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EXPLORING THE NATURE OF EXPLODING MASSIVE STARS WITH HIGH RESOLUTION

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EXECUTIVE SUMMARY

Core-collapse supernovae (CCSNe) are the violent explosions of massive stars at the end of their evolutionary lives. CCSNe play an important role in the dynamics of galaxies—injecting energy, producing and expelling heavy elements, and triggering formation of new star systems. CCSN simulation is a nexus of exotic basic physics—neutrinos, extreme gravitation, and nuclear physics. We are using 3D simulations to explore the variation in explosions and ejecta that result from the known variations in properties of massive stars (initial mass, composition, rotation, etc.) and to understand the impact of resource limitations on those outcomes. Because CCSNe are major contributors to the elemental composition of planets (including Earth), we have computed a 3D model that captures that element production in detail. Another model, limited in time and geometry, explores extremely high resolution to gauge the impact of resolution limits imposed by current supercomputers.

RESEARCH CHALLENGE

In CCSNe, the explosion is achieved by heating material in the cavity between (~200 km radius) accretion shock and the neutron star (NS) newly formed by the collapse of the star's iron core. The heating comes from neutrinos emitted from the NS, which release the gravitational binding energy of the NS and are absorbed in the cavity. This requires energy resolved (spectral) neutrino transport coupling the NS and the heating cavity. After an explosion begins (the last 80–90% of the simulation), the evolution of the nuclear isotopes in the ejecta require a reaction network. Larger networks can directly capture the evolution of more species and more accurately account for the input of energy into the expanding ejecta. In addition to the strength and composition of the explosion, CCSNe are important targets for observation by neutrino and gravitational wave detectors. The pre-collapse progenitors come in wide variety, driven largely by variations in the initial mass, rotation, and composition. To account for this variation in the CCSN outcomes and impacts on the evolution of heavy element abundances and compare to observed CCSN properties, wide ranging sets of models must be built. We are building a modest set of 3D models that span initial stellar parameters and exploring the impact of resource-limited resolution on current and prior CCSN simulations by all groups

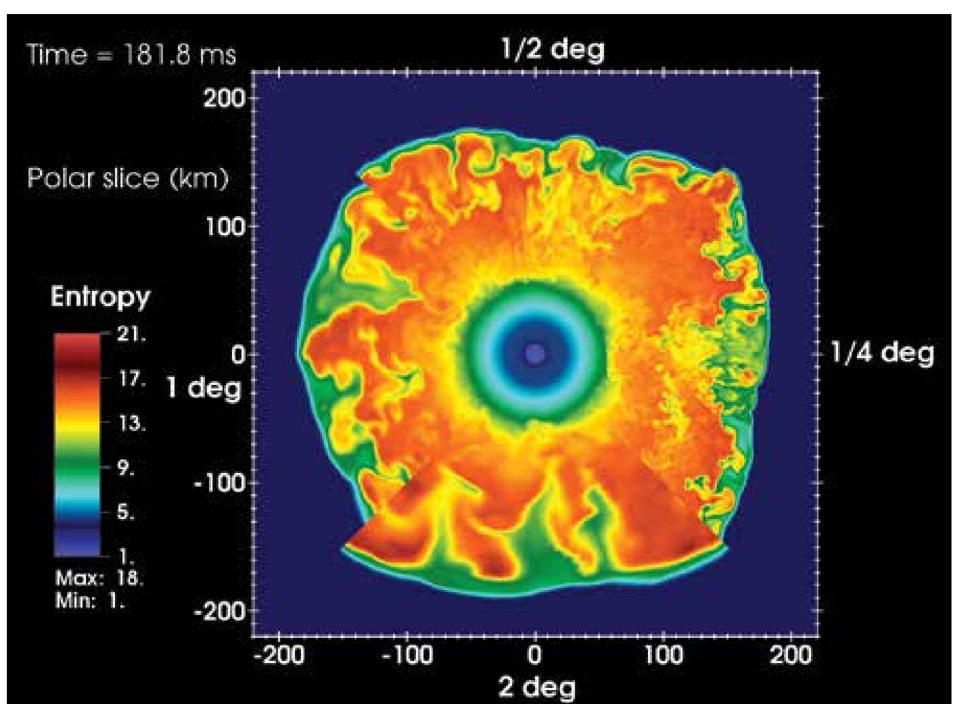

Figure 1: Slice in entropy through the 90° wedge models of various angular resolutions (2° to ¼°) in pre-supernova convective phase. As resolution increases, the number of fine structures increases, but the character of the models with regions of lower entropy inflow (green) and upwelling heated material (orange) remains.

METHODS & CODES

We have developed the custom multiphysics code Chimera [1,2] for CCSN. It couples the hydrodynamics of a self-gravitating fluid with active nuclear reactions (burning) taking place in the ejecta, and neutrino transport to carry energy from the inner core to the heating. The hydrodynamics is solved with a dimensionally split piecewise parabolic finite volume scheme. Gravity is solved by global multipole expansion of the Poisson equation. Nuclear burning is solved by the backward Euler method for a finite sized reaction network (14 or 160 species). Neutrino transport is solved by a finite differenced implementation of energy resolved flux limited diffusion that couples all neutrino species to a comprehensive set of neutrino-matter interactions.

RESULTS & IMPACT

One simulation computes a high-resolution (1/4°) model with limited geometry (90°x90° wedge along equator) during the pre-explosive convection phase, which is compared with lower-resolution models (1/2° to 2°) computed elsewhere to understand the impact of the lower resolution on other simulations [3]. We were able to measure the development of the cascade of turbulent energy to small scales and show that it is similar to previous work [4] done using parameterized neutrino transport. We also see (Fig. 1) that the large plumes with sinking streams in the low-resolution models (resolutions similar to our pre-Blue Waters work [5] and other published results [6]) transform in the high resolution (1/4°) Blue Waters simulation to rising and sinking "clouds" of smaller-scale features. These models indicate that the 1° models of our full-geometry 3D Blue Waters models should be sufficiently resolved and allay concerns that future gains in available capability must be thrown primarily into achieving better resolution.

Another simulation follows the collapse and explosion of a lower-mass star (9.6 solar masses) with the primordial initial composition (only Big Bang hydrogen and helium) [7]. Stars at the low-end of the massive star scale have lower densities in the material around the core, so that when it is accreting onto the stalled shock, it provides less ram pressure for the neutrino-heated material in the cavity to overcome. Because it explodes more quickly with less neutrino heating, some of the outermost ejecta (Fig. 2) is neutron rich and can form rare isotopes such as calcium-48. In this 3D model, we used a larger nuclear reaction network with 160 nuclear species that allows the direct tracking of calcium-48 formation *in situ*. Previous identification of lower-mass CCSN as sites for production of calcium-48 [8] and other neutron-rich isotopes relied on post-processing with passive tracers.

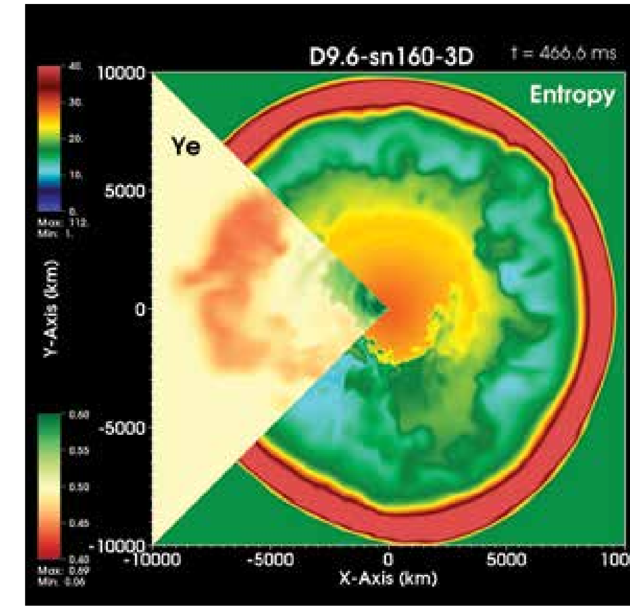

Figure 2: Slice through expanding ejecta of 9.6 solar mass model. Low-entropy (blue) material behind shock (reddish) is neutron-rich (low, orange, electron fraction "Ye" in cut-out) permitting the formation of neutron-rich calcium-48.

We are also computing 1°-resolution models of several other stellar progenitors to examine the variation in initial stellar mass. All of these models are being compared to less costly 2D models of the same and similar progenitors to better leverage the 3D results to broader applicability. For all our models, we will compute post-processed isotope production with very large (8,000 species) networks and compute neutrino and gravitational wave signals for comparison to future observations.

WHY BLUE WATERS

CCSN simulations are large, lengthy, and expensive, requiring 1000+ coupled nodes. Even a single 3D simulation can overwhelm the available allocations for a single project at other large sites, but with Blue Waters we can perform about three simulations per year.