Determining the role of the tachocline in solar dynamo creation; Modeling the surface appearance of solar magnetic fields (Need to cogently combine these ideas)

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Abstract

The Sun is magnetically active due to a magnetic dynamo which is powered by the solar convective zone. Numerical simulations have offered great insight into the nature of the magnetic fields within the Sun's convective zone. However, generally these simulations have been done for too large of rotation rates and too large of characteristic convective motions. Here I propose to create a suite of 3-D numerical simulations of the solar convective zone with accurate solar rotation and velocity profiles. My primary goal is to determine the role of the solar tachocline in producing and sustaining the solar magnetic dynamo. Furthermore, a more detailed set of simulations which include large-scale details of the solar photosphere will be created and post-processed in order to directly compare simulation data with data such as that gathered by spacecraft such as the Solar Dynamics Observatory.

1 Intro

The Sun is a magneticly active star. Its magnetism arises from an organized dynamo which is seated in the turbulent plasma motions in the solar convection zone, which constitutes roughly the outer 30% of the solar radius. In the presence of convective motions, magnetic fields and solar rotation couple 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 which is generally referred to as solar activity, including magnetic storms and coronoal mass ejections. Such activity propagates towards Earth, threatening to disrupt power grids and aircraft operations and to endanger astronauts and satellites. It is clear that the Sun's magnetism affects our increasingly technological society, and understanding the nature of the dynamo that drives solar magnetism is of paramount importance.

While current models lack the power to accurately predict the stellar magnetic environment over long time scales, our understanding of the workings of the solar dynamo have vastly improved over the past decade. Helioseismology, which probes the Sun's radial structure and sub-surface convective flows using acoustic oscillations, has revealed that the solar differential rotation profile extends through the bulk of the convective zone with two distinct shear regions. A near-surface shear layer occupies roughly the outer 5% of the Sun and a secondary shear layer, called the tachocline, resides at the base of the convective zone and separates the differentially rotating convective zone from the uniformly rotating radiative zone. Traditionally, it has been believed that the tachocline generates the magnetic dynamo. In such a model, 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 and manifesting as sunspots.

The current theory of the processes that govern the solar dynamo has been largely informed by large-scale 3-D numerical simulations. Such simulations have proven that global magnetic structures can be generated and persist even in the turbulence of the solar convective zone. However, most simulations of solar convection are truly simulations of Sun-like stars rather than the Sun itself. Such simulations model starts with greater rotation rates and greater convective flow velocities than our sun. It has recently been discovered that these simulations may not perfectly reflect the physics that happens in the Sun as the amplitudes of large scale convective motions in the sun are likely much smaller than anticipated and assumed in past simulations (Lord et al. 2014). Through lowering the stellar rotation rate to that of the solar rotation rate (roughly 25 days around the equator and 35 days around the poles) and decreasing the amplitudes of convective motions within modeled solar convection zones, it is now possible to gain an understanding of the physics at work within the Sun itself through simulations, rather than just sun-like stars.

In the context of accepted dynamo theory, an unsettling result has arisen in recent simulations of sun-like stars in that there is a disagreement regarding the necessity of the tachocline in generating the solar magnetic dynamo. Stable solar dynamos have been created 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: is the tachocline a necessary ingredient in the production of the solar toroidal magnetic field? Furthermore, is a tachocline necessary to produce a solar dynamo? Those simulations which produced opposing results were made with different codes using differing models for subgrid processes at various stellar rotation rates. Consequently, it is impossible to meaningfully compare the results of the simulations directly. The data required to determine the necessity and role of the tachocline are missing.

Furthermore, while simulations of stellar magnetic dynamos have proven irreplaceable in gaining insight to the structure and evolution of long-term cycles, they lack applicability to measured data and day-to-day predictive power. With the wealth of spacecraft currently gathering data on the Sun in addition to the numerous missions which are scheduled to launch within the next decade, now is the time to bridge the gap between theoretical dynamo simulations and direct observations of solar activity.

2 Proposed Research: Tachocline

I propose a series of hydrodynamical simulations of the Sun's convective zone which test the role of a tachocline in the generation of a solar magnetic dynamo. This suite of simulations will model the majority of the convective zone, from its base around $R = 0.713R_\odot$ up to nearly its outer layer around $R = 0.97R_\odot$. The primary differences between simulations in this suite will be whether or not the convective zone is modelled with or without a tachocline at its base. While it has been the general assumption that toroidal magnetic wreaths are generated within the tachocline, this assumption has not yet been put to the test. As a keystone of the theory of solar dynamo creation, the importance of the tachocline must be understood in order to make any meaningful predictions of the behavior of solar magnetism.

I will use the widely-known Anelastic Spherical Harmonic (ASH, Clune et al. 1999) spectral solver, which I will have access to through my advisor, Ben Brown, to create my simulations. The use of a well-established code such as ASH will allow me to efficiently model the solar convective zone in spherical coordinates and gain and understanding of the physics driving the solar dynamo without having to worry about generating a fully functional modelling 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*.

3 Proposed Research: Observables

While simulations are extremely beneficial in gaining an understanding of 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: one which spans the entirety of the solar convective zone and reaches out to the solar photosphere in order to determine the behavior of the magnetic fields at the observable surface of the Sun. In efforts to model the true physics of the Sun as acurately as possible, these simulations will capture supergranular scales but will ignore small scale granulation. This simplification will be made for two reasons. First, the small scale motion of granulation is unlikely to greatly affect the overall motions of the vast solar convective zone (as they have characteristic length scales roughly two orders of magnitude apart). Second, the computational load that would be required to resolve granular scales would push the number of CPU hours required for a project of this magnitude past that which is feasible to acquire on state-of-the-art machines.

Numerous post-processing techniques would be used on the photospheric data given by these simulations in order to create synthetic observables. Atmospheric and radiative transfer models would be used to transform simulation data (which is known precisely in terms of fields and velocities) into observable phenomena (namely, sunspots). Presumably, simulations which 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 behave similarly to real sunspots, then we know that our theory of the dynamo is working properly and we will have taken a step towards being able to predict solar weather through pattern recognition.

The synthetic observables created by these simulations would be directly comparable to data from the Solar Dynamics Observatory (SDO) and the Van Allen Probes. Those structures and behavioral patterns which arise in the results of the proposed simulations can offer insights into the workings of the real solar convective zone and can potentially be used to predict unusual solar activity in the future. Furthermore, the scheduled Solar Orbiter Collaboration (SCO) will be the first spacecraft to study

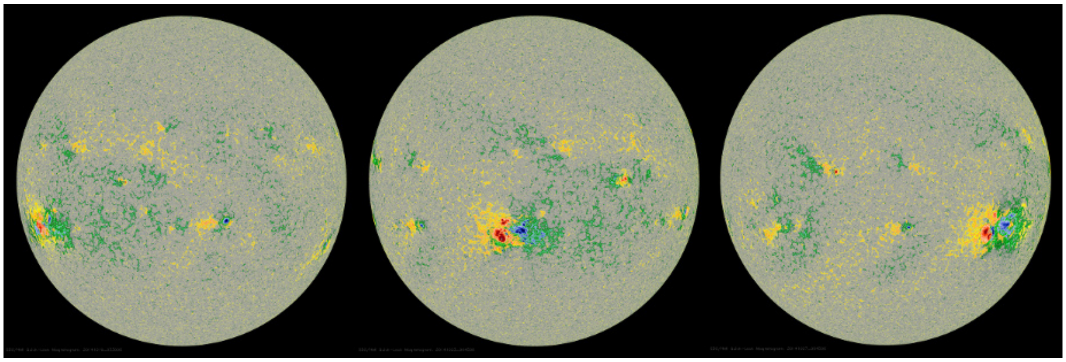

Figure 1: SDO Colorized magnetogram images of solar active region AR 12192, taken on 10/19/2014, 10/23/2014, and 10/27/2014, respectively. Simulated observables could mimic the behavior of regions such as this and help us understand when and why they release solar flares such as the X3.1 flare released on 10/24/2014.

the solar poles in detail. While current spacecraft will prove beneficial in drawing ties between theoretical structure and actual magnetic structures near the solar equator, SCO will offer an opportunity to understand the results of such simulations along the solar poles.

4 My Qualifications

My education has prepared me to think as both a physicist and a computer scientist when approaching problems and writing code. In 2012, I worked with Pacific Northwest National Laboratory's (PNNL) Data Intensive Scientific Computing group and gained an understanding of the challenges 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) created by others for my own purposes. Furthermore, I learned numerous techniques for debugging and optimizing my routines—techniques which will certainly come in handy while trying to get a simulation base fully operational and ready to be sent on to a supercomputer.

Furthermore, 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 information about the data at those frequencies 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 massive 3D simulations.

Coupled with my strong undergraduate education in physics, I am in the process of learning the fundamentals of fluid mechanics and plasma physics necessary to understand the processes which govern the motion of the solar convective zone. As such, by the beginning of the 2015 academic year, I will be well-poised to tackle these proposed problems.

5 Relevance to NASA

The proposed work fits perfectly with NASA's 2014 Strategic plan objectives 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."

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 over recent years, it has progressed with an untested assumption as a cornerstone and a series of impressive simulations with no tangible connection to observables. After recent simulations have disagreed regading the importance of the tachocline in the production of the solar magnetic dynamo, it is time to put the assumed importance of the tachocline to the test. Furthermore, it is time to connect simulations to the real world. In order to have a consistent, predictive theory on the behavior of the solar magnetic field, it is necessary to connect theoretical calculations—those largely present in large-scale numerical simulations—with tangible observables. Only once these two sources of data are connected will we be able to possibly predict upcoming solar magnetic behavior.

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