MONTE CARLO NEUTRINO CLOSURES IN 3D GRMHD SIMULATIONS OF CORE-COLLAPSE SUPERNOVAE AND NEUTRON STAR MERGERS

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EXECUTIVE SUMMARY

The transport of neutrinos plays a dominant role in engine-driving core-collapse supernovae, but results from simulations of neutrino transport depend sensitively on the method and implementation details of neutrino transport codes. We have enhanced the open-source Monte Carlo neutrino transport code Sedonu and compared the results against a discrete ordinates transport code to verify for the first time multidimensional Boltzmann neutrino transport algorithms. We used these results to assess the accuracy of approximate two-moment transport schemes. We then motivate the use of time-independent Monte Carlo transport calculations in future large-scale time-dependent supernova simulations. In an orthogonal study, we also analyzed how gravitational waves—the only signal other than neutrinos that directly reflects conditions deep within the explosion—could inform our understanding of dynamics in exotic supernovae.

RESEARCH CHALLENGE

Core-collapse supernovae are immense explosions following the collapse of massive stars; they release around 10^{53} ergs in neutrinos and result in explosions with kinetic energies of around 10^{51} ergs [1]. These supernovae are the origin of most of the elements of which we and the world around us are made. The extreme conditions during the explosions are also wonderful laboratories for a wide range of physics, including nuclear structure, general relativity, neutrino interactions, and magnetohydrodynamical instabilities. Though we know *what* causes these explosions, understanding *how* they happen is a difficult and computationally intense problem that has been an active area of research for over 50 years.

In the canonical theory, neutrinos emitted from the dense inner core heat and drive turbulence in matter that pushes a shock wave through the collapsing star, resulting in explosion. Due to the complexity of the involved physics and dynamics, computation has become the primary tool for understanding this mechanism. In particular, the transport of neutrinos in these systems is modeled by the six-dimensional (plus time) integro-differential Boltzmann equation, which cannot currently be adequately simulated for the duration of the explosion. The neutrino transport component of simulations is treated by many different methods, all of which include some level of approximation, even in the largest and most sophisticated simulations. Small differences in how neutrino transport is implemented can lead to entirely different simulation outcomes. Understanding the mechanism that leads to stellar explosion thus requires both improved simulation techniques to more accurately treat neutrino transport and a means of ensuring that the techniques and discretization choices adequately simulate the physics they represent. Though verification efforts of Boltzmann-level transport schemes have been performed in spherical symmetry, in this project we make the first jump to verification of Boltzmann transport in multiple spatial dimensions. We also motivate improvements to more approximate transport methods.

METHODS & CODES

We use a variety of simulation codes to approach the problem from different directions. The key component of this project is the open-source Monte Carlo neutrino transport code Sedonu, which computes with high accuracy time-independent effects (e.g., instantaneous heating/cooling and lepton gain/loss rates) of neutrinos on one, two, and three-dimensional stationary fluid snapshots. With a paucity of direct data to validate against, we compare Monte Carlo results to those from a vastly different discrete ordinates method [2] to allow us to quantify how well we understand supernova neutrinos as we work toward a working theory of neutrino-driven core-collapse supernovae. We also assess the accuracy of popular approximate two-moment transport schemes [3] used in multidimensional core-collapse simulations. In addition, we couple Sedonu to the open-source supernova code GR1D [4]. The latter code simulates stellar core collapse in spherical symmetry using an approximate neutrino transport method, while Sedonu informs the transport approximation to bring it closer to the exact solution. Finally, we perform three-dimensional test calculations using snapshots from simulations using the open-source package Zelmani [5,6].

RESULTS & IMPACT

Understanding the core-collapse supernova engine requires not only ever-increasing simulation size and complexity, but an understanding of how well these methods reflect the physics they are meant to simulate. With this in mind, we developed a new version of the open-source Monte Carlo neutrino transport code Sedonu, in which we implemented the random walk approximation. This improvement, along with many other feature additions and optimizations made as part of this project, makes the code capable of calculating highly accurate steady-state neutrino fields and interaction rates through the entire system without resorting to artificial boundary conditions. We performed the first multi-dimensional comparison of full Boltzmann neutrino transport methods, using Sedonu and the discrete ordinates code of [2]. Given that core collapse simulation results depend sensitively on small details of the neutrino transport implementation, this provides a much-needed measurement of the numerical errors associated with each method, and provides the first multi-dimensional code verification tools to the community.

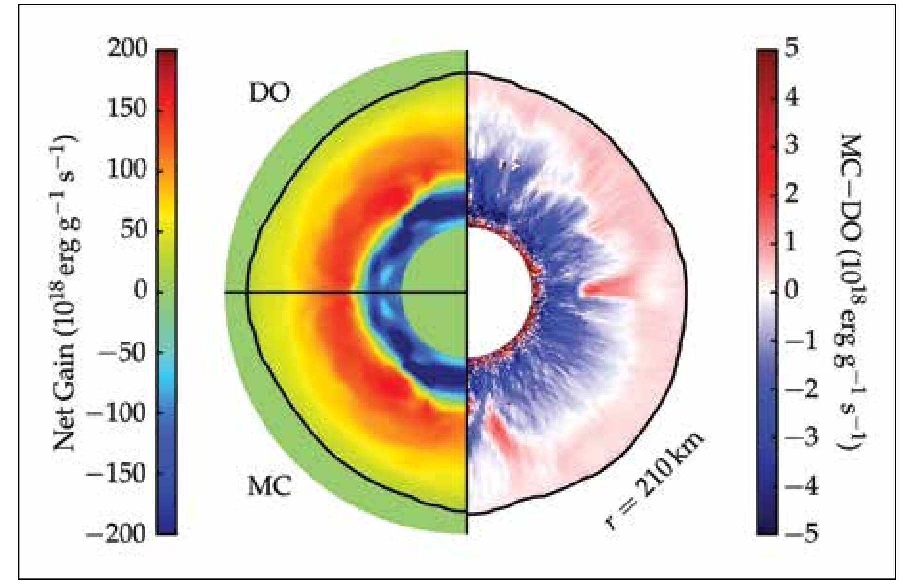

Figure 1: The heating rate in a supernova snapshot computed by the Monte Carlo code Sedonu (bottom left) and the discrete ordinates code of [1] (top left). They agree very well, but the small differences between them (right) could make the difference between an explosion and a dud in a dynamical simulation.

Observations of neutrinos and gravitational waves from nearby supernovae both give direct, unobscured information about the nature of the processes occurring deep within the collapsing star that lead to explosion. In addition to the above studies of neutrinos in supernovae, we performed a parameter study to determine what gravitational wave signals from rotating core collapse can tell us about the nature of matter at super-nuclear densities. In this study, we performed over 1,800 axisymmetric (2D) core collapse simulations. We used 18 different parameterizations for nuclear matter properties and over 100 rotation profiles, and concluded that differences in the descriptions of nuclear matter allowed by current constraints are not likely discernible by current gravitational wave detectors, even for a galactic supernova. We also established a simple universal relationship between the gravitational wave frequency and properties of the collapsed core. The resulting publicly available data set is an order of magnitude larger than those in previous studies and represents the first thorough exploration of both rotation and nuclear matter parameters.

WHY BLUE WATERS

Without access to the unique Blue Waters environment, the careful method development and verification in this project would not have been possible. The fellowship allocation enabled these calculations independently from other resources, since the calculations are far too large for local clusters and are separate from other resource requests. This project is targeted at working toward large-scale three-dimensional core-collapse simulations with a Monte Carlo-informed approximate method for neutrino transport. The domain-replication parallelism used in this approach requires both a large amount of compute time and a large amount of memory on each node. Blue Waters provides a unique environment with both of these components. In addition, the support staff with both domain and system expertise significantly simplify the task of implementing and optimizing our algorithms on Blue Waters, allowing user time to be spent on science and development rather than code porting.

PUBLICATIONS AND DATA SETS

Richers, S., et al., Equation of state effects on gravitational waves from rotating core collapse. *Physical Review D*, 95:6 (2017), DOI: 10.1103/PhysRevD.95.063019.

Richers, S., et al., Equation of state effects on gravitational waves from rotating core collapse [Data set]. *Zenodo* (2017).

Richers, S., et al., A detailed comparison of multi-dimensional Boltzmann neutrino transport methods in core-collapse supernovae [Data set]. *Zenodo* (2017).

A fifth-year Ph.D. student in physics at California Institute of Technology when he completed this research, Sherwood Richers was working under the direction of Christian Ott. He successfully defended his dissertation in June 2017 and will graduate in June 2018.