Improving Polar Field Observations from the Ground

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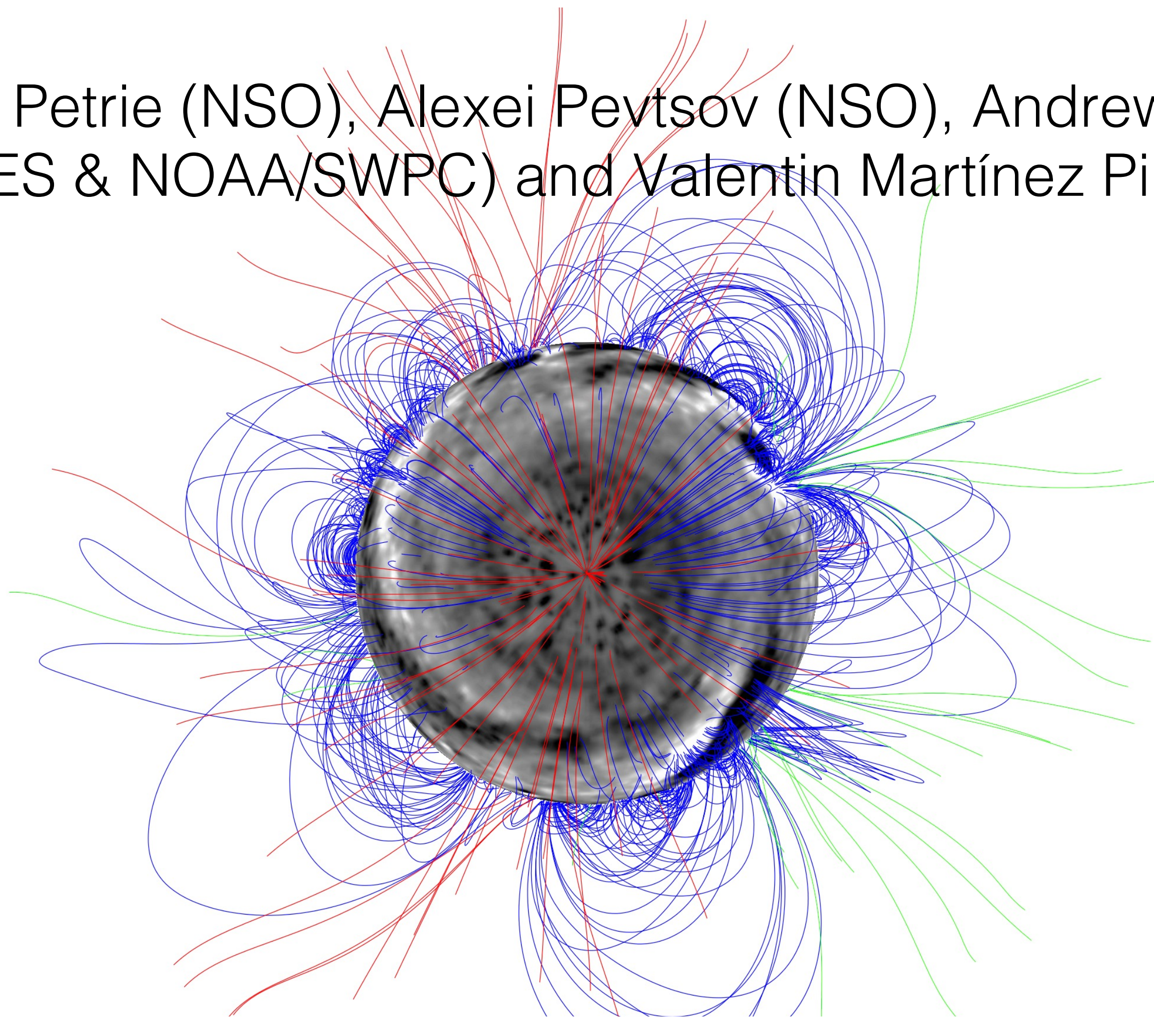
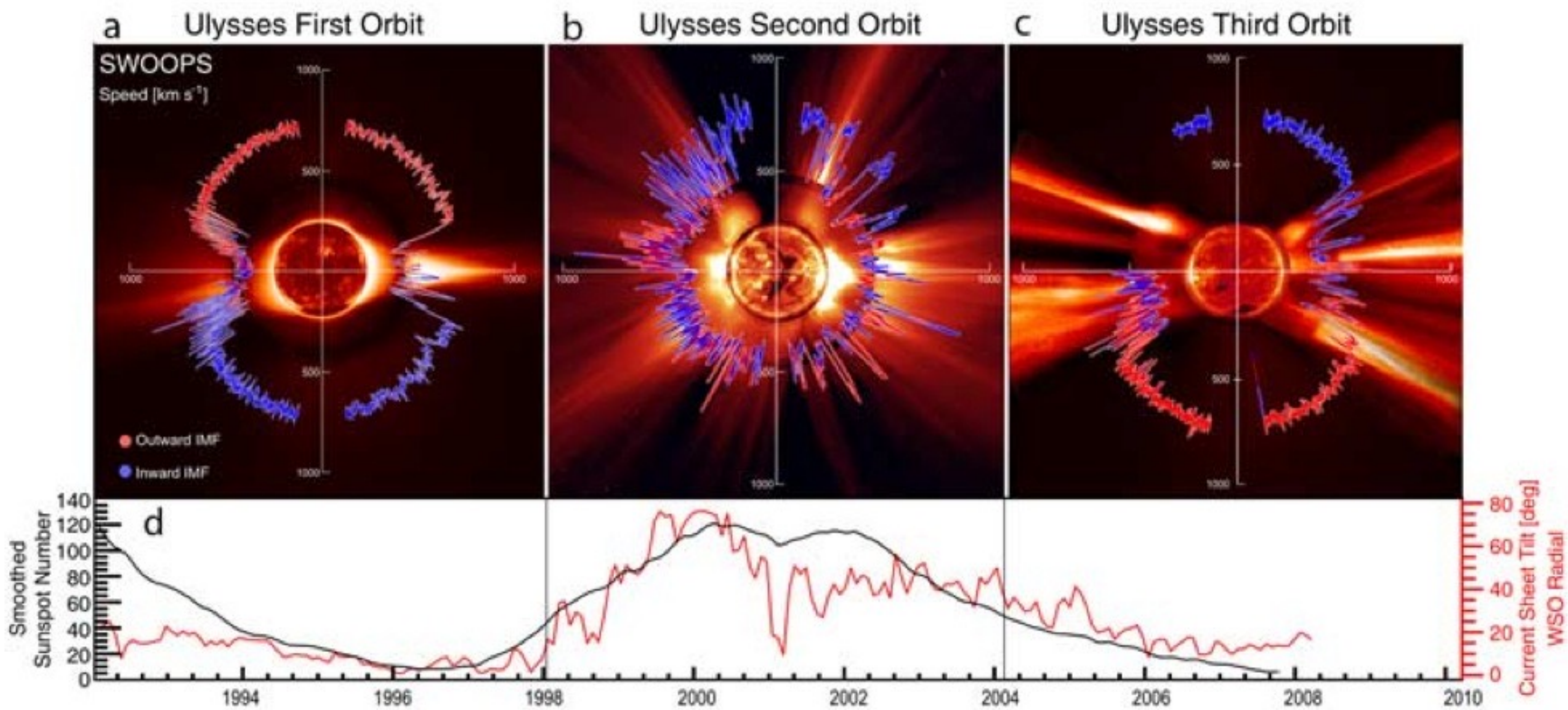


Polar influence over corona and heliosphere



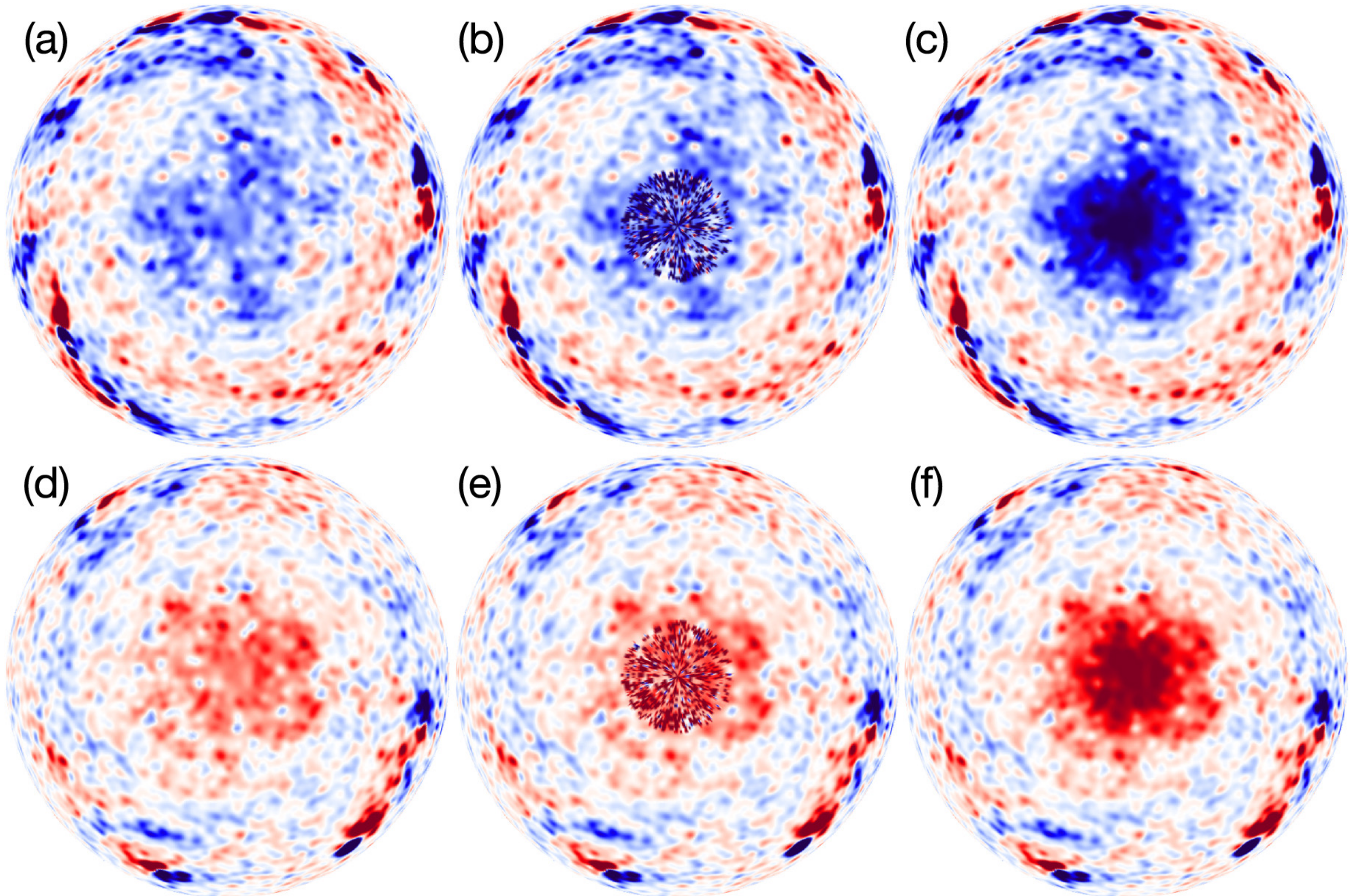
(a-c) Polar plots of the solar wind speed, colored by IMF polarity, for Ulysses' three polar orbits. (d) Contemporaneous values for the smoothed sunspot number (black) and heliospheric current sheet tilt (red). In Figures a-c, the solar wind speed is plotted over characteristic solar images for solar minimum for cycle 22 (8/17/96), solar maximum for cycle 23 (12/07/00), and solar minimum for cycle 23 (03/28/06) from SOHO/EIT, the Mauna Loa K coronagraph, and the SOHO C2 white light coronagraph. From McComas et al. (2008).

Solar minimum (1st & 3rd orbits): large-scale organization by polar fields.
Solar maximum (2nd orbit): chaos.

‘Open flux problem’: how to resolve the persistent underestimation of the radial interplanetary magnetic field by heliospheric models using surface magnetograms? Table from Linker et al. (2017)

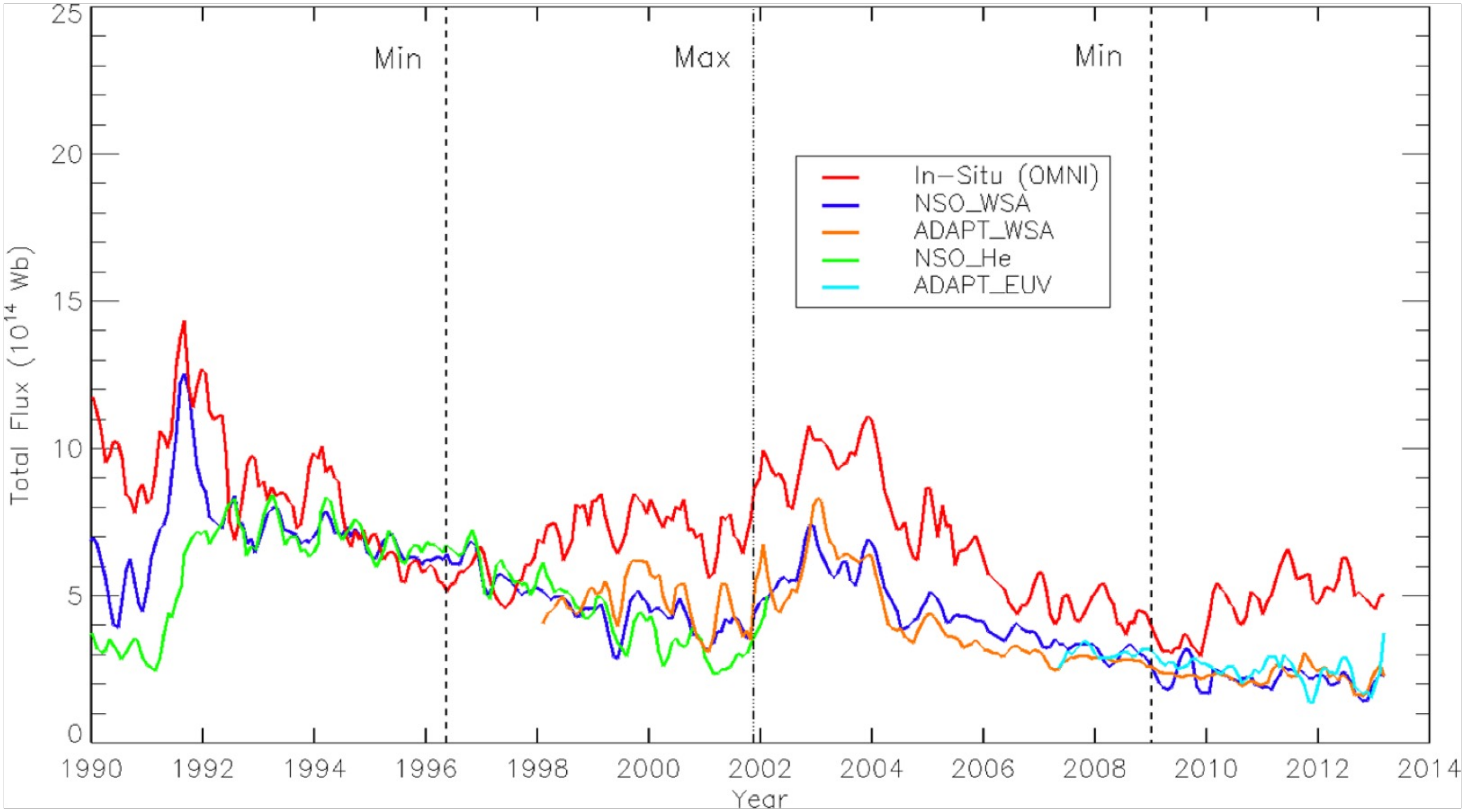
Table 1
Summary of Results from all of the Model/Map Combinations

1 Magnetic Map	2 Unsigned Flux (10^{22} Mx)	3 Average Polar Field (G) South/North	4 Model	5 Open Field Area (Difference) (10^{21} cm^2)	6 Open Flux (B_r at 1 au, nT)
Observed				7.6 (EUV)	1.7–2.2 (OMNI)
ADAPT, far side	17.9	3.1 (S)	PFSS, 2.5R_{SS}	5.8 (−1.8)	0.75
(NSO VSM magnetograms)		−2.6 (N)	PFSS, 2.0R_{SS}	6.9 (−0.7)	0.94
			MHD	8.9 (+1.3)	1.35
ADAPT, far side	17.6	3.1 (S)	PFSS, 2.5R_{SS}	6.3 (−1.3)	0.82
AR polarity reversed		−2.6 (N)	PFSS, 2.0R_{SS}	7.4 (−0.2)	1.03
			MHD	8.7 (+1.1)	1.33
ADAPT, no far side	14.8	3.1 (S)	PFSS, 2.5R_{SS}	6.1 (−1.5)	0.76
		−2.6 (N)	PFSS, 2.0R_{SS}	7.1 (−0.5)	0.94
			MHD	9.3 (+1.7)	1.28
GONG daily synoptic	11.4	2.6 (S)	PFSS, 2.5R_{SS}	6.0 (−1.6)	0.62
		−2.4 (N)	PFSS, 2.0R_{SS}	7.0 (−0.6)	0.75
GONG synoptic	11.3	2.6 (S)	PFSS, 2.5R_{SS}	6.3 (−1.3)	0.64
		−2.4 (N)	PFSS, 2.0R_{SS}	7.3 (−0.3)	0.77
HMI LOS daily updated	12.9	2.8 (S)	PFSS, 2.5R_{SS}	5.8 (−1.8)	0.66
		−2.7 (N)	PFSS, 2.0R_{SS}	6.7 (−0.9)	0.79
HMI LOS synoptic	13.9	2.9 (S)	PFSS, 2.5R_{SS}	5.4 (−2.2)	0.65
		−2.7 (N)	PFSS, 2.0R_{SS}	6.3 (−1.3)	0.79
HMI vector synoptic	15.1	3.5 (S)	PFSS, 2.5R_{SS}	5.4 (−2.2)	0.80
		−3.7 (N)	PFSS, 2.0R_{SS}	6.3 (−1.3)	0.96
LMSAL ESFAM	13.2	3.9 (S)	PFSS, 2.5R_{SS}	4.3 (−3.3)	0.64
(MDI magnetograms)		−2.4 (N)	PFSS, 2.0R_{SS}	5.3 (−2.3)	0.78
			MHD	7.8 (+0.2)	1.12
MDI daily updated	18.4	3.5 (S)	PFSS, 2.5R_{SS}	4.8 (−2.8)	0.75
		−3.2 (N)	PFSS, 2.0R_{SS}	5.7 (−1.9)	0.92
MDI synoptic	18.2	3.3 (S)	PFSS, 2.5R_{SS}	5.1 (−2.5)	0.73
		−3.2 (N)	PFSS, 2.0R_{SS}	5.9 (−1.7)	0.90
VSM synoptic	16.3	3.4 (S)	PFSS, 2.5R_{SS}	5.5 (−2.1)	0.79
		−3.3 (N)	PFSS, 2.0R_{SS}	6.4 (−1.2)	0.96



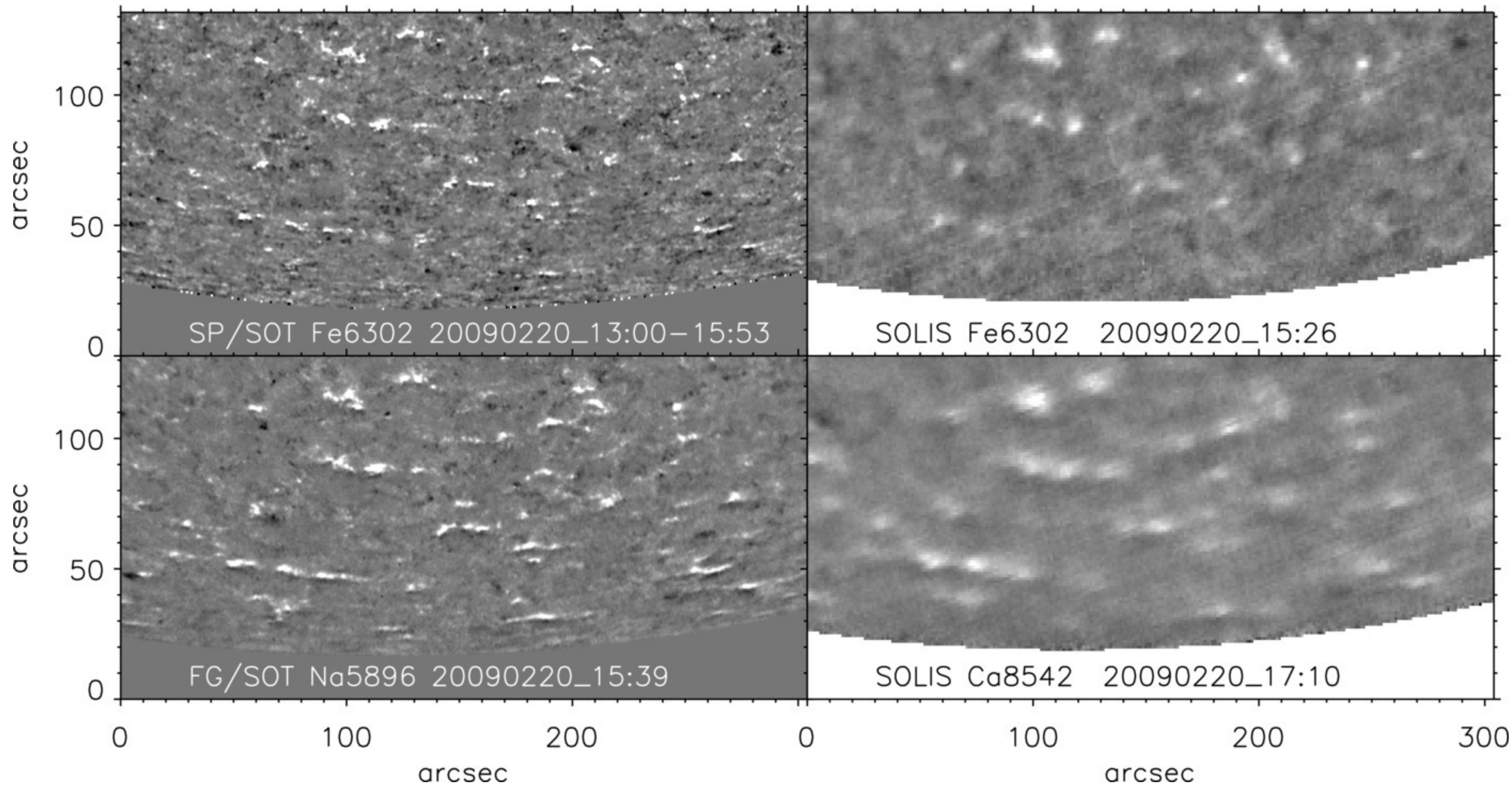
Polar view of the radial photospheric magnetic field for CR 2097/2098. (a) north pole based on standard processing techniques. Panel (d) south pole based on standard processing techniques. Panels (b) and (e) show the same magnetogram as (a)/(d) but with small-scale polarities (biased toward the sign of the existing field) added to the polar regions. Panels (c) and (f) show the same magnetogram as (a)/(d) but with increased, but smooth polar field contribution. From Riley et al. (2019).

Using potential field source-surface and magnetohydrodynamic models, Riley et al. (2019) demonstrate that the additional polar flux can (at least partially) resolve the open flux problem.



Total open flux, smoothed with running mean with a temporal window of three rotations, derived from WSA using NSO diachronic (*blue line*) and synchronic ADAPT (*orange line*) maps, *in-situ* observations (*red line*), and observations of He and EUV coronal holes (*green* and *cyan* lines, respectively). From Wallace et al. (2019).

The magnetogram-based interplanetary field agrees with the observed better during activity minimum than maximum.

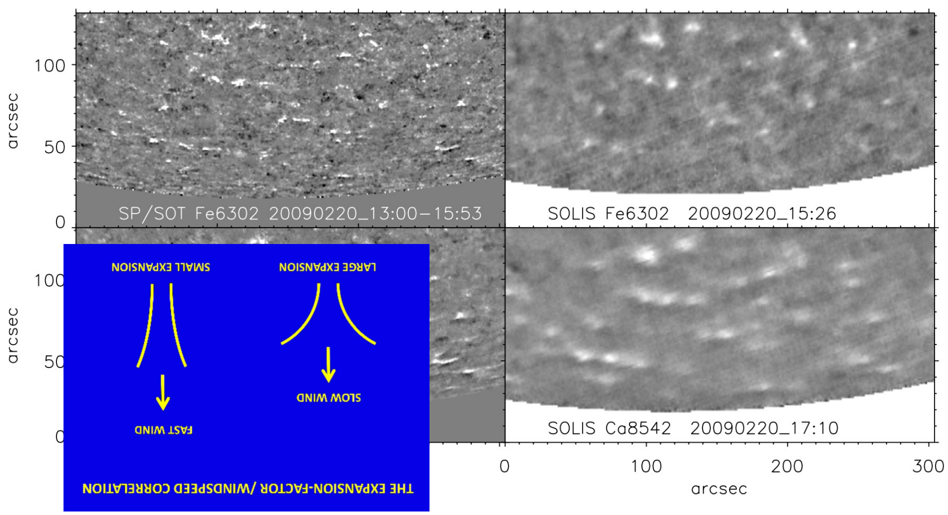


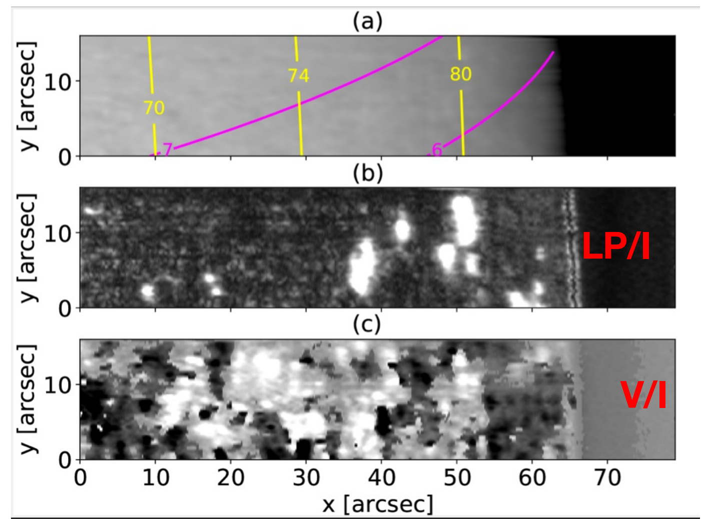
Nearly simultaneous south pole line-of-sight field observations with the pole tipped toward Earth by 7º.04. Left: Hinode observations. Right: SOLIS/VSM observations. Top row shows photospheric (630.2 nm) observations, bottom row shows low and mid chromosphere observations. White represents the fields directed toward the observer and black away. VSM and SP observations saturate at ±30G, and FG observation saturates at ±0.006 I_C in circular polarization. From Jin et al. (2013).

Boundary data: the solar poles

Jin et al., 2013

Earth is magnetically connected to the poles a majority of the time

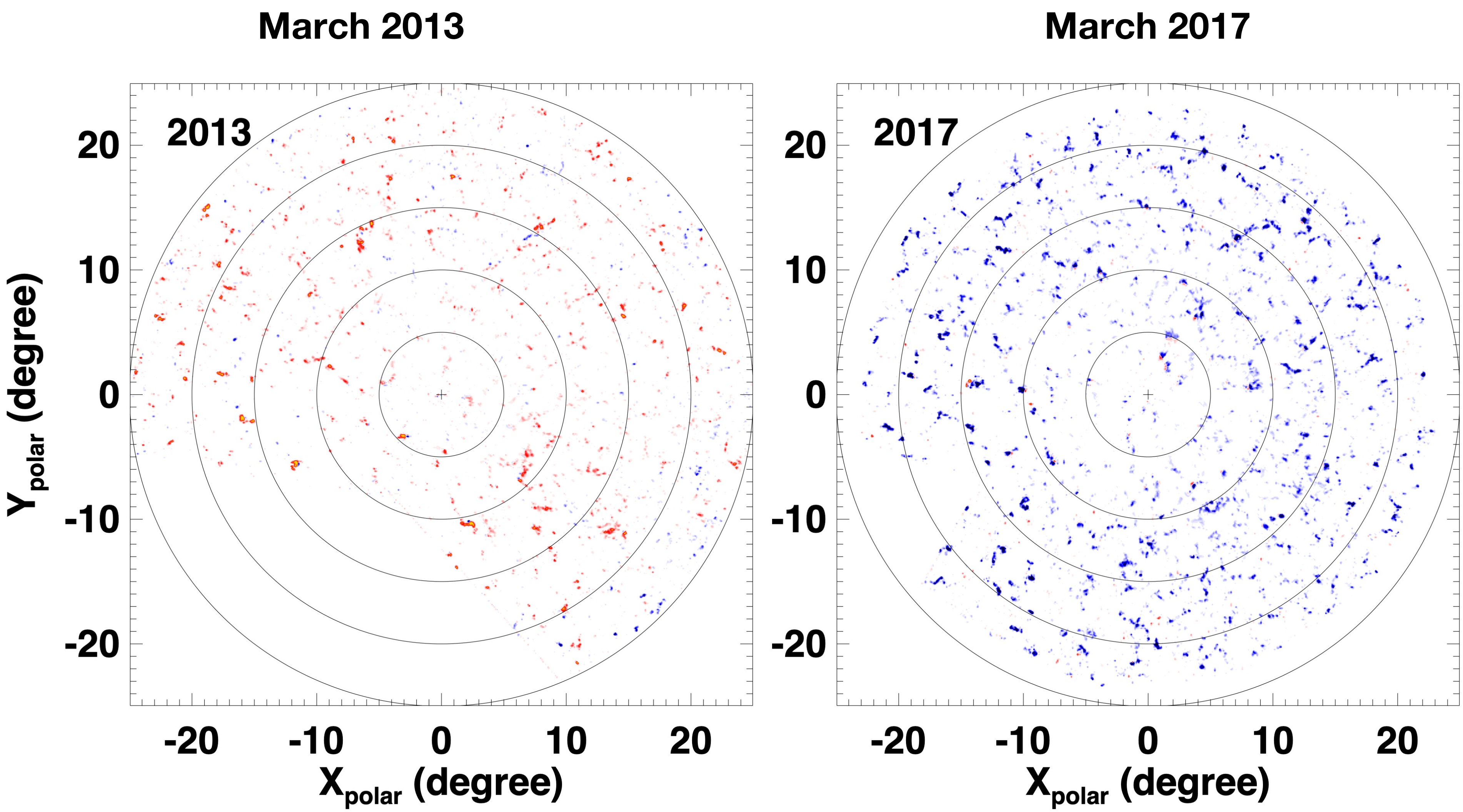




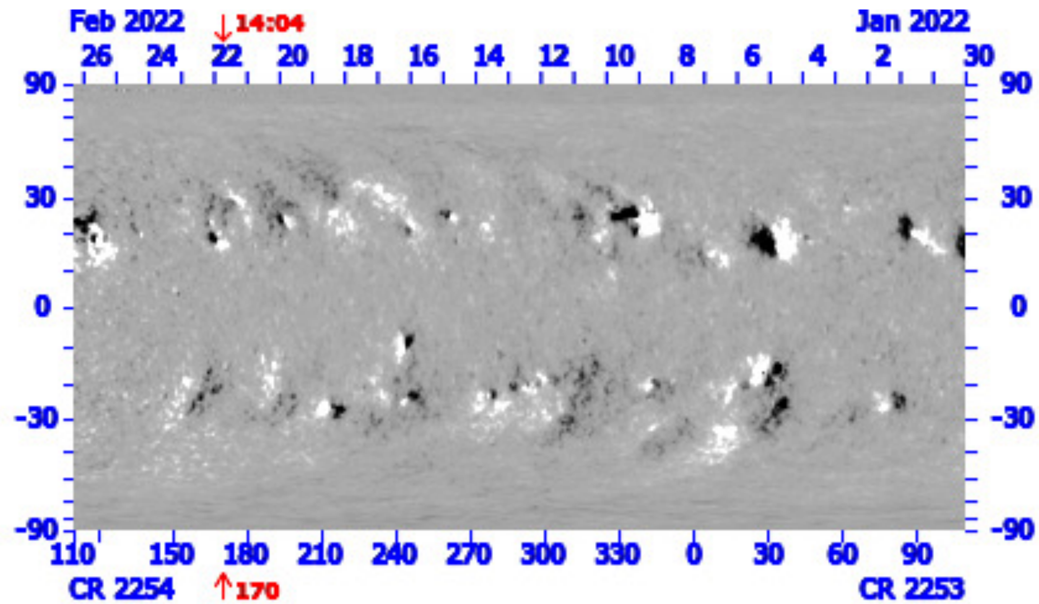
- Polar observations suffer from projection effects and lack of sensitivity to $B_{\perp}$
- From the Earth line-of-sight we can improve sensitivity to $B_{\perp}$: higher aperture, IR
- Compensate for atmospheric distortion via AO/GLAO
- Observe photosphere & chromosphere

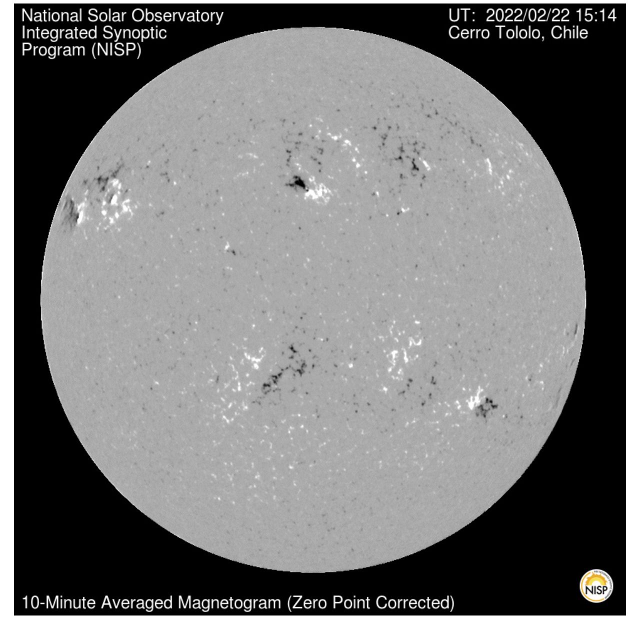
The polar fields are important, but difficult to observe from (near) Earth

- Their magnetic configuration is relatively simple with predominantly near-vertical field lines, but this corresponds to transverse field orientations as seen from Earth, where the polar fields are observed with a large (>80°) viewing angle.
- The Zeeman effect makes these transverse signals much harder to observe than the longitudinal signals; typically, sensitivity to transverse fields is one order of magnitude lower.
- Moreover, the ~kG facular fields that dominate the poles are small (~5″ across as observed from Earth) and sparsely distributed: the overall polar field is only of order 5-10 G.
- This sensitivity problem renders the polar fields relatively poorly constrained in our current modeling efforts.

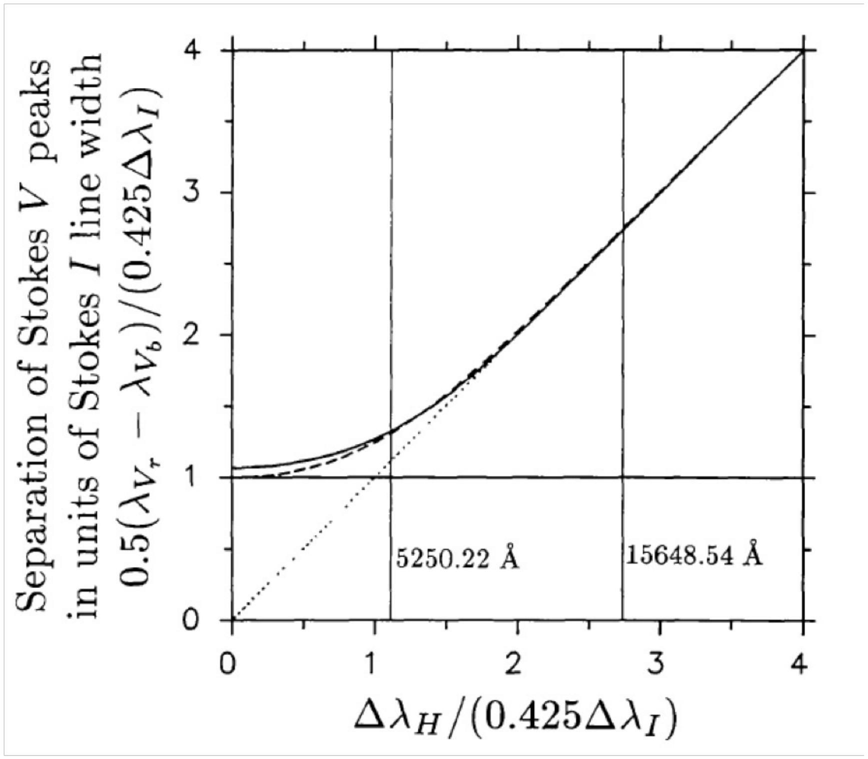


Synoptic maps of the south polar radial flux density constructed from Hinode SOT/SP scans for the polar vector magnetic field observed in the Fe I line at 630.2 nm. Positive/negative flux density is represented by red/blue, saturated at ±500 G. Level 2 data produced by the HAO/CSAC were used. The left panel shows the map for March 2013 at an early stage of the polarity reversal from positive to negative. The right panel shows the map for March 2017 after the polarity reversal was complete.





- The GONG instrument was originally designed for helioseismology; magnetograms were added later using a half-wave plate, but the instrument design is not optimal for this application.
- Issues with the magnetic zero-point need constant monitoring in the reduction pipelines.
- GONG provides only line-of-sight fields, unlike SOLIS/VSM and SDO/HMI.
- Increased magnetic sensitivity, resolution, and well-calibrated vector capabilities are mandatory for improved solar wind modeling.
- This is particularly relevant for the polar regions, where all current synoptic data fail to provide satisfactory sensitivity - and to resolve the “open flux problem”.



Better Sensitivity with Infrared

The benefit of making magnetic field Zeeman observations. Left: separation of Stokes V peaks for various Voigt profiles at a magnetic field of 1 kG for a visible line and an IR line. The Zeeman splitting of the 1565 nm IR line is fully resolved at this magnetic field strength, and the weak field approximation does not need to be used to interpret the spectra. Image reproduced from Stenflo et al. (1987) by Penn, Liv. Rev. Sol. Phys. (2014).

- Magnetic field measurements measure a shift in the components of a spectral line, and this shift is most easily measured if it is large relative to the observed line width.
- The ratio of the Zeeman splitting divided by the spectral line width gives us a measure of the magnetic resolution of a spectral line, and that value is $g_{\text{eff}}\lambda$.
- Ideally spectral lines with inherently large g_{eff} and with long wavelengths are the best for making sensitive magnetic measurements.
- The IR lines near 1.5 micron have sensitivities to LOS fields twice that of visible lines used by the VSM, HMI and SOT/SP, and four times higher for transverse fields, besides smaller image disturbances from the Earth's atmosphere.

Summary

- Accurate polar field measurements are critically important for the study of the global heliosphere and space weather (also the dynamo).
- However, the average polar field strength is low, about 5 - 10 G and mostly perpendicular to our line of sight, posing a sensitivity problem.
- To improve polar field observation from the ground, we estimate that a telescope with a 50cm aperture is required to achieve the necessary (10^{-4}) polarization sensitivity, and to measure the line-of-sight field with a sensitivity of 1 G per 0.5″ pixel, with ground-layer adaptive optics to achieve 1″ spatial resolution with stable image quality.
- A full-disk spectro-magnetograph similar to the SOLIS/VSM observing the Fe I line at 1564.8 nm and the He I line at 1083.0 nm, could give photospheric and chromospheric coverage with the required sensitivity.
- A network of such telescopes (next-generation GONG, or ngGONG) would produce data essential to space weather modeling, and is also crucial for encounter, multi-messenger missions such as Parker Solar Probe and Solar Orbiter.

Why is it important for the Helio2024 Decadal

- How the WP links to the statement of task:
  - *The structure of the Sun and the properties of its outer layers in their static and active states*
  - *The characteristics and physics of the interplanetary medium from the surface of the Sun to interstellar space beyond the boundary of the heliosphere*
  - *The space weather pipeline from basic research to applications to operations, including the research-to-operations-to-research loop that strengthens forecasting and other predictive capabilities.*
- Describe the highest priority science goals to be addressed in the period of the survey.
  - *Obtain regular and usable polar data from the photosphere and chromosphere*
- *Develop a comprehensive ranked research strategy that provides an ambitious but realistic approach to address these goals that includes ground- and space-based investigations as well as data and computing infrastructure to support the research strategy*
  - *Continuing the synoptic polar observations with Hinode, start one with DKIST*
  - *Ingestion of synoptic data into models*
  - *Ensure requirements flow down to ngGONG*

Category: Basic Research
Primary topic: Solar Physics
Secondary topic: Space Weather Research to Operations to Research Loop