THE COMPUTATIONAL KEYS TO THE SUPERNOVA PUZZLE: HOW MULTIPLE 3D RADIATION/HYDRODYNAMIC MODELS CAN UNLOCK THE SUPERNOVA MYSTERY

Allocation: NSF PRAC/5,800 and 15,000 Knh
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EXECUTIVE SUMMARY

The mechanism of supernova explosions is a long-standing problem in theoretical astrophysics. Its obstinacy is intertwined with the broad range of physics necessary to address the phenomenon and the challenging numerical context, involving the coupling of multidimensional hydrodynamics with neutrino radiation transfer in violently turbulent flow. This project explores solutions to this decades-old conundrum with the state-of-the-art 3D code Fornax. The overarching goal is to determine the mechanism of explosion, explosion energies, residual neutron star masses, nucleosynthesis, and explosion morphologies. Various other observational diagnostics such as radioactive nickel yields, neutrino and gravitational-wave signatures, and newly born pulsar kicks are also of interest. This initiative is enabled by the novel algorithms in Fornax that yield speedups of factors of five to 10 over previous codes. This enables multiple 3D simulations, rather than just one, to be performed each year and, hence, permits a previously unprecedented exploration of parameter space.

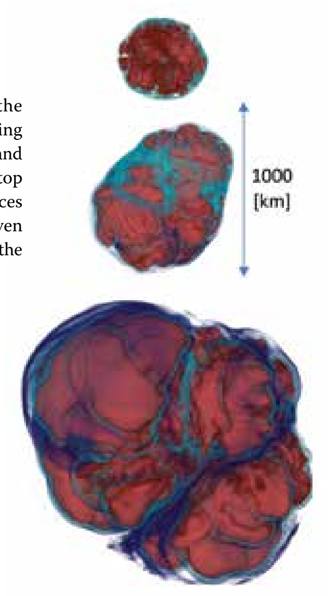

Figure 1: Volume rendering of the entropy distribution of the exploding core of a 19-solar-mass star 200, 300, and 400 milliseconds after core bounce (top to bottom). The outer bluish veil traces the shock wave. The explosion is driven in part by neutrino-heated bubbles in the turbulent inner convective core.

RESEARCH CHALLENGE

Core-collapse supernovae dramatically announce the death of massive stars and the birth of neutron stars and black holes. During this violent process, a combination of high-density nuclear physics, multidimensional hydrodynamics, radiation transport, and neutrino physics determines whether and how the star explodes. However, the precise mechanism of explosion has not been pinned down, and this 50-year-old puzzle is one of the central remaining unsolved problems in theoretical astrophysics. Nevertheless, we are now at a crossroads. An early phase of modern supernova theory involved routine spherical simulations. This allowed explorations in parameter and progenitor space to fully characterize the phenomenon as a function of all-important quantities. Mistakes could be made quickly and an overarching understanding in 1-D could be achieved.

However, researchers knew that the cores were unstable to hydrodynamic overturn and turbulence that could not be captured in one dimension. The next phase of discovery occurred when technique and hardware advanced sufficiently so that 2D calculations became as routine as 1-D had been. This phase gave scientists a glimpse of the effects of turbulence and convection with state-of-the-art neutrino transport. At the end of this phase, a few 3D simulations appeared, but each of these simulations required approximately one year of simulation time on high-performance computing resources. As a result, researchers obtained only glimpses of the range of outcomes and their dependence on parameters in the full 3D of Nature.

With the help of Blue Waters, the research team has now entered what it believes to be the third phase of modern supernova theory, wherein multiple 3D simulations can now be performed each year, each requiring approximately one month of wall-clock time. This phase ramped up at the beginning of 2019 and is starting to reveal the full systematic dependence of full-physics 3D supernova simulations on progenitor, microphysics, and resolution. Fully characterizing the supernova phenomenon in this way, with multiple 3D simulations each year, has been the goal of supernova theory for decades and is the ultimate astrophysics Grand Challenge.

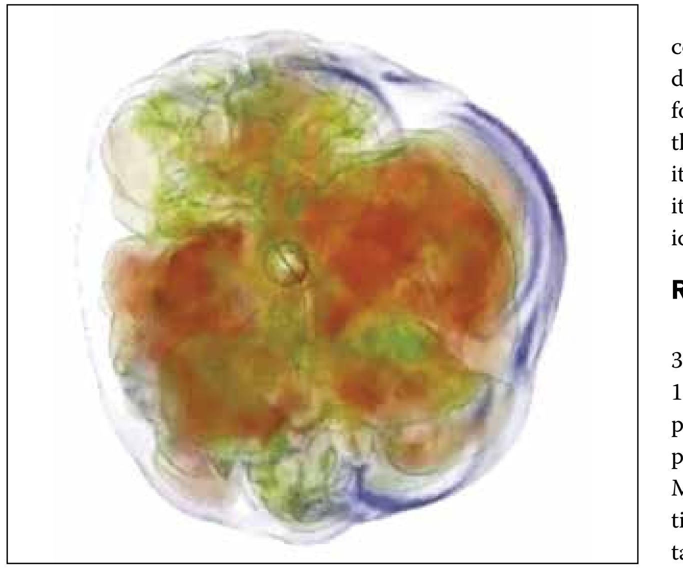

Figure 2: The explosion of the turbulent core of a 60-solar-mass star, volume-rendered in entropy. Red is high entropy, green is intermediate entropy, and blue marks the position of the supernova shock wave. The sphere near the center is the newly born proto-neutron star, depicted as an iso-mass-density contour at 10^{11} g cm^{-3}.

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, to measure gravitational waves (LIGO), study pulsars, and interpret laboratory nuclear reaction rate measurements in light of stellar nucleosynthesis. In addition, such studies support the experimental nuclear physics program of the NSF by exploring nucleosynthesis in astrophysical explosions, the properties of the neutrino, and the equation of state and phases of dense nuclear matter. Moreover, these investigations connect directly with the lower-energy programs of FRIB and FAIR, the high-energy experiments carried out at RHIC and the LHC, and the hyperon–hyperon and hyperon–nucleon programs of JPARC, GSI, JLAB, and NICA.

METHODS & CODES

The research team developed a new multidimensional, multigroup radiation/hydrodynamic code, Fornax, for the study of core-collapse supernovae. Fornax is a directionally unsplit Godunov-type code that employs spherical coordinates, solves the comoving-frame, multigroup, two-moment, velocity-dependent transport equations to O(v/c), uses the M1 tensor closure for the second and third moments of the radiation fields, and employs a dendritic spherical grid. Fluxes at cell faces are computed with an HLLC Riemann solver based on left and right states reconstructed from the underlying volume-averaged states. Three species of neutrino are followed using an explicit Godunov characteristic method applied to the radiation transport operators and an implicit solver for the radiation source terms. In this way, the radiative transport and transfer are handled locally, without the need for a global solution on the entire mesh.

The team thereby significantly reduced the computational complexity and communication overhead of traditional multidimensional radiative transfer solutions by bypassing the need for global iterative solvers. In summary, the main advantages of the Fornax code are its efficiency owing to its explicit nature, its excellent strong scaling to hundreds of thousands of cores, its truly multidimensional transport solution, and interior static mesh derefinement.

RESULTS & IMPACT

Using Blue Waters, the research team has performed a suite of 3D runs of the collapse, bounce, and explosion (most often) of 9-, 10-, 12-, 13-, 14-, 15-, 16-, 17-, 18-, 19-, 25-, and 60-solar-mass progenitor massive stars. This is the most extensive set of 3D supernova simulations with the necessary realism ever performed. Moreover, the team has been able to conduct the highest-resolution full-physics simulations ever performed, calculate the gravitational wave and neutrino signatures, explore pulsar kick speeds, and establish debris morphologies and compositions.

WHY BLUE WATERS

For the team's code, Fornax, the Blue Waters architecture in the MPI/CPU context, with its large per-node memory and rapid interconnect, provides the quickest turnaround for these 3D supernova simulations of any available high-performance computing resource.

PUBLICATIONS & DATA SETS

A. Burrows, D. Radice, and D. Vartanyan, "Three-dimensional supernova explosion simulations of 9-, 10-, 11-, 12-, and 13-solar-mass stars," *Mon. Not. Roy. Astron. Soc.*, vol. 482, p. 3153, 2019, doi: 10.1093/mnras/stz543.

M. A. Skinner, J. Dolence, A. Burrows, D. Radice, and D. Vartanyan, "Fornax: A flexible code for multiphysics astrophysical simulations," *Ap. J. Suppl.*, vol. 241, no. 7, 2019, doi: 10.3847/1538-4365/ab007f.

H. Nagakura, A. Burrows, D. Radice, and D. Vartanyan, "Towards an understanding of the resolution dependence of core-collapse supernova simulations," *Mon. Not. Roy. Astron. Soc.*, 2019, doi: 10.1093/mnras/stz2730.

A. Burrows, D. Vartanyan, J. C. Dolence, M. A. Skinner, and D. Radice, "Crucial physical dependencies of the core-collapse supernova mechanism," *Space Sci. Rev.*, vol. 214, no. 33, 2018, doi: 10.1007/s11214-017-0450-9.

D. Vartanyan, A. Burrows, D. Radice, M. A. Skinner, and J. C. Dolence, "Revival of the fittest: Exploding core-collapse supernovae," *Mon. Not. Roy. Astron. Soc.*, vol. 477, no. 3, p. 3091, 2018, doi: 10.1093/mnras/sty809.

D. Radice, V. Morozova, A. Burrows, D. Vartanyan, and H. Nagakura, "Characterizing the gravitational wave signal from core-collapse supernovae," *Ap.J. Lett.*, vol. 876, p. L9, 2019, doi: 10.3847/2041-8213/ab191a.