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S-process nucleosynthesis in primordial AGB stars

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Despite the lack of iron seeds and provided partial mixing of protons takes place below the convective envelope, it is shown that the production of s-process elements can be efficient in primordial AGB stars. The synthesis proceeds as follows: neutrons are mainly produced by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction and captured by the abundant C-Ne isotopes to synthesized heavier species which will then serve as efficient seed elements for the s-process thanks to their larger neutron cross sections. When the bottleneck formed by the $^{33}\text{S}(n, \alpha)^{30}\text{Si}$ is passed, the synthesis of s-elements proceeds in a standard way. Under the assumption that protons can diffuse below the envelope, primordial AGB stars are expected to be s-process enriched and to exhibit strong signatures of Pb and Bi.

1. Introduction

The study of primordial stars has been recently revived through a series of theoretical works (e.g. [1–4]) and new observations of very metal-poor stars (e.g. [5,6]). These stars, also referred to as population III stars, theoretically formed soon after the Big Bang from the fragmentation of primordial gas condensations at redshifts of the order of $z \simeq 30$. Their initial mass function is largely unknown and, although massive stars are expected to be the main component of this stellar population, it is not excluded that intermediate mass stars may have also formed in quite numerous amounts.

The initial composition of Population III stars is characterized by the absence of metals and in particular of CNO elements. This peculiarity slightly affects the evolution of low- and intermediate-mass stars. Briefly, during the main sequence, stars more massive than $\sim 1 M_{\odot}$ cannot activate the CN cycle because of the absence of the catalytic seeds. As a consequence they contract until the central temperature reaches 10^8K and the 3α reaction ignites. When the central carbon mass fraction exceeds $\sim 10^{-11}$, the CNO cycle takes over the nuclear energy production and a standard evolution resumes. At the end of the core He burning phase, primordial stars suffer mixing episodes during which the carbon produced in the He burning shell mixes with the envelope. The pollution of the H-rich regions in CNO elements will later allow the CN cycle to operate in the H burning shell and the thermal pulse phase to occur (see e.g [7] for more details). The star then enters the thermally pulsing AGB phase characterized by recurrent instabilities in the He burning shell followed by deep third dredges-up.

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2. The production of s-elements

The role of AGB stars as strong contributors to the production of s-elements in the universe is now widely accepted. The major neutron source is believed to be $^{13}\text{C}(\alpha, n)^{16}\text{O}$ at low temperatures during the radiative interpulse phase, followed by $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ above $T \gtrsim 3 \times 10^8 \text{K}$ in the convective pulse. The scenario for the production of s-elements relies on the operation of a partial mixing (PM) of protons from the H-rich region (the convective envelope) into the ^{12}C -rich region (the region previously occupied by the thermal pulse) at the time of third dredge-up. Through the following sequence of reactions $^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$ a “ ^{13}C pocket” forms which constitutes the reservoir for the neutron production. The details of the transport mechanisms are still poorly understood and are believed to originate from convective overshooting and/or rotationally induced mixing.

Assuming an exponentially decreasing proton profile below the envelope over an extension representing 5% of the radial pulse extension and using realistic stellar models, we computed the full nucleosynthesis taking place in the region of PM [8]. Because population III stars are initially devoid of metals, the s-process nucleosynthesis operates slightly differently: instead of being traditionally captured by the abundant and reactive iron seeds, neutrons in primordial stars are captured by the only present CNOF-Ne isotopes. The so-produced species heavier than Ne are characterized by larger neutron capture cross sections than the C-Ne isotopes and capture neutrons even more efficiently. The neutron flow is however partially stopped by the bottle neck formed by the recycling reaction $^{33}\text{S}(n, \alpha)^{30}\text{Si}$. Let us note that neglecting this reaction would increase the amount of produced s-elements by a factor of about 5. When the bottle neck is passed, radiative neutron captures followed by β -decays lead to the synthesis of all s-elements up to Pb and Bi (Fig. 1). Basically, at very low-metallicities neutron captures start on light elements instead of iron seed nuclei. It is worth emphasizing that the first neutron exposure is efficient enough to synthesize all s-elements and mostly Pb and Bi. This is due to the fact that as the metallicity decreases, more neutrons are available per seed nuclei. The conditions for the s-process nucleosynthesis depend mainly on the relative proton-to-carbon ratios in the PM region $[Y_p/Y(^{12}\text{C})]$, where $Y(A) = X(A)/A$ is the abundance of A by number. In regions where $Y_p/Y(^{12}\text{C}) \lesssim 10^{-2}$, the production of ^{13}C is small and the s-process is inefficient. In the domain $10^{-2} \lesssim Y_p/Y(^{12}\text{C}) \lesssim 1$, the neutron density is relatively high ($N_n \gtrsim 10^{-9} \text{cm}^{-3}$) and s-elements are produced. Finally, if $Y_p/Y(^{12}\text{C}) \gtrsim 1$, ^{14}N is largely produced and prevents further neutron captures by heavy species. During thermal pulses, temperatures up to $4 \times 10^8 \text{K}$ are reached at the bottom of the convective region leading to a second neutron exposure by $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$. For the duration of the pulse ($\lesssim 50 \text{yr}$ in a $3 M_\odot$ model) the neutron density reaches $N_n = 10^{15} \text{cm}^{-3}$ and produces some (minor) rearrangements of specific s-only elements (see [9] for more details).

3. Conclusion

Provided PM of protons is acting in zero-metallicity stars as in more metal rich stars, we showed that an efficient s-process nucleosynthesis can take place, leading preferentially to the production of Pb and Bi. Recent observations of low-metallicity stars (down to $[\text{Fe}/\text{H}] = -3.1$) presenting large Pb overabundances ($[\text{Pb}/\text{hs}] \gtrsim 1$, where hs denotes heavy s-elements such as Ba, La or Ce support this finding [6]. But problems still remain in

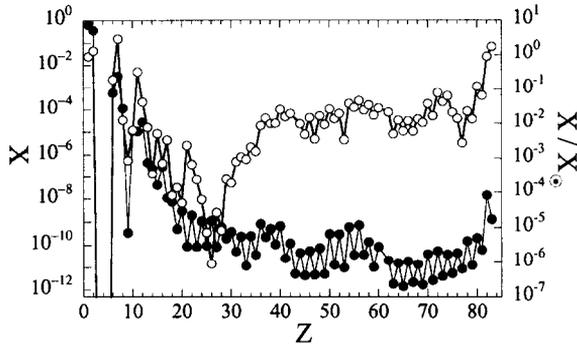


Figure 1. Mass fraction (full circle) and relative to solar abundances (open circle) at the surface of a $3 M_{\odot}$ AGB after 22 thermal pulses and partial mixing of protons below the envelope. Note the overabundance of Pb and Bi, the heaviest elements possibly produced by the s-process.

particular because not all metal-deficient stars exhibit a strong Pb overabundance as predicted from the PM scenario. For example [5,10] found metal-poor s-process enriched stars with no Pb-to-s overabundance, i.e. $[\text{Pb}/\text{hs}] \simeq 0$. These observations can only be accounted for if a less efficient s-process is at work and an obvious way of reducing the neutron capture efficiency would be to decrease the amount of ^{13}C in the PM model. There are however no physical mechanisms that could be invoked to justify such a reduction (see [10] for a discussion). Two new scenarios have been suggested recently to account for the observations. The first one calls for extraordinary mixing of H from the envelope directly into the thermal pulse [11] and the second one to the rotationally induced mixing of protons [12]. In both cases, consistent simulations remain to be performed.

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