Solar Physics from Unconventional Viewpoints

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We explore new opportunities for solar physics that could be realized by future missions providing sustained observations from vantage points away from the Sun-Earth line (SEL). These include observations from the far side of the Sun, at high latitudes including over the solar poles, or from near-quadrature angles relative to the Earth (e.g., the Sun-Earth L4 & L5 Lagrange points). Such observations fill known holes in our scientific understanding of the three-dimensional, time-evolving Sun and heliosphere, and have the potential to open new frontiers through discoveries enabled by novel viewpoints.

Non-Sun-Earth-Line (SEL) Observations to Date

The first non-SEL line observations were obtained by the two Helios spacecraft launched in 1974 and 1976, which made primarily in-situ measurements and stayed close to the ecliptic plane. The only spacecraft to explore significantly outside of the ecliptic was Ulysses (1990-2009), which achieved a near-polar orbit via a Jupiter swing-by, and made in-situ measurements between 1.3 and 5.4 AU from the Sun. The corona and inner heliosphere have been observed through non-SEL imaging since 2006 when the twin STEREO spacecraft were launched. STEREO's imaging and in-situ measurements have been made all around the Sun, but near the ecliptic plane.

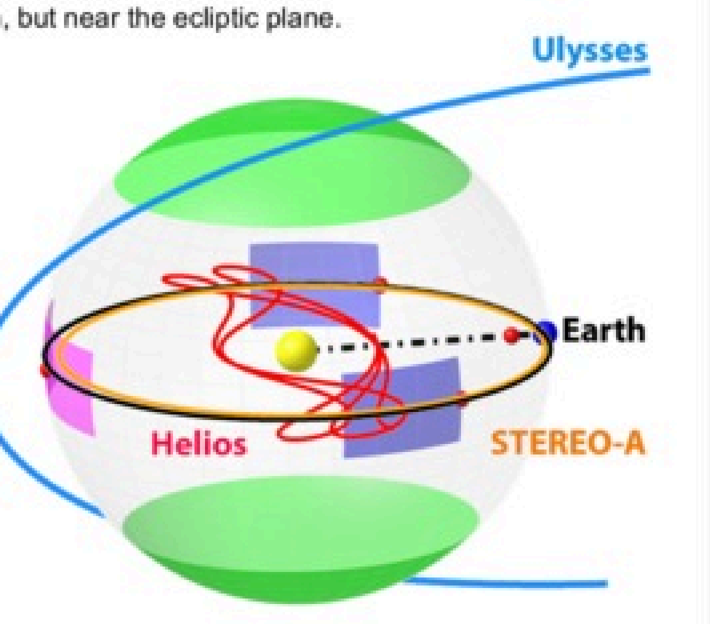

***Fig. 1.** An overview of interesting vantage points, highlighting previous non-Sun-Earth-line (non-SEL) missions. Sun and Earth are shown as yellow and blue dots, and Lagrange points as red dots (radial scale deformed for clarity). The SEL is indicated as a black dot-dashed line (intersecting L1 and Earth). The quadrature views are shown as blue patches (intersecting L4 and L5); the far-side view as a pink patch (intersecting L3); and the polar views as green patches. Sample STEREO orbit is in orange, Helios orbits in red, and Ulysses orbit in light blue. The Helios orbits are relative to the Earth, i.e., Heliocentric Earth Ecliptic coordinates; the other orbits are in Heliocentric Inertial coordinates.*

Science Enabled by Non-SEL observations

The scientific benefit of non-SEL observations has been demonstrated by past and current missions, but, to a large extent, these observations merely whet our appetite for more comprehensive and sustained measurements. **Table 1** highlights open science questions, and **Table 2** (left column) describes the specific benefits of non-SEL views.

Table 1

Regime	Open questions
Solar interior and dynamo	What are the solar surface/interior flow/magnetic field patterns vs. longitude, latitude and depth, and how do they constrain dynamo models?
Solar atmosphere/ global connections	What is the structure of the global coronal and heliospheric magnetic field? What are the source regions of the solar wind? How is magnetic energy stored/released during eruption, and role do helicity/topology play? How do local and global magnetic fields interact?
Solar-wind/ heliospheric transients	How do transients evolve and interact with the ambient solar wind as they move through the heliosphere?
Space-weather prediction/ modeling	How can we improve prediction of space weather on time scales of days, weeks, months, or longer? How can we improve forecast of space-weather impacts at the Earth & throughout the solar system?

References

Appourchaux, T., Liewer, P., Watt, M., et al. 2009, Experimental Astronomy, 23, 1079
Appourchaux, T., Auchère, F., Antonucci, E., et al. 2014, in Adv. Solar Sail., Macdonald, M. (ed), Springer, 259
Bogart, R. S., Baldner, C. S., Basu, S. 2015, ApJ, 807, 2
Fan, Y., Gibson, S. E., Tomczyk, S. 2018, ApJ, submitted
Gibson, S. E., Kucera, T. A., White, S. M. et al. 2016, Front. Astron. Space Sci., 8
Gopalswamy, N., Davila, J. M., St. Cyr, O. C., et al. 2011, JASTP, 73, 658
Lavraud, B., Liu, Y., Segura, K., et al. 2016, JASTP, 146, 171
Liewer, P. C., Qiu, J., & Lindsey, C. 2017, Sol. Phys., 292, 146
McIntosh, P.S. 1979, UAG-70, NOAA Space Environment Laboratory, Boulder, CO.
McIntosh, P.S. 2003, A. Wilson (ed.), ESA SP-535, ESTEC, Noordwijk, Netherlands, 807
Vourlidas, A. 2015, Space Weather, 2015SW001173
Vourlidas, A., & Bruinsma, S. 2018, Space Weather, 16, 5
Webb, D. F., Biesecker, D. A., Gopalswamy, N., et al. 2010, Space Research Today, 178, 10
Webb, D. F., Gibson, S. E., Hewins, I. M., McFadden, et al. 2018, Front. Astron. Space. Sci., submitted, 2018
Xiong, M. & Liu, Y. 2014, in Taikong, ISSI-BJ Magazine, 4, August 20144

Table 2

Benefits from non-SEL vantage (assumes existence of complementary SEL observations)	Measurement and view (see below)	Stereo	SO	PSP
Helioseismic inversions probe deeper	1 **P/Q/F**	no	**limited**	no
Better coverage of global magnetic boundary; Comprehensive view of flux emergence and evolution	1 **P/Q/F**	no	**limited**	no
Magnetic vector boundary disambiguated; Polar fields and flows directly observed	1 - 2 **P/Q**; 1 - 2 **P**	no	**yes** (1)	no
Input to coronal 3D modeling	3 - 6 **P/Q**	**yes** (3; 6)	**yes** (3; 4; 6)	no
Longitudinal coverage enabling monitoring of "seasons" of space weather	1; 3; 6 **P/Q/F**	**limited** (3)	**limited** (1; 3; 6)	no
Simultaneous boundary/limb views of CMEs and precursors; global interactions comprehensively observed	1 - 6 **P/Q**	**yes** (3; 6)	**limited** (1; 3; 4; 6)	no
Solar-wind source regions connected to heliospheric imaging/in-situ measurements	1 – 8 **P/Q**	**yes** (3; 6; 7')	**yes** (1; 3; 4; 6; 7'; 8)	**yes** (7'; 8)
Improved monitoring and modeling of Earth-intersecting (planet-interesting) transients	1 - 9 **P/Q (P/Q/F)**	**limited** (3; 6; 7')	**limited** (1; 3; 4; 6; 7'; 8)	**limited** (7'; 8)
Longitudinal structure of the Alfven surface and of CMEs, CIRs, and shocks revealed	6 - 7 **P**	no	no	no
Line-of-sight measurements of southward-directed magnetic field	5; 9 **P**	no	no	no
More lines of sight to reconstruct 3D solar-wind structures	6 - 7 **P/Q**	**yes** (6 - 7')	**yes** (6 - 7')	**limited** (7')
Improved irradiance measurements enabling better thermosphere/ionosphere models	3; 10 **Q**	**limited** (3)	no	no

Views	Measurements needed
Polar (**P**)	1. Full-disk Doppler vector magnetographs (photosphere)
	2. Chromospheric spectropolarimeters
Quadrature (**Q**)	3. Full-Sun multiwavelength coronal imagers
	4. Multiwavelength coronal spectrometers
	5. Polarimetric coronagraphs
Farside (**F**)	6. White-light/multiwavelength coronagraphs
	7. Heliospheric imagers (HIs) with polarizers (7' = no polarizer)
	8. In-situ solar wind measurements
	9. Faraday rotation (e.g. beacon signals between spacecraft and Earth)
	10. Irradiance monitors

Discovery space

Opportunities for discoveries by non-SEL spacecraft abound. The polar view in particular could enable an unprecedented characterization of solar spectral irradiance, with as-yet-to-be-determined impact on our understanding of the Sun as a star. Beyond this -- we have never observed the solar poles with imagers. What will we see? Based on recent images from planetary missions (***Fig. 2 c-d***), direct observations of the poles is likely to reveal far more complex and beautiful structure than anything we have been able to piece together from our current near-ecliptic view (***Fig. 2 a-b***).

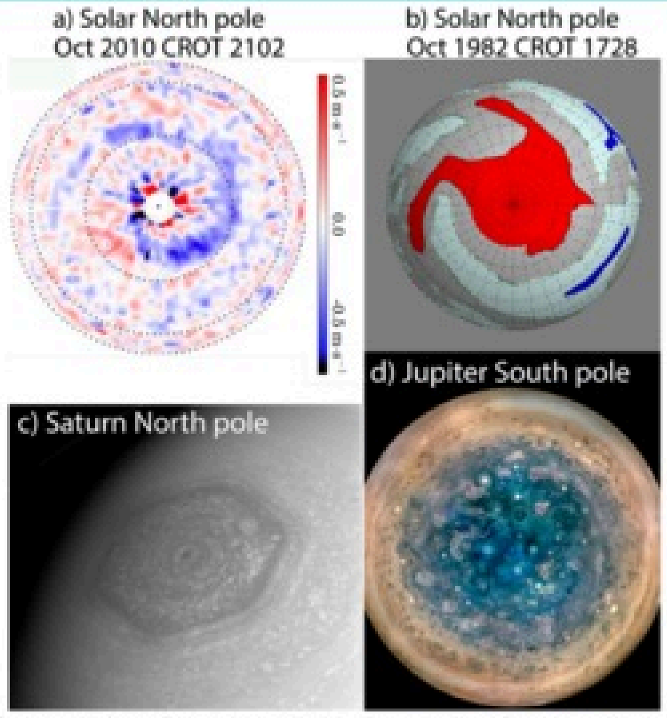

***Fig. 2.** (a) Ring-diagram analysis of near-surface flow anomalies indicate spiral flow patterns at the poles (Bogart et al., 2015). (b) Observations of large-scale, high-latitude magnetic features spanning multiple decades (McIntosh 1979; 2003) similarly demonstrate spiral structure at the poles (Webb et al., 2018; red=negative coronal hole, blue=positive coronal hole, grey = negative polarity quiet Sun, light blue = positive polarity quiet Sun, dark green=filaments). (c) View centered on Saturn's north pole. North is up and rotated 33 degrees to the left. The image was taken with the Cassini spacecraft wide-angle camera on June 14, 2013 using a spectral filter sensitive to wavelengths of near-infrared light centered at 752 nanometers. (Source: NASA JPL). d) Multiple images combined show Jupiter's south pole, as seen by NASA's Juno spacecraft from an altitude of 32,000 miles. The oval features are cyclones. (Credit: NASA/JPL - Caltech/SwRI/MSSS/Betsy Asher Hall/Gervasio Robles).*

Future missions and gap analysis

Non-SEL observations have the potential for transformative progress. **Table 2** describes the measurements needed from the various non-SEL vantages (colors correlated to science areas shown in **Table 1**).

The forthcoming Solar Orbiter (SO) mission, which will orbit the sun between 0.28 - 0.7 AU and reach a maximum inclination of ~30-34° out of the ecliptic by the end of its extended mission in 2029-2030, will provide the first detailed mapping of the sun's polar magnetic fields. In addition,

Parker Solar Probe (PSP) will explore the outer corona and inner heliosphere with very rapid solar encounters, as close as 9.86 solar radii from the center of the Sun. ***Fig. 3*** shows sample orbits for both spacecraft.

It is undeniable that both SO and PSP will provide unique data and views of the coronal and heliospheric environment and enhance the sophistication of multi-viewpoint analysis, far beyond STEREO. However, they are necessarily limited to the science achievable by the instruments they have on board, and in their ability to obtain the sustained measurements needed for longer-time-frame studies and space-weather monitoring (see **Table 2**).

The idea of a mission to the Lagrange L5 point has been explored in several concepts in recent years (*Webb et al., 2010; Gopalswamy et al., 2011; Vourlidas et al., 2015; Lavraud et al., 2016*). It has obvious advantages for space-weather research and forecasting, and it also addresses many of the open science questions (see **Table 2**). Such analyses depend upon the existence of complementary SEL observations.

Imaging of the solar poles has been a long-held desire of the solar community ever since the cancellation of the imaging sister payload to Ulysses. Mission concepts have been proposed for the ESA large mission competition (e.g., POLARIS; *Appourchaux et al., 2009, 2014*), and the Chinese space program (SPORT: *Xiong & Liu 2014*). The Solar Polar Imager (SPI) concept was discussed in the Heliophysics Decadal Survey (*Liewer et al., 2009*). As **Table 2** demonstrates, comprehensive and unique science is achieved from a polar vantage, and this polar vantage provides the most opportunities for discovery (***Fig. 2).***

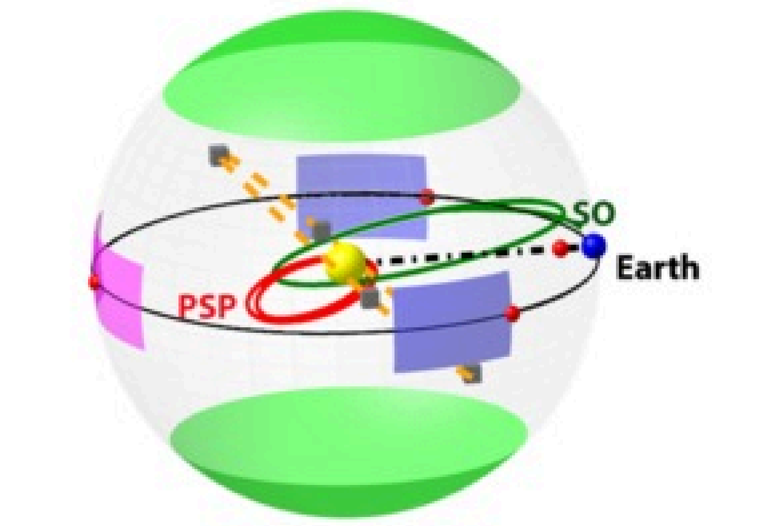

***Fig. 3.** Interesting viewpoints shown as in **Fig. 1**, with Parker Solar Probe (PSP; red) and Solar Orbiter (SO; green) orbits overlaid. The dashed orange line represents a sample "diamond" orbit with four spacecraft (grey cubes) 90 degrees apart, reaching as high as 75 degrees heliolatitude (Vourlidas et al. 2018).*

Space Weather

In addition to all that may be gained scientifically from non-SEL observations, there are clear benefits of such measurements for space-weather prediction and monitoring. **Table 1** (last row) highlights driving questions, and **Table 2** (left column) describes the specific benefits of non-SEL views. Of utmost importance, non-SEL line configurations seem to be our best option for quantifying the magnetic field entrained in the CME. We note that ***from the poles, the line-of-sight field is B_z***, the southward component critical to geoeffectiveness (***Fig. 4***).

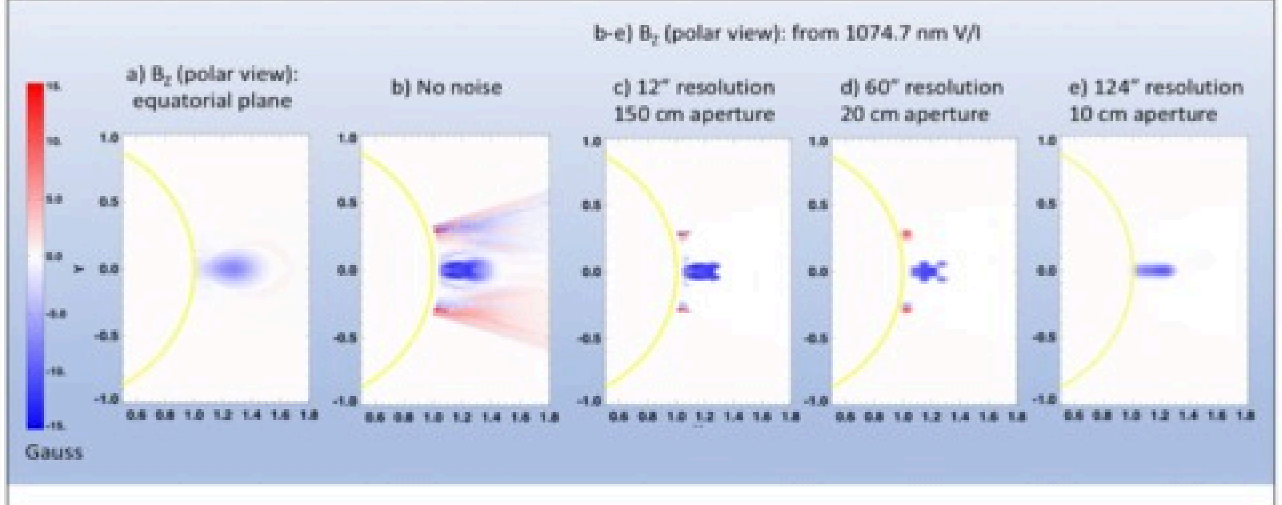

***Fig. 4.** B_z for a simulated, erupting CME (Fan et al., 2018) viewed from the North pole. a) Simulation ground truth B_z in equatorial plane. b) B_z inverted from ratio of forward-modeled (Gibson et al., 2016) Stokes circular polarization V and intensity I. c) B_z values with signal-to-noise ratio > 3, based on a 1.5 meter telescope,12" spatial resolution, and 5 minute integration. d-e) Same except with lower resolution/smaller telescope apertures as indicated. Note that the sign and strength of the pre-eruptive core field is captured for all.*

Conclusions

Non-SEL vantages present unique opportunities for answering the outstanding science questions of heliophysics, for improving space-weather monitoring and prediction, and for revealing new discoveries about our Sun and solar system. All three of the viewpoints considered in this paper are of interest. The quadrature (e.g., L5) vantage combines relative ease of access with substantial space-weather operational advantage. However, the polar vantage is the most compelling scientifically, and would achieve essentially the same space-weather operational capability as quadrature. For this reason, it is essential that investment in and demonstration of the technologies needed for polar missions are prioritized over the next few years so that by the next decadal survey community proposals for solar polar missions will not only be scientifically justified, but technologically robust.