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Nucleosynthesis in 2D Core-Collapse Supernova Long-Term Simulations of 11.2 and 17.0 $M_\odot$ Progenitors

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We perform detailed nucleosynthesis calculations for two long-term, 2D simulations of core-collapse supernovae. We find that elements are produced up to Ru (Z = 44) and observe abundance patterns that are characteristic of a νp-process. One important characteristic of the long-term simulation is that there is still accretion of matter onto the proto-neutron star and unbinding of matter in some other regions at the time when the simulations stop (around 7s). Dividing the tracer particles into different bins according to their peak temperatures enables us to study and compare the nuclear compositions of these bins for the different simulations.

KEYWORDS: core-collapse supernovae, nucleosynthesis, νp-process

1. Introduction

Core-collapse supernovae (CCSNe) play an important role in galactic chemical evolution as the earliest providers of α-elements up to iron. Thus, in order to understand the abundance patterns of metal-poor stars, it is crucial to study nucleosynthesis in CCSNe of various progenitor masses. Until recently, large studies of CCSNe comprising many different progenitor masses or investigations of the long-term evolution of single events could only be performed in spherical symmetry, since multi-dimensional CCSN simulations have a high computational cost and are difficult to perform. These studies do not only serve the purpose of investigating the explosion characteristics of the different progenitors, but also help understand the explosive nucleosynthesis of α-elements beyond Si and their distribution in the galaxy through space and time.

In the past, many studies have been conducted to gain a better understanding of the nucleosynthesis associated with CCSNe and their role in enriching the interstellar medium with α-element and Fe group nuclei (e.g., [1, 2]). As CCSNe have been the first explosive events to occur in the young galaxy, the compositions of very metal-poor stars can be interpreted as the results of several nearby CCSNe, without any contributions from type I SNe or neutron star mergers.

Nakamura et al. (2015) [3] recently performed CCSN simulations with axial symmetry for a broad range of progenitor masses. For several of those models, the simulation time has been extended to several seconds after core bounce.

2. Method

We perform this study using WINNET, a nuclear network based on the REACLIB reaction library which enables us to follow all relevant reactions up to Z_{max}, which we set to 60. The reaction rates employed for this study are the same as in [4]. All the tracer trajectories are individually extrapolated until the temperature drops below $T_9 = 0.01$, using an adiabatic expansion with constant velocity.

2.1 Ejection criteria

Although the supernova explosions are simulated for a long time after core bounce, there is still accretion of matter around the equatorial regions and simultaneous outflow towards the poles at the end of the simulations. Therefore, it is important to define a criterion for the successful ejection of tracer particles. Testing different criteria reveals that the majority of the hot tracers that encounter the outgoing shock during the simulation are found to be ejected independently from the applied criterion. As a consequence, the ejected amounts of nuclei that are produced in explosive nucleosynthesis can be predicted within small uncertainties. We choose a prescription that combines a local criterion (positive radial velocity and positive total energy) and the fact that some tracers far away from the center but within a certain angle around the poles will encounter the outgoing shock only after the end of the simulation. This second aspect is taken into account by including all matter within an angle of 45° around the poles. For the 11.2 $M_\odot$ model we observe a strong outflow in only one polar direction and therefore add material only around one pole. For the final results also the (unprocessed) progenitor material from outside the computational domain within the same opening angle is added to the ejected composition.

As the composition of the particles is heavily dependent on their peak temperatures during the simulation, we divide them into 20 bins according to their peak temperature in the simulation. Using this method, we want to test if we are able to make bin-by-bin nucleosynthesis predictions that can be easily applied in the future in order to give estimates also for CCSNe simulations of other progenitors.

3. Results

Figure 1 shows the isotopic [X/Fe] distributions for both progenitors after decay to stability. Connected data points of the same colour represent different isotopes of the same element. All nuclei

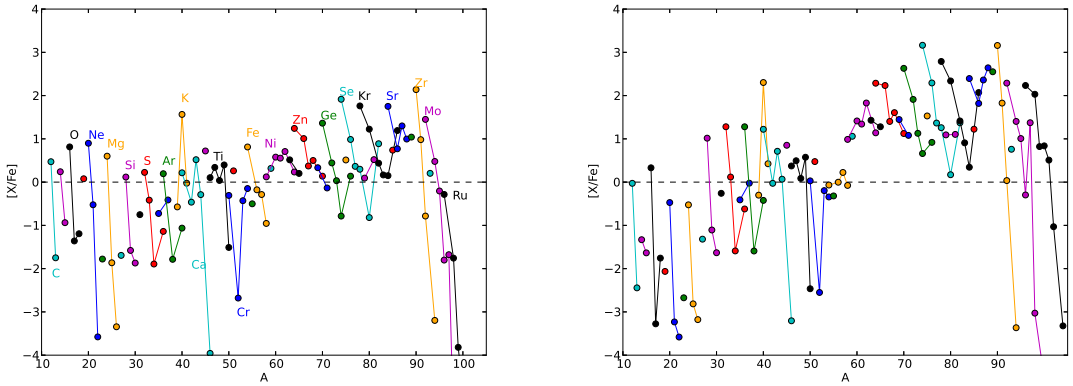

Fig. 1. Compositions of the ejecta for the 17.0 $M_\odot$ (left) and the 11.2 $M_\odot$ (right) progenitors, where we have used the quantity $[X/Fe] = \log(Y_X/Y_{Fe})_{calc} - \log(Y_X/Y_{Fe})_\odot$. Both compositions reveal a strong νp-process signature.

with $T_{1/2} < 10^9$ yr are considered to be completely decayed, which is the reason for the large [^{40}K/Fe] value ($T_{1/2}(^{40}K) = 1.28 \times 10^9$ yr). The solar abundances are from Lodders et al. (2009) [5].

The slight overproduction of α-elements up to Ti is typical of CCSNe [2]. The high abundances of neutron-deficient isotopes for Z > 32 (Ge and beyond) are a clear signature of the νp-process, a mechanism of the rapid proton capture process that allows to bypass the ^{64}Ge waiting point by means of $\bar{\nu}$-captures on free protons, converting them to neutrons which can be captured by ^{64}Ge and other neutron-deficient isotopes [6].

In addition to the detailed nuclear compositions obtained by post-processing around 6000 tracer particles per simulation, we are interested in studying the possibility of predicting the compositions of CCSN ejecta directly from the simulation (i.e., without the need to post-process every tracer). We have therefore divided the tracers into 20 bins according to their peak temperatures, which enables us to compare the nuclear compositions of the individual bins across different SN simulations. The bin compositions are obtained by summing up the individual tracer compositions, weighted by tracer mass. Such a comparison of the compositions from three temperature bins is shown in Figure 2. The overall agreement is quite good, with the exception of the highest-temperature bin ($T_9 > 8.0$), where the tracer distribution is quite inhomogeneous, in contrast to the other bins. It is possible that a further sub-division according to Y_e can improve the agreement. Note that since this is a comparison between only two CCSN simulations, its predictive power is limited. However it presents a promising base for more thorough investigations.

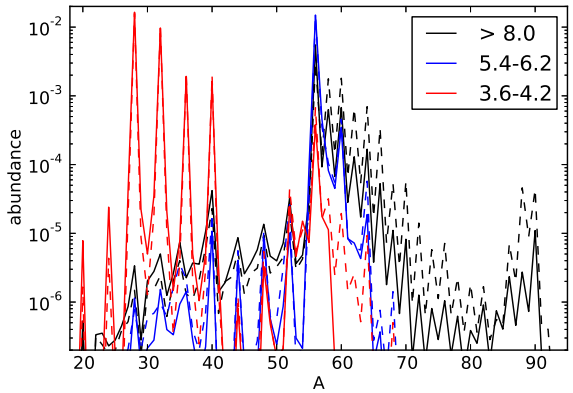

Fig. 2. Abundance distributions of individual temperature bins (see text) for the 17.0 $M_\odot$ (solid lines) and the 11.2 $M_\odot$ (dashed lines) SN models. The numbers indicate the temperature range of the different bins in units of GK.

Acknowledgements

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