Shedding New Light on Exploding Stars:
Terascale Simulations of Core Collapse Supernovae and Their Nucleosynthesis

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Executive Summary

The search for the explosion mechanism of core collapse supernovae and the computation of the nucleosynthesis in these spectacular stellar explosions is one of the most important and most challenging problems in computational nuclear astrophysics. Core collapse supernovae are among the most energetic explosions in the Cosmos, releasing 10^{53} erg of energy in the form of neutrinos of all flavors at a staggering rate of 10^{57} neutrinos per second and 10^{45} Watts, disrupting almost entirely stars more massive than ten Suns and disseminating and producing many of the elements in the Periodic Table heavier than hydrodgen and helium, without which life as we know it would not exist. They are a nexus for nuclear physics, particle physics, fluid dynamics, radiation transport, and general relativity, and serve as cosmic laboratories for physics beyond the Standard Model and for matter at extremes of density, temperature, and neutronization that cannot be produced in terrestrial laboratories.

These are exciting times for supernova modelers. The advent of next-generation neutrino detectors such as Super-Kamiokande and the Sudbury Neutrino Observatory promise thousands of neutrino events in the next Galactic supernova. These will provide detailed neutrino "light curves" from which supernova models can be diagnosed and improved. Gravitational wave observatories such as LIGO and VIRGO will be on line soon and will bring additional and complementary information from deep within the explosion. The myriad data from current ground- and space-based observatories such as the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Chandra X-Ray Observatory are mounting, bringing us information in all wavebands about the composition and morphology of supernova ejecta, which in turn provides a fingerprint of the explosion mechanism and supernova nucleosynthesis. The availability of new radioactive beam facilities such as HRIBF at ORNL and NSCL at MSU will enable measurements of reaction rates and nuclear structure properties of beta-unstable nuclei key to nucleosynthesis in supernovae, which in turn provides invaluable diagnostics of conditions deep within the exploding layers and, consequently, of the explosion mechanism itself. The construction of a next-generation facility (RIA) to measure lifetimes and capture cross sections of radioactive neutron-rich nuclei will provide foundational data for studies of the r-process in supernovae. New facilities to measure neutrino–nucleus cross sections, such as the proposed ORLaND facility at Oak Ridge, will provide the bed rock on which theoretical predictions of the many weak interaction rates that define supernova dynamics and play an important role in supernova nucleosynthesis during p-process, r-process, and neutrino nucleosynthesis in supernovae may rest. Finally, the advent of TeraScale computing resources has made it possible to seriously consider the realistic multidimensional simulations that will be required to ascertain the explosion mechanism and understand all of its accompanying observables.

Current supernova theory centers around the idea that the supernova shock wave—formed when the iron core of a massive star collapses gravitationally and rebounds at high densities—stalls as a result of enervating losses to nuclear dissociation and neutrinos. The failure of a "prompt" supernova mechanism sets the stage for a "delayed" mechanism whereby the shock is reenergized by the intense neutrino flux emerging fron the proto-neutron star at the center of the explosion. This process depends critically on the neutrino luminosities, spectra, and angular distributions, necessitating accurate simulation of neutrino transport and, consequently, a solution of the one- and multidimensional neutrino Boltzmann kinetic equations, or a good approximation of them. This decade has also seen the emergence of multidimensional supernova models suggesting that convection in the proto-neutron star and convection directly beneath the supernova shock wave may be important in aiding the neutrino reheating process. And the need to investigate rotation's role in the mechanism, among other things, provides an additional compelling reason to consider multidimensional models.

The "global" requirements of accurate multidimensional, multifrequency (neutrino-energy–dependent) radiation transport and radiation hydrodynamics must, further, be supplanted by commensurate improvements in the "local" microphysics, such as modeling the sub-nuclear density thermodynamic state of the stellar core, the neutrino–nucleus interactions in the core, and the high-density neutrino interactions with the strongly correlated nucleons in the proto-neutron star. This will require the marriage of state of the art supernova simulation and nuclear structure computation. These developments will be important for modeling both the explosion mechanism and supernova nucleosynthesis. Moreover, there is mounting evidence for neutrino mass and mixing. The possibility of active-active and active-sterile neutrino mixing presents a challenge for describing neutrino transport in the proto-neutron star and, again, exciting possibilities for both the explosion mechanism and supernova nucleosynthesis.

Several characteristics define the supernova application as one that is ideal for a TeraScale computing initiative: (1) At the heart of the solution of the multidimensional integro-partial differential equations governing the radiation hydrodynamics of supernova explosions and the nuclear structure computations required to provide input to these equations is the solution of large sparse linear systems of equations involving as many as 10^{11} unknowns and requiring 10s of Terabytes of memory. These systems must be solved multiple times per time step for of order 10^{4-5} time steps. This will require TeraScale resources and beyond, driving current and future technology development. (2) The supernova application is a multiscale, multidimensional, multiphysics application. We must, for example, come to grips with the turbulent environment in the wake of the supernova shock, the disparate time scales associated with the neutrino–matter interactions and the explosion, and the disparate spatial scales associated with nucleon–nucleon correlations in the proto-neutron star and the evolution of the proto-neutron star itself. (3) The supernova application is a single TeraScale application that will drive the development of enabling technologies in several areas: scalable radiation transport and radiation hydrodynamics, scalable algorithms for the solution of large sparse systems of linear equations, and collaborative visualization, which in turn will have an impact in other areas, including, but not limited to, combustion modeling, climate modeling, inertial confinement fusion, rocket design, medicine, and stockpile stewardship.

We have assembled a team of 17 investigators from 11 institutions nationwide to address this problem. Team members include Polly Baker (UIUC/NCSA), John Blondin (NCSU), Steve Bruenn (FAU), David Dean (ORNL/UTK), Jack Dongarra (UTK), George Fuller (UCSD), Wick Haxton (UW/INT), John Hayes (UCSD), Jim Lattimer (SUNYSB), Brad Meyer (Clemson), Tony Mezzacappa (ORNL), Madappa Prakash (SUNYSB), Faisal Saied (UIUC/NCSA), Paul Saylor (UIUC/NCSA), Mike Strayer (ORNL/UTK), Doug Swesty (SUNYSB), and Ross Toedte (ORNL). Our team is balanced, bringing together expertise in computer science, radiation transport, nuclear structure, visualization, and supernova science, and is founded on long-term, successful collaborations among its members. Moreover, the team brings leverage and liaisons from numerous other programs, across agencies, including NASA HPCC, DoE HPCC, DoE ASCI, NSF PACI, and DoD Modernization.

Developments in multidimensional radiation transport and radiation hydrodynamics, computational nuclear structure, and visualization that will enable a new class of supernova models will occur in several "generations." Scalable one-dimensional, multifrequency Boltzmann transport and two- and three-dimensional flux-limited diffusion will be developed; methods to compute scalable preconditioners and to solve scalably the large sparse linear systems of equations that arise when the multidimensional radiation hydrodynamics equations are finite differenced or that are integral to the nuclear structure computations will be developed; five levels of sophistication in nuclear structure modeling will be implemented in computing the stellar core thermodynamic state and the neutrino–matter interactions important in core collapse, the post–core-bounce neutrino heating, and supernova nucleosynthesis; and the development of unique representations for supernova data, the deployment and customization of current collaborative visualization tools for supernova and supernova nucleosynthesis modeling, and instrumentation of our codes for adaptation to new visualization capabilities will be carried out.

To achieve the sustained Teraflop speeds needed to realistically model supernovae and supernova nucleosynthesis, we will consider hybrid programming models (MPI plus OpenMP) for clusters of Distributed-Shared Memory platforms, consider memory placement strategies, develop cache-aware codes, instrument our codes for monitoring parallel performance, and look to enhanced parallel debuggers and parallel tools.

A number of factors will ensure that our project is completed successfully: We have a single TeraScale application that will serve as a drawing focus. We have identified all of the key research areas in this application and have put together a representative team of experts to consider it. We have also established collaborations with a number of the SciDAC ISICs. Finally, we have staged our effort for success: beginning with simpler, partially integrated models, and ending with more complex, fully integrated models.

More information may be obtained at our project Web site: http://www.phy.ornl.gov/tsi/.