Towards a more complete understanding of solar convection

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1 Background & Motivation

The Sun exhibits active magnetism which cycles in magnitude every 11 years. This magnetism arises from an organized dynamo seated in the turbulent plasma motions of the solar convective zone, which occupies roughly the outer 30% of the Sun's radius. This activity manifests itself in the collection of phenomena generally referred to as solar activity, including magnetic storms and coronal mass ejections. Such activity propagates towards Earth, threatening disruption of power grids and aircraft operations as well as endangering astronauts and satellites. The motivation to understand the Sun's magnetism in our increasingly technological society is great. A critical step in protecting our society from the Sun's magnetism is to gain an understanding of the nature of the dynamo that generates the Sun's magnetic fields Nordlund et al. (2009); Charbonneau (2014).

To understand the dynamo that drives the Sun's magnetism, we must understand the convection which powers that dynamo. Numerical studies of convection in stratified domain have a rich history in the past decade. The early work of Graham (1975), Hurlburt et al. (1984), and others in simple, plane-parallel atmospheres provided rich insight into the nature of stratified convection and provided a basis in a field which now regularly creates both complex, 3D global models of convection (e.g., Brown et al. (2010) and Guerrero et al. (2016)) and smaller scale local area models with more complex physics (e.g., Stein & Nordlund (2012) and Rempel (2014)). From these efforts we have learned a great deal about the nature of convection, and have even created beautiful simulations which even *look* like the convection we see on the surface of the Sun.

Unfortunately, the great advances made in computational prowess within the solar physics community seem to have surpassed our fundamental knowledge in the field. There is currently a so-called "Solar Convective Conundrum" which has two components. Both components of this conundrum are present in the recent observations by Hanasoge et al. (2012) (Fig. 1a). First, they observed solar convective velocities two orders of magnitude smaller than theory predicts. Second, their observations showed that there was less power at large length scales than short length scales – exactly the opposite of what we expect. The two-part convective conundrum – the presence of low convective amplitudes and the lack of "giant cells" at large length scales – has baffled the community since it came to light.

More recent work by Greer et al. (2015) (Fig. 1b) argue that the convective velocity amplitude is perhaps not so low as previously reported, but there is still a distinct lack of giant cells imprinting on the near-surface flows in this work. Even simpler doppler measurements of the velocity fields at the solar surface which are not muddied by complex helioseismic inversions lack giant cells (e.g., Hathaway et al. (2015) & Fig. 1c). The motions of surface granules and the slightly deeper supergranules are clearly present, but no larger length scale is distinct.

The difficulty in the lack of giant cells is exemplified by the work of Lord et al. (2014), who showed that the length scale of convective motions is determined by the depth in the atmosphere at which they are driven. Unstable, convecting layers drive motions whose scale is proportionate to the local density scale height. Deep in the atmosphere, the density scale height is large, and so we expect the bottom of the convection zone to drive large, giant cells which imprint through to the surface. The lack of their presence shows either a lack of our fundamental understanding of convection or a

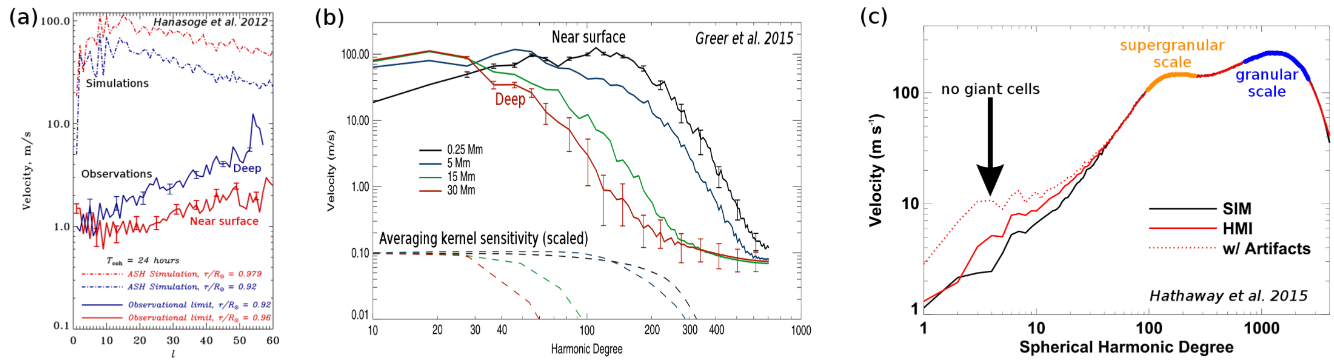

Figure 1: (a) Power spectra of solar convective velocities are shown for both observations and simulations, and both near the surface and deeper Hanasoge et al. (2012). Observations are obtained using time-distance helioseismology, and show velocities roughly two orders of magnitude lower than those predicted by simulations, and a decrease in power approaching larger length scales rather than the opposite. (b) Further observations of solar velocity power using ring-diagram helioseismology. Here, velocity magnitudes are roughly in line with those predicted by simulations, but show decreasing power as larger scales are approached, unlike what is expected from simulations Greer et al. (2015). A simple spectrum of horizontal velocities at the solar surface, obtained using line-of-sight Doppler velocities Hathaway et al. (2015). The length scales of surface granules and deeper supergranules appear as distinct features, but the hypothesized giant cells are not observed at low wavenumber.

systematic problem with our observational methods – and the former is more likely.

Our inability to observe giant cells hints at the possibility that giant cells are never driven in the first place, which would mean that the deep convection zone is not stably stratified. Some recent work (Brandenburg (2016), Käpylä et al. (2017)) has sought to understand the nature of convection – and explain the lack of giant cells – when nonlocal effects are included and observed. These efforts are, however, often extensions of already complex theory (Mixing Length Theory) or simulations which include a large amount of physics, but not a careful study of how those physics determine the solution.

Drawing on the knowledge and expertise of those in the physics community who study incompressible, unstratified Rayleigh-Bénard convection, I have recently examined hydrodynamic, compressible convection in simple stratified domains Anders & Brown (2017). I discovered that these somewhat complicated systems *transport heat largely in the same way as simple incompressible systems.* This was accomplished by setting up a simple experiment, understanding the different control parameters on the experiment and how they affected the convective states, and then setting up a controlled parameter space study.

Here I present two simple, small experiments which aim to understand the nature of convection in which giant cells are not driven. I will use methods similar to that in my recently published work to create simple, controlled experiments on comprehensible atmospheres in order to gain a deep understanding of the underlying convective physics.

2 Proposed Project

In simple simulations of convection, motions are often driven by enforced boundary conditions on the thermodynamic state. This creates boundary layers at the top and bottom of the atmosphere, and convection is strongly driven within those boundary layers. The situation in the Sun is less black-and-white. There is a positive radial gradient of opacity within the Sun, such that at radii near the solar surface, radiative flux is inefficient and convection is required to carry the solar luminosity outwards.

This divergence of radiative flux acts like an internal heating term which drives the convection weakly at the base of the solar convective zone and more strongly near the top of the solar convection zone. Further, the upper boundary layer of the Sun is not determined by the local thermal diffusivity (which is very small), but rather by the ionization and recombination of hydrogen.

We propose two simple experiments to test these two aspects of solar convective driving. In the first, we will study the nature of Kramers' opacity, which decreases with depth, and the internally heated convection which this drives. In the second, we will carefully study the effects of hydrogen ionization on convection in order to determine the nature of convection when new physics determines a different length scale for the driving region than the natural physics of the thermal boundary layer.

2.1 Mini Project 1: Kramers' Opacity

Many careful studies of convection employ a constant opacity and thus, a constant conductivity. The transport of heat within the atmosphere, in addition to convective transport, is often quantified through Fourier's law of conduction (Lecoanet et al., 2014), in which the radiative (conductive) flux is proportional to the conductivity and the temperature gradient. A constant opacity in time and space allows for the creation of simple measurements of the heat transport in the evolved atmosphere compared to the initial atmosphere.

While a constant conductivity is the go-to choice for many in the physics community who study incompressible Rayleigh-Bénard convection, it is often not the choice for those in the heliophysics or astrophysics communities. Instead, these communities generally employ a Kramers' opacity, in which the opacity is proportional to T^3/ρ, where T is temperature and ρ is density. This means that the conductivity is proportional to ρ/T^3, which changes significantly throughout the depth of the solar convection zone. Unfortunately, there have never been systematic, careful studies of the effects of Kramers' opacity on stratified convection.

What experimental knob determines the Mach number? At what value of the Rayleigh number does convection turn on (and thus, at what *supercriticality* are other studies being run)? What is the appropriate reference state which is in hydrostatic and thermal equilibrium? What are the parameters of that reference state that determine key quantities of the evolved convection, and what can we learn about the evolved convection from them?

After determining what the appropriate reference state is for a simple convective experiment where the Kramer's opacity is operating, and after determining how to systematically compare similar atmospheres at low and high Mach number, we will study the importance of nonlinearities in this opacity term on the resultant convection. In downflows (where density is high and temperature is low), we expect the opacity to be small compared to downflows, and the opposite to be true for upflows. If this is the case, then the "entropy rain" formulation presented in Brandenburg (2016) may be an appropriate adjustment to the Mixing Length theory of convection. However, at low Mach number, where variations in T and ρ are small in upflows compared to downflows, we anticipate that this effect will be unimportant. Near the solar surface, the Mach number is nearly 1, and this is likely significant. However, deep in the convective zone, the Mach number is very small ($\mathrm{O}(10^{-5})$), and so this effect is likely quite unimportant.

We want to quantify *how important* the nonlinearities in the opacity are for nonlocal transport, and also what effects these might have on the resultant stratification (and thus convective driving) of the solar convection zone.

2.2 Mini Project 2: Hydrogen recombination

Most studies of convection are driven either by the choice of fixed boundary conditions (hot at bottom, cold at top) or through the volumetric depoisition of energy throughout the domain (internal heating). Here we propose a project in which we utilize a nonlinear equation of state to represent the ionization / reionization of hydrogen near the surface of the Sun. We examine the effects that this has on the driving boundary layer region near the top of the simulation, and we do blahblahblah.

In order to carefully study the effects of the ionization of hydrogen, or other similar phase changes, we must first understand the reference state for such an atmosphere. It will no longer simply be polytropic, as the nonlinear EOS rules out the simple polytropic assumption. Once the appropriate state which is in hydrostatic and thermal equilibrium despite this phase change is discovered, we will then carefully study the effects of the temperature of ionization (which will in turn determine its depth), and also the ionization energy of the transition. In standard simulations of convection, the interactions of the flows with a hard boundary forms a thin boundary layer, which scales downwards as the diffusivities shrink, and this boundary generally drives convection. We suspect that we can create atmospheres with larger or smaller boundary layers than the natural thermal boundary length scale, which will nominally drive convection on different length scales than the natural one. We are interested in seeing how these "too large" convective flows interact with their surroundings, and in seeing how the atmosphere naturally evolves in the presence of these flows.

We are particularly interested in determining the effects of *where* in the atmosphere the transition from ionized to neutral Hydrogen occurs, and also *how much energy* is involved in the ionization process. These are two simple controls which can be examined in full detail through a suite of simulations. We hypothesize that, for sufficiently energetic ionization processes (such as that of neutral hydrogen), a natural boundary layer will form between an overlying stable layer and underlying convecting region in the atmosphere. We are further interested in determining how the ionization energy determines the length scale of the boundary layer.

Using these two control knobs, we are very interested in determining the startification of the evolved solution. This will tell us how large of a region is driving convection (is it a small layer near the reionization, or does it extend to a great depth below that? We are also very interested in the filling factor of convection compared to simple boundary-driven convection.

3 Numerical Tools and Feasibility

I will use the open-source Dedalus[1] pseudospectral framework Burns et al. (2016) to carry out my simulations. Dedalus is a flexible solver of general partial differential equations, making it extremely easy to study diverse sets of equations under many different atmospheric constraints. I have already published one paper using this tool Anders & Brown (2017), have submitted another paper, and am now adept at using it to create suites of simulations in short timeframes.

I will primarily study 2D convective solutions in plane-parallel atmospheres in order to gain intuition about the mean behavior of vertical profiles within the atmosphere. Once I have a grasp on how my measurements vary in 2D across parameter space, I will run select 3D simulations to verify whether or not that behavior holds in 3D, as I did in my previous paper Anders & Brown (2017). In cases where 2D and 3D diverge, I will quantify how and why they do so, but most questions I am asking are quite basic, and most of the systems I propose to study here have not been studied in the compressible context, at least not recently. By primarily studying in 2D, and by carefully selecting my 3D runs once I know which parameters I must examine more carefully, I can complete a full suite

[1] http://dedalus-project.org/

of simulations, such as those in my previous paper Anders & Brown (2017), using roughly 3 million CPU-hours. Through my advisor, I have access to an allocation on NASA Pleiades of roughly 20 million CPU-hours/year, so one- or two- of the following projects of the scope I am proposing can be completed each year.

Furthermore, my recent work (Anders, Brown, & Oishi 2018, submitted to PRFluids) has shown that properly constructed boundary value problems, coupled with initial value problems, can fast-forward the slow thermal evolution of these convective simulations. This work was done in Boussinesq, Rayleigh-Bénard convection but can be easily extended to stratified convection, and will greatly extend both the number of simulations we are able to complete and the level of turbulent driving (while attaining converged atmospheres) that we are able to solve.

3.1 Timeline of proposed work

Year 1 (Fall 2018 - Summer 2019):

- Finalize work on Internally Heated convection, which will be started Spring-Summer 2018. Submit a short paper summarizing the methods and results of this work to the Astrophysical Journal by mid-Fall 2018. Release code upon submission such that the community can use it.
- Delve into literature on past work regarding ionizing convection and moist convection. Understand the pieces of physics necessary to correctly implement a nonlinear equation of state. Begin to develop Dedalus simulations of ionizing convection by end of 2018.
- Fully Develop ionizing convection code. Determine the range of parameter space to be studied and execute the simulations within this range. Analyze data, and have a short paper written and submitted on them to the Astrophysical Journal by the end of summer 2019.

Year 2 (Fall 2019 - Spring 2020):

- Begin literature review on Kramer's opacity late summer 2019-early fall 2020. Understand past work done, and implementing both time-dependent (fully nonlinear) and time-independent versions of the Kramer's opacity in simple atmospheres. Run a suite of simulations at high- and low- Mach number by end of year 2019.
- Analyze data from Kramer's opacity results and prepare a small paper to submit to the Astrophysical Journal Letters by end of Winter 2020.
- Combine work from five published papers into a thesis, to be defended at the end of Spring 2020.

4 Relevance to NASA

The proposed work fits with NASA's 2014 Strategic Plan objective 1.4: "Understand the Sun and its interactions with Earth and the solar system, including space weather." Specifically, I aim to help answer the fundamental question, "What causes the Sun to vary?" This work also aims to answer one of the three overarching science goals in chapter 4.1 of NASA's 2014 Science Plan: "Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond earth." In order to understand how to predict space weather appropriately, we need to understand the processes that cause this weather. It is clear from recent work that our understanding of the fundamentals of convection is not as perfect as we once thought, and now is an exciting time to clarify our theory and determine which parts of it fail and which parts hold true under more examination. Only once we understand the fundamental nature of stratified, compresible convection can we begin to understand how it drives the dynamo in the Sun in the presence of many complications such as differential rotation, shear layers near the base and top of the convection zone, and magnetism.

The work has been motivated by data from the Helioseismic and Magnetic Imager (HMI) onboard the NASA Solar Dynamics Observtory (SDO) spacecraft Hanasoge et al. (2012); Greer et al. (2015); Hathaway et al. (2015), and will continue to be informed by new helioiseismic measurements made from SDO data, and from the new measurements which will be made possible by the upcoming joint NASA-ESA Solar Orbiter's Polarimetric and Helioseismic Imager (PHI).

5 Summary

Recent observations call into question our fundamental understanding of stratified convection in systems such as the solar convection zone Hanasoge et al. (2012); Greer et al. (2015). Here we present three focused, scoped studies of stratified convection which probe the specific effects of individual elements of convection in the Sun. Convection must carry flux in the Sun's convective envelope, because the radiative flux becomes too small and deposits energy there, acting essentially like internal heating. Convection is driven at the surface of the Sun due to the ionization and recombination of hydrogen near the solar photosphere. The magnitude of the flux that must be carried by convection varies greatly throughout the depth of the convection zone due to the increase of opacity with height.

We propose to probe the first of these elements by studying simple internal heating systems, the second of these elements by studying convection with a nonlinear equation of state / phase change, and the third of these elements by studying convection with a realistic opacity profile in the context of our knowledge from the first two experiments. Due to the developed nature of our computational tool, Dedalus, the simulations for these projects can be implemented and carried out on short timescales, and the body of work suggested here should be finished within two years, by the end of the spring of 2019.

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