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Self-consistent ^{13}C pocket in low mass AGB stars and related nucleosynthesis

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Abstract. We present new results concerning the self-consistent formation of a tiny ^{13}C pocket in a star with initial mass $M = 3\ M_\odot$ and solar metallicity during the *Asymptotic Giant Branch* phase. The introduction of an exponentially decaying profile of velocity below the convective envelope during third dredge up episodes allows a small amount of protons to diffuse in the ^{4}He- and ^{12}C- rich zone, leading to the formation of a ^{13}C-rich layer, whose extension varies from pulse to pulse. The resulting *s*-process nucleosynthesis is discussed and compared with previous models. Moreover, new models show an enhancement factor of about 50% in the efficiency of *Third dredge up*, which starts when the core mass $M_{\rm H} \simeq 0.58\ M_\odot$, in better agreement with the observed C-star luminosity function.

Key words. *s*-process – AGB stars – nucleosynthesis

1. Introduction

During the *Asymptotic Giant Branch* (AGB) phase, the energy required to supply the surface irradiation is mainly provided by the shell H-burning, located just below the inner border of a deep convective envelope. The H-shell burning is recurrently interrupted by a series of thermonuclear runaways (*Thermal Pulses*, TPs) driven by a violent He ignition. As a consequence of a TP, the region between the two shells (He intershell) becomes unstable to convection for a short period, the external layers expand and, later on, the H-shell burning temporarily dies down. In the He intershell, He is partially converted to ^{12}C with a typical resulting mass fraction (in the top layers of this region) $X(^{12}\mathrm{C}) \sim 0.25$. Two neutron sources operate in the He intershell, due to α captures on ^{13}C and ^{22}Ne. The $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ reaction occurs in radiative conditions in the interpulse period, when the temperature reaches $T = 1 \cdot 10^{8}$ K. The $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ reaction is marginally activated during the convective pulse, where the temperature rises up to $T \sim 3{\cdot}10^{8}$ K. The ^{13}C neutron source covers the major role in the production of *s* elements in low mass stars Gallino et al. (1998). The ^{13}C left in the ashes of H-burning cannot justify the *s*-process distribution observed in AGB stars, thus some mechanism is needed in order to allow a small amount of protons from the envelope to diffuse into the top layers of the He intershell.

This occurs just after a TP, when the shell H-burning is off and the inner border of the convective envelope penetrates into the H-exausted region. This is the so called *Third*

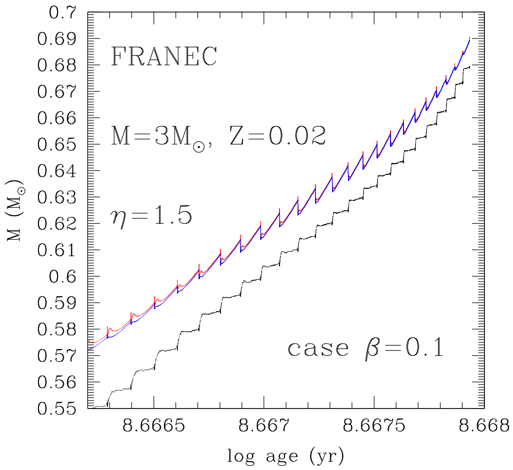

Fig. 1. Thermal Pulse AGB phase for a star with initial mass $M = 3\ M_\odot$ and solar metallicity.

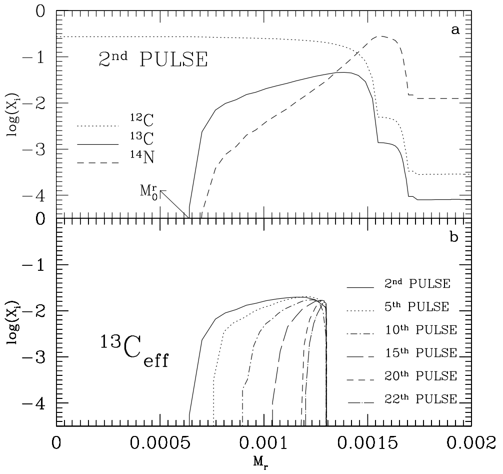

Fig. 2. panel *a*: abundances profiles in the ^{13}C *pocket* at the second TP with TDU (M_0^r=0.5876 $M_\odot$); panel *b*: evolution of the ^{13}C pocket pulse by pulse.

Dredge Up (TDU) episode, responsible for the surface chemical enrichment of ^{12}C and *s*-elements observed in AGB stars. Proton diffusion has been obtained by introducing, in the FRANEC code, at the bottom of the convective envelope, an exponentially decaying profile of the convective velocity:

$$v = v_{bce} \exp\left(-\frac{z}{\beta H_p}\right), \tag{1}$$

where z is distance from the convective boundary, v_{bce} is the average element velocity at the convective boundary (as derived by means of the mixing length theory), H_p the pressure scale height at the convective boundary (Cristallo et al. 2001; Chieffi et al. 2001). Applying this algorithm to the convective boundaries, we obtain a negligible amount of overshoot, except when convection penetrates into a region with lower opacity (as in the case of TDU).

2. New models

Results presented here refer to a star with initial mass $M = 3\ M_\odot$ and $Z = 0.02$; mass loss is taken into account adopting the Reimers's formula Reimers (1975), setting $\eta = 1.5$. Along the TP-AGB phase (lasting for about 2 Myr) TDU occurs self-consistently for 22 pulses and starts at $M_{\rm H} \simeq 0.58\ M_\odot$. The introduction of the velocity profile helps TDU to occur earlier and to be more efficient (Chieffi et al. 2001), by at least 50% (for β=0.1), with respect

TP	Previous models		New models	
n.	M_H	M_{TDU}	M_H	M_{TDU}
1	0.611	0.10	0.583	0.12
2	0.618	0.50	0.589	0.70
3	0.625	1.00	0.594	1.25
4	0.631	1.50	0.600	2.10
5	0.637	1.90	0.605	3.10
6	0.643	2.10	0.610	4.00
7	0.648	2.20	0.615	4.40
8	0.654	2.40	0.619	4.80
9	0.659	2.40	0.624	5.00
10	0.664	2.50	0.628	5.20
11	0.669	2.70	0.632	5.00
12	0.673	2.80	0.636	4.75
13	0.678	2.80	0.641	4.75
14	0.682	2.70	0.645	4.60
15	0.686	2.60	0.649	4.60
16	0.690	2.40	0.654	4.20
17	0.695	2.20	0.658	3.60
18	0.699	2.00	0.663	2.80
19	0.703	1.80	0.668	2.60
20	0.707	1.70	0.673	2.00
21	0.711	1.50	0.678	1.20
22	0.715	1.40	0.684	0.20
23	0.719	1.30	-	-
24	0.723	1.20	-	-
25	0.727	1.00	-	-
TOT		46.7		71.0

Table 1. Extension in mass (in units of $M_\odot$) of the H-exhausted core and dredged up material (in units of 10^{-3} $M_\odot$) for pulses with TDU in the previous models Straniero et al. (1997) and in the new models.

to Straniero et al. (1997). Data are shown in Table 1 and summarized in Fig. 1

Proton diffusion into the top layers of the He intershell allows the formation of a tiny ^{13}C- and ^{14}N-rich zone, whose profiles are plotted in Fig. 2 (panel *a*). The extension in mass of this pocket decreases pulse by pulse, starting from 6.6×10^{-4} $M_\odot$ at the 2nd thermal pulse with TDU, down to 1×10^{-4} $M_\odot$ at the last pulse with TDU. Fig. 2 (panel *b*) shows the evolution of ^{13}C in the pocket vs. mass: here we plot the *effective* mass fraction $X(^{13}\mathrm{C}_{\mathrm{eff}})$, where $X(^{13}\mathrm{C}_{\mathrm{eff}})=X(^{13}\mathrm{C})-\mathrm{X}(^{14}\mathrm{N})$. This variable is introduced under the assumption that every ^{14}N seed present in the ^{13}C pocket captures a neutron because of its large abundance and its resonant (n,γ) cross section (see, *e.g.* Lugaro et al. 2003) Note that the residual ^{14}N nuclei in the upper layers of the pocket will be totally converted into ^{22}Ne during the following convective pulse. The *s*-process distribution has been calculated by a *post-processing* technique, using the outputs of the FRANEC code (*e.g.*, temperatures, densities and extension in mass of each TP), and parameterizing the profiles showed in Fig. 2 in nine zones, each of them characterized by a different $X(^{13}\mathrm{C}_{\mathrm{eff}})$ and extension in mass.

Preliminary results are displayed in Fig. 3 where we report the production factors of *s*-processed isotopes with respect to the initial abundances, using an updated set of neutron capture cross sections Bao et al. (2000). The production factors are calculated for the He intershell matter cumulatively mixed with the envelope by TDU episodes. Filled circles represent *s*-only isotopes, while small crosses are for all other isotopes involved in the *s*-process; solar abundances used for reference are from Anders & Grevesse (1989). The distribution showed in panel *a* doesn't reproduce the solar *main component*, *i.e.* the *s*-process distribution for A≥90. Instead, the distribution found is characterized by a lower production for the heavier nuclei beyond Ba with respect to the lighter ones. The ^{13}C source is of primary nature, therefore, for a given ^{13}C profile, the neutron exposure scales approximately as the inverse of metallicity. In agreement with the above statement, we calculated the *s*-process distribution by slightly decreasing the metallicity in the *post-process* code. Panel *b* shows our best approach to the *main component* obtained at Z=0.017. A further decrease in metallicity would overproduce the heavy *s*-isotopes without changing the production of nuclei with A<130. We compare the distribution shown in panel *b* with the best fit to the *main component* obtained by Gallino et al. (1998), where a constant ^{13}C-pocket per pulse was chosen together with a *standard* ^{13}C profile (see Gallino et al. 1998,for details). Despite the shape of the profile in panel *b* is quite flat, there's a discrepancy by 30% in the production ratio ^{136}Ba/^{124}Te that cannot be resolved.

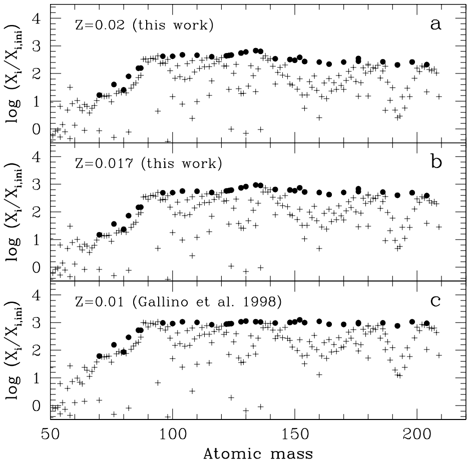

Fig. 3. Comparison of *s*-process predictions in new (panel *a* and *b*), and previous models (Gallino et al. 1998,panel *c*).

3. Conclusions

A self-consistent formation of the ^{13}C pocket has been found in an AGB star of $M = 3$ $M_\odot$ and $Z = 0.02$. The ensuing *s*-process has been calculated and compared with previous models Gallino et al. (1998), but we notice that there is a too high ^{136}Ba/^{124}Te ratio: this problem needs further investigation.

We also pointed out the effect of such algorithm over the TDU mechanism: it enhances its efficiency, and causes it to start at a deeper C-O core mass coordinate. This last point is very important for low mass stars ($M \leq 4$ $M_\odot$), since the stellar luminosity of an AGB star direcly correlates with its core mass Paczynski (1970). The new model attains the C-star stage when its luminosity is significantly lower than found in previous models; a better agreement with the observed C-star luminosity function (in the Galaxy and in the Magellanic Clouds) is, therefore, obtained.

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