Progress report for: "Fundamental studies into the solar convective conundrum: Do giant cells exist?"

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1 Work accomplished Fall 2018 - Feb 2019:

My work in Fall 2018-Spring 2019 was instructed by both an unanticipated opportunity which arose over the summer of 2018 and an unusual development (which has led to another unanticipated opportunity) in the original research plan. I will describe both of these below, including how they are informing the work of spring and summer 2019.

1.1 Unanticipated opportunity: Predicting the Rossby number in rotating systems

During the summer of 2018, I helped mentor a post-baccalaureate researcher on a project studying rotating convection. This student left our research group for industry at the end of the summer, but the project she had been working on had progressed to a point where its results were promising and nearing publication significance. I took responsibility for this project in the late summer of 2018 and throughout fall 2019, and it has since been published in The Astrophysical Journal (**?**).

Recent work by **?** suggests that rotational effects could be one possible solution or explanation to the "Solar Convective Conundrum," the apparent absence of large-scale motions at the solar photosphere and the focus of my NESSF proposal. More specifically, they posit that flows in the deep solar convective interior could be very rotationally constrained, or at very low Rossby number. The Rossby number is an output parameter in convective simulations and hard to specify in the initial conditions, but in our recently published work, **?**, we demonstrated a manner of specifying the Rossby number of simulations *a priori*, and showed that this specification was fairly robust in the low-Rossby number limit, which is of potential interest for the solar interior.

This recently published work has lead to fruitful discussions with multiple scientists at CU Boulder, both who are experts in rotating convection (Drs. Keith Julien and Ian Grooms) and who are experts in solar convection (Dr. Nick Featherstone), and potential collaborations with them may come forth as a result of this paper. I will describe these collaborations more fully in section 2.2.

1.2 Unusual development: Specifying the Mach number with a Kramer's opacity

In addition to writing and publishing **?** during the fall of 2018, I worked on the proposed work in our originally accepted NESSF, as quoted here:

> "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 paper to The Astrophysical Journal on the nature of convection with Kramers' opacity at both low and high Mach number by end of spring 2019."

Unfortunately, we learned that while using realistic free-free Kramer's opacity scalings with temperature and density, it is difficult if not impossible to study low-Mach-number convection in a simple simulation. We expect very low Mach number flows in the deep solar interior where such a Kramer's opacity prescription is valid, but the true Sun has a complex photosphere and vast density stratification that also lead to these effects. We concluded that the originally proposed Kramer's-opacity-convection simulations required additional layers of complexity (e.g., artificial surface cooling) that would muddle our understanding of the fundamental physics we wanted to study (entrainment of warm fluid into cold downflows and the resultant restratification caused by this).

Rather than studying the complex Kramer's opacity convection as in **?**, we have pursued a more focused study of entrainment mechanisms in the solar convection zone. Recently, Dr. Daniel Lecoanet has performed an in-depth study of entrainment in Boussinesq thermals (**?**, in review). I have formed a collaboration with Dr. Lecoanet in order to extend his work to a case more applicable to the solar context and the original research questions of interest. Since late fall 2018, we have been studying the evolution and entrainment of cold thermals in stratified domains. This effort is partially motivated by the work of **?**, in which that author described the effects of "entropy rain" as one possible mechanism for resolving the solar convective conundrum. In **?**, the author studies propagating buoyantly-neutral propagating vortex rings as one possible dynamical manifestation of this rain.

The collaboration between myself and Dr. Lecoanet is an extension of his own Boussinesq work and the work of Brandenburg. Rather than studying neutrally-buoyant vortex rings, we are studying buoyant thermal perturbations which self-consistently evolve into propagating vortex rings in which we can carefully quantify the degree to which warm fluid is entrained into these structures and the manner in which the buoyant vortex rings interact with the strong density stratification of the solar convection zone. We aim to extend the simple linear theory of the Boussinesq case to the more-complex fully compressible, stratified case, and we also plan to study the differences in entrainment in the case of laminar flows (which are more typical of standard simulations) and turbulent flows (which are more typical of the true Sun). In the simple, single-thermal systems we are studying, we are capable of resolving much more turbulent flows than typical simulations of solar-like convection, and we can more adequately answer whether entrainment in these structures is a primarily laminar or turbulent process.

2 Future plans for 2019-2020 work and deviations from the original plan

Forthcoming work according to the original proposal is as follows:

Year 1 (Summer 2019):

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

Year 2 (Fall 2019 - Spring/Summer 2020):

- 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.

This general outline still holds true to my plans for the upcoming academic year: I will do research this summer and next fall, then graduate in the spring or early summer and hopefully move on to a postdoctoral position at a new university.

Currently, my plan is to work on the originally proposed research (modern, parameterized simulations of ionizing convection) in an effort to gain an understanding of the size of convective elements driven at the surface. However, due to the unexpected turns which arose over the past year, there are a few other projects that I may also investigate coincidentally with these ionizing simulations. I have no misconceptions that I will be able to study *all* of these projects over the next year, but it should be feasible to perhaps work on the initially proposed work as well as one of the following opportunities that has arisen in discussions with colleagues and collaborators over the past year.

2.1 Possible mini-project 1: Kramer's opacity thermals

In the study of thermals that I am currently conducting to learn about entrainment in the solar convective envelope (see section 1.2), I am using a simple, constant-thermal-conductivity specification in order to study the simple underlying physics. Adding in a nonlinear, Kramer's-like opacity to these thermal simulations is trivial, and with the tools I have already developed it would be very easy to see if such a nonlinear opacity affects the magnitude of entrainment in these experiments measurably. Such a complication is beyond the scope of the current paper on stratified thermals, but this small, letter-length project would get closer to answering the questions I posed in project 1 of my original application.

2.2 Possible mini-project 2: Continuing rotation work

As I mentioned earlier, the work published in **?** has potentially launched two future collaborations: one with Drs. Julien and Grooms, and another with Dr. Featherstone.

The first project would be a more careful study of the results that we published in **?** with the goal of determining *what physical mechanism* is responsible for setting the Rossby number. Put differently, in our recent work we showed that, empirically, the Rossby number is fairly constant if you set your experiment up in the proper way that we describe, but the study with Drs. Julien and Grooms could elucidate *why* our prescription sets the Rossby number, and whether or not such a prescription is accurate in the solar regime.

The second possible collaboration here, with Dr. Featherstone, would use our results from simple cartesian domains and study them using turbulent convection simulations in spherical shells. This work would help us understand if our results for setting the Rossby number are valid when flows become turbulent and when more complex geometries are present.

2.3 Possible mini-project 3: Accelerated evolution of stratified, overshooting convection

In my second paper, I studied a method of fast-forwarding through the long relaxation of the atmosphere's thermal structure in a simple, boussinesq convective system. A fellow graduate student in our research group and I have some promising first results of an extension of this method to stratified, compressible simulations. This method shows promise for saving millions, if not billions, of cpu-hours in future work by allowing computer time to be used on studying "useful" parts of simulations (in which the thermal structure is relaxed and the convective flows are no longer rearranging it) rather than transient phases. I worked through much of the intricate details of this project over a year ago, but have since been more invested in other projects, and returning to this project could produce great results with little extra input effort compared to most of the other projects presented here.