GENERAL RELATIVISTIC NEUTRINO RADIATION TRANSPORT: UNDERSTANDING THE DRIVING FORCE BEHIND COSMIC EXPLOSIONS

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EXECUTIVE SUMMARY

Calculating the behavior of neutrinos within core-collapse supernovae and neutron star mergers is key to understanding the mechanism behind the explosions and the formation of most elements in the universe. I apply a highly accurate Monte Carlo radiation transport method to simulate neutrinos in these environments to understand the detailed structure of the radiation field that current approximate methods are unable to probe. Using these results, I am then able to improve the current approximate methods.

RESEARCH CHALLENGE

The collapse of the cores of massive stars and collisions between neutron stars are known to produce some of the most powerful explosions in the universe, but it is unclear how these occur. The extreme density and temperature of the matter in these events also make them the likely sole source of all the elements in the universe other than hydrogen, helium, and lithium [1–3]. Lurking behind the bright flash and explosive ejection of every imaginable element in both types of events is the elusive neutrino [4,5]. Neutrinos, which ordinarily interact so weakly with matter that experimentalists have great difficulty even detecting them, are the dominant couriers of energy and determine which elements form in the ejecta. Since we cannot see the interiors of these events where all the explosion-launching work is being done, we have to rely on numerical models to advance our understanding of the nonlinear dynamics. Simulating the behavior and impact of neutrinos remains particularly challenging, since it is a seven-dimensional problem (three spatial dimensions, two independent directions, neutrino energy, and time). I use an advanced Monte Carlo method to calculate the structure and impact of the six-dimensional (ignoring time-dependence) distribution of neutrinos in these systems. The results of this work help us to interpret models and observations and to pave the way for new computational methods that are both accurate and efficient.

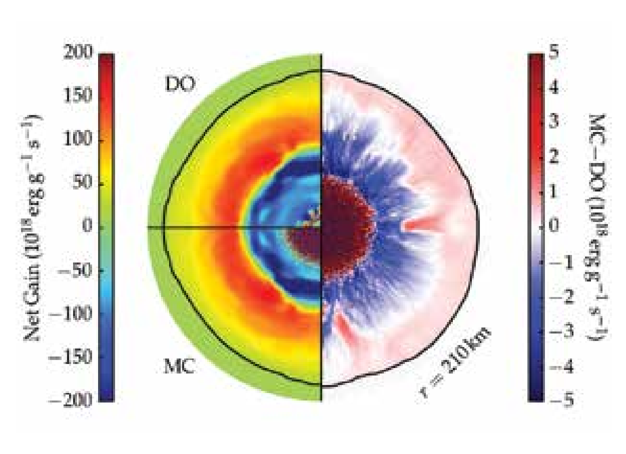

Figure 1: The battle of neutrino transport methods. The left side shows the rate at which neutrinos are depositing (red) or removing (blue) energy from a core-collapse supernova using a discrete ordinates method (top) and my Monte Carlo method (bottom). The difference (right) is small, but significant.

METHODS & CODES

I calculated the steady-state radiation field in core-collapse supernovae and neutron star mergers using Sedonu [6], an open-source, general relativistic Monte Carlo neutrino radiation transport code. Sedonu samples the trajectories of a large number of individual neutrinos that are emitted from, absorb into, and scatter off a three-dimensional background matter profile. When a large number of these trajectories are calculated and averaged together, the outcome is a very detailed and highly accurate picture of what the neutrino radiation is doing at every point in space, at every energy, and in every direction. The physics that goes into calculating what each individual neutrino does is also fairly complete. General relativity is fully considered by evolving the particles along curved trajectories around the central neutron star or black hole. Detailed absorption, emission, and scattering rates are included via the NuLib library [7], and I include fully energy- and angle-dependent inelastic scattering processes. Once all the trajectories have been simulated, I also use the resulting neutrino distribution function to calculate the rate that neutrinos annihilate with anti-neutrinos.

RESULTS & IMPACT

Understanding the mechanisms behind the explosions from core-collapse supernovae and mergers is a longstanding problem that will likely not be solved without advances in the treatment of neutrino radiation transport. These calculations of Monte Carlo radiation transport are far more accurate than more efficient methods and elucidate where the latter need to be modified to enable high-accuracy simulations without the large expense of Monte Carlo radiation transport calculations. The detailed results pave the way for the next generation of models.

In addition, radiation transport is a problem in a wide variety of disciplines and has been a major component of high-performance computing since its inception. Each application of radiation transport has unique challenges, but algorithm development on state-of-the-art hardware in core-collapse supernovae is coupled to that in accretion disks, weather, and nuclear reactors, to name a few. The code Sedonu is open-source to facilitate rapid advances in the field at large.

WHY BLUE WATERS

Monte Carlo radiation transport requires a large number of test particles to be simulated to get smooth, converged results. In my calculations of the radiation field in three-dimensional neutron star mergers, I simulate around 1.3 trillion particles. Doing so requires: (1) a large amount of memory on each node so each node can fit the entire problem, and (2) many nodes to repeat the problem enough times to get a solution with little noise. Blue Waters is the prime computer of its time for doing these calculations. The project staff have been very valuable in helping to optimize the code to make effective use of vector parallelism.

PUBLICATIONS & DATA SETS

Richers, S., et al., A Detailed Comparison of Multidimensional Boltzmann Neutrino Transport Methods in Core-collapse Supernovae. *The Astrophysical Journal*, 847:2 (2017), DOI:10.3847/1538-4357/aa8bb2.

Richers, S., et al., A Detailed Comparison of Multidimensional Boltzmann Neutrino Transport Methods in Core-collapse Supernovae (dataset). *Zenodo* (2017), DOI:10.5281/zenodo.807765.

Currently a postdoctoral student at North Carolina State University, Sherwood Richers did his Blue Waters Graduate Fellow work at the California Institute of Technology, where he received his PhD in June 2018.