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The s-process in massive stars: the Shell C-burning contribution

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In massive stars the s−process (slow neutron capture process) is activated at different temperatures, during He−burning and during convective shell C−burning. At solar metallicity, the neutron capture process in the convective C−shell adds a substantial contribution to the s−process yields made by the previous core He−burning, and the final results carry the signature of both processes. With decreasing metallicity, the contribution of the C−burning shell to the weak s−process rapidly decreases, because of the effect of the primary neutron poisons. On the other hand, also the s−process efficiency in the He core decreases with metallicity.

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1. Introduction

In massive stars (M $\geq$ 10M$_\odot$) the weak s$-$process is ascribed to produce most of the s component between the iron peak and the strontium peak (e.g., Raiteri et al. 1993 [1]). Neutrons for the weak s$-$process are provided by (α,n) reactions, mainly by ^{22}Ne(α,n)^{25}Mg. During presupernova evolution of a massive star, the convective core He$-$burning and the convective shell C$-$burning are the main astrophysical sites where the s$-$process nucleosynthesis takes place. Several papers analysed the weak s$-$process during core He$-$burning in massive stars: e.g. Couch et al. 1974 [2], Lamb et al. 1977 [3], Prantzos et al. 1987 [4], Raiteri et al. 1991a [5].
The ^{22}Ne abundance changes linearly with the initial metallicity of the star (secondary$-$like isotope) because it is produced by $\alpha-$capture starting from the ^{14}N, which was built by the initial CNO during the previous H$-$burning. ^{14}N is converted into ^{18}O via the ^{14}N(α,γ)^{18}F(β^+)^{18}O chain at the beginning of core He$-$burning. When the ^{4}He abundance is decreased to $\sim$ 0.1, the temperature in the core starts to increase and, if it gets higher than 2.5$\cdot$10^8 K, ^{18}O is converted into ^{22}Ne via ^{18}O(α,γ)^{22}Ne. For this reason ^{22}Ne(α,n)^{25}Mg becomes efficient only in the last phases of He$-$burning, close to He exhaustion, when the central temperature reaches 3$-$3.5$\cdot$10^8 K (Raiteri et al. 1991a [5]).
The convective shell C$-$burning phase is active over the major part of the He$-$core ashes, at a temperature close to 1 GK (1 GK = 10^9 K) and a density close to 10^5 g$\cdot$cm^{-3} at the bottom of the shell. The final supernova nucleosynthesis will modify the abundances at the bottom of the C$-$shell, but the outer C$-$burning processed material will be ejected almost unchanged by the explosion (A. Heger 2006 [6], M. Limongi 2006 [7], Rauscher et al. 2002 [8]). Carbon burns via the ^{12}C(^{12}C,α)^{20}Ne (the $\alpha-$particles source for the activation of the ^{22}Ne(α,n)^{25}Mg reaction) and the ^{12}C(^{12}C,p)^{23}Na (the protons source) channels. Arnett & Truran 1969 [9] provided a detailed study of the C$-$burning nucleosynthesis at different temperatures for the light isotopes. Raiteri et al. 1991b [10] pointed out a strong s nucleosynthesis may occur during this phase, over a short evolution time scale (of the order of 1 yr) but with a high neutron density where neutrons are provided by the residual ^{22}Ne in the He$-$Core ashes. With a full network included, recent papers follow the evolution of the star up to the supernova explosion (Limongi et al. 2000 [11] and M. Limongi 2006 [7], Woosley et al. 2002 [12] and A. Heger 2006 [6]), which confirm that the ^{22}Ne(α,n)^{25}Mg is the most important neutron source in the C$-$burning shell and in the previous He core.
In this paper we analyse the weak s$-$process in the convective shell C$-$burning conditions in some detail.

2. The convective shell C$-$burning

The convective C shell burns and reprocesses the ashes of the previous convective core He$-$burning. For this reason, we choose as initial abundances at the C$-$burning ignition the abundances at He exhaustion. The hydrostatic evolution up to the core He$-$burning is provided by the FRANEC code version of Chieffi & Straniero 1989 [13]. During this phase, the nucleosynthesis is followed by a post$-$processing multi$-$zone code (Käppeler et al. 1994 [14]). In Fig. 1 the He core final abundances normalised to solar ($X_i/X_\odot$) are plotted for a 25 M$_\odot$ with [Fe/H]= 0 and $-$1 models, between ^{57}Fe and ^{93}Nb. The ^{22}Ne(α,n)^{25}Mg rate used in our calculations was adopted from Jaeger et al. 2001 [15].

Regarding the C shell, a one−zone model is used to follow the s nucleosynthesis. With respect to

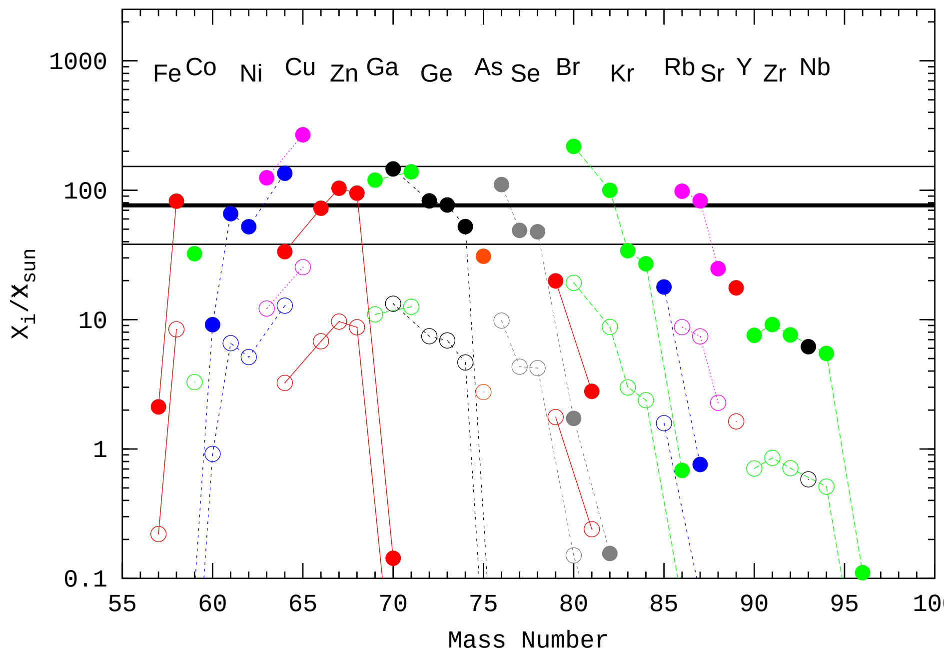

Figure 1: The isotopic abundances normalised to solar at He exhaustion for a 25 $M_\odot$, [Fe/H] = 0 (full circles) and [Fe/H] = −1 (empty circles). The ^{16}O mass fraction is indicated by the thick black line; the thin lines correspond to the ^{16}O overabundance multiplied and divided by a factor of two.

Raiteri et al. 1991b [10] the C shell network is extended to account for all unstable isotopes with terrestrial β^- decay half lives longer than 5 min. This extension is required because of the large neutron density involved in the neutron capture process in the C shell (it is not a classic s−process, with neutron densities of $10^{11}-10^{12}$ n·cm^{-3}). In Fig. 2 the C shell isotopic abundances normalised to solar ($X_i/X_\odot$) are plotted between ^{57}Fe and ^{93}Nb for a 25 $M_\odot$ model with [Fe/H]= 0 and −1.

2.1 Neutron sources

In the convective C shell, the ^{22}Ne(α,n)^{25}Mg reaction is still the most important neutron source at solar metallicity. We recall that at the temperature in the He core ($kT \sim 30$ keV) the ^{22}Ne(α,n)^{25}Mg uncertainty is a factor of two. Changing the ^{22}Ne(α,n)^{25}Mg rate in the He core within a factor of two affects the ^{22}Ne abundance at core He exhaustion so that the ^{22}Ne abundance at the C−burning ignition in the shell is different. The ^{22}Ne(α,n)^{25}Mg uncertainty in the C−shell conditions ($kT \sim 90$ keV) is smaller than a factor of two, but the efficiency of the neutron capture process is strongly affected also by the initial ^{22}Ne. As an example, in our calculations the ^{22}Ne mass fraction at core He exhaustion for a 25 $M_\odot$ of solar metallicity is $9.8 \cdot 10^{-3}$. The ^{22}Ne(α,n)^{25}Mg rate used is the recommended rate by Jaeger et al. 2001 [15]. Using the lower limit by Käppeler et al. 1994 [14] (∼ 50 % higher than our standard rate at He core temperatures), the ^{22}Ne mass fraction at He exhaustion in the same case is $8.0 \cdot 10^{-3}$. In this second case, the

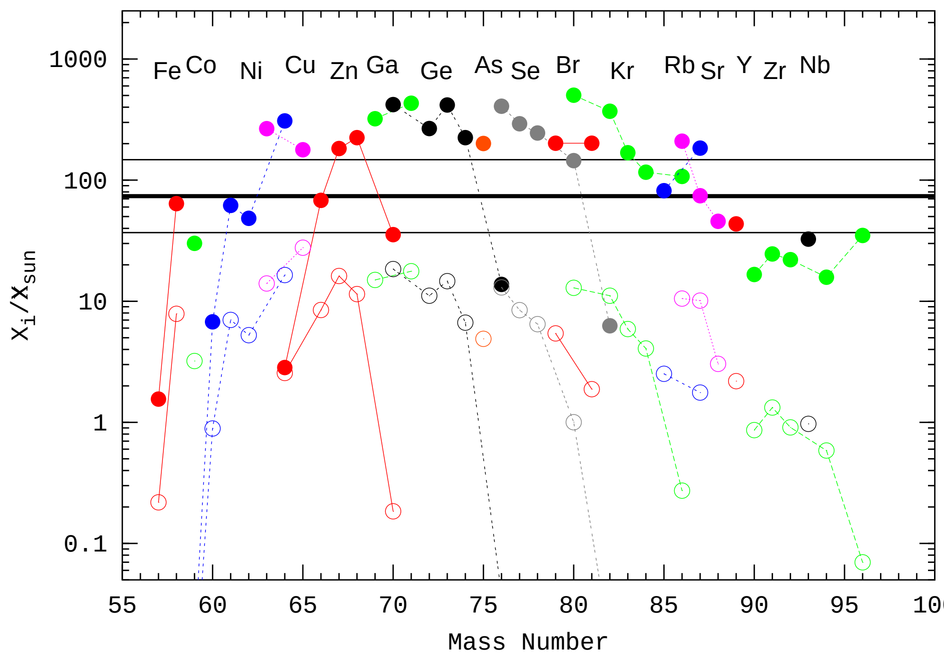

Figure 2: The final isotopic abundances normalised to solar in the convective C$-$burning shell for a 25 $M_\odot$ star and [Fe/H] = 0 (full circles) and [Fe/H] = -1 (empty circles). The ^{16}O mass fraction is indicated by the thick black line; the thin lines correspond to the ^{16}O overabundance multiplied and divided by a factor of two.

s$-$process is more efficient in the He core, and less ^{22}Ne is available at the beginning of the following shell C$-$burning. At the end of the shell C$-$burning, the ^{22}Ne mass fraction is a few 10^{-4} in both cases, but the s processed material has been differently exposed in the He core and in the C shell.

The other neutron sources have a negligible contribution to the total neutron fluence at solar metallicity, but some of them are important because they replace neutrons produced via ^{22}Ne(α,n)^{25}Mg and captured by light isotopes (recycle effect on the light neutron poisons, Travaglio et al. 19996 [16]). In shell C$-$burning conditions, ^{13}C is produced via the ^{12}C(n,γ)^{13}C channel. The ^{13}C depletion, however, occurs in the ^{13}C(α,n)^{16}O reaction (Drotleff et al. 1994 [17]), which recycles the neutrons captured by ^{12}C. For this reason ^{12}C is not a poison for the neutron capture process in the C shell. ^{17}O is produced via the ^{16}O(n,γ)^{17}O, and ^{17}O(α,n)^{20}Ne (Caughlan & Fowler 1988 [18]) partially recycles the neutrons captured by ^{16}O. Other reactions involved in the depletion of ^{17}O are ^{17}O(p,α)^{14}N and ^{17}O(n,α)^{14}C. The ^{21}Ne(α,n)^{24}Mg (Angulo et al. 1999 [19]) reaction partially recycles the neutrons captured by the ^{20}Ne(n,γ)^{21}Ne channel (Limongi et al. 2000 [11]). The other (α,n) reactions on ^{18}O, ^{25}Mg and ^{26}Mg, provide a negligible contribution to the neutron fluence in C$-$burning conditions.

In shell C$-$burning conditions, the neutron capture process efficiency beyond iron may be affected by uncertainties in the neutron capture cross sections of the light neutron poisons like ^{16}O, ^{24}Mg, ^{25}Mg, ^{23}Na. Along the neutron capture path, also the cross section uncertainty of several isotopes may affect the final abundances of the heavier isotopes (e.g., ^{62}Ni, see Nassar et al. 2005 [20]) by a propagation effect. All these arguments will be discussed in more detail in a forthcoming paper.

2.2 Metallicities lower than solar

As recalled in §1, the ^{22}Ne(α,n)^{25}Mg is a secondary$-$like neutron source. This implies that the amount of ^{22}Ne available for neutron production scales with the initial metallicity of the star. During core He$-$burning, the main neutron poison is ^{25}Mg that is secondary$-$like, since it is mainly produced directly by the ^{22}Ne(α,n)^{25}Mg reaction (Raiteri et al. 1991a [5]). Thus, the weak s$-$process yields change roughly linearly with metallicity (Fig. 1).
Instead, in the convective C shell, besides secondary$-$like neutron poisons as ^{25}Mg, there are primary$-$like neutron poisons (^{16}O, ^{24}Mg, ^{23}Na...), which do not depend on the metallicity. Therefore, the s$-$process efficiency decreases strongly with decreasing metallicity. For [Fe/H]= -1, the neutron exposure in the C$-$shell ($\tau = \int v_T n_n(t)dt$, where v_T is the thermal velocity and n_n(t) is the neutron density) decreases by a factor of 8.5, and the number of neutrons captured per iron seed decreases by a factor of 3.1 (see Fig. 2). While in the He core both the neutron exposure and the number of neutrons captured per iron seed do not change at metallicities lower than solar (except that for [Fe/H] ≤ -2 the primary$-$like neutron poisons are not negligible any more, so also the s$-$process in the He core is not purely secondary$-$like for very low metallicities), in the C shell the s$-$process efficiency decreases more rapidly than the initial metallicity. This implies that, at metallicities lower than solar, the weak s$-$process mainly comes from the He core because of its lower dependence on the initial metallicity of the star with respect the s$-$process in the C shell. At [Fe/H]= -1, the neutron capture process in the C$-$shell still affects the abundances of neutron rich isotopes (e.g., ^{70}Zn, ^{86}Kr) and a few other branching points (e.g., the stable Br isotopes and ^{80}Kr are affected by the branching point at ^{79}Se) with respect to the He core contribution (Fig. 3).

At very low metallicities ([Fe/H] ≤ -2) the s$-$process in the C$-$shell does not give important contributions any more. The metallicity dependence of the weak s$-$process is confirmed by spectroscopic observations of copper (Bisterzo et al. 2005 [21]), and there are strong indications from germanium as well (Cowan et al. 2005 [22])).

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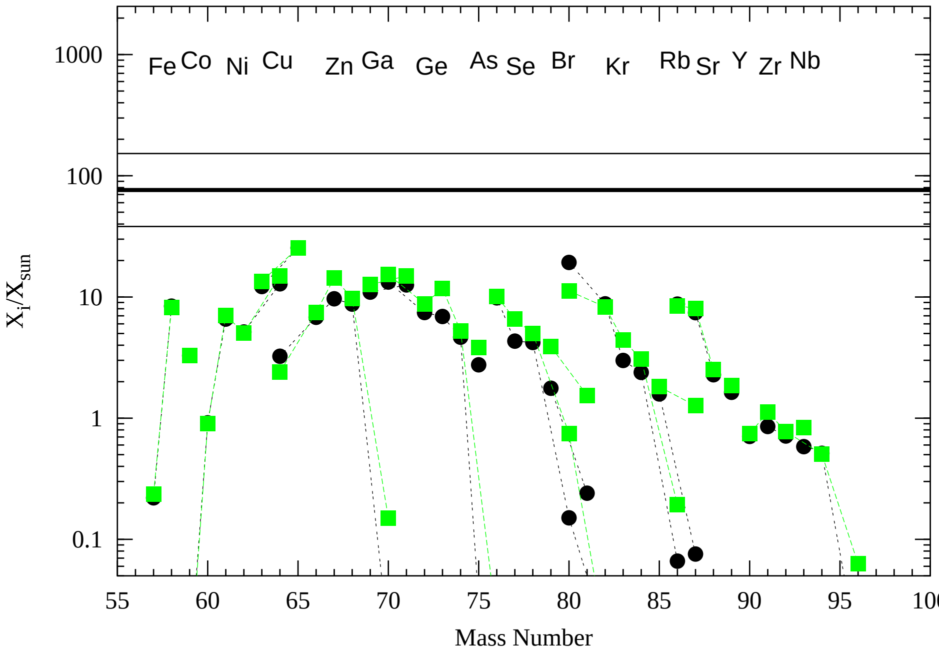

Figure 3: The final abundances normalised to solar at core He exhaustion (squares) and in the convective C−burning shell (circles) for a 25 $M_\odot$ star with [Fe/H] = −1. The ^{16}O mass fraction is indicated by the thick black line; the thin lines correspond to the ^{16}O overabundance multiplied and divided by a factor of two.

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