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3D GENERAL-RELATIVISTIC RADIATION-HYDRODYNAMIC SIMULATIONS OF CORE-COLLAPSE SUPERNOVAE

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EXECUTIVE SUMMARY

Core-collapse supernovae (CCSNe) are the magnificent explosions of massive stars. They are the birth sites of black holes and neutron stars, and they enrich the interstellar medium with the chemical elements produced by thermonuclear fusion. From these elements, planets form and life develops.

Using Blue Waters, we carried out the very first *ab initio* full 3D general-relativistic radiation-hydrodynamics CCSN simulations, focusing on the phase between initial collapse and the onset of explosion. We investigated the CCSN evolution of a 27-solar-mass progenitor star and followed the supernova engine for approximately 400 milliseconds in full 3D. We found the onset of an explosion driven by a combination of neutrino energy deposition and turbulent convection. The explosion develops in a large-scale asymmetric way, which is consistent with recent astronomical observations of supernovae remnants.

RESEARCH CHALLENGE

CCSNe are cosmic engines where neutron stars and black holes are born. They expel the nuclear products of stellar evolution into the interstellar medium, driving cosmic chemical evolution and providing the foundations for planetary systems and life itself. CCSN shock waves sweep up the interstellar gas and can trigger or shut off the formation of new stars in galaxies.

After the initial collapse of the inner core, a shock wave is launched into the outer core. The shock, however, soon stalls. It requires a reenergizing CCSN mechanism to explode the star. This CCSN mechanism has evaded understanding for almost six decades of theory and computation. The reasons for this are rooted in the complexity of the problem: Understanding CCSNe requires the solution of large coupled systems of partial differential equations describing gravity, magnetohydrodynamics, and neutrino transport (i.e., Boltzmann transport, which is a 6+1D problem). Moreover, astronomical observations show that CCSNe are fundamentally 3D, and turbulent flow is a key ingredient, necessitating a 3D treatment in simulations. Finally, CCSN simulations must be multiscale, requiring spatial resolution as small as ~50 meters to capture the inertial range of turbulent flow while at the same time encompassing at the very least the innermost ~10,000 km of the star. Ultimately, the entire star will need to be simulated (with a radius of ~10^9 km for a red supergiant like Betelgeuse).

METHODS & CODES

We employ our 3D general-relativistic radiation-hydrodynamics code, Zelmani. This is an open-source code based on the Cactus framework that uses components of the open-source Einstein Toolkit. Zelmani is the only U.S.-based code that is fully general-relativistic and based on numerical relativity. The key new development enabling our simulations is the ZelmaniM1 component, which implements full 3D multispecies, multienergy radiation-hydrodynamics in the two-moment "M1" approximation. In M1, the Boltzmann equation is expanded in angular moments. The equations for radiation energy (a scalar) and flux (a 3-vector) are evolved and the system is closed with a local algebraic closure relation. Extensive tests show that this approach yields accurate results for CCSN neutrino radiation fields.

We employ a single 27-solar-mass progenitor star and carry out the initial collapse phase in 1D using our open-source code GR1D. We map to 3D at 20 milliseconds after core bounce (the time of protoneutron star formation). In order to study the effects of numerical resolution on shock revival, we carry out simulations with spatial resolution of 1.5 km and 3 km in the region behind the stalled shock. We study the impact of imposed symmetries by simulating in full unconstrained 3D and in an octant of the 3D cube.

RESULTS & IMPACT

In this first set of full 3D CCSN simulations, we confirm that the well-studied "neutrino mechanism," in combination with turbulent convection, is indeed able to drive 3D CCSNe. The neutrino mechanism relies on the deposition below the shock of a small fraction (5 to 10%) of the neutrinos emitted from the edge of the protoneutron star. The neutrino energy is deposited in the gas, driving up temperature, thermal pressure, and establishing an entropy gradient that is unstable to buoyant convection. This convection is highly turbulent (theoretical Reynolds number of order 10^{13}) since viscosity is extremely small. This turbulent neutrino-driven convection exerts effective turbulent pressure that jointly with the thermal pressure helps push out the shock and explode the star. Fig. 1 shows a volume rendering of the specific entropy distribution within the CCSN shock as the explosion is developing. There are large high-entropy bubbles that develop over time ("volume filling convection") and push out the shock. The sphere-like object in the center is the low-entropy region inside the protoneutron star. The shock is strongly deformed and shows many small-to-large-scale protrusions. These are created by convective bubbles that impinge on the shock from below. The explosion is globally asymmetric and elongated along one axis. Similar geometries are found in deep astronomical observations of CCSN remnants.

Furthermore, we find that low spatial resolution artificially favors explosion, because it traps turbulent kinetic energy at large scale where it can effectively help shock expansion. This result emphasizes the need for high-resolution simulations in addition to including the full set of physics ingredients. Comparing our octant 3D simulations with full 3D, we find that in the latter, explosions develop more easily. This is because the expanding large high-entropy bubbles that form in full 3D tend to have complex geometry that cannot be captured by a simulation that is constrained to an octant.

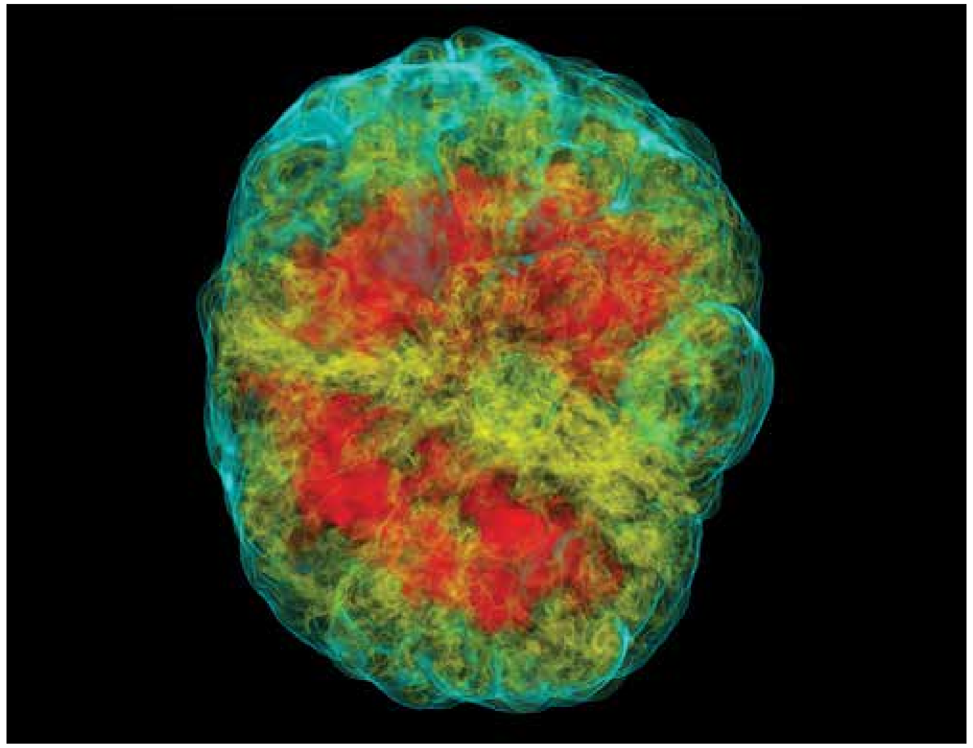

Figure 1: Volume rendering of the specific entropy distribution in a 3D core-collapse supernova at the onset of explosion. The region shown is 600 km^3. Red and yellow colors correspond to higher entropy regions while green, blue, and dark colors correspond to regions of lower entropy.

WHY BLUE WATERS

Blue Waters has been absolutely essential to this project. While our simulations typically use "only" 400 nodes, and other HPC systems could accommodate a single simulation, Blue Waters is the only U.S. resource that allows us to carry out multiples of such simulations with high throughput. Without Blue Waters, this project would have taken many years to complete.

PUBLICATIONS AND DATA SETS

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Blackman, J., et al., A Numerical Relativity Waveform Surrogate Model for Generically Precessing Binary Black Hole Mergers. *Phys. Rev. D.*, 96, 024058 (2017), DOI: 10.1103/PhysRevD.96.024058.

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