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

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 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 supernova 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 planetary systems and life itself. CCSN shock waves sweep up the interstellar gas and can trigger planetary systems and life itself.

We employ a 3D general-relativistic radiation-hydrodynamics code, Zelmani. This is an open-source code based on the Cactus Toolkit. Zelmani is the only U.S.-based code that is fully coupled-gravity, radiation-energy and flux (a 3-vector) and momentum. Extensive tests show that this approach yields results for CCSN neutrino radiation fields.

In our simulations, we find that the stalled shock. We study the impact of imposed symmetries on shock revival, we carried out 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 include the full set of physics ingredients. Comparing our results for CCSN remnants.

However, we find that local flow 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 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.

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 multiphysics of such simulations with high throughput. Without Blue Waters, this project would have taken many years to complete.

PUBLICATIONS AND DATA SETS