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

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Abstract. The ^{13}C(α, n)^{16}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}C burns radiatively, in a thin pocket which forms in the top layers of the He-intershell, by proton capture on the abundant ^{12}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}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}C-pocket forms for an AGB model with $M = 2\,M_{\odot}$ and [Fe/H] = −2.3. In particular, we concentrate on three isotopes (^{89}Y, ^{139}La and ^{208}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}He, ^{12}C and *s*-process elements to the surface (third dredge-up, TDU).

The major neutron source in low-mass AGB stars is the ^{13}C(α,n)^{16}O reaction, which burns radiatively during the interpulse period in a thin region at the top of the He-intershell (^{13}C-pocket). The physical mechanism that allows the formation of the ^{13}C-pocket is debated. A small number of protons are assumed to penetrate from the envelope into the He-intershell during TDU episodes (Iben & Renzini 1982). Then, at H reignition, a large amount of ^{13}C is synthesised in the top layers of the intershell by the ^{12}C(p,γ)^{13}N($\beta^{+}\nu$)^{13}C nuclear chain. This ^{13}C is of primary origin and, therefore, independent of the metallicity. During the interpulse, the H-burning shell ad-

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 $^{13}C(\alpha,n)^{16}O$ 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, 2003; 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 diffusive 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 on 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 $M = 2\,M_\odot$ and [Fe/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[1] 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 $^{14}N(n,p)^{14}C$. 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 $X(^{13}C) > X(^{14}N)$ (we find $X(^{208}Pb) = 4.5 \times 10^{-5}$), while Y and La show definitely lower abundances: $X(^{89}Y) \approx X(^{139}La) \approx 6 \times 10^{-9}$. 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 $X(^{13}C) < X(^{14}N)$.

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[2]. 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 [La/Y] and [Pb/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.

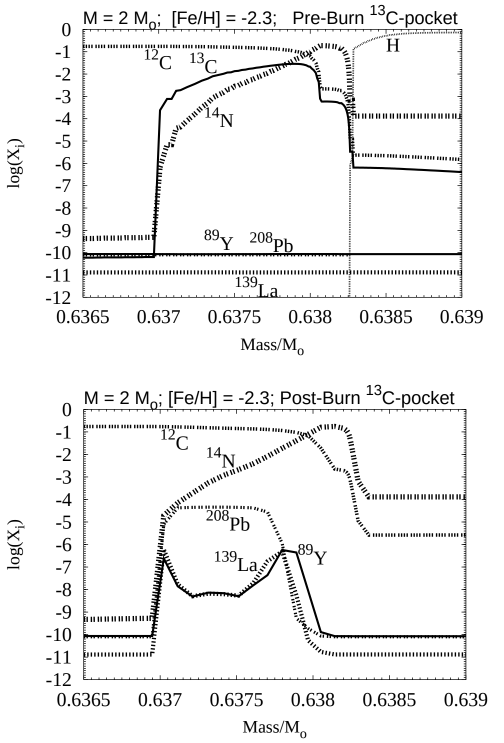

Fig. 1. ^{13}C-pocket mass region for a full evolutionary AGB model of $M = 2\,M_{\odot}$ and [Fe/H] $= -2.3$ (C09) after the first TDU, at the pocket formation (top panel) and at the end of the ^{13}C burning (*bottom panel*).

ST $\times$ 2 down to ST/24). These results are compared with models with an added fourth zone with $X(^{13}\mathrm{C}) < X(^{14}\mathrm{N})$ (Table 1, second group). This has been done to simulate the effect induced by the outer tail of the pocket shown in Fig. 1 by C09 model on post-processing calculation results. C09 obtain a final [La/Y] = 0.45 and [Pb/La] = 1.30. With the post-processing method and a range of standard ^{13}C-pockets, [La/Y] reaches a maximum value of about 0.9 (case ST/6) and [Pb/La] $\approx$ 2.2 (case ST/1.5). When adding the fourth zone, minimal variations are found for large and low ^{13}C-pocket efficiencies, while appreciable differences are found in the intermediate cases. For large ^{13}C abundances (case ST$\times$2), the addition of fourth zone leads to a large production of light elements (Ne, Na and Mg) whose poisoning effect induces a slightly decrease in the final s-process element surface overabundances. For very low ^{13}C efficiencies the s-process production is mainly due to the ^{22}Ne(α, n)^{25}Mg reaction (Bisterzo et al. 2010). 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 2 we select the highest ^{13}C-pocket case (case ST $\times$ 2) and we test the effect of an added fourth zone with different $X(^{13}\mathrm{C})$ values (assuming $X(^{14}\mathrm{N})$ 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 $X(^{13}\mathrm{C}) = 3.8 \times 10^{-4}$ (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 $X(^{13}\mathrm{C}) > X(^{14}\mathrm{N})$. A first interesting consequence caused by the addition of an outer tail in the pocket with $X(^{13}\mathrm{C}) < X(^{14}\mathrm{N})$ is that the maximum [La/Y] value attained with different ^{13}C-efficiencies is reduced to about 0.5. Moreover, with a calibrated extra $X(^{13}\mathrm{C})$ in the tails of the pocket, the maximum [Pb/La] is reduced to 1.4 dex. Comparison between theory and observations

Table 1. Envelope abundances of [Y/Fe], [La/Fe], [Pb/Fe] and their ratios, [La/Y] and [Pb/La], for a post-processing model of $M = 2\,M_\odot$ and [Fe/H] = −2.3 and various ^{13}C-pocket efficiencies (from ST × 2 down to ST/24). The first group lists the results obtained with the standard ^{13}C-pocket, while in the second group a further fourth zone with $X(^{13}\mathrm{C}) < X(^{14}\mathrm{N})$ is added.

Cases		ST × 2	ST	ST/1.5	ST/2	ST/6	ST/12	ST/24
	[Y/Fe]	1.68	1.39	1.33	1.35	1.98	2.35	2.45
	[La/Fe]	2.18	1.88	1.92	2.10	2.85	2.94	2.71
	[Pb/Fe]	4.22	4.12	4.09	4.06	3.82	3.44	2.69
	[La/Y]	0.50	0.49	0.59	0.75	0.87	0.59	0.26
	[Pb/La]	2.04	2.24	2.17	1.96	0.97	0.50	-0.02
	$X(^{13}\mathrm{C})$=	7.2E-2	3.7E-2	2.5E-2	1.9E-2	6.2E-3	3.1E-3	1.6E-3
	$X(^{14}\mathrm{N})$=	2.7E-1	1.4E-1	9.3E-2	7.1E-2	2.3E-2	1.2E-2	5.8E-3
zone 4	[Y/Fe]	1.58	1.75	1.89	2.00	2.40	2.58	2.64
$X(^{13}\mathrm{C}) < X(^{14}\mathrm{N})$	[La/Fe]	2.10	2.25	2.42	2.54	2.92	2.97	2.80
	[Pb/Fe]	4.04	4.02	3.99	3.97	3.76	3.43	2.84
	[La/Y]	0.52	0.50	0.53	0.54	0.52	0.39	0.16
	[Pb/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 × 2 and an added fourth zone with different $X(^{13}\mathrm{C})$ values, from 0 (standard case) up to 4.3×10^{-3}. $X(^{14}\mathrm{N})$ is assumed to be negligible. In the last column the results obtained by C09 are listed.

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

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