Future Directions in Simulations of Core Collapse Supernovae

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Beginning with the first numerical simulations of core collapse supernovae conducted by Colgate and White, three decades of supernova modeling have laid the foundation on which current supernova theory rests and from which all future modeling efforts must stem. These prior modeling efforts have established a supernova paradigm, i.e., that core collapse supernovae are driven by a neutrino shock heating by an intense three-flavor neutrino flux emanating from the nascent neutron star, and have advanced our understanding of the rich microphysics operative in these catastrophic stellar events. Nonetheless, although a theoretical framework is now in place, fundamental questions about the explosion mechanism and the explosions themselves remain. For example: Precisely what causes core collapse supernova explosions? Is the neutrino heating largely responsible, or do multidimensional effects such as convection and rotation play an important role? And how do stellar magnetic fields affect the dynamics? Is there room for a complete paradigm shift, i.e., from our current paradigm that core collapse supernovae are driven by neutrino heating to a new paradigm that these explosions are MHD jets? No doubt, core collapse supernovae are not spherically symmetric. Understanding them and their role in the cosmic hierarchy will not be complete until we understand, for example, the polarization of their emitted light and the origin of neutron star kicks. Nonetheless, the recipe for explosion and the character of the explosion are different. Consequently, any truly complete supernova modeling program must include and coordinate simulations in one, two, and three dimensions. The decreasingly sophisticated microphysics in current one-, two-, and three-dimensional simulations, respectively, is an added reason to coordinate such simulations.

Answers to these remaining fundamental questions will rely not only on increasingly sophisticated multidimensional radiation hydrodynamics simulations, but on increasingly sophisticated input nuclear physics, i.e., electron capture rates, high-density neutrino opacities, and neutrino–nucleus cross sections. Recent advances in computational nuclear structure have demonstrated that parameterized weak interaction rates on nuclei may be orders of magnitude in error, and the use of an ensemble of nuclei rather than a single representative nucleus, in conjunction with these improved weak interaction rates, may yield significant quantitative changes in current supernova models. Moreover, work has begun to compute the neutrino opacities in the highly-correlated, high-density nucleon soup in the proto-neutron star. The neutrino fluxes, particularly at very late times, may be altered by the altered opacities, in turn potentially affecting supernova shock reheating, nucleosynthesis, and terrestrial neutrino signatures. Finally, core collapse supernovae are important for, among other things, their role in nucleosynthesis and Galactic chemical evolution. There are now compelling observational and theoretical arguments that the r-process occurs in these explosive environments. In addition, neutrino nucleosynthesis in these environments leads to the unique production of some of Nature's rarest isotopes. In both cases, predictions of core collapse supernova nucleosynthesis will rely on state of the art neutrino–nucleus cross sections.

With computational capabilities at Terascale levels—increasing toward Petascale levels—and with mounting data from ground- and space-based observing and experimental facilities, we are entering a new era in supernova modeling in which realistic multidimensional simulations may be carried out and in which increasingly sophisticated models will be held to ever more stringent observational constraints. Next-generation neutrino detectors such as Super-Kamiokande and the Sudbury Neutrino Observatory and proposed novel facilities such as OMNIS and LAND promise thousands of neutrino events in the next Galactic supernova and new capabilities to detect and distinguish multiflavor neutrino signatures. These facilities 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 online at the turn of the millenium and will bring complementary information from deep within the explosion, telling us about rotation and different modes of convection in the stellar core, both of which may play a role in the explosion mechanism. 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 will enable measurements of nuclear masses and reaction rates involving unstable proton- and neutron-rich nuclei crucial to nucleosynthesis in supernovae, providing invaluable diagnostics of conditions deep within the exploding layers and, consequently, of the explosion mechanism itself, as well as foundational data for neutron capture on nuclei, at the heart of r-process nucleosynthesis. Finally, existing and proposed facilities to measure neutrino–nucleus cross sections, such as KARMEN and ORLaND, will provide experimental guideposts to gauge the theoretical predictions of the many neutrino–nucleus cross sections needed to model supernova dynamics and p-process, r-process, and neutrino nucleosynthesis.

In short, these are exciting times for core collapse supernova modelers. I will review the current state of the art in the field and outline future directions in simulations of this important class of stellar explosions.

*Research sponsored by the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.