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THREE-DIMENSIONAL CORE-COLLAPSE SUPERNOVA SIMULATIONS

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EXECUTIVE SUMMARY:

Core-collapse supernovae are the most common type and occur when the iron core of a massive star collapses to a neutron star. Releasing its gravitational binding energy as neutrinos, the protoneutron star (PNS) for a few seconds outshines the rest of the observable universe. Capturing a small fraction of this energy is thought to power the explosion of at least the most frequent supernovae, though detailed calculations proving this paradigm are still lacking. We conduct three-dimensional radiation/hydrodynamic simulations of core-collapse supernovae with the goal of determining the mechanism of explosion, using the newly developed and tested code Fornax, incorporating state-of-the-art microphysics and methodologies.

INTRODUCTION

Viewed as a nuclear physics laboratory, core collapse supernovae produce the highest densities of matter and energy in the modern universe. They thus probe the nuclear and particle physics of matter at super-nuclear density, high temperature, and at extremes of isospin. They are also responsible for creating most of the elements in nature, many of which are produced as radioactive precursors, both neutron-rich (r- process) and neutron-poor (explosive nucleosynthesis). The neutrino signal they emit carries information about the nuclear equation of state, and the strength of their explosion is sensitive to how both the neutrinos and ultra-dense matter are treated. Supernovae, thus, probe the same sort of physics as the Facility for Rare Isotope Beams, the Argonne Tandem Linac Accelerator System, and low-energy runs at Brookhaven's Relativistic Heavy Ion Collider, the Facility for Antiproton and Ion Research in Damstadt, Germany, CERN's SPS Heavy Ion and Neutrino Experiment, and Russia's Nuclotron-based Ion Collider Facility. Our project employs our new state-of-the-art radiation/hydrodynamics code Fornax to simulate the physics of core collapse and explosion in three spatial dimensions. This effort supports NSF's experimental nuclear physics program by exploring nucleosynthesis in astrophysical explosions, the properties of the neutrino, and the equation of state and phases of dense nuclear matter. A solution to the core-collapse supernova problem would benefit ongoing efforts of observers and instrument designers in the United States and around the world engaged in projects to determine the origin of the elements, measure gravitational waves (LIGO), and interpret laboratory nuclear reaction rate measurements in light of stellar nucleosynthesis.

METHODS & RESULTS

Fornax is a new code for multidimensional, self-gravitating, radiation hydrodynamics that is second-order accurate in space and time and was designed from scratch with the core-collapse supernova problem in mind. The code solves the equations of compressible hydrodynamics with an arbitrary equation of state, coupled to the multigroup two-moment equations for neutrino transport and the Poisson equation for gravity. The equations are solved on a fixed Eulerian grid, enhanced by a mechanism for static mesh derefinement in the inner zones. All of the these transport related terms are treated explicitly in time and are updated with the same time-step as the hydrodynamics. After core bounce, explicit time integration is not only simpler and generally more accurate, it is also faster than globally coupled time-implicit transport solves that are typically employed in radiation hydrodynamics methods. The latter allows us to avoid angular Courant limits at the center, while maintaining accuracy and enabling us to employ the useful spherical coordinate system natural for the supernova problem. We have spent much of the first phase of our Blue Waters effort developing, testing, and running Fornax. Our project has received a modest extension, and we hope to have 3D simulation results to report in 2016.

WHY BLUE WATERS

It is not possible to explore this central problem in nuclear astrophysics without supercomputer resources such as Blue Waters. Its Cray architecture comports very nicely with our code architecture, and the large number of cores available enables the exploitation of our code's efficient parallelism. On a small, Beowulf-like cluster, we estimate that one calculation would take a few decades to perform, while requiring only one month on Blue Waters, using one-quarter of the machine.