, & Martínez-Roger (1996) calibrations of $T_{\rm eff}$ with various colours for main-sequence dwarf stars. The results are listed in Table 2. The appropriate transformations between the different photometric systems necessary for use of the Alonso et al. calibrations were carried out as described in Sivarani et al. (2004). With the exception of temperatures based on the $B-V$ colour, which are open to possible problems due to the effect of molecular carbon absorption on the B-band flux, the colour-based estimates of $T_{\rm eff}$ agree with one another to within $\sim 125-200$K.

As an alternative, and likely better approach to estimation of temperature, we have also made determinations based on the Fe I excitation equilbrium. The effective temperatures derived from this procedure, also listed in Table 2, fall within 100K of the average of the colour-based estimates of $T_{\rm eff}$ (not including the $B-V$ temperature estimate). In particular, they agree very well (within 50K) with the $V-K$-based temperature, which is expected to be a superior colour-based estimator owing to the large leverage from the widely-separated wavelengths of the bands involved, and the fact that both the V and K bands are relatively free of potentially-corrupting molecular carbon features. We adopt the Fe I excitation equilibrium estimates of $T_{\rm eff}$ for the remainder of our analysis.

Estimates of the surface gravity, log g, were obtained by making use of the Fe I/Fe II ionisation equilibrium. The microturbulence was determined in the usual way, by requiring that the abundances derived from the Fe I lines be independent of their equivalent widths. The main-sequence gravity of CS 31080-095 that we obtain (log g = 4.50) is consistent with the classification by Schuster et al. (2005) of this star as a dwarf. The gravities we obtain for CS 22958-042 (log g = 3.50) and CS 29528-041 (log g = 4.00) are also consistent with the Schuster et al. classification of these stars as main-sequence TO stars. The slightly lower gravity of CS 22958-042 may indicate that it is a subgiant that has evolved slightly away from the main-sequence turnoff.

4. Abundances

The model atmospheres (`OSMARCS`; see Gustafsson et al. 2003 and references therein, with appropriate levels of C and N enhancement), the current version of the spectrum synthesis code (`turbospectrum`; Alvarez & Plez 1998), and the linelists that we employ are the same as described in previous papers of this series (Hill et al. 2000; Depagne et al. 2002; François et al. 2003). We also make use of the CH molecular linelist compiled by Plez (Plez & Cohen 2005) . The NH and C_2 molecular linelists are taken from the Kurucz database (`http://kurucz.harvard.edu/linelists/linesmol/`). Our complete set of derived elemental compositions is listed in Table 3. In this Table, errors on $\log(\epsilon)$ are assigned, for stars with multiple lines, based on the errors in the mean (i.e., $\sigma(\log(\epsilon))/\sqrt{(N)}$). No errors are listed for elements in which only one line was measured. Errors on [X/Fe] for each element, where we have taken into account additional sources of error due to adopted 100K errors in $T_{\rm eff}$ and 0.5 dex in $\log g$, are on the order of 0.10-0.15 dex. The solar abundances used here are the values from Asplund, Grevesse, & Sauval (2005).

Inspection of Table 3 reveals that one of our stars, CS 22958−042, has no detectable Ba ([Ba/Fe] < −0.53), and thus is classified as a CEMP-no star according to Beers & Christlieb (2005). The other two stars exhibit moderate enhancements of Ba ([Ba/Fe] = +0.77 and +0.97). These values of Ba enrichment fall below the level suggested by Beers & Christlieb for the CEMP-s classification ([Ba/Fe > +1.0), but they do satisfy the criterion for Ba-rich stars employed by Ryan et al. (2005), [Ba/Fe]> +0.50, which is also adopted by Aoki et al. (in preparation). It is worth noting that the Sr abundances in these two stars are quite low, [Sr/Fe] = −0.41 (CS 31080−095) and [Sr/Fe] = −0.20 (CS 29528−041). CS 31080−095 and CS 22958−042 are more carbon rich than they are nitrogen rich. In contrast, CS 29528−041 is far more nitrogen rich than it is carbon rich. In fact, it appears to be one of the most N-enhanced stars ([N/Fe] = +3.0) yet found among the CEMP class of objects. In the following subsections we consider the nature of the light elements, oxygen and other alpha elements, the odd-Z elements, the iron-peak elements, and the neutron-capture elements in our three program stars.

4.1. The Light Elements Li, C, N, and the $^{12}C/^{13}C$ ratios

We detect the Li I 670.7 nm doublet in both CS 31080−095 and CS 29528−041 (see Fig. 1); a lithium abundance A(Li) ~ 1.7 is derived for both of these stars. The Li feature is not detected in our spectrum of CS 22958−042 ; we derive an upper limit of A(Li) < 0.6 (for a 3σ detection). It would clearly be of interest to obtain higher-S/N spectra of this star in order to strengthen this limit.

Both CS 31080−095 and CS 22958−042 exhibit very large carbon enhancements, [C/Fe] = +2.75 and [C/Fe] = +3.15, respectively. The carbon abundance estimates are obtained using the average of those derived from the CH and C_2 features. In CS 29528−041 the C_2 lines are not detected; only the weak CH lines could be used for estimates of the carbon abundance in this star. Nitrogen abundance estimates for our stars are obtained from the CN 388.3 nm band (see Fig. 2). For CS 22958−042 and CS 29528−041 we also make use of the NH band at 336 nm for the nitrogen abundances. The NH lines and CN lines give slightly different abundances. Since the NH lines are noisier, we adopt the nitrogen abundance derived from the CN lines. The ^{13}CH lines at 401.9 nm (see Fig. 3) and the ^{13}C, ^{12}C 474.0 nm lines are used for obtaining estimates of the ^{12}C/^{13}C ratio. Only a weak lower limit on the ^{12}C/^{13}C ratio could be found for CS 31080−095 , while a clear determination of ^{12}C/^{13}C = 9.0 is found for CS 22958−042 . The high $T_{\rm eff}$ and moderate carbon enhancement in CS 29528−041 does not allow any useful limits to be placed on ^{12}C/^{13}C for this star, as the ^{13}C features are very weak.

4.2. Oxygen and other alpha elements

Estimates of oxygen abundances for our stars are derived from a LTE analysis of the O I 777.4nm triplet, which is known to be affected by NLTE (Kiselman 1991; Takeda 1994; Gratton et al. 1999; Kiselman 2001) and 3D effects (Asplund 2005). In CS 31080−095 the O I triplet lines are quite strong; we derive [O/Fe] = +2.35. We do not detect the O I 777.4 nm lines in CS 29528−041 , hence we can only obtain an upper limit of [O/Fe] < +1.4 (for a 3σ detection). Table 3 lists estimated NLTE O abundances for these three stars, using the corrections computed by Gratton et al. (1999).

Magnesium is overabundant by ∼ +0.65 dex with respect to iron in CS 31080−095 . In CS 22958−042 and CS 29528−041 [Mg/Fe] = +0.32 and +0.4, respectively, similar to most other very metal-poor stars. Silicon is overabundant by +0.05 to +0.15 dex in both CS 31080−095 and CS 22958−042 . Calcium is also overabundant, in all three stars, by from +0.2 to +0.4 dex.

4.3. The odd-Z elements

Sodium abundances for our stars are determined using the Na I D lines, which can be affected by NLTE. We have applied corrections for NLTE from Baumüller et al. (1998), as listed in their Table 2. The Na I D lines for CS 22958−042 exhibit a significant interstellar component, but are well separated from

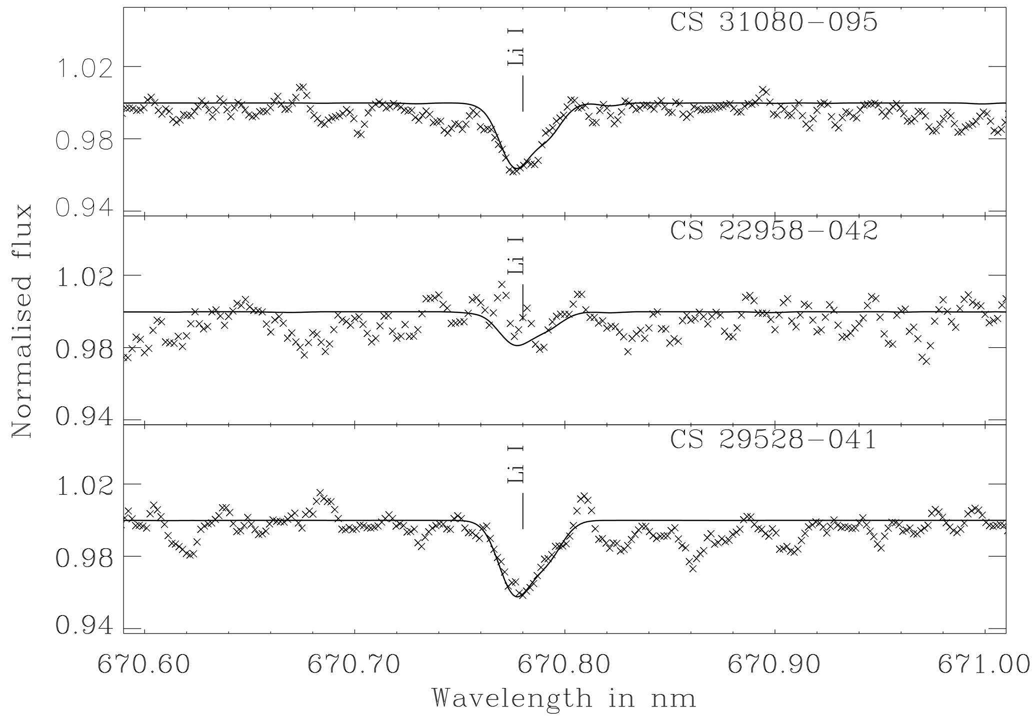

Fig. 1. The observed spectra of CS 31080−095 , CS 22958−042 , and CS 29528−041 in the region of the Li I 670.7 nm doublet are shown as crosses (x). Synthetic spectra in this region are represented by solid lines. Li is not detected in CS 22958−042 .

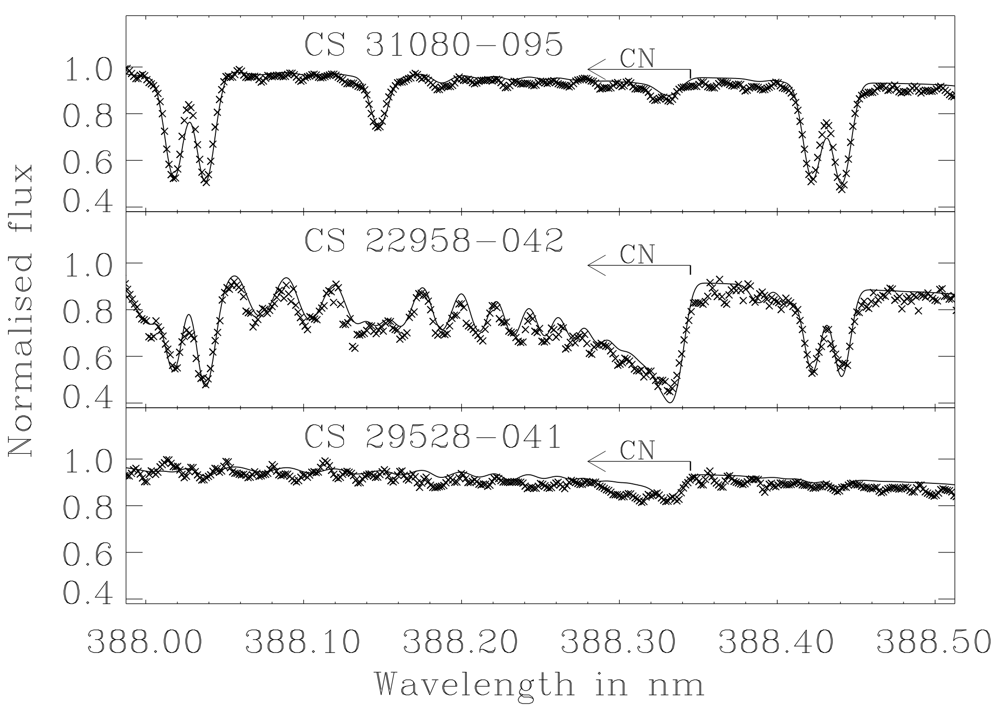

Fig. 2. The observed spectra of CS 31080−095 , CS 22958−042 , and CS 29528−041 in the region of the CN 388.3 nm band are shown as crosses (x), while synthetic spectra in this region are represented with solid lines. The strong CN bands in CS 22958−042 indicate a larger overabundance of nitrogen in CS 22958−042 as compared to CS 31080−095 . In CS 29528−041 the CN bands are weak, but the derived nitrogen abundances are high; this arises because of the lower carbon abundance and higher effective temperature in this star, as compared to the other two. CS 29528−041 and CS 22958−042 also exhibit detectable NH 336 nm bands (not shown).

Table 2. Photometry and adopted atmospheric parameters

Observable/parameters	CS 31080-095	CS 22958-042	CS 29528-041
V	12.989	14.516	14.60
$B-V$	0.521	0.479	0.42
$U-B$	−0.291	···	−0.19
$V-R$	0.317	0.294	···
$V-I$	0.617	0.614	···
$V-K$	1.397	1.303	1.292
$J-H$	0.272	0.227	0.314
$J-K$	0.350	0.302	0.339
E(B−V)	0.009	0.025	0.030
$T_{\rm eff}\,(B-V)_0$	5671	5897	6378
$T_{\rm eff}\,(V-R)_0$	5964	6221	···
$T_{\rm eff}\,(V-I)_0$	6020	6146	···
$T_{\rm eff}\,(R-I)_0$	6224	6135	···
$T_{\rm eff}\,(V-K)_0$	6077	6344	6199
$T_{\rm eff}\,(J-H)_0$	5940	6277	5947
$T_{\rm eff}\,(J-K)_0$	5822	6156	6266
$T_{\rm eff}$ (Fe lines)	6050	6250	6150
Adopted $T_{\rm eff}$	6050	6250	6150
Adopted log g	4.50	3.50	4.00
Adopted [Fe/H]	−2.85	−2.85	−3.30
Adopted ξ_t (km s^{-1})	1.0	1.5	1.3

it due to the high radial velocity of this star. In CS 29528−041 the Na I D1 line merges with the interstellar Na I D2 line, so we derive the Na abundance from the D2 line alone. Aluminum is underabundant in all three stars. The suggested NLTE corrections of +0.65 dex, as prescribed by Baumüller and Gehren (1997), are applied to all three stars.

4.4. The iron-peak elements

The derived abundances of titanium, scandium, vanadium, chromium, manganese, cobalt, and nickel are similar in all three stars, and close to the values reported for halo stars in the same metallicity range by previous workers (e.g., Cayrel et al. 2004).

4.5. The neutron-capture elements

We derive strontium abundance estimates for our stars from the Sr II 407.7 nm and 421.5 nm lines. All three of our program stars exhibit Sr underabundances, from −0.2 to −0.4 dex. A weak Y II line at 377.4 nm is also detected in CS 31080−095, from which we derive [Y/Fe] = −0.35. Barium is moderately overabundant in both CS 31080−095 and CS 29528−041, while it appears to be quite low in CS 22958−042. Barium abundances were estimated from the Ba II 455.4 nm and 493.4 nm lines. Due to the underabundance of barium in CS 22958−042 we could not detect any Ba II lines, and we derive a upper limit of [Ba/Fe] < −0.53 (for a 3σ detection). We have adopted the hyperfi ne splitting provided by McWilliam (1998) for Ba II; we have assumed a solar isotopic fraction for Barium.

5. Discussion

Here we consider the derived abundances and carbon isotope ratios for our three program stars, and compare them with those observed in other CEMP stars. Table 4 lists the available information for CEMP-no, CEMP-s, and CEMP-r/s stars. Two moderately Ba-enhanced stars in our sample are classifi ed as a fourth group called CEMP-no/s stars. We fi rst discuss the derived carbon and nitrogen abundances for our CEMP stars. We next describe the nature of oxygen, followed by a discussion of sodium, magnesium, and other heavier elements. The variation of the carbon isotope ratio ^{12}C/^{13}C with derived lithium abundance in these stars is then considered.

5.1. Carbon and nitrogen abundances in CEMP stars

CS 31080−095 and CS 22958−042 exhibit strong enhancements in both carbon and nitrogen, similar to most CEMP stars. CS 22958−042 stands out as one of the most carbon-rich of the known CEMP stars. CS 29528−041 exhibits one of the largest nitrogen abundances yet observed for CEMP stars.

Figure 4 shows that there is an overall, broad correlation of C overabundance with N overabundance for most CEMP stars. Note that the "carbon-normal" stars, shown in the lower-left portion of this Figure, taken from Spite et al. (2005), display a clear anti-correlation between C and N due to mixing with CNO-cycled material (see also Spite et al. 2006). C and N have two distinct nucleosynthetic paths of formation. C is made by He burning in the triple-α process. However, production of N requires H burning, i.e., two proton captures on ^{12}C. The production site of primary C, He burning, is void of protons.

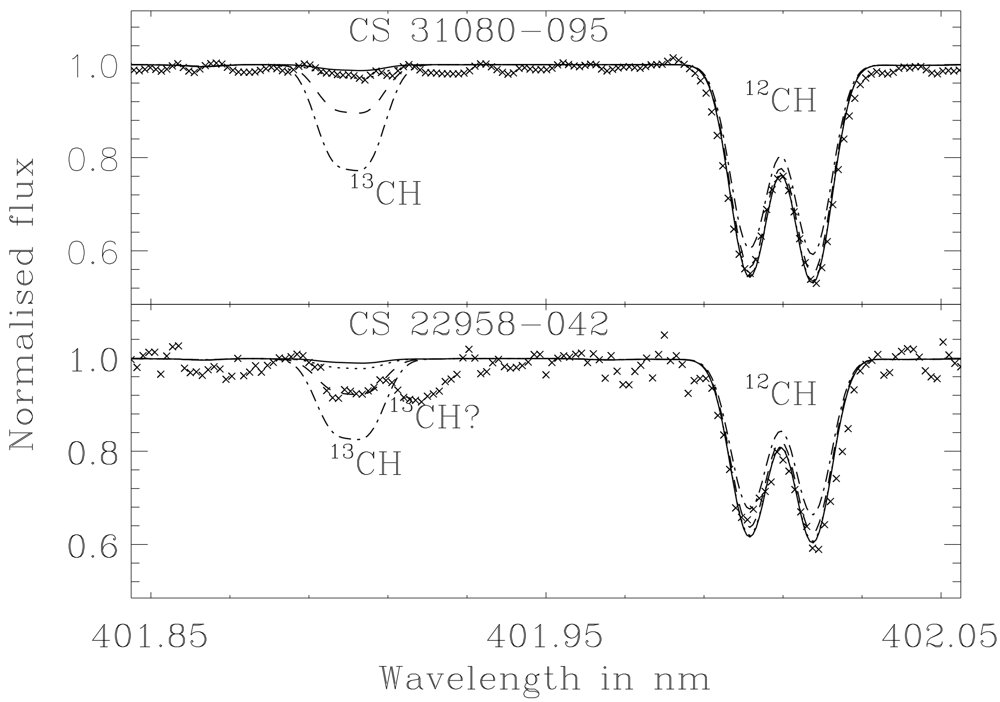

Fig. 3. The observed spectra for the two stars in our sample with meaningful measurements or limits on the $^{12}C/^{13}C$ ratios are shown as crosses (x), while the solid, dotted, dashed, dash-dotted, lines represent synthetic spectra for various $^{12}C/^{13}C$ ratios; 99, 40, 9, and 3, respectively. For CS 29528−041 , $^{12}C/^{13}C$ ratios between 3 and 99 all fall within a 2 σ limit for detection, hence we do not provide any limits for this star.

Primary C somehow has to be mixed out of the He-burning region and into the H-rich outer layers under conditions that are still hot enough to allow effective proton capture. Thus, in a sense, it is not surprising to see high C and N together. However, in stellar models it is very difficult to realize the specific conditions for the He- and H-burning and mixing that can produce the observed abundance patterns quantitatively. For a long time the only solid nuclear production site for primary N has been considered to be Hot-Bottom Burning (HBB) in intermediate-mass stars. Carbon is produced in the He-shell flashes, and dredged up into the envelope after the thermal pulse. In between He-shell flashes, during the interpulse phase of the thermal pulse cycle, the convective envelope connects with the outer layers of the H-burning shell, and C in the envelope is transformed into N. As displayed, for example, by the $4-6M_{\odot}$ models of Herwig (2004), the mass-averaged ejecta of such intermediate-mass stars of very metal-poor (VMP; [Fe/H] < -2.0) composition can show [N/Fe] $\sim +2$ to $+3$. Hot-bottom burning in intermediate-mass stars is characterized by very efficient conversion of C and O into N. This finding is model independent. The overabundance of carbon in $4-6M_{\odot}$ VMP models is in the range [C/Fe] $\sim +1$ to $+2$.

For stars that do not show any sign of the main component of the s-process, and no sign of binarity, one has to consider the possibility of other sources for the observed C and N overabundance pattern. Massive stars have been often dismissed in the past because of the inability of standard models to produce primary N. This inability is related to the above-mentioned necessity of mixing He-burning products (C!) out into the H-burning region. Recent models by Hirschi et al. (2006) and Meynet, Ekström, & Maeder (2006) are examples of massive, MMP ([Fe/H] < -6.0) models that include the effect of rotationally-induced mixing. This mixing has the desired effect of producing large amounts of primary N (which is required in order to match the observed behavior of [N/O] at low metallicity, even among "carbon normal" stars; see Chiappini et al. 2006). We have marked the C and N abundance of the wind-ejecta for one of their rotating $60M_{\odot}$ models with [Fe/H] $= -6.6$ in Figure 4. As far as C and N are concerned, the abundance signature is similar to HBB intermediate-mass stars.

The regions covered by HBB and non-HBB AGB models are indicated in Figure 4 as solid lines. Note that because these (as well as the massive-star model predictions) are primary yields, they shift along diagonals through zero in the [C/Fe]-[N/Fe] diagram as a function of [Fe/H]. There is more than a one dex difference in [Fe/H] between the HBB models and the non-HBB models. It seems that these two classes of models define the boundaries of the region occupied by the CEMP stars. Most CEMP stars in Figure 4 are located in an intermediate regime, showing larger N and smaller C overabundances than the 2 and $3M_{\odot}$ AGB stars predict, but less N and more C than the HBB AGB stars predict. One of our program stars, CS 22958−042 , falls into this category as well. Note, however, that CS 31080−095 exhibits [N/Fe] and [C/Fe] ratios that are almost in perfect agreement with the non-HBB models. Most other CEMP stars exhibit too much N to be explained by stan-

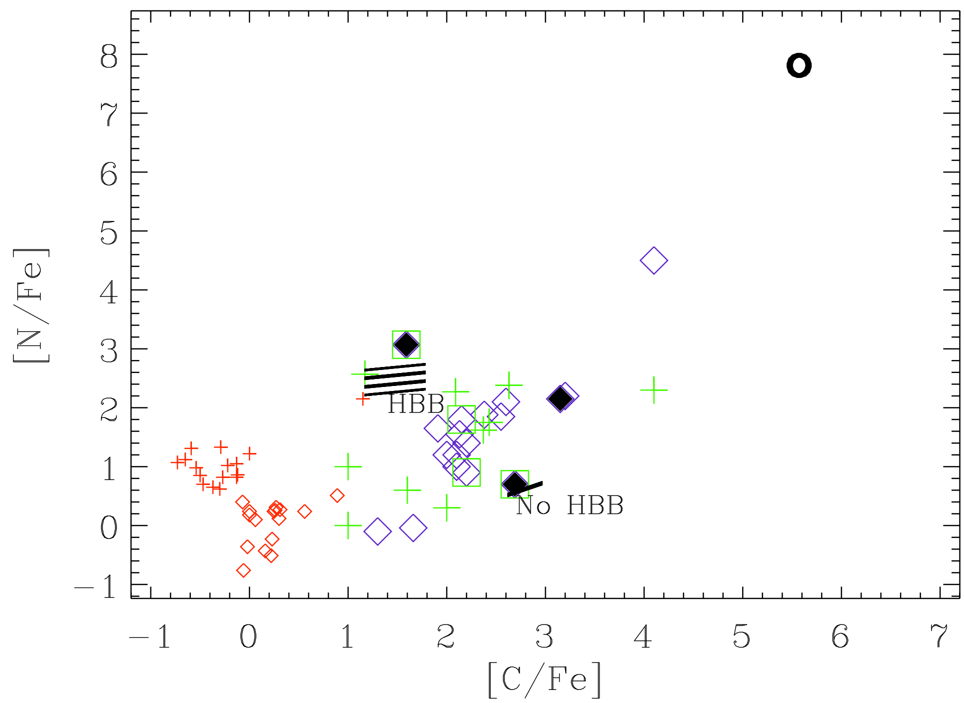

Fig. 4. The variation of [N/Fe] with [C/Fe] for our program stars and for other stars from the recent literature. The smaller symbols represent metal-poor giants from Spite et al. (2005). The + symbol represents the mixed giants and the ⋄ represents unmixed giants. The larger symbols represent the CEMP stars listed in Table 4. The large + signs represent stars with log g < 3.5 and the large ⋄ represents stars with log g > 3.5. The CEMP stars with significant Li detections are shown with a □ surrounding them. Our program stars are indicated with filled symbols. The region corresponding to AGB models with HBB and non-HBB predictions by Herwig (2004) are shown as straight lines. The circle represents the predicted composition of the wind ejecta for a $60M_\odot$ model with metallicity [Fe/H] = −6.6 (Hirschi et al. 2006)

dard low-mass AGB stellar companions. It is interesting to note that the extra mixing, or cool-bottom burning on the AGB, that has been mentioned above in the context of Li abundances, could also be a process that might increase the N abundance in 2 and $3M_\odot$ very metal-poor AGB stars, possibly to the extent required to agree with observations. Unfortunately, no quantitative models are currently available that consider this effect.

CS 29528−041 is special in that it is one of the very few CEMP stars that exhibits the high N and low C expected from HBB AGB stars. There have been searches conducted by Johnson et al. (2005) for CEMP stars with low [C/N] ratios, as predicted by current AGB models. These authors employed the near-UV NH lines, rather than the CN lines, which may be weak in low [C/N] stars; no obvious examples of stars exhibiting the expected ratio were found. The apparent paucity of N-rich EMP stars should be a matter of concern. If the hypothesis that CEMP-s stars are mass-transfer binaries with AGB stars as donors is correct, then why do we not see the occasional Nitrogen-Enhanced Metal-Poor (NEMP) star that had a HBB AGB star as a companion? The C and N abundances suggest that CS 29528−041 is at least one candidate for these "missing" NEMP stars.

5.2. Oxygen

The two stars CS 31080−095 and CS 22958−042, which exhibit typical C and N overabundances with respect to other CEMP stars in the literature, also show significant O overabundances of [O/Fe] = +2.35 and +1.35, respectively. At solar-like metallicities the production of O from AGB stars is negligible. It seems therefore at first sight surprising to see large overabundances of O in stars that are at least considered to be substantially polluted by AGB stars. However, at VMP composition, and at even lower metallicity, AGB stars are efficient producers of primary O. In the yield predictions by Herwig (2004), the overabundance of O ranges from [O/Fe] = +1.84 for the $2M_\odot$ case to [O/Fe] = +0.39 for the $6M_\odot$ case. Again, because these are primary yields, they would to first order shift upwards at lower [Fe/H]. Note that the O overabundance in the yields of Herwig (2004) has to be considered a minimum, as no convective extra mixing has been taken into account, which would serve to increase the O abundance in the AGB intershell region, and consequently increase the yields. Such an enhanced O intershell abundance is supported by observations of hot H-deficient central stars of planetary nebulae (Werner & Herwig 2006).

For CS 29528−041 , the low upper limit for O is consistent with HBB AGB predictions. For CS 31080−095 and CS 22958−042 , the O abundance fits into the picture of non-

HBB AGB stars as the nuclear production site of the observed abundances.

5.3. Sodium

Sodium is an extremely important element for understanding the nuclear production site of CEMP-star abundances. A small amount of secondary Na can be made in C-burning in massive stars. However, with the large overabundances of Na observed in many CEMP stars, as in two of our stars (CS 22958−042: [Na/Fe] = +2.82 and CS 29528−041: [Na/Fe] = +1.20), we need to look for a primary source of Na.

As explained above, primary production of ^{14}N is difficult because it requires the He-burning ashes to be exposed to H-burning again, and this requires mixing. For Na this concept has to be taken two steps further. Once there is primary ^{14}N from subsequent He- and H-burning, the ^{14}N has to be brought back into the region of He-burning in order to capture two α-particles. The result is the production of primary ^{22}Ne. The ^{22}Ne now has to either capture a neutron or a proton in order to make ^{23}Na. Through the recurrent, and inter-connected He-shell flash and dredge-up mixing events, AGB stars provide a natural environment for producing signifi cant amounts of primary Na. In fact, stars of all mass, the non-HBB and the HBB AGB stars alike, are predicted to produce primary Na. Primary ^{14}N is present in the H-burning ashes of the H-shell after a few thermal pulses with dredge-up. This ^{14}N is engulfed into the next He-shell flash, and transformed into ^{22}Ne. In non-HBB AGB stars a neutron released from the ^{22}Ne(α,n)^{25}Mg reaction can be captured by ^{22}Ne again, leading to the production of ^{23}Na. Note that the ^{22}Ne n-capture is very efficient. In the more-massive AGB stars the dominant effect is the Ne-Na cyle burning during HBB of dredged-up ^{22}Ne. In any case, the predicted AGB production range is [Na/Fe] $\sim$ +1.0 to $\sim$ +1.7. Again, since this is a primary production, this number would to fi rst order shift upward for lower [Fe/H].

Hence, while rotating massive stars have been shown to be able to mix primary C out of the core into the H-burning shell, and thus produce primary N, Na production requires that this N be once again exposed to He-burning. This may be difficult to achieve in massive stars.

Sodium in CS 31080−095 is very low, which poses a problem if one is to interpret its observed CNO abundances as a result of AGB pollution. The low Na abundance in CS 31080−095 does in fact fi t, together with its high Mg and low Al abundance, the well-known odd-even pattern that is characteristic for massive-star yields at low metallicity. The other two stars show this odd-even pattern, however starting at Mg, because they apparently had some additional primary contribution of Na that fi lled in the low Na expected from the odd-even effect.

5.4. Neutron-capture elements

The fi rst s-process peak elements Sr and Y are low in all three of our program stars (Y was only determined in CS 31080−095), at the same level of fi eld giants of the same metallicity (François et al., in preparation). A moderate over-abundance of the second peak s-process element Ba is found in CS 31080−095 and CS 29528−041. These two stars seem to resist a clear classifi cation into either CEMP-s or CEMP-no, as can be seen in Fig. 5, in which the [Ba/Fe] and [Sr/Ba] ratios are shown for all of the CEMP stars. The CEMP-no stars reported by Aoki et al. (2002b) are mildly C-rich and have much lower Ba than our two stars. The same is true for the other CEMP-no stars listed in Table 4. Nevertheless, at very low metallicities we may just be seeing an r-process component of Ba. However, in this case, Sr should be higher than is observed in our program stars. More heavy-element information, based on larger numbers of CEMP stars, is clearly needed to determine the nuclear origin of the heavy elements.

In Table 4 we have grouped CS 31080−095 and CS 29528−041 into a new class, CEMP-no/s, which includes stars that exhibit intermediate properties between the CEMP-no and CEMP-s classes. The reverse situation occurs for CS 22949-037 (Depagne et al. 2002), which displays a moderate enhancement of Sr and a low Ba abundance.

CS 31080−095 and CS 22958−042 exhibit exactly opposing behaviour with regard to Ba and Na. This could be the result of a non-HBB AGB star with some extra mixing. However, in order to obtain a large C overabundance, the AGB star must have dredge-up. This would bring up both Na and Ba in non-HBB AGB stars, both arising from n-capture nucleosynthesis. While CS 31080−095 exhibits a moderate Ba overabundance it is Na underabundant, while CS 22958−042 shows the opposite behaviour; Na is strongly enhanced and Ba is underabundant.

5.5. Lithium in CEMP stars

Lithium is detected, or an upper limit is provided, for a few CEMP stars, although the number of such stars with adequate S/N spectra available is still small. For CEMP-s stars the nucleosynthetic source is most likely a former AGB companion star, now a white dwarf. During their evolution towards the AGB phase low- and intermediate-mass stars are expected to deplete their initial Li abundance. Giants and cool dwarfs should show low Li abundances, due to convection-driven depletion taking place in the star itself. This is in fact the case for G77-61, CS 22948-027, CS 29497-034, and LP 625-44.

For the warm dwarfs (with T_{eff} >5700K), in which Li should be preserved, there are stars that exhibit a Li value slightly below the Spite Plateau, which indicates that Li has been destroyed (or partially destroyed) due to mixing processes in the progenitor(s) responsible for the C and (often) N enhancement. This is the case for CS 31080−095 and CS 29528−041 , which have Li detections at values that lie below the Spite Plateau. There are other CEMP stars, such as CS 22958−042 or CS 29497-030, which, considering their effective temperatures and surface gravities, should not have depleted Li, but instead exhibit Li abundances that are considerably below the Spite Plateau. While the case of the stars slightly below the Spite Plateau can be explained by mass transfer of Li-depleted material from an AGB companion, the case

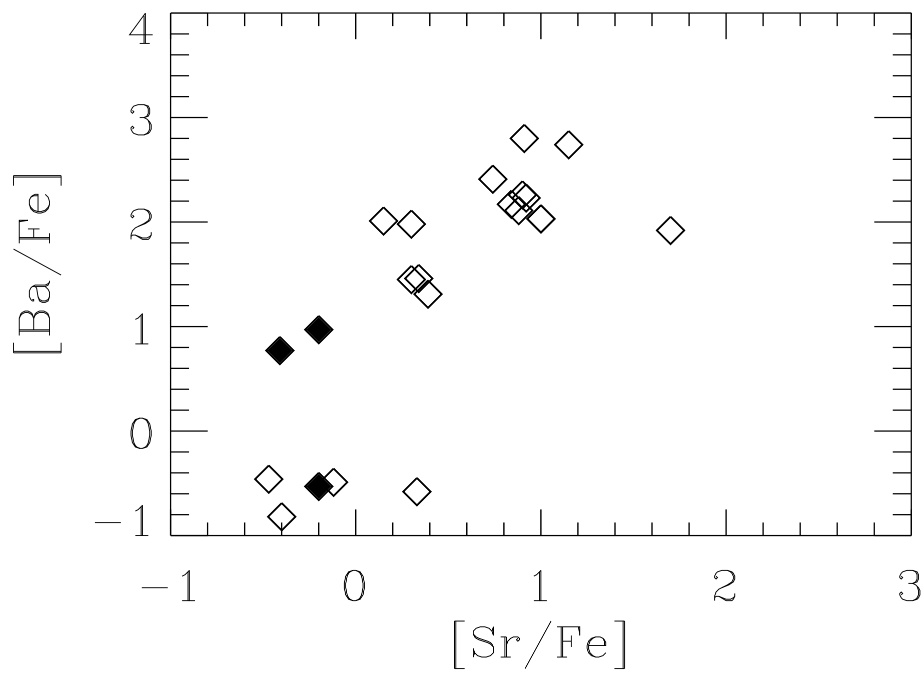

Fig. 5. The variation of [Ba/Fe] with [Sr/Fe] for CEMP stars. The three CEMP stars studied in this paper are shown as filled ⋄ symbols. CS 31080−095 and CS 29528−041 , with their high Ba abundances for their Sr abundances, may represent an s-process origin for Ba, as they have a similar [Sr/Ba] ratio.

of CS 22958−042 requires mass transfer of Li-poor material onto a star which was already Li-poor.

Finally, there is the case of the two CEMP-s stars, LP 706-7 and CS 22898-027, which have Li abundances corresponding to the Spite Plateau. This implies that the donor star has *produced* some Li, and that the amount of Li produced is finely tuned so as to keep the observed Li of the companion star that has received this material close to the Spite Plateau value. A similar situation has been suggested for the main-sequence turnoff stars in the globular cluster NGC 6397 (Bonifacio et al. 2002).

Several mechanisms exist during the Red Giant Branch (RGB) phase, as well as the AGB phase, that can in fact produce Li. On the RGB, a mechanism based on enhanced, rotationally-induced mixing, has been proposed and explored by Denissenkov & Herwig (2004). This process is a particularly effective variant of the cool-bottom processing proposed to explain some of the abundance anomalies in corundum grains and globular clusters (Wasserburg, Boothroyd, & Sackmann 1995; Boothroyd & Sackmann 1999). The enhanced extra mixing on the RGB can produce Li in a star that has previously depleted all its primordial Li, but it cannot produce the large, primary overabundances of C, N, and O that are observed in the CEMP stars. However, if enhanced extra mixing is possible and observed in RGB stars, it may be possible in AGB stars as well. This possibility has not been yet been considered in any AGB evolution model of VMP composition. The only quantitative treatment of such an evolution scenario was by Nollett, Busso, & Wasserburg (2003), who focused on isotopic ratios in solar metallicity AGB stars, but not on Li. We may, nevertheless, speculate that dwarf CEMP-s stars with detectable Li may be the result of enhanced extra mixing during the AGB phase of their companions. We cannot exclude this Li origin for CS 31080−095. The fact that the enhanced extra-mixing models on the RGB predict a low $^{12}C/^{13}C$ ratio is not necessarily in disagreement with the high $^{12}C/^{13}C$ measured in CS 31080−095, because the enhanced extra mixing may only be a transitional phase, followed (or preceeded) by efficient third dredge-up of primary ^{12}C. Third dredge-up will increase the $^{12}C/^{13}C$ ratio, but in low-mass AGB stars Li could still survive, at least partially. Clearly, a detailed theoretical investigation of this scenario is highly desirable.

Another mechanism to produce Li in AGB stars is the well-known HBB process, which operates in more massive AGB stars. The lower mass limit for HBB decreases with declining metallicity, and is at about $3.5M_\odot$ for [Fe/H] = −2.3. Li production by HBB, together with the efficient transformation of primary C into N, is a robust prediction of intermediate mass stellar evolution. CS 29528−041 seems to be a star that fits this pattern.

Finally, a number of studies of the evolution of zero metallicity, Extremely Metal-Poor (EMP; [Fe/H] < −3.0) or Ultra Metal-Poor (UMP; [Fe/H] < −4.0) AGB models have suggested that the so-called H-ingestion flash may need to be invoked in order to account for the observed abundance patterns in some of the more extreme CEMP stars (Fujimoto, Ikeda,

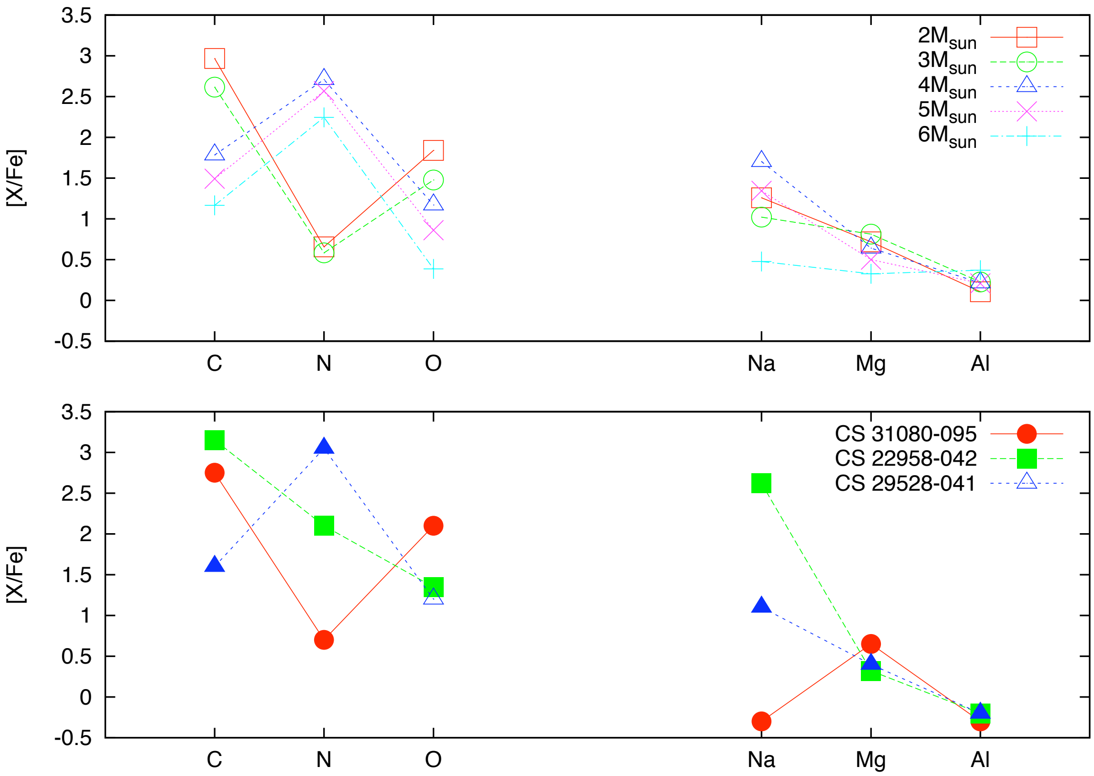

Fig. 6. Overabundances for AGB model ejecta (top panel) for Z=0.0001 ([Fe/H] = −2.3) and the observed abundance patterns in our stars (lower panel). The open symbol in the lower panel indicates an upper limit. The abundances of CS 22958-042 show good agreement with the predictions for HBB AGB stars, like the 4-6$M_\odot$ cases. The other two stars show signatures that are better explained with lower mass AGB models, however, the high observed N abundance requires additional mixing processes in AGB stars, while the spread in Na between the two stars may be larger than expected from current AGB models.

& Iben 2000; Herwig 2003; Iwamoto et al. 2004; Suda et al. 2004). As was first described by Herwig & Langer (2001) in the context of the born-again evolution of post-AGB stars (Werner & Herwig 2006), and confirmed by Iwamoto et al. (2004) for VMP stars and by Suda et al. (2004) for the specific case of EMP and HMP (Hyper Metal-Poor; [Fe/H] < −5.0) AGB stars, the H-ingestion flash can also be a source of Li. Unfortunately, the quantitative abundance evolution of this event is currently very uncertain because of our poor understanding of the coupled mixing and burning processes that are involved. It is likely that a H-ingestion flash that produces Li is followed by several thermal pulses with efficient ^{12}C dredge-up, which would also make this scenario a candidate for explaining the observed Li abundance in CS 31080−095.

5.6. Carbon isotopic ratios

Most of the CEMP-s stars exhibit carbon isotope ratios in the range ^{12}C/^{13}C ∼ 10-20, but the CEMP-no stars, including CS 22958−042, have ^{12}C/^{13}C ∼ 3-10. One exception is the star CS 29502-092. Figure 7 shows the variation of ^{12}C/^{13}C with lithium abundance for those CEMP stars in which a detection or limits on these two quantities have been reported. The CEMP stars with detected lithium appear to possess higher ^{12}C/^{13}C ratios. Clearly, additional efforts to detect, or place significant limits, on both ^{12}C/^{13}C and Li in CEMP stars are necessary in the future.

Standard VMP AGB star models predict that the HBB variant has ^{12}C/^{13}C ∼ 10, while the non-HBB cases have very large ratios, on the order of $10^3 - 10^4$. The simple fact that none of the CEMP stars (in particular the CEMP-s and CEMP-r/s stars) listed in Table 4 has such a high C-isotopic ratio is probably the clearest evidence that standard AGB models are neglecting some mixing mechanism. The extra-mixing process discussed above to acount for the lower than expected C/N ratios in all CEMP-s stars is qualitatively suitable to provide the observed C isotopic ratios.

6. Conclusions

The origin of the observed abundance signatures of CEMP stars remains enigmatic. Figure 6 provides a summary of how the observed abundances in our stars compare to the predicted abundances in AGB ejecta of very low metallicity. It should be recognized that the stars have lower iron abundances than the models. Because all the overabundances shown are dominated by the primary production in AGB stars, this could be corrected by just adding the Fe abundance difference (in logarithmic units). However, a comparison of models and actual stellar observations includes the problems of mass transfer and dilution. For that reason one should not pay too much attention

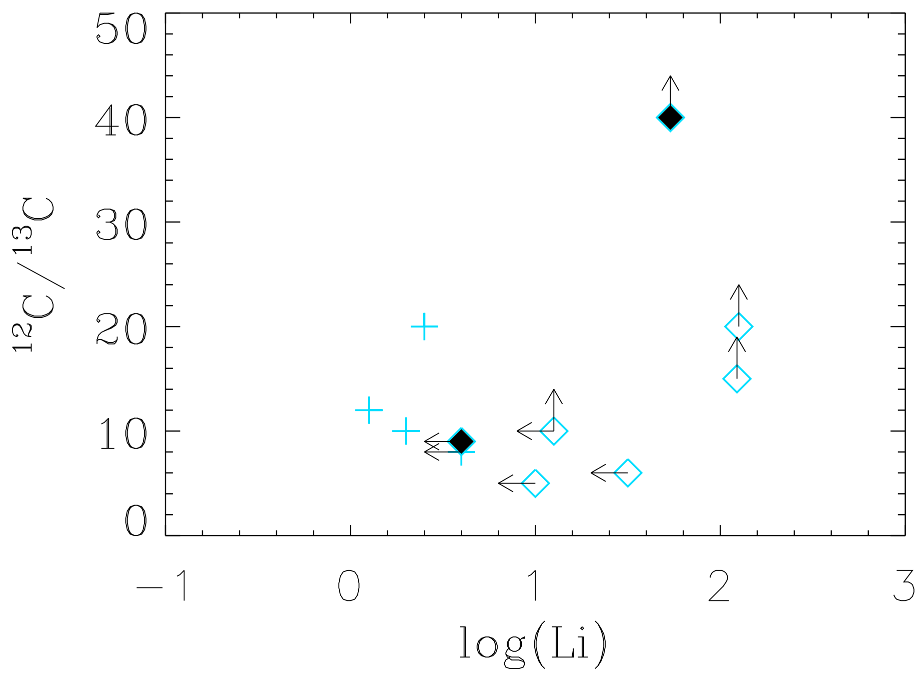

Fig. 7. The variation of carbon isotope ratios with the A(Li) in CEMP stars for which Li has been detected. The symbols are as defined in Figure 4. The arrows represent limits. Note that the Li-rich CEMP stars tend to possess high $^{12}C/^{13}C$ ratios.

to the absolute overabundances within 0.5 or 1 dex, but rather, focus on the abundance patterns.

In our small sample CS 29528−041 is probably the most straightforward case. All of the available elemental evidence seems to point toward pollution from a HBB AGB star. CS 29528−041 is one of the very few NEMP stars known. The existence of NEMP stars is predicted by standard stellar evolution, in conjunction with the binary mass-transfer scenario, for CEMP-s stars. The moderate Ba overabundance in this star may be related to the large mass of the polluting AGB star. The s-process in these (or any VMP AGB stars for that matter) is not yet understood. The CNO abundances would also be compatible with pollution from a massive, rotating star. However, the observed Li, Na, and Ba abundances clearly favour the AGB alternative.

For CS 22958−042 the AGB connection is strongly suggested by the probably very short period (assuming the measured rapid velocity variation is correct), which implies that this star may be a member of a post-common-envelope binary. This *must* be the case if the overabundances are attributed to mass-transfer from an AGB star. We can only speculate about the effects that a common-envelope phase may have on the nuclear signatures found in a CEMP star that formed from this mechanism. One scenario could involve several thermal pulses with efficient dredge-up which cause the observed overabundance in C, N, O and Na. However, before the s-process production can get fully underway, AGB evolution is terminated by the onset of common-envelope evolution. This could explain the absence of Ba in this star. Another CEMP star with a short period is HE 0024-2523 (Lucatello et al. 2003), which must be a post-common envelope object as well. However, in that star Ba (and other heavy elements) are overabundant without doubt. These two short-period binaries have contrasting Na signatures. Na is underabundant in HE 0024-2523, but CS 22958−042 is one of the most Na-rich stars yet found.

Similar to HE 0024-2523, CS 22958−042 has a very large C/O ratio, although O is significantly overabundant. For CS 22958−042 , C/O= 48, while for HE 0024-2523 it is 100. A very large C/O ratio may present a problem for the AGB mass-transfer scenario, because a non-HBB AGB star can only deliver material with a C/O ratio less than anywhere inside of it. The material dredged up to the surface is usually the intershell material, which contains, almost independent of metallicity, a primary amount of O from one to a few percent by mass, and 20% to maybe 25% by mass of carbon[1]. Thus, a reasonable range for the C/O ratio in the intershell layers of AGB stars (including the VMP AGB stars) is < 32. Even if the AGB star dumps this most heavily-polluted material onto the CEMP star we now observe, the resulting C/O ratio cannot become larger than it is in this intershell layer. For both short-period systems known, the C/O ratio could be a problem, but perhaps more so for HE 0024-2523.

Clearly, common-envelope evolution introduces a whole new family of possible evolutionary outcomes. Nevertheless, it is noteworthy that we may have observed here the second short-

[1] These C and O abundances are for models without extra convective mixing. However, if such convective extra mixing is included, both C and O increase and the C/O ratio does not change much.

period CEMP star, and it seems to be significantly different from the previous known case, HE 0024-2523. One could consider that one of the two in fact is not a post-common envelope, but has an inert low-mass MS companion instead. However, for explaining both the s-process enhancement in HE 0024-2523 and the high Na in CS 22958−042 , VMP AGB stars are the best present guess for a nuclear production site.

Finally, CS 31080−095 could be an AGB mass-transfer object if the non-HBB VMP AGB star experienced some extra mixing. This could account for the observed Li, C, and N abundances. The O abundance in this star certainly is high compared to the predictions of this scenario, but would not rule it out. The problem is the low Na abundance, which excludes AGB progenitors that are more massive than 2 $M_{\odot}$. Perhaps a less massive AGB star in which the ^{22}Ne source is not at all activated is involved. The Ba could still come from the ^{13}C neutron source. The larger $^{12}C/^{13}C$ ratio (> 40) in this star is consistent with this picture, and inconsistent with the obvious alternatives; the isotopic carbon ratios in HBB AGB stars ($^{12}C/^{13}C \sim 10$) as well as the wind ejecta of rotating massive stars ($^{12}C/^{13}C \sim 4$) are obviously much lower than the observed limit.

Our discussion has clearly shown that current understanding of the origin of the observed abundance patterns in CEMP stars is still in its infancy. The large observed overabundances of some elements in CEMP stars probe one or more important primary nuclear production sites, including those that may have set the stage for the following galactic chemical evolution. Yet, we remain far from having even identified the main players in this game. One task to be addressed is to develop a better understanding of mixing in stars of all masses, and to seek to obtain a better understanding of the impact of binary evolution on nucleosynthesis. A significant increase in the numbers of CEMP stars with available detailed elemental abundance analyses is also an obvious next step.

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Table 3. Elemental and isotopic ratio measurements for three CEMP stars

Element	Object						
	CS 31080−095		CS 22958−042		CS 29528-041		Sun
	log(ϵ)	[X/Fe]	log(ϵ)	[X/Fe]	log(ϵ)	[X/Fe]	log(ϵ)
Li	1.73±0.05	···	<0.6	···	1.71±0.05	···	1.10
C(CH)	8.25±0.01	+2.69 ±0.14	8.70±0.01	+3.15±0.12	6.70±0.08	+1.59±0.15	8.41
C(C2)	8.35±0.01	+2.79 ±0.14	8.70±0.01	+3.15±0.12	···	···	8.41
N(NH)		···	7.05±0.02	+2.10±0.12	7.50±0.1	+3.00±0.15	7.80
N(CN)	5.65±0.01	+0.70 ±0.11	7.10±0.01	+2.15±0.11	7.57±0.06	+3.07±0.13	7.80
O(LTE)	8.17±0.05	+2.35 ±0.12	7.17±0.05	+1.35±0.11	<6.77	<+1.40±0.10	8.67
O(NLTE)	8.05±0.05	+2.23 ±0.12	6.94±0.05	+1.12±0.11	<6.77	<+1.40±0.10	8.67
Na(LTE)	3.20±0.05	−0.28±0.12	6.30±0.10	+2.82±0.15	4.23±0.05	+1.20±0.11	6.33
Na(NLTE)	3.00±0.05	−0.48±0.12	6.10±0.10	+2.62±0.15	4.02±0.05	+1.00±0.11	6.33
Mg I	5.38	+0.65 ±0.12	5.05±0.04	+0.32±0.15	4.68±0.01	+0.40±0.11	7.58
Al(LTE)	2.67	−0.95±0.11	2.77	−0.85±0.10	2.77	−0.85±0.10	6.47
Al(NLTE)	3.32	−0.30±0.11	3.32	−0.20±0.10	3.32	−0.20±0.10	6.47
Si I	4.75	+0.05 ±0.15	4.85	+0.15±0.10	4.05	−0.20±0.10	7.55
Ca I	3.68±0.05	+0.17 ±0.13	3.87±0.06	+0.36±0.15	3.46±0.03	+0.40±0.15	6.36
Sc II	0.30±0.05	−0.02±0.14	0.37±0.05	+0.05±0.11	0.13±0.03	+0.26±0.15	3.17
Ti I	2.59±0.03	+0.42 ±0.16	2.60	+0.43±0.10	2.32±0.04	+0.40±0.15	5.02
Ti II	2.39±0.01	+0.22 ±0.11	2.36±0.07	+0.19±0.14	2.12±0.007	+0.40±0.10	5.02
V I	1.15±0.05	+0.00 ±0.12	1.10	−0.05±0.10	0.70	+0.00±0.15	4.00
Cr I	2.84±0.03	+0.02 ±0.12	2.67±0.04	−0.15±0.11	2.20±0.01	−0.17±0.11	5.67
Mn I	2.33±0.05	−0.21±0.13	2.33±0.05	−0.21±0.14	1.59±0.07	−0.50±0.15	5.39
Fe I	4.65±0.003	−0.00±0.10	4.65±0.04	+0.00±0.10	4.20±0.002	+0.00±0.10	7.50
Fe II	4.66±0.02	−0.05±0.11	4.57±0.09	−0.08±0.12	4.20±0.02	+0.00±0.10	7.50
Co I	2.38±0.03	+0.31 ±0.11	2.27±0.14	+0.20±0.18	1.62±0.04	+0.00±0.15	4.92
Ni I	3.49±0.03	+0.09 ±0.16	3.31±0.10	−0.09±0.16	2.95±0.01	+0.00±0.12	6.25
Zn I	2.33±0.08	+0.58 ±0.15	···	···	···	···	4.60
Sr II	−0.29±0.05	−0.41±0.12	−0.53	−0.20±0.11	−0.53	−0.20±0.10	2.97
Y II	−0.96±0.05	−0.35±0.13	···	···	···	···	2.24
Ba II	0.05±0.05	+0.77 ±0.15	<−1.40	<−0.53±0.16	−0.23	+0.97±0.10	2.13
$^{12}C/^{13}C$	> 40		9.0±2.0	···	···	···	···

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Table 4. Elemental abundances and $^{12}C/^{13}C$ ratios for CEMP stars

Star	T_{eff}	log g	[Fe/H]	[C/Fe]	[O/Fe]	[N/Fe]	[Mg/Fe]	[Sr/Fe]	[Ba/Fe]	$^{12}C/^{13}C$	A(Li)	Ref
CEMP-no stars[a]												
CS 22877-001	5100	2.2	−2.71	+1.0	···	+0.0	+0.29	−0.12	−0.49	>10	···	4
CS 22949-037	4900	1.7	−3.79	+1.17	+1.98	+2.57	+1.56	+0.33	−0.58	4	···	10,17
CS 22957-027	5100	1.4	−3.11	+2.37	···	+1.62	+0.69	−0.56	−1.23	8	···	3,19
CS 22958-042	6250	3.5	−2.85	+3.15	+1.12	+2.15	+0.32	−0.2	<−0.53	9	<0.6	TP
CS 29498-043	4600	1.2	−3.53	+2.09	+2.43	+2.27	+1.75	−0.47	−0.46	6	···	3,7
CS 29502-092	5000	2.1	−2.77	+1.0	···	+1.0	+0.37	−0.40	−0.82	20	···	4
G 77-61	4000	5.0	−4.0	+3.2	+2.2	+2.2	+0.49	···	···	5	<1.0	18
HE 0007-1832	6515	3.8	−2.65	+2.55	···	+1.85	···	···	+0.16	10	···	9
HE 0107-5240	5180	2.2	−5.3	+4.1	···	+2.3	···	···	···	···	···	8
HE 1327-2326	6180	3.7	−5.6	+4.1	2.8	+4.5	···	+1.1	< +1.5	···	< 1.5	11,11a,21
CEMP-no/s stars[b]												
CS 29528-041	6166	4.0	−3.30	+1.59	<1.40	+3.07	+0.4	−0.2	+0.97	···	1.71	TP
CS 31080-095	6100	4.5	−2.85	+2.69	2.23	+0.70	+0.65	−0.41	+0.77	>40	1.73	TP
CEMP-s stars[c]												
CS 22880-074	5850	3.8	−1.93	+1.3	···	−0.1	···	+0.39	+1.31	>40	···	3,19
CS 22942-019	5000	2.4	−2.64	+2.0	···	+0.3	···	+1.7	+1.92	8	···	3,19
CS 30301-015	4750	0.8	−2.64	+1.6	···	+0.6	···	+0.3	+1.45	6	···	3
CEMP-r/s stars[d]												
CS 22898-027	6250	3.7	−2.26	+2.2	···	+0.9	···	+0.92	+2.23	>20	2.10	3,19
CS 22948-027	4600	1.0	−2.57	+2.43	···	+1.75	+0.31	+0.90	+2.26	10	0.30	3,19
CS 29497-030	6650	3.5	−2.70	+2.38	+1.67	+1.88	+0.64	+0.84	+2.17	>10	<1.10	20
	7000	4.1	−2.57	+2.30	+1.48	+2.12	+0.44	+1.34	+2.32	···	···	13
CS 29497-034	4800	1.8	−2.90	+2.63	···	+2.38	+0.72	+1.00	+2.03	12	0.10	12
CS 29526-110	6500	3.2	−2.38	+2.2	···	+1.4	···	+0.88	+2.11	···	···	5
CS 31062-012	5600	3.0	−2.55	+2.1	···	+1.2	···	+0.30	+1.98	8	···	3,6
CS 31062-050	5600	3.0	−2.33	+2.0	···	+1.2	+0.84	+0.91	+2.80	8	···	3,6
HE 0024-2523	6625	4.3	−2.67	+2.6	+0.40	+2.1	+0.73	+0.34	+1.46	6	1.50	15
LP 625-44	5500	2.8	−2.71	+2.1	···	+1.0	···	+1.15	+2.74	20	0.40	1,2
LP 706-7	6250	4.5	−2.74	+2.15	···	+1.80	···	+0.15	+2.01	>15	2.09	3,16
HE 0143-0441	6370	4.4	−2.16	+1.66	···	−0.04	···	···	+2.31	10	···	9
HE 0338-3945	6160	4.1	−2.42	+2.13	+1.40	+1.55	+0.30	+0.74	+2.41	10	···	14
HE 2148-1247	6380	4.3	−2.3	+1.91	···	+1.65	···	···	+2.36	10	···	9

[a][C/Fe]> +1.0 and [Ba/Fe] < 0.0 (Beers & Christlieb (2005)
[b][C/Fe]> +1.0 and +0.5 < [Ba/Fe] < +1.0
[c][C/Fe]> +1.0, [Ba/Fe] > +1.0, and [Ba/Eu] > +0.5 (Beers & Christlieb (2005)
[d][C/Fe]> +1.0 and 0.0 < [Ba/Fe] < +0.5 (Beers & Christlieb (2005)

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