

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

Evan H. Anders

Advisor: Benjamin P. Brown

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

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

Preliminary work into rotating convection in our research group revealed some interesting results during the summer of 2018, and I chose to gain a greater understanding of these results and publish them during fall 2018. This work was recently published in The Astrophysical Journal ([Anders et al., 2019](#)).

Recent work by e.g., [Featherstone & Hindman \(2016\)](#) 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, if flows in the deep solar convective interior are heavily influenced by the rotation of the Sun, they may not manifest themselves in the way that traditional mixing length theory or simulations predict. If rotation is the dominant force on these deep convective flows, they are at very low *Rossby number* (Ro). Unfortunately, Ro is an *output* parameter in convective simulations and it is difficult to specify its value *a priori*. In our recently published work, [Anders et al. \(2019\)](#), we demonstrated a manner of specifying the Rossby number of simulations in the initial conditions, as we demonstrate in Fig. 1, which is Figure 1 of [Anders et al. \(2019\)](#).

This recently published work has lead to fruitful discussions with multiple scientists across campus at CU Boulder, including those who are experts in rotating convection (Drs. Keith Julien and Ian Grooms) and also experts in solar convection simulations (Dr. Nick Featherstone). These discussions have led to potential collaborations which further explore the results of [Anders et al. \(2019\)](#), and I will describe these possibilities more fully in section [2.2](#).

1.2 Convection with Kramer’s opacity and thermals

During the fall of 2018, I additionally worked on “project 1” in our original NESSF proposal, 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.”

Through this preliminary work, I have realized that the fundamental process that I proposed to study is that of *entrainment*, and that the initially proposed project is too complex of a starting point for a detailed study of this phenomenon. Recently, Dr. Daniel Lecoanet (Princeton) has performed an in-depth study of entrainment in Boussinesq thermals (Lecoanet & Jeevanjee, 2018, in review). A thermal is a region of cold (or hot) fluid that evolves from rest according to buoyant forces, and they were able to easily study entrainment in these thermals in both the laminar and turbulent regime. I have formed a collaboration with Dr. Lecoanet in order to extend his work to study entrainment of thermals in stratified domains under the fully compressible equations. These simulations are, in some way, a simple model of a phenomenon that some believe to be a solution to the Solar Convective Conundrum: “entropy rain,” as described by Brandenburg (2016). These simple thermal simulations will allow us to understanding how the complexities of the fully compressible equations and highly stratified domains will be important to understanding whether or not the entropy rain hypothesis is valid.

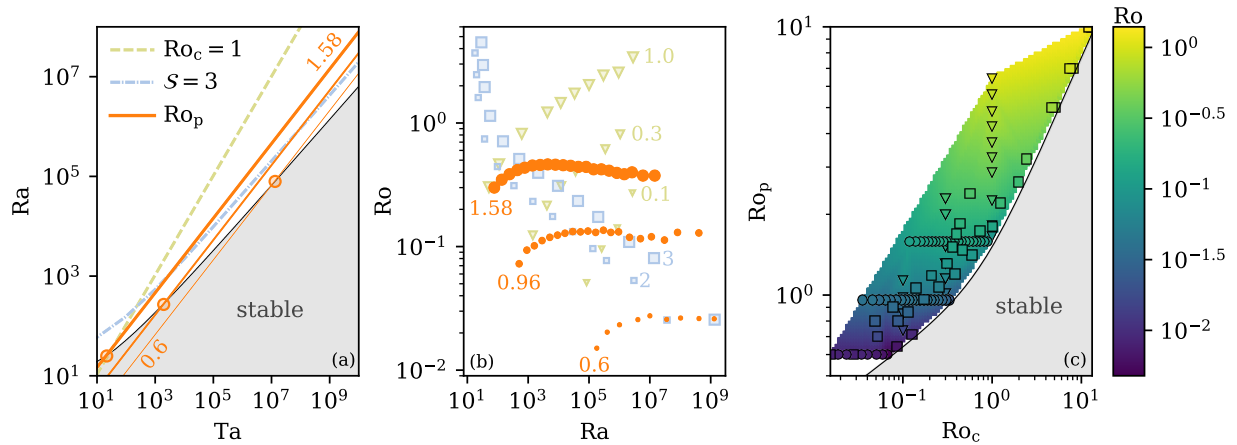


Figure 1: Figure 1 of Anders et al. (2019) is shown. In (a), we show the parameter space of rotating convection, with Rayleigh number (Ra, ratio of buoyant driving to diffusive damping) on the y -axis and the Taylor number (Ta, strength of rotation compared to diffusive damping) on the x -axis. We also show three types of “paths” through this space that simulations can follow in blue (constant supercriticality, \mathcal{S}), green (constant “convective Rossby number,” Ro_c), and orange (constant “predictive Rossby number,” Ro_p). In (b), we show that along the orange paths, at constant Ro_p , the evolved Rossby number (Ro) of simulations is roughly constant across orders of magnitude of Ra, while the other two paths show increasing or decreasing Ro . In (c), we show that the evolved Rossby number is roughly a function of Ro_p alone, and not significantly a function of the commonly-used Ro_c . These results imply that by choosing the value of Ro_p and walking along these paths in parameter space, the degree of rotational constraint of simulations can be chosen by construction. If the solar interior is, in fact, at low Ro , this finding allows us to probe that dynamical regime.

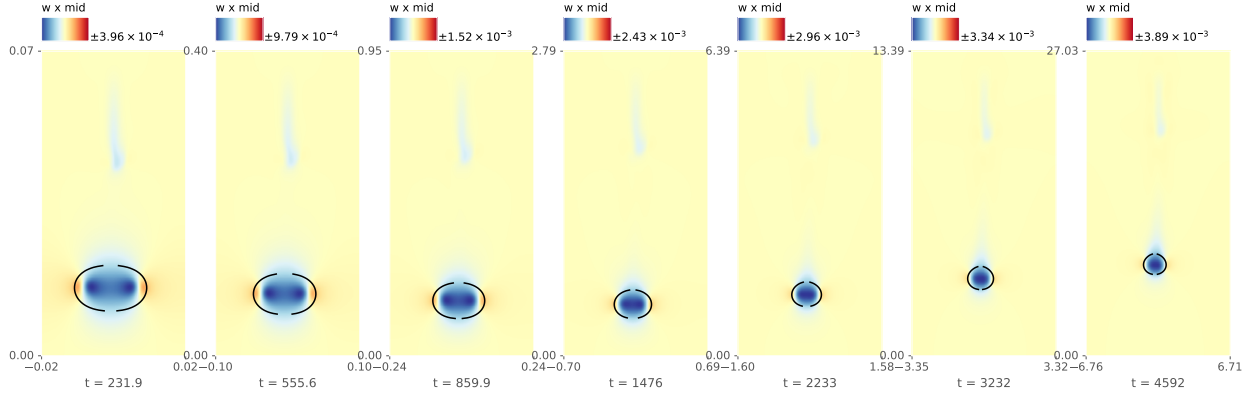


Figure 2: Snapshots of the vertical velocity field in the $y - z$ plane of 3D simulations are shown at late times in the evolution of laminar thermals (Reynolds number ~ 600). From left to right, the atmosphere through which the thermal is falling is stratified by $n_\rho = [0.1, 0.5, 1, 2, 3, 4, 5]$ density scale heights, so the simulation on the left is essentially in the Boussinesq limit of Lecoanet & Jeevanjee (2018) and the simulation on the right is highly stratified. The thermal tracking algorithm of Lecoanet & Jeevanjee (2018) has been extended to work robustly in stratified domains, and the black outlines show the boundaries of the thermal obtained by this algorithm. These preliminary simulations are informing work that will be submitted for publication by the end of spring 2019.

I have been studying stratified thermals since late fall 2018, and currently have a fully functioning code for simulating and analyzing thermals, as in Fig. 2. We aim to come up with a robust theory of the behavior of laminar thermals (Reynolds number $[Re] \sim 600$, Fig. 2) which describes the downward propagation and entrainment of these fluid regions at both small and large stratification. Once we fully understand this theory, we will study whether this linear theory describes the evolution of turbulent thermals ($Re \sim 6000$), whose evolution more accurately reflects that of the solar context. This work will be submitted for publication by the end of spring 2019, as laid out in the original NESSF timeline.

2 Future plans for 2019-2020

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 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. While it would be impossible to study all three of the following projects coincidentally with ionizing convection, it should be feasible to 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 numerically 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. Such a complication is beyond the scope of the current paper on stratified thermals (e.g., Fig. 2), but this small, letter-length project would probe the same scientific answer as my originally proposed project 1: *does a nonlinear, solar-like opacity reduce entrainment in cold downflows?*

2.2 Possible mini-project 2: Continuing rotation work

As I mentioned earlier, the work published in Anders et al. (2019) has potentially launched future collaborations with, e.g., Drs. Julien, Grooms, and/or Featherstone. Working alongside these experts, I could further study the results published in Anders et al. (2019) 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 hold the “predictive Rossby number” constant. A follow-up project would aim to understand the physical mechanism in the Navier-Stokes equations that leads to this result, and understand if the Rossby number can be predicted in the solar regime.

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

In my second paper (Anders et al., 2018), 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, and I could follow up on these results without too much time investment. This method shows promise for saving millions 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.

References

- Anders, E. H., Brown, B. P., & Oishi, J. S. 2018, *Accelerated evolution of convective simulations*, Physical Review Fluids, 3, 083502
- Anders, E. H., Manduca, C. M., Brown, B. P., Oishi, J. S., & Vasil, G. M. 2019, *Predicting the Rossby Number in Convective Experiments*, The Astrophysical Journal, 872, 138
- Brandenburg, A. 2016, *Stellar Mixing Length Theory with Entropy Rain*, The Astrophysical Journal, 832, 6
- Featherstone, N. A., & Hindman, B. W. 2016, *The Emergence of Solar Supergranulation as a Natural Consequence of Rotationally Constrained Interior Convection*, The Astrophysical Journal, 830, L15
- Lecoanet, D., & Jeevanjee, N. 2018, *Entrainment in Resolved, Turbulent Dry Thermals*, arXiv e-prints, arXiv:1804.09326

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 :

 Degrees, Certificates and Licensure

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

 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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Fall 2014 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
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

Spring 2015 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
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

Fall 2015 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
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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Spring 2016 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
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

Fall 2016 UC Boulder		-----		
College Arts & Sciences GRAD	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

Spring 2017 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
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

Fall 2017 UC Boulder		-----		
College Arts & Sciences GRAD	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

Spring 2018 UC Boulder		-----		
College Arts & Sciences GRAD	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

Fall 2018 UC Boulder		-----		
College Arts & Sciences GRAD	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

Spring 2019 UC Boulder		-----		
College Arts & Sciences GRAD	ASTROPHYSICAL & PLANETARY SCI			
Doctoral Dissertation	ASTR 8990	(5.0)	***	0.0
ATT	5.0	EARNED	0.0	GPAHRS
			0.0	GPAPTS
			0.00	GPA
				0.000

 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.