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

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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 with accurate solar rotation and convective velocity profiles. 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 for the purpose of post-processing 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.

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. 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 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 and 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 over the past decade. It is observationally proven that the surface of the sun rotates differentially, and that 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 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,

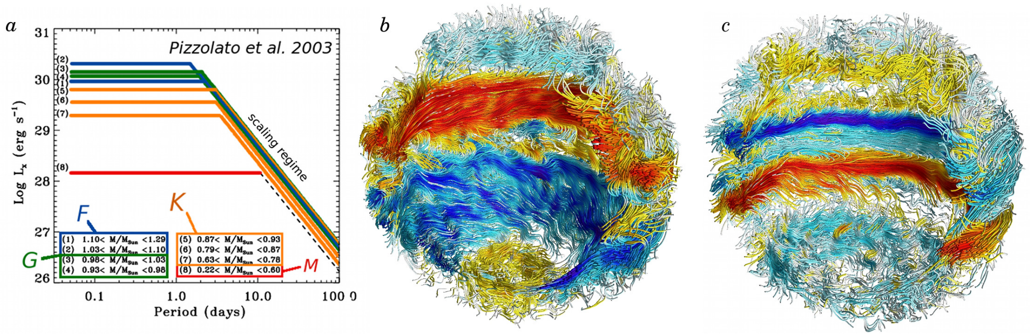

Figure 1: (a) Observationally measured stellar x-ray luminosity is plotted versus stellar rotation period. There is a clear increase in x-ray luminosity (powered by stellar magnetism) as rotation period decreases (Pizzolato et al. 2003). (b) Global scale toroidal wreaths of magnetism have been obtained 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).

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. 1*a*). 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. 1*b&c*.

In light accepted dynamo theory, an unsettling result has arisen in recent simulations of Sun-like stars. Recent simulations disagree on 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 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 realate 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 0.5 $R_\odot$ while the other simulation will stop at the base of the convective zone around 0.713 $R_\odot$, 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; Lucie Alvan 2014). The use of a 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 machiens.

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) 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

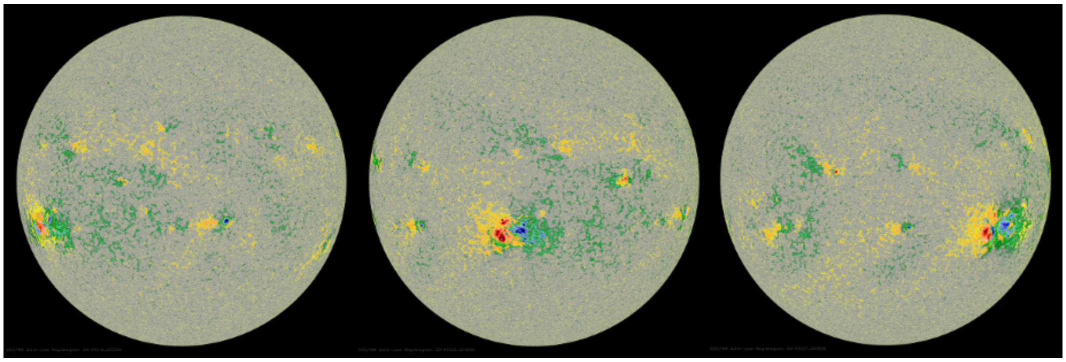

Figure 2: SDO HMI colorized magnetogram images of solar active region AR 12192, taken on 10/19/2014, 10/23/2014, and 10/27/2014, respectively. Simulated observables could mimic the behavior of regions such as this and help us understand when and why they release solar flares such as the X3.1 flare released on 10/24/2014.

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 synthetic observables can be tested against data from current spacecraft (namely, SDO) in order to understand familiar structures, synthesized observables can also be used to make predictions about phenomena that will be observed by SCO along the solar poles.

4 Timeline of proposed work

Year 1: Create and execute first suite of simulations. Successfully gather data necessary to determine the role of the solar tachocline.

Year 2: Analyze simulated data to gain an understanding of the tachocline's role in generating the solar dynamo. Begin work on second suite of simulations to be used in the creation of simulated observables.

Year 3: Create simulated observables. Compare the evolution of interesting simulated events to similar observed events. Make predictions regarding polar data from upcoming Solar Orbiter.

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.

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