GENERATION, EVOLUTION AND DESTRUCTION OF SOLAR MAGNETIC FIELDS

(Measuring & Modeling the small-scale magnetic flux of the Sun)

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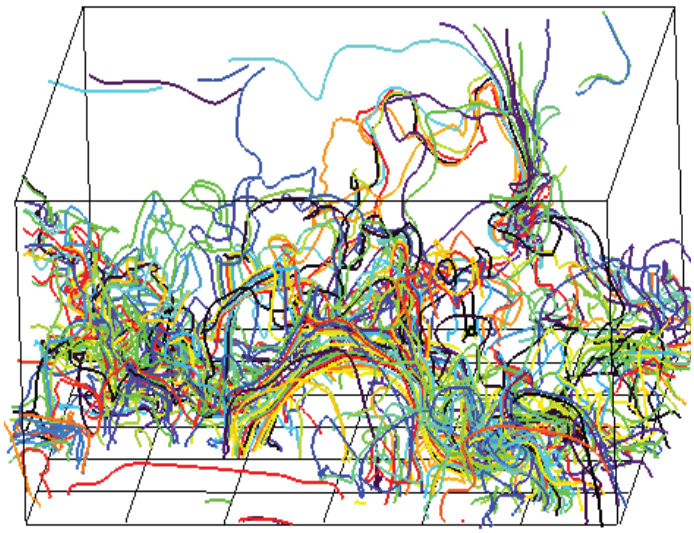
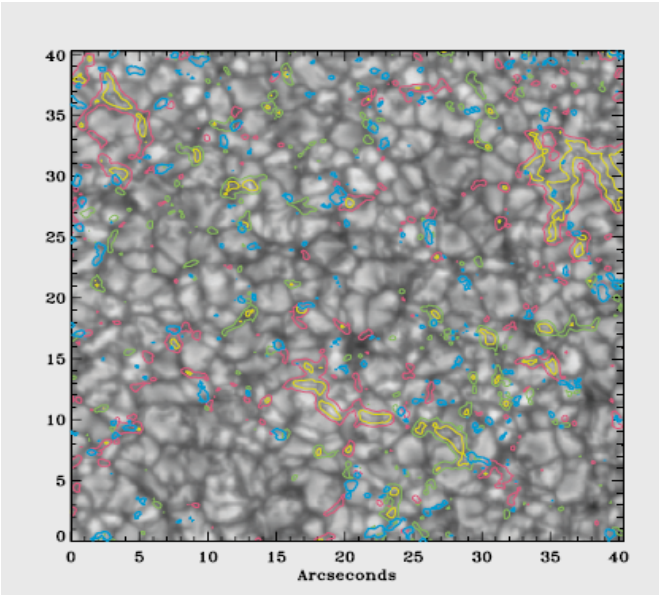


Modeling: Result from a simulation of magnetoconvection by Stein and Norlund (2006).



Observation: HINODE observations of continuum intensity with contours of longitudinal (red and green contours) and transverse field (blue) superimposed. (Lites et al. 2008)

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Introduction

Magnetic fields are important throughout astrophysics, including solar and stellar physics, but their role is poorly understood. This is in part because direct plasma physics experiments and simulations cannot access the regimes important to astrophysics. The Sun provides the only natural laboratory where crucial properties of non-linear dynamics in highly ionized magnetic plasma can be well observed and understood, and models can be tested and refined.

More specifically, magnetic fields control the inconstant Sun. The complex magnetic field that threads the solar photosphere shapes the Sun's entire atmosphere and provides the power for its hearty and frequent explosions (Metcalf et al. 2008). The interaction of interior convection and the magnetic field produces stress that leads to magnetic heating of the layers above. Thus, understanding all aspects of the solar magnetic field is crucial to understanding solar variability and its direct impact on the Earth.

Magnetic fields are important in the heating and energetics of both the quiet and active sun. This interaction may also change atmospheric properties in a way that alters abundance determinations (Asplund 2005: Scott et al. 2009: Socas-Navarro & Norton 2008). To understand the magnetically driven energization of the solar atmosphere, it is essential to have an accurate quantitative observational characterization of the magnetic fields and their evolutionary properties, as well as accurate models to obtain physical parameters.

In the following sections, we introduce the Sun's small scale field and how it is measured, describe several current results and questions in the science of the solar magnetic field, and discuss modeling and instrument capabilities required to tackle them

The Solar magnetic field

The Sun exhibits two general patterns of magnetic field: an oscillating global field related to the 11 year sunspot cycle and evidenced by coherent, patterned emergence, breakup, and diffusion of sunspots and their associated active regions; and a universal, apparently random background of small concentrations of magnetic flux on all observable scales to the limit of current observations. Observed magnetic poles vary in size and flux from ~100km diameter features with $\sim 10^{15}$ Mx, through large active regions with a few times 10^{22} Mx. At scales ~10Mm, flux concentrated into downflows between supergranules forms the solar magnetic network of flux concentrations that survive tens of hours; on smaller scales shorter-lived "intranetwork" concentrations exist within supergranules; and below ~1Mm, magnetic flux concentrations can be seen forming in the intergranular lanes, analogous to (but shorter lived than) the supergranular network. This small scale flux appears to be produced independently the solar cycle (e.g. Parnell et al. 2009 & refs therein), and is collectively referred to as the solar "magnetic carpet" (Title & Schrijver 1998). Neither the global nor the background magnetic field are well understood theoretically, though recent advances in modeling and measurement have yielded new insight.

Measurement

Magnetic fields on the Sun are currently measured via the Zeeman splitting, typically in a photospheric spectral line. Spectropolarimetry yields the most sensitive and complete diagnostics of the magnetic field, but yields small fields of view and/or spatiotemporal resolution. Spectral imaging techniques such as scanned filters or Fourier tachometry provide either line-of-sight magnetic field measurements (via the antisymmetric Zeeman splitting in Stokes V) or full vector measurements (via the symmetric splitting in Stokes Q and U) over an entire image plane simultaneously. New instrument techniques, such as image slicing (Lin 2006) or spectral stereoscopy (DeForest et al. 2004), are under current development to enable higher sensitivity. Magnetic field measurements that use the Hanle scattering-depolarization effect are under active development by several groups (e.g. Stenflo et al. 2002, Trujillo-Bueno et al. 2006).

Understanding the solar dynamo

Understanding the solar dynamo has applications well beyond solar and stellar physics, because of the limitations of current dynamo theory and modeling.

The magnetic and kinematic Reynolds numbers Re_m and Re, and their ratio (the Prandlt number P_m), determine dynamo behavior. In hot rarefied plasmas, such as the warm and hot phases of the ISM, $P_m>>1$ and a small-scale dynamo is theoretically well established. In contrast, $P_m<<1$ in the Sun's convective zone, in planets, and in proto-stellar disks, all of which have disordered fluctuating small scale magnetic fields and are expected to be in a turbulent state (e.g., Brandenburg & Subramanian 2005, Schekochihin et al. 2004,2005,2007). This case is neither as well explored nor as well understood as $P_m>>1$. For example, the presence of the magnetic carpet is likely related to small-scale dynamo action as numerically simulated by Cattaneo 1999; Cattaneo et al. 2003; Stein and Nordlund, 2006, Voegler & Schuessler 2007. However, these simulations all have $P_m \geq 1$ (Figure 1).

To understand solar activity and solar variability as well as magnetism of other astrophysical systems, we need to understand these processes in detail. Because quite small scale turbulent fields can in principle be resolved on its surface, the Sun provides us with a unique "laboratory" to advance our understanding of dynamo processes.

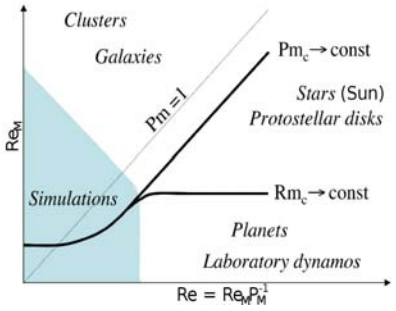


Figure 1: The stability curve of turbulent small-scale dynamo vs. Re and Re_m. Numerical effects limit current simulations to regimes that are more viscous and resistive than astrophysical systems such as the Sun, requiring direct observation to make progress.

There are two generic types of dynamo. A large-scale or *mean field dynamo* generates magnetic fields at scales larger than the energy-containing scale of the turbulence, whereas a *small-scale dynamo* amplifies magnetic fluctuation energy below the energy-containing scale of the turbulence. The small-scale dynamo is usually a much faster process than the mean-field dynamo, and the large-scale field produced by the latter can be treated as approximately constant on the timescale of the small-scale dynamo. It has been hypothesized (e.g. Voegler & Schuessler 2007) that both classes of dynamo exist in the Sun, with a separate small-scale process driven by convective turnover and a global dynamo controlled by bulk flows. These two scales of dynamo are not wholly independent: they are coupled by shredding and aggregation of flux. On the Sun, there is a cross-scale equilibrium between these processes (Schrijver et al. 1997). Currently unresolved physics dominates both the solar network and the smallest currently-resolvable (100km) flux concentrations (Lamb et al. 2008, 2008b).

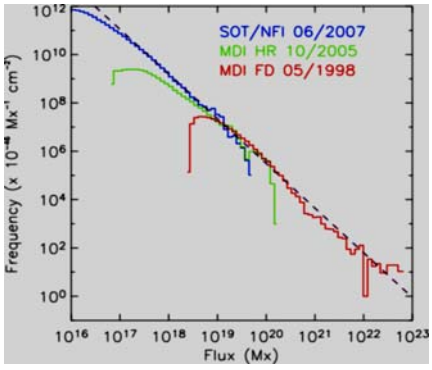


Figure 2. Flux concentration frequency vs. flux, detected by computer vision, follows a -1.8 power law across three instruments and nearly six decades in flux (Parnell et al. 2009). Is the slope break at the small end from instrument effects, or from the Sun?

Small scale activity on the Sun would influence the global dynamo even in the absence of direct coupling between the large and small scale dynamos. Models that attempt to explain large-scale solar magnetic fields are based on theories involving large averages (mean field, Weiss and Thompson, 2008). Turbulent convection is believed to stretch and amplify the magnetic field while differential rotation, meridional circulation, and the tachocline shear layer at the base of the convection zone are believed to organize a deep, large-scale solar magnetic field of several 100 kgauss. Properties, such as diffusion and helicity, that must be assumed in these models are produced by small-scale turbulent processes and have not yet been measured.

High spatial, temporal, and spectral resolution is needed to observe the turbulent vorticity and the diffusion of small-scale magnetic fields to measure these properties and how they evolve with the solar cycle.

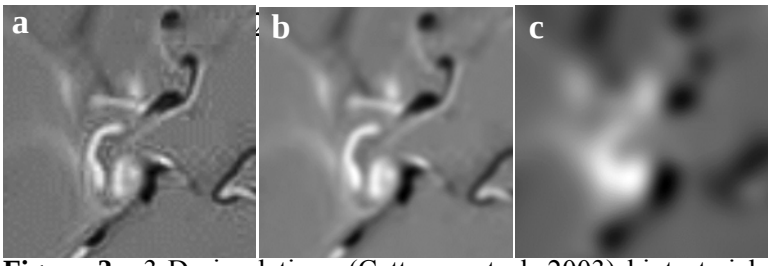


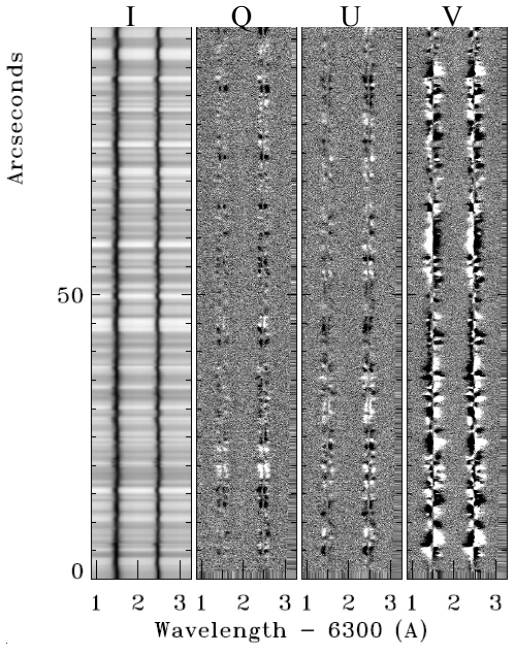
Figure 3. 3-D simulations (Cattaneo et al. 2003) hint at rich, new phenomena just below currently accessible spatial resolution. (**a**) At full (10km grid) resolution, miniature vortices and convective flux tube collapse are visible in intergranular lanes. (**b**) Simulated 4 meter telescope (e.g. ATST) resolves the vortices and horizontal twisted flux tubes. (**c**) Simulated 1 meter telescope fails to resolve the important small-scale dynamics.

Two dynamos, or one?

Although it is commonly hypothesized that at least two separate dynamo mechanisms exist in the Sun (e.g. Leighton 1964, Voegler & Schuessler 2007), the frequency of flux concentrations on the Sun shows a (-1.8) power law versus contained magnetic flux, over nearly six decades in flux, suggesting that the dominant formation mechanism of flux features is scale invariant from global scales to nearly the smallest currently observable scales (Parnell et al. 2009; Figure 2). (If two separate mechanisms were injecting flux on different scales, one would expect a "break" in the power law somewhere between those scales.) Simulations by Stein & Nordlund (2006) also suggest scale invariance on all currently accessible scales.

This extremely wide hierarchy of scale poses many questions: How do strong fields and weak fields interact? Does the weak-field component have a large-scale structure? How are they generated? How do they contribute to chromospheric and coronal magnetism and heating? How do they influence determination of elemental abundances?

Figure 4. Stokes polarimetry at 630nm of the quiet Sun shows ubiquitous transient horizontal magnetic fields (Lites et al. 2008) even in quiet Sun. A much larger aperture is needed to resolve the mixed polarity fields and study their evolution on short time scales.



The curve in Figure 2 shows a break at the small end of the distribution; this may be caused by either proximity of the detection threshold or a change in the physics. There is reason to think that the dynamics of magnetoconvection change below the scale of granulation, which dominates solar convection: granulation imposes an effective diffusion constant on larger flux features, which is absent on smaller scales, allowing convective collapse, vortical mixing, and related phenomena. 3-D magnetoconvection models (Figure 3) show different behavior on sub-100km scales than on larger ones, hinting that *the energetically dominant spatial scale for the solar dynamo may be immediately below the scales accessible with current (meter-class) solar telescopes.*

To address these questions we must resolve individual magnetic flux concentrations and observe their emergence and dynamics. We must measure the distribution functions of field strength, field direction and "flux tube" sizes and compare these with theoretical models. This also requires observing plasma motions and relating them to the magnetic field.

Horizontal Fields: a “smoking gun” for the small-scale dynamo?

Recent work with GONG+ (Harvey et al. 2007) and Hinode (Lites et al. 2008, Ichikawa et al. 2008) shows a ubiquitous presence of strong, horizontal fields throughout the quiet Sun (Figure 4), even in supergranular interiors (internetwork). The similarity of the density functions and of the occurrence rates in plage and quiet regions of these horizontal fields suggests that indeed a local dynamo process is generating these fields (Ichikawa and Tsuneta 2009). These fields telescope; ~0.2" resolution) observes only part of the distribution, adding further urgency to the need for much finer resolution measurements.

Magnetic and Current Helicity

Helicity plays a fundamental role in evolution and topology of solar magnetic fields on different spatial and temporal scales (Pevtsov et al., 2008; Pevtsov, 2008, Pevtsov and Longscope, 2009). Helicity is essential for the effective operation of a dynamo, but excessive helicity may suppress the dynamo action. To ensure efficient operation of the dynamo, helicity has to be removed from the dynamo region and transported to the corona (Brandenburg, 2007). On their way to the surface, magnetic fields can accumulate additional helicity by interacting with convective turbulence. Since coronal fields can store only a limited amount of helicity it needs to be removed from the sun via coronal mass ejections.

Is active region helicity primarily due to interaction with convection or produced by the large-scale dynamo? What is the contribution of surface horizontal flows? The propagation of twist to the corona depends on the emergence of twisted fields, surface flows and Alfven waves and can provide information on the origin of magnetic helicity (Nandy, 2006; Chae, 2007). Detailed modeling combined with high-resolution vector magnetograms of large number of active regions will allow us to separate dynamo and turbulence contribution to the helicity.

We need high spatial resolution vector magnetograms to provide crucial information about evolution of magnetic field twist during flux emergence. To detect helicity "pumping" by Alfven waves will require a computation of electric currents inside individual “flux tubes” -- a task well outside the ability of existing ground and space-based telescopes.

Fine-scale observations of magnetic helicity in the quiet sun are necessary to understand the role, if any, of a small-scale dynamo. The coriolis force affects large scale flows and results in hemisphere-dependent helicity in the global dynamo. In contrast, the small-scale photospheric flows are not strongly affected by the Coriolis force, so helicity from a small-scale dynamo is expected to be hemisphere independent (Pevtsov & Longcope 2009). If the local dynamo simply recycles flux generated by a global dynamo and shredded by convection, the hemispheric helicity rule should be present. Testing the presence of a small-scale dynamo requires observations of vector magnetic fields with spatial resolution significantly better than 0.1 arcsec.

Small-Scale Magnetic Flux Concentrations

The photospheric magnetic field is organized in small fibrils or “flux tubes”, which account for a significant fraction of all the magnetic flux threading the photosphere. These structures are mostly unresolved by current telescopes, yet aggregation of this unresolved flux is the dominant mechanism by which small-scale flux concentrations form (Lamb et al. 2008). Magnetic field lines are the most likely channels for transporting convective energy into the upper atmosphere, which is the source of UV and X-ray radiation from the Sun, which in turn affects the Earth’s atmosphere. Detailed observations of these fundamental building blocks of stellar magnetic fields are crucial for our understanding not only of the activity and heating of the outer atmospheres of late-type stars, but also of other astrophysical situations such as the accretion disks of compact objects, or proto-planetary environments. Current solar telescopes cannot

provide the required spectroscopy and polarimetry at an angular resolution to explore the enigmatic "flux tube" structures (e.g. Figure 3).

Theoretical calculations and numerical simulations suggest that small-scale flux concentrations are formed by convective intensification by the photospheric flow field: flux is continually swept to the intergranular downflow regions where it is concentrated, twisted by local vorticity in the intergranular downflows, and radiatively cooled to form coherent flux bundles. The flux concentrations are highly dynamic, undergoing constant merging, shearing, fragmentation and reformation leading to substructures predicted to be on the order of a few tens of kilometers in scale. Interaction of the flux concentrations with convection buffets, bends, and twists the magnetic field, which heats the upper atmosphere via MHD waves and intertwining of magnetic lines leading to magnetic reconnection and ohmic dissipation of currents.

In spite of the significant progress in adaptive optics (Rimmele, 2004; Langangen et al. 2007), current observations lack the spatial and temporal resolution necessary to verify these theoretical predictions of small-scale flux formation and flow-field interactions (Stein and Nordlund, 2006). Flux-associated bright points are observed to undergo constant splitting and merging on time scales of 10-100 seconds in response to granular flows, similar to the turbulent 3D simulations. However, observations of the formation and decay mechanisms of flux tubes, or of the expected vorticity, are lacking. Such observations require vector magnetic field measurements on spatial scales of a few tens of km combined with a temporal resolution on the order of 10 seconds.

Small-Scale Flux and Solar Atmospheric Heating

Investigating the role of small-scale flux dynamics in powering the Sun's outer atmosphere also requires new levels of spatial and temporal resolution. The TRACE mission (Handy et al. 1999; Schrijver et al. 1999) has shown that coronal fine structure exists on arcsecond scales and very likely below this level as well. However, chromospheric and transition region motions are still not fully resolved in time or space, and the magnetic topology relating the photosphere to the corona remains completely unclear. For example, transition region emissions from hot coronal loop foot points correlate only on the large scales to magnetic field sites in the lower atmosphere (Berger et al. 1999, Nagata et al. 2006). At smaller scales, transition region emissions do not directly overlie Ca II K-line chromospheric bright points or G-band bright points in the photosphere. Thus coronal loops do not appear to be vertically anchored to their associated flux concentrations in the photosphere. Are magnetic field lines entangled by motions as they rise through the atmosphere? Or are the transition region emissions (and perhaps coronal loop heating sources) located at the interface regions of expanding magnetic field lines from the photosphere? Can we correlate flux motions in the photosphere with impulsive events in higher layers of the atmosphere such as spicules and transition region explosive events and ultimately with episodic heating of coronal loops?

MHD waves propagating along magnetic fibrils are a likely candidate for transporting energy to the upper atmosphere (Zagarashvili & Skhirtladze, 2008). In many cases, detailed model predictions, including detailed simulations of observable quantities, such as spectral line profiles or Stokes profiles, are available. The spatial resolution in these models is of the order of a few tens of kilometers and similar resolution data are required to test them.

Small-scale magnetic flux also plays a large role in the total irradiance budget of the Sun. An accurate physical model of flux concentrations, however, is still lacking. Fully resolved measurements of small-scale flux irradiance as a function of disk position are needed in order to complete a realistic physical model of these important elements.

Addressing these issues requires simultaneous vector magnetometry in multiple layers of the solar atmosphere and drives the temporal resolution requirement even lower, perhaps to one second time scales or less. Only a much larger solar telescope than currently available will achieve the resolution and photon flux requirements and will also allow investigations of the role

of small scale flux in energy transport to the outer atmosphere, addressing such issues as chromospheric heating or the source of the fast solar wind in open-field regions.

Magnetoconvection and Flux Transport

The simulations predict that cold plasma forms narrow, turbulent downdraft plumes (Stein and Nordlund, 2006). However, there is no observational evidence for these small-scale (significantly smaller than 0.”1) vortex flows within the intergranular lanes. A large aperture telescope is needed to resolve the small-scale structures and dynamics of convection and verify or disprove the predictions of the models.

Vortical plasma motions, such as those that occur in the downdrafts, will stretch and amplify any seed magnetic fields, producing a small-scale dynamo. The downdrafts may also pump the small-scale magnetic flux produced down towards the base of the convection zone. Convective flows may be important in breaking up the magnetic “flux tubes” into smaller elements and in merging individual “flux tubes” into larger structures. They also may shuffle around the atmospheric magnetic loop foot points and launch MHD waves that propagate into the upper atmosphere.

The ability to resolve and track individual “flux tubes” is needed to understand how magnetic field is organized into larger scale patterns such as meso- and supergranular scales. For example, there is a controversy about the relation of magnetic fields and supergranulation. Does the supergranular scale diverging flow advect magnetic field to the network at the supergranule boundaries? Or, is it the magnetic field that produces the observed supergranulation pattern?

Another example of how a magnetoconvective process that occurs on very small scales (<100 km) causes a global phenomena are the solar p-mode oscillations. Numerical simulations provide detailed predictions on how convective energy is converted into acoustic energy, which may contribute to the heating of the lower chromosphere. While the spatial and temporal resolution of current facilities is sufficient to verify the existence of acoustic events, they are unable to study the underlying physical mechanisms and to verify model predictions. Surface cooling producing low entropy fluid is part of the process, but according to model predictions, turbulence below the surface is the more important driver. One of the remaining challenges is to understand quantitatively the origin of the oscillation mode line asymmetries. This is part of the bigger challenge of understanding the dynamical interaction of oscillations with convection.

Ultra high spatial resolution along with excellent temporal resolution is required to verify the exciting results of numerical simulations. Also needed are measurements of spectral line profiles with sufficient spectral resolution so that the information contained in the details of line profiles can be revealed.

The Advanced Technology Solar Telescope, the tool to make it happen

We have demonstrated that measuring and characterizing evolution of the very fine scale solar magnetic field is crucial to myriad topics, from astrophysical dynamo theory to solar coronal heating. The largest current telescopes are limited by diffraction to ~0".12 (~80km) spatial resolution (at λ= 500 nm), and a new, larger aperture telescope is required to make progress. Because so many science questions surrounding the solar dynamo and related phenomena require the highest possible spatial resolution, and because models predict different qualitative behavior of flux just below currently observable scales, progress on many crucial issues throughout solar physics is essentially impossible without finer spatial resolution measurements than can be obtained today.

The ATST project will enable breakthrough science that has impact throughout solar and stellar physics and the astrophysics of plasmas. Many crucial advances and breakthrough science are anticipated in the transition to the ATST, a 4 meter telescope (0".03, or 20km, ultimate

resolution). ATST will provide direct measurements of magnetic flux emergence, twist, oscillations, transport and cancellation rates in the quiet sun from magnetograms that have 16 times better resolution (pixel area) or 30 times better sensitivity (or a compromise between the two) than with the current largest solar telescopes. ATST is appropriately sized to address every single science question outlined in this document, revolutionizing basic understanding of why the Sun has a magnetic field and how that field gives rise to the solar chromosphere and corona. Because the Sun is the most readily observable system with comparable magnetic Reynolds and Prandtl numbers, results from ATST will have broad impact on understanding of astrophysical dynamos on scales from planetary magnetospheres to galactic accretion disks.

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