The Need for Consistent, Comprehensive Inner Heliosphere Data

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Goal

The main science goal presented in this white paper is the capability to reliably track individual packets of solar wind from the low corona to 1 AU by 2050. This capability is essential for understanding how the Sun generates and accelerates the solar wind, and how the solar wind impacts the Earth. Better tracing of solar wind is primarily a logistical matter of providing coverage to best leverage our current capabilities, rather than a challenge necessitating fundamental innovations in theory or technology. By utilizing current satellite constellation technology with high TRL, we can produce powerful new science results. Reliable plasma parcel tracing capability is the means by which the field will achieve further vital advances in solar theory, solar wind modeling, and space weather forecasting.

Motivation

Today, multiple high-resolution imagers characterize plasma within a few solar radii above the Sun's surface. Simultaneously, multiple spacecraft characterize the solar wind in situ at 1AU. Parker Solar Probe, Solar Orbiter, and the recently selected PUNCH mission are critical for understanding the processes that occur between these locations. However, this still leaves a significant measurement gap in the intervening region along the Earth-Sun line, and near-complete inaccessibility to the rest of the inner heliosphere. This narrow and patchy coverage has helped fuel many decades of debate and conjecture on the release and energization of solar plasma, which remain open questions in solar and heliospheric physics. Simulations are insufficient to model this region without more data insight, as many spatial scale ranges could be important to solar wind evolution, and it is computationally prohibitive to run simulations covering them all.

The dearth of data covering the inner heliosphere has also stifled advances in space weather research, solar magnetic field modeling, and coronal dynamics. Photospheric models based on synoptic maps remain hopelessly flux imbalanced whenever features appear on the far side, due to a lack of 360˚ magnetic coverage of the Sun. Real-time data coverage will allow for tighter and more accurate prediction windows, and will enable the community to advance from nowcasting to true forecasting of eruptions and CMEs.[1]

Coronal observers only have access to reliable magnetic data for about two-thirds of the Sun's visible hemisphere before line-of-sight issues become a major factor, and many questions of coronal dynamics remain unresolved due to projection and plane-of-sky effects. Observing coronal plasma with current tools also presents several challenges. Today, concerted observations from two angles are only possible on the rare occasions when STEREO-Ahead and SDO are in quadrature. The low corona is imaged in the EUV, while upper corona observations are made in white light. Intensity varies with plasma density squared in the EUV, but simply with density in white light; this obfuscates the true behavior of coherent structures. As such, our ability to characterize solar wind generation and acceleration is limited.

The ability to consistently trace plasma parcels will be unachievable without inner heliospheric observations taken at sufficiently high spatial and temporal cadence, and from a suitable range of distances. The high-cost, high-eccentricity orbit missions upon which we currently rely will not suffice

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[1] See submitted WP "Multi-vantage-point solar and heliospheric observations to advance physical understanding of the corona and solar wind" by Arge et al.

for the challenges facing heliophysics, nor for the desired state of space weather forecasting. Additionally, the field cannot afford to lose the few steady sources of solar and heliospheric data that we currently have and which are nearing the end of their mission lifespans (e.g., SDO, SOHO, ACE) without equal replacements or improvements planned.

In order to remedy this situation and accomplish the aforementioned goal, we need reliable, high-resolution data measuring solar wind plasma:

- **Magnetic fields**
- **Particle density**
- **Composition**
- **Velocities**

These measurements need to have a cadence on the scale of minutes or better, spaced at regular intervals encircling the entire Sun, and at regular distances covering out to at least 1 AU.

Challenges

There are both scientific and structural challenges to this goal, covered separately here. The former relates to the problem of conducting science across a vast range of spatial scales and data types. Typically, near-Sun observations are conducted in the EUV, while imaging of the middle and upper corona use white light, and *in situ* observations rely primarily on magnetic field and particle data. An apples-to-apples approach would facilitate positive identifications of solar wind parcels and directly monitor evolution by providing compositional data throughout the spatial ranges, providing the best direct benefit to the science goal. This can be accomplished by using spectral measurements for remote sensing and plasma composition measurements for *in situ* measurements at each distance.

The structural challenge relates to the types of mission proposals which have succeeded.[2] As previously mentioned, solar missions tend to focus on large, single spacecraft like SDO or SOHO. There has been significant historical resistance to replacing such large-budget missions with high resolution and regular orbits, which will result in a loss of coverage that will adversely impact solar and broader heliospheric research and seriously regress forecasting capabilities. Our field cannot afford to lose ground needlessly.

For major missions with irregular orbits, such as Parker Solar Probe (PSP) and Solar Orbiter (SolO), the data results are a relatively small set of high-quality measurements. Most observations in the mission dataset will be unique, not easily comparable either to other events observed by the craft, or to lower-resolution observations from other craft in different orbits. While these missions produce powerful new science, **the context provided by universal coverage is critical for researchers to extract the maximum physical insight from unreplicable observations**. Data collection and continuity can be produced by constellations of smaller missions that have greater spatial distribution and more uniform instrumentation.

Implementation Plan

Work has already begun on attempting to match structures escaping the Sun from the low corona to signatures seen in *in situ* solar wind signatures at 1 AU (references). This approach currently requires back-mapping using heliospheric models such as the Wang-Sheeley-Arge model, which are not meant to trace origin regions to high accuracy, and cannot predict or interpret which processes predominate in the distance between the remote sensing data and the *in situ* data. Improving the capabilities of models like this one is just one type of major scientific and predictive advance that can be made with whole heliospheric observations. This intermediate region along the Sun-Earth line should be the first target for

[2] Comprehensive coverage of the Sun will require many scientists with a range of specialties. Professional bias in science towards publication-producing work results in researchers who provide mission code or data support finding funding or advancement opportunities scarce, despite the criticality of their work. This challenge is covered in more detail in the submitted WP “Heliophysics is Interdisciplinary” (Verniero et al.), but it is referenced here as well because it is critical to address in order to advance heliospheric research.

new data measurements. **By 2030, there should be data access to this area via an *in situ* mission located at L4 or L5, with plans being implemented to expand analogous coverage around the Sun using a "string of pearls" satellite constellation with an orbit of roughly 0.5 AU.**

Spectroscopy is one particularly useful tool for bridging the gap between remote sensing observations and *in situ* particle data such as composition. By using spectral analysis for identifying source regions of solar wind packets in the corona, and combining this with compositional signatures in the wind at different distances along the Sun-Earth line (to begin with, extending around the Sun as we approach 2050), we can analyze data sets investigating the same basic quantities at a large range of distances. This will help equalize some of the challenges which have plagued solar wind research in the past, effectively ensuring that the comparisons and conclusions reached are scientifically robust. **A constellation of small craft spectrometers should be planned for 360˚ in-plane solar coverage by 2035.** These could follow orbits similar to those of the STEREO mission, but with perhaps six smaller spacecraft rather than two more complex ones. MMS has recently exhibited just how successful a small group of identical spacecraft can be when flown together through regions of interest; small spectrometers spaced evenly around the Sun at 1 AU would be far less constrained orbitally, and well within current technological capabilities.

From this enhanced coverage, it will be possible to trace individual packets of solar wind with a high level of confidence from the corona to 1 AU, placing vital science results within reach for the first time. Studies will be conducted to conclude how much solar wind structure is frozen-in near the Sun, and how much is determined by turbulence within flux tubes as the wind propagates outward through the heliosphere. Other analyses will be needed to determine which spatial scales of wind structures predominate at which distances from the Sun. This in turn will allow modelers to adapt and greatly enhance solar wind simulations. All of the space weather tools which depend upon these simulations will then implement these changes, allowing for advances in accuracy and smaller windows for space weather event arrivals. This chain reaction will vastly increase our understanding of solar wind physics and space weather science.

Summary of Recommended Implementation Steps and Outcome

	2020—2030	**2030—2040**	**2040—2050**
Data Availability	—Solar wind in-situ mission at L4/L5 —360˚ solar magnetic field coverage via constellation of magnetometers at 1 AU	—Solar wind "string of pearls" in-situ mission around 0.5 AU —360˚ solar coverage via constellation of small craft spectrometers at 1 AU	
Studies Made Possible by Coverage	—Complete life-cycle coverage of magnetic structures —3D studies of solar wind structures	—Identification of important solar wind spatial scales —Determination of plasma propagation characteristics	—Reliable tracing of individual solar wind parcels
Resultant Impacts for Heliophysics	—Improved solar wind propagation models	—Advances in space weather forecasting accuracy —Data-driven solar wind modeling	—Understanding of solar wind creation, evolution, and propagation