H-He Shell Interactions and Nucleosynthesis in Massive Population III Stars

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Abstract. We report on our ongoing investigation into the nucleosynthetic and hydrodynamic nature of mixing at the interface between the H- and He-convection zones in massive Pop III stars. Studying recent a grid of 26 1D stellar evolution simulations with different mixing assumptions, we find that H-He interactions occur in 23/26 cases. We demonstrate the nucleosynthesis expected in a H-He interaction in an 80M\textsubscript{☉} star. Finally, we describe our progress in simulating a Pop III double convection zone in the PPMStar hydrodynamics code.

Keywords: Population III, stars, abundances, CEMP, i-process

Pop III stars are thought to have produced and released the first elements heavier than those created in the Big Bang \textsuperscript{1}. The most metal-poor stars we observe today may be the most direct descendants of Pop III stars and are a powerful diagnostic in our study of early cosmic chemical evolution \textsuperscript{2}.

Interactions between H and He-convection layers have been seen in 1D stellar evolution simulations of massive Pop III stars \textsuperscript{3,4,5} but until recently, have not been investigated in detail.

Similar convective-reactive events occur in additional environments, such as He-shell flashes in low-Z low-mass stars \textsuperscript{6,7,8}, post-AGB stars \textsuperscript{9}, rapidly-accreting white dwarfs \textsuperscript{10}, and low-Z Super-AGB stars \textsuperscript{11}. In these cases—just as Pop III stars—likely leading to the i-process with neutron densities $\approx 10^{13-15}$ cm$^{-3}$, first discussed by Cowan & Rose \textsuperscript{12}.

We have explored the possibility that the abundance patterns of the CEMP-no stars SMSS J031300, HE 1327-2326 and HE 0107-5240, among the most iron-poor stars known, could be explained by highly energetic, convective H-He shell interactions in massive Pop-III stars \textsuperscript{13} without a strong odd-even effect. Based on a 45 M\textsubscript{☉} stellar model that undergoes a H/He convective-reactive event during
C-core burning, we ran single-zone calculations to ascertain the nucleosynthesis which may result from such an event. For these simulations we found neutron densities of $\approx 6 \times 10^{13}$ cm$^{-3}$, leading to striking similarities with the abundance patterns existing in some of the most metal-poor stars, particularly in abundance ratio trends seen from Na-Si and Ti-Mn.

We have run a grid of 26 models using the MESA stellar evolution code [14] over a mass range of $15 - 140 \text{M}_\odot$. For each initial mass, we use 5 different sets of mixing assumptions in order to explore the dependence of H-He interactions on macrophysical modelling choices. Our findings indicate that there are three distinct modes for the interaction: firstly, as in Clarkson et al. [13] a convective H and He-shell interaction. Secondly, a convective H-shell mixing into a convective He-core and thirdly, a convective H-shell mixing down into a radiative He-shell.

Although difficult to constrain from 1D simulations, we have performed additional single zone calculations more, with the aim to further explore the abundances of HE 0107-5240 and HE 2317-2326. We ran simulations with $T = 2.5 \times 10^8$ K and $\rho = 1.9 \times 10^2$ g cm$^{-3}$ from the He-shell of an 80$\text{M}_\odot$ model from our grid of Pop III models with 1% H added, by mass. Preliminary results are shown in Fig. 1. We find that in order to simultaneously reproduce both light and trans-Fe elements in these stars the total neutron exposure must be a factor of 4 smaller than we previously reported.

![Fig. 1. Abundances of CEMP-no stars HE 0107-5240 and HE 2317-2326 in purple and black are shown with single zone calculations (red and blue stars) based on an 80$\text{M}_\odot$ stellar evolution simulation.](image)

We have begun using the explicit PPMstar code [15] to investigate these events. Our initial suite of simulations contain the He-shell flash convection zone and the bottom of the H-burning convection zone, separated by a radiative zone of 25,000 km (Fig 2). Initially we are driving these convection zones by a constant volume heating at the bottom of the He convection zone and a corresponding cooling at the top of the H-burning convection zone. In order to realistically
model this Pop III stellar environment, several code modifications were made. In future simulations, we will be including a simplified network to model the nuclear feedback expected from the mixing of H and He-burning material. The aim of these simulations is to answer the hypothesis [13] that such an event may led to a GOSH-like instability and could potentially eject material from the star. We hope to determine whether such an event would occur, and if so, how would it unfold in a full 4π-3D environment in terms of possible asymmetries in the entrainment and how would the model respond to the nuclear feedback?

Fig. 2. 3D simulation of convective H and He-burning shells on a $768^3$ grid. Only the first 50,000 km of the H-shell is simulated in order to adequately resolve the stable layer. Colours show vorticity.
The first message stars may have experienced violent convective-reactive interactions at the interface of the H- and He-burning regions. Three dimensional simulations with nuclear feedback are now being constructed to investigate this stellar and nuclear astrophysics environment. A light-element i process could be triggered, and may result in abundance patterns observed in CEMP-no stars without strong odd-even effect.

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