

S-process nucleosynthesis during Hot dredge-ups

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We present new results of the nucleosynthesis of s-elements in hot AGB stars. In the framework of the overshoot model, we show that the s-process nucleosynthesis depends sensitively on the thermodynamical conditions of the mixing zone and depending on the stellar mass and unknown overshoot parameter a large variety of s-process efficiencies can be found. We also provide a qualitative description of the production of s elements as a function of the stellar mass and metallicity. This mechanism could account for the large range of s-process efficiencies determined through the [Pb/Ce] values in low-metallicity stars.

1. Introduction

Our current understanding of the s-process in AGB stars involves the radiative burning of ^{13}C as the main source of neutrons. So far the reaction $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, which is activated at higher temperature inside hot thermal pulses, has been discarded because of the lack of observational evidence of the main by-product ^{25}Mg . The ^{13}C seeds are formed through the reactions $^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$ at the time of the 3rd dredge-up (3DUP) when protons are injected in the carbon-rich region left by the pulse. The mechanisms at the origin of proton mixing remains however largely unknown and relies on overshoot [1], rotationally induced mixing [2] or mixing by gravity waves [3].

2. S-process in the overshoot model

In the overshoot model, mixing below the convective envelope is treated as a diffusive process characterized by the diffusion coefficient

$$D_{\text{over}}(r < r^{\text{env,bot}}) = D_{\text{conv}}^{\text{env,bot}} \times e^{\frac{(r^{\text{env,bot}} - r)}{f_{\text{over}} \times H_{\text{p}}^{\text{env,bot}}}} \quad (1)$$

where the convective diffusion coefficient ($D_{\text{conv}}^{\text{env,bot}}$), radius ($r^{\text{env,bot}}$) and pressure scale height ($H_{\text{p}}^{\text{env,bot}}$) are estimated at the envelope boundary. In this model f_{over} remains the unknown overshoot parameter which determines the extent of the mixing zone. The higher f_{over} , the deeper (and hotter) the mixing.

In low-metallicity and/or massive AGB stars, relatively high temperatures can be found at the base of the convective envelope. In this circumstance, the nuclear proton lifetime

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can be comparable with (or even smaller than) the mixing timescale and protons can burn while being transported. To study this complex interplay between the nuclear and diffusive processes, it is necessary to solve simultaneously the coupled nucleosynthesis and diffusion equations, namely the system of equations

$$\frac{\partial Y_i}{\partial t} = \text{nuclear terms} + \frac{\partial}{\partial m_r} \left[(4\pi r^2 \rho)^2 D \frac{\partial Y_i}{\partial m_r} \right], \quad (2)$$

where Y_i is the molar abundance of species i .

The s-process nucleosynthesis is studied in the 16th pulse of a $3M_\odot$ $Z = 10^{-4}$ model computed with the stellar evolution code STAREVOL [4]. The temperature at the base of the convective envelope at the time of the 3DUP is $T_8^{\text{env}} \simeq 0.4$ ($T_8 = T \times 10^{-8}\text{K}$) which is high enough for the nuclear and diffusive processes to compete.

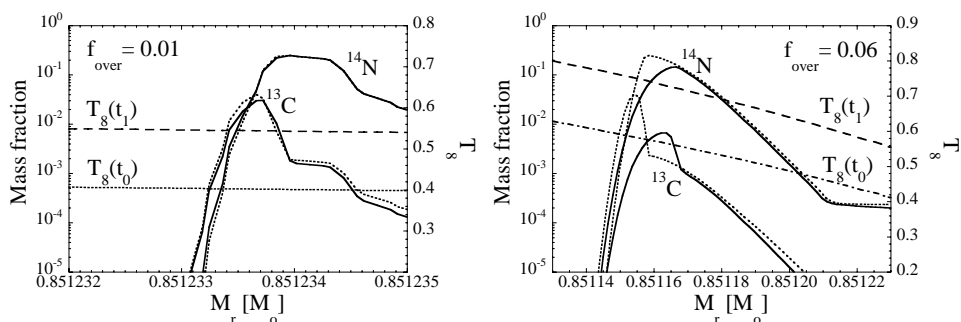


Figure 1. ^{13}C and ^{14}N profiles (solid lines) resulting from the diffusive overshoot with $f_{\text{over}} = 0.01$ (left) and $f_{\text{over}} = 0.06$ (right) at the end of the 3DUP phase. The dotted lines correspond to the ^{13}C and ^{14}N profiles that would have been obtained without considering the coupling between the nuclear and diffusion processes. Also given are the temperature profiles in the corresponding mass region at the beginning, $T_8(t_0)$, and at the end, $T_8(t_1)$, of the 3DUP phase.

In Fig. 1 we present the ^{13}C and ^{14}N profiles at the end of the 3DUP resulting from proton diffusion in “cool” ($f_{\text{over}} = 0.01$) and “hot” ($f_{\text{over}} = 0.06$) layers. In the hot environment ($0.5 \lesssim T_8^{\text{env}} \lesssim 0.7$), the nuclear H-burning competes with the diffusion process, so that ^{13}C and ^{14}N are produced and transported at the same time. The result of this complex interplay is the building-up of a massive ^{14}N layer that engulf the ^{13}C pocket. Contrary to the “cool” case, the ^{13}C abundance is always lower than the ^{14}N abundance and wherever neutrons are produced by $^{13}\text{C}(\alpha, n)^{16}\text{O}$, they will be dominantly captured by the abundant ^{14}N neutron-poison rather than by the Fe seed nuclei. The consequences for the s-process are drastic as illustrated in Fig. 2 which shows that in this

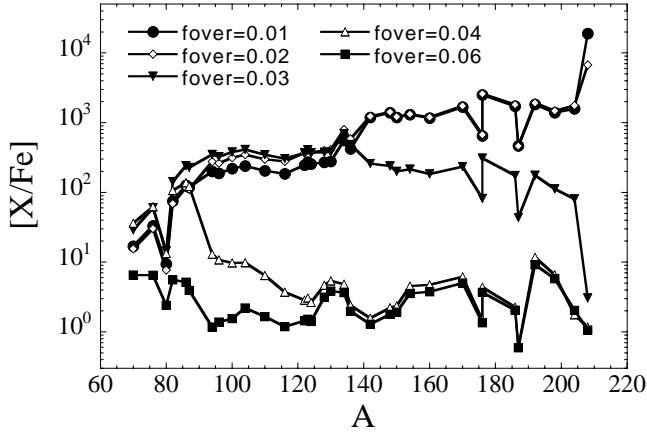


Figure 2. Overproduction factors (with respect to solar) of s-only nuclei at the end of the interpulse phase in the partial mixing zone resulting from the diffusive overshooting model for different values of f_{over} . Each distribution is mass-averaged over the corresponding mixing zone $\Delta M = 1, 2, 5, 6, 14 \times 10^{-5} M_{\odot}$ for $f_{\text{over}} = 0.01, 0.02, 0.03, 0.04, 0.06$, respectively.

specific case, the production of s-elements is totally suppressed. We further investigated the dependence of this nucleosynthesis on the thermodynamical conditions of the mixing zone by varying f_{over} , i.e. by injecting protons in regions of different temperatures. The results are displayed in Fig. 2 and show that a large range of s-process efficiencies can be achieved. In particular, deep diffusions characterized by $f_{\text{over}} > 0.03$ tend to efficiently suppress the production of s-elements in this model.

3. Mass and metallicity dependence of the s-process efficiency

From a grid of AGB models computed with $f_{\text{over}} = 0.03$, we determined the mean temperature at the base of the convective envelope and plotted these values as a function of the mass and metallicity of the star. Schematically, these lines (Fig. 3) delineates 3 regions : (i) if $T_8^{\text{env}} \lesssim 0.4$, the s-process is very efficient, (ii) if $T_8^{\text{env}} \gtrsim 0.7$ protons are burnt in fly and no s-elements are produced and (iii) in the intermediate region $0.4 \lesssim T_8^{\text{env}} \lesssim 0.7$ a wide range of s-process efficiencies can be found. This figure shows that the s-process efficiency is expected to significantly decrease as the metallicity drops and/or the mass increases. In particular, the s-process should not be significantly affected by the conditions below the convective envelope in solar-metallicity stars less massive than $5 M_{\odot}$. Concerning stars in the transitional zone, it remains extremely difficult to predict the s-process efficiency since small modifications to the unknown overshoot parameter f_{over} (that could also possibly vary with the stellar mass and metallicity) can have a considerable impact on the final s-process distribution.

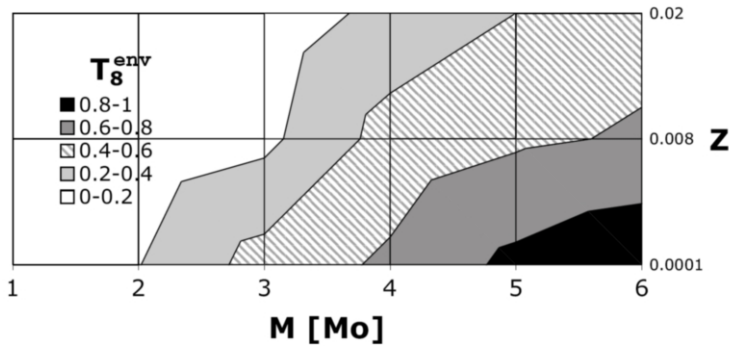


Figure 3. Temperature at the base of the convective envelope (T_8^{env}) at the time of the 3DUP for a grid of AGB models of mass $M = 1, 2, 3, 4, 5, 6 M_\odot$ and metallicity $Z = 0.02, 0.008$ and 0.0001 .

In the light of observations, we consider that this mechanism could account for the large range of reported efficiencies as indicated by the $[\text{Pb}/\text{Ce}]$ values [5,6] determined in low-metallicity AGB stars. In particular, this mechanism could explain the observations of s-rich low-metallicity stars that are not overabundant in Pb.

4. Conclusion

The s-process nucleosynthesis resulting from diffusive overshoot in hot AGB stars is found to depend sensitively on the thermodynamical conditions in the mixing zone. For these AGB stars, coupling of diffusion and nuclear burning induces the overlapping of the ^{14}N -rich and ^{13}C -rich layers, which strongly inhibits the production of s-elements. Depending on the unknown overshoot parameter and the mass of the AGB star, a wide range of s-process efficiencies can be naturally explained at a given metallicity.

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