Convective Conundrums in the Asteroseismic Age: The interplay of rotation and magnetism in stellar convection

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1. Motivation

Asteroseismology The advent of asteroseismic science has closely paralleled that of exoplanetary science. Early ground-based observations of stellar pulsations (e.g., Kjeldsen & Frandsen 1991; Bouchy & Carrier 2001; Bedding et al. 2001) have given way to datasets larger than 10^4 stars (e.g., Yu et al. 2018; Santos et al. 2019) in the age of CoRoT, Kepler, and K2 data. Another 20,000 asteroseismically-interesting targets are being observed in the TESS satellite's two-year mission (Schofield et al. 2019). By 2030 we expect to have observed 10^7 pulsating red giants and 10^5 dwarfs and subgiants (Huber et al. 2019). In addition to teaching us about the nature of stellar interiors, asteroseismology enables the accurate measurement of stellar ages, masses, and radii, which in turn facilitates studies in galactic archaeology and exoplanetary measurements. Asteroseismic measurements generally rely on one-dimensional (1D) stellar structure models, and these models have some known deficiencies (Buldgen 2019), in particular their handling of three-dimensional (3D) dynamical phenomena like convection, rotation, and magnetism. The exponential rise in asteroseismic targets demands a continued investment in the theory that informs these stellar models and asteroseismic measurements.

State-of-the-art stellar strucuture models are produced by 1D codes like MESA (Paxton et al. 2011). Unfortunately, MESA models necessarily depend on 1D parameterizations of convection and often employ the decades-old mixing length theory (MLT, Böhm-Vitense 1958). While some aspects of convection are adequately described by MLT, it fails in a number of situations. For example, 1D stellar models incorrectly produce pulsations in the surface layers of Sun-like stars, while 3D models of convection in these layers fare better (Jørgensen & Weiss 2019). Additionally, 1D models assume spherical symmetry and generally neglect magnetic and rotational effects. Observations of stellar flares (Kowalski 2016) and magnetically-induced pulsational frequency shifts (Santos et al. 2018) suggest that magnetism should not be neglected. Furthermore, the Sun exhibits differential rotation characterized by latitudinal variations in angular velocity within the solar convection zone (Thompson et al. 1996; Schou et al. 1998), and latitudinal differential rotation has now been observed in other stars (Benomar et al. 2018). Together, these observations suggest that 1D parameterizations of convection which neglect complicating effects cannot sufficiently capture the complexities of stars. In order to properly and fully utilize the large stores of incoming asteroseismic data, we must improve the models on which asteroseismic inversions rely.

The Solar Convective Conundrum The outer 30% of the Sun is a highly stratified convective envelope, and recent observations reveal that we lack a fundamental understanding of dynamics in this region. Various helioseismic observations (Hanasoge et al. 2012; Greer et al. 2015) detect convective velocity magnitudes which are two orders of magnitude disparate. Furthermore, these observations, as well as measurements of solar surface velocities (Hathaway et al. 2015), have an unexpected absence of velocity at large spatial scales. In short, we do not observe large-scale "giant cells" driven by buoyant motions deep in the solar convection zone. These measurements, and the absence of giant cells, consitute the Solar Convective Conundrum.

Two primary hypotheses which aim to explain the absence of giant cells are the "Entropy Rain" hypothesis and the hypothesis of a rotationally constrained solar convective interior. The entropy rain hypothesis, first suggested by Spruit (1997), posits that theory over-predicts the importance of upflows and that *downflows* are predominantly responsible for carrying the solar luminosity across the solar convection zone. Recent theory and simulations, including some of my own work, suggest that small, intense downflows can indeed survive through the depth of the convection zone and may be more important than upflows in solar-like convection (Brandenburg 2016; Käpylä et al. 2017; Anders et al. 2019a). To date, this work neglects magnetism and rotation, and it is unclear how these complicating effects interact with these fast, powerful downflows. Meanwhile, the rotationally constrained interior hypothesis suggests that Coriolis forces dominate the dynamics of deep solar convection, and that these forces mask giant cells. Simulations by Featherstone & Hindman (2016) show that as convective flows become more rotationally constrained, dominant convective velocities are pushed to smaller length scales. However, rotational effects on simulations can be hard to quantify; some simulations which nominally rotate at the solar rate show *anti-solar* differential rotation (Gastine et al. 2014), and other rotationally constrained simulations exhibit Jupiter-like bands (Brun et al. 2017). Regardless, current results and hypotheses suggest that the interplay between downflows and rotational effects must be better understood in stellar convection.

Modern convective simulations The earliest simulations in stellar-like convection (Graham 1975; Hurlburt et al. 1984; Cattaneo et al. 1991; Brummell et al. 1996, 1998) often sought to gain understand in simplified systems. Cartesian geometry was employed, and convective flows in the presence of one or more complicating effects (stratification, rotation, magnetism, etc.) were explored. Despite vast modern computational resources, similar studies (e.g., Wood & Brummell 2012; Anders & Brown 2017; Wood & Brummell 2018) have become rare in the past two decades, and the highly laminar results of simulations from twenty years ago are often the state-of-the-art.

Recently, numericists have often switched from aiming to simply understand convection to trying to reproduce precisely aspects of solar or stellar convection. Large scale, "global" simulations of spherical rotating magnetoconvection have recreated cycling dynamos and differential rotation profiles (Brown et al. 2010, 2011; Guerrero et al. 2016; Hotta et al. 2016; Brun et al. 2017; Strugarek et al. 2018). Small scale simulations of magnetoconvection with realistic radiative transfer appear strikingly similar to solar surface convection and sunspots (Stein & Nordlund 1998; Rempel et al. 2009; Stein & Nordlund 2012; Rempel 2014). These simulations have also shaped the manner in which some observers interact with simulations, and the raw data of Rempel (2014)'s simulations have been treated extensively as high-resolution observations of solar convection (see e.g., Van Kooten & Cranmer 2017; Shchukina & Trujillo Bueno 2019, and others). Unfortunately, simulations fail to reproduce some important aspects of solar convection (Hanasoge et al. 2015), and realistic simulations should partner with simplified models where these discrepancies can be explored and understood. Simple models can be used to carefully explore the importance of effects like rotation and magnetism in a comprehensible setting. By taking advantage of knowledge gained through simple simulations, we can produce better "realistic" simulations which more accurately reflect aspects of true solar convection. Built upon this more careful understanding of fundamental stellar convection, these realistic simulations can produce valuable synthetic observables for asteroseismologists, helioseismologists, and scientists who will soon use the NSF's Daniel K. Inouye Solar Telescope (DKIST) to study the solar surface at high resolution.

2. Intellectual Merit

Rotating magnetoconvection across all scales Over the course of my postdoctoral studies, I will take advantage of the flexibility of the Dedalus pseudospectral framework (Burns et al. 2019), which I have become proficient at using during my graduate career, to study numerical simulations at three different scales. In task A, I will study simulations of discrete events, or thermals (as in Anders et al. 2019a), which model individual stellar convective downflows and can achieve high levels of turbulence. In task B, I will study simulations of mesoscale convection (as in Anders & Brown 2017) to gain an understanding of how these effects behave in the presence of the convective-radiative interface at the base of a solar-like convective zone. In task C, I will study simulations of global stellar convection (as in Lecoanet et al. 2018), developing and using new community tools to study the importance of rotation and magnetism over Kelvin-Helmholtz timescales. Each task is expected to take one full year of my three-year postdoctoral fellowship.

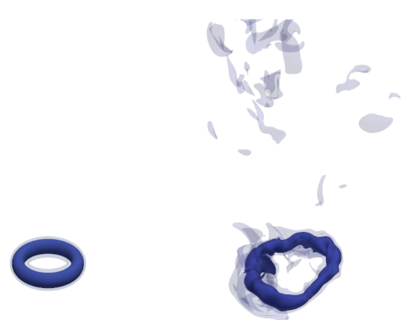

Fig. 1.— 3D visualizations of the entropy perturbation of evolved thermals in the laminar (left) and turbulent (right) regimes.

Task A: Dynamics of individual downflows In the envelopes of lower main sequence stars, convection occurs in the presence of extreme stratification. Stratified convection is characterized by powerful, localized downflows, and broad, slow upflows. Recent theory and observations (e.g., Hanasoge et al. 2015; Brandenburg 2016; Käpylä et al. 2017; Anders et al. 2019a) suggest that downflows may be the predominant mechanism for transporting stellar luminosity in these convective zones. Furthermore, Tobias et al. (1998) showed that downflows in convection can effectively pump magnetic fields downwards in certain regimes. These results suggest that downflows in stratified convection deserve careful study.

Downflows may turbulently break up into distinct pieces as they fall and these pieces can be modeled as thermals. Thermals are regions of cold fluid which accelerate due to buoyancy forces and shape themselves into vortex rings; evolved thermals are visualized in Fig. 1. Thermals are observed and studied in the Earth's atmosphere and are well understood in the Boussinesq limit.

Thermals provide an excellent model of stellar downflows because they are relatively easy to model analytically and to simulate. Hydrodynamic thermals in stratified domains have a solution which is essentially fully specified by: (a) the stratification of the background atmosphere and (b) whether they are laminar or turbulent. Thanks to my work in Anders et al. (2019a), the influence of stratification on thermals is now understood. During my postdoctoral studies, I will study thermals in a fixed high-stratification regime and gain a theoretical and experimental understanding of the effects of magnetism and rotation on thermal evolution. In a purely hydrodynamical context, Lecoanet & Jeevanjee (2018) showed that turbulence does not appreciably change the evolution of thermals. However, turbulence creates smaller scale structures in the propagating thermals which may be important in the context of rotation or magnetism. Over the course of Task A, I will try to answer two fundamental questions about stellar downflows:

1. Can stellar downflows transit the full depth of their convective envelopes, or do rotational or magnetic processes inhibit their propagation?
2. How much energy do downflows transport, and in which regimes do rotational and magnetic effects change their energy fluxes?

Task A.1: Rotational filtering of downflows In order to study the effects of rotation, I will study thermals in simple Cartesian domains. These plane-parallel atmospheres exist at a fixed latitude and experiencing Coriolis forces from a global rotation rate. I propose to study downflows at the equator, poles, and mid-latitudes. At each of these latitudes, I will study flows which experience varying degrees of rotational constraint. I will initially study laminar thermals to understand parameter space, but will later examine select turbulent simulations in all regimes which exhibit distinctly different behavior. The primary goal of these studies will be to determine at which latitudes, and at which degrees of rotational constraint Coriolis forces prevent thermals from transiting the convection zone. Understanding these questions will help constrain the effect of stellar rotation on how much energy downflows can transport.

Task A.2: Magnetic filtering of downflows I will secondarily study thermals in the presence of magnetism but absence of rotation. The inclusion of magnetism requires a choice of initial magnetic field setup, and I will study both cases in which there is a uniform background field and where there is a thin horizontal sheet of magnetism for the thermal to pass through (as in Tobias et al. 1998). I will vary the orientation of the initial magnetic fields and the strength of magnetic forces on the flows, in a manner analagous to the rotational simulations in Task A.1. This work will be the magnetic complement to Task A.1, further constraining regimes in which downflows can effectively propagate through a stellar convection zone to transport the stellar luminosity.

Task B: Mesoscale interactions at the radiative-convective boundary In solar-like stars, the strongly stratified convective zone overlies a stable interior radiative zone. In the Sun, the radiative-convective boundary (RCB) is characterized by a transition from moderate instability to strong stability. Now that downflows are considered a crucial element of stellar convection, it is crucial to understand how these downflows interact with the RCB.

Helioseismic measurements suggest that the RCB is thin – roughly 5% of a pressure scale height at the base of the convection zone, or 1% of a solar radius (Basu 1997). However, dynamics in simulations rarely achieve such a thin RCB, often times producing RCB thicknesses which are too thick or too thin by up to an order of magnitude (see e.g., Hotta 2017; Käpylä 2018). This suggests that simulations of stellar convection are in the wrong stiffness regime (Brummell et al. 2002; Couston et al. 2017). Furthermore, magnetism can appreciably alter deep velocity magnitudes, which can in turn affect RCB thicknesses (Hotta et al. 2015). It is widely thought that dynamics in the RCB are a critical ingredient in generating the solar dynamo and magnetic

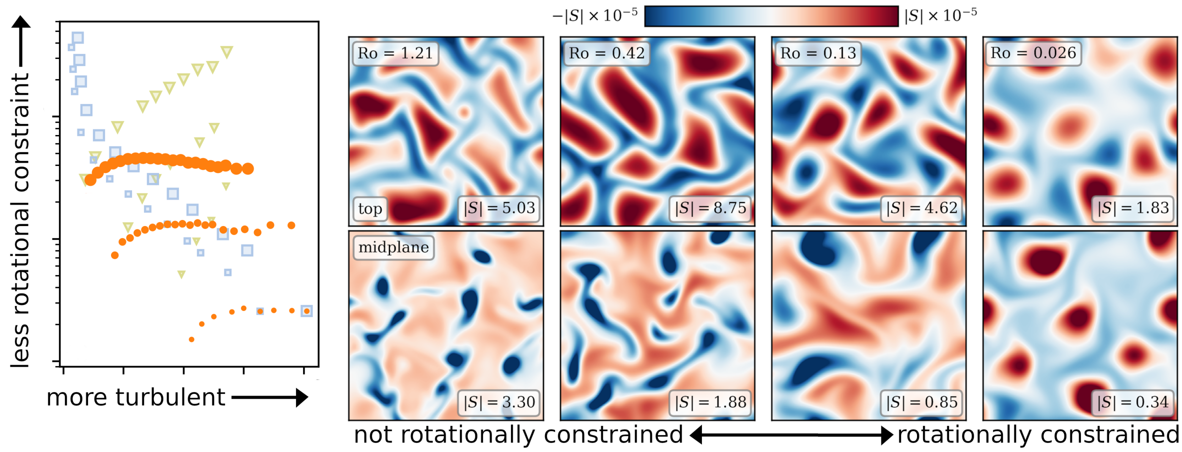

Fig. 2.— (left, Fig 1b of Anders et al. (2019b)) The degree of rotational constraint is difficult to predict as a function of turbulence in convective simulations. Along traditional paths through parameter space (green triangles and blue squares), rotational constraint varies strongly as a function of turbulence. However, when our newly discovered "predictive Rossby number" is held constant (orange circles), the degree of rotational constraint can be held constant while turbulence is increased. (right eight panels, Fig. 2 of Anders et al. (2019b)) As rotational constraint increases (from left to right), traditional granular convective patterns give way to quasi-two-dimensional vortical columns of convection with very little difference between the top of the atmosphere and the atmospheric midplane (top row vs. bottom row). Rotational constraint modifies convective dynamics, so simulating in the proper rotational regime that reflects the Sun or another star being studied is crucial.

field, and so understanding the effects of a too-thick or too-thin RCB is crucial. I propose studying how the stiffness of the RCB, which determines how hard of a "wall" convective motions hit at that interface, affects the transport of angular momentum and magnetic fields into the radiative zone by downflows. I will only conduct these simulations in flow regimes where downflows can feasibly transit the solar convection zone, as determined by Task A. In those regimes, the goal of this task is to determine how angular momentum and magnetism are pumped into the RCB as a function of RCB stiffness.

Task B.1: The critical magnetic field Convection in the presence of a strong magnetic field will have dynamics which are strongly affected by that field. Similarly, a weak magnetic field will not noticeably affect convective motions. There is therefore a critical field strength at which convection passes from being weakly to strongly affected by magnetism. Observationally, one would expect stars with more vigorous convection to have a higher critical field strength, and hotter stars will likely have more vigorous convection and higher critical field strengths. Unfortunately, the mapping of this intuition to simulations is not straightforward, and it is difficult to predict simulation flow regimes *a priori*. The goal of this task is to determine the critical field strength.

In rotating convection, an analagous argument can be made, where convection in the presence of rapid rotation is strongly affected by Coriolis forces, and this is not true in the presence of slow rotation. During my graduate career, I identified the critical angular velocity in convective simulations, analagous to the critical magnetic field I am searching for here (Anders et al. 2019b, and Fig. 2). Using similar methods to this work, I will determine the critical magnetic field strength in these mesoscale simulations. Understanding the critical magnetic field and angular velocity will enable the stellar modeling community to more accurately study convection with proper force balances.

Task B.2: Downflow interactions at the RCB In this task, I will study how downflows pump angular momentum and magnetism into or across the RCB. I will study both very stiff RCBs, which act similar to hard wall boundaries, and very soft RCBs which convective motions can easily pass through. Using this knowledge gained in task B.1, I will study simulations of convection in the magnetic and rotational regimes where task A revealed that downflows could transit the full convection zone.

Tobias et al. (1998) showed that convective motions can effectively pump magnetic fields across soft RCBs in certain parameter regimes. Here I will extend that work to determine if magnetic fields and angular momentum are capable of being pumped into stiff RCBs by convective motions. It is widely believed that shearing motions in the solar RCB are a critical piece of the solar dynamo, but observations (Basu 1997) suggest that the solar RCB is stiff. If convective motions are not able to pump magnetic fields into a stiff RCB, then a different mechanism must be responsible for generating new magnetic fields. Furthermore, a stiff RCB could potentially insulate the solar radiative interior from convectively-driven angular momentum transport, which could help explain why the solar differential rotation profile gives way to a uniformly rotating interior beneath the RCB.

Task C: Global studies in relaxed atmospheres The capstone project of my postdoctoral studies will study convection at the largest scales: global spherical simulations of rotating magnetoconvection. The tools to perform these simulations in Dedalus already exist (Lecoanet et al. 2018) and have been tested; a visualization of basic outputs from these simulations is shown in Fig. 3. One major barrier to performing turbulent global simulations is that they are costly, and some of these costs are unavoidable: highly resolved, turbulent simulations necessarily take small timesteps, and therefore simulation times are very long. However, some of the expense of these simulations is often time wasted waiting for the atmospheric structure and mean flows to converge to an equilibrium state. For example, the thermal structure of the Sun is thought to evolve over its Kelvin-Helmholtz timescale of 10^7 years, which is significantly longer than its convective overturn time of five minutes at the solar surface, although still much shorter than its main sequence lifetime (Anders et al. 2018). As simulations approach the turbulent regime of stars, relaxation and dynamical timescales become extremely disparate, and in general numericists must choose between having state-of-the-art turbulence or converged, statistically equilibrium dynamics – but not both. During this third task, I will de-

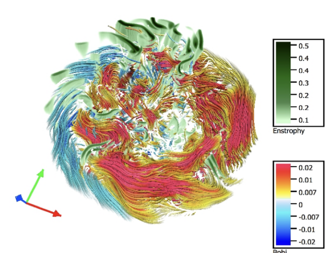

Fig. 3.— A volume rendering of a global dynamo simulation in Dedalus. Enstrophy, or the magnitude of vorticity, is shown in green. Red and blue lines denote the magnitude and direction of azimuthal magnetic field.

velop, test, and utilize a community tool which effectively establishes mean flows and evolves atmospheric structures by taking much larger timesteps than those of convection. By doing so, I will enable global dynamo simulations which are both in thermal equilibrium and exhibiting state-of-the-art turbulence.

During my graduate career, I studied a mechanism for accelerating the long thermal relaxation timescale in convective systems (Anders et al. 2018). In this work, we discovered that a tool like the one I am proposing here can be feasibly implemented and tested for accuracy. While studying turbulent flows, we found that our tool reached a relaxed state using an order of magnitude fewer computational resources than when waiting for a standard thermal relaxation timescale. These speedups make achieving thermal relaxation in state-of-the-art simulations feasible.

Task C.1: Accelerated evolution of global simulations During my postdoctoral studies, I will extend my accelerated evolution method to the evolution of thermodynamic and angular momentum profiles in global simulations. The development of this extension will be grounded in understandings gained in tasks A and B. In particular, task A will inform which terms in the equations importantly adjust the mean field in certain regimes, and task B will inform how to implement this technique near RCB-like interfaces. As I did in Anders et al. (2018), I will verify that this method produces the same results as a long relaxation in modest parameter regimes to build trust in the method. This module will be made public, and will be designed so as to flexibly interact with arbitrary simulation data so that users of codes beyond Dedalus can benefit from the computational speed-ups of this tool.

Task C.2: Relaxed simulations of the solar dynamo I will study simulations of the interior solar convection zone in regimes where flows feel the effects of both rotation and magnetism, using the knowledge from task B.1 to determine how to set up such simulations. Using the tool developed in task C.1, I will accelerate the evolution of these simulations. I am predominantly interested in the relaxed differential rotation profiles that appear as a function of rotational constraint, and how these differential rotation profiles affect the time evolution of the magnetic dynamo. In most modern dynamo simulations, the evolution of magnetic fields are measured during the relaxation process, and it is possible that the time-dependent dynamo behavior of the simulation is strongly influenced by the underlying evolution of the mean state.

While these simulations will be largely targeted in the solar context, the accelerated evolution tools which will be developed and tested here could have great benefits for asteroseismic research. Recently, Jørgensen & Weiss (2019) coupled 3D, global simulations with 1-dimensional stellar structure tools in order to more accurately produce stellar structure profiles to great success. The fast equilibration of angular momentum and thermal profiles described here is essentially equivalent to taking timesteps which superstep the convective motions, similar to those taken in any 1D stellar structure model. Put simply, these accelerated evolution techniques would be a first step to enabling a generalized coupling of 1-dimensional stellar structure codes with realistic statistics from converged global convection. Future asteroseismic inversions will then benefit from stellar structure models which are influenced by 3D convection including complicating effects like magnetism and rotation.

Computational Feasibility Tasks A-C are arranged logically from smallest to largest scales, and also from least to most computationally expensive. Based on the work in Anders & Brown (2017); Anders et al. (2018, 2019b,a), Dedalus takes $\mathcal{O}(10^3)$ cpu-sec per iteration for a run with a grid resolution of 384^3 on a system comparable to NASA Pleiades. Task A runs of thermals will take $\mathcal{O}(10^4)$ iterations each, while turbulent runs in tasks B and C will take $\mathcal{O}(10^6)$ iterations each. Laminar thermal simulations thus cost roughly 5000 cpu-hours each, while turbulent thermals cost roughly 10^5 cpu-hours each. State-of-the-art simulations in tasks B and C will cost roughly 10^6 cpu-hours each. The projects described here total 5-10 million cpu-hours per year in tasks B and C, with less (2-3 million cpu-hours) in the first year while thermals are being studied.

The computational cost of task A should be feasible to obtain on Northwestern's 11,800-core Quest supercomputer. In order to increase my access to computational resources and to allow for larger scale runs in tasks B and C, I will leverage my AAPF fellowship and apply for time on NSF XSEDE resources such as Stampede2, Comet, or Bridges.

Collaborative studies at CIERA Northwestern university, and specifically the Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), is the perfect location for me to carry out the work proposed here. Dr. Daniel Lecoanet, who will be my primary advisor and collaborator, is one of Dedalus' founders. His expertise using Dedalus and his past work on thermals (Lecoanet & Jeevanjee 2018; Tarshish et al. 2018), convection (Lecoanet & Quataert 2013; Lecoanet et al. 2014; Couston et al. 2017), rotating convection (Couston et al. 2019), and global simulations (Lecoanet et al. 2018) make him excellently qualified to advise me on the projects proposed here. Furthermore, I have already published a paper on thermals in close collaboration with Dr. Lecoanet (Anders et al. 2019a), so task A will serve as an excellent transition project into my postdoctoral studies on my arrival. In addition to Dr. Lecoanet, Dr. Yoram Lithwick would be an excellent partner for collaboration due to his past work on rotating convection (Barker et al. 2014) and his continuing collaborations studying careful and numerical problems in fluid disks (Lee et al. 2019) and planetary systems (Hadden & Lithwick 2018). CIERA houses many experts in computational fluid dynamics beyond Drs. Lecoanet & Lithwick, such as Profs. Sasha Tchekhovskoy & Claude-Andre Faucher-Giguere. I look forward to joining the astrophysical fluid dynamics group at CIERA where I will have many opportunities to discuss and develop new numerical techniques, strategies, and applications across astrophysics.

Furthermore, in addition to the focused educational and outreach projects described below in section 3, CIERA will provide me with numerous small scale opportunities to participate in public outreach. CIERA's Astronomy on Tap program as well as its CIERA Astronomer Evenings provide bite-sized and accessible ways to interact with the public. Dearborn Observatory's observation tours are very similar to the public open houses I helped host at CU Boulder's Sommers-Bausch observatory. The state-of-the-art Adler planetarium also provides similar opportunities such as its *'Scopes in the City* program or its Space Visualization Lab astronomy conversations. This program aligns with NSF broader impact goals in a couple of ways. First, it improves STEM educator development at two levels: young career scientists (graduate students) and high school educators. Second, it widely increases public engagement with authentic science at the high school level through the wide deployment of these modules.

3. Broader Impacts

Improving physics education outcomes through partnerships between pedagogical and scientific experts High schools in the greater Chicago area are failing to properly educate children, particularly in the sciences. These schools perform poorly on standardized tests, with recent scores showing roughly only 40% of high schoolers being considered proficient on Illinois' Science Assessment. Furthermore, there are documented trends which show that low test scores are highly correlated with the degree of poverty of students in these schools. These trends are troubling, but affecting these outcomes from a university position, or from the outside, is difficult. While single-day university outings to schools are newsworthy, there is no evidence that such programs have lasting effects on educational outcomes. On the other hand, a "teach-the-teacher" method of improving educational outcomes at the high school level has been shown to have some success. However, the success of such programs requires the buy-in of those teachers, and therefore should offer them opportunities to engage and contribute meaningfully.

Many high school physics teachers are not necessarily experts on physics content, and could benefit from collaborative curriculum design with the consultation of experts (e.g., graduate students at CIERA). Modern research on physics education at the collegiate level suggests that professors who lecture without employing modern pedagogical techniques achieve reduced student learning outcomes. As a result, expert researchers, who are not pedagogical experts, would benefit from exposure to best pedagogical practices. I propose the creation of a workshop series during which graduate students and local high school teachers partner to collaboratively build pedagogically- and scientifically- sound teaching modules that can be used in high school classrooms across the Chicago area and the nation. These workshops will occur over the course of a ten-week time interval, will take 2-3 hours apiece, and will occur at a frequency of once or twice a week. On a personal scale, these workshops will expose young career scientists to some basic of teaching pedagogical research while also improving content knowledge of high school teachers. On a larger scale, this program will produce well-informed, bite-sized teaching modules which can be used widely in high schools, and will leverage connections and input from high school teachers to help ensure adoption of these modules in the classrooms.

Collaborative development Participation from educators will be crucial for the success of the program proposed here. I will partner with local teacher organizations such as Physics Northwest, the Illinoise State Physics Project (ISPP), and the Chicago Section of the American Association of Physics Teachers (CSAAPT). Physics Northwestern's monthly meetings, ISPP's quarterly meetings, and CSAAPT's biannual meetings will be excellent venues in which to advertise the program and build a professional network of interested educators in the Chicago area. Furthermore, CIERA's *Reach for the Stars* program, a GK-12 program, has partnered with many local area high schools over the past decade and will serve as an excellent in-house link to this audience. In addition to working with local high school educators through these avenues, I will reach out to experts in Northwestern University's School of Education and Social Policy to enlist their assistance in the development of my workshop series.

While building up these cross-disciplinary collaborations, I will work alongside Michelle Paulsen, CIERA's Director of Education, Outreach, and Communications Programs, to develop my workshop series. Michelle has experience as a high school physics teacher and has been the chair of a large suburban high school's science department. Furthermore, Michelle has been instrumental in the creation of CIERA's RCTP program, which develops the presentation skills of young career scientists and includes cross-disciplinary collaborations and a ten-week workshop series similar to the one I propose here. This workshop series will take place during the summer quarter, at a time when high school educators and graduate student schedules are not constrained by the school year.

Workshop outcomes The workshops will include lecture portions in which professional educators teach scientists about modern pedagogical techniques. These will be followed by collaborative small group work in which scientists and educators co-design their teaching modules. Over the course of the workshop series, individual groups will work incrementally to develop one robust and focused course module. The topic of this module will be specified before the start of the workshop series by the educator using a Next Generation Science Standards (NGSS) disciplinary core idea in physics which their students struggle to learn, and which they feel they could improve with input from an expert in the field. During the development of each course module, an NGSS scientific practice, such as planning and carrying out investigations, will also be chosen by the group to incorporate into the module so that students have opportunities to participate in scientific practices as well as learn scientific ideas.

The capstone of this workshop series for educators will be the production and use of these modules in their own classrooms. However, graduate student participants do not have classes of students to return to with this content. Fortunately, CIERA has a close connection with the Chicago Public Library system, and CIERA graduate students are already running data science clubs for interested area high school students. I will work with the library, CIERA, and these data science clubs to create a venue where graduate student graduates of this program can teach these modules to interested students.

While these modules will naturally be implemented in the classrooms of the teachers who participate in this workshop series, I will work to ensure further distribution of these modules. In my later years at CIERA, in addition to using connections with Physics Northwestern, ISPP, and CSAAPT to foster educator excitement in this program, I will use these avenues to advertise the specific modules that have been created. They will be made publically available on the American Association of Physics Teachers online ComPADRE system, which stores resources for physics and astronomy educators and is publically available. These modules will also be made available on CIERA's website, just as products from current programs like *Reach for the Stars* are.

Outcomes In short, this workshop series will partner CIERA's science experts (graduate students) with local pedagogical experts (high school teachers) to teach science experts pedagogical principles while also producing widely-used teaching modules. This series will have the specific aims of:

1. Exposing interested graduate students at CIERA to best practices in teaching pedagogy, and providing those students with a teaching experience.
2. Providing high school educators with a strong lesson plan for teaching their students a topic that they struggle with.

3. Connecting university scientists with teachers and teaching organizations in the greater Chicago area to create lasting partnerships between scientific and pedagogical experts.
4. Distributing bite-sized teaching modules appropriate to the high school level which simultaneously teach core ideas and scientific practices, as defined by Next Generation Science Standards (NGSS).

4. Personal career growth and development

During my graduate career I participated twice in the University of California Santa Cruz's Institute for Scientist and Engineering Educators Professional Development Program (UCSC ISEE PDP), an NSF-funded program during which early career scientists spend roughly 100 hours learning the basics of teaching pedagogy while developing and teaching an authentic STEM inquiry activity. I further spent three years as a graduate student administrator with the CU-STARs group (University of Colorado Science Technology and Astronomy RecruitS). CU-STARs is a combined "outreach" and "inreach" program with the dual aims of increasing STEM engagement for students at underserved, rural schools across Colorado while decreasing attrition of underrepresented groups in CU Boulder's Astrophysical and Planetary Sciences department. On top of these activities, I was a co-instructor of record for an introductory Python programming course two years ago, and my co-instructor and I completely redesigned the course curriculum before we taught the course. These experiences have greatly informed the design of the programs presented below, and have provided me with the tools to succeed at implementing these programs.

My graduate career and the experiences within it have given me confidence that I enjoy teaching as much as research, and so my eventual career goal is to become a professor at the university level. By developing the course proposed in section **??**, I will get to continue to hone my own course design and teaching skills while also providing many early career scientists an opportunity to interact with teaching in a substantial way. Through my outreach experience in CU STARs, I have an understanding of how to interact with high school programs and teachers, which will be necessary for the development of my course in section **??**. Furthermore, one of my many roles as a graduate student administrator in STARs was to mentor undergraduate students, and this experience has laid the groundwork for my desire to set up the mentoring program described in section **??**. I know that in addition to research duties, being a professor includes a great deal of teaching, departmental service, and collaboration with university institutions. These proposed programs will help me to continue to develop as a teacher, as a negoatiator, and as an active contributor to a healthy departmental culture.

5. Summary and Perspectives

Observations of pulsating stars are becoming plentiful, and asteroseismic processing of those observations requires models which depend upon simple studies of convection. However, observations of the Sun have revealed that our parameterizations of convection do not adequately describe this complex process in the stellar and solar context. Numerical simulations at all scales and all levels of complexity have been useful tools for building theory and understanding or reproducing observations. Modern simulations often focus on overly complex systems, and here I propose simulations at both small and large scales which sequentially build upon and inform one another.

The simulations proposed are necssary and timely. As continued observations pour into our databases from current and future missions, it is crucial that we do not allow the theoretical pieces of observational pipelines to be neglected. Current convective models cannot explain the Convective Conundrum and the combined effects of downflows, rotation, and magnetism is unclear and has not been well explored. Furthermore, at a time when simulations are increasingly being treated as obervations, the development of tools such as those in Task C which help ensure that convective models more accurately reflect the physics at work in stars is crucial.

The fundamental problems presented here are of broad scientific interest, but are specifically topics of NSF investigation, as evidenced by the NSF's support for the DKIST telescope which will soon come online. The collaborative studies centered at CIERA will address the following key questions:

- Is the Sun in a regime where entropy rain is its dominant convective process and in which rotation and magnetism do not prevent this mechanism from occuring?
- Is the stability of the RCB important in driving the solar dynamo and the Sun's latitudinal differential rotation profile?
- What rotational regime is the Sun in, and what can we learn about dynamo evolution in that regime?

As stated previously, the work designed as Task A will occupy my research time during my first year while I lay the groundwork for my mentorship program and course on teaching pedagogy. Task B will occupy my time during my second year, while I launch my mentorship program, teach my class for the first time, and work to improve both of these programs. I will cap off my time at CIERA with task C while I work to ensure that the programs and classes that I set up smoothly transition to new leadership when I leave so that future students can continue to benefit from these programs.