Sources of uncertainties in the s-process in massive stars: convection and reaction rates

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Abstract. Current models of s-nucleosynthesis in massive stars (\(M \sim 15 M_\odot\) to \(30 M_\odot\)) are able to reproduce some main features of the abundance distributions of heavy isotopes in the solar system, at least in the \(A \sim 60 \sim 90\) mass range. The efficiency of the process and the above specified mass range for the s-nuclei are still heavily uncertain due to both nuclear reaction rates and stellar models uncertainties. A series of s-process simulations with stellar models in the \(15 \sim 30 M_\odot\) (mass at ZAMS) and metallicity \(Z = 0.02\) mass have been performed to analyse the impact of the overshooting model used on the s-process yields. As in a previous exploratory work performed with stellar models having \(M_{\text{ZAMS}} = 25 M_\odot\) and \(Z = 0.02\), enhancements factors in the range 2-5 are found in the final s-process efficiency when overshooting is inserted in the models.

Key words. Nucleosynthesis — Abundances — Convection — Stars: evolution — Stars: interior

1. Introduction

It is known that the core He-burning in massive stars \((M_{\text{ZAMS}} \gtrsim 15 M_\odot)\) gives rise to suitable physical conditions for the development of neutron-capture nucleosynthesis (so-called “weak” s-process component) which should give birth to s-species in the \(60 \sim A \sim 90\) mass range (see e.g. Pumo et al. 2006).

Although the general features of this process seem to be well established, there are still uncertainties linked to both nuclear physics and stellar evolution modelling (see e.g. Arcoragi et al. [1991], Raiteri et al. [1993], Rayet & Hashimoto [2000], The et al. [2000], Costa et al. [2000], Rayet et al. [2001], Costa et al. [2003], but less work has been done on the uncertainties due to stellar evolution modelling and, in particular, on the convective overshooting (see Pumo et al. 2006 and references therein).

In the light of our previous study on this topic (Costa et al. 2006), which show enhancements of about a factor 2-3 in the s-process efficiency when overshooting is inserted in stellar models having \(M_{\text{ZAMS}} = 25 M_\odot\) and \(Z = 0.02\), we believe it is worthwhile examining this issue further by analysing other stellar models with different masses and metallicities. In par-
ticular we have started exploring the role of the convective overshooting on the s-process in stellar models with different initial masses, postponing to a future work an analysis based on other initial metallicities.

2. Stellar evolution and nucleosynthesis codes

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 Costa et al. (2006), but with the $^{12}$C($\alpha$,γ)$^{16}$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 a diffusion equation (see Costa et al. 2006 for details) having the following diffusion coefficient for the overshooting regions:

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

where $D_0$ is the value of diffusion coefficient at the upper radial edge of the convection zone established through the Schwarzchild criterion, $z = |r - r_{\text{edge}}|$ is the radial distance from the same edge, $H_p$ is the pressure scale height while $f$ is the so-called overshooting parameter.

The s-nucleosynthesis code and the coupling of nucleosynthesis simulations with stellar evolution data (through a “post-processing” technique) are the same described in detailed in Costa et al. (2006).

3. Models and results

We performed s-process simulations with $M_{\text{ZAMS}} = 15, 20, 30 \, M_\odot$ stellar models having initial metallicity $Z = 0.02$ for $f = 10^{-5}$ (model without overshooting), 0.01, 0.02, 0.035. Moreover, we repeated the s-process simulations made by Costa et al. (2006) with $M_{\text{ZAMS}} = 25 \, M_\odot$ stellar models for $f = 10^{-5}$ and 0.01, in order to study the effect of a change in $^{12}$C($\alpha$,γ)$^{16}$O reaction rate in the stellar evolution code.

Some preliminary results concerning $M_{\text{ZAMS}} = 15, 25 \, M_\odot$ are summarised in Table 1 while the overproduction factors as a function of nuclear mass number $A$ are
report in Fig. 1 and 2. The data concerning other stellar masses are still under analysis.

As already suggested by Costa et al. (2006), models using overshooting give rise to a “better performance” in terms of s-process efficiency compared with “no-overshooting” models. Moreover significant changes are obtained in our results with different values for the overshooting parameter \( f \) and the link between the \( f \) value and the s-process indicators values is monotonic. This is particularly clear for \( M_{ZAMS} = 15 M_\odot \) models, where all the s-process efficiency “indicators” gradually grow when passing from \( f = 0.01 \) to \( f = 0.035 \).

Also evident is the higher performance of the s-process in the 25 \( M_\odot \) models compared to the corresponding 15 \( M_\odot \) models.

From Fig. 2 and the (b) and (c) groups in Table 1 that show a comparison between the results obtained with two different rates for the \( ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \) reaction, one can see that the use of the NACRE rate gives rise to an average lower s-process efficiency, despite the MCZME value is nearly unchanged.

For a preliminary interpretation of the last two observed features, it can be said that:

(i) it is known that the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \) reaction (main neutron source for the weak s-process) becomes efficient only for \( T \gtrsim 2.5 \times 10^8 \) K, so 15 \( M_\odot \) models produce s-nuclides during the very last stages of the He-burning phase leading to a lower s-process efficiency compared to 25 \( M_\odot \) models, because the lower mass models burn helium at a “time averaged” lower temperature;

(ii) the lower s-process efficiency obtained with the NACRE rate for \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \) could be connected to the smaller lifetimes of the He-burning phase in the new 25 \( M_\odot \) models compared to those from Costa et al. (2006), as lifetime has a direct impact on the neutron exposure of the s-process seed (mainly \(^{56}\text{Fe} \)), but it could be also due to a higher availability of \( \alpha \) particles during the late He-burning phase, as less \( \alpha \) particles are consumed by the \(^{13}\text{C}(\alpha,\gamma)^{16}\text{O} \) reaction due to the lower rate, as suggested by The et al. (2000).

A deeper analysis, involving also other masses and other metallicities, will allow us to better analyse and eventually confirm our preliminary interpretations.

### Table 1. Parameters describing the s-process efficiency as defined in Costa et al. (2006) for stellar models with \( M_{ZAMS} = 15 M_\odot \) (a) and for stellar models with \( M_{ZAMS} = 25 M_\odot \) (b), (c). The (b) group includes data from new calculations, while the (c) group data are taken from Costa et al. (2006).

| \( f \) | \( f_0 \) | \( \Delta_{\text{max}} \) | \( n_0 \) | \( \text{MCZME} \) | \( \text{Duration [sec]} \) |
|------|------|------|------|------|------|
| (a) 10^{-3} | 9.80 | 87 - 88 | 1.19 | 1.89M_\odot | 5.25 \times 10^{13} |
| 0.01 | 15.45 | 88 - 90 | 1.80 | 2.54M_\odot | 5.73 \times 10^{13} |
| 0.02 | 27.32 | 88 - 90 | 2.50 | 2.90M_\odot | 5.16 \times 10^{13} |
| 0.035 | 55.96 | 88 - 94 | 3.35 | 3.56M_\odot | 4.40 \times 10^{13} |
| (b) 10^{-3} | 92.92 | 89 - 94 | 3.96 | 5.40M_\odot | 2.32 \times 10^{13} |
| 0.01 | 164.72 | 92 - 100 | 4.68 | 6.48M_\odot | 2.13 \times 10^{13} |
| 0.02 | 246.13 | 94 - 104 | 5.22 | 6.93M_\odot | 2.27 \times 10^{13} |

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