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

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The mechanism of supernova explosions is a long-standing problem in theoretical astrophysics. Its obstinacy is intertwined with the need to understand neutrinos, the mysterious particles emitted during supernova explosions, and their interaction with the surrounding medium. The problem involves understanding the dynamics of the shock wave, the energy distribution of the exploding star, and the complex interplay between the neutrino signals and the neutrino physics that determines their behavior.

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 computer and hardware advanced sufficiently so that 2D calculations became routine. Turbulence and convection could now be captured. With the help of Blue Waters, the research team has now entered a 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-3D physics on progenitor, microphysical, and resolution effects. 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.

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 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–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(ν), 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. 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.

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/CPUP context, with its large per-node memory and rapid interconnect, provides the quickest turnaround for those 3D supernova simulations of any available high-performance computing resource.

PUBLICATIONS & DATA SETS