Low-metallicity AGB models: the H profile in the $^{13}\text{C}$-pocket and the effect on the $s$-process

S. Bisterzo$^1$ and S. Cristallo$^{2,3}$

$^1$ Dipartimento di Fisica Generale, Università di Torino, 10125 (To) Italy
e-mail: bisterzo@ph.unito.it
$^2$ Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, 18071 Granada, Spain
$^3$ INAF Osservatorio Astronomico di Collurania, via M. Maggini, 64100 Teramo, Italy

Abstract. The $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction is the major neutron source in low-mass asymptotic giant branch (AGB) stars, where the main and the strong $s$-process components are synthesised. After a third dredge-up (TDU) episode, $^{13}\text{C}$ burns radiatively, in a thin pocket which forms in the top layers of the He-intershell, by proton capture on the abundant $^{12}\text{C}$. Therefore, mixing of a few protons from the H-rich envelope into the He-rich region is required. However, the origin and the efficiency of this mixing episode are still matters for debate and, consequently, the formation of the $^{13}\text{C}$-pocket represents a significant source of uncertainty that affects AGB models. We analyse the effects on the nucleosynthesis of the $s$-elements caused by the variation of the hydrogen profile in the region where the $^{13}\text{C}$-pocket forms for an AGB model with $M = 2 M_\odot$ and $[\text{Fe/H}] = -2.3$. In particular, we concentrate on three isotopes ($^{89}\text{Y}$, $^{139}\text{La}$ and $^{208}\text{Pb}$), chosen as representative of the three $s$-process peaks.

Key words. Stars: C and $s$ rich – Stars: abundances – Stars: nucleosynthesis

1. Introduction

During their thermally pulsing (TP) phase, low-mass asymptotic giant branch (AGB) stars are the site of the main and the strong component of the $s$-process, which is responsible for the nucleosynthesis of half the nuclei from Sr to Pb/Bi. After a limited number of pulses, the convective envelope penetrates into the He-intershell at the quenching of each convective instability, mixing freshly synthesized $^4\text{He}$, $^{12}\text{C}$ and $s$-process elements to the surface (third dredge-up, TDU).

Send offprint requests to: P. Bonifacio
vances in mass, compressing and heating the underlying material, and at $T \approx 0.9 \times 10^8$ K the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction starts releasing neutrons in radiative conditions. Later on, the synthesised $s$-process nuclei are engulfed and diluted in the next convective region generated by TP.

Different evolutionary and post-processing codes have been developed in recent years to understand nucleosynthesis in low-mass AGB stars (e.g. Straniero et al. 1995, Gallino et al. 1998, Goriely & Mowlavi 2000, Karakas & Lattanzio 2003, 2007, Campbell & Lattanzio 2008, Straniero et al. 2006). Several mechanisms have been proposed to reproduce the mixing leading to the $^{13}$C-pocket formation. These include semi-convection, models with rotation (Langer et al. 1999, Herwig et al. 2003, Siess et al. 2004), gravity waves (Denissenkov & Tout 2003), exponential diffusional overshooting at the borders of all convective zones (Herwig et al. 1997) and opacity-induced overshooting at the base of the convective envelope (Straniero et al. 2006). A clear answer to the properties of such mixing has not been reached yet.

We test here the effects of the nucleosynthesis of the $s$ elements by adopting different H profiles in the region of the $^{13}$C-pocket forming after the first TDU of an AGB model with initially $M = 2M_\odot$ and $[\text{Fe}/\text{H}] = -2.3$. Comparison between the full evolutionary FRANEC (Frascati Raphson-Newton Evolutionary Code) models (Cristallo et al. 2009), hereinafter C09) and FRANEC models coupled with a post-processing nucleosynthesis method (Gallino et al. 1998, Bisterzo et al. 2010) are presented.

2. Results

C09 introduce a mixing algorithm which depends on a free parameter $\beta$ in their full evolutionary models to mimic the formation of a transition zone between the fully convective envelope and the radiatively stable H-exhausted core. Thus, a partial mixing of protons takes place and leads to the formation of a $^{13}$C rich layer. Its mass and profile decrease with the number of pulses (see C09, their figs 4 and 8).

Fig. 1 top panel, shows this region. In the uppermost layers of the pocket, where protons are more abundant, the $^{13}$C-pocket overlaps with a $^{14}$N-pocket, which forms via the $^{13}$C(p,$\gamma$)$^{14}$N reaction. $^{14}$N acts as a neutron poison via the resonant reaction $^{14}$N(n,p)$^{15}$C. Thus by subtracting neutrons from the nucleosynthesis of the $s$-process elements. Fig. 1 bottom panel, shows the same mass region at the end of the $^{13}$C burning. We concentrate on three isotopes, $^{89}$Y, $^{139}$La and $^{208}$Pb, chosen as representative of the three $s$-process peaks. As expected, at this low metallicity, a large amount of $^{208}$Pb is produced (Gallino et al. 1998). Maximum Pb production occurs in the central layers of the pocket where $X(^{13}\text{C}) > X(^{14}\text{N})$ (we find $X(^{208}\text{Pb}) = 4.5 \times 10^{-5}$), while Y and La show definitely lower abundances: $X(^{89}\text{Y}) \approx X(^{139}\text{La}) \approx 6 \times 10^{-7}$. In the outer and inner regions of the pocket, however, $^{89}$Y and $^{139}$La show peaked distributions. Note that, in the outer tail, $s$-process elements are efficiently synthesised even if $X(^{13}\text{C}) < X(^{14}\text{N})$.

In order to test the effect of these tails on Y, La and Pb with different H profiles, we use the post-processing nucleosynthesis models described by Bisterzo et al. (2010). We adopt the H profile of Gallino et al. (1998, case ST, their fig. 2). Then we introduce a further region in the pocket (with mass $M = 4 \times 10^{-4} M_\odot$) in which we change the abundances of $^{13}$C and $^{14}$N to simulate different H profiles in the tails. We multiply or divide by different factors the $^{13}$C and $^{14}$N abundances in the pocket. Note that the H profile and the mass of the pocket are kept constant pulse by pulse. The envelope abundances of the two $s$-process indices $[\text{La}/\text{Y}]$ and $[\text{Pb}/\text{La}]$ obtained with the post-processing method are shown in Tables 1 and 2. In Table 1 first group, we show the results computed with standard $^{13}$C-pockets (with three zones as Gallino et al. 1998) for various $^{13}$C-pocket efficiencies (from

1 See C09 for the procedure followed to calibrate it.

2 In fact a range of $^{13}$C-pockets is introduced in order to interpret the spread in the $s$-elements observed in CEMP-$s$ stars.
process element surface overabundances. For very low \(^{13}\)C efficiencies the \(s\)-process production is mainly due to the \(^{22}\)Ne(\(\alpha\), \(n\))\(^{23}\)Mg reaction ([Bisterzo et al. 2011]). This minimizes the effects of additional \(^{13}\)C and \(^{14}\)N. For intermediate cases the introduction of the fourth zone instead reduces the maximum [La/Y] to about 0.5 dex and the maximum [Pb/La] to about 1.6 dex. In Table 1 we select the highest \(^{13}\)C-pocket case (case ST \(\times\) 2) and we test the effect of an added fourth zone with different \(X(^{13}\)C) values (assuming \(X(^{14}\)N) is negligible). We choose the ST \(\times\) 2 case because previous comparisons done at larger metallicities (C09) indicate that the best agreement between post-processed and full evolutionary models is found with this case. The standard case with three zones only (column II) gives [La/Y] = 0.50 and [Pb/La] = 2.04, while the addition of a fourth zone with \(X(^{13}\)C) = 3.8 \(\times\) 10\(^{-4}\) (test III) definitely lowers the [Pb/La] ratio (to 1.47) leaving practically untouched the [La/Y] ratio (at 0.56). Thus, a reasonable agreement between this test and C09 is found even at such low metallicities. After verifying that the tails of the \(^{13}\)C-pocket affect the \(s\) distribution, one may constrain the choice of the H profile through a study of spectroscopic observations in CEMP-\(s\) stars. Note that, for disc metallicities, the tails of the pocket do not influence the \(s\) distribution noticeably.

3. Conclusions

The maximum amount of \(^{13}\)C and \(^{14}\)N in the pocket and different hydrogen profiles (and therefore the amount of \(^{13}\)C and \(^{14}\)N in the tails of the pocket) modify the \(s\) abundance distribution. In particular, the \(s\)-process indices [La/Y] and [Pb/La] are sensitive to the tails of the pocket. At [Fe/H] = \(-2.3\) a large amount of \(^{208}\)Pb is produced when \(X(^{13}\)C) > \(X(^{14}\)N). A first interesting consequence caused by the addition of an outer tail in the pocket with \(X(^{13}\)C) < \(X(^{14}\)N) is that the maximum [La/Y] value attained with different \(^{13}\)C-efficiencies is reduced to about 0.5. Moreover, with a calibrated extra \(X(^{13}\)C) in the tails of the pocket, the maximum [Pb/La] is reduced to 1.4 dex. Comparison between theory and observations

![Fig. 1. \(^{13}\)C-pocket mass region for a full evolutionary AGB model of \(M = 2 M_\odot\) and [Fe/H] = \(-2.3\) (C09) after the first TDU, at the pocket formation (top panel) and at the end of the \(^{13}\)C burning (bottom panel).](image-url)
Table 1. Envelope abundances of \([\text{Y}/\text{Fe}], [\text{La}/\text{Fe}], [\text{Pb}/\text{Fe}]\) and their ratios, [\text{La}/\text{Y}] and [\text{Pb}/\text{La}], for a post-processing model of \(M = 2 M_\odot\) and \([\text{Fe}/\text{H}] = -2.3\) and various \(^{13}\text{C}\)-pocket efficiencies (from \(ST \times 2\) down to \(ST/24\)). The first group lists the results obtained with the standard \(^{13}\text{C}\)-pocket, while in the second group a further fourth zone with \(X(^{13}\text{C}) < X(^{14}\text{N})\) is added.

<table>
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<th>Cases</th>
<th>ST \times 2</th>
<th>ST</th>
<th>ST/1.5</th>
<th>ST/2</th>
<th>ST/6</th>
<th>ST/12</th>
<th>ST/24</th>
</tr>
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<tbody>
<tr>
<td>[\text{Y}/\text{Fe}]</td>
<td>1.68</td>
<td>1.39</td>
<td>1.33</td>
<td>1.35</td>
<td>1.98</td>
<td>2.35</td>
<td>2.45</td>
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<tr>
<td>[\text{La}/\text{Fe}]</td>
<td>2.18</td>
<td>1.88</td>
<td>1.92</td>
<td>2.10</td>
<td>2.85</td>
<td>2.94</td>
<td>2.71</td>
</tr>
<tr>
<td>[\text{Pb}/\text{Fe}]</td>
<td>4.22</td>
<td>4.12</td>
<td>4.09</td>
<td>4.06</td>
<td>3.82</td>
<td>3.44</td>
<td>2.69</td>
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<tr>
<td>[\text{La}/\text{Y}]</td>
<td>0.50</td>
<td>0.49</td>
<td>0.59</td>
<td>0.75</td>
<td>0.87</td>
<td>0.59</td>
<td>0.26</td>
</tr>
<tr>
<td>[\text{Pb}/\text{La}]</td>
<td>2.04</td>
<td>2.24</td>
<td>2.17</td>
<td>1.96</td>
<td>0.97</td>
<td>0.50</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

\[X(^{13}\text{C}) = \]
[2.18E-1 | 1.4E-1 | 9.3E-2 | 7.1E-2 | 2.3E-2 | 1.2E-2 | 5.8E-3 | 3.7E-2 | 3.5E-2 | 2.5E-2 | 1.9E-2 | 3.1E-3 | 1.6E-3]

\[X(^{14}\text{N}) = \]
[2.10 | 2.25 | 2.42 | 2.54 | 2.92 | 2.97 | 2.80 | 4.04 | 4.02 | 3.99 | 3.97 | 3.76 | 3.43 | 2.84]

\[X(^{13}\text{C}) < X(^{14}\text{N})\] zone 4

| \[\text{Y}/\text{Fe}\] | 1.58 | 1.75 | 1.89 | 2.00 | 2.40 | 2.58 | 2.64 |
| \[\text{La}/\text{Fe}\] | 2.10 | 2.25 | 2.42 | 2.54 | 2.92 | 2.97 | 2.80 |
| \[\text{Pb}/\text{Fe}\] | 4.04 | 4.02 | 3.99 | 3.97 | 3.76 | 3.43 | 2.84 |
| \[\text{La}/\text{Y}\] | 0.52 | 0.50 | 0.53 | 0.54 | 0.52 | 0.39 | 0.16 |
| \[\text{Pb}/\text{La}\] | 1.94 | 1.77 | 1.57 | 1.43 | 0.84 | 0.46 | 0.04 |

Table 2. The same as Table [1] but for a case \(ST \times 2\) and an added fourth zone with different \(X(^{13}\text{C})\) values, from 0 (standard case) up to \(4.3 \times 10^{-3}\). \(X(^{14}\text{N})\) is assumed to be negligible. In the last column the results obtained by C09 are listed.

| zone 4, standard I test II test III test IV test V test VI test VII test C09 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \[X(^{13}\text{C})\] | 0.0 | 2.9E-4 | 3.5E-4 | 3.8E-4 | 4.8E-4 | 5.8E-4 | 1.2E-3 | 4.3E-3 |
| \[\text{Y}/\text{Fe}\] | 1.68 | 2.23 | 2.21 | 2.19 | 2.09 | 1.97 | 1.74 | 1.75 | 1.12 |
| \[\text{La}/\text{Fe}\] | 2.18 | 2.60 | 2.65 | 2.75 | 2.80 | 2.76 | 2.48 | 2.27 | 1.57 |
| \[\text{Pb}/\text{Fe}\] | 4.22 | 4.21 | 4.23 | 4.22 | 4.23 | 4.24 | 4.29 | 4.33 | 2.88 |
| \[\text{La}/\text{Y}\] | 0.50 | 0.37 | 0.44 | 0.56 | 0.71 | 0.79 | 0.74 | 0.52 | 0.45 |
| \[\text{Pb}/\text{La}\] | 2.04 | 1.61 | 1.58 | 1.47 | 1.43 | 1.48 | 1.81 | 2.06 | 1.30 |

in CEMP-s stars is then needed in order to constrain the choice of the \(H\) profile in the central and outer regions of the \(^{13}\text{C}\)-pocket during AGB nucleosynthesis.

Acknowledgements. We are grateful to Roberto Gallino for helpful comments and discussions.

References

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