Graduate Research Plan Statement

Core-collapse supernovae (CCSNe; SNe) signify the end of the high-mass stellar lifecycle, serve as the primary producer of heavy elements throughout galaxies, and mark the formation of compact objects. Computational population studies of SNe are a powerful tool to constrain and characterize the physics we infer from limited observational data. Modeling the evolution, explosion, and observables of a diverse set of progenitor stars can help us better understand the end of the high-mass stellar lifecycle from a statistical standpoint. *To reduce the complexity of simulating SNe, many existing studies assume initial conditions that diverge from observed stellar populations.* In this era of data-driven astronomy, ensuring accurate theoretical predictions of CCSNe is critical to understanding observational data, particularly with the expected influx of SNe observations from upcoming all-sky transient surveys such as Vera Rubin Observatory and Roman Space Telescope.

Intellectual Merit

While CCSNe have been studied extensively, the computational models that aim to unify observation with theory often make nonphysical simplifications, particularly in 1D methods. SNe population studies often model the explosion of idealized stellar progenitors[1, 2]. *We know from observation that these simplifications are physically unrealistic.* This introduces degeneracy into our current correlations between progenitor characteristics and CCSNe observables[3]. **As an NSF Graduate Research Fellow, I plan to develop a 1D pipeline that simulates the evolution, explosion, and observables of a diverse, physically realistic high-mass stellar population.** This study will provide deeper insight into the interface between CCSNe theory and observation furthers our understanding of how to accurately infer progenitor properties and SNe characteristics from limited electromagnetic data. Given my current research on the statistical correlation between SNe progenitors and observables, and my experience with a varied set of computational methods and tools, I believe I am uniquely suited to conduct this study. This pipeline can be broken down into three distinct phases: (i) evolution of a new progenitor grid, (ii) updating SNe physics, and (iii) investigating the effects of parameter degeneracy on observables.

Modeling the evolution of a diverse stellar population. Observations show that massive stars (≥ 8-10 M_{sun}), particularly progenitors of CCSNe, often evolve in complex, multiple-star systems[4]. Supernovae are highly sensitive to the environment of their progenitors. Two identical stars with that evolve with different environmental variables, such as mass loss or rotation rate, can produce significantly different supernovae – or may not explode at all[5,6]. The current grid(s) of progenitors used for large-scale, statistical CCSNe studies are typically generated under the assumption of a non-rotating, singular stellar evolution model, and details of the modeling process are not publicly available[2]. **I plan to use the open-source stellar evolution code, MESA, to evolve a new grid of rotating progenitors from main sequence to core-collapse.** This will allow for the introduction of rotation and multiplicity into progenitor models and enable the investigation of the degeneracy between progenitor parameters and the resulting CCSNe.

Improving explosion methods in effective and multi-dimensional simulations. Due to the multi-dimensional nature of the processes that drive the explosion mechanism of CCSNe, 1D methods typically omit key physical phenomena[7]. However, recent simulations demonstrate that an effective implementation of these 2D and 3D processes, such as turbulence, can be successfully used in large SNe population studies[8]. **Using the FLASH/STIR framework[8], I will update 1D CCSNe simulations to include effective progenitor rotation through the methods of Ekström et al[9].** Because FLASH supports multi-dimensional simulations, we will also be able to investigate the complete three-dimensional case for select progenitor models of interest. This flexibility provides excellent verification for our effective 1D methods through comparison between a broad dataset of single- and multi-dimensional results, using key parameters such as explodability and explosion energy.

Simulating observational signals and nucleosynthesis measurements. The most impactful aspect of these diverse population studies is the potential for data-driven investigations in conjunction with observational data. Lightcurves (LCs) serve as the characteristic electromagnetic (EM) observable of SNe and have been modeled for simulated explosions of all dimensions through 1D radiative transport codes.

While current methods of LC modeling do support stellar rotation; spectral simulations often do not[10]. **Using this new progenitor population, I will model rotationally dependent observables with SNEC[10] and contrast with non-rotational, multi-D observables simulated through SuperNu.** I also plan to use my existing familiarity with nuclear reaction networks such as CFNET to investigate the nucleosynthetic behavior of successful explosions and provide further insight into inferred observables.

This work is suited to the computational and academic resources at Michigan State University. My intended PI, Dr. Sean Couch has extensive experience with FLASH/STIR, and also has unique collaborations with the nuclear astrophysics community at MSU. With the data from current all-sky SNe surveys such as ASAS-SN and the potential for new transient identification and follow-up observations by Rubin and Roman, bridging the gap between theory and observation is essential to scientific progress. In addition, characterizing the physics involved in CCSNe can lead to new understanding of the compact objects that form in their wake, allowing us to connect EM measurements to a new set of multi-messenger observatories such as Advanced LIGO/Virgo, LISA, and IceCube-Gen2. *By simulating the physics and observations of CCSNe where all initial progenitor characteristics are known through the entire stellar lifecycle, we can ensure that accurate, well-characterized inferences and correlations can be developed from observational data.*

Broader Impacts

Investigating the drivers of core-collapse supernovae and further exploring the parameters that can characterize and transform our observations of these transient events is a critical step towards successful multi-messenger astronomy. The Decadal Survey on Astronomy and Astrophysics 2020[11] identifies the exploration of stellar demographics (Sec. 2.1.1) as an area of scientific interest, which aligns directly with the goals of this work. In addition, this investigation supports NSF Strategic Objective 2.2, Enhance Research Capability, by *promoting open-source, accessible science* by using publicly available simulation codes as the foundation of the pipeline. This approach allows for reproducibility and verification of our results by the community while increasing the potential for citizen science.

Conducting this study at MSU also promotes increased societal impact through mentorship and community-focused science. MSU Astronomy's existing Stellar Mentorship Program focuses on inter-departmental mentorship at all levels, from first-year undergraduates to faculty. The university also has a long-standing collaboration with the Abrams Planetarium, and currently co-hosts (i) the Astronomical Horizons lecture series, which brings current developments in astronomy to the public, and (ii) public observing nights that are open to the surrounding community. **In addition to joining these existing collaborations, I plan to develop a hands-on, introductory course in astronomy research in collaboration with the surrounding school system and Lansing Community College.** Using the observational resources offered by Abrams Planetarium, this course will introduce students of all backgrounds, from high schoolers to returning non-traditional students, to scientific research in an accessible environment. The curriculum will have an emphasis on project-based, collaborative learning experiences that focus on exploration and skill development rather than relying on traditional metrics of knowledge assessment. My background in scientific leadership, communication, and education through programs and initiatives such as NASA L'SPACE, COS Ambassadors, and the NC State CSDA REU make me the ideal candidate to successfully develop and implement such a collaboration. Collectively, these initiatives promote progress through NSF Strategic Objective 1.1 (Ensure Accessibility and Inclusivity).

References.

[1] Sukhbold et al. 2016, *ApJ*; [2] Woosely et al. 2002, *ApJ*; [3] Dessart et al. 2019, *A&A*; [4] Winters et al. 2019, *ApJ*; [5] Laplace et al. 2021, *A&A*; [6] Fang et al. 2024, *arXiv*; [7] Burrows & Vartanyan 2021, *Nature*; [8] Couch et al. 2020; *ApJ*; [9] Ekström et al. 2012, *A&A*; [10] Morozova et al. 2015, *ApJ*; [11] Astro2020, The National Academies Press.