The solar dynamo: Understanding the tachocline's role and bridging the gap between simulation and observation

Evan Anders

Advisor: Benjamin Brown
LASP, University of Colorado at Boulder

Abstract

Dynamo action powered by solar convection causes the Sun to be magnetically active. The workings of the solar magnetic dynamo have been greatly informed by numerical simulations. Traditionally, these simulations have described solar-type stars with high rotation rates and large characteristic convective motions compared to solar values. Here I propose a suite of 3-D numerical simulations of the solar convective zone which implements accurate solar rotation and convective velocity profiles and will be developed using the state-of-the-art anelastic spherical harmonics (ASH) code. My primary goal is to determine the role of the solar tachocline, the rotational shear layer at the base of the convective zone, in the production and sustenance of the solar magnetic dynamo. Furthermore, I propose a set of simulations of increased complexity that will include the supergranulation of the solar photosphere. Data from these simulations will be post-processed to create synthetic observables. Such mock-observables will be compared directly to data gathered by the Solar Dynamics Observatory and used to predict observations of the upcoming Solar Orbiter. 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 is a magneticly active star. Its 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. Magnetic fields and solar rotation couple in the presence of convective motions to produce global wreaths of magnetism which drive the Sun's 22-year cycle of magnetic activity. 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. It is clear that the Sun's magnetism affects our increasingly technological society; understanding the nature of the dynamo that drives solar magnetism is of paramount importance (Miesch & Toomre 2009; Charbonneau 2014).

While current simulations lack the power to predict accurately the stellar magnetic environment over long time scales, they have provided great insight into the mechanisms underlying the solar dynamo. It is observationally proven that the surface of the sun rotates differentially; the poles rotate roughly every 35 days while the equator rotates every 25 days. By probing the Sun's radial structure and sub-surface convective
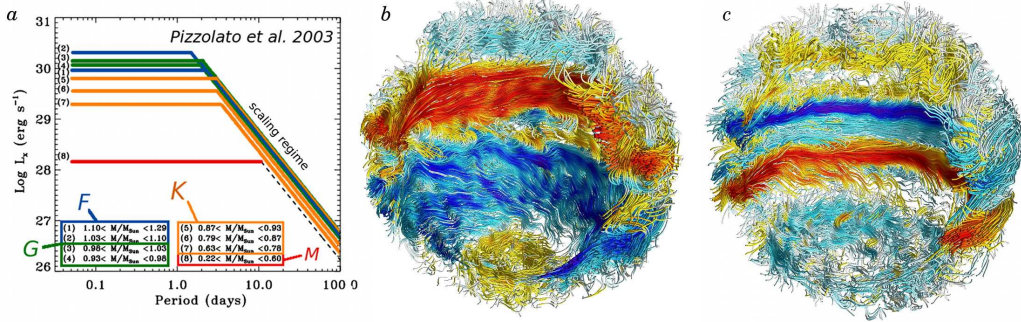
Figure 1: (a) Observationally measured stellar x-ray luminosity is plotted versus stellar rotation period. There is a clear increase in x-ray luminosity (powered by stellar magnetism) as rotation period decreases (Pizzolato et al. 2003). (b) Global scale toroidal wreaths of magnetism have been obtained using the ASH code to numerically simulate Sun-like stars. There is a clear polarity inversion in which the simulation fields cyclically reverse (c) every five years (Brown et al. 2011).

flows using acoustic oscillations, helioseismology has revealed that the solar differential rotation profile extends through the bulk of the convective zone and has two distinct shear regions. A near-surface shear layer occupies roughly the outer 5% of the Sun. A secondary shear layer, called the tachocline, separates the differentially rotating convective zone from the uniformly rotating radiative zone located radially inward. Traditional models of the solar dynamo, namely Babcock-Leighton flux-transport dynamo models and interface dynamo models, state that the tachocline drives the production of toroidal magnetic fields that fuel the solar dynamo and manifest at the solar surface as sunspots and active regions. In such models, magnetic fields generated in the convective zone are transported inward to the tachocline, where magnetic wreaths are built before buoyantly rising to the solar surface (Miesch & Toomre 2009).

Meaningfully creating numeric simulations of the solar environment requires working with wide ranges of spatial and temporal timescales. However, the underlying equations at the heart of these magnetohydrodynamic (MHD) simulations—which express conservation of mass, momentum, and energy and account for magnetic induction—are simple (Charbonneau 2014). Most current simulations have studied stars with higher rotation rates than the Sun, as the strength of the magnetic dynamo increases proportionally to the stellar rotation rate (see Fig. 1a). Such simulations have informed solar dynamo theory and generated self-sustaining, buoyantly-rising toroidal wreaths of magnetism with polarity shifts on long time scales, shown in Fig. 1b&c.

In light of accepted dynamo theory, an unsettling result has arisen in recent simulations of Sun-like stars. There is disagreement regarding whether the tachocline is a necessary ingredient in the sustenance of the solar magnetic dynamo. Cyclic, Sun-like dynamos have been achieved in 3-D numerical simulations both with (Ghizaru et al. 2010; Racine et al. 2011) and without (Brown et al. 2011; Nelson et al. 2013) the presence of a tachocline. This begs the fundamental question: does the solar toroidal magnetic field—and, thus, the solar dynamo—require the presence of a tachocline? Those simulations which produced opposing results were created using different codes

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and differing models for subgrid processes at various stellar rotation rates. Consequently, it is impossible to compare the results of the simulations directly. The data required to determine the role of the tachocline are missing.

Additionally, most simulations of solar convection simulate Sun-*like* stars rather than the Sun itself. Such simulations model stars with greater rotation rates and convective flow velocities than the Sun. Furthermore, it has recently been discovered that these simulations self-consistently achieve amplitudes of large scale convective motions much larger than those present in the Sun (Lord et al. 2014). Such a discrepancy calls for a new set of solar numerical simulations which more accurately describes convective flows. The Rossby number, the ratio of convective timescales to rotation timescales, appears to control the nature of global-scale dynamo action. At low Rossby numbers, cycles and global organization emerge self-consistently. By lowering the convective amplitudes, we can achieve the low Rossby regime at solar parameters. This allows us to explore the physics of the global-dynamo action in the Sun itself, rather than making inferences about the solar dynamo from rapidly rotating solar-like stars.

While simulations of stellar magnetic dynamos have proven irreplaceable in gaining insight into the structure and evolution of long-term cycles, they fail to relate to *in-situ* measurements of solar magnetism and cannot provide insight on short time scales. With the wealth of spacecraft either currently or soon-to-be gathering data on the Sun, now is the time to bridge the gap between theoretical dynamo simulations and direct observations of solar activity.

2   Does the tachocline drive the Sun's toroidal magnetic fields?

I propose a set of MHD simulations of the Sun's convective zone to test the tachocline's role in generating the solar magnetic dynamo. These simulations will model the solar convective zone from its base up to the base of the outer convective shear layer, stopping around $R = 0.97R_\odot$. These simulations will include identical rotation rates and convective timescales, but one simulation will include the shear effects of the tachocline by extending down to about $0.5R_\odot$ while the other simulation will stop at the base of the convective zone around $0.713R_\odot$, neglecting the tachocline. The background stellar structure (taken from a MESA solar model) will be otherwise identical between the simulations. Dynamo theory champions the tachocline as the seat of the toroidal component of the solar magnetic field, and it is time to put this theory to the test. By building two simulations which are identical other than the presence or lack of a tachocline, we can directly test this theory. The data from such simulations can provide greater certainty regarding the importance of the tachocline in the generation and maintenance of the solar dynamo.

I will use the Anelastic Spherical Harmonic (ASH, Clune et al. 1999) spectral solver, which I will have access to through my advisor, Dr. Benjamin P. Brown, to create my simulations. The ASH code is the current state-of-the-art code for modeling the global solar dynamo (Miesch & Toomre 2009; Brun et al. 2011; Alvan et al. 2014). Using such a well-established code will allow me to efficiently simulate the solar convective zone in spherical coordinates and gain and understanding of the physics at work without having to worry about generating a fully functional solving suite. Naturally, work

of this magnitude requires access to massively parallel computing resources. As a CU Boulder student, I have access to the school's local supercomputer, *Janus*. Additionally, I will work with Ben Brown to acquire CPU time on state-of-the art supercomputers such as the NSF XSEDE resources and NASA's *Pleiades*.

I have been well prepared by my past education to undertake simulations of this magnitude. In 2012, I worked with Pacific Northwest National Laboratory's (PNNL) Data Intensive Scientific Computing group and gained an understanding of the challenges that are faced in the creation of large, scientific computations. In addition to learning the struggles faced in efficiently creating massively parallelised algorithms, I learned how to effectively understand and utilize computational tools (such as ASH). I also learned techniques for debugging and optimizing my routines.

Additionally, over the summer of 2013 I participated in the NSF Science Undergraduate Research Fellowship program at the Laser Interferometer Gravitational-wave Observatory (LIGO). During my time at LIGO Hanford, it was my task to create a computational tool which analyzed LIGO science run data at specific frequencies and output those analyses in user-friendly text files. This experience taught me how to interact with massive quantities of data, how to organize that data meaningfully in files, and how to effectively plot and visualize such data. All of these skills will be exceptionally useful at all stages in the creation of massive 3-D simulations.

In addition to my strong undergraduate education in physics, I am in the process of learning the fundamentals of fluid mechanics and plasma physics necessary to understand and implement the MHD processes governing motion within the solar convective zone.

3 Simulated observables: Connecting observations and simulations

While simulations provide great insight into the physical trends occuring within a system, they often fall short of a direct connection to observable data. Thus, I propose a second suite of simulations that spans the entirety of the solar convective zone and reaches out to the solar photosphere to display the behavior of magnetic fields at the observable surface of the Sun. In efforts to accurately portray the physics at work, these simulations will capture supergranular scales. Including supergranular scales at the photosphere will allow us to explore the emergence of active regions and their coupling to deep magnetism. Small scale granulation will be ignored for two reasons. First, the motions of granulation are roughly two orders of magnitude smaller than the motions of the vast solar convective zone, making granular contributions unimportant. Second, the computational load of resolving granular scales would push our simulation workload past a feasibly acquirable number of CPU hours on state-of-the-art machines.

Numerous post-processing techniques will be used on the photospheric data produced by these simulations in order to create synthetic observables. Simulation data, which is known precisely in terms of fields and velocities, will be incorporated into atmospheric and radiative transfer models to create mock-observables. Possible "observables" will include irradiance maps which reveal the location of sunspots and detailed synthetic line profiles in the solar atmosphere, comparable to those measured by the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO)
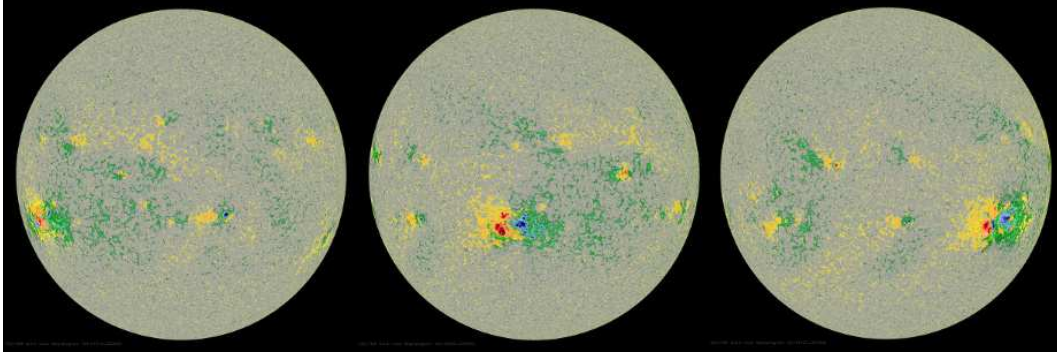
Figure 2: SDO HMI colorized magnetogram images of solar active region AR 12192, taken on 10/19/2014, 10/23/2014, and 10/27/2014, respectively. Simulated observables could mimic the behavior of regions such as this and help us understand when and why they release solar flares such as the X3.1 flare released on 10/24/2014.

for magnetic mapping (see Fig. 2). Simulations that accurately capture the physics at work within the solar convective zone will create patterns similar to those observed at the solar surface. If simulated sunspots and active regions show behaviors like those observed at the solar photosphere, it will be evident that our theory of the dynamo is functional. Furthermore, the scheduled Solar Orbiter (NASA-ESA) will be the first spacecraft to study the solar poles in detail. While comparing simulated observables to data from current spacecraft (SDO) will be beneficial, such "observables" can also be used to make predictions about phenomena that will be observed by the Solar Orbiter along the solar poles.

4   Timeline of proposed work

Year 1:   Acquire access to ASH code and learn how to interface with it. Create and execute first suite of simulations, successfully gathering all data necessary to determine the role of the solar tachocline. Begin work on analysis routines.

Year 2:   Analyze simulated data to gain an understanding of the tachocline's role in generating the solar dynamo. Publish a peer-reviewed article on the findings of the simulations. Research necessary techniques for and begin work on a second suite of simulations to be used in the creation of simulated observables.

Year 3:   Run second simulation set and create simulated observables, including data directly comparable to that currently gathered by SDO and to be gathered by the Solar Orbiter. Compare the evolution of interesting simulated events to similar observed events. Make predictions on expected phenomena in upcoming polar data from the Solar Orbiter.

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5   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.

6   Summary

In order to predict extreme space conditions caused by the Sun's magnetic activity, we must have an intricate understanding of the behavior of the Sun's magnetic dynamo. While solar dynamo theory has progressed impressively in recent years, its progression has been marked by a series of impressive simulations with no tangible connection to observables that utilize an untested assumption as a theoretical cornerstone. After recent simulations' disagreements regarding the tachocline's role in producing the solar magnetic dynamo, it is time to put the assumed importance of the tachocline to the test. Furthermore, in order to have a consistent, predictive theory on solar magnetism, it is necessary to connect theoretical numerical simulations with tangible observables. Only when these two sources of insight are brought together will NASA's Science Plan goal of predicting extreme conditions in space be realizable. The wealth of Solar Dynamics Observatory data available alongside the upcoming launch of the Solar Orbiter set the present as the perfect time to connect theory and observation.

Alvan, L., Brun, A. S., & Mathis, S. 2014, A&A, 565
Brown, B. P., et al. 2011, Astrophys. J., 731
Brun, A. S., Miesch, M. S., & Toomre, J. 2011, Astrophys. J., 742
Charbonneau, P. 2014, Annu. Rev. Fluid Mech., 52, 251
Clune, T., et al. 1999, Parallel Comput., 25, 361
Ghizaru, M., Charbonneau, P., & Smolarkiewicz, P. 2010, Astrophys. J. Lett., 715
Lord, J. W., et al. 2014, Astrophys. J., 793
Miesch, M. S., & Toomre, J. 2009, Annu. Rev. Fluid Mech., 41, 317
Nelson, N. J., et al. 2013, Astrophys. J., 762
Pizzolato, N., et al. 2003, A&A, 397
Racine, E., et al. 2011, Astrophys. J., 735, 46

Timeline of Graduate Studies

Evan Anders

Department of Astrophysical and Planetary Sciences
University of Colorado at Boulder

August 2014: Begin graduate studies including graduate coursework. Assume position of Teaching Assistant for 2014-2015 academic year.

May 2015: Begin work as a graduate Research Assistant with Dr. Benjamin P. Brown.

September 2015: Start of proposed funding from NESSF.

Fall 2015: Build initial dynamo models with and without tachocline.

January 2016: (1) Complete first departmental qualifier for PhD candidacy, "COMPS I", a comprehensive test over five core courses: Atomic & Molecular Processes, Mathematical Methods, Fluid Mechanics, Observations & Statistics, and Radiative Processes. (2) Begin assessing the tachocline's role in setting cycle periods.

May 2016: Complete graduate courses. Further time in the department will be devoted entirely to research.

Fall 2016: Write and publish a peer-reviewed article regarding the tachocline's role in the production and sustenance of the solar dynamo.

December 2016: Complete second departmental qualifier for PhD candidacy, "COMPS II", a defense of completed research. If successful, move on to PhD candidacy.

Spring 2017: Build dynamo models which include the solar photosphere. Begin development of post-processing techniques to create simulated observables.

Summer 2017: Create simulated observables which parallel data taken by the Solar Dynamics Observatory (SDO) and the future Solar Orbiter.

Fall 2017-Spring 2018: Analyze simulated observables, comparing them to current SDO data and predicting phenomena that the Solar Orbiter will observe.

Summer 2018: Write and publish a peer-reviewed article covering findings and predictions informed by simulated observables.

August 2018: Completion of proposed funding from NESSF.

May 2019: Anticipated graduation date.

Benjamin Brown

Biographical Sketch
Department of Astrophysical and Planetary Sciences
University of Colorado, Boulder
`bpbrown@colorado.edu`

Professional Preparation

Harvey Mudd College	Physics	BS May 2003
University of Colorado, Boulder	Astrophysics	PhD August 2009
University of Wisconsin, Madison	Astronomy	Postdoc September 2009 – August 2013
University of California, Santa Barbara	KITP	Postdoc September 2013 – July 2014

Appointments

Assistant Professor	University of Colorado, Boulder	August 2014 –
Research Associate	Kavli Institute for Theoretical Physics	September 2013 – July 2014
Postdoctoral Fellow	University of Wisconsin, Madison	September 2009 – August 2013
NSF AAPF	University of Wisconsin, Madison	September 2009 – August 2013

Five Publications Most Relevant to Proposed Work (out of 24 total)

- Lecoanet, D., **Brown**, B. P., Zweibel, E. G., Burns, K., Oishi, J. S, & Vasil, G. M., "Conduction in low-Mach number flows: part I linear & weakly nonlinear regimes", 2014, *The Astrophysical Journal*, 797, 94:1–16
- Vasil, G. M., Lecoanet, D., **Brown**, B. P., Wood, T. S., & Zweibel, E. G., "Energy conservation and gravity waves in sound-proof treatments of stellar interiors: Part II Lagrangian constrained analysis", 2013, *The Astrophysical Journal* 773, 169:1–23
- **Brown**, B. P., Vasil, G. M., & Zweibel, E. G., "Energy conservation and gravity waves in sound-proof treatments of stellar interiors: Part I anelastic approximations", 2012, *The Astrophysical Journal* 756, 109:1–20
- **Brown**, B. P., Miesch, M. S., Browning, M. K., Brun, A. S., & Toomre, J., "Magnetic cycles in a convective dynamo simulation of a young solar-type star", 2011, *The Astrophysical Journal*, 731, 69:1–19
- **Brown**, B. P., Browning, M. K., Brun, A. S., Miesch, M. S., & Toomre, J., "Persistent magnetic wreaths in a rapidly rotating sun", 2010, *The Astrophysical Journal*, 711, 424–438

Synergistic activities

Brown has been involved in modelling stellar convection since 2003, when he began using the anelastic spherical harmonic (ASH) code to study the coupling of convection, rotation and magnetic dynamo action in the Sun and in other solar-type stars. He has published results on magnetohydrodynamic processes in stellar interiors and has extensive experience with fluid dynamics in stratified atmospheres appropriate to stellar interiors. He is a member of the closed-source ASH code development team, and is a member of the development team for the open-source Dedalus framework. Brown has served as a mentor for four undergraduate students while at University of Wisconsin, Madison, designing and managing research projects that ranged between 3 months and 1 year in length, and in one case lead to a succesful undergraduate thesis.

Evan Anders

Biographical Sketch
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University of Colorado, Boulder
`evan.anders@colorado.edu`

Professional Preparation

Whitworth University	Physics	BS, May 2014
	Math & Computer Science	Minors, May 2014
University of Colorado, Boulder	Astrophysics	PhD, Expected Graduation: 2019

Most Relevant Courses

Fluid Mechanics	Plasma Physics	Computational Physics	Software Engineering

Relevant Research Experience

- LIGO (Laser Interferometer Gravitational-wave Observatory), Hanford Observatory. NSF SURF Fellow, Summer 2013. Project: Spectral Line Monitoring Tool.
- Pacific Northwest National Laboratory (PNNL). DOE SULI Intern, Summer 2012. Project: Global Arrays in NumPy (GAiN).

Summary

Anders has a strong background in physics and computational methods. He learned professional software development techniques while working as part of a team creating an Android application for his undergraduate school newspaper. Thanks to his time at PNNL, he has developed and improved parallel algorithms and learned the difficulties intrinsic to large-scale computation. During his time at LIGO Hanford Observatory, he dealt with large data sets and wrote computational techniques for organization, storage, and visualization. His coursework has included numerous complex computational projects including an undergraduate simulation of interacting charged particles and a graduate implementation of Maxwell's equations.

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January 30, 2015

Dear Colleagues,

It is a pleasure to recommend Evan Anders for the NASA Earth and Space Science Fellowship (NESSF) program. Evan is a first year graduate student in the Department of Astrophysical and Planetary Sciences (APS) at the University of Colorado, Boulder. Evan was a student in my graduate Mathematical Methods class in Fall of 2014. Evan was one of my top students in this class. This intensive class is a core course within the APS graduate curriculum. Students are expected to master analytic and numeric techniques, and took on very open ended projects in simulating partial differential equations within our novel Dedalus pseudospectral framework. Evan undertook a novel project studying electromagnetic waves in fiber optic systems. I was very impressed with his work on the project and in the class as a whole.

Evan has proposed a novel project for his NESSF supported research "The solar dynamo: Understanding the tachocline's role and bridging the gap between simulation and observation". His proposed work will help directly resolve a significant debate in current solar dynamo theory. Namely, what role does the tachocline play in the cyclic global solar dynamo? His work will further provide a direct bridge between global-scale simulations and observations by capturing the photosphere and creating synthetic observables. This represents a significant step in connecting simulations and observations, and will provide both a stringent test of the achieved numerical simulations while also answering important questions about the inner workings of the solar dynamo. Evan came up with this project on his own after reading the dynamo literature and wrote this proposal single-handedly.

In summary, Evan has proposed a novel and interesting project which will answer important questions about the nature of the solar dynamo and will provide a crucial bridge between modern numerical simulations and solar observations. Evan has significant computational and mathematical skills, which make him very well suited for successfully achieving the proposed research. I strongly recommend Evan Anders for the NASA NESSF and very much look forward to working with him on this research.

Benjamin Brown

Assistant Professor in Solar Physics
Department of Astrophysical and Planetary Sciences

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SUMMARY OF ADVANCED PLACEMENT CREDIT:

    Art 2D Design   3.00
    US History   3.00
    Biology   2.00
    Biology (Cont)   2.00
    Chemistry   3.00
    Chemistry (Cont)   3.00
    US History (Cont)   3.00
    Calculus AB   4.00
    Physics B   3.00
    Physics B (Cont)   4.00

Course	Title	Credits	Grade	QualPts
	2010 Fall Semester			
EL126	Women Writers	3.00	A	12.00
PE153	American Ballroom Dance	1.00	A	4.00
PE152	Swing and Lindy Hop	1.00	A	4.00
EL110	Writing I: Writing/Naturl Wrld	3.00	A	12.00
EN110	Engineering Orientation	1.00	S	0.00
GE125	First Year Seminar	1.00	P	0.00
MA172	Calculus II	4.00	A	16.00
SN201	Intermediate Spanish	4.00	A	16.00

        PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	18.00	16.00	64.00	4.00
WHITWORTH CUMULATIVE DATA:	18.00	16.00	64.00	4.00

Total credits earned: 48.00

                2011 Jan Term
TH241   New Testament   3.00 A   12.00

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	3.00	3.00	12.00	4.00
WHITWORTH CUMULATIVE DATA:	21.00	19.00	76.00	4.00

Total credits earned: 51.00

                2011 Spring Semester
EN171	Engineering Graphics & CAD	3.00	A	12.00
CS171	Computer Science I	3.00	A	12.00
MA273	Calculus III	4.00	A	16.00
PS153	General Physics II	4.00	A	16.00
SN202	Intermediate Spanish II	4.00	A	16.00

Course	Title	Credits	Grade	QualPts
PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	18.00	18.00	72.00	4.00
WHITWORTH CUMULATIVE DATA:	39.00	37.00	148.00	4.00

Total credits earned: 69.00

                2011 Fall Semester
TH382	Campus Ministry	2.00	A	8.00
CH161L	General Chemistry I Lab	1.00	A	4.00
CS172	Computer Science II	3.00	A	12.00
EN211	Statics	3.00	A	12.00
MA281	Differential Equations	3.00	A	12.00
MA278	Discrete Mathematics	3.00	A	12.00
PS251W	General Physics III	4.00	A	16.00

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	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	19.00	19.00	76.00	4.00
WHITWORTH CUMULATIVE DATA:	58.00	56.00	224.00	4.00

Total credits earned: 88.00

                2012 Jan Term
CS371   Windows Applications Dev   3.00 A   12.00

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	3.00	3.00	12.00	4.00
WHITWORTH CUMULATIVE DATA:	61.00	59.00	236.00	4.00

Total credits earned: 91.00

                2012 Spring Semester
TH382	Campus Ministry	1.00	A	4.00
CS274	Ethic, Soc & Leg Issues in CS	3.00	A	12.00
PS373	Electronics	4.00	A	16.00
CS273	Data Structures	3.00	A	12.00
PS357	Math Meth for Engnrs/Scntsts	4.00	A	16.00

        PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	15.00	15.00	60.00	4.00
WHITWORTH CUMULATIVE DATA:	76.00	74.00	296.00	4.00

Total credits earned: 106.00

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Course	Title	Credits Grade QualPts

2012 Fall Semester

Course	Title	Credits	Grade	QualPts
CS320	Qual Assurance Software Develp	3.00	A	12.00
EN390	INTERN: Parallel Computing	1.00	S	0.00
CO250	Western Civ II	4.00	A	16.00
CS278	Comp Organiztn & Assemblr Prog	3.00	A	12.00
CS374W	Database Management	3.00	P	0.00
PS451	Electricty and Magnetism I	4.00	A	16.00

PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	18.00	14.00	56.00	4.00
WHITWORTH CUMULATIVE DATA:	94.00	88.00	352.00	4.00
Total credits earned: 124.00				

2013 Jan Term

Course	Title	Credits	Grade	QualPts
PS271	Computational Physics	3.00	A	12.00
FW149	Swimming for Fitness	1.00	A	4.00

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	4.00	4.00	16.00	4.00
WHITWORTH CUMULATIVE DATA:	98.00	92.00	368.00	4.00
Total credits earned: 128.00				

2013 Spring Semester

Course	Title	Credits	Grade	QualPts
EN396	Robotics	1.00	S	0.00
PS200	Physics Outreach	1.00	S	0.00
PS363	Thermodynamics	4.00	A	16.00
PS453	Electricity and Magnetism II	3.00	A	12.00
SP113	Interpersonal Communication	3.00	A	12.00

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	12.00	10.00	40.00	4.00
WHITWORTH CUMULATIVE DATA:	110.00	102.00	408.00	4.00
Total credits earned: 140.00				

2013 Fall Semester

Course	Title	Credits	Grade	QualPts
EN351	Dynamics	3.00	A	12.00
MA330	Linear Algebra	3.00	A	12.00
PH201	Logic	3.00	A	12.00
PS455	Quantum Mechanics	4.00	A	16.00
PS471	Research in Physics	1.00	S	0.00

PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	14.00	13.00	52.00	4.00
WHITWORTH CUMULATIVE DATA:	124.00	115.00	460.00	4.00
Total credits earned: 154.00				

2014 Jan Term

Course	Title	Credits	Grade	QualPts
PS495	TA:PS-271 Computational Phys	2.00	S	0.00

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	2.00	0.00	0.00	0.00
WHITWORTH CUMULATIVE DATA:	126.00	115.00	460.00	4.00
Total credits earned: 156.00				

2014 Spring Semester

Course	Title	Credits	Grade	QualPts
CO350	Western Civ III: Capitalism	4.00	A	16.00
CS472	Software Engineering	3.00	A	12.00
PS371	Optics	4.00	A	16.00
PS353	Advanced Dynamics	4.00	A	16.00

PROVOST'S HONOR ROLL   MEMBER LAUREATE SOCIETY

	Earned	CredCalc	QualPts	GPA
WHITWORTH SEMESTER/TERM DATA:	15.00	15.00	60.00	4.00
WHITWORTH CUMULATIVE DATA:	141.00	130.00	520.00	4.00
Total credits earned: 171.00				

-------------- Degree Earned 05/14 ---------------
Bachelor of Science
  Major: Physics
  Minor: Mathematics
       Computer Science
  Graduation Honors: Summa Cum Laude

End of official record.

Evan H. Anders
PO Box 725
Colbert WA 99005-0725

NAME: Anders, Evan Henry
STUDENT NR: ████████/104330960   BIRTHDATE : 02/12/XXXX
PRINT DATE: ████████

Requested By: Evan Henry Anders

Other Institutions Attended:

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

==
COURSE TITLE   CRSE NR   UNITS   GRADE   PNTS
==

-------   Fall 2014 UC Boulder   ------
    College Arts & Sciences GRAD   Astrophysical & Planetary Sci

Course Title	CRSE NR	UNITS	GRADE	PNTS
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 Dark Matter	ASTR 6000	1.0	B+	3.3

   ATT 11.0 EARNED 11.0 GPAHRS 11.0 GPAPTS 42.10   GPA 3.827

CUMULATIVE CREDITS :

	TR UNITS	CU UNITS	TOT UNITS	QUAL UNITS	QUAL PTS	GPA
GRAD	0.0	11.0	11.0	11.0	42.10	3.827

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