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

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Abstract

The Sun is magnetically active due to a magnetic dynamo powered by the solar convective zone. Numerical simulations have offered great insight into the nature of the magnetic fields intrinsic to this dynamo. Traditionally, these simulations are carried out for solar-type stars with high rotation rates and characteristic convective motions much larger than those realisable within the Sun. Here I propose to create 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 producing and sustaining the solar magnetic dynamo. Furthermore, a more detailed set of simulations which include the supergranulation of the solar photosphere will be created and post-processed to create synthetic observable which will be directly comparable with data such as that gathered the Solar Dynamics Observatory and other spacecraft.

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 which is generally referred to as solar activity, including magnetic storms and coronal mass ejections. Such activity propagates towards Earth, threatening disruption 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.

While current simulations lack the power to accurately predict 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 has Observationally, it is known that the surface of the sun rotates differentially, with the poles rotating roughly every 35 days and the equator rotating every 25 days. Through 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 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 located radially inward. Traditional models of the solar dynamo, namely Babcock-Leighton flux-transport dynamo models and interface dynamo models, have stated that the tachocline drives the production of the toroidal magnetic fields which fuel the solar dynamo and manifest at the solar surface as sunspots (Miesch & Toomre 2009). 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.

Numerically simulating the solar environment requires working with wide ranges of spatial and temporal timescales, which is one of the main sources of difficulty in creating meaningful simualtions. Regardless of this, the underlying equations at the heart of these magnetohydrodynamic (MHD) simulations are quite simple, expressing conservation of mass, momentum, and energy and accounting for magnetic induction (Charbonneau 2014). Most simulations have modelled stars with higher rotation rates than the sun, as the strength of the magnetic dynamo increases with increasing rotation rate (see Fig. 1a). Such simulations have largely informed solar dynamo theory and have even generated self-sustaining, buoyantly-rising toroidal wreaths of magnetism with polarity shifts on long time scales, such as those shown in Fig. 1b&c.

In the context of accepted dynamo theory, an unsettling result has arisen in recent simulations of Sun-like stars: there is a disagreement regarding the necessity of the tachocline in sustaining 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.

Additionally, most simulations of solar convection simulate 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 accurately capture the physics at work in the Sun as they assume much larger amplitudes of large scale convective motions than those that are actually present in the Sun (Lord et al. 2014). Such a discovery calls for a new set of solar numerical simulations with a more accurate description of convective flows than that which has existed in previous simulations.

Through lowering the stellar rotation rate to that of the solar rotation rate 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. Furthermore, while simulations of stellar magnetic dynamos have proven irreplaceable in gaining insight into the structure and evolution of long-term cycles, they fail to compare to *in-situ* measurements of solar magnetism and cannot provide insight on short-term scales. With the wealth of spacecraft currently gathering data on the Sun in addition to the numerous missions

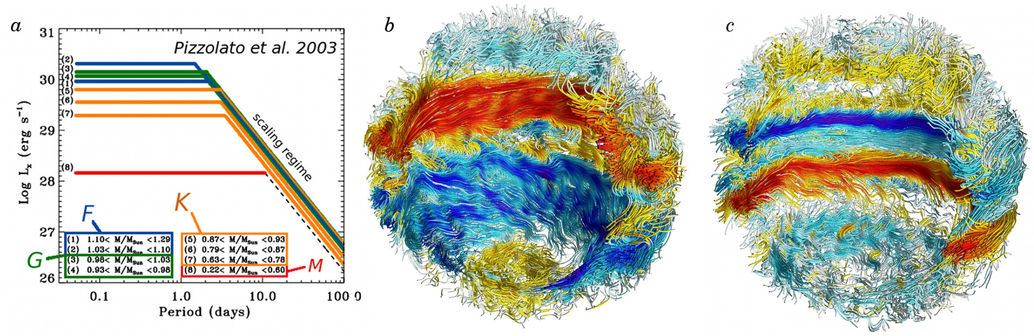

Figure 1: (a) Observationally determined relations between magnitude of stellar x-ray luminosity versus rotation period showing a clear increase in x-ray luminosity (powered by stellar magnetism) with decreasing rotation periods (Pizzolato et al. 2003). (b) Toroidal wreaths of magnetism obtained through numerical simulations with the ASH code which show a clear polarity inversion (c) over long time scales.

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 Does the tachocline drive the sun's toroidal magnetic fields?

I propose a set of hydrodynamical simulations of the Sun's convective zone which test the role of a tachocline in the generation of a solar magnetic dynamo. These simulations will model the majority of the solar convective zone, from its base around $R = 0.713R_\odot$ up into the base of the outer 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 and one simulation will not. As dynamo theory champions the tachocline as the seat of the toroidal component of the solar magnetic field, it is time to put this theory to the test. The likeness of these simulations will allow for a direct comparison of their results, allowing a certainty regarding the role—or lack thereof—of the tachocline in generating and maintaining the solar dynamo.

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*.

I have been well prepared by my past education to undertake the creation of a simulation 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 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.

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 and implement the processes which govern the motion of the solar convective zone.

3 Simulated observables: Connecting observations and simulations

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.

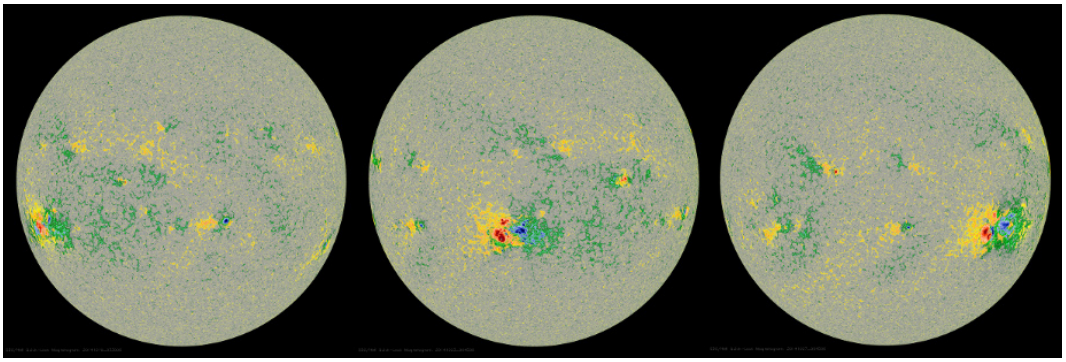

Figure 2: SDO Colorized magnetogram images of solar active region AR 12192, taken on 10/19/2014, 10/23/2014, and 10/27/2014, respectively. Simulated observables could mimic the behavior of regions such as this and help us understand when and why they release solar flares such as the X3.1 flare released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

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 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 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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