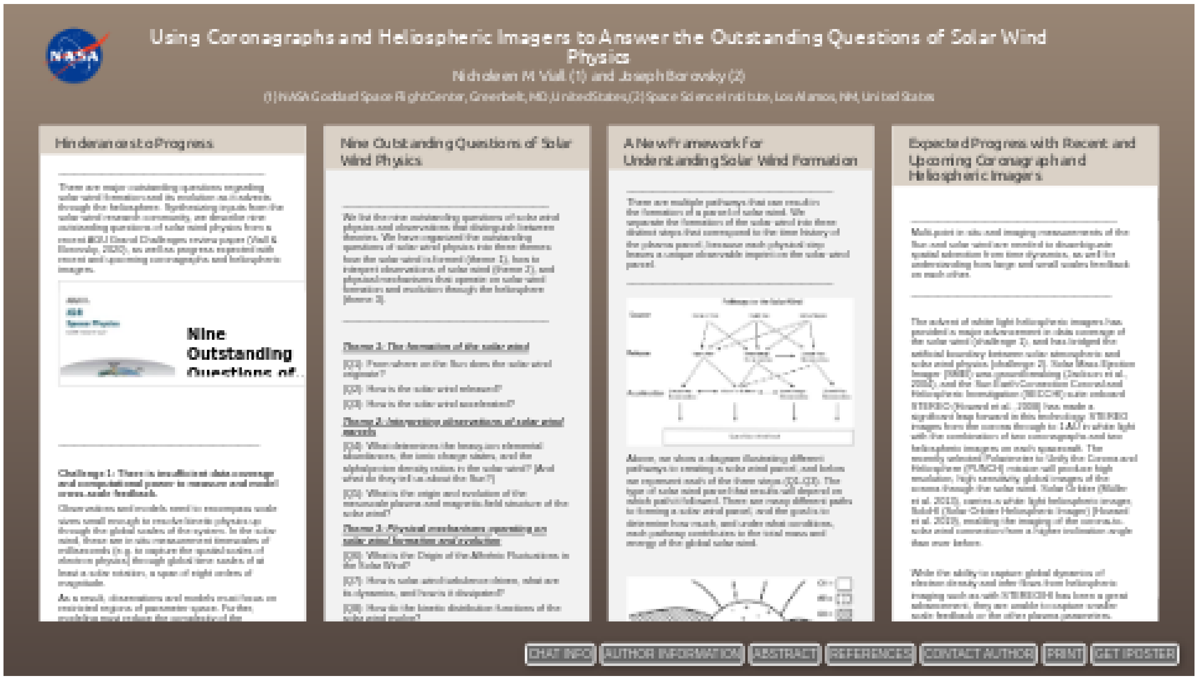
Using Coronagraphs and Heliospheric Imagers to Answer the Outstanding Questions of Solar Wind Physics



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HINDERANCES TO PROGRESS

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, we describe nine outstanding questions of solar wind physics from a recent AGU Grand Challenges review paper (Viall & Borovsky, 2020), as well as progress expected with recent and upcoming coronagraphs and heliospheric imagers.

Nine Outstanding Questions of Solar Wind Physics

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Challenge 1: There is insufficient data coverage and computational power to measure and model cross-scale feedback.

Observations and models need to 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) 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.

Challenge 2: Silos of Knowledge. The plasma-physics regimes of the Sun and solar 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. Additionally, there is an artificial boundary of research between solar atmospheric and solar wind science, imposed by different observational techniques, rather than by physics. 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.

NINE OUTSTANDING QUESTIONS OF SOLAR WIND PHYSICS

We list the nine outstanding questions of solar wind physics and observations that distinguish between theories. We have organized the outstanding questions of solar wind physics into three 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).

Theme 1: The formation of the solar wind

(Q1): From where on the Sun does the solar wind originate?

(Q2): How is the solar wind released?

(Q3): How is the solar wind accelerated?

Theme 2: Interpreting observations of solar wind parcels

(Q4): 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?)

(Q5): What is the origin and evolution of the mesoscale plasma and magnetic-field structure of the solar wind?

Theme 3: Physical mechanisms operating on solar wind formation and evolution

(Q6): What is the Origin of the Alfvénic Fluctuations in the Solar Wind?

(Q7): How is solar-wind turbulence driven, what are its dynamics, and how is it dissipated?

(Q8): How do the kinetic distribution functions of the solar wind evolve?

(Q9): What are the roles of solar wind structure and turbulence on the transport of energetic particles in the heliosphere?

Next, we list the observational signatures that can distinguish between competing physical processes. Theme 1 questions regarding solar wind formation are separated into conserved quantities that can be measured in situ throughout the heliosphere, and those that can only be used 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.

Answering the Nine Science Questions

Theme 1: The formation of the solar wind

(Q1): ***Near Sun***: solar connectivity maps combined with velocity vectors/flow tracks in images

Conserved quantities: solar connectivity maps combined with: enhancement of low first ionization potential (FIP) elements; alpha/proton; heat flux intensity; specific entropy*

(Q2): ***Near Sun***: in/out flow pairs in images; flux ropes; changes in T; changes in Tpar/Tperp

Conserved quantities: mass-dependent heavy ion dropouts; abundance of sulfur; composition changes (abundance of low 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; Tpar/Tperp; Tions; Alfvénicity

Conserved quantities: alpha/proton; charge states of heavy ions; specific entropy*

Theme 2: Interpreting observations of solar wind parcels

(Q4): Matched remote spectroscopic measurements and in situ composition. Specifically, the T; Tpar/Tperp; density; and velocity of protons and electrons. Charge states, abundances, and distribution functions of heavy elements such as helium, sulfur, and at least one additional high and low FIP element

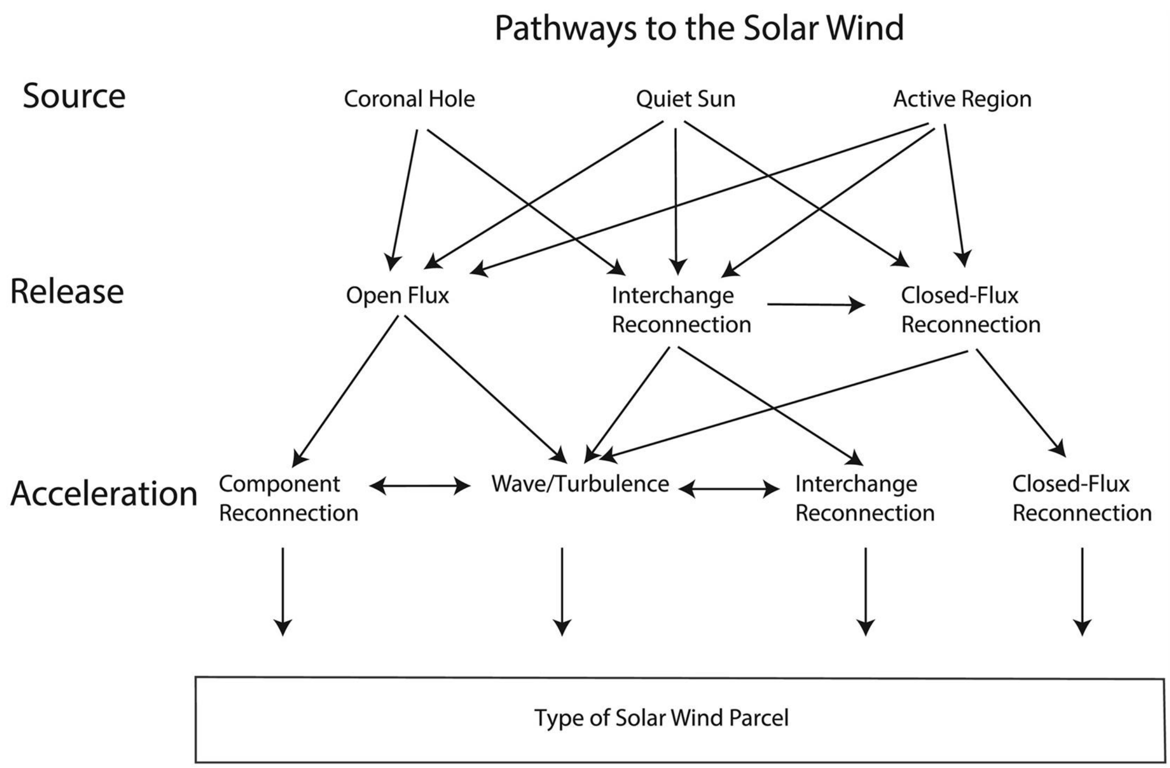
(Q5): Constellations with matched in situ composition; 4π, time dependent coverage of the Sun; solar connectivity maps

Theme 3: Physical mechanisms operating on solar wind formation and evolution

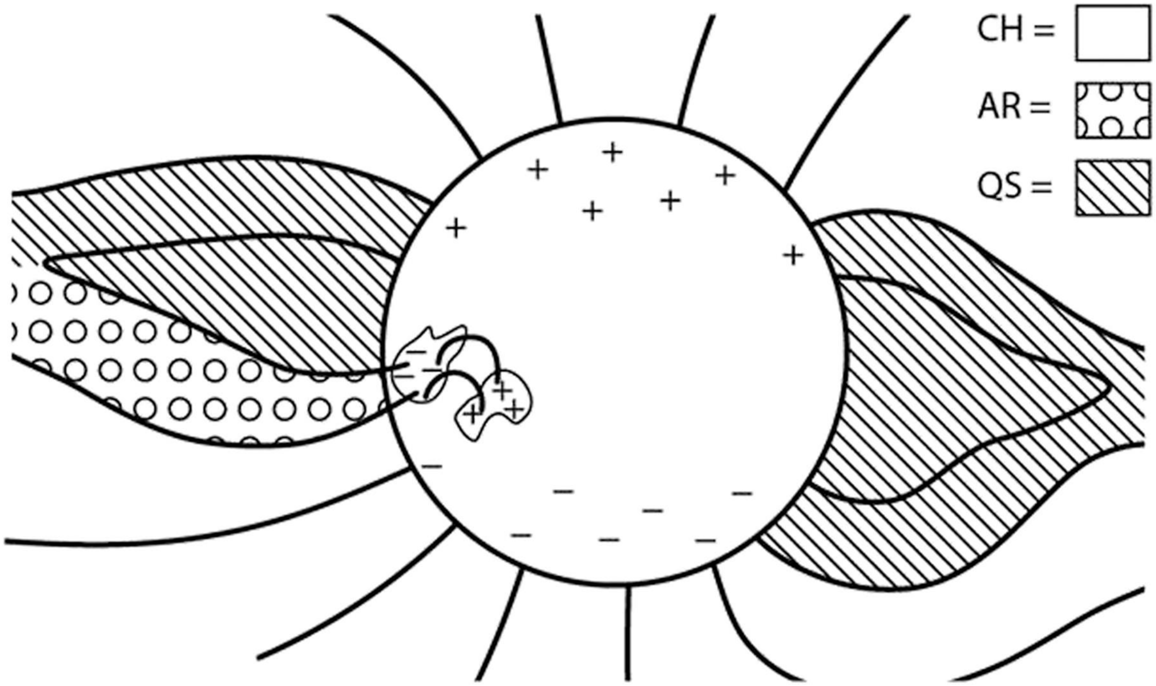
(Q6-9): 4π coverage of the heliosphere via constellations of spacecraft measuring high time resolution particle distribution functions and energetic particles

A NEW FRAMEWORK FOR UNDERSTANDING SOLAR WIND FORMATION

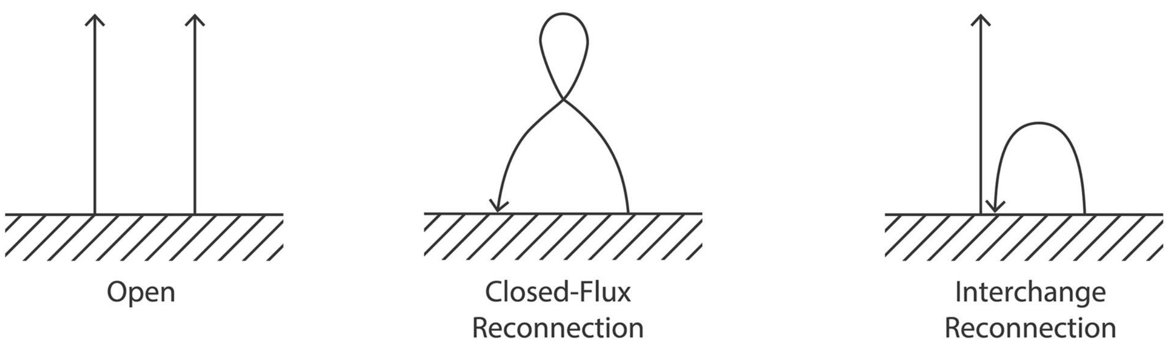
There are multiple pathways that can result in the formation of a parcel of solar wind. We separate the formation of the solar wind into three distinct steps that correspond to the time history of the plasma parcel, because each physical step leaves a unique observable imprint on the solar wind parcel.



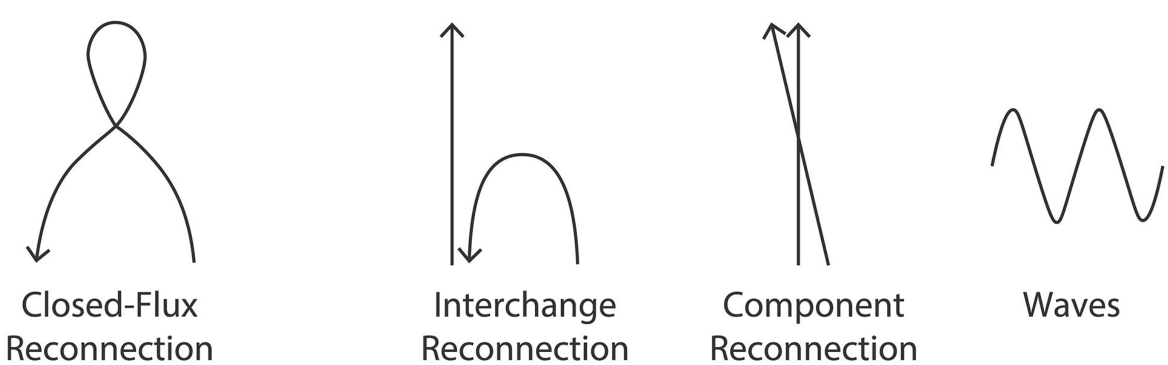
Above, we show a diagram illustrating different pathways to creating a solar wind parcel, and below we represent each of the three steps (Q1-Q3). The type of solar wind parcel that results will depend on which path it followed. There are many different paths to forming a solar wind parcel, and the goal is to determine how much, and under what conditions, each pathway contributes to the total mass and energy of the global solar wind.



Q1: From where on the Sun does the solar wind originate? We represent different source locations of solar wind on the Sun with patterns and show magnetic fields as black lines. An active region is present under the left streamer. The streamer on the left has plasma from the active region and plasma from the quiet Sun in it. The streamer on the right only has quiet Sun plasma in it.



Q2: How is the solar wind released? The plasma may already be on open fields, or it may be on closed−fields, requiring closed-flux reconnection, or interchange reconnection for it to be released into the solar wind. The reconnection may or may not be energetically important.



Q3: How is the solar wind accelerated? We show a cartoon representation of the four different mechanisms of acceleration: closed−flux reconnection, interchange reconnection, component reconnection, and wave/turbulence heating.

Some examples of paths to solar wind formation using the new framework:

- AR under a streamer (Q1), plasma released through closed-flux reconnection at the streamer tip (Q2), accelerated through waves/turbulence (Q3), e.g. streamer blobs
- CH plasma (Q1), on open field lines (Q2), accelerated through waves/turbulence, e.g. classical 'fast wind'
- CH plasma (Q1), released and accelerated through interchange recconnection (Q2 and Q3), e.g. coronal jets
- QS plasma (Q1), released through interchange reconnection at the open-closed boundary (Q2), accelerated through waves/turbulence (Q3)
- CH plasma (Q1), on open field lines (Q2), accelerated through component reconnection (Q3)

EXPECTED PROGRESS WITH RECENT AND UPCOMING CORONAGRAPH AND HELIOSPHERIC IMAGERS

Multi-point in situ and imaging measurements of the Sun and solar wind are needed to disambiguate spatial advection from time dynamics, as well for understanding how large and small scales feedback on each other.

The advent of white light heliospheric imagers has provided a major advancement in data coverage of the solar wind (challenge 1), and has bridged the artificial boundary between solar atmospheric and solar wind physics (challenge 2). Solar Mass Ejection Imager (SMEI) was groundbreaking (Jackson et al., 2004), and the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) suite onboard STEREO (Howard et al., 2008) has made a significant leap forward in this technology. STEREO images from the corona through to 1 AU in white light with the combination of two coronagraphs and two heliospheric imagers on each spacecraft. The recently selected Polarimeter to Unify the Corona and Heliosphere (PUNCH) mission will produce high resolution, high sensitivity, global images of the corona through the solar wind. Solar Orbiter (Müller et al. 2013), carries a white light heliospheric imager, SoloHI (Solar Orbiter Heliospheric Imager) (Howard et al. 2019), enabling the imaging of the corona-to-solar wind connection from a higher inclination angle than ever before.

While the ability to capture global dynamics of electron density and infer flows from heliospheric imaging such as with STEREO/HI has been a great advancement, they are unable to capture smaller scale feedback or the other plasma parameters. Parker Solar Probe/WISPR (Vourlidas et al. 2016) has resolved small flux ropes and smaller density fluctuations than STEREO can, but neither WISPR nor PUNCH will capture kinetic-to-global scale dynamics.

Here we list recent and upcoming missions with coronagraphs and Heliospheric imagers and the Outstanding Solar Wind questions they are likely to make significant progress on.

Theme 1: The formation of the solar wind

(Q1): Combined with Solar Connectivity models, Solar Orbiter/SoloHI and Metis; COronal Diagnostic EXperiment (CODEX); The Solaris Solar Polar MIDEX Mission

(Q2): Parker Solar Probe (PSP)/WISPR; CODEX; Solar Orbiter/SoloHI and Metis

(Q3): CODEX; PUNCH; PSP/WISPR; Solar Orbiter/SoloHI and Metis; Solaris

Theme 2: Interpreting observations of solar wind parcels

(Q4): Imagers/coronagraphs provide context

(Q5): PUNCH; The Solaris Solar Polar MIDEX Mission

Theme 3: Physical mechanisms operating on solar wind formation and evolution

(Q6): Imagers/coronagraphs provide context

(Q7): PUNCH; Solar Orbiter/SoloHI and Metis; Parker Solar Probe/ WISPR

(Q8): Imagers/coronagraphs provide context

(Q9): Imagers/coronagraphs provide context

See AGU Posters:

- SH028-0002 "The Polarimeter to UNify the Corona and Heliosphere (PUNCH) Small Explorer Mission: Status and Next Steps" Craig E. DeForest et al.
- SH028-0011 "The Coronal Diagnostic Experiment (CODEX)" Jeffrey S Newmark et al.
- SH011-0003 "The Solaris Solar Polar Mission: Exploring one of the last Unexplored Regions of the Solar System" Don Hassler et al.

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ABSTRACT

As a part of the American Geophysical Union's Centennial celebration, the Journal of Geophysical Research commissioned papers on the Grand Challenges in the Earth and Space Sciences. We present our Grand Challenge paper on nine outstanding questions of solar wind physics that synthesizes input from the heliophysics community. These involve questions about the formation of the solar wind, about the inherent properties of the solar wind (and what the properties say about its formation), and about the evolution of the solar wind. The nine questions focus on (1) origin locations on the Sun, (2) plasma release, (3) acceleration, (4) heavy-ion abundances and charge states, (5) magnetic structure, (6) Alfven waves, (7) turbulence, (8) distribution-function evolution, and (9) energetic-particle transport. We address the aspects of these questions where progress is being made with the coronagraphs and heliospheric imagers on current missions such as Solar TErrestrial RElations Observatory (STEREO), Parker Solar Probe, and Solar Orbiter. We conclude with the aspects that require observations from the coronagraphs and heliospheric imagers on the upcoming missions Polarimeter to Unify the Corona and Heliosphere (PUNCH), COronal Diagnostic EXperiment (CODEX), as well as a mission with a polar view, such as Solaris.

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