Nucleosynthesis in Core-Collapse Supernovae

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Introduction and Motivation

The nucleosynthesis which occurs in core-collapse supernovae (CCSN) is one of the most important sources of elements in the Universe. Elements from oxygen through iron come predominantly from supernovae, and contributions of heavier elements are also possible through processes like the weak r-process, the gamma process, and the light element primary process. The composition of the ejecta is directly linked to the mechanism of the explosion, thus simulations of high physical fidelity are needed to explore what elements and isotopes CCSN can contribute to Galactic Chemical Evolution (GCE). However, much of our understanding of CCSN nucleosynthesis comes from parameterized models, often one dimensional, that fail to address essential physics, including turbulent flow/instability and neutrino-matter interactions.

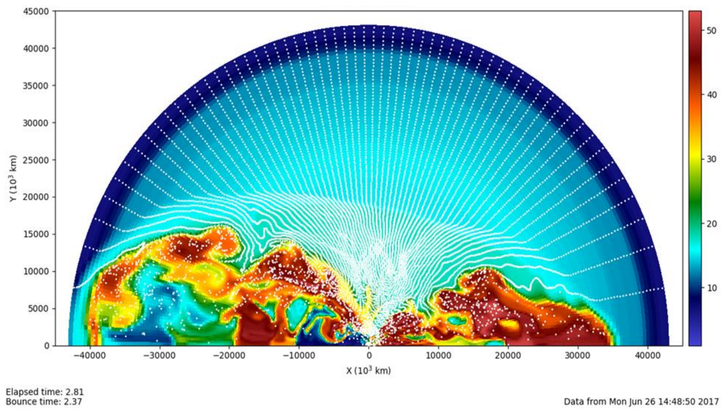


Figure 1: Distribution of tracer particles in 2D B-series model, as well as the dynamic behavior of particles hit by the shockwave. The underlying color shows the mean atomic mass, indicative of the elemental composition.

Objectives and Methods

Here we present nucleosynthesis results from self-consistent CCSN simulations computed with CHIMERA, a multi-dimensional neutrino radiation-hydrodynamics code. The incorporation of key physical processes within the CHIMERA models removes uncertainty in the nucleosynthesis related to the generation of the explosion itself. Due to the large computational cost, CHIMERA models are not run as long as the parameterized models, nor can they utilize the same extensive reaction networks within the simulation. Our predictions therefore rely on results of the nuclear reaction network used within the CHIMERA simulations and on post-processing analysis of representative thermodynamic histories using an extensive network.

To enable post-processing, we placed passive Lagrangian tracer particles, each representing a mass element within the star, in a grid uniform in mass throughout the model. The particles record thermodynamic histories for individual mass elements as they move throughout the explosion, which can then be used in post-processing nucleosynthesis and data analysis. The post-processing tools must extrapolate to times after the CHIMERA simulation to allow the nucleosynthesis to complete (see Harris et al 2017), as well as to compute nucleosynthesis with larger, more realistic reaction networks.

References

J. A. Harris, W. R. Hix, M. A. Chertkow, S. W. Bruenn, E. J. Lentz, O. E. B. Messer, et al. (2018), ApJ, in prep.

J. A. Harris, W. R. Hix, M. A. Chertkow, C. T. Lee, E. J. Lentz & O. E. B. Messer (2017), ApJ, 843 2.

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The impact of multi-dimensions

With multi-dimensional models, initial radius is no longer a unique marker of nucleosynthetic outcome. Not only the completeness of the nucleosynthesis, but in fact the final nucleosynthesis process, can depend on their initial latitude on the grid. Although the initial structure of the star is spherical (here a 12 solar mass, solar-metallicity, non-rotating model from Woosley & Heger 2007), the shockwave in the multi-dimensional CHIMERA models is stronger along the poles (see Fig. 1). The polar outflows, which drive matter strongly outward, are accompanied by a persistent equatorial accretion stream. Therefore, it becomes possible for matter to become captured in downwards flows and to reach extremely high temperatures near the center of the star. These particles enter nuclear statistical equilibrium (NSE) due to the high temperatures they experience, and are also exposed to a much higher neutrino flux due to their proximity to the proto-neutron star before they are ultimately ejected. Both of these facts significantly impact their nucleosynthetic evolution.

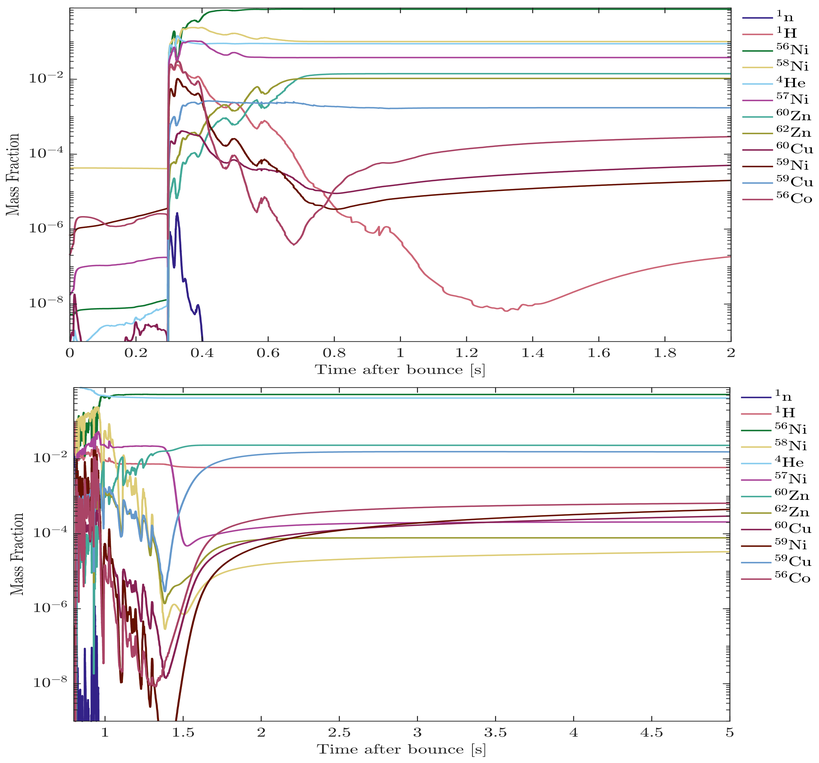


Figure 2: Mass fraction predictions using an external 160-species nuclear network for two particles with the same initial radius for the 12 $M_\odot$ model, one placed on the pole (top) and one placed near the equator (bottom).

Results

Figure 2 illustrates how strongly the dynamics of the explosion can affect the nucleosynthesis, demonstrating the need to address the fluid flow for obtaining accurate nucleosynthesis predictions. For the polar tracer (top), the shockwave reaches the initially silicon-rich matter 300 ms after bounce, driving that tracer outward and resulting in complete silicon burning, which produces largely ^{56}Ni and >10% ^{4}He. However, the equatorial particle continues to fall toward the neutron star and becomes part of the “hot bubble”. When it is eventually ejected after 900 ms, its nucleosynthesis is initially dominated by alpha particles—resulting in the material tracked by this tracer undergoing alpha-rich freeze-out, expanding much faster than it was able to cool, producing far fewer heavy elements like ^{56}Ni. Further, note the significant abundance of free protons, the fingerprint of this tracer’s much larger neutrino exposure. Similar effects, repeated throughout the interior of the star, result in a much greater diversity of thermodynamic conditions, and hence nucleosynthesis outcomes, in multi-dimensional models (see Harris et al 2017).

Future Directions

A unique feature of CHIMERA is the ability to use larger nuclear reaction networks within CCSN simulations. We have completed our first CCSN simulations using an inline 160 species network, starting from a 9.6 $M_\odot$ zero-metallicity star (Heger, 2015), making this the most sophisticated model to date for CCSN nucleosynthesis.

The lowest mass iron core-collapse supernovae are distinct from their more massive brethren, with their explosion mechanism and nucleosynthesis being more like electron capture supernovae resulting from Oxygen-Neon white dwarves. This is very evident in the Figure below.

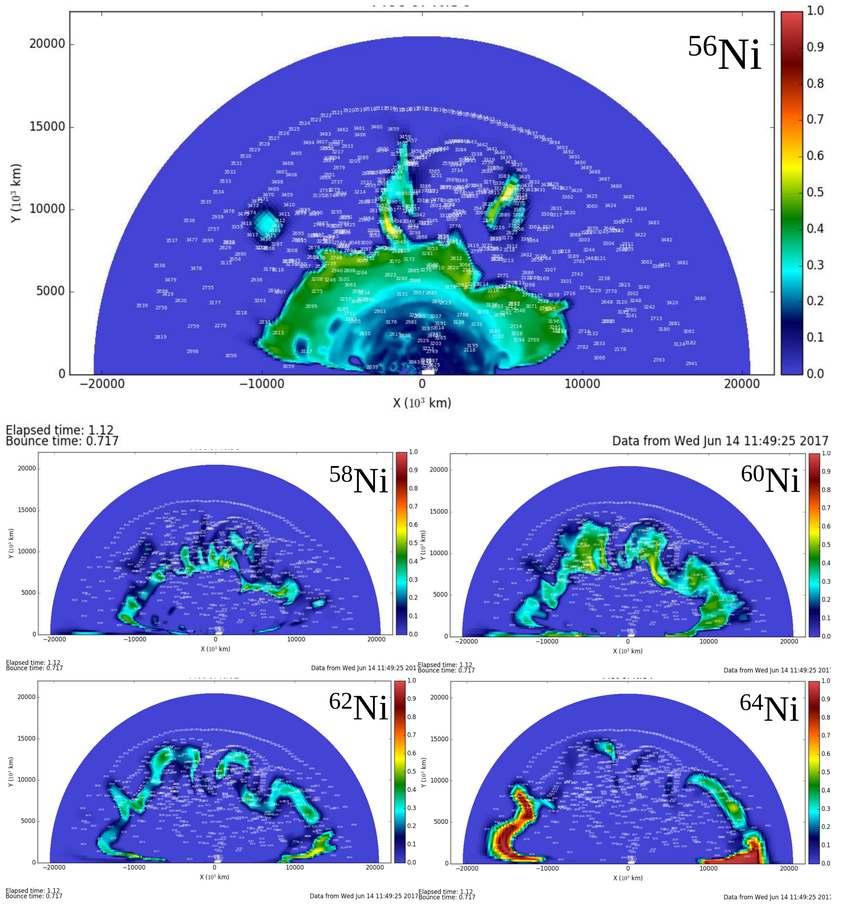


Figure 3: The mass fractions of nickel isotopes. Tracer positions are evident by number.

Preliminary Findings

Figure 3 shows regions of concentrated nickel production for various isotopes in the CCSN at the same moment. The heaviest isotope of nickel, ^{64}Ni, is present at the largest radius, with an intense concentration near the equator. Lighter isotopes of nickel appear at progressively smaller radii, with the concentration of the lightest nickel isotope, ^{56}Ni, much nearer to the proto-neutron star with a much more uniform distribution. Note the different ejecta geometry from Figure 1. Further, the dominant isotopes of nickel produced for the two types of stars differ: the 12 solar mass model produces primarily ^{56}Ni, while this model produces a broad range of neutron-rich nickel.

By generating nucleosynthesis predictions using realistic networks across the range of progenitor mass and metallicity, we will be able to highlight the differences between the nucleosynthesis in CCSN such as this and their more massive brethren. Combining realistic networks that cover the energetically significant processes with post-processing analysis of the heavier elements in multi-dimensional, neutrino-driven CCSN simulations will provide the most definitive predictions to date of the GCE contributions from CCSN today back to the earliest stars in the universe.