Towards a more complete understanding of Stratified, Compressible Convection

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Abstract

Blah blah blah. This project supports objective 1.4 of NASA's 2014 Strategic Plan and will assist in developing "the knowledge and capability to detect and predict extreme conditions in space" in accordance with NASA's overarching Heliophysics science goals.

1 Introduction

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 and Hurlburt et al. 1984 and others in simple domains 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, Guerrero et al. 2016, and many others) and smaller scale local area models with more complex physics (e.g., Stein & Nordlund 2012, 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. Recent observations by Hanasoge et al. 2012 (Fig. 1a) show that deep velocities in the solar convection zone are much lower than we would anticipate from our knowledge of simulations. While the more recent observations of Greer et al. 2015 (Fig. 1b) argue that the problem is perhaps not so bad as it appeared a few years before, observations do not line up with simulations. The standard picture of convection from simulations is that deeper motions are driven more intensely, and thus, through mass conservation, should imprint as the strongest motions at the solar surface. This is what is seen in simulations, and which was verified by the work of Lord et al. 2014. However, this is

Figure 1: (a) The big old problem that hanasoge showed, (b) horizontal power spectrum of the solar surface, (c) something? Superadiabaticity profile?

precisely not what we see at the solar surface. The horizontal velocity power spectrum at the solar surface shows excess of power in granular and supergranular scales, but the "giant cells" which are theorized to be driven at the base of the 14-density-scale-height-deep convection zone are not observed (Hathaway et al., 2015).

This paints a troubling picture. Years of simulation results – and the Mixing Length Theory of convection that they inform – seem to be wrong. One fundamental problem is that we, as a community, are so focused on ensuring that the physics in our simulations are as "correct" as we can make them that we ignore the fact that we do not understand the effects of each piece of physics on the nature of convection. When running large, 3D, complex simulations, computational cost often limits the number of simulations which can be run, and parameter space studies are often out of the question.

Drawing on the knowledge and expertise of those in the physics community who study incompressible, unstratified Rayleigh-Bénard convection, we have recently examined hydrodynamic, compressible convection in simple stratified domains Anders & Brown 2017. We discovered that these somewhat complicated systems *transport heat in the same way as incompressible systems*, and that the Mach number of convection can be easily specified *a priori*. By setting up a simple experiment, we were able to learn something concrete about the fundamental nature of convection.

Here we propose a trio of similar, small experiments. In each experiment, we test the effects of one new piece of physics in order to gain an understanding of how they influence the convective motions and in order to gain a frame of reference for how to understand these effects in simulations with more complicated, "more realistic" physics.

2 Numerical Tools

I will use Dedalus, because it's awesome and it allows us to study many flexible atmospheres under many equation sets easily.

I'll primarily use 2D simulations to get intuition about the answers I'm trying to solve, then verify them in 3D, as I did in my paper. The sims shown there took about 3M CPU hours to complete, and I have access to an allocation of 20M CPU hours / year on Pleiades, which means that I can complete a few projects of that scope within a year's time.

Furthermore, recent work (Anders, Brown, & Oishi 2018, submitted to PRFluids) has been done to use boundary value problems along with initial value problems to fast-forward the slow thermal evolution of these convective simulations. This work was done in Boussinesq convection but can be easily extended to stratified convection, and will greatly extend the number of simulations we will be capable of performing given our modest allocation.

3 Project 1: Internally heated convection

Our first experiment involves the study of atmospheres where a constant internal heating term is included in the energy equation. This is the simplest form of internal heating, and is similar to that which has been studied in Rayleigh-Bénard convection,

just with compressibility and stratification included (e.g., Goluskin & Spiegel 2012). We have found that these systems can be constructed so as to naturally include stable layers underlying unstable, convection regions. These systems are important to study, because the changing opacities in the interior of the solar convective zone effectively act like an internal heating term, depositing energy and driving convection.

We find that these systems essentially have the same input control parameters as simple polytropic convection (Anders & Brown, 2017), which include the Rayleigh number (Ra, the strength of convective driving and amount of turbulence), the Prandtl number (Pr, the ratio of the thermal to viscous diffusivity), the characteristic superadiabaticity of the atmosphere (which sets the Mach number of the flows), and the depth of the atmosphere. In the internally heated systems, we find that the magnitude of the internal heating directly relates to the superadiabaticity of the atmosphere, and thus Ma, but we must split up the depth into two parameters: the depth of the *unstable* region, and the depth of the new *stable* region. In Anders & Brown 2017, we explored the effects of the magnitude of the superadiabaticity on the resulting convection, and found that – except where the Mach number is very high – it has almost no effect on the other properties of the convective flows.

In this project, we will focus on understanding how the depth of the atmosphere, and the amount of stratification felt by the flows, affects the resultant convection. We will set the depth of the convection zone (to 1, 3, and then 5 density scale heights), and for each of these depths we will run simulations for shallow and deep radiative zones. We will examine the evolved stratification of these atmospheres in order to determine where convection is driven and where it is not. Preliminary results show that the so-called "Deardorff zones" present in the simulations of Käpylä et al. 2017 are also present in these simple simulations of internally heated convection and do not require complex forms of the conductivity to be achieved. We expect that the extent of these subadiabatic zones in which convection carries the flux can be determined *a priori* in these simple simulations, but further work must be done.

We're looking for the motions at the surface and also the stratification.

4 Project 2: Nonlinear EOS convection

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.

Figure 2: (a) word (b) word (c) word

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.

Things we can study: stratification of evolved solution. Stable layers? filling factors. Power spectrum.

5 Project 3: Realistic Opacities

While it is convenient to use a constant conductivity (and thus opacity) in the energy equation, as this makes the interpretation of results very simple, this greatly over-simplifies the form of radiative conductivity in natural systems like the Sun. In this project, we will carefully implement a kramer's opacity of the form $\kappa \propto T^3/\rho$. We will run experiments at low and high Mach number, some in which κ is constant with time and some in which κ is allowed to evolved with time. We anticipate that at low Mach number, the deviations from the initial state will be small, and the fully nonlinear effects of this term will not be important. At high Mach number, however, like the solar surface, we expect this term to vary significantly from the high temperature, low density upflows to the low temperature, high density downflows.

We are curious to see if this more realistic form of the conductivity significantly changes the transport properties of the overall convection: does it affect the heat transport (Nu)? How does the change in the adiabatic temperature gradient under this formulation change our intuition? We can likely naturally have heavily driven regions and lightly driven regions of naturally-occuring, internally heated convection. Our studies from project 1 will help inform how to interpret the divergence of this flux term as an internal heating source.

6 Timeline of proposed work

Year 1:

- (Fall '18) Finalize Internally Heated convection work, submit a paper to ApJL.
- (Spring-Summer '19) Run simulations of nonlinear EOS, write paper, submit to ApJ. Begin opacity project.

Year 2:

- (Fall '19 - Spring '20) Finalize opacity project, submit ApJ. Write and finalize thesis by end of Spring '20.

7 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." This work also fits in with one of the three overarching science goals of the Heliophysics section 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." Furthermore, simulated observables created by this work will be directly comparable to data retrieved by the currently operational Solar Dynamics Observatory and the future NASA-ESA Solar Orbiter mission.

8 Summary

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