The effect of r-process enhancement in binary CEMP-s/r stars

S. Bisterzo∗
Dipartimento di Fisica Generale, Università di Torino, via P. Giuria 1, 10025 Torino, Italy
E-mail: bisterzo@ph.unito.it

R. Gallino
Dipartimento di Fisica Generale, Università di Torino, via P. Giuria 1, 10025 Torino, Italy
INAF Osservatorio Astronomico di Collurania, via M. Maggini, 64100 Teramo, Italy
E-mail: gallino@ph.unito.it

About half of carbon and s-process enhanced metal-poor stars (CEMP-s) show a high r-process enrichment (CEMP-s/r), incompatible with a pure s-process contribution. CEMP-s stars are of low mass (M < 0.9 M⊙) and belong to binary systems. The C and s-process enrichment results from mass transfer by the winds of the primary AGB companion (now a white dwarf). The nucleosynthesis of the r-process, instead, is believed to occur in massive stars exploding as Supernovae of Type II. The most representative r-process element is Eu (95% of solar Eu).

We suggest that the r-process enrichment was already present by local SNII pollution in the molecular cloud from which the binary system formed. The initial r-enhancement does not affect the s-process nucleosynthesis. However, the s-process indicators [hs/ls] (where ls is defined as the average of Y and Zr; hs as the average of La, Nd, Sm) and [Pb/hs] may depend on the initial r-enhancement. For instance, the hs-peak has to account of an r-process contribution estimated to be 30% for solar La, 40% for solar Nd, and 70% for solar Sm. A large spread of [Eu/Fe] is observed in unevolved halo stars up to [Eu/Fe] ~ 2. In presence of a very high initial r-enrichment of the molecular cloud, the maximum [hs/Fe] predicted in CEMP-s/r stars may increase up to 0.3 dex. Instead, the spread of [Y,Zr/Fe] observed in unevolved halo stars reaches a maximum of only ~ 0.5 dex, not affecting much the predicted [ls/Fe]. This is in agreement with observations of CEMP-s/r stars that show an observed [hs/ls] in average higher than that observed in CEMP-s. Preliminary results are presented.
1. Introduction

It is commonly believed that the $s$- and $r$-processes derive from separate astrophysical sites \[1\]. The nucleosynthesis of the $s$-process occurs in stars of low mass ($1.3 \leq M/M_\odot \leq 8$) during their thermally pulsing asymptotic giant branch (TP-AGB) phase. The main neutron source is the $^{13}\text{C}(\alpha, n)^{16}\text{O}$, which burns radiatively at $T \sim 0.9 \times 10^8$ K during the interpulse period in the region between the H- and He-shell (He-intershell). A second neutron source, $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, is marginally activated at the bottom of the recurrent convective thermal instability (thermal pulse, TP) in the He-intershell, mainly affecting the abundance at the branching points that are sensitive to temperature and neutron density. The $s$-process elements are mixed with the surface during the third dredge-up (TDU) episodes, in which the convective envelope engulfs part of the He-intershell, after the quenching of a TP. We refer to the reviews by \[2, 3\] for major details on the AGB nucleosynthesis.

Instead, the physical environment for the $r$-process is still unknown, although SNII are the most promising candidates. For elements from Ba to Bi, observations of very metal-poor stars with high $r$-enhancement (e.g., CS 22892–052 \[4\]) show an abundance distribution well reproduced by a scaled solar $r$-process residual contribution \[5\]. Instead, lighter neutron capture elements with $Z \leq 47$ show values lower than the scaled solar-system $r$-process \[6, 7\]. The nucleosynthesis site(s) and the exact contributions from different primary processes to Sr, Y, Zr is highly debated \[8, 9, 10, 11, 12\], although also related to massive stars. A large spread is observed for $[\text{Eu}/\text{Fe}]$ and for $[\text{Sr,Y,Zr}/\text{Fe}]$ in unevolved halo stars. For $[\text{Fe/H}] < -2$, different ranges are observed for Eu and Sr, Y, Zr: $-1 \leq [\text{Eu}/\text{Fe}] \leq 2$ with an average around 0.5 dex, while $-1 \leq [\text{Sr,Y,Zr}/\text{Fe}] \leq 0.5$ with an average around 0 dex \[8, 12\]. This may be interpreted as a signature of incomplete mixing in the gas cloud from which these stars have formed \[13, 14\], as well as an indication of different and uncorrelated primary process contributions.

In the last years, a quite large number of carbon and $s$-process enhanced metal-poor (CEMP-$s$) stars have been detected. CEMP-$s$ are main-sequence/turnoff or giants of low mass ($M < 0.9 M_\odot$). The most plausible explanation for their peculiar high $s$-element abundances is mass transfer by stellar winds from the most massive AGB companion (now a white dwarf). About half of these CEMP-$s$ stars are also highly enhanced in $r$-process elements (CEMP-$s/r$). The observed $r$-enhancement in these stars reflects the observations of unevolved Galactic stars at low metallicity. CEMP-$s/r$ stars show abundance patterns incompatible with a pure $s$-process nucleosynthesis. While a pure $s$-process predicts $[\text{La}/\text{Eu}] \sim 0.8 - 1.1$ (where La and Eu are typical $s$- and $r$-process elements, respectively), CEMP-$s/r$ stars show $0.0 \leq [\text{La}/\text{Eu}] \leq 0.4$, with $[\text{La}/\text{Fe}]$ and $[\text{Eu}/\text{Fe}]$ up to $\sim 2$ dex. Different scenarios have been proposed in the literature to explain the origin of CEMP-$s/r$ (e.g., \[13, 16\]).

We suggest that the molecular cloud from which the binary system formed was already enriched in $r$-process elements by local pollution of SNII ejecta \[1, 15\]. This hypothesis is supported by numerical simulations by \[17\], who found that SNII explosion in a molecular cloud may trigger the formation of binary systems. These simulations may explain the very high fraction of CEMP-$s/r$ ($\sim 50\%$) among the CEMP-$s$.

We present here a preliminary analysis of a comparison between AGB theoretical predictions and spectroscopic observations of CEMP-$s$ and CEMP-$s/r$ stars. A detailed discussion will be
presented in Bisterzo et al. (in preparation).

2. Results

Among CEMP-s stars in the literature, we selected only those with Eu detection. About half of them are CEMP-s/r.

In Fig. 1, we analyse the s-process indicator [hs/ls] (where ls = Y, Zr and hs = La, Nd, Sm) versus metallicity, by comparing CEMP-s/r and CEMP-s observations with AGB models of initial mass $M = 1.3 M_\odot$ (left panel) or $1.5 M_\odot$ (right panel). AGB models are described by [19] (updated by [20]). Starting from the case ‘ST’ defined by [19, 5], a range of $^{13}$C-pockets is adopted by multiplying or dividing the $^{13}$C (and $^{14}$N) in the pocket by different factors. Theoretical lines in the Figure represent pure s-process AGB predictions for cases from ‘ST×2’ down to ‘ST/150’. For simplicity, in this preliminary analysis we distinguish between main-sequence/turnoff stars or subgiants having not suffered the first dredge-up (FDU) episode (diamonds in left panel), and late subgiants or giants (down-rotated triangles in right panel). The FDU involves about 80% of the mass of the star [2]. In case of binary systems with mass transfer like CEMP-s stars, this mixing strongly dilutes the C and s-rich material previously transferred from the AGB companion. This means that the [El/Fe] observed in a CEMP-s giant is about 1 dex lower than in the envelope of the AGB companion\(^1\). CEMP-s/r stars are represented by big symbols while CEMP-s by little symbols. References are given in the caption of the Figures. In average, CEMP-s/r stars show higher [hs/ls] than CEMP-s. Moreover, some CEMP-s/r have an observed [hs/ls] ratio higher than the AGB predictions, but still compatible within the errorbars.

In Fig. 2, the observed [hs/ls] ratio is compared with AGB models of initial masses $M = 1.3 M_\odot$ (left panel) or $1.5 M_\odot$ (right panel) with a high initial r-process enhancement, $[r/Fe]^{ini} = 2.0$ dex (corresponding to $[Eu/Fe]^{ini} = 2.0$ dex). Only CEMP-s/r stars are shown in this Figure (big symbols). The choice of the initial r-process contribution to heavy elements was based on the r-process solar predictions [5, 20]. In particular, we applied an initial r-process contribution of 30% to solar La, 40% to solar Nd, and 70% to solar Sm. In first approximation we assumed a solar-scaled Y and Zr. This because the [Y,Zr/Fe] ratios observed in unevolved halo stars reach maximum values of about 0.5 dex, which little affects the [ls/Fe] in CEMP-s. The resulting maximum [hs/ls]$_{s+r}$ with $[r/Fe]^{ini} = 2.0$ shown in Fig. 2 is about 0.3 dex higher than the predicted [hs/ls]$_{s}$ with no initial r-enhancement. Note that the s-process index [hs/ls]$_{s}$ is independent of the dilution factor if no initial r-enhancement is adopted (Fig. 1, right panel). Instead, in case of a high initial r-enhancement, the dilution factor affects [hs/ls]$_{s+r}$, because both stars belonging to the binary system are initially r-enriched. In Fig. 2, right panel, a dil = 1.0 dex is applied.

3. Conclusions

To explain the origin of CEMP-s/r, we hypothesised that the molecular cloud from which the binary system formed was already enriched in r-process elements. Subsequently, the s-process

\(^1\)To simulate mixing processes we define the logarithmic ratio ‘dil’ as dil = log ($\frac{M_{env}}{M_{AGB}^{trans}}$), where $M_{env}$ represents the mass of the convective envelope of the observed star before the mixing, and $\Delta M_{AGB}^{trans}$ is the AGB total mass transferred (see [20]).
elements synthesised by the AGB companion are transferred by stellar winds on to the observed star. The \( s \)-process nucleosynthesis is not affected by the initial \( r \)-enhancement of the molecular cloud. However, for high \( r \)-process enrichment \((\text{[r/Fe]}^{\text{ini}} = 2)\), one should account for the \( r \)-process contribution to solar La, Nd and Sm (30\%, 40\%, 70\%). In agreement with the \([\text{Y}, \text{Zr}/\text{Fe}]\) observed in unevolved halo stars, we adopt solar scaled initial Y and Zr values. This increases \([\text{hs}/\text{ls}]\) by \( \sim 0.3 \) dex. This is sustained by observations in CEMP-\( s/r \) stars, which show an \([\text{hs}/\text{ls}]\) ratio in average higher than that observed in CEMP-\( s \). Note that the \([\text{hs}/\text{ls}]\) observed in CEMP-\( s/r \) stars may be in agreement with pure \( s \)-process predictions within the errorbars. A deeper analysis will be given in Bisterzo et al., in preparation.
References

[1] Burbidge, E. M., Burbidge, G. R., Fowler, W. A., Hoyle, F. 1957, Rev. Mod. Phys., 29, 4
[2] Busso, M., Gallino, R. & Wasserburg, G. J., 1999, ARA&A, 37, 239
[3] Käppeler, F., et al., 2010, Rev. Mod. Phys., accepted
[4] Sneden, C., et al. 2003, ApJ, 591, 936
[5] Arlandini et al. (1999), ApJ, 525, 886
[6] Wasserburg, G. J., Busso, M. & Gallino, R. 1996, ApJ, 466, L109
[7] Sneden, C., Cowan, J. J., Gallino, R. (2008), ARA&A, 46, 241
[8] Travaglio et al. 2004, ApJ, 601, 864
[9] Farouqi, K., et al. 2010, ApJ, 712, 1359
[10] Pignatari, M. et al. 2010, ApJ, 710, 1557
[11] Qian, Y.-Z. & Wasserburg, G.J. 2008, ApJ, 687, 272
[12] Montes, F., et al. 2007, ApJ, 671, 1685
[13] Ishimaru, Y., & Wanajo, S. 1999, ApJ, 511, L33
[14] Travaglio, C., Galli, D., & Burkert, A. 2001, ApJ, 547, 217
[15] Jonsell et al. (2006), A&A, 451, 651
[16] Cohen et al. (2003), ApJ, 588, 1082
[17] Vanhala & Cameron (1998), ApJ, 508, 291
[18] Bisterzo et al. (2009), PASA, 26, 314
[19] Gallino et al. (1998), ApJ, 497, 388
[20] Bisterzo et al. (2010), MNRAS, 404, 1529
[21] Aoki, W., et al. 2002b, ApJ, 580, 1149
[22] Aoki, W., et al. 2006, ApJ, 650, 127
[23] Aoki, W. et al. 2008, ApJ, 678, 1351
[24] Barklem, P. S. et al. 2005, A&A, 439, 129
[25] Behara, N. T., et al. 2010, A&A, 513, A72
[26] Cohen, J. G. et al. 2006, AJ, 132, 137
[27] Ivans et al. (2005), ApJ, 627, 145
[28] Johnson, J. A., & Bolte, M. 2002, ApJ, 579, 87
[29] Johnson, J. A., & Bolte, M. 2004, ApJ, 605, 462
[30] Thompson, I. B. et al. 2008, ApJ, 677, 556
[31] Tsangarides, S. A. 2005, Ph.D. Thesis, Open University (United Kingdom), DAI-C 66/04
[32] Aoki, W. et al. 2002a, PASJ, 54, 427
[33] Barbuy, B., et al. 2005, A&A, 429, 1031
[34] Goswami, A., & Aoki, W. 2010, MNRAS, 404, 253
[35] Goswami, A., et al. 2006, MNRAS, 372, 343
[36] Masseron, T. et al. 2006, A&A, 455, 1059
[37] Roederer, I. U. et al. 2008, ApJ, 679, 1549
[38] Van Eck, S., Goriely, S., Jorissen, A., Plez, B. 2003, A&A, 404, 291