Solar Magnetism and Structure from the Poles

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The generation of the solar magnetic field and its subsequent driving of activity remains a major outstanding question in heliophysics. Our current understanding of the Sun, its atmosphere, and the connection to the heliosphere is severely limited by the lack of nearly ANY observations of the polar regions. Dynamo model development lacks critical constraints of the polar magnetic field as a result. Better quantitative knowledge of high-latitude convection, meridional circulation and differential rotation are crucial for understanding magnetic flux transport, polar field reversals, solar cycle models and predictions. Measuring these flows will significantly further our understanding of the solar dynamo, the ultimate driver of solar activity, and of space weather. Until these observations are obtained, the lack of constraints means it is impossible to differentiate between models or meaningfully improve models.

Unraveling this mystery has broad implications not only for promoting a deeper knowledge of the Sun itself, but also for understanding the Sun's influences on the heliosphere, the geospace environment, and our technological society. Such influences regulate space weather that has increasing economic impacts on our technological society as our reliance on telecommunications systems, power grids, and GPS systems continues to grow. As a readily observable example of an astrophysical magneto-hydrodynamic (MHD) dynamo, the Sun also provides unique insights into the generation of magnetic fields by turbulent plasma flows that occur throughout the universe, from planetary and stellar interiors to black hole accretion disks to interstellar clouds.

The global magnetic polarity of the Sun reverses during each sunspot cycle. Understanding how such regularity arises from the highly turbulent conditions of the solar convection zone, and how magnetic flux emerges from the solar interior to power solar variability is a formidable challenge. The polar fields reverse at about the time of sunspot cycle maximum. While it is clear that this reversal results from the transport of magnetic flux elements in the near surface layers, it is unclear which processes dominate this transport. The poleward meridional flow (that dominates at low latitudes) may not extend all the way to the poles. While the horizontal random-walk of vertical magnetic structures by the evolving cellular convection should extend to the polar regions, the implications of the transport of the ubiquitous horizontal fields remains very uncertain. The polar fields reach their maximum strength near the end (minimum) of each sunspot cycle. This field strength has been empirically shown to be the best predictor of the size of the following sunspot cycle, but how the polar fields are translated into sunspot fields is still highly uncertain. Thus, for developing physics-based forecasts of solar activity, it is extremely important to investigate the structure and evolution of the polar magnetic fields and the mechanisms of magnetic flux transport.

There is no doubt that both theoretical and observational approaches are required to take up this challenge. On the observational side, measuring high-latitude solar internal flows is of the greatest importance. Differential rotation and shallow meridional flows have been reliably measured by helioseismology techniques up to latitude of about 60°. It is essential to extend these measurements to the polar region as we continue to advance our understanding of solar dynamics as a whole. It is the polar region where converging meridional flow, carrying magnetic flux, must turn downward towards the solar interior, and it is the polar region where magnetic polarity reversal takes place in the surface layers. Moreover, it is only observations of the polar region that can resolve the great uncertainty of polar magnetic field structure present in modern solar synoptic maps, which serve as fundamental inputs for many solar physics and space weather studies. Finally, it is the polar regions that hold the greatest promise for revolutionizing our understanding of deep solar convection. It is there, where changes in convective structure and associated flows (such as a long-suspected polar vortex), and which derive from the presently unknown deep convective velocity spectrum, are expected to be most readily visible at the surface.

What are the patterns of subsurface flows at high latitudes?

In the past three decades, determination of the solar internal rotation profile and near-surface meridional circulation by means of global and local helioseismology has revolutionized solar dynamo theory. Rotational shear has long been an essential ingredient in all solar dynamo models, as the principal generation mechanism for the global-scale toroidal magnetic flux that ultimately emerges from the solar interior to form active regions. More recent flux-transport dynamo models have further identified flux advection by the mean meridional circulation as a key factor in the establishment of cyclic magnetic activity. In particular, the poleward advection of emergent toroidal flux from lower latitudes may account for the polarity reversals of the polar field and thus the cyclic reversals of the global dipole moment. Possible correlations between the high-latitude meridional flow speed and activity patterns, such as cycle amplitude and duration, are necessary to distinguish among various dynamo paradigms. Regardless of the dynamo mechanism, surface flux transport models indicate that the strength and distribution of the polar magnetic field (crucial for coupling to the heliosphere) is sensitive to the amplitude and structure of the high-latitude meridional circulation. Determination of the differential rotation and the meridional circulation in the polar regions will thus provide unprecedented insights into the dynamics of the convection zone, the operation of the solar dynamo, and the solar-terrestrial interaction, bringing the helioseismology revolution to its ultimate fruition.

The unique advantages of a high-latitude vantage point will also enable us to improve measurements of the large-scale and meridional flows in the deep convection zone by means of the ground-breaking techniques of stereoscopic helioseismology. Coordinated observations with an in-ecliptic instrument such as SDO/HMI or GONG would provide the very long baselines needed to measure the relatively long-wavelength modes that sample the deep interior with local helioseismology. Such measurements are challenging but extremely important, since deep-seated flow signatures such as zonal jets may offer the most reliable probe of sub-surface magnetism.

What are the characteristics of the surface magnetic flux at the poles?

Synoptic observations of solar magnetic fields have shown evidence for transport of magnetic flux of the following polarity of bipolar active regions towards the poles. When a sufficient amount of the flux reaches the polar regions it changes the mean polarity of these regions, which in turns reverses the global polarity of the mean poloidal field. However, how the process of the polarity reversal actually occurs in detail and how it couples to the deeper convection zone is unknown. What processes determine the distribution and subsequent evolution of surface and subsurface polar flux after the reversal? How much of the polar flux is concentrated in high-strength elements and how much appears in diffuse weak-field areas? These most basic and intriguing questions of the solar magnetism problem will be addressed by a large field-of-view magnetograph viewing the pole from an inclination much greater than the maximum of 7° provided by the ecliptic or even the 30° provided by currently operating missions (Solar Orbiter).

How are surface magnetic field and subsurface flows dynamically coupled?

The most well-established signature of dynamical coupling between the zonal and meridional flows, magnetic fields, and thermal gradients is that of the solar torsional oscillations. These are alternating bands of east-west zonal flow that evolve in close correspondence with the solar activity cycle. Two components are evident from the data - a low-latitude branch that propagates equatorward in conjunction with bands of magnetic activity and a high-latitude branch that propagates poleward on a comparable time scale. The high-latitude branch is stronger and deeper and may arise from distinct dynamical influences. Correlated meridional flows and thermal signatures are known for the low-latitude branch, but are currently undetectable for the high-latitude branch. An out-of-ecliptic vantage point will provide an unprecedented opportunity to observe such correlations and in particular their phase relationships, providing important constraints to theoretical and numerical models of the solar convection zone and dynamo.

Variations of the meridional flow with the solar cycle induced by magnetic or thermal forcing also have important consequences for determining the strength and distribution of the polar field and the timing of polarity reversals. Coordinated observations of the meridional flow and the magnetic field in the polar regions will provide quantitative estimates of flux transport and will thus elucidate the physical mechanisms that underlie cyclic solar activity.

What is the structure and evolution of solar convection?

Magnetic flux transport by turbulent convection may contribute to the cyclic reversal of the large-scale poloidal field by working in concert with the meridional circulation and differential rotation. Not only does convection influence magnetism, but the converse is also true; magnetism can influence the structure of convection, and investigating the nature of this nonlinear feedback provides valuable insight into both phenomena. In particular, the structure and evolution of supergranulation in polar coronal holes, where a nearly unipolar flux permeates the photosphere, may be significantly different than that at lower latitudes where the flux distribution exhibits mixed polarity. The Lorentz force tends to decrease convective length scales but magnetically-induced enhancements in radiative cooling may counteract this effect. Careful observations at high latitudes over extended time intervals (at least hundreds of days for reliable statistics) are needed to clarify the subtle nonlinear feedbacks between solar convection, magnetism, and radiation.

Observational signatures of giant cells are notoriously difficult to glean from photospheric observations, but a high-latitude vantage point will provide new opportunities. The maintenance of mean flows by global convective motions is expected to produce thermal gradients between the equator and pole that may be detectable by helioseismic inversions or by photospheric irradiance measurements. Furthermore, theoretical and numerical models predict a change in morphology between global convective motions at high and low latitudes in rotating spherical shells. The transition between polar and equatorial convective modes occurs near the so-called tangent cylinder, a cylindrical surface aligned with the rotation axis and tangent to the base of the convection zone. This tangent cylinder intersects with the solar surface at about 45° latitude. Possible changes in the subsurface flow fields inferred from local helioseismic inversions inside and outside the tangent cylinder may provide a valuable and previously unexploited observational signature of the elusive but extremely important giant cells. *Hinode* measurements have already revealed a systematic high-latitude alignment of supergranules that may reflect the underlying influence of giant cells.