The Science Case for a 4π Perspective: A Polar/Global View for Understanding the Solar Cycle

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Will we, in 2050, look back and wonder at our lack of success in predicting the last three solar cycles? A critical gap in our knowledge of the solar cycle drivers arises because we can only see a fraction of the Sun at a time, and our ability to view the poles is severely compromised by our lack of latitude. *Here we make the case that long-duration, truly global (not just from the ecliptic) observations of the Sun's magnetic and velocity fields are required to understand the solar dynamo.* These new observations must be coupled with theoretical development of dynamo models together with long-term data analysis of internal convection and flows, surface motions, and magnetic field evolution.

In the early 2010's, the two STEREO spacecraft (together with near-Earth spacecraft) provided a 360° in-ecliptic view of the solar atmosphere with coronagraphs and EUV imaging. Earlier, in 1994, 2000, and 2007, Ulysses' suite of all *in situ* particle and field instruments sampled local heliospheric conditions at high latitudes at different phases of the solar cycle. These missions produced significant scientific breakthroughs; however, their *lack of photospheric velocity and magnetic field imaging* greatly limits the ability to measure the solar interior and model the solar cycle. Solar Orbiter (SO) promises to partly fill this gap with measurements away from the Sun-Earth line which, at the end of this decade, will eventually reach an orbital inclination of nearly 34°. During its high-latitude perihelion passes, SO will provide critical information about the surface magnetic field and Doppler velocity -- along with data from an impressive suite of *in situ* and other remote sensing measurements. As exciting as this opportunity is, SO campaigns *will capture only 10-day snapshots from middle latitudes*. Solaris, a pathfinding Explorer mission that promises to reach 75° and spend > 3 months over each pole, has recently been selected for Phase A. If realized, Solaris carries a compact Doppler magnetograph capable of finally measuring the (largely unknown) strength and structure of polar magnetic fields and flows.

Arguably, the polar regions are crucial for placing constraints on dynamo and convection models. Notably, the most reliable empirical models depend on the strength of the unipolar magnetic field that accumulates around the pole near minimum to predict the following cycle. The limiting effects of uncertainty in high-latitude fields on heliospheric models and space weather are discussed in other white papers[1]. It is also in the polar region where meridional flows converge, where fluid motions occur in the absence of any active regions, and where convective structures may differ from their equatorial counterparts in ways that provide new insight into their properties at depth.

Continuous, months-long observations of photospheric velocity are a powerful tool for measuring the solar interior. The power of helioseismology for probing the interior of the Sun has been

[1] The Science Case for a 4π Perspective: A Polar/Global View for Studying the Evolution & Propagation of the Solar Wind and Solar Transients, Vourlidas et al.; The Science Case for a 4π Perspective: A Polar/Global View of the Heliosphere, Gibson et al; The Science Case for a 4π Perspective: A Polar/Global View of Space Weather Magnetic Origins, Gibson et al.

proven by observations from views along the Sun-Earth line from both ground (e.g., GONG and BISON) and space (GOLF, VIRGO and MDI on SOHO and HMI on SDO). In particular, *global helioseismology,* which uses the Sun's resonant modes manifesting as solar surface oscillations, revealed the Sun's internal structure and rotation as never before. The "tachocline", a boundary layer between the rigidly rotating core and differentially-rotating convective envelope, was measured, and the variations of differential rotation with depth probed over a range of latitude (Schou et al. 1998; Christensen-Dalsgaard & Thompson, 2007). However, global helioseismology (HS) is fundamentally *limited to detecting interior features that are axisymmetric in longitude and symmetric about the equator*. Global HS measurements of meridional flow, which is antisymmetric about the equator, are thus not possible. Furthermore, sensitivity to subsurface structures decreases rapidly away from the equator due to the nature of the modes themselves, so *the high-latitude subsurface is not visible* to global HS techniques from the ecliptic.

By analyzing acoustic wave packets rather than resonant modes, various flavors of *local helioseismology* provide a sensitive tool for imaging the time-varying structure and flows for local areas of the Sun (e.g. Gizon et al., 2010). For example, *ring-diagram analysis* measures distortions of the power spectrum of acoustic wave fields due to flows (Hill, 1988; Schou & Bogart, 1998). *Time-distance analysis (*Duvall et al., 1993; Kosovichev, 1996*)* determines sub-surface structure and flows by examining correlations between different points on the surface. Since both ends of a ray path must be resolved, observations from a single vantage point are necessarily limited to fairly shallow waves and thus near-surface structures. Finally, *holography* infers sub-surface inhomogeneities from perturbations of the acoustic wave field and has been used to examine structure below sunspots and, along with multi-skip time-distance, to detect active regions on the far side of the Sun (e.g. Lindsey & Braun, 1997; Chang et al., 1997, Zhao et al., 2019). In contrast with global HS, *local techniques have the power to study how solar structure and dynamics vary with longitude and latitude, and to distinguish differences between the northern and southern hemispheres*. However, measurements can be made only on the visible disk and, until SO, from the Sun-Earth line. Combined measurements from other heliospheric vantage points are required to look deeper with local helioseismology. ***High latitude observations are required to trace ray paths that go far from the equator and to probe flows in the 'zone of the unknown' in the polar subsurface regions.***

Surface observations of Doppler velocity and convection cells, as well as correlation tracking of features, have been used to study meridional circulation, torsional oscillations, supergranule patterns, and convective flows (e.g. Howe et al. 2018; Hathaway & Upton 2020). These, along with observations of magnetic flux emergence over solar-cycle time scales provide inputs and constraints for surface-flux-transport and dynamo models (e.g. Mackay & Yeates 2012). However, distinguishing longitude and time variations in these quantities is difficult with only a near-Earth perspective, and high-latitude resolution and sensitivity are severely compromised.

Despite the strides made over the past two decades with improving near-Earth measurements, important questions about solar internal structure and flows remain. Helioseismology and surface measurements have provided a tantalizing glimpse of multi-cell meridional flow patterns, with variation in radius, latitude, and time; however, different methods give conflicting results (e.g. Hathaway 2012; Hanasoge et al. 2015; Chen 2019). In particular *because of the geometric* *limitations, great uncertainty remains about the polar structure and flows, and about the strength and distribution of polar magnetic flux* (Petrie 2015; Sun et al. 2015; Tsuneta et al. 2008).

These unknowns leave critical gaps in observational constraints on solar dynamo models. They are particularly significant for models building on the popular Babcock-Leighton flux-transport dynamo paradigm, as the cyclic reversals of polar fields in those models are sensitive both to the structure of the high-latitude meridional flow and to the magnetic flux budget associated with the transport and evolution of magnetic fields over the solar cycle (e.g. Hathaway 2015). These quantities are also essential for understanding the fundamental physics of convection and its role in the dynamo (see review by Charbonneau 2014). For example, observations from multiple vantages may reveal important differences in the structure and transport between polar and equatorial convective modes that determine global mean flow properties (Miesch 2005; Featherstone & Hindman 2016; Hindman et al. 2020; see also *The Science Case for a Polar Perspective: Discovery Space,*" a whitepaper by Hassler et al.)

Continued progress requires a series of steps in the coming decades. First, observations from SO campaigns at mid latitudes must be analyzed and incorporated into modeling efforts to refine future requirements. Second, a polar pathfinder, such as Solaris, should spend sufficient time at high latitude (e.g., 2-3 months above 60° over each pole) to perform local helioseismology to illuminate dynamo mysteries through unobscured views of polar fields and flows. On a complementary development track, we must begin working toward ongoing observations of the *entire* Sun for better understanding of interior flows through HS, improved sensitivity to azimuthal variations, and more complete knowledge of solar flux emergence and transport over the course of a solar cycle. Additional benefits for terrestrial and planetary space weather are obvious.

Ultimately a coordinated network of spacecraft must be deployed to provide rapid, reliable, continuous coverage of the *entire* Sun to observe the progression of solar activity. Depending on the results of SO and the polar pathfinder, the optimal distribution and instrument complement could be determined for a flagship 4π configuration. Data recovery from distant spacecraft is a technological challenge that NASA must address in the coming decades for many reasons. Other driving technical developments include propulsion, autonomy, and data compression.

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