# Outstanding Questions in Solar Wind Physics

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**The Current State.** There are major outstanding questions regarding solar wind formation and its evolution as it advects through the heliosphere. Synthesizing inputs from the solar wind research community, nine outstanding questions of solar wind physics from a recent AGU Grand Challenges review paper[1] are described in this white paper, as well as potential solutions.

**Issue 1: Insufficient data coverage and computational power to measure and model cross-scale feedback.** This is a problem that all sub-disciplines of Heliophysics are encountering [2,3]. The overarching challenge that hinders progress is the need for observations and modeling that encompass scale sizes small enough to resolve kinetic physics up through the global scales of the system. In the solar wind, these are in situ measurement timescales of milliseconds (e.g. to capture the spatial scales of electron physics) up through global time scales of at least a solar rotation, a span of eight orders of magnitude. As a result, observations and models must focus on restricted regions of parameter space. Further, modeling must reduce the complexity of the phenomena it mimics: e.g. restricting the spatial scales and timescales, approximating the physical interactions, and reducing the dimensionality.

Observationally, the solar wind is sparsely sampled, making it nearly impossible to link all relevant temporal and spatial scales. The majority of in situ observations largely consists of single point measurements clustered near L1 and Earth's magnetosphere. Currently there are (at most) three additional simultaneous measurements made in situ with Parker Solar Probe, Solar Orbiter, and STEREO A. This comes nowhere close to covering the orders-of-magnitude of scale sizes necessary for understanding the Sun-heliosphere as a system. While the ability to capture global dynamics of electron density and infer flows from heliospheric imaging such as STEREO/HI has been a great advancement, they are unable to capture smaller scale feedback or the other plasma parameters. The latest advancement, PUNCH, will have sufficient temporal and spatial resolution to capture meso-to-global dynamics, but the resolution is still orders of magnitude away from resolving kinetic scales, and the measurement is still limited to electron density and flows.

**Issue 2: Silos of Knowledge.** Another obstacle to unraveling solar wind physics is the artificial boundary of research between solar atmospheric physics and solar wind physics forced by different observational techniques, rather than by physics[4]. The plasma-physics regimes of the Sun and solar

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[1] See Viall, N.M. and Borovsky, J.E. (2020), Nine Outstanding Questions of Solar Wind Physics. J. Geophys. Res. Space Physics, Grand Challenges in the Earth and Space Sciences, 125: e2018JA026005. doi:10.1029/2018JA026005
[2] See submitted WP 'Mesoscale dynamics – the key to unlocking the universal physics of multiscale feedback' by Kepko et al.
[3] See submitted WP 'Exploring the critical coronal transition region' by Vourlidas et al.
[4] See submitted WP 'A Strategy for Coherent and Comprehensive Observations of the Middle Corona' by Seaton et al.
[5] See submitted WP 'The Sun-Earth Connection as a Single System: Data Analysis and Processing Needs of Current and Future Missions' by Alzate et al.
[6] See submitted WP 'Coronal Heating' by Klimchuk et al.
[7] See submitted WP 'The structured and turbulent nature of the solar wind between the injection and the inertial range' by Di Matteo et al.
[8] See submitted WP 'Multi-vantage-point solar & heliospheric observations to advance physical understanding of the corona and solar wind' by Arge et al.
[9] See submitted WP 'The Science Case for a 4π Perspective: A Polar/Global View of the Heliosphere' by Gibson et al.
[10] See submitted WP 'Multi-Point Compositional Measurements of Solar Wind and Transient Phenomena' by Rivera et al.

atmosphere are very different from that of the solar wind (collisional versus collisionless; sub- versus super-Alfvénic and super-sonic; Reynolds numbers; plasma beta), so modeling approaches, observing techniques, and physical intuition are not easily transferred from one regime to the other [5]. The physical transitions rarely correspond to the observational boundaries, which are driven by the available observational techniques, such as spectroscopy, and imaging in the wavelengths with dominant emission. The formation of the solar wind is tied to the coronal heating problem[6], which itself is driven by the transfer of energy from the convection zone of the Sun through the layers of the solar atmosphere; many knowledge silos are involved in this transfer of energy. In a particular example of silos, theories of coronal heating and formation of the solar wind traditionally treat wave energization and reconnection separately. However, they are not mutually exclusive – reconnection involves waves, can lead to new waves, and waves can trigger reconnection, illustrating an example of why expertise in both needs to be maintained and brought together.

**Science Questions to Address**: We have organized the outstanding questions of solar wind physics into 3 themes: how the solar wind is formed (theme 1), how to interpret observations of solar wind (theme 2), and physical mechanisms that operate on solar wind formation and evolution through the heliosphere (theme 3).

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| ***The formation of the solar wind*** | (1): From where on the Sun does the solar wind originate? |
| | (2): How is the solar wind released? |
| | (3): How is the solar wind accelerated? |
| ***Interpreting observations of solar wind parcels*** | (4): What determines the heavy-ion elemental abundances, the ionic charge states, and the alpha/proton density ratios in the solar wind? (And what do they tell us about the Sun?) |
| | (5): What is the origin and evolution of the mesoscale plasma and magnetic-field structure of the solar wind? |
| ***Physical mechanisms operating on solar wind formation and evolution*** | (6): What is the Origin of the Alfvénic Fluctuations in the Solar Wind? |
| | (7): How is solar-wind turbulence driven, what are its dynamics, and how is it dissipated? |
| | (8): How do the kinetic distribution functions of the solar wind evolve? |
| | (9): What are the roles of solar wind structure and turbulence on the transport of energetic particles in the heliosphere? |

The first theme separates the formation of the solar wind into three distinct steps that correspond to the time history of the plasma parcel, because each physical step leaves a unique observable imprint on the solar wind parcel. There are many different paths to forming a solar wind parcel, and the goal is to determine how much, and under what conditions, each pathway contributes to the total mass and energy of the global solar wind.

Theme 2 relates to the properties of the solar wind and how to interpret the plasma signatures of solar wind plasma parcels in the context of physical mechanisms. In principle, if the answers to the first three questions and the energization of the solar atmosphere were fully understood, these would not be separate questions. With the current state of understanding, though, they are separate. Some quantities in the solar wind evolve as the solar wind advects outwards, while others are conserved as imprints of coronal heating and solar wind formation (Table 2). Some aspects of what determines the conserved plasma signatures are understood, while others are not.

Theme 3 focuses on the underlying physical mechanisms that operate on solar wind formation and evolution[7], and are linked to the answers of themes 1 and 2. These processes change the solar wind plasma and particle populations as the solar wind advects outward and lead to plasma parameters that are not conserved (Table 2).

**Closing on the science questions**. The table below lists the observational requirements to distinguish between competing physical processes. Theme 1 questions on solar wind formation are separated into conserved quantities that can be measured in situ throughout the heliosphere, and those that can only be obtained close to the Sun, e.g. in remote images and the in situ measurements of Parker Solar Probe, Helios and Solar Orbiter. Specific entropy, marked with an asterisk, is not a conserved quantity, but is correlated with, and therefore a tracer of, those that are.

| ***The formation of the solar wind*** |
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| (Q1): ***near Sun***: solar connectivity maps[8] combined with: velocity vectors/flow tracks in images and ***conserved quantities***: solar connectivity maps combined with: FIP; alpha/proton; heat flux intensity; specific entropy* |
| (Q2): ***near Sun***: imaging in/out flow pairs and flux ropes; changes in T; changes in $T_{par}/T_{perp}$ ***conserved quantities***: mass-dependent heavy ion dropouts; abundance of Sulfur; composition changes (FIP or alpha/proton) that occur with changes in magnetic field, heat flux, or density; specific entropy* |
| (Q3): ***near Sun***: global, time-dependent acceleration profiles; T; $T_{par}/T_{perp}$; $T_{ions}$; Alfvénicity ***conserved quantities***: alpha/proton; charge states of heavy ions; specific entropy* |
| ***Interpreting observations of solar wind parcels*** |
| (Q4): Matched remote spectroscopic measurements and in situ composition[6]. i.e. distribution functions; T; $T_{par}/T_{perp}$; density; velocity; of protons, electrons, and charge states, abundances, and distribution functions of the heavy elements He, Sulfur, and at least one additional high and low FIP element |
| (Q5): Constellations with matched in situ composition; $4\pi$, time dependent coverage of the Sun; solar connectivity maps, magnetic field and strahl |
| ***Physical mechanisms operating on solar wind formation and evolution*** |
| (Q6-9): $4\pi$ coverage of the heliosphere via constellations of spacecraft measuring high time resolution particle distribution functions, magnetic fields, and energetic particles. |

In summary, the goal is to understand the complex nature of the 3D, time-variable Sun and its multitude of consequences in the heliosphere. *Multi-point in situ and imaging measurements are needed to disambiguate spatial advection from time dynamics, as well for understanding how large and small scales feedback on each other*. To put it all together, the $4\pi$, time-dependent coverage of the Sun is critical [9]. The measurements need to be velocity, temperature, and density, of different particle populations (electrons, protons, and heavy elements[10], including charge states and FIP). Our current state-of-the-art is a piecemeal approach that stitches this information together.

In addition to this comprehensive observing system, we need *fully 3D physics-based models that have time-dependent driving of the photosphere through the chromosphere, corona, solar wind, through the Alfven zone*. For the evolution of the heliosphere, high temporal and spatial resolution simulations of solar wind propagation and kinetic dissipation are needed. By 2050, we would reliably be able to know the connectivity such that any solar wind plasma parcel low in the corona can be traced to any in situ spacecraft in the inner heliosphere and to Earth. Answering the 9 questions listed above is important for ultimate physical understanding and space weather forecasting.