Brandon Barker - Research Statement

Core-collapse supernovae (CCSNe) are the spectacular explosions that accompany the deaths of massive stars. CCSNe have been the subject of ongoing research for decades but *the explosion mechanism is still not fully understood*. Proper treatment of the CCSN problem requires all areas of physics; in particular, general relativistic gravity, complex neutrino transport, turbulent magnetohydrodynamics, and nuclear physics. CCSNe are the primary engines of galactic chemical evolution; many of the elements heavier than H and He are synthesized here, those necessary to life in particular. Furthermore, a complete view of CCSNe is necessary for understanding the compact objects that arise from core-collapse, such as the binary neutron stars and stellar mass black holes that have been detected by Advanced LIGO and Advanced Virgo[1].

Intellectual Merit

As current high-fidelity CCSN simulations lack the ability to properly predict electromagnetic (EM) emission, **I propose to investigate the explosion mechanism driving CCSNe by further developing the current CCSN simulation capabilities to provide accurate EM predictions.** While yielding far more insights into the processes at work in the CCSN, it will also allow for comparison with observational astronomy. This collaboration of full multimessenger signals is a yet untapped resource that could give new insights into the explosion mechanism. The proposed project is broken down into three stages: (i) upgrading our nuclear physics, (ii) getting 1D LC and EM information, and (iii) going to multiple dimensions. My background in stellar astrophysics and computational methods makes this project a natural next step.

Upgrading our nuclear physics. In the hot interior of massive stars, material is said to be in nuclear statistical equilibrium (NSE), meaning that forward and backward reactions are balanced such that elemental abundances are given by relatively simple statistical relations. Current high-fidelity CCSN simulations assume that NSE is satisfied throughout the entire star. While this is a good approximation in the interior regions of interest most pertinent to the explosion, it breaks down quickly at large radii so that only the central regions can be accurately modelled. **I will work to transition the equation of state (EOS) to the non-NSE regime in the FLASH code.** This will allow for whole-star simulations and more accurate nucleosynthesis calculations. Inclusion of the outer regions of the star will also allow for modelling of the neutrino-driven wind – a supersonic outflow of stellar material powered by neutrinos emitted from the core of the star. This wind is proposed as a possible site of heavy element nucleosynthesis. We can then begin to meaningfully study the full nucleosynthetic signatures of CCSNe.

Getting 1D LC and EM information. The ultimate goal of the study of the CCSN explosion mechanism is the ability to *make predictions* and *understand observations*. Armed with a more realistic EOS and accurate nucleosynthesis, I will study the EM signals emitted during a CCSN. To achieve this, **I will use a new model for driving 1D explosions that includes the crucial effects of turbulence and convection and map simulation data into SuperNu[2], a multi-D Monte Carlo radiation transport code, to produce the EM signals.** This is imperative as, to date, we have only one observation of a CCSN that includes any signals other than electromagnetic. The FLASH code is already capable of handling the gravitational wave (GW) and neutrino emission, so this extension will provide complete predictions of the multimessenger signals. With this, we can begin to make direct connections between physical conditions of the explosion and what is observed. An understanding of how, for example, uncertain nuclear physics affects the electromagnetic signals is crucial to the success of the CCSN problem. This will allow us to compare our findings to observations and, for the first time, connect observations of CCNSe with details of the progenitor stars.

Going to multiple dimensions. The final goal of this project is the ability to run fully 3D CCSN simulations that for the first time include a proper treatment of the non-NSE EOS and EM information. **This project will push the frontiers of current high fidelity 3D simulations and greatly enhance their explanatory and predictive powers.** Due to the extreme computational resources required of these simulations, the simulations would begin during years 3-4 using computing allocations available to Dr. Sean Couch, the PI of the Michigan State University (MSU) research group. At this stage of the project, I will have the ability to study the full range of multimessenger signals from CCSNe including EM, GW, and neutrino signals in addition to the nucleosynthetic signatures of the explosion. With all of this in hand, we can make *accurate* and *meaningful* predictions of how the various physics that go into the CCSN impact the explosion, and how that in turn affects the observations.

Broader Impact

The work presented here will result in the advancement of our understanding of the CCSN explosion mechanism, galactic evolution, and ultimately, the origin of the elements including those that comprise life. **The results of this work will promote constructive collaboration between theoretical stellar astrophysicists and observational astronomers.** EM data produced through this project can be compared against observational data as a benchmarking tool and may also be used by observers to inform future studies. This project aligns with the goals of the DOE's Scientific Discovery through Advanced Computing (SciDAC) initiative, as well as the National Strategic Computing Initiative, in the push to exascale computing. MSU houses the Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory, Facility for Rare Isotope Beams, and a new Department of Computational Mathematics, Science and Engineering and as such it the ideal campus for this interdisciplinary work. In an effort to reach first generation students, I will create a chapter of Ask A Scientist at MSU utilizing my connections with the national organization. To best leverage the available resources, I plan to create collaborations with existing programs at MSU such as the 4-H Michigan Extension, MSU Science Fair, and first generation student mentor program. I will travel to rural Michigan schools to show first generation and low income students that a college education and career in science are options for them. Through this chapter of Ask A Scientist, these communities can continue to benefit after the conclusion of my graduate studies. *Astronomy has amazing potential to transform both lives and communities*[1] *and the NSF GRFP would give me the resources necessary to begin my career while using my research as a tool for change.*

[1] Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Phys. Rev. Lett., 116, 061102

[2] Wollaeger, R. T., van Rossum, D. R., Graziani, C., et al. 2013, The Astrophysical Journal Supplement Series, 209, 36

[1] https://www.nature.com/collections/xtxtmqfrgf