

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

Evan H. Anders

*Advisor: Benjamin P. Brown*

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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.

# Timeline of Graduate Studies

Evan H. Anders

*Advisor: Benjamin P. Brown*

*Laboratory for Atmospheric and Space Physics (LASP) & University of Colorado – Boulder*

**Fall 2014 - Spring 2015:** Began graduate studies and worked as a Teaching Assistant.

**Summer 2015:** Began work as a graduate Research Assistant with Dr. Benjamin P. Brown. *Awarded CU Boulder’s 3-year George Ellery Hale Graduate Student Fellowship.*

**Fall 2015:** *Hale fellowship funding began.*

**January 2016:** Completed department qualifier Comprehensive Exam I with highest marks in cohort.

**Spring-Summer 2016:** Began studies of stratified, compressible convection.

**Fall 2016:** Completed second and final departmental Ph.D. qualifier, Comprehensive Exam II, which was essentially a master’s thesis defense. Received “High Pass” distinction, and advanced to Ph.D. candidacy.

**Spring 2017:** Improved work from Comprehensive Exam II and submitted it to Phys. Rev. Fluids (Anders & Brown 2017, Phys. Rev. Fluids). Finished graduate coursework.

**Summer - Fall 2017:** Conducted work on accelerated evolution project for fast-forwarding convective solutions in order to save computational time (published in Paper 2, below).

**Spring 2018:** Paper 2 (Anders, Brown, & Oishi 2018, Phys. Rev. Fluids) published. Got married April 2018.

**Summer 2018:** Exploratory work on Kramer’s opacity, as proposed in initial application, and work on stratified, rotating convection. *End of funding of Hale fellowship.*

**Fall 2018:** *Start of funding from NESSF18.* Further exploratory work on Kramer’s opacity and thermals project. Submitted and published paper 3 (Anders et al. 2019, ApJ) on rotating, stratified convection.

**Spring 2019:** Run thermals simulations, write thermals paper, submit to The Astrophysical Journal by end of semester.

**Summer 2019 - Spring 2020:** Study ionizing convection as well as one of the other mini-projects laid out in my renewal proposal, part 2. Submit a paper on one of these projects by end of year 2019. Wrap up and submit other project by end of Spring or Summer 2020.

**Spring - Summer 2020:** Write and defend thesis and graduate with Ph. D. in Astrophysical & Planetary Sciences.

## UNOFFICIAL TRANSCRIPT

NAME: Anders, Evan Henry  
 STUDENT NR: 104330960  
 PRINT DATE: 03/01/2019

BIRTHDATE :

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 Degrees, Certificates and Licensure

Master of Science  
 CU Boulder  
 College Arts & Sciences GRAD  
 Major : Astrophysical & Planetary Sci  
 DEC 15, 2016

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 Other Institutions Attended:

HIGHER EDUC. INSTITUTIONS: Whitworth University  
 DEGREE: BAC 05/2014  
 Spokane WA  
 09/10 - 05/14

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COURSE TITLE	CRSE NR	UNITS	GRADE	PNTS
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 College Arts & Sciences GRAD  
 Fall 2014 UC Boulder  
 Astrophysical & Planetary Sci  
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Atomic and Molecular Processes	ASTR 5110	4.0	A-	14.8
Cosmochemistry	ASTR 5330	3.0	A	12.0
Mathematical Methods	ASTR 5540	3.0	A	12.0
Seminar in Astrophysics	ASTR 6000	1.0	B+	3.3
Dark Matter				
ATT	11.0	EARNED	11.0	GPAHRS
			11.0	GPAPTS
			42.10	GPA
				3.827

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 College Arts & Sciences GRAD  
 Spring 2015 UC Boulder  
 Astrophysical & Planetary Sci  
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Intro Plasma Physics	ASTR 5150	3.0	A	12.0
Intro to Fluid Dynamics	ASTR 5400	3.0	A	12.0
Observations & Statistic	ASTR 5550	3.0	A	12.0
Seminar in Planetary Science	ASTR 5835	1.0	A-	3.7
Mars Science Lab				
ATT	10.0	EARNED	10.0	GPAHRS
			10.0	GPAPTS
			39.70	GPA
				3.970

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 College Arts & Sciences GRAD  
 Fall 2015 UC Boulder  
 Astrophysical & Planetary Sci  
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Radiative/Dynamic Process	ASTR 5120	4.0	A	16.0
Astro/Space Plasmas	ASTR 5140	3.0	A	12.0
Seminar in Planetary Science	ASTR 5835	1.0	A	4.0
Venus after Venus Express				
ATT	8.0	EARNED	8.0	GPAHRS
			8.0	GPAPTS
			32.00	GPA
				4.000

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COURSE TITLE	CRSE NR	UNITS	GRADE	PNTS
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 College Arts & Sciences GRAD  
 Spring 2016 UC Boulder  
 Astrophysical & Planetary Sci  
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Stellar Structure & Evol	ASTR 5700	3.0	A	12.0
Seminar in Astrophysics	ASTR 6000	1.0	A	4.0
Space/GB Detector				
Special Topics in APAS	ASTR 7500	3.0	A	12.0
Doctoral Dissertation	ASTR 8990	5.0	IP	0.0
ATT	12.0	EARNED	7.0	GPAHRS
			7.0	GPAPTS
			28.00	GPA
				4.000

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 College Arts & Sciences GRAD  
 Fall 2016 UC Boulder  
 Astrophysical & Planetary Sci  
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Doctoral Dissertation	ASTR 8990	5.0	IP	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

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 College Arts & Sciences GRAD  
 Spring 2017 UC Boulder  
 Astrophysical & Planetary Sci  
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Special Topics in APAS	ASTR 7500	3.0	A	12.0
Doctoral Dissertation	ASTR 8990	6.0	IP	0.0
ATT	9.0	EARNED	3.0	GPAHRS
			3.0	GPAPTS
			12.00	GPA
				4.000

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 College Arts & Sciences GRAD  
 Fall 2017 UC Boulder  
 Astrophysical & Planetary Sci  
 -----

Doctoral Dissertation	ASTR 8990	5.0	IP	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

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 College Arts & Sciences GRAD  
 Spring 2018 UC Boulder  
 Astrophysical & Planetary Sci  
 -----

Doctoral Dissertation	ASTR 8990	5.0	IP	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

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 College Arts & Sciences GRAD  
 Fall 2018 UC Boulder  
 Astrophysical & Planetary Sci  
 -----

Doctoral Dissertation	ASTR 8990	5.0	IP	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

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 College Arts & Sciences GRAD  
 Spring 2019 UC Boulder  
 Astrophysical & Planetary Sci  
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Doctoral Dissertation	ASTR 8990	(5.0)	***	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

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 CUMULATIVE CREDITS :

	TR UNITS	CU UNITS	TOT UNITS	QUAL UNITS	QUAL PTS	GPA
GRAD	0.0	39.0	39.0	39.0	153.80	3.944

UNOFFICIAL TRANSCRIPT

NAME: Anders, Evan Henry  
STUDENT NR: 104330960  
PRINT DATE: 03/01/2019

BIRTHDATE :

\*\*\*\*\* END OF ACADEMIC RECORD \*\*\*\*\*

## **Budget Justification**

### **University of Colorado (CU – Boulder)**

### **Laboratory for Atmospheric and Space Physics (LASP)**

*All costs are in U.S. dollars (USD)*

#### **1) Future Investigator (FI) Stipend**

The student requests the full stipend amount of \$35,000 per year. The stipend amount requested is based on the University of Colorado's prevailing rate.

#### **2) University Fees/Tuition**

The Student requests the full \$10,000 per year to cover graduate student tuition, fees, and healthcare. Graduate student tuition is requested in accordance with University policy.

#### **3) FI Allowances**

Student requests that any remaining funds from the \$10,000 allowance will be used for travel to the AGU fall conference (or equivalent domestic scientific conference) for the FI in each year to collaborate with peers.

LASP's Travel Basis of Estimate is outlined below:

1. Airfare is based on an average of actual booking costs from the previous quarter recorded by Christopherson Business Travel, the booking agency for the University of Colorado. Travel costs are estimates. Upon contract award, actual travel costs will be billed pursuant to CU travel policy.
2. Per Diem rates are taken from current government rate sites.
3. Car Rental is estimated at \$55/day, which is based on the State of Colorado's negotiated rates plus estimates for taxes and gasoline. Local ground transportation will be used in lieu of a car rental if available.
4. Ground Transportation costs include daily parking at the airport and transportation to and from the airport and are estimated based on historical costs experienced.
5. Conference Registration Fees are estimated using the most recent fee available on the conference web site or historical costs.

Remaining funds from the \$10,000 allowance will be used to purchase textbooks/supplies in support of the proposed effort

#### **4) Indirect Charges**

Per the NESSF19R Funding Opportunity Announcement, indirect costs will not be requested or recovered on participant support costs.