CEMP-S AND CEMP-S/R STARS: LAST UPDATE

Bisterzo, S.,¹,², Gallino, R.,¹,³, Straniero, O.,⁴, Cristallo, S.,³, Käppeler, F.,⁵ and Wiescher, M.,⁶

Abstract. We provide an updated discussion of the sample of CEMP-s and CEMP-s/r stars collected from the literature. Observations are compared with the theoretical nucleosynthesis models of asymptotic giant branch (AGB) stars presented by Bisterzo et al. (2010, 2011, 2012), in the light of the most recent spectroscopic results.

1 Introduction and open problems

Metal-poor stars are key objects to investigate the origin of the elements in the early Universe. The very high resolution and signal-to-noise ratio reached in the last decades by different survey projects (HET/HRS, Keck/HIRES, Magellan/MIKE, Subaru/HDS, and VLT/UVES) allowed the discovery of several chemically peculiar objects.

Known metal-poor stars are classified in several groups, following their chemical peculiarities (Beers et al. 2005; Aoki et al. 2007). About 10% of halo stars show an enhanced carbon abundance (Carbon Enhanced Metal-Poor, CEMP); this fraction increases up to ~30% by decreasing metallicity ([Fe/H] < −3). For metallicities lower than [Fe/H] ~ −4.5, the analysis is still statistically insignificant with only four objects known (three of which are C-rich; see Yong et al. 2013 and references therein). CEMP stars are distinguished in four subclasses based on the degree of enhancement detected among neutron capture elements: CEMP-s (s-process enriched; [Ba/Fe] > 1 and [Ba/Eu] > 0.5), CEMP-s/r (s- and r-process enriched; [Ba/Fe] > 1 and 0 < [Ba/Eu] < 0.5), CEMP-r (r-process enriched; [Eu/Fe] > 0.3 and [Ba/Eu] < 0), CEMP-no (with

¹ Department of Physics, University of Turin, Italy
² INAF - Astrophysical Observatory Turin, Turin, Italy
³ B2FH Association-c/o Strada Osservatorio 20, 10023 Turin, Italy
⁴ INAF - Osservatorio Astronomico di Collurania, Teramo, Italy
⁵ KIT - Karlsruhe Institute of Technology, Karlsruhe, Germany
⁶ Department of Physics, University of Notre Dame, Notre Dame, IN

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sub-solar s-process abundances; \([\text{Eu},\text{Ba}/\text{Fe}] < 0\), and CEMP-\(\alpha\) stars (with a large excess of C, N, O and \(\alpha\)-elements). Note that most of the metal-poor r-rich stars known are not carbon enhanced and are classified as r-II (with \([\text{Eu}/\text{Fe}] \geq 1\)) or r-I (\(0.3 \leq [\text{Eu}/\text{Fe}] \leq 1\)). About 80\% of CEMP stars are CEMP-s, and about half of CEMP-s with measured Eu are also r-rich (CEMP-s/r). We focus our analysis on these two last classes of stars.

The s-process mainly occurs in stars of low initial mass (\(M \sim 1–3\,M_\odot\)) during their thermally pulsing asymptotic giant branch phase (TP-AGB), at rather low neutron densities (\(n_n \sim 10^7\) neutrons/cm\(^3\)). The major neutron source of the s-process in AGBs is the \(^{13}\text{C}(\alpha, n)^{16}\text{O}\) reaction, which burns radiatively (at \(T \sim 0.9\times10^8\) K) in a thin layer at the top of the He-intershell (called \(^{13}\text{C}\)-pocket) during the interpulse periods. A second neutron source is marginally activated during the convective thermal pulses (\(T > 2.5\times10^8\) K), mainly affecting isotopes close to the branching points. An additional s-process component comes from massive stars during core He and shell C burning (\(n_n \sim 10^{12}\) neutrons/cm\(^3\)) and contributes to neutron capture isotopes up to \(A \sim 90\). The r-process requires high neutron densities (up to \(n_n \sim 10^{22}\) neutrons/cm\(^3\)) to produce neutron rich isotopes far from the stability valley and its origin is currently attributed to explosive nucleosynthesis in massive stars. For extended reviews on the s- and r-processes we refer to Käppeler et al. (2011) and Thielemann et al. (2011).

The carbon enhancement coupled with high s-process abundances detected in CEMP-s is associated to binary systems, where the more massive companion (now an invisible white dwarf) evolved faster through the TP-AGB and polluted the observed CEMP-s star by mass transfer through efficient stellar winds. Indeed CEMP-s are old main-sequence or giant stars, with low metallicity ([Fe/H] \(\leq 2\)) and low initial mass (\(M < 0.9\,M_\odot\)), which lie far from the TP-AGB phase: as sustained by radial velocity studies by Lucatello et al. (2005), their surface composition has to be modified by accretion of material from one (or more) companion(s).

Large uncertainties still affect AGB models and s-process nucleosynthesis, as the evaluation of the mass-loss, the efficiency of the third dredge-up (TDU, a mixing episode that permits partial mixing processes between material of the He-intershell and the convective envelope), the formation of the \(^{13}\text{C}\)-pocket (Herwig 2005; Straniero, Gallino & Cristallo 2006). In case of binary systems, the amount of mass accreted and the distance between the two stars also influence the s-enhancement. In this context, we study the behavior of the ratios between the three s-process peaks, \(l_s\) (light-s elements at \(N = 50\), i.e. Sr-Y-Zr), \(h_s\) (heavy-s elements at \(N = 82\), i.e. Ba-La-Ce) and Pb (at \(N = 126\)): the \([\text{hs}/\text{ls}]\) and \([\text{Pb}/\text{hs}]\) ratios are extremely valuable indexes for the s-process as they are independent of both the TDU efficiency in the AGB star and the dilution of the AGB material on the companion.

In addition, the C and s-material observed on the surface is affected by internal mixing occurring during the stellar life: e.g., radiative acceleration competes with gravitational settling during the lengthy main-sequence phase, while thermohaline instabilities may reach deep layers on a shorter time-scale if not prevented by the
other two processes. The resulting abundance alteration is very difficult to estimate (e.g., Richard et al. 2002; Vauclair 2004; Stancliffe et al. 2007; Stancliffe & Glebbeek 2008; Vauclair & Théado 2012), especially if rotation or magnetic fields are included in the analysis. The comparison between theoretical predictions and observations helps to establish the efficiency of non-convective mixing in the envelope of the observed star during their main-sequence phase. Present results by Bisterzo et al. (2008, 2011) seem to indicate that no efficient mixing takes place in main-sequence stars. This agrees with model calculations by Thompson et al. (2008), who showed that gravitational settling can confine the efficiency of thermohaline mixing in these low-mass metal-poor stars. However, the statistic was limited to seventeen main-sequence stars. For stars on the red giant branch, having undergone the first dredge-up episode (FDU), all mixing processes occurred during the main-sequence phase are erased.

As already found for disk stars (e.g., post-AGB, Ba stars; Busso et al. 2001; Abia et al. 2002), for a given metallicity a range of $^{13}$C-pocket strengths has been hypothesized to interpret the observations in CEMP-s stars. A clear definition of the properties of the mixing processes at radiative/convective interfaces that lead to the formation of the $^{13}$C-pocket has not been reached yet. Moreover, models including rotation, gravity waves or magnetic fields may influence the formation of the $^{13}$C-pocket (Langer et al. 1999; Denissenkov & Tout 2003; Herwig, Langer & Lugaro 2003; Siess, Goriely & Langer 2004; Piersanti et al. 2013). This translates into different s-process distributions.

CEMP-s/r are among the most enigmatic stars because the s- and r- processes are commonly related to different nucleosynthesis environments. Ba (or La) and Eu are adopted as reference elements to investigate the competition between the two processes, given that $\sim$80% of solar Ba (or $\sim$70% of solar La) is synthesized by AGBs, while $\sim$94% of solar Eu is produced by the r-process. A pure s-process predicts $[\text{Ba,La/Eu}] \sim 1$, while CEMP-s/r show an observed $[\text{Ba,La/Eu}]$ ratio down to zero. It is ascertained that a pure s-process is not sufficient to explain the observations in CEMP-s/r and different scenarios have been proposed in literature (Cohen et al. 2003 and references therein; Zijlstra 2004; Jonsell et al. 2006; Aoki et al. 2006; Sneden, Cowan & Gallino 2008; Bisterzo et al. 2009; Lugaro et al. 2012). The origin of CEMP-s/r is highly debated and an unanimous interpretation is not given by the scientific community.

Our hypothesis has been discussed in detail by Bisterzo et al. (2011). We assume that the r-enhancement detected in peculiar stars with very low metallicities may be due to local Supernova(e) explosion(s), leading to an r-enrichment of molecular clouds from which CEMP-s/r stars may have formed. The observed CEMP-s/r and the more massive AGB companion belong to the binary system and have the same initial r-enhancement. The more massive star is supposed to evolve through the TP-AGB phase, synthesizing s-elements and polluting the observed companion through stellar winds. The choice of the initial r-enhancement (scaled to Eu) for elements heavier than Ba is based on the solar isotopic r-process contributions deduced with the residual method. The hypothesis of different initial r-process enhancements derives from on the spread observed in $[\text{Eu/Fe}]$ in the Galactic halo.
Despite a few spectroscopic binaries, r-rich objects do not belong to binary systems, suggesting that their r-process enhancement reveals the chemical inhomogeneity of the interstellar medium of the Galactic halo (Hansen et al. 2011). Possibly, the strong r-enhancement seen in r-II stars results from the pollution of the pristine molecular cloud by a neighbor Supernova (Aoki et al. 2010).

While the origin of neutron capture elements lighter than Ba is complex, likely resulting from the competition of a multiplicity of r-process components (Travaglio et al. 2004; Honda et al. 2006, 2007), r-abundance distribution of elements heavier than Ba observed in r-rich stars exhibits a scaled-solar r-process pattern (Sneden et al. 2008). As shown by Bisterzo et al. (2011) and references therein), an initial r-enhancement based on the same solar-scaled r-abundances distribution plausibly explains the r-enrichment in CEMP-s/r stars within uncertainties. This may imply that the r-elements detected in CEMP-s/r and in r-rich stars have a common origin. Seventeen CEMP-s/r stars with large r-enhancement ([Eu/Fe] > 1.5 and 0 < [Ba,La/Eu] < 0.5; called CEMP-sII/rII) and five CEMP-s/r with mild r-enhancement (1.0 < [Eu/Fe] < 1.5 and 0 < [Ba,La/Eu] < 0.5; called CEMP-sII/rI) were discussed by Bisterzo et al. (2011, 2012). The current fraction of known r-II stars seems compatible with the number of CEMP-sII/rII stars. However, the metallicity of r-II stars is on average ~0.3 dex lower than that of CEMP-sII/rII stars: r-II stars range from −3.4 ≤ [Fe/H] ≤ −2.5 ([Fe/H]_{averaged} = −2.8) and CEMP-sII/rII from −3.0 ≤ [Fe/H] ≤ −2.0 ([Fe/H]_{averaged} = −2.5). Aoki et al. (2010) highlight that, while more observations are needed for [Fe/H] ≤ −3, the upper metallicity limit given for r-II stars is well constrained by the large sample of objects detected for [Fe/H] ≥ −2.5. The number of r-I stars is greater than r-II stars and covers a larger metallicity range (up to [Fe/H] ∼ −1.5; e.g., SAGA database and Aoki et al. 2010). Five r-I stars have been analyzed at very-high resolution and the abundance pattern of neutron-capture elements heavier than Ba is quite similar to that of the solar r-process component. Their lower Eu abundance is likely more difficult to be disentangled from the averaged enrichment seen in the halo ([Eu/Fe] ∼ 0.5), which results from a multiplicity of SNe events that exploded during the Galactic lifetime.

Masseron et al. (2010) found a linear correlation between [Ba/Fe] and [Eu/Fe] observed in CEMP-s/r, and Lugaro et al. (2012) suggested a sort of connection in the origin of Ba and Eu in these stars. Current low-metallicity AGB models do not reach the physical conditions needed to increase [Ba/Eu], even under extreme conditions (e.g., PIE episodes, see Cristallo et al. 2009 and references therein). Moreover, solar abundances and neutron capture rates close to La and Eu isotopes (corresponding to a theoretical [La/Eu] ratio for pure s-process material close to 1

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1CS 22892-052, CS 22183-031, CS 22953-003, CS 29491-069, CS 29497-004, CS 31078-018, CS 31082-001, HE 1219-0312 by Hayek et al. (2009); HE 1523-0901, HE 2327-5642, SDSS J2357-0052, HE 2224+0143, HE 1127-1143, HE 0432-0923, HE 0430-4901, CS 22875-029, CS 22888-047; see SAGA database for references.

2BD +173248, CS 30306-132, HE0420+0123, HD 221170, HD 115444.
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dex) are known with high accuracy. Therefore, we underline that, at present, AGB predictions can not interpret \([\text{Ba/Eu}] \sim 0\) together with \([\text{Ba/Fe}] \sim 2\), without the assumption of an initial r-enhancement.

In the next Section we examine the results found by Bisterzo et al. (2010, 2011, 2012), in the light of the most recent spectroscopic information.

2 Newly discovered CEMP-s and CEMP-s/r stars, updated results and future prospects

Since the last two years, new CEMP-s and CEMP-s/r stars have been discovered and previous spectroscopic analyses have been complemented with more detected elements. We discuss these updates in the light of Bisterzo et al. (2011, 2012) using the AGB models described by Bisterzo et al. (2010).

CEMP-s/r stars appear to have on average higher \([\text{hs/Fe}]\) than CEMP-s stars. This seems to agree with AGB model predictions if a high initial r-process enhancement of the molecular cloud is adopted \([r/\text{Fe}]_{\text{ini}} = 2.0; \text{see discussion by Bisterzo et al. (2011)}\). In particular, the predicted \([\text{hs/ls}]\) ratios reach values as high as 1.3 dex.³

In Fig. 1 we show the behavior of \([\text{hs/ls}]\) versus metallicity for AGB models with initial mass \(M = 1.3 \, M_\odot\) and \(1.5 \, M_\odot\) (top and bottom panels, respectively) and a range of \(^{13}\)C-pockets, compared with observations of CEMP-s and CEMP-s/r stars available in literature. In the right panels no initial r-enhancement is assumed, while in the left panels CEMP-s/r stars are compared to AGB models with an initial r-enhancement of \([r/\text{Fe}]_{\text{ini}} = 2.0\). We made an accurate choice of the CEMP-s and CEMP-s/r sample, based on the number of s-process elements detected for each star (see Table 2 by Bisterzo et al. 2011; blue symbols). If only Sr and Ba are detected among the s-elements, the star is not displayed in Fig. 1. Fig. 2 shows the same as the right panels of Fig. 1 but for \([\text{Pb/hs}]\) without initial r-enhancement. Allen et al. (2012) revised five stars already known in literature and studied seven new objects (red symbols). CS 29528–028 by Aoki et al. (2007) is now classified as CEMP-s/r stars owing to the high Eu newly detected by Allen et al. (2012) \([\text{Eu/Fe}] = 2.16\). CS 29503–010, for which only Ba was available among the s-elements (Aoki et al. 2007), also belongs to the CEMP-s/r stars, with \([\text{Eu/Fe}] = 1.69\). Discrepant abundances have been found by the two analyses \((\Delta[\text{Fe/H}] = 0.3 \, \text{dex})\), with a strongly reduced metallicity: CS 29503–010 was classified as a CH disk star \(([\text{Fe/H}] = -1.09; \text{Aoki et al. (2007)}\), while Allen et al. (2012) find \([\text{Fe/H}] = -1.69\). A more recent study by Yong et al. (2013) provide \([\text{Fe/H}] = -1.39\), with \([\text{Ba/Fe}] = 1.51\) more consistent with Aoki et al. (2007). The CEMP-s/r main-sequence stars CS 29526–110 and CS 22183–015 were studied by Cohen et

³An \([r/\text{Fe}]_{\text{ini}} = 2.0\) may affect the final \([\text{hs/Fe}]\), because \(\sim 30\%\) of solar La, \(\sim 40\%\) of solar Nd and \(\sim 70\%\) of solar Sm are synthesized by the r-process. Note that we exclude Sr from the hs-elements and Ba from the hs-peak because they are mainly affected by higher spectroscopic uncertainties (Busso et al. 1995) due to NLTE effects (Short & Hauschildt 2006; Mashonkina et al. 2008; Andrievsky et al. 2011), especially by decreasing the metallicity.
For CS 29526–110, Allen et al. (2012) determine s- and r-enhancements stronger than Aoki et al. (2002) ([ls/Fe] = 1.54, [hs/Fe] = 2.38 and [Eu/Fe] = 2.28, instead of [ls/Fe] = 1.00, [hs/Fe] = 1.88 and [Eu/Fe] = 1.73). The opposite result is seen for CS 22183–015: Allen et al. (2012) considered this star a giant, as found by Johnson & Bolte (2002), with [ls/Fe] = 0.64, [hs/Fe] = 1.53 and [Eu/Fe] = 1.37, while Cohen et al. (2006) classified CS 22183–015 as a main-sequence star with [ls/Fe] = 0.55, [hs/Fe] = 1.76 and [Eu/Fe] = 1.70. In perfect agreement are instead the abundances of the CEMP-s/r CS 22898–027, with [ls/Fe] = 0.9, [hs/Fe] = 2.2 and [Eu/Fe] = 1.9 (Allen et al. 2012). Other objects analyzed by Allen et al. (2012) are: the CEMP-s giant CS 29512–073 ([Fe/H] = −2.06), the two CEMP-s BS 16077–077 and BS 16080–175, a CEMP-s/r CS 22887–048, and the CEMP-s/r giant BS 17436+058. Two of them were members of the sample first presented by Tsangarides (2005): BS 17436+058, which is now classified as CEMP-s/r owing to the higher revised Eu abundance ([Eu/Fe] = 1.13), and BS 16080–175.

Placco et al. (2013) provide a detailed analysis of two newly discovered stars, the CEMP-s HE 2138–3336 (black plus symbol) and the CEMP-s/r HE 2258–6358 ([Eu/Fe] = 1.68; violet diamond). HE 2138–3336 ([Fe/H] = −2.79) has the highest [Pb/Fe] abundance ratio measured so far if non-local thermodynamic equilibrium corrections are included ([Pb/Fe] = +3.84), second only to the CEMP-s/r CS 29497–030 ([Pb/Fe] = 3.65; Ivans et al. 2005). Cui et al. (2013) discovered a new CEMP-s/r giant, HE 1405–0822 with [Eu/Fe] = 1.54 (green diamond). A large number of both s- and r- process elements are detected for this star, including two lines for Nb ([Nb/Fe] = 0.98 ± 0.30). As Tc, Nb is an indicator of the binarity of the stars. This is the second CEMP-s/r star with Nb determination (see CS 29497–030 by Ivans et al. 2005). [Nb/Zr] = 0.18 supports the binary scenario.

Matrozis et al. (2012; brown diamond) provided an independent analysis for the CEMP-s/r giant HD 209621 by Goswami & Aoki (2010). While metallicity and effective temperature found by both works are in agreement ([Fe/H] = −1.9; Teff = 4400 and 4500 K), the gravity estimated by Matrozis et al. (2012) is much lower than that found by Goswami & Aoki (2010) log g = 1.0 and 2.0 cgs). The discrepancy previously detected among the light s-elements ([Zr/Y] ∼ 1.4) has been substantially reduced ([Zr/Y] = 0.5), in better agreement with theoretical AGB models.

Pereira et al. (2012) study the new high-velocity CH giant CD-62+1346 with [Fe/H] = −1.6 and high carbon and s-element abundances (brown ‘x’). They also discuss HD 5223 (Goswami et al. 2006), showing that it is another example of a high-velocity CH star that exceeds the Galactic escape velocity. Unfortunately, no Eu abundance is given for these stars.

G 24–25 is a CH metal-poor subgiant ([Fe/H] = −1.4) studied by Liu et al. (2012) yellow diamond), with a period of P = 3452 ± 67 days (Latham et al. 2002).

It is noteworthy that SDSS J1707+58 is now discovered to be an RR Lyrae star (Kinman et al. 2012; see Stancliffe et al. 2013 for a theoretical interpretation), instead of a main-sequence CEMP-s star (Aoki et al. 2008). SDSS J1707+58 is one
of the most metal-poor RR Lyrae stars known to date with $[\text{Fe/H}] = -2.92$, about 0.4 dex lower than that found by Aoki et al. (2008). It shows a high s-process abundance, with $[\text{Ba/Fe}] = 2.83 \pm 0.51$ (Sr has larger errors with $[\text{Sr/Fe}] = 0.75 \pm 0.65$). Owing to the limited number of revised observations, SDSS J1707+58 is not included in Fig. 1. Another RR Lyrae star showing mild s-process enhancement is TY Gru (Preston et al. 2006).

Additional newly discovered CEMP-s stars (for which only Sr and Ba among s-elements are detected) are: ten stars by Aoki et al. (2013) SDSS J0002+2928, SDSS J0126+0607, SDSS J1245-0738, SDSS J1349-0229, SDSS J1734+4316, SDSS J1836+6317, SDSS J1626+1458, as well as SDSS J0711+6702, SDSS J1036+1212, SDSS J1646+2824, having enhanced Ba but subsolar $[\text{Sr/Fe}]$. Among them, three exhibit large excesses of Ba ($[\text{Ba/Fe}] > 1$; SDSS J1836+6317 and SDSS J1734+4316; SDSS J0126+0607 has Ba = +3.2). One exhibits a moderate excess of Ba ($[\text{Ba/Fe}] = +0.8$; SDSS J0711+6702). SDSS J1836+6317 and SDSS J12450738 are CEMP-s stars with large excesses of Na and Mg. Two new CEMP-s have been analysed by Spite et al. (2013), SDSS J111407.07+182831.7 and SDSS J114323.42+202058.0 ($[\text{Fe/H}] < -3$), very likely belonging to binary systems. Two additional possible CEMP-s are analyzed by Yong et al. (2013): HE 02071423 and 52972-1213-507. Note that for these last stars no information is available among r-process elements. For accurate analyses additional data are needed.

The number of CEMP-s/r stars has increased from seventeen to twenty-four. By looking at the stars having not undergone the first dredge-up episode (top panels), the range covered by the averaged $[h\alpha/l\alpha]$ ratios in CEMP-s/r stars (large symbols) seems to agree better with that of CEMP-s stars (small symbols) if the stars by Allen et al. (2012) are included in the analysis. This may suggest that similar $[h\alpha/l\alpha]$ are shown by main-sequence CEMP-s and CEMP-s/r stars. However, we strongly highlight the discrepant abundances obtained for some stars by different authors (e.g., CS 29503-010 with $\Delta[\text{Fe/H}] = 0.6$ dex). As discussed by Allen et al. (2012), different authors employ different procedures which could involve different line lists, atomic data for the lines used, adopted solar abundances, model atmospheres, and spectrum synthesis codes. This suggests a sort of caution in combining data from the literature, and we propose that detailed analyses of individual stars are the more suitable starting point to improve theoretical AGB models and to understand the discrepancies still present between theory and observations (see Bisterzo et al. 2012).

An updated study of the CEMP-s and CEMP-s/r stars recently discovered is planned. Promising spectroscopic results are expected in the near future (e.g., GAIA-ESO mission, as well as SkyMapper and LAMOST surveys, or the planned TMT facility). This will significantly increase the number of newly discovered stars, which are observed with high resolution, and will help to shed light on the presently debated issues on the origin of CEMP-s and CEMP-s/r stars.

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Fig. 1. Right panels: theoretical predictions of \([\text{hs/ls}]\) versus metallicity for AGB models with initial mass \(M = 1.3\) and \(1.5\,M_\odot\) (top and bottom panels, respectively). A range of \(^{13}\text{C}\)-pockets (cases \(\text{ST} \times 2 - \text{ST/45}\)) is needed to interpret the observations of CEMP-s and CEMP-s/r stars. We display with blue symbols the sample of stars analyzed by Bisterzo et al. 2011. As made by Bisterzo et al. 2011 main-sequence/turn-off and subgiants not having suffered FDU are compared with \(M = 1.3\,M_\odot\) model (top panel); subgiants/giants are compared with \(M = 1.5\,M_\odot\) models and \(\text{dil} = 1.0\) dex to simulate FDU mixing (bottom panel). CEMP-s stars without europium detection are indicated by blue plus symbols. With respect to previous works, the following objects are added to the sample: Allen et al. 2012 studied 9 CEMP-s/r stars (big red diamonds), and three CEMP-s stars (small red diamonds); Placco et al. 2013 discovered a new CEMP-s/r giant (HE 2258–6358; violet big diamond) and a CEMP-s main-sequence turnoff star (HE 2138–3336; black plus symbol, for which a low upper limit for Eu is detected); the new CEMP-s/r giant HE 1405–0822 by Cui et al. 2013; Placco et al. 2013 discovered a CEMP-s giant HE 2258–6358 (HE 2258–6358; violet big diamond); Placco et al. 2013 discovered a CEMP-s main-sequence turnoff star (HE 2138–3336; black plus symbol, for which a low upper limit for Eu is detected); the new CEMP-s/r giant HE 1405–0822 by Cui et al. 2013; the CH star G 24–25 by Liu et al. 2012; the CEMP-s/r giant HD 209621 by Matrozis et al. 2012; the CEMP-s star CD 621346 by Pereira et al. 2012; the CEMP-s/r giant HD 209621 by Matrozis et al. 2012.

Left panels: same as the right panels, but CEMP-s/r are compared with AGB models with high initial r-enhancement \([r/Fe]_{\text{ini}} = 2.0\). Typical error bars are \([\text{hs/ls}] \sim 0.3; \,[\text{Fe/H}] \sim 0.2\).

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Fig. 2. The same as Fig. 1 right panels, but for [Pb/hs] versus metallicity.

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