

NuGrid: s process in massive stars

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The s -process production in massive stars at very low metallicities is expected to be negligible due to the low abundance of the neutron source ^{22}Ne , to primary neutron poisons and decreasing iron seed abundances. However, recent models of massive stars including the effects of rotation show that a strong production of ^{22}Ne is possible in the helium core, as a consequence of the primary nitrogen production (observed in halo metal poor stars). Using the PPN post-processing code (developed within the NuGrid collaboration), we study the impact of this primary ^{22}Ne on the s process. We find a large production of s elements between strontium and barium, starting with the amount of primary ^{22}Ne predicted by stellar models including the effects of rotation. There are several key reaction rate uncertainties influencing the s -process efficiency. For example, within the nuclear reaction rate uncertainty, the $^{17}\text{O}(\alpha, \gamma)$ reaction may either be critically important or negligible. We also report on the development of the new parallel (MPI) post-processing (MPPNP) variant of the PPN code designed to follow the complete nucleosynthesis in stars on highly resolved grids. We present here the first post-processing run from the ZAMS up to the end of helium burning for a $15 M_{\odot}$ model.

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1. Introduction

Massive stars are known to produce elements heavier than the iron group via rapid neutron captures during their explosion, *r* process (see for example the contribution by Qian and Kratz et al. [1]) and also via slow neutron captures (*s* process) during the pre-supernova evolution, forming the so-called weak *s* component. The weak *s* process in massive stars with initial solar like composition is well understood. ^{22}Ne is the main neutron source and it is produced starting from the initial CNO isotopes (The et al. [2, 3], Raiteri et al. [4, 5], Pignatari et al. in prep.). The weak *s* process, producing mostly elements in the atomic mass range $60 \lesssim A \lesssim 90$, starts at the end of helium burning when the temperature is high enough to activate $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$. More massive stars reach higher temperatures at the end of He-burning and therefore burn more ^{22}Ne . Consequently *s*-process production during central helium burning increases with increasing stellar mass. The ^{22}Ne left over from helium burning is the main neutron source during the subsequent carbon shell burning. The carbon shell *s*-process contribution depends on the history of convective zones after the He-core burning and on several nuclear uncertainties (e. g. the rate of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction). The standard *s*-process production in massive stars depends on the initial metallicity. At low metallicity, the low iron seed abundance, the low ^{22}Ne content and the increasing strength of primary neutron poisons limits the *s*-process efficiency, permitting only negligible production of *s* elements (e. g. Raiteri et al. [6]).

2. Weak *s* process at low metallicity in rotating stars

At solar metallicity, the main effect of rotation on the *s*-process production is the enlargement of the convective helium core due to additional mixing and therefore a behaviour like non-rotating more massive stars [7]. Thus a $25 M_{\odot}$ star with rotation behaves like a non-rotating star with mass between 30 and $40 M_{\odot}$. Hence the *s*-process efficiency in He-core burning is enhanced in rotating stars (Frischknecht et al. in prep.).

At low metallicity, the impact of rotation is more important. Indeed, at the start of core He-burning, carbon and oxygen are mixed upward into hydrogen rich regions leading to a strong production of nitrogen (see Meynet et al. [8] and Hirschi [9]). Part of this primary nitrogen may enter the convective He core and be transformed into primary ^{22}Ne by α -captures. As a consequence, with respect to the non-rotating models, the ^{22}Ne available in the He-core is strongly enhanced. According to Hirschi et al. [10], about 1% in mass of the helium core is composed of ^{22}Ne at the *s*-process activation.

The stellar evolution calculations described above do not follow *s*-process nucleosynthesis. In this Section, we present simplified one-zone *s*-process calculations (using a thermodynamic trajectory that best mimics the full multi-zone evolution) following the nucleosynthesis up to the end of He-burning. For these calculations, we used the one-zone PPN code (see next Section and contribution by Herwig for more details) and an initial metallicity of $Z=10^{-6}$. In order to reproduce the effect of rotational mixing on the helium burning core composition in the one-zone calculation, we replaced 1% in mass of ^4He by ^{22}Ne at the start of helium burning. The primary ^{22}Ne enhances the *s* process compared to the non-rotating case, where negligible amounts of *s* elements are produced. The highest nucleosynthesis efficiency is around Sr with overproduction

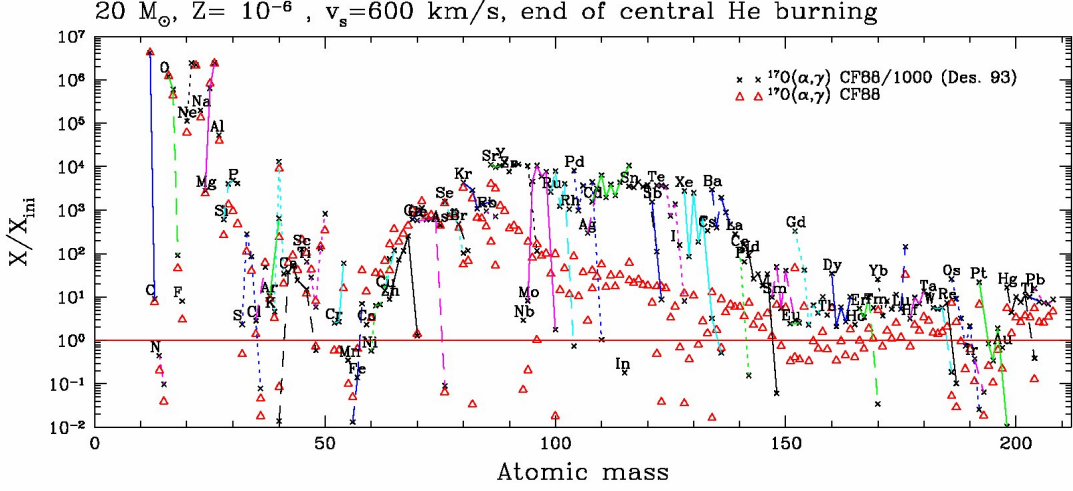


Figure 1: The overproduction factors after He-burning in the one-zone post-processing calculations. Using a low $^{17}\text{O}(\alpha, \gamma)$ rate (black crosses) leads to a strong increase of *s*-process overproduction between Sr and Ba. Isotopes with X_i/X_{ini} below the lower limit are not plotted.

factors (X_i/X_{ini}) between thousand and ten thousand. As can be seen in Fig. 1, iron seeds and in general elements lighter than strontium feed the *s* nucleosynthesis in the mass region between strontium (Sr) and barium (Ba). Beyond Ba, the *s* efficiency rapidly falls, depending on the total neutron exposure. The major neutron poisons are ^{16}O , ^{25}Mg and ^{22}Ne , where ^{16}O is the strongest neutron absorber. Whether or not ^{16}O is an efficient poison depends on the ratio of $^{17}\text{O}(\alpha, \gamma)$ to $^{17}\text{O}(\alpha, n)$. According to the study of Descouvemont [11], the (α, γ) channel should be orders of magnitude weaker than the (α, n) channel, in which case the neutrons captured by ^{16}O are recycled by $^{17}\text{O}(\alpha, n)$. On the other hand, using the rates of Caughlan and Fowler [12], $^{17}\text{O}(\alpha, \gamma)$ is about a factor ten slower than $^{17}\text{O}(\alpha, n)$ and a significant fraction of neutrons captured by ^{16}O are not re-emitted. In this case, ^{16}O is the strongest neutron poison. In Fig. 1, we show the importance of the $^{17}\text{O}(\alpha, \gamma)$ rate by comparing the isotopic distributions obtained using the rate of Caughlan and Fowler [12] (red triangles) and using this same rate divided by a factor 1000 to reproduce the $(\alpha, \gamma)/(\alpha, n)$ ratio suggested by Descouvemont [11] (black crosses). The different *s*-process production between the two calculations demonstrates the importance of the $^{17}\text{O}(\alpha, \gamma)$ to $^{17}\text{O}(\alpha, n)$ ratio for the *s* process at low metallicity. This was also suggested by Rayet and Hashimoto [13] in standard *s*-process calculations in massive stars at low metallicity. However, because of the large primary ^{22}Ne production in rotating stars, in the present calculations the impact of the $^{17}\text{O}(\alpha, \gamma)$ to $^{17}\text{O}(\alpha, n)$ ratio on the *s*-process efficiency is much stronger than in Rayet and Hashimoto [13]. A better knowledge of these two rates at He-burning temperature is highly desirable in order to obtain more reliable *s*-process calculations at very low metallicity. The strong production of *s* elements between Sr and Ba is in agreement with Pignatari et al. [14], where the $^{17}\text{O}(\alpha, \gamma)$ rate of Descouvemont [11] is used and where the amount of primary ^{22}Ne is in agreement with Hirschi et al. [10]. The boosted *s* process due to primary ^{14}N production may provide a new *s*-process component with important implications for nucleosynthesis at low metallicity. Massive rotating

stars may therefore contribute considerable amounts of isotopic abundances between Sr and Ba to the Galactic chemical evolution at halo metallicities, which could provide a possibility to explain the high Sr enrichment and the high Sr/Ba ratio (see Pignatari et al. [14] for more details). In order to make a quantitative and more precise statement about the importance of this *s* process occurring in rotating low-metallicity stars, further investigations are needed.

3. Multi-zone parallel post-processing code, MPPNP

Although only a few isotopes are crucial for the energy generation in massive stars, many more are important for the nucleosynthesis, for example to determine how much *s* process is made in massive stars. Since it is not necessary to follow many of these species within a stellar evolution calculation, within the NuGrid collaboration (see contribution by Herwig for code details), we developed a post-processing network (PPN), that allows us to follow the complete nucleosynthesis taking place in massive stars. It also enables testing of the importance of various reaction rates and especially the use of the same set of nuclear reactions in different stellar environments. The multi-zone variant of the post-processing code, MPPNP, uses MPI and is therefore much faster than a serial code. Using MPPNP, we have post-processed a full stellar evolution model of $15 M_{\odot}$ at $Z=0.01$ calculated with the Geneva code [15] from the ZAMS up to the end of helium burning with a 400-isotope network up to Ag. The overabundance pattern at the end of the core He-burning phase is shown in Fig. 2. As expected, the weak *s*-process production in a $15 M_{\odot}$ star is modest, with overproduction factors up to 10 for *s*-only isotopes between iron and strontium. This is due to the low central temperature reached at the end of the core He-burning phase in a $15 M_{\odot}$ star (compared to more massive stars) with a marginal activation of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ during He-burning. We are currently testing MPPNP in the advanced stages and we plan to calculate the full nucleosynthesis for a large range of masses and metallicities. The MPPNP code can also post-process AGB models (see contribution by Pignatari) and another variant of PPN, called TPPNP will follow trajectories of multi-dimensional simulations of supernova explosion and convective-reactive events in stars.

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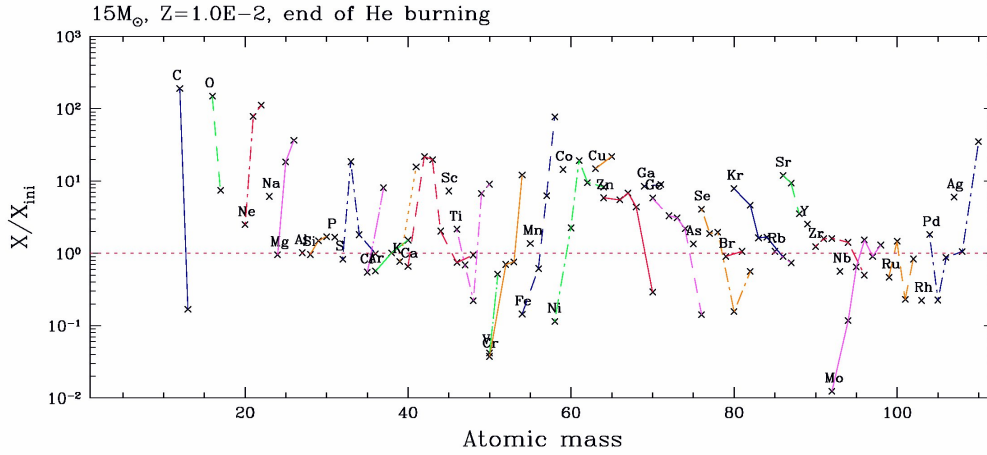


Figure 2: Overproduction factors in the convective core at the end of He-burning. Isotopes with X_i/X_{ini} below the lower limit are not plotted.

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