CORE-COLLAPSE SUPERNOVAE THROUGH COSMIC TIME

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EXECUTIVE SUMMARY:

We study the explosive deaths of massive stars, supernovae, and their contribution to the evolution of the elemental content of the universe. Core-collapse supernovae (CCSNe) are tightly coupled multi-physics events without natural symmetry and require physically and spatially detailed 3D simulations to resolve. The progenitor stars of CCSNe vary in mass, heavy element composition, rotation, and other parameters that affect how the explosion develops, or if it develops at all, and the elemental abundances of the ejecta. Over the course of our project we will compute CCSN models that broadly cover the range of masses and compositions representative of massive stars throughout the history of the universe. In prelude to that survey, we are conducting studies with Blue Waters that will assess the impact of spatial resolution on our simulations.

INTRODUCTION

The inner iron core of a massive star (with mass more than about eight solar masses) collapses in less than 1 second to a (hot or proto) neutron star about 100 km across, releasing about 10^{53} ergs (10^{46} J = 100 B) of energy primarily in the form of neutrinos. When the collapse is halted, the outer core rebounds for a shock that stalls above the newly formed proto-neutron star (PNS). Neutrino heating of the in-falling material located just outside the PNS creates a layer of buoyantly unstable fluid that rises convectively and after several hundred milliseconds drives an outward shock wave. Once launched, about a full simulated second is required to build the typical 1 B explosion energy [1] and most of the element production [2].

CCSNe are important sources of many of the elements and are important contributors to the evolution of chemical abundances in galaxies and new stars. Variations of the initial mass and composition (built up through previous generations of stars, including supernovae) not only impact the strength of explosions, but the relative and absolute abundances of heavy elements in the ejecta. No 3D simulation with an *ab initio* explosion (as opposed to a parameterized one) has been evolved long enough to compute the required element synthesis.

METHODS & RESULTS

To capture the required physics in CCSNe we use a code we constructed call Chimera. It includes fluid dynamics, multi-pole self-gravitation with spherical general relativity corrections, radial neutrino transport with a full set of neutrino–matter interactions, a dense nuclear equation of state, and a nuclear network to track nuclear burning in the outer layers and ejecta.

To date, our group has worked mostly with 2D simulations. In a recent study covering a range of masses [1], we obtained appropriately energetic explosions from all four tested progenitors (12–25 solar masses). These simulations also clearly demonstrated that much longer simulations were required to obtain basic supernova properties like explosion energy and ejecta abundances. While the shock is revived by neutrino heating and fluid instabilities about 250 ms after bounce, development of the full explosion energy can take a full second more [1], which has a large impact on the required length of the runs. The conclusion of nuclear burning and the sorting of ejecta from non-ejecta take similarly long periods [2]. Our primary goal with Blue Waters is to move from simple 2D explosions to full 3D that also cover the range of stellar initial abundances.

Our first full-physics and well-resolved 3D model (180 x 180 zones in angle; 540 in radius) showed a delay of shock revival (explosion) of about 100 ms relative to its 2D counterpart [3] (or rather we should say the 2D model revived 100 ms earlier as the imposed symmetry of 2D is artificial). Fig. 1 depicts the heated and convective fluid behind the shock at 250 ms after core bounce with numerous rising convective plumes (yellow-green and red) pressing against the shock upon which the inner part of the star continued to accrete. The accreting matter passed in streams between the plumes and released gravitational binding energy that contributed to the heating. The 2D model had only a couple of large plumes with a single stream and began to explode at this epoch. During the delay in the 3D model, the plumes grew in angular size and this seemed to be important for the initiation of explosion [3]. These effects will be explored more thoroughly when we have completed more simulations.

The effects of resolution on 3D CCSN simulations are largely unknown and are our current focus. Insufficient resolution of the plumes and accretion streams could lead to excess dissipation of the accretion before it can contribute to the heating, truncate the turbulent cascade, and numerically stiffen plumes so they grow to large scales more quickly. To explore these issues we are running reduced-resolution models on Blue Waters and are engaged in other tests of 3D resolution. This will help maximize the usefulness of our large survey of simulations.

WHY BLUE WATERS?

Well-resolved 3D simulations of CCSNe require more than a thousand nodes for up to 1,000 hours of wall-clock time to fully develop the explosion (32,000 core hours). Blue Waters is in a rare class of machines that can sustain the required throughput of simulations at this size to fully evolve even a few 3D supernova models in a year and provide the needed infrastructure for data analysis and handling. Future Track-1 systems will continue to accelerate discovery in this area

FIGURE 1: Volume rendering of entropy in heated region of 15 solar-mass star 250 ms after core bounce, about 100 ms before the explosion initiates [3]. Blue corresponds to the shock position and yellow-green and red to progressively more heated material in rising convective plumes. [Credit: Mike Matheson, Oak Ridge Leadership Computing Facility. Animated version available at ChimeraSN.org]