Towards a more complete understanding of solar convection

Evan H. Anders

Advisor: Benjamin P. Brown
Laboratory for Atmospheric and Space Physics (LASP) & University of Colorado at Boulder

1 Background & Motivation

The Sun exhibits a 22-year active magnetic cycle. An organized dynamo seated in the turbulent plasma motions of the solar convective zone drives this magnetism. Solar magnetism manifests itself in the collection of phenomena generally referred to as solar activity, including magnetic storms and coronal mass ejections. Energetic particles ejected by this activity propagate towards Earth, threatening to disrupt power grids and aircraft operations in addition to endangering astronauts and satellites. Understanding the nature of the dynamo that generates the Sun's magnetic fields is a critical step to protecting our society from the threats of solar activity (Charbonneau, 2014).

The solar dynamo is powered by convection, and an understanding of that convection is essential to understanding how solar magnetism is generated. The early work of Graham (1975), Hurlburt et al. (1984), and others who studied convection in plane-parallel atmospheres provided rich insight into the nature of solar-like stratified convection. From this basis, the field has blossomed into one which now regularly creates complex, 3D global models of convectively-driven dynamos (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)). These efforts have taught us a great deal about the nature of convection, and beautiful modern simulations even visually resemble the convection observed on the solar surface.

Unfortunately, the great advances made in computational prowess within the solar convection community have surpassed our fundamental knowledge in the field. This is clear in the "Solar Convective Conundrum," in which observations and theory starkly disagree. The helioseismic measurements of Hanasoge et al. (2012) and Greer et al. (2015) (Fig. 1a) showed an absence of power in the solar velocity spectrum at large length scales. Simulations hypothesized that large-scale "giant cells" should be driven by deep convective motions and visible throughout the solar convective zone, but we do not see these giant cells. Even simpler doppler measurements of the velocity fields at the solar surface, which are not muddied by complex helioseismic inversions, lack giant cells (Hathaway et al. 2015 & Fig. 1b). The motions of surface granules and the slightly deeper supergranules are clearly present, but no larger length scale is distinct. These combined observational inferences make clear that the lack of giant cells remains a conundrum and deserves further exploration.

The lack of giant cells is disturbing, as is exemplified by the work of Lord et al. (2014). They performed radiative magnetohydrodynamic simulations of the solar photosphere and convective zone using the MURaM code. These simulations showed that the length scale of convective motions is determined by the depth in the atmosphere at which they are driven. Deep convection drives larger scale motions due to the increasing nature of the local density

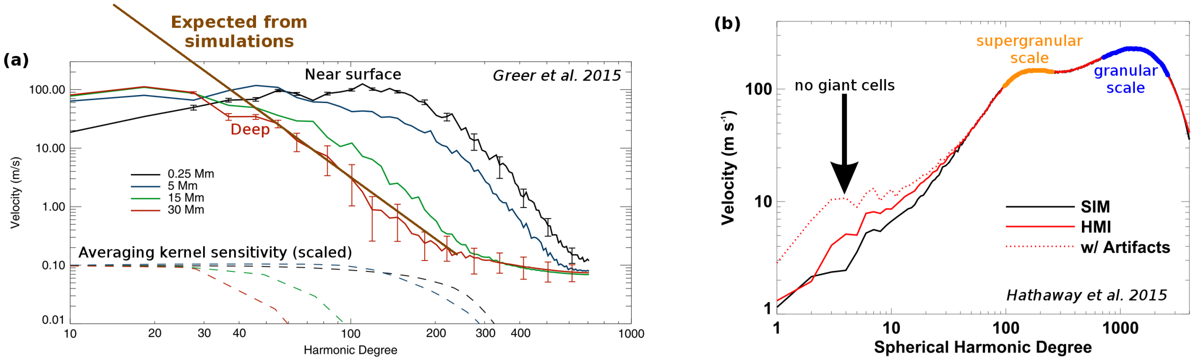

Figure 1: (a) Ring-diagram helioseismic observations of the solar velocity power spectrum at various depths. Here, velocity magnitudes are roughly in line with those predicted by simulations, but show decreasing power as larger scales are approached, unlike what is expected from simulations Greer et al. (2015). (b) 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.

scale height with depth. These deep motions which are driven at high density should imprint hugely on the surface motions. The lack of their presence in our observations implies that our models are missing a piece of physics. Either processes in the solar convection zone mask the deeper motions, or *they are never driven in the first place.*

In order to determine the fate of giant cells, there is a need to return to simple convective models to understand how the presence of convection modifies the underlying atmospheric stratification, and how this stratification in turn affects the observable convection at the surface of the atmosphere. Here I present two simple, small experiments which aim to elucidate fundamental aspects of solar convection, and to determine whether either of these mechanisms is the reason that we do not see giant cells at the solar surface. I will use methods similar to those I employed in my recently published work (Anders & Brown, 2017) to create simple, controlled experiments studying turbulent compressible convection in stratified atmospheres to gain a deep understanding of the underlying convective physics. Furthermore, the knowledge gained in forthcoming work (Anders, Brown, & Oishi 2018, submitted to PRFluids), in which we discovered a mechanism for self-consistently converging convective simulations on short timescales, will be used to make these projects manageable on human timescales.

2 Proposed Project

In simulations of convection, motions are often driven by enforced boundary conditions on the thermodynamic state. Boundary layers at the top and bottom of the atmosphere naturally arise, and convection is strongly driven within those boundary layers. Convective driving in the Sun is more complex. A positive radial gradient of opacity within the Sun decreases the efficiency with which radiation can carry the solar luminosity with increasing height in the convective zone. This results in a divergence of radiative flux which deposits energy in the convective layers, and this energy must in turn be carried by convective motions. In other words, the convection in the Sun is not driven by a sharp lower boundary but rather through naturally occuring internal heating. Further, the upper boundary layer of the solar convective zone does not arise because of a hard upper boundary, but rather because of radiative losses at the photosphere, paired with the ionization and recombination of hydrogen. These two effects – the internal driving of solar convection and the driving of convection at the solar surface by hydrogen ioniziation – have not been studied carefully in at least two decades.

Recent exciting work by Käpylä et al. (2017) exhibited convection zones in which deep layers of the convection zone are stable, a setup in which giant cells would not be driven. The authors attribute these deep, stable layers to their inclusion of Kramers' opacity effects which drives convection internally in a manner similar to that in the Sun. However, forthcoming work by my advisor and collaborators (Brown et al. 2018 in prep, Oishi et al. 2018 in prep) shows that stable lower-layers of convective zones naturally arise where convective zones overly stable regions and convective motions are at low Mach number. Further, first results from work that I am conducting on stratified, internally heated convection (modeled after simpler studes, e.g., Goluskin & Spiegel (2012)), show that these stable convecting layers arise naturally when internal heating is the mechanism which drives convection, even in the presence of a constant radiative conductivity throughout the depth of the atmosphere.

Since the process of internal heating – not the complex form of a Kramers' opacity – appears to be the fundamental cause of the stratification effects seen recently by Käpylä et al. (2017), the first project that I propose in year 1 is a careful study of the effects of Kramers' opacity on convection. The second project I propose in year 2 is a careful study of the effects of hydrogen ionization near the surface of the Sun, building on the previous work of e.g., Rast & Toomre (1993).

2.1 Project 1: Effect of Kramers' opacity on solar convection

Many careful studies of convection employ a constant radiative conductivity. The transport of heat within an optically thick atmosphere, in the absence of convective transport, is often quantified by Fourier's law of conduction (Lecoanet et al., 2014), in which the radiative flux is proportional to the conductivity and the temperature gradient. While a constant conductivity in time and space allows for the creation of simple measurements of the heat transport in the evolved atmosphere compared to the initial atmosphere, such an assumption about the conductivity is coupled with unrealistic assumptions regarding the functional form of the opacity.

While a constant radiative 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 radiative conductivity which is a function of the temperature, density, and the Kramers' opacity (Barekat & Brandenburg, 2014; Brandenburg, 2016; Käpylä et al., 2017). This results in a vastly varying conductivity throughout the depth of the atmosphere, which makes the interpretation of the solution much more difficult but which more carefully captures the physics of nature.

In order to study the importance of Kramers' opacity, a frame of reference must be constructed in which to study this varying opacity. For example, what atmospheric parameter determines the Mach number of evolved flows? At what value of the Rayleigh number does convection turn on (and thus, at what *supercriticality* are other studies being run)? What are the parameters of the initial state that determine key quantities of the evolved convection, and what can we learn about the evolved convection from them? Only by answering these simple questions can a careful study of Kramers' Opacity be carried out. Through answering these questions about basic polytropic systems, I was able to determine that regardless of Mach number, basic stratified compressible convection *transports heat in the same manner as unstratified, incompressible Rayleigh-Bénard convection* (Anders & Brown, 2017).

After determining how to carry out controlled experiments studying the role of Kramers' opacity, I will study the importance of the nonlinear nature of this opacity on convection. In downflows (where density is high and temperature is low), the radiative conductivity should be low compared to upflows. However, at low Mach number, where variations in T and ρ are small in upflows and downflows, we anticipate that this effect will be unimportant. In the Sun, the Mach number of convection ranges from nearly Mach 1 at the surface to very low Mach number deep in the interior, where Mach number is $O(10^{-5})$. Thus, it is important to understand how this complex form of opacity interacts with convection at both high and low Mach number in order to understand how it influences solar convection.

In summary, my goal in year 1 is to quantify the importance of nonlinearities in the opacity felt by solar convection. My motivation is to understand the importance of these nonlinearities on nonlocal convective transport and atmospheric stratification. If comparatively high opacity in the downflows enhances the importance of nonlocal transport at all Mach numbers, then the "entropy rain" addition to convective theory expanded by Brandenburg (2016) and explored by Käpylä et al. (2017) could be an essential element of solar convection, and this nonlocal transport could drastically change the stratification of deep convection where low-entropy fluid falls and then resides. If this effect consistently leads to marginal stability in the deep convection zone, this could be the right explanation for the lack of observed giant cells.

2.2 Project 2: Solar convection influenced by Hydrogen ionization and 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 (Käpylä et al., 2017), or the natural thermal boundary layer that forms near the upper surface (Anders & Brown, 2017). 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. The solar surface convective boundary layer, which is much larger than the local thermal diffusion length scale, is determined at least in part by the depth at which hydrogen ionizes and recombines. The large convective boundary near the solar surface drives relatively large convective elements, and the length scale of those elements likely plays an important role on the convective dynamics. If the size of these elements allows them to persist deep in the atmosphere, they could significantly alter the mean stratification deep in the convective zone. 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.

I will implement the basic nature of hydrogen ionization and recombination through the use of a nonlinear equation of state built around a single-atmoic level model of particles, similar to that used in Rast & Toomre (1993). This work in year 2 will further be guided by prior studies on moist convection (e.g., Leconte et al. (2017)), in which phase changes resulting in cloud formation are studied. We will study the effects of hydrogen ionization on atmospheric stratification in two ways. First, we will determine the effects of the *location* of the ionizing layer in order to determine if we can naturally make transitions from stable regions (above) to convecting regions (below) occur, as in the Sun. We will also determine the effects of the *extent* of the ionizing layer, to determine if this changes the average length scale of convective elements, and to determine if there is any correlation between the length scale of convective elements driven at the surface, the atmospheric stratification, and the average power spectrum of motions near the surface.

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 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. Our run scripts for using Dedalus to study stratified atmospheres are themselves publically available[2]. Blah Blah Blah Reproducibility Blah Blah.

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. 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 10 million CPU-hours. Through my advisor, I have access to an allocation on NASA Pleiades of roughly 20 million CPU-hours/year, so the proposed projects are feasible.

4 Timeline of proposed work

Year 1 (Fall 2018 - Summer 2019):

- *Project 1:* 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

[1] http://dedalus-project.org/
[2] https://bitbucket.org/exoweather/polytrope

in these atmospheres by end of year 2018. Run simulations, analyze data, and submit a 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.

- *Project 2:* 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):

- *Project 2:* Run simulations of ionizing convection, analyze data, and submit a paper to The Astrophysical Journal by the end of year 2019.
- *Academic progression:* 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?" by understanding the nature of stratified convection present at the solar photosphere. 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 fundamental understanding of solar convection is flawed, and now is an exciting time to clarify our theory and determine which parts of it fail under closer examination.

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. This work will additionally be informed by the new measurements which will be made possible by the upcoming joint NASA-ESA Solar Orbiter's Polarimetric and Helioseismic Imager (PHI), and will help explain conundrums arising from those observations.

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 proposed here will be finished within two years.

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