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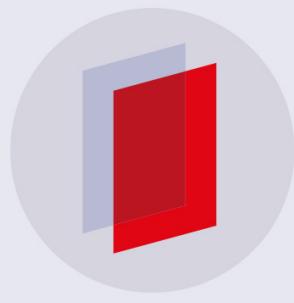
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# A sensitivity study of s-process: the impact of uncertainties from nuclear reaction rates

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## Abstract.

The slow neutron capture process (s-process) is responsible for the production of about half the elements beyond the Fe-peak. The production sites and the conditions under which the different components of s-process occur are relatively well established. A detailed quantitative understanding of s-process nucleosynthesis may yield light in physical processes, e.g. convection and mixing, taking place in the production sites. For this, it is important that the impact of uncertainties in the nuclear physics is well understood. In this work we perform a study of the sensitivity of s-process nucleosynthesis, with particular emphasis in the main component, on the nuclear reaction rates. Our aims are: to quantify the current uncertainties in the production factors of s-process elements originating from nuclear physics and, to identify key nuclear reactions that require more precise experimental determinations.

In this work we studied two different production sites in which s-process occurs with very different neutron exposures: 1) a low-mass extremely metal-poor star during the He-core flash ( $n_n$  reaching up to values of  $\sim 10^{14} \text{ cm}^{-3}$ ); 2) the TP-AGB phase of a  $M_\odot$ ,  $Z=0.01$  model, the typical site of the main s-process component ( $n_n$  up to  $10^8 - 10^9 \text{ cm}^{-3}$ ). In the first case, the main variation in the production of s-process elements comes from the neutron poisons and with relative variations around 30%-50%. In the second, the neutron poison are not as important because of the higher metallicity of the star that actually acts as a seed and therefore, the final error of the abundances are much lower around 10%-25%.

## 1. Introduction

S-process production sites are well identified although the s-process mechanisms given in the stars are still not really understood as the creation of the  $^{13}\text{C}$  pocket, the exact temperatures or mixing and convection processes. In order to improve the models and understand those physical processes, is necessary to have a good understanding of the nuclear physics, identify how the uncertainties of the nuclear rates affect the final results of the models and try to minimize this effect [1].

In this work, the impact of the nuclear uncertainties, concretely the uncertainties of the neutron capture rates, have been studied in two different s-process production sites.

The first site occurs in extremely metal poor stars (EMP). In our case, the mass of the star is  $M = 1M_\odot$  and the metallicity  $Z = 10^{-7}$ . Models of low-mass EMP stars predict that, during the He-core flash, a proton ingestion episode (PIE) takes place in which protons are ingested into the He-burning core [2]. Ingested protons are swiftly captured by  $^{12}\text{C}$  at typical temperatures of  $T \sim 2 \cdot 10^8 \text{ K}$ , triggering the production of neutrons by the sequence



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$^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}(\beta+)^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ . The free neutrons lead to the production of s-process elements. Because of the high temperatures, alpha-captures on  $^{13}\text{C}$  are very fast, leading to large neutron densities, with typical values of the order of  $10^{14}\text{cm}^{-3}$  [3, 4].

The second case studied is a more common place for the production of s-process, the thermal pulses on the AGB phase of low- and intermediate-mass stars. Specifically, we have studied a  $M = 3M_{\odot}$  and  $Z = 0.01$  model. Low-mass AGB stars are characterized by the nuclear burning of hydrogen and helium shells on top of the electron degenerate core. After each thermal pulse there is a mixing of protons from the envelope with the inter-shell rich in  $^{12}\text{C}$ . Then, this  $^{12}\text{C}$  captures the protons forming a  $^{13}\text{C}$  pocket in the top of the inter-shell region. The advance in mass of the H-burning shell compresses and heats the pockets and the  $^{13}\text{C}$  nuclides start capturing  $\alpha$  particles and releasing neutrons by  $^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ . This free neutrons allow a very efficient s-process nucleosynthesis in a small radiative zone. Another marginal neutron source is the  $^{22}\text{Ne}(\alpha, \text{n})^{25}\text{Mg}$  that is activated at the bottom of the He-convective shell if temperature reaches values of  $T \sim 3 \cdot 10^8$  K [5, 6].

## 2. Method

The calculations presented here are based on the GARSTEC code [7]. The rates used are taken from KADoNiS database [8], NACRE database [9] and JINA REACLIB library [10]. To do the uncertainty study, a post-processing code is used. This code contains 2383 different reactions and 804 isotopes. The first step of our work was to associate an error or uncertainty to each neutron capture rate. To do so, we used the error factors for each neutron capture recommended in [11]. In that work, the experimental errors of the radiative neutron capture rates are taken from KADoNiS database [8] corrected with the stellar enhancement factor (SEF) and presented as error factors ( $x_{var}$ ) with  $2\sigma$ . In addition to the radiative neutron capture rates two extra neutron capture rates are taken into account:  $^{14}\text{N}(\text{n}, \text{p})^{13}\text{C}$  and  $^{17}\text{O}(\text{n}, \alpha)^{14}\text{C}$ . The experimental errors are taken at 30 keV from [12] and [13] and converted into factors following [11]. For the neutron capture rates without experimental error, a factor of 2 uncertainty is assumed.

Two different methods have been used in order to study the impact of the nuclear uncertainties on the final abundances.

### 2.1. Monte-Carlo

The Monte-Carlo method consists in varying all the rates simultaneously, where each rate is drawn from a random distribution associated with its error. Following Rauscher's work [11] and in order to avoid negative rates we use  $r_j = f \cdot r_{0j}$  where  $f = e^{x_{rand}}$  and  $x_{rand}$  is uniformly distributed between  $-\log(x_{var}) < x_{rand} < \log(x_{var})$ . This method consistently quantifies the effect of the uncertainties of all the neutron capture rates over the final abundances of the different elements. It does not allow, however, to identify which reactions are the dominant source of errors for each elements. This is an important limitation of the method. Therefore, we have also developed an individual rate study, as described below.

### 2.2. Power law expansion

In order to find out which reactions contribute most to the final error of the abundance of each element is necessary to do an individual study of the rate variation effects.

First, for each reaction  $j$  several s-process calculations are performed, where the rate of the reaction,  $\langle \sigma v \rangle_j$  is varied systematically between a factor 2 up and down. The variation of element abundances obtained are well described by a logarithmic expansion:

$$\alpha_{ij} = \frac{\partial \log(X_i)}{\partial \log(\langle \sigma \cdot v \rangle_j)}. \quad (1)$$

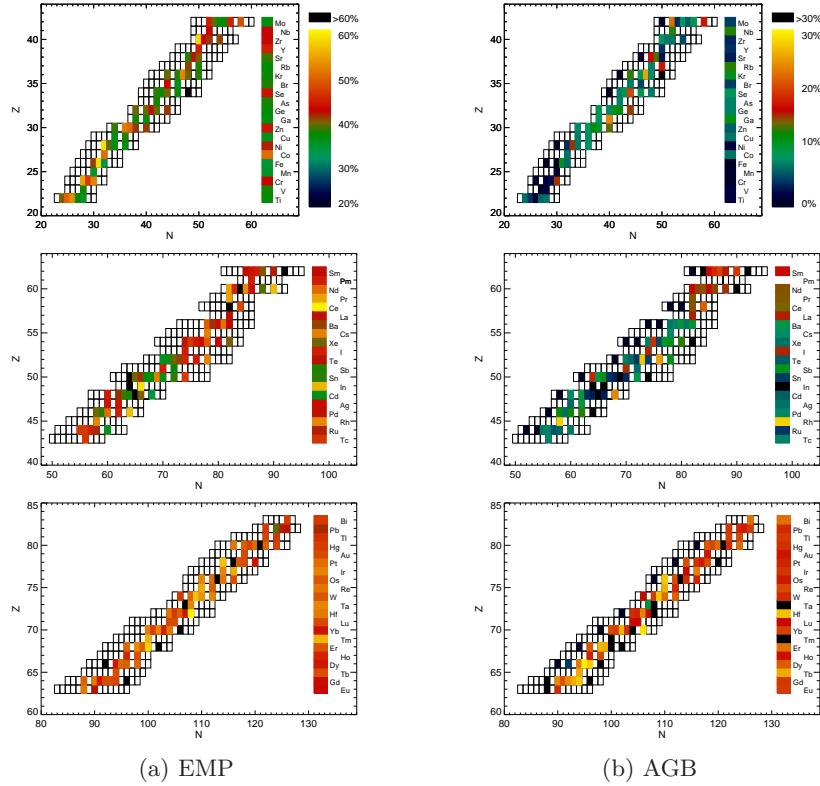


Figure 1: Total error on the isotopes final abundances. The column on the right is the total error of the element calculated using the isotopes errors. Left: EMP stars. Right: Low mass AGB stars

$X_i$  is the mass fraction of the  $i$  isotope and  $X_{0i}$  is the mass fraction of the isotope without any rate variation. To derive the final abundance for an element taking into account all the s-reactions we used a power-law expansion [14],

$$\frac{X_i}{X_{0i}} = \prod_j (f^{\alpha_{ij}}). \quad (2)$$

This method is very useful for studying the individual rate uncertainties contributions to the final abundances and to determine which reactions significantly affect the final results. Comparing the results with the Monte-Carlo, we found differences between methods around  $-2.5\% \pm 5\%$  for the EMP case and  $2.5\% \pm 10\%$  for the AGB one. These values are lower than the errors and thus, we can consider that the methods give equivalent results and the second one is used to do the study.

### 3. Results and Summary

In figure 1 the errors of the final abundances for the different elements and isotopes resulting from the contribution of all the neutron capture rates uncertainties are plotted. For the EMP case (left) we find that the average error is around 30%-50% and for the AGB case (right), the error is much lower, between 10% and 25%. From figure 2 it is possible to identify the reactions whose uncertainties contribute most to the final error. For the EMP, the main contributions to the error come from the neutron poison, light isotopes (as  $^{16}\text{O}$ ,  $^{17}\text{O}$  or  $^{14}\text{N}$ ) of primary origin synthesized by helium burning that capture neutrons. As the star has very low metallicity, the ratio between the neutron captures of the light isotopes of primary origin and heavy isotopes is

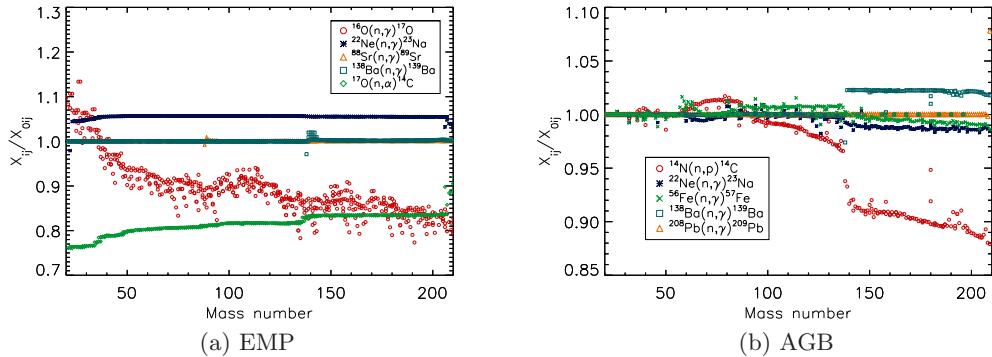


Figure 2: Effect of the variation of certain rates within their uncertainties to the isotopes final abundances. This errors are plotted against the mass number. Left: EMP stars. Right: Low mass AGB stars

very high ( $\sigma_{light}X_{light}/\sigma_{heavy}X_{heavy} \sim 1500$  [4]). Then, the uncertainties on the nuclear capture rates of these light isotopes will be the main source of the errors due to the nuclear rates.

For the AGB case, as the metallicity is higher, the ratio  $\sigma_{light}X_{light}/\sigma_{heavy}X_{heavy}$  will be much lower ( $\sim 100$ ) and the impact of the neutron capture rates of the heavy isotopes more significant. The average error of the final abundances for this case is around 10%-25%. In figure 2 is possible to identify the reactions that significantly affect the final abundances. The major contribution comes from the uncertainty on the neutron capture rate of  $^{14}\text{N}$ , a neutron poison that captures the neutrons that are released. Other contributions to the error come from the uncertainties on the neutron captures rates of the heavy isotopes that affect the final abundances of the local isotopes (see for example the effect of the neutron capture rate of the  $^{138}\text{Ba}$ ). The diminution of the final errors with comparison with the EMP case is due to the lower uncertainties associated to the significant neutron captures rates of heavy isotopes compared with the uncertainties of the neutron poison.

Further details and complementary results will be published in a paper on preparation.

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