INTRODUCTION

Massive stars (M>8 M☉) undergo core collapse with a kinetic energy release of 10⁵ⁱ erg. While sophisticated multi-dimensional models are needed for an accurate study of the explosion mechanism, they are computationally too expensive for detailed nucleosynthesis studies. However, precise nucleosynthesis predictions are needed to understand the supernova contribution to the heavy elements and the abundances observed in metal-poor stars. Here, we use spherically symmetric core-collapse simulations with detailed microphysics and neutrino physics combined with a novel method to artificially trigger the explosion.

ARTIFICIAL EXPLOSIONS

Several methods have been proposed in the past to produce an artificial explosion:

1. "Thermal bomb/Piston": the explosion is triggered either by increasing the temperature or by placing a piston in the star at the end of silicon burning, respectively [7,8]. Limitations: These methods miss the physics of collapse, bounce, and the onset of the explosion. For example, the electron fraction Ye (a crucial quantity for the nucleosynthesis) cannot evolve and becomes inconsistent, especially in the interiormost ejecta. The mass cut has to be placed by hand.

2. "Absorption": this method triggers the explosion by increasing the neutrino absorption and emission rates in the heating region by a constant factor

\[ \nu_e + n \rightarrow \nu + e^- \]

\[ \nu_e + p \rightarrow \nu + e^+ \]

Small factors do not significantly affect the system (except for additional energy deposition) but results in sub-energetic explosions. Large factors change the system beyond additional energy deposition [2,3].

AIM

The aim of this project is to model long term self-consistent explosions for core-collapse nucleosynthesis. We present a novel method to artificially trigger the explosion for detailed nucleosynthesis studies.

THE CODE

We model the core collapse, bounce and subsequent explosion of a 15 M☉ progenitor with the code Agile-IDA5, an adaptive-mesh relativistic hydrodynamic code, which includes the isotropic diffusion source approximation for the neutrino transport (IDSA) [6]. This provides a computationally efficient framework for our study.

THE METHOD

In the neutrino-delayed explosion mechanism, it is believed that the deposition of neutrino energy revives the stalled shock and powers the explosion. We artificially trigger the explosion by depositing a small amount of additional energy (from mu and tau neutrinos) into the heating region after bounce, mimicking more efficient neutrino heating as seen in multi-dimensional simulations [1]. This heating term is introduced only in the heating region into the heating region after bounce, mimicking more efficient neutrino heating as seen in multi-dimensional simulations [1]. This heating term is introduced only in the heating region after bounce, mimicking more efficient neutrino heating as seen in multi-dimensional simulations [1].

- push factor (p): It regulates the strength of the explosion. We have used multi-dimensional simulations to constrain this parameter
- time cut (t): After an explosion is detected, the extra heating is switched off with an exponential factor.

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REFERENCES


RESULTS

Push/No Push comparison. The figure left the radial velocity, density, electron fraction and entropy as a function of radius at 300ms after bounce of two simulations. Both simulations use the same progenitor (s15), but only the red curves show an explosion (positive radial velocity propagating outward). The red curve also shows the characteristic peak in electron fraction on the edge of the neutron star, the density peak from the propagating explosion, and much greater entropy in the star due to the explosion. We have used multi-D simulations to constrain the parameters in PUSH.

Push-Absorption comparison. We performed a simulation (simulation G) by modifying the neutrino absorption rates by a factor of 7 (a=7). We compare the results with a simulation that used a push factor of p=1.5 (simulation C). Both methods show similar explosion properties. Our novel method (PUSH) [1] is comparable to the absorption method used by Fischer et al., [2] e.g. However, we do not alter the reactions setting the electron fraction (Ye). This results in a more reliable prediction of this quantity crucial for nucleosynthesis.

Electron Fraction. The code contains all weak interactions to correctly describe the electron fraction Ye. We notice that the exploding models show a region with Ye > 0.5 (that is, a proton-rich site). This quantity is crucial for accurate nucleosynthesis yields. For instance, Ye determines the composition of the innermost ejecta (enhanced abundances of S, Si, Ti and Zn). [3]

Progenitor Comparison. The four figures directly to the left show the radial velocity, radius, electron fraction, and entropy as a function of radius at 400ms after bounce for four different progenitors, where the number shown in the legend indicates the progenitor mass in solar masses. The explosion times vary because of the different masses, it can be seen in the velocity plot that s15 and s20 exploded well before the others.

CONCLUSIONS

1. Spherically symmetric simulations combined with PUSH provide an improved framework for detailed nucleosynthesis studies.
2. PUSH results in explosion properties similar to other published methods, such as absorption, but with a more reliable electron fraction.
3. We extended the simulation beyond the NSE regime by including a modern non-NSE EOS, [4] e.g.