HIGH-RESOLUTION 3D SIMULATIONS OF CORE-COLLAPSE SUPERNOVAE

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FIGURE 1 (BACKGROUND): Volume rendering of the specific entropy of a developing asymmetric explosion in a 3D core-collapse supernova. The volume shown is 5003 km3. Yellow contours are regions of very high entropy corresponding to outward moving bubbles/filaments of neutrino-driven turbulent convection. The bright sphere at the center is the proto-neutron star core. The time shown is 360 ms after core bounce and protoneutron star formation. The maximum shock radius at this time is 410 km.

EXECUTIVE SUMMARY:

Core-collapse supernovae are turbulent and dramatic events. Neutrinos deposit energy in the region behind the supernova shock wave and drive buoyant turbulent convection at physical Reynold's numbers up to 10^{17}. Neutrino-driven turbulence is anisotropic, mildly compressible, and only quasi-stationary. Blue Waters-enabled simulations have shown that turbulence provides an effective pressure that can amount to 50% of the total pressure behind the supernova shock wave and thus plays a crucial role in driving the explosion. Because of its importance in the explosion mechanism, it is essential to gain a full qualitative and quantitative understanding of core-collapse supernova turbulence. The results of our high-resolution reduced-physics simulations showed, perhaps surprisingly, that core-collapse supernova turbulence behaved like Kolmogorov turbulence at high resolution. Our simulations also indicated that all current simulations severely under-resolve turbulence, artificially trapping turbulent kinetic energy at large scales where it is most beneficial for launching an explosion.

INTRODUCTION

Core-collapse supernovae (CCSNe) mark the explosive ends of the lives of massive stars with mass greater than 8–10 times the mass of our Sun. There is about one supernova explosion per second in the universe. Time-domain astronomers now discover multiple CCSNe per day and there is abundant evidence linking these explosions to massive stars, yet we do not yet fully understand how the initial collapse of a massive star's core turns into an explosion. The collapse proceeds until a proto-neutron star forms and a shock wave launches. This shock wave, however, does not immediately explode the star. It stalls due to energy losses to nuclear dissociation of heavy nuclei and to neutrinos that stream away from behind the shock.

Neutrinos dominate the energetics of the CCSN problem and it has been hypothesized and shown in some simulations that the re-absorption of a small fraction (~10%) of the outgoing neutrino luminosity can help revive the stalled shock and drive an explosion. Over the last two decades it has become clear that multi-dimensional dynamics, in particular neutrino-driven turbulent convection, plays a crucial role in the explosion mechanism. More recently, our group and the Princeton group led by Prof. Adam Burrows have shown that turbulence is key to the explosion mechanism.

Simulating CCSNe is an extremely computationally intensive, but highly appealing research problem. All four fundamental forces of physics (gravity, electromagnetic, weak, and strong forces) go into CCSNe simulations, which makes them truly multi-physics. They also must be multi-dimensional (ideally 3D, since turbulence is unphysical in 2D) and multi-scale, since small-scale turbulent regions must be resolved while the entire inner regions O(10,000) km of the star must be contained on the grid.

METHODS & RESULTS

We carried out our full-physics global 3D CCSN simulations with our code *Zelmani* that is based on the open-source Einstein Toolkit [1] and the Cactus [2] framework. *Zelmani* is fully general relativistic (GR) with dynamical spacetime evolution, employs full Berger–Oliger adaptive mesh refinement (AMR), and implements GR hydrodynamics with finite-volume methods. Neutrinos are treated either with an efficient but very approximate leakage scheme or with two-moment energy-dependent radiation transport with an analytic closure relation (M1). In this M1 approach, the fluxes are handled time explicitly and only local interaction terms are treated time implicitly. This makes the code efficient and lets full adaptive mesh refinement (AMR) simulations scale well to 16,000–32,000 Blue Waters cores for typical problem sizes.

Fig. 1 shows a snapshot of our most recent 3D GR radiation-hydrodynamics CCSN simulations on Blue Waters while it was in transition to a strongly asymmetric explosion. It is to date the most highly resolved CCSN simulation with 3D radiation hydrodynamics. The entire region behind the shock was resolved with linear resolution of 1.5 km, corresponding to an angular resolution of 0.43° at a radius of 200 km, which is a factor of about five higher than previous work. We carried out a second, lower-resolution simulation with everything else fixed. This simulation transitioned to explosion about 50 ms earlier than the high-resolution simulation, indicating that low resolution indeed artificially favored explosion as we suggested previously with our 3D GR leakage simulations [3].

In order to study the resolution dependence of CCSN turbulence in more detail, we carried out reduced-physics semi-global simulations (in a 3D wedge) with the high-order GR hydrodynamics code WhiskyTHC. We reduced the physics to the bare minimum to capture qualitatively all major ingredients to the CCSN problem. With this setup, we were able to scale our simulations to 65,536 cores and follow neutrino-driven convection at an unprecedented 0.09° angular and 191 m radial resolution, more than 15 times higher resolution than the highest-resolution published simulation. Fig. 2 shows a key result of this study. As resolution increased, the flow became increasingly fine grained and large-scale plumes broke into much finer filaments and smaller plumes. Our very highest resolution resolved substantial turbulent inertial range and the turbulent cascade exhibited a Kolmogorov-type scaling. This was an important result because it had been unclear previously if CCSN turbulence should be Kolmogorov in nature or not. We also found that lower-resolution simulations artificially trapped turbulent kinetic energy at large scales due to a numerical "bottleneck" in the turbulent cascade.

WHY BLUE WATERS?

Blue Waters was essential for our CCSN simulation work; it allowed us to push our simulations to unprecedented resolution and physical detail. No other machine would allow us to carry out simulations at this scale and rate of throughput. The Blue Waters/NCSA team facilitated this throughput that resulted in rapid turn-around of science results. Future Track-1 systems would allow even higher-resolution, more physically detailed, and longer-duration CCSN simulations to more completely track the development of the explosion, explosive nucleosynthesis, and neutron star recoil. However, architectural changes between Blue Waters and a future Track-1 system will require a new approach to parallel computing. We have already started to develop a next-generation code that will be designed specifically to perform on next-generation architectures.

PUBLICATIONS

Abdikamalov, E., et al., Neutrino-driven Turbulent Convection and Standing Accretion Shock Instability in Three-dimensional Core-collapse Supernovae. *Astrophys. J.*, 808:1 (2015), 70, doi:10.1088/0004-637X/808/1/70.

Couch, S. M., and C. D. Ott, The Role of Turbulence in Neutrino-driven Core-collapse Supernova Explosions. *Astrophys. J.*, 799:1 (2015), 5, doi:10.1088/0004-637X/799/1/5.

Radice, D., S. M. Couch, and C. D. Ott, Implicit large eddy simulations of anisotropic weakly compressible turbulence with application to core-collapse supernovae. *Comput. Astrophys. Cosmol.*, 2 (2015), 7, doi:10.1186/s40668-015-0011-0.

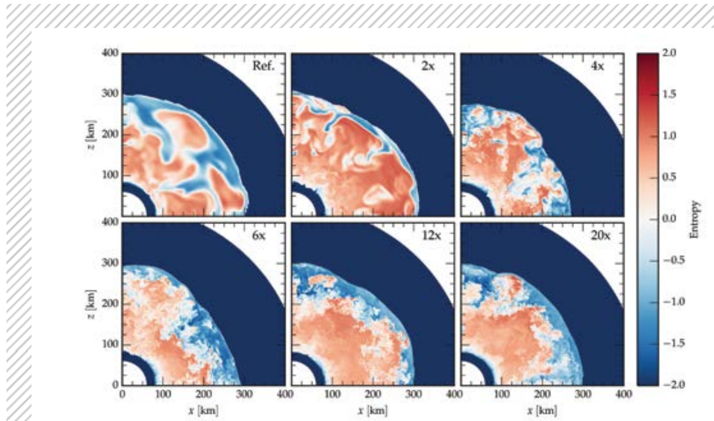

FIGURE 2: Entropy distribution (arbitrary units) in 2D slices of 3D semi-global simulations of neutrino-driven turbulent convection in core-collapse supernovae. The top left panel is the reference resolution and the remaining panels are snapshots from simulations with increased resolution as denoted in the top right of each panel. The flow structure changed dramatically with increasing resolution.