Where Does the Inner Heliosphere End?

Teresa Nieves-Chinchilla [1], Sanchita Pal [1,2], Fernando Carcaboso [1,3],
Tarik M. Salman [1,2], Laura Rodríguez-García [4], Nada Al-Haddad [2],
Florian Regnault [6], Erika Palmerio [5], Emma E. Davies [6], and Nathalia Alzate [1,7]

[1] *Heliophysics Science Division, NASA Goddard Space Flight Center, MD 20771, USA*
[2] *Department of Physics and Astronomy, George Mason University, Fairfax, VA, 22030, USA*
[3] *The Catholic University of America, Washington, DC 20064, USA*
[4] *Space Research Group, Universidad de Alcalá, Alcalá de Henares, 28801 Madrid, Spain*
[5] *Predictive Science Inc., San Diego, CA 92121, USA*
[6] *Space Science Center, University of New Hampshire, Durham, NH 03824, USA*
[7] *ADNET Systems, Inc., Greenbelt, MD 20771, USA*

Synopsis

The characteristic signatures of large-scale structures (LSSs) that originate from the Sun can be conceptualized as a distinguishing feature between the inner and outer heliosphere domains. In the inner heliosphere, solar wind structures and streams collide and interact more intensely with each other to strongly bend the Archimedean spiral pattern of the interplanetary magnetic field, also known as Parker's spiral. Traditionally, the inner-outer interface of the heliosphere has been approximated to be at Earth's distance from the Sun, but with the advent and discoveries of various planetary missions and space exploration, we have learned that the LSS imprints in the solar wind can be observed after 1 AU and even at a much larger heliocentric distance beyond this. Therefore, these sorts of findings bring forward the scientific question about the potential radial extent of the inner domain of our heliosphere, from an LSS perspective.

This white paper motivates the need to investigate the spatial and temporal shape of the heliosphere in a more extensive manner. The paper addresses the existing status of fundamental heliospheric research and provides possible future recommendations to advance our understanding of our home, the Sun's atmosphere, and the effect of the Sun's activity on the local space environment.

1 Background

The effects of the Sun on its sphere of influence, the heliosphere have been our long-standing curiosity. The heliosphere is a spatial cavity, filled with magnetized solar wind plasma in the interstellar medium. It contains the solar system with a G2 main-sequence star: the Sun, its planetary companions, their satellites, the asteroids, the comets, and also encompasses each of their own particular gas and plasma environments. The central region of our solar system has the Sun whose atmosphere starts with its luminous disk called the photosphere and ends with the super hot corona. The corona is the source of the solar wind, an outward continuous streaming supersonic flow, filling the solar system with ions, electrons, and energetic particles [e.g. Rodríguez-García et al. 2021].

The role of the Sun in shaping the heliosphere and influencing the planetary atmosphere is now widely explored (see Figure 1 for an artist's impression of the solar system's boundaries). The latest estimates indicate that the radial extent of the heliosphere goes beyond the heliospheric distance of 85 AU [Richardson et al. 2022]. The termination shock (see Figure 1), where the supersonic solar wind becomes subsonic is located at 80-100 AU. Then, at the edge of our heliosphere, the solar wind achieves pressure balance with interstellar plasma. This is termed the heliopause (see Figure 1), located at approximately 119 AU [e.g. Stone et al. 2019].

With increasing distance from the Sun, solar wind streams become more vulnerable to their neighboring flows. They intensely collide and interact with each other, resulting in a strongly-bent spiral magnetic field. Additionally, as the solar wind expands further out from the Sun, the coronal imprints on the solar wind plasma get increasingly lost. Near 1 AU, the average inclination of the solar wind magnetic field to the radial direction is about 45 degrees [Parker 1958]. The compression and deflection of large-scale streams resulting from the interactions with neighboring flows at this distance are believed to be significant [Schwenn & Marsch 1990].

This also leads us to physically discriminate between the inner and outer domains of the heliosphere, but the interface between both domains is extremely difficult to pinpoint. Traditionally, this division has been primarily influenced by our own vantage point, viewing from the Earth out into the heliospheric abyss. The division is based on the dynamically-evolving nature of the magnetized solar wind plasma, leading to different descriptions of plasma environments in the two domains. To achieve a profound knowledge of the large-scale phenomena in the heliosphere, an extensive understanding of the two domains is crucial.

It was initially believed that the outer boundary of the inner heliosphere lies somewhere around 1 AU. However, Voyager and Pioneer spacecraft observations have revealed that solar wind dynamics and interacting flows may still appear beyond this point, which may modify and reprocess their original nature [Burlaga 1984]. A review paper by Richardson et al. [2006] on large-scale solar transients discusses their evolution at very large heliospheric distances (0.3–30 AU) and infers that they expand by a factor of 5 beyond 1 AU until 10–15 AU, where they reach equilibrium with the ambient solar wind. Also, from recent studies by [e.g. Witasse et al. 2017; Palmerio et al. 2021; Davies et al. 2021, 2022], it is evident that even beyond 5 AU, heliospheric large-scale structures (LSSs) may appear with their inherent morphology still intact and interact with each other. Thus, as the planetary assets have increased over recent years, we have learned that LSSs can still bend the spiral magnetic field beyond 1 AU. This imposes the question on the potential boundary of the inner heliosphere, which was previously considered as 1 AU, and underlines the need for comprehensive fundamental research beyond Earth's orbit.

The rationale behind identifying a more reasonable inner-outer heliosphere interface can be seen in interplanetary (IP) shock observations as well. A large IP shock resulting from a solar transient was observed as far as 78 AU [Richardson et al. 2008]. In addition to that, from Voyager 2 observations of interplanetary CME sheaths downstream of IP shocks, [Richardson

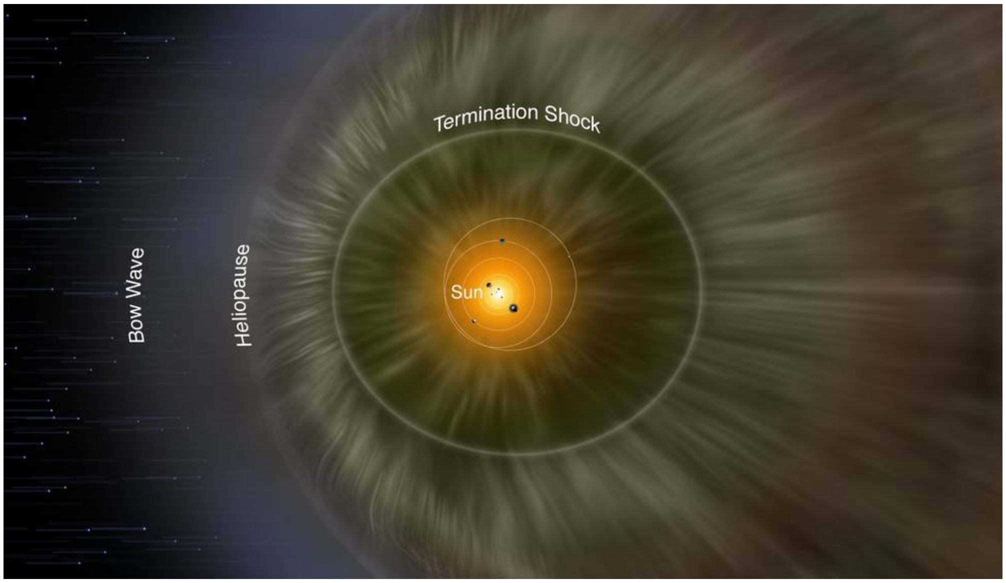

Figure 1: Illustration showing the current understanding of the heliosphere. *Credits: NASA/IBEX/Adler Planetarium.*

2010] found shock dissipation mechanism to change profoundly before and after 35 AU. Inside 35 AU, reflected ions contributed significantly to the dissipation of energy at shocks, whereas beyond 35 AU, pickup ions were responsible for shock dissipation. This further demonstrates the need to identify the potential radial extent of the inner heliosphere which can serve as an important step in sectionizing the fundamentally different governing physics of large-scale phenomena in the inner and outer heliosphere domains.

Our paper focuses on the challenges in determining the potential boundary or radial extent of the inner heliosphere from an LSS perspective. This addresses one of the topics of the Solar and Space Physics Decadal Survey, dealing with the characteristics and physics of the interplanetary medium from the Sun to the boundary of the heliosphere. Knowing this potential boundary has importance in determining space weather impacts far away from the Sun and exploring the nature of the dynamic evolution of LSSs. Furthermore, this will have important implications for future deep-space explorations.

2 The Most Important Science Challenges in the Field that have Arisen from Recent Studies

The propagation and dynamic evolution of LSSs in the highly-structured solar wind constitute a major portion of heliospheric science. Originating from the Sun, the LSSs include coronal mass ejections (CMEs) and the heliospheric current sheet (HCS). Formed later in the Sun's atmosphere, stream interaction regions (SIRs) and/or shock waves are also examples of LSSs that can strongly bend the spiral magnetic field. The LSSs are smeared and lose their internal coherent properties while propagating away from the Sun. Their intrinsic magnetic properties can significantly change via evolutionary processes [see the review of Manchester et al. 2017], including erosion with surrounding ambient fields [Pal et al. 2021; Pal 2022], weakening magnetic field and plasma properties making them difficult to distinguish from the background. Thus, LSS-driven variabilities in the solar wind and their nature of interactions with the surrounding medium have a strong correlation with heliospheric distance and can provide important information about the potential radial extent of the inner heliosphere domain. At this boundary, LSS-driven disturbances are approximated to truncate. Therefore, specific research utilizing the interplay between the solar wind and LSSs beyond 1 AU will provide a macroscopic estimation of this inner heliosphere boundary, from an LSS perspective.

This opens the following questions:

- How do LSSs drive variability in the global configuration of the solar wind and where does it start losing its primordial solar–coronal imprints?
- How does the inner heliosphere boundary dynamically change with the radial distance?
- Does the inner-outer heliosphere interface change with the solar cycle?

3 Recommendations

A multi-step approach is required to achieve the primary scientific objective mentioned in this paper. The addition of spacecraft to the current fleet, improvements in remote-sensing imaging techniques, and a concentrated modeling effort to map the propagation of LSSs beyond the near-Earth space are some initiatives that can be employed in the future to address this.

- **Multi-point mission constellation or swarm of spacecraft covering a wide range of radial separations from the Sun**. The advances in the understanding of the inner heliosphere physics are basically derived from planetary missions, but it is critical to conceptualize a dedicated constellation of space-based assets, with orbits and fields of view beyond Earth's orbit that will provide a systematic and comprehensive set of data to track LSS footprints in the inner heliosphere with improved precision. In addition, an effort needs to be made by the community to call for future planetary missions beyond 1 AU to have dedicated instrumentation for heliospheric science. Such new data sets can have a significant impact on enhancing existing statistical theories and improving 3D magnetohydrodynamic (MHD) modeling capabilities. This will also ensure a much-improved utilization of data-driven machine learning approaches.
- **Coordinate solar–heliospheric missions with planetary missions.** To meet this paper's scientific objective in future solar–heliospheric missions, it will help to investigate inner heliospheric properties at different distances from the Sun and to coordinate the outcomes of these missions. For this reason, it is necessary to standardize the database and instruments that are/will be part of different missions, as it is important to have similar, inter-calibrated, and time-synchronized instruments and standards of data products in order to compare measurements and increase the number of observations. Such an increased number of observations will go a long way in reducing the uncertainties of mathematical and statistical approaches.

4 Concluding Remarks

Investigation of unique plasma environments and LSSs in the solar wind via in-situ measurements and remote-sensing observations, with a constellation of spacecraft, has led to the continuous growth of our knowledge of the heliosphere. However, this knowledge is very much constrained in and around 1 AU or near-Earth space, with considerable gaps in understanding closer to the Sun and far out from the Sun (beyond Earth's orbit). Historic missions, such as Parker Solar Probe and Solar Orbiter, with trajectories coinciding with uncharted heliospheric distances, will uncover newer concepts of LSSs closer to the Sun. However, a comprehensive understanding of the spatial and temporal scale variation of LSS-driven disturbances, especially beyond Earth, is yet to be fully explored and achieved, which is crucial to improve our knowledge of large-scale physical mechanisms in the inner heliosphere domain.

The aim of our paper is to promote fundamental research in an attempt to better understand the structure, composition, and nature of the mentioned heliospheric domains and thereby remedy the deficiencies of the current concept of heliospheric science. The integration of the outlined recommendations in this paper has the potential to also improve the precision of predicting space weather beyond near-Earth space, which is of paramount importance for future deep-space exploration missions.

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