The s-process nucleosynthesis in low mass stars: impact of the uncertainties in the nuclear physics determined by Monte Carlo variations

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Abstract. We investigated the impact of uncertainties in neutron-capture and weak reactions (on heavy elements) on the s−process nucleosynthesis in low-mass stars using a Monte-Carlo based approach. We performed extensive nuclear reaction network calculations that include newly evaluated temperature-dependent upper and lower limits for the individual reaction rates. Our sophisticated approach is able to evaluate the reactions that impact more significantly the final abundances. We found that β-decay rate uncertainties affect typically nuclides near s-process branchings, whereas most of the uncertainty in the final abundances is caused by uncertainties in neutron capture rates, either directly producing or destroying the nuclide of interest. Combined total nuclear uncertainties due to reactions on heavy elements are approximately 50%.

Keywords: nucleosynthesis, AGB stars, nuclear reactions, s-process

1 Introduction

The s-process nucleosynthesis is a source of heavy elements beyond iron in the universe, taking place in stellar burning environments. There are two astronomical conditions and corresponding classes of the s-process. The s-process occurs (i) during the AGB phase of low mass stars producing heavy nuclei up to Pb and Bi, called the main s-process; (ii) in He-core and C-shell burning phases of massive stars representing the lighter components (up to $A \approx 90$), categorised as the weak s-process. Here, we investigate the main s-process production in

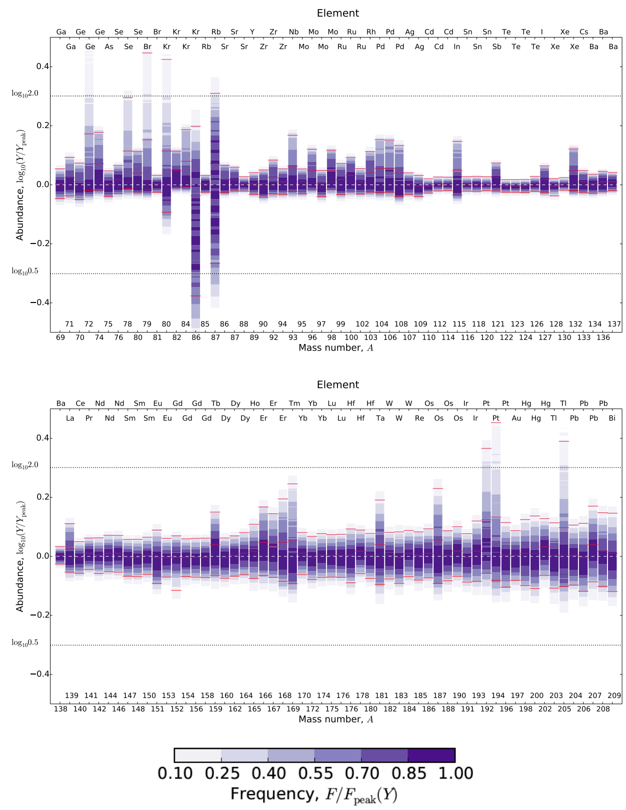

Fig. 1. Total production uncertainties in the s-process abundances at the end of a thermodynamic trajectory approximating a ^{13}C pocket in a 3M$_\odot$ stars of solar metallicity. The color shading denotes the probabilistic frequency and the 90% probability intervals up and down are marked for each nuclide with the red lines. The final abundances are normalised by the final abundance at the peak of the distribution. Horizontal dotted lines indicate a factor of two uncertainties.

low-mass AGB stars. There are several well known uncertainties concerning this production. In this work, we explore the nuclear reaction side, in particular the uncertainties in neutron captures and beta decays on intermediate and heavy isotopes. Our approach is to vary simultaneously all reaction rates in a Monte Carlo (MC) framework rather than one reaction at a time. We followed the same procedure as presented in detail in [1]. Furthermore, we use temperature-dependent uncertainties based both on experimental and theoretical studies as we have already done for several other processes: the s-process in massive star, γ-process in core collapse SNe and γ-process in supernovae type Ia ([2,1,3].) On the astrophysical side, the evolution of low-mass stars is complex, especially during the TP-AGB phase ([4]). It is thus not feasible to repeat such simulations 10000 times as required by the MC procedure to complete a sensitivity study. We thus have to approximate the thermodynamic conditions inside the star with a trajectory following the key phase that we are studying (for details see [5]).

2 Results

As can be seen in Fig. 1, the overall uncertainties at the end of the trajectory approximating a ^{13}C pocket in a 3 $M_\odot$ star of solar metallicity are generally small. Indeed, most of them are smaller than 50%. This is not too surprising since the relevant temperature range ($\sim$8 keV) is accessible to experimental measurements so many of the relevant rates. There are nevertheless several nuclides, for which uncertainties are larger than a factor of two. These are generally nuclides around branching points such as ^{86}Kr. We also notice a propagation effect for nuclides more massive than ^{138}Ba. This is due to the combined effect of uncertainties in neutron capture rates above ^{138}Ba. In most cases, rates dominating the nuclear uncertainties are the neutron captures either directly producing or destroying the nuclide in question (for the full list see [5]). There are, however, three neutron-capture rates that play a significant role in the uncertainty for many nuclides during the ^{13}C-pocket conditions. These are the neutron capture rates on ^{56}Fe, ^{64}Ni, and ^{138}Ba. For a detailed analysis of the how the importance of these key rates are determined by examining the correlation between a change in a reaction rate and the change of an abundance, we refer the reader to [5].

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References

1. Rauscher, T., Nishimura, N., Hirschi, R., Cescutti, G., Murphy, A. St.J., Heger, A.: Uncertainties in the production of p nuclei in massive stars obtained from Monte Carlo variations. MNRAS 463, 4153 (2016). doi:10.1093/mnras/stw2266
2. Nishimura, N., Hirschi, R., Rauscher, T., Murphy, A. St.J., Cescutti, G.: Uncertainties in s-process nucleosynthesis in massive stars determined by Monte Carlo variations. MNRAS 469, 1752 (2017). doi:10.1093/mnras/stx696
3. Nishimura, N., Rauscher, T., Hirschi, R., Murphy, A. St.J., Cescutti, G., Travaglio, C.: Uncertainties in the production of p nuclides in thermonuclear supernovae determined by Monte Carlo variations. MNRAS 474, 3133 (2018). doi:10.1093/mnras/stx3033
4. Cristallo S., Straniero O., Piersanti L., Gobrecht D.: Evolution, Nucleosynthesis, and Yields of AGB Stars at Different Metallicities. III. Intermediate-mass Models, Revised Low-mass Models, and the ph-FRUITY Interface. ApJS, 219, 40 (2015). doi:10.1088/0067-0049/219/2/40
5. Cescutti, G., Hirschi, R., Nishimura, N., den Hartogh, J. W., Rauscher, T., Murphy, A. St.J, Cristallo, S.: Uncertainties in s-process nucleosynthesis in low-mass stars determined from Monte Carlo variations. MNRAS 478, 4101 (2018). doi:10.1093/mnras/sty1185