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Production of s-nuclei in massive stars: impact of convective overshooting

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Abstract. We have explored the role of the convective overshooting on the production of s-nuclei in stellar models having different initial masses and metallicities ($15 \leq M_{ZAMS}/M_{\odot} \leq 30$; $10^{5} \leq Z \leq 0.04$). The results show enhancements in the production of s-nuclei until a factor ~ 6 (measured as the average overproduction factor of the 6 s-only nuclear species with $60 \lesssim A \lesssim 90$) when convective overshooting is inserted in the models, compared to results obtained with the same models but without convective overshooting. An interpretation of these results is briefly presented.

Key words. Nucleosynthesis, abundances - Convection - Stars: evolution - Stars: interior

1. Introduction

It is widely accepted that the core He-burning in massive stars ($M_{ZAMS} \gtrsim$ 10-15 $M_{\odot}$) gives rise to suitable physical conditions for the development of neutron-capture nucleosynthesis, the so-called "weak" s-process component which should give birth to s-nuclei in the $60 \lesssim A \lesssim 90$ mass range (see e.g. Woosley et al. 2002, and references therein).

Although the general features of this component seem to be well established, there are still some open questions linked to both the nuclear physics and stellar evolution modelling (see e.g. Arcoragi et al. 1991; Raiteri et al. 1993; Rayet & Hashimoto 2000; The et al. 2000; Hoffman et al. 2001; Woosley et al. 2002; Pumo et al. 2006, hereafter Paper I; Costa et al. 2006, hereafter Paper II).

Uncertainties due to nuclear physics have been examined by many authors (see e.g. Rayet & Hashimoto 2000; The et al. 2000; Hoffman et al. 2001), but less work has been done on the impact of uncertainties due to stellar evolution modelling and, in particular, on the impact of uncertainties due to convective overshooting (see e.g. Paper I and references therein).

In the light of our previous studies on this topic (Paper I and Paper II), which show a not negligible impact of the convective overshooting on the s-process during core He-burning in a 25 $M_{\odot}$ star (ZAMS mass) with an initial metallicity of $Z = 0.02$, we believe it is worthwhile examining this issue further by analysing the s-process efficiency in other stel-

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lar models with different mass and metallicity ($15 \leq M_{ZAMS}/M_{\odot} \leq 30$; $10^5 \leq Z \leq 0.04$).

2. Input physics

2.1. The stellar evolution code

The stellar data have been calculated starting from ZAMS until the end of core He-burning using the stellar evolution code Star2003 in the version described in detail in Paper II, but with the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate taken from NACRE (Nuclear Astrophysics Compilation of REaction rates, Angulo et al. 1999).

As for the mixing, the convection is treated as a diffusive process, so nuclear species abundance changes are calculated with the following diffusion equation:

$$\frac{dX}{dt} = \left(\frac{\partial X}{\partial t}\right)_{nuc} + \frac{\partial}{\partial m_r}\left[\left(4\pi r^2 \rho\right)^2 D \frac{\partial X}{\partial m_r}\right]_{mix}, \quad (1)$$

where the first term on the right is the time derivative of a given isotopic abundance (mass fraction) due to nuclear reactions, while the second is the diffusive term that describes mixing.

The difference among convective, overshooting and radiative regions lies on the value used for the diffusion coefficient D.

In convective zones (established through the Schwarzschild criterion) the diffusion coefficient is given by

$$D_{conv} = \frac{1}{3} v_c l \quad (2)$$

where v_c is the average velocity of convective elements derived according to the mixing length theory and $l = \alpha \cdot H_p$ is the mixing length (H_p is the pressure scale height and α is mixing length parameter put to 1.7 in our calculations).

Beyond convective zones (overshooting regions), the following diffusion coefficient is used instead:

$$D_{over} = D_0 exp \frac{-2z}{H_v} \quad \text{with} \quad H_v = f \cdot H_p \quad (3)$$

where D_0 is taken equal to the value of D_{conv} at the upper radial edge of the convective core, $z = |r - r_{edge}|$ is the radial distance from the same edge, and f is the so-called overshooting parameter which determines the overall efficiency of convective overshooting. For $z \gg 1$ (radiative regions) the diffusion coefficient is ~ 0, and abundance changes are only due to the nuclear reaction term in eq. (1).

2.2. The nucleosynthesis code

The s-nucleosynthesis code and the s-process network are the same described in Paper I and Paper II. As regards the coupling of nucleosynthesis simulations with stellar evolution data, the "post-processing" technique is used according to the prescriptions described by Prantzos et al. (1987).

3. Models and results

We performed s-process simulations with 15, 20, 25 and 30 $M_{\odot}$ (ZAMS mass) stellar models having initial metallicity Z=0.02 and with 20 $M_{\odot}$ stellar model having different metallicities (from 10^{-5} to 0.04), for f=10^{-5} (model without overshooting), 0.01, 0.02 and 0.035.

The s-process efficiency was analysed in terms of the following parameters:

- the average overproduction factor F_0 for the 6 s-only nuclei ^{70}Ge, ^{76}Se, ^{80}Kr, ^{82}Kr, ^{86}Sr and ^{87}Sr, given by

$$F_0 = \frac{1}{N_s}\sum_i F_i \text{ with } F_i = \frac{X_i}{X_{i,ini}}, N_s = 6 \quad (4)$$

  where F_i is the overproduction factor, X_i is the mass fraction (averaged over the convective He-burning core) of s-only nucleus i at the end of s-process, $X_{i,ini}$ is the initial mass fraction of the same nucleus and N_s is the number of the s-only nuclei within the mass range $60 \leq A \leq 87$;
- the maximum mass number A_{max} for which the species in the $60 \leq A \leq A_{max}$ mass range are overproduced by at least a factor of about 10 and 5 (respectively first and second value in the third Col. of the Table 1);
- the number of neutrons captured per ^{56}Fe seed nucleus n_c;

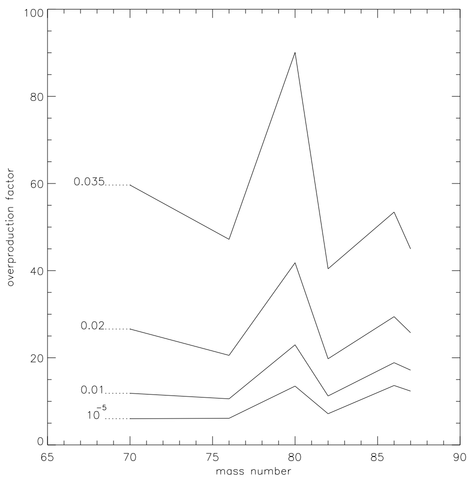

Fig. 1. Overproduction factor for the six s-species ^{70}Ge, ^{76}Se, ^{80}Kr, ^{82}Kr, ^{86}Sr and ^{87}Sr, for 15 $M_{\odot}$ stellar models with overshooting parameter f=10^{-5}, 0.01, 0.02 and 0.035 (see labels).

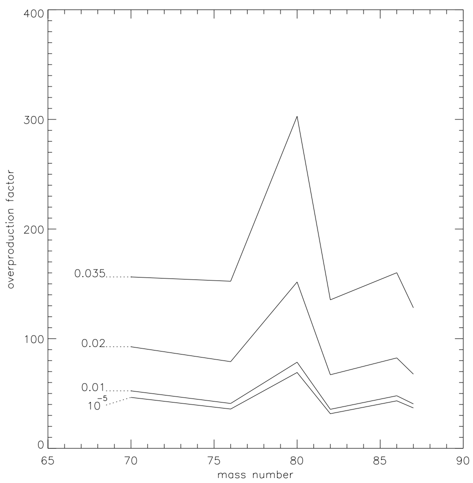

Fig. 2. As in Fig. 1, but for 20 $M_{\odot}$ stellar models with overshooting parameter f=10^{-5}, 0.01, 0.02 and 0.035 (see labels).

- the maximum convection zone mass extension (hereafter MCZME) during core He-burning s-process;
- the duration of core He-burning s-process.

Some preliminary results concerning stellar models of M_{ZAMS} = 15, 20 and 25 $M_{\odot}$ with

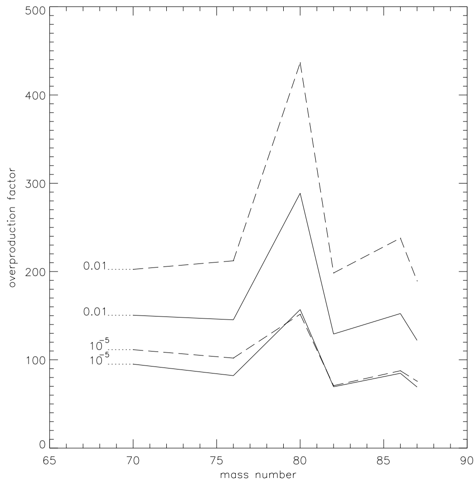

Fig. 3. As in Fig. 1, but for 25 $M_{\odot}$ stellar models with overshooting parameter f=10^{-5} and 0.01 (see labels). Solid lines are concerned with stellar models using the NACRE rate for $^{12}C(\alpha,\gamma)^{16}O$, while dashed lines are data from Paper I and Paper II, using an older rate.

Z = 0.02 are summarised in terms of the previous parameters in Table 1, and the overproduction factors as a function of nuclear mass number A are reported in Figures 1, 2 and 3. The data concerning other stellar masses and different metallicities are still under analysis.

4. Discussion

For all our stellar models of different initial mass, the s-process efficiency increases when overshooting is inserted in the evolutionary computations compared with "no-overshooting" models, as already found in Paper I and Paper II for simulations referring to a 25 $M_{\odot}$ star model. Moreover an essentially monotonic link between the f value and the s-process efficiency is evident for all our models, as witnessed by the fact that all the s-process efficiency indicators gradually grow when passing from f = 0.01 to 0.035 for a given initial mass. Also evident is the higher s-process efficiency when we progressively increase the mass of the models from 15 $M_{\odot}$ to 25 $M_{\odot}$ for a given f value. This increase in s-process efficiency is connected to the fact that

Table 1. Parameters describing the s-process efficiency (see text) for stellar models with $M_{ZAMS} = 15\ M_\odot$ (a), $M_{ZAMS} = 20\ M_\odot$ (b) and $M_{ZAMS} = 25\ M_\odot$ (c). All the models are calculated for metallicity Z =0.02.

	f	F_0	A_{max}	n_c	$MCZME$	$Duration$ [sec]
(a)	10^{-5}	9.80	87 – 88	1.19	$1.89M_\odot$	$5.25 \cdot 10^{13}$
	0.01	15.45	88 – 90	1.80	$2.54M_\odot$	$5.73 \cdot 10^{13}$
	0.02	27.32	88 – 90	2.50	$2.90M_\odot$	$5.16 \cdot 10^{13}$
	0.035	55.96	88 – 94	3.35	$3.56M_\odot$	$4.40 \cdot 10^{13}$
(b)	10^{-5}	43.85	88 – 94	3.03	$3.26M_\odot$	$3.74 \cdot 10^{13}$
	0.01	49.31	89 – 94	3.19	$3.94M_\odot$	$3.79 \cdot 10^{13}$
	0.02	90.10	91 – 96	3.90	$4.41M_\odot$	$3.65 \cdot 10^{13}$
	0.035	172.56	92 – 100	4.74	$4.81M_\odot$	$3.59 \cdot 10^{13}$
(c)	10^{-5}	92.92	89 – 94	3.96	$5.40M_\odot$	$2.32 \cdot 10^{13}$
	0.01	164.72	92 – 100	4.68	$6.48M_\odot$	$2.13 \cdot 10^{13}$

the main neutron source for the weak s-process (the reaction $^{22}Ne\,(\alpha\,,n)\,^{25}Mg$) becomes efficient only for $T \gtrsim 2,5{\cdot}10^8\ K$, so the production of s-nuclei is more and more efficient when increasing the initial stellar mass, because the more massive models burn helium at a "time averaged" higher temperature.

In addition we confirm the behaviour found in the work of Costa et al. (2008), where the use of the NACRE rate gives rise to a lower s-process efficiency (see Fig. 3). Such a behaviour seems to be connected both to the smaller lifetime of the He-burning phase in our new 25 $M_\odot$ models — compared to those from Paper I and Paper II — that has a direct impact on the neutron exposure of the s-process seed (mainly ^{56}Fe), and to a higher availability of α particles during the late He-burning phase because less α particles are consumed by the $^{12}C\,(\alpha\,,\gamma)\,^{16}O$ reaction due to the lower rate, as suggested by The et al. (2000). However a deeper analysis, involving other masses and different metallicities, is necessary to confirm our statements.

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