

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 (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 muddled 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

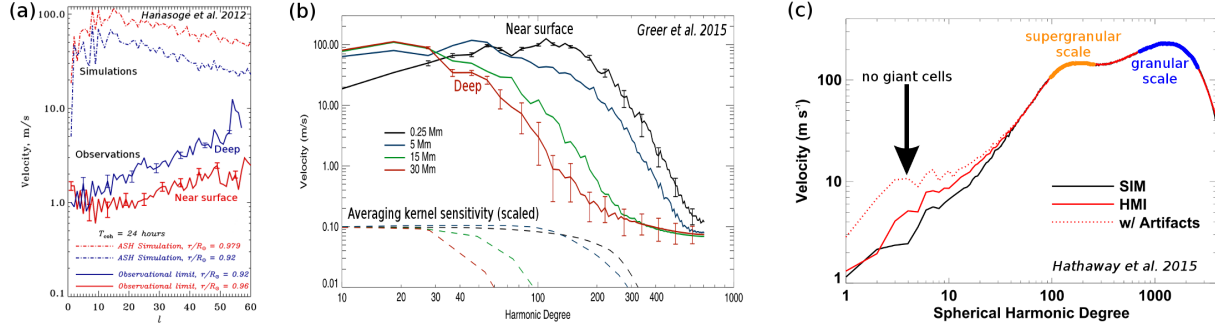


Figure 1: (a) Power spectra of solar convective velocities are shown for both observations and simulations, and both near the surface and deeper [Hanasoge et al. \(2012\)](#). Observations are obtained using time-distance helioseismology, and show velocities roughly two orders of magnitude lower than 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.

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 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 con-

vection 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.

This work will be informed by current work which we are performing, in which we are studying simple internally heated convection – similar to work which is done in boussinesq convection (e.g., [Goluskin & Spiegel \(2012\)](#)) – in stratified compressible domains. We are discovering how internally heated convection creates stable and unstable layers, and the nature of the evolved stratification compared to the initial stratification set up by the internal heating.

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 ($O(10^{-5})$), 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

Convection is strongly driven at the solar surface by the ionization and recombination of hydrogen. This piece of physics is absent from many studies of solar convection. Instead, surface convection is often driven by either an imposed entropy draining layer at the upper boundary, or the natural thermal boundary layer that forms near the upper surface and conducts the necessary energy across the upper boundary. These methods have a considerable problem in that the size of low entropy convective elements which form at the surface are determined either by the pre-imposed size of the entropy draining region or the natural size of the thermal boundary layer (which depends on the opacity).

The scale of convective driving near the photosphere of the Sun is *much* larger than the natural thermal diffusive length scale. It is determined by the depth of hydrogen ionization, and this large thermal boundary layer and the large convective elements it creates likely plays an important role on the convective dynamics. We aim to study the difference in the nature of convection – especially in the surface power spectrum – when hydrogen recombination is the driver of convection near the upper boundary, rather than the other more common methods.

We will implement the basic nature of hydrogen ionization and recombination through the use of a nonlinear equation of state rather than just the standard ideal gas equation of state which is often used in convective studies. By adjusting the power of this recombination (how much energy is released or absorbed), and also the depth of this recombination, we can study the effects of this form of driving on the convection.

This work will be guided by previous studies of ionizing convection (e.g., refs and refs) and also work on moist convection, in which simple convection with a nonlinear equation of

state and cloud formation can be studied (e.g., ref).

3 Numerical Tools and Feasibility

I will use the open-source Dedalus¹ 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), will soon submit 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 the systems I propose to study here have not been studied carefully 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 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 easily completed each year.

Furthermore, forthcoming work (Anders, Brown, & Oishi 2018, to be submitted to PRFluids in February) has shown that properly constructed boundary 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 that we are able to resolve, allowing us to study simulations more like the Sun.

4 Timeline of proposed work

Year 1 (Fall 2018 - Summer 2019):

- Conduct literature review on convection with Kramers' opacity early fall 2018. Understand past work done, and implement fully compressible equations with Kramers' opacity in simple atmospheres. Understand how to control the Mach number in these atmospheres by end of year 2018.
- Run simulations, analyze data, and submit a short paper to The Astrophysical Journal on the nature of convection with Kramers' opacity at both low and high Mach number by end of spring 2018.

¹<http://dedalus-project.org/>

- Conduct literature review on past work done on ionizing convection and moist convection. Construct appropriate atmospheres for studying ionizing convection, and learn what aspects of these atmospheres control different aspects of the evolved solutions.

Year 2 (Fall 2019 - Spring 2020):

- Run simulations of ionizing convection, analyze data, and submit a short paper to The Astrophysical Journal by the end of year 2019.
- Combine work from five published (or submitted) papers into a thesis, to be defended at the end of Spring 2020.

5 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, compressible 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 Observatory (SDO) spacecraft ([Hanasoge et al., 2012](#); [Greer et al., 2015](#); [Hathaway et al., 2015](#)), and will continue to be informed by new helioseismic 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).

6 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](#)). We propose two focused, scoped studies of the mechanisms which drive the Sun’s convection at the base and top of the solar convection zone. These studies will carefully probe the specific physics of these mechanisms and compare the nature of convection *with* these elements to simpler studies *without* them. 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 2020.

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