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 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 (cite), but include a new parameter which determines the depth of the radiative zone below the convecting region. We will do runs from low to high Ra for various values of the depth of the radiative zone and the magnitude of the internal heating to determine the evolved stratification of these systems and the magnitude of velocity power at the surface of these simulations. We anticipate that we will see stuff like in Kapyla 2017.

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

3 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.

4 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 oversimplifies the form of radiative conductivity in natural systems like the Sun. In this project, we will carefully implement a kramer's opacity – both fully nonlinear and initial condition based – and we will do blahblahblah with it.

5 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.

6 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.

7 Summary

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