Three-dimensional simulations of mixing in the first stars

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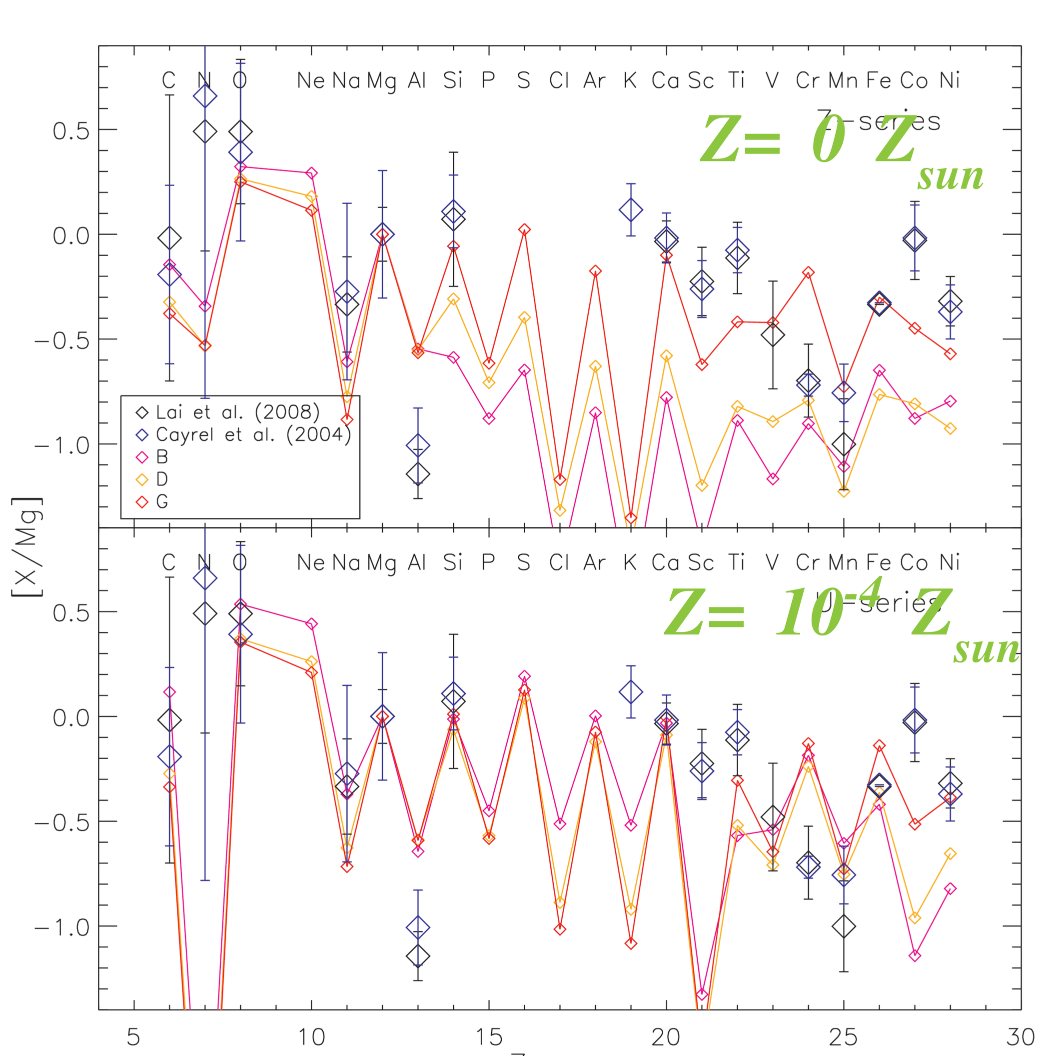
Abstract

The first stars in the Universe cannot yet be directly observed, but clues to their nature can be found in their nucleosynthetic imprint on ancient metal-poor stars being surveyed in the Galactic halo today. How the first metals reached the next generation of stars is a result of several hydrodynamical processes, beginning with how heavy elements mixed with the interiors of stars prior to their breakout into the early IGM. We present 2 and 3 dimensional simulations of mixing and fallback within core-collapse supernovae at Z = 0 and 10-4 Zsun, and solar metallicity. We follow mixing and fallback within the stellar envelope, and find that the primary contributors of metals to the early universe were 15 - 40 solar mass core-collapse supernovae with explosion energies of less than 2.4x1051 ergs. These roughly circular, moderately energetic explosions adequately reproduce the abundance patterns found in the extremely metal-poor (EMP) stars surveyed to date.

Core-collapse supernovae and the abundances of metal-poor stars

So far, more than 30 EMP stars with [Fe/H] ~ 3.0 have been found. EMP stars show a low scatter in their abundance ratios, suggesting that they were formed from gas that was well mixed and likely enriched by a representative sample of the first supernovae in the Universe. These abundances do not match the distinctive odd-even pattern in the ejecta of pair instability supernovae, so we must look to core-collapse supernovae to eject the materials that enrich the gas from which EMP stars formed. Matching the theoretical yields of core-collapse supernovae with these abundance ratios may provide some clues to the initial mass and explosion energy of these first supernovae.

2d yields and EMP star abundances

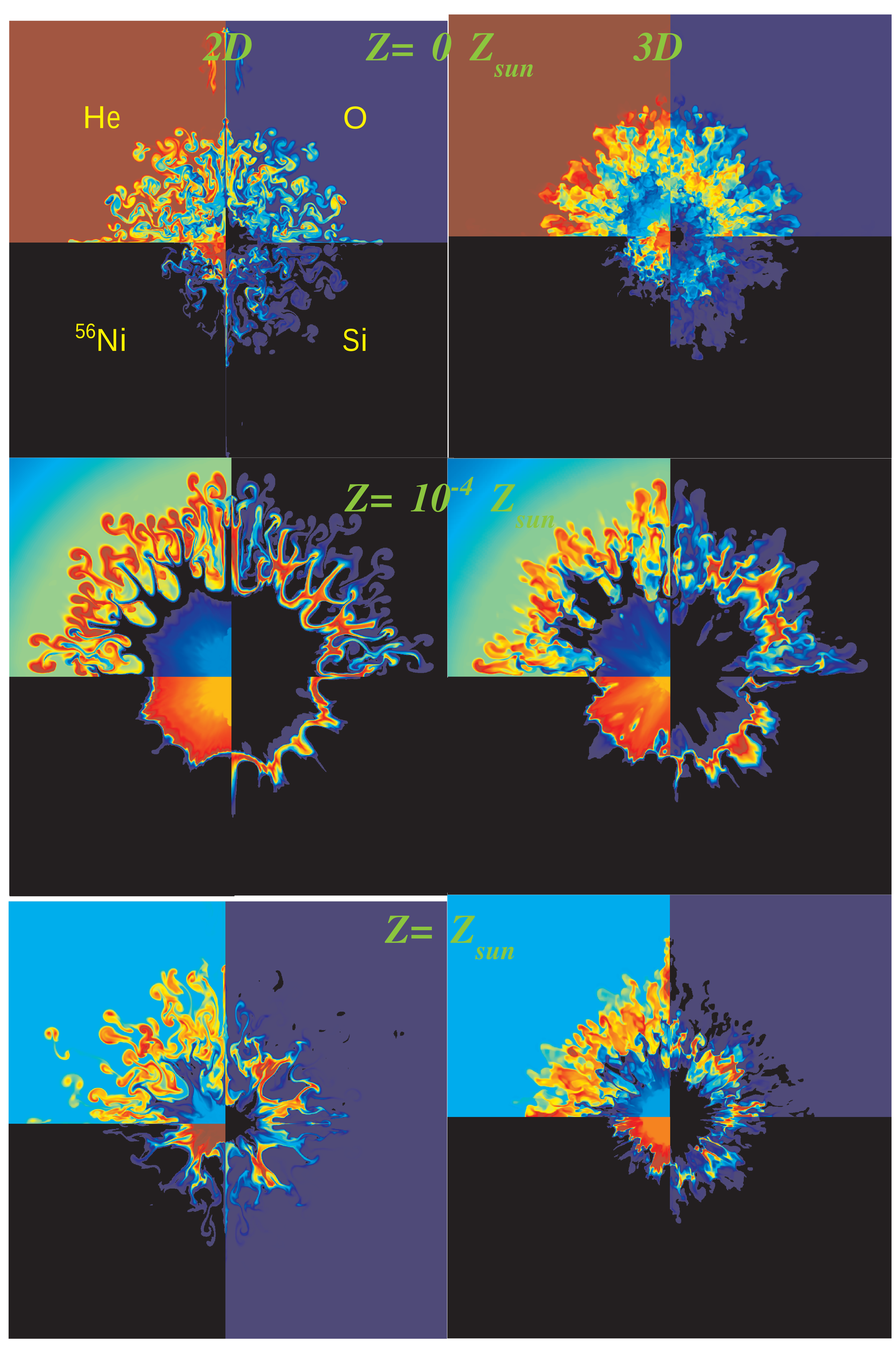


The final nucleosynthetic yield of a supernova is determined by the amount of mixing and fallback it experiences during its explosion; these are nonlinear processes that ought to be modeled in more than one dimension. Joggerst et al. (2010) performed two dimensional simulations of 36 such explosions with CASTRO, and found that the IMF averaged yields of red zero metallicity supernovae with moderate explosion energies of less than 2.4x1051 ergs were sufficient to explain the abundance patterns in EMP stars, as shown above. But how different would these simulations look if performed in three dimensions?

The CASTRO code

We use CASTRO, a new, Eulerian AMR hydrodynamics code, to perform our calculations. The two dimensional simulations are performed in cylindrical coordinates, while we use Cartesian coordinates for the three dimensional calculations. The equations of hydrodynamics are integrated using a higher-order, unsplit Gudunov scheme, and the code advances by subcycling in time. Though CASTRO can calculate full self gravity, a simple monopole approximation for the gravitational potential is sufficient for the simulations presented here. We use an equation of state that incorporates contributions from a perfect gas as well as radiation, and include energy deposition from the decay of ^{56}Ni.

2d vs. 3d simulations



Simulation setup

The one dimensional supernova models used to initialize our calculations were computed with KEPLER. They represent presupernova progenitor models from 15 solar mass stars evolved to the point of collapse, and then exploded artificially by means of a piston. They are followed in one dimension using Kepler to the point at which all nuclear burning has ceased, and then mapped into either two or three dimensions in CASTRO.

In order to minimize the amount of computational resources used, the calculations were started on 128^n grids (where n in the dimensionality of the simulation) with two levels of refinement. When the shock neared the edge of the grid, the calculations were "embiggened:" the size of the simulation was doubled, and an additional level of refinement was added to the least refined layer, keeping the number of top-level grid cells in the simulation equal to 128^n.

2D and 3D simulations are similar

Shown in the center of the poster are the two-dimensional results (at left) and two dimensional slices through the XY plane of the three-dimensional simulations (at right). The shape of the instabilities is different in three than in two dimensions, as expected. The Rayleigh-Taylor "fingers" are longer and thinner, in line with what other three dimensional simulations of this instability have found, but the overall extent of mixing is similar. The similarity between the two and three dimensional simulations imply that yields calculated using two dimensional simulations are fairly robust, and a good case can be made for zero metallicity supernovae of explosion energy < 2.4×10^{51} ergs and masses < 40 M_{sun} providing the bulk of enrichment in the early Universe.

We did not find the greater mixing and higher heavy element velocites found in the three dimensional simulations of a 15 M_{su}n supernova of Hammer et al. (2009), likely in part because of the different (and more realistic) explosion mechanism they used. We plan to perform these simulations with an entropy, rather than piston, driven explosion, which should shed light on whether these differences are due to our respective codes or something more fundamental.

Acknowledgments

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