1 Summary

Stellar models are some of the most successful theories which astronomers have developed, underpinning current understanding of topics as diverse as exoplanet habitability[1] to the age of the universe[2]. As all models must, models of stellar structure and evolution (SSE) make a number of simplifying assumptions such as assuming spherical symmetry or that there are no non-trivial, non-radial components to any interior vector fields; despite these assumptions, for the majority of the history of stellar models, observational data did not reach levels of precision sufficient to probe the domains where these assumptions break down[3]. This is no longer the case, the advent of high-precision astronomy — from Kepler through to TESS and the upcoming PLATO observatory — have rapidly progressed our observational understanding of stellar physics well beyond our theoretical understanding[4]. My work in computational stellar modeling directly addresses these modern challenges by introducing wholly new paradigms which allow us to relax the assumption of spherical symmetry. Further, my work places a strong emphasis on long term usability, achievability, and student accessibility.

2 Current Research

In my current work I am leading the software development of a novel SSE program, `SERiF`, which — for the first time — will model the full three dimensional structure of a star through its entire life. `SERiF` solves the 3D equations of stellar structure using a deformable finite element discretization thus allowing for non-radial properties, such as surface luminosity variations described by $\ell > 0$ spherical harmonics, to naturally emerge. This work is a *moonshot* project and a major part of the larger international collaboration *4D-STAR*. If successful, `SERiF` will allow researchers to model, to the highest precision yet possible, seismic properties of high mass stars, the core physics of very low mass stars, the effects of magnetic fields on mass loss rates, and almost certainly new questions which we don't yet know to ask.

`SERiF` is in the very early stages of development, and it is not yet a useful scientific tool, that is a milestone which remains a few years away. Despite that, significant contributions to stellar modeling are being made along the way. A key component of any SSE program is *microphysics*, prescriptions describing nuclear fusion rates, equations of state, and both radiative and conductive opacities. I have developed a new nuclear network implementation, `GridFire`, which provides the first open source, fully dynamic, nuclear network implementation optimized for stellar evolution burning (as opposed to the nuclear statistical equilibrium conditions present during core collapse supernovae). `GridFire` is in the final stages of its development and soon will be used to probe the Gaia M dwarf gap[5] in order to investigate if a more topologically complete network can recreate the slant to that feature, which is not yet understood[6].

I have not undertaken such a large project lightly, and I expect to spend much of my career supporting, developing, and extending `SERiF` or tools like it. This long term commitment provides

[1] Howard, Andrew W., Marcy, Geoffery W., & Bryson, Stephen T. 2012, ApJ Supplement Series, 201, 2
[2] Valci, David., et al. 2020, Journal of Cosmology and Astroparticle Physics, 12, 002
[3] Zhou, Y., et al. 2025, MNRAS, 540, 4
[4] Aerts, Conny. 2021, Reviews of Modern Physics, 93, 1
[5] Wei-Chun, J., et al. 2018, ApJ Letters, 861, 1
[6] Boudreaux, E. M., Garcia Soto, A., & Chaboyer, B. C. 2024, ApJ, 965, 1

a clear framework for new research ares — as new models allow us to probe new regimes, support student-lead research, and pursue diverse funding opportunities.

3 Research Plans

My research plans may be generally divided into two segments: over the next 3-5 years, and beyond that. This segmentation is due to the nature of work such as mine. Scientific software development is not a process which progresses at a breakneck pace. Therefore, the next three to five years of my work will be focused on bringing `SERiF` from its current state as a framework and technical demonstration / proof of concept, to a fully fledged 3D SSE program. Once `SERiF` is operational and able to answer new questions my work will shift to probing regions of stellar physics which were inaccessible to astronomers with 1D models.

3.1 `SERiF` Development Phase

Currently `SERiF` is a robust framework which can be built upon. During the next three to five years I will undertake this as a modular process. The first stage, for which I am currently engaged with international collaborators based at KU Leuven, is to discritize the three dimensional equations of stellar structure and evolution in a manner suitable for use with finite element methods. This is primarily a mathematical challenge, with the major hurdles being encoding topologically complex external gravitational potential boundary conditions — without a priori knowledge of the surface shape of the domain — onto the surface of the model and development of a efficient approximate inversion method for the Jacobian matrix of the final system. For this work we have brought together both a mathematics graduate student and postdoc at KU Leuven along with myself. Over the coming year we will optimize our discritization so that the mathematical base of `SERiF` is sound and numerically stable.

In parallel to this work, I will continue to develop the microphysics libraries which serve as the other essential half of any SSE code. `GridFire` is already nearing completion and will provide ample intermediate project opportunities. I will use its more complex and complete handling of network topology along with the Dartmouth Stellar Evolution program (DSEP) — a well tested 1D SSE model, optimized for low mass stars — to build the most physically complete models of stars near the convective transition mass ($\sim 3.5\mathrm{M}_{\odot}$). These stars are known to experience periodic mixing events due to asymmetric production and destruction of ^{3}He during the proton-proton I chain. These mixing events partially explain a $\sim 17\%$ paucity in stellar density seen in the Gaia CMD (the gap) for the local stellar volume[7]; however, that feature is slanted with respect to the color axis and that slant is not explained by any current generation models. Due to the sensitivity of the gap to core physics conditions and the fact that seismology is impractical for such low mass stars, the gap provides one of the most promising avenues for studying the deep interior physics of the most common class of star in the universe. `GridFire` may provide additional burning or freeze-out pathways for stars spanning the main sequence thus explaining the slant. On the other hand it may not which would definitively show that the structure of the gap is a function of more than the nuclear burning rates of a star. Generally then, while `SERiF` will not be able to produce many publications during its development, because development is so modularized, intermediate publications will originate from work on individual modules or supporting projects.

Additionally, aside from `GridFire`, other microphysics libraries are required, most pressingly an auto-differentiable equation of state library but also radiative and conductive opacity prescriptions.

[7] van Sanders, J. L., & Pinsonneault, M. H. 2012, ApJ, 751, 98

These additional microphysics libraries similar lend themselves to intermediate publications as well as focused funding for both calibration and case studies.

Due to the modular way in which this software has been developed there are many opportunities for students at all levels to contribute. Undergraduates can take on important, yet self-contained, tasks such as the aforementioned investigation into the gap slant when using `GridFire`. Graduate students can develop new physics modules, calibrate them, and then study their effects on any number of regimes. All-in-all this style of development and research work lends itself well the analogy of a composer. Any realm of stellar physics wherein models do not yet capture observations can, should, and will be explored as new and more detailed physics comes on line.

3.2 Post-SERiF Science Phase

Development of `SERiF` will not go on forever, at some point we will end up with a functioning scientific tool. It is at this stage where the real power of novel models becomes clear. Currently there are many open questions about stellar physics; for example, what are the mass loss rates of various classes of stars and how do both these and stellar magnetic fields affect the atmospheres of orbiting planets? Not all open questions will be easy to answer; however, as we probe the 3D regime some answers are sure to emerge immediately, while others will at least be better constrained. After `SERiF` development is complete then I will shift focus to **using these new 3D models to place constraints on the most important open questions in stellar physics.** This will include the development, along with the *4D-STAR* collaboration, of the first three dimensional grid of stellar isochrones, opening the potential for dramatically more constrained age estimates of stellar clusters.

This stage of work in particular will be attractive for funding agencies, as novel computational work has historically been high impact[8]. Further, while the computational cost of three dimensional models is of course more than that of one dimensional models the strong emphasis — being placed from the outset — on high performance computing will result in projects based on `SERiF` being not just novel but also tractable. I will seek funding from the National Science Foundation and NASA to run a large number of simulations on supercomputing resources such as XSEDE and at the NASA advanced supercomputing (NAS) division.

Similarly to the development stage, this stage provides a pleathora of opportunities for **student-led** research. Undergraduates can realistically write papers — making use of pre-computed models — on, for example, planetary atmosphere loss as a way to calibrate mass loss rates of their host stars. Graduate students can spend their dissertations delving deeply into the some new physics only discoverable in three dimensions. Post doctoral researchers will have the opportunity to significantly extend the captured physics of these programs or to lead small to medium scale observational campaigns focused on focused on finding observational signatures of newly predicted physics. This leaves the door open then for both computing focused funding and observational funding.

4 Conclusion

My research, both current and planned, focuses on the development of novel computational models. These are developed in a modular fashion which encourages intermediate projects of various scales. Further, this research is well suited to high performance computing funding while also leaving the door open for supporting observational grants. Astrophysics is at the cusp of a revolution in stellar physics — 3D models of stellar structure and evolution are the key to unlocking this — and, if hired, I will bring my field-leading expertiese in such models to your department.

[8] Varga, A. 2018, ApJ Supplement Series, 236, 1