Toward Three-Dimensional, Multiphysics, Petascale Simulations of Core Collapse Supernovae

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Ascertaining the explosion mechanism of core collapse supernovae is one of the most important unsolved problems in astrophysics. These explosions of massive stars more than ten times the mass of the Sun are responsible for producing and disseminating many of the elements in the Universe without which life would not exist. Past simulations in one and two spatial dimensions have shown that the core collapse supernova mechanism will rely in no small part on the production, transport, and interaction of radiation-like particles known as neutrinos. Multidimensional neutrino transport ultimately defines this to be a petascale application, requiring the solution of coupled, seven-dimensional, integro-partial differential equations for the neutrino distribution functions, which give the distribution of neutrinos in direction and energy for every spatial location and instant of time. In addition, fluid instabilities, stellar core rotation and magnetic fields, Einsteinian (as opposed to Newtonian) gravity, nuclear physics, and particle physics all play a role. No detailed predictions of element synthesis and other important supernova observables can be made until the explosion mechanism is pinned down. Recent hydrodynamics-only simulations in three spatial dimensions demonstrate that all these ingredients must be included in three-dimensional, as opposed to one- and two-dimensional, models - these simulations demonstrate that supernova dynamics in two and three spatial dimensions will be fundamentally different in identifiable ways. A research program based on three, staged simulation lines has been defined. Simulations in each line will proceed to three spatial dimensions and to the petascale, with each subsequent stage bringing increased realism. The implicit differencing of the neutrino transport equations will require the solution of nonlinear algebraic equations using Newton-Krylov techniques on tens of thousands of processors. AMR and load balancing will add to this challenge. Parallel I/O on increasing numbers of processors will become ever more important. And current simulations produce tens of terabytes of output data, and this data generation rate is expected to rise in the next few years to hundreds of terabytes per simulation. Enabling a geographically distributed team via advanced networking and remote visualization is also a need that must be met. And the representation and rendering of multidimensional supernova simulation data is presenting increasingly difficult challenges as both the dimensionality and the complexity of the data increase. Significant advances in three-dimensional supernova simulations together with the advances that will enable these simulations will result in a quantum leap in our understanding of how we came to be in the Universe.