

# JGR Space Physics

## FEATURE ARTICLE

10.1029/2018JA026005



### Key Points:

- Nine outstanding questions of solar wind physics are synthesized from inputs from the heliospheric research community
- New ways of viewing these questions are put forth, and suggestions for future progress are offered
- Calls are made for improved measurements, simulations, and plasma physics theory

### Correspondence to:

N. M. Viall,  
nicholeen.m.viall@nasa.gov

### Citation:

Viall, N. M., & Borovsky, J. E. (2020). Nine outstanding questions of solar wind physics. *Journal of Geophysical Research: Space Physics*, 125, e2018JA026005. <https://doi.org/10.1029/2018JA026005>

Received 10 SEP 2019

Accepted 22 JAN 2020

Accepted article online 4 JUN 2020

©2020. The Authors.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

## Nine Outstanding Questions of Solar Wind Physics

Nicholeen M. Viall<sup>1</sup> and Joseph E. Borovsky<sup>2</sup>

<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, MD, USA, <sup>2</sup>Center for Space Plasma Physics, Space Science Institute, Boulder, CO, USA

**Abstract** In situ measurements of the solar wind have been available for almost 60 years, and in that time plasma physics simulation capabilities have commenced and ground-based solar observations have expanded into space-based solar observations. These observations and simulations have yielded an increasingly improved knowledge of fundamental physics and have delivered a remarkable understanding of the solar wind and its complexity. Yet there are longstanding major unsolved questions. Synthesizing inputs from the solar wind research community, nine outstanding questions of solar wind physics are developed and discussed in this commentary. 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 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) Alfvén waves, (7) turbulence, (8) distribution-function evolution, and (9) energetic-particle transport. On these nine questions we offer suggestions for future progress, forward looking on what is likely to be accomplished in near future with data from Parker Solar Probe, from Solar Orbiter, from the Daniel K. Inouye Solar Telescope (DKIST), and from Polarimeter to Unify the Corona and Heliosphere (PUNCH). Calls are made for improved measurements, for higher-resolution simulations, and for advances in plasma physics theory.

**Plain Language Summary** The Sun's atmosphere, called the solar corona, is a very hot plasma (ions and electrons) that reaches temperatures of 1000000 K or more. The coronal plasma continually expands away from the Sun, carrying solar magnetic field with it. This is the solar wind. It reaches speeds of hundreds of kilometers per second and fills the solar system. The space carved out by the solar wind flow defines the heliosphere. The formation of the solar wind and its evolution as it flows away from the Sun is fundamental to how the Sun and stars get rid of stressed magnetic fields and involves physical processes that operate throughout the universe. Additionally, the solar wind constantly bombards Earth's magnetic field and plasma environment, driving dynamics called space weather. The solar wind is the medium through which larger space weather events from solar storms propagate. Understanding the solar wind is therefore key for understanding the space environment around Earth. In this paper, we synthesize input from the heliophysics community on the outstanding questions of solar wind physics. We describe the current state of research, an updated framework for understanding solar wind formation, and future needs and opportunities for progress, including what is likely to be accomplished in near future with data from Parker Solar Probe, from Solar Orbiter, from the Daniel K. Inouye Solar Telescope (DKIST), and from Polarimeter to Unify the Corona and Heliosphere (PUNCH).

## 1. Introduction: What Have Been the Obstacles to Progress in Solar Wind Physics?

The solar wind is the hot, supersonic flow of plasma and magnetic field from the Sun that defines the heliosphere. It has been studied with in situ measurements since the 1960s (Ness, 1996; Neugebauer, 1997; Obridko & Vaisberg, 2017). Excellent reviews of the rapid progress of solar wind physics can be found (e.g., Cranmer et al., 2017; Paz Miralles & Sanchez Alveida, 2011; Schrijver & Siscoe, 2009; Schwenn & Marsch, 1991a, 1991b; von Steiger, 2008). Decade after decade, advancements in modeling, instrumentation, and remote observations have resulted in major progress toward understanding the solar wind and its fundamental physics.

Despite these advancements, there are still major outstanding questions regarding the solar wind formation and its evolution. The overarching challenge that has hindered 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 time scales 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 8 orders of magnitude. This is a major challenge for models and observations. 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: for example, restricting the spatial scales and time scales, approximating the physical interactions, and reducing the dimensionality.

Observationally, the solar wind is sparsely sampled, making it even more difficult to link relevant time and spatial scales. The majority of observations consist of single point, in situ measurements made near 1 AU. Since the launch of Wind in 1994, followed by Solar and Heliospheric Observatory (SOHO) in 1995, Advanced Composition Explorer (ACE) in 1997, and Deep Space Climate Observatory (DSCOVR) in 2015, there have been continuous plasma and field measurements at L1 to monitor the Earth-impacting solar wind (King & Papitashvili, 2005). In 2006, Solar Terrestrial Relations Observatory (STEREO) commenced two additional sets of in situ measurements at ~1 AU. The two STEREO spacecraft are on slightly different orbits than Earth so that they separate in longitude from each other and Earth with time. With the L1 monitors, they provide observations at three different longitudes at approximately the same times and latitudes. Inside of 1 AU, the two Helios spacecraft (Helios A was launched in 1974 and deactivated in 1985; Helios B was launched in 1976 and deactivated in 1979) provided sets of in situ measurements between 0.3 and 1 AU. Ulysses, launched in 1990 and ceased operation in 2009, provided the only out-of-ecliptic, latitude-dependent data set. The Voyager 1 and 2 spacecraft, both launched in 1977, provide virtually the only solar wind measurements beyond 5 AU. A few planetary missions during their cruise provide measurements at these and other locations (e.g., Cassini), but these are for brief periods of time. Multipoint in situ measurements are needed to disambiguate spatial advection from time dynamics, as well as for understanding how large and small scales feedback on each other. Including all of the missions described above, there are typically only somewhere between 5 and 10 spacecraft measuring the solar wind in situ at a given time. This comes nowhere close to covering the ~8 orders of magnitude of scale size necessary for understanding the Sun-heliosphere as a system, though opportunities to fill in some of this coverage with white light imaging of electron density (discussed below) are now coming online.

Another obstacle to solar wind physics is the artificial boundary between solar atmospheric physics and solar wind physics forced by different observational techniques, rather than by physics. Telescope-based solar physics is a much older field, with remote observations of the Sun going back hundreds of years (von der Luhe, 2009). It has historically been tied to the field of astrophysics, especially in the comparison of the Sun to other stars. Solar wind physics on the other hand is relatively young (decades), and its in-situ-based research community has often been more closely tied to geophysics, especially on the solar wind interaction with the Earth. 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 supersonic; Reynolds numbers; plasma  $\beta$ , ...), so modeling approaches, observing techniques, and physical intuition are not easily transferred from one regime to the other. The transition between these physical regimes rarely correspond to the boundaries between observational regimes, driven by the available observational techniques.

The advent of white light heliospheric imagers has bridged the artificial boundary between solar atmospheric and solar wind physics. 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 (Muller et al., 2013), currently scheduled to launch in February 2020, will carry a white light heliospheric imager, Solar Orbiter Heliospheric Imager (SoloHI) (Howard et al., 2013), enabling the imaging of the corona-to-solar wind connection from a higher inclination angle than ever before.

The field of heliophysics is progressing in a fashion such that the previously distinct regimes of solar physics and solar wind physics are finally connecting in quantitative ways. Both modeling and observational capabilities have reached the level of detail where studying the complex nature of the 3-D, time-dynamic Sun

**Table 1**

*Nine Outstanding Questions of Solar Wind Physics*

**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?

and its multitude of consequences in the heliosphere (in this case, the solar wind) is possible. Solar Orbiter has a suite of in situ instruments, including measurements of elemental composition and charge states of ions, as well as remote imaging in different wavelengths to link the solar atmosphere with the solar wind. After decades of planning (Feldman et al., 1990; Randolph, 1996), the launch of the Parker Solar Probe (Fox et al., 2016) in 2018 (previously planned as Starprobe, Solar Probe, and Solar Probe Plus) makes the connection of solar wind physics to solar physics now highly opportune. The first results from Parker Solar Probe have already provided important new constraints on solar wind physics. Bale et al. (2019) show evidence for plasma instabilities, as well as rapid reversals in the magnetic field lasting minutes called “switchbacks” at larger amplitudes and at a higher occurrence rate than ever observed before. Kasper et al. (2019) use the strahl and velocity to show that these switchbacks take the form of S-shaped bends in the magnetic field and also show the solar wind has a larger azimuthal velocity, (corotational with the solar corona) than theories predict. Howard et al. (2013) show evidence for the predicted dust-free zone around the Sun. Additionally, they resolve small flux ropes and small-scale density structures and fluctuations within

streamers. Lastly, McComas et al. (2019) highlights the importance of the magnetic field structure in the solar wind for energetic particle transport.

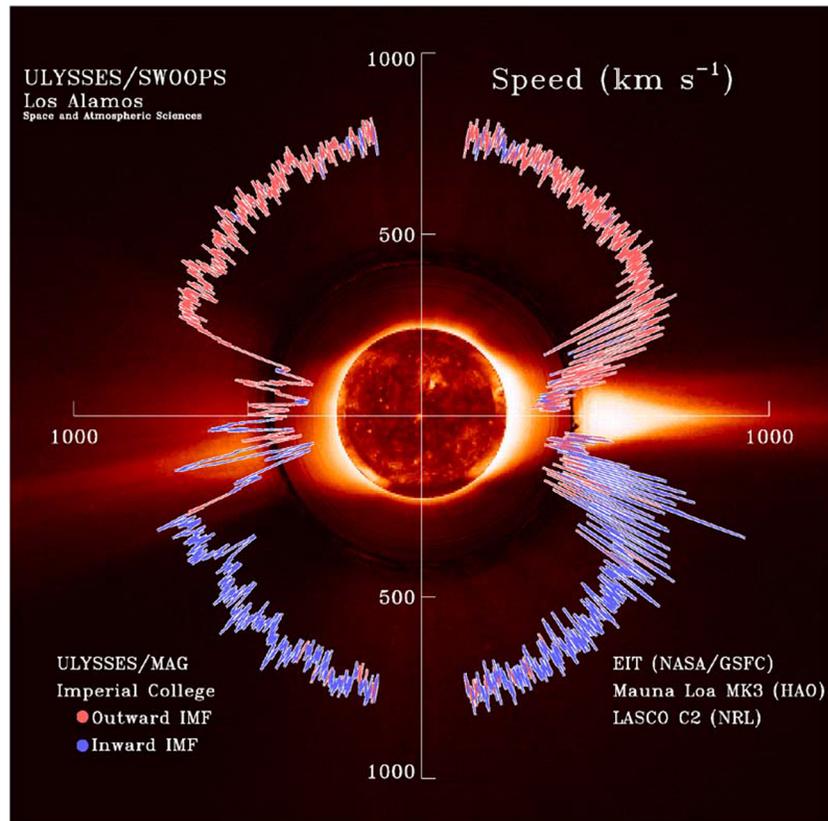
## 2. Nine Outstanding Questions of Solar Wind Physics

Table 1 lists the nine outstanding questions of solar wind physics that are discussed in this paper. The discussion of the nine questions is not ordered by importance but rather into three groups according to how they arise in thinking about 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). Note that the related topics of coronal mass ejections (CMEs) Kilpua et al. (2019) and magnetic reconnection (Hesse & Cassak, 2019) are covered in other Grand Challenge papers.

### 2.1. Theme 1, The Formation of the Solar Wind

The first overarching theme we discuss is the formation of the solar wind. It has long been known that the magnetic field lines that thread the solar corona are rooted in the solar convection zone where they are constantly stirred and energized, and it is this energy that is supplied by this convection (plus the energy contained in emerging magnetic flux) that heats the solar atmosphere and accelerates the wind. Understanding the detailed mechanisms for the conversion, transport, and deposition of energy that heats coronal plasma and that accelerates the solar wind is a major outstanding question in heliophysics.

Historically, the formation of the solar wind has been addressed using the well-known paradigm of two types of wind: fast and slow. The fast/slow paradigm has had a long history because it explains many of the global, average properties of the solar wind. Observations show that the slow solar wind is slower, denser, and has higher charge states, lower alpha/proton abundance ratios, lower proton specific entropy, high variability in these properties, a lack of homogeneity, and lower Alfvénicity than the fast solar wind does. The slow wind also has higher abundances of elements with low first ionization potentials (FIPs), similar to the abundances measured in the solar corona, while the fast wind has FIP abundances close to photospheric values. The Ulysses speed-versus-latitude plot (Figure 1) also illustrates the global fast/slow nature of the solar wind. This Ulysses plot demonstrates that the fast solar wind at high latitudes originates from areas of the solar corona called coronal holes (CHs) that are cooler and less dense, and so they produce less extreme ultraviolet (EUV) emission than the rest of the corona. Note that the Ulysses data of Figure 1 were taken over 5 years (1992–1997), while the overlaid composite image of the solar atmosphere is from 17 August 1996. The composite image therefore does not capture any of the evolution of structure in the solar corona that occurred during the 5 years over which the Ulysses in situ measurements were taken. In the ecliptic, by association, fast, non-CME wind comes from the equatorial extensions of CHs (Arge et al., 2004; Bame et al., 1976; Krieger et al., 1973) and times when the magnetic dipole of the Sun (and therefore polar CHs) is tilted

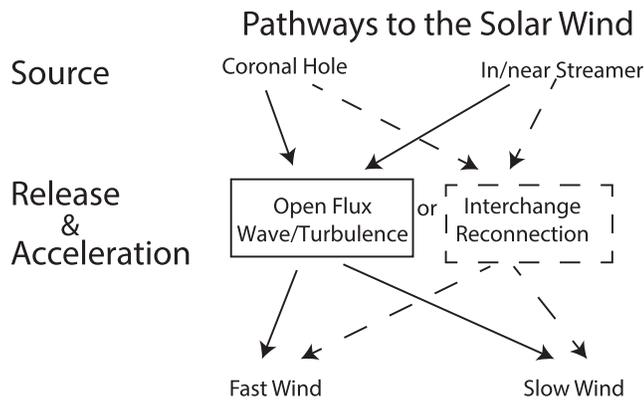


**Figure 1.** Solar wind speed and magnetic polarity measured by Ulysses, as a function of heliographic latitude, overlaid with images from EIT, the HAO Mauna Loa coronagraph, and LASCO C2 coronagraph. Adapted from McComas et al., 1998.

relative to the ecliptic. Also by association, slow wind is correlated with coronal streamers, which are observed at the same latitudes as the slow solar wind in Ulysses and ecliptic solar wind measurements. Coronal streamers are hotter, denser, and brighter than other regions of the solar corona.

The theoretical paradigm to explain these global fast and slow wind associations with coronal structures are divided into two general categories: waves/turbulence, or magnetic reconnection/loop opening (see review by Cranmer, 2009). The two types of theories differ in the energization mechanism as well as the release mechanisms. In magnetohydrodynamic (MHD) wave/turbulence models, the release of solar wind plasma from the solar corona into the heliosphere occurs exclusively on open field lines. The energization that heats the corona and accelerates the wind is MHD waves and turbulence; the degree to which the open magnetic field expands with radius determines the nature of the energy deposition, resulting in slow and dense wind or fast and tenuous wind (Cranmer et al., 2007; Wang & Sheeley, 1990). Heat conduction along the magnetic field is a crucial piece of the connection. In contrast, in the original theory of interchange reconnection to form the solar wind (Fisk, 2003; Fisk et al., 1999; Tu et al., 2005), the release mechanism of the solar wind plasma from the corona is magnetic reconnection and takes the form of “interchange reconnection” wherein a closed magnetic field line reconnects with an open one (Crooker et al., 2002). The reconnection energizes the plasma, and smaller loops of closed magnetic field begin with cooler plasma that produce faster, tenuous wind, while larger, hotter loops produce denser, slower wind.

We illustrate this historical paradigm in Figure 2. The top indicates the two sources: CHs and inside or near streamers. The release and acceleration mechanisms are linked together, with the interchange reconnection (IR) paths in dashed lines and wave/turbulence paths in solid. In the historical paradigm, the outstanding question was as follows: Is it waves/turbulence on open flux, or is it reconnection of open flux with closed flux? The bottom of Figure 2 indicates the two options for types of wind in this paradigm: a fast wind or a slow wind.



**Figure 2.** Historical paradigm to explain the pathway to the solar wind. There are only two sources: CHs and in/near streamers. The release mechanism and acceleration mechanism (dashed lines indicate interchange reconnection, solid indicates wave/turbulence on open fields) are linked, and the result is the fast and slow wind.

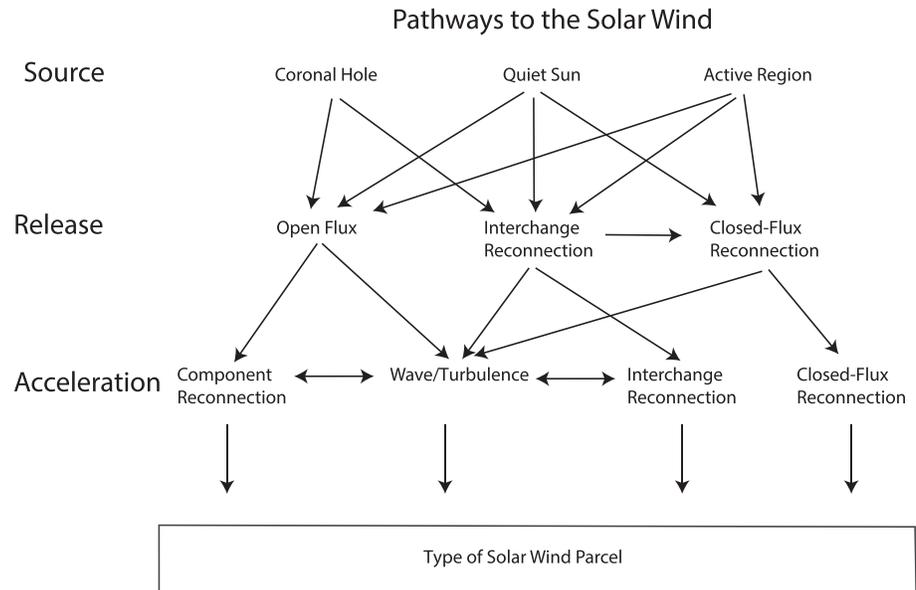
We argue for a new framework for understanding solar wind formation. First, both reconnection and wave/turbulence theories can explain the long-term average fast/slow wind properties, which is one indication that it is time to refine the framework in a way that distinguishes between theories. Furthermore, there is a growing understanding that it is not accurate to treat different theories as mutually exclusive; rather, the relevant question is how much each theory plays a role in the solar wind formation. Some of these long-term relationships can be expressed as a scaling law, indicating that electromagnetic energy per particle added to the plasma is roughly fixed (Schwadron & McComas, 2003). Since these energy balance requirements are satisfied on average and by many theories, locations and times where these long-term relationships are not satisfied are likely to provide new insights into the mechanisms at work. Indeed, there are observations that show solar wind parcels that do not fit neatly into the historical paradigm. For example, there are wind parcels that are accelerated to slow speeds but have composition and Alfvénicity of faster wind (D’Amicis et al., 2019; Roberts et al., 1987; Stakhiv et al., 2015). Also not fitting the historical paradigm, observed solar wind charge states and speed distributions are not bimodal but actually suggest a continuum of states (Zurbuchen et al., 1999).

Three examples of solar wind that do not fit neatly into the historical paradigm also illustrate a new way to understand the plasma pathway to the solar wind, which is to consider the time history of the plasma parcel. The first example is plasma blobs emitted from the tips of helmet streamers (located at the heliospheric current sheet, HCS). They are now known to be the result of reconnection at the HCS (Kepko et al., 2016; Rappazzo et al., 2005; Sanchez-Diaz, Rouillard, Davies, Lavraud, Pinto, et al., 2017; Sanchez-Diaz, Rouillard, Davies, Lavraud, Sheeley, et al., 2017). In contrast to the interchange reconnection solar wind formation theory, as well as to CMEs, the reconnection that creates streamer plasma blobs is not observed to impart much acceleration or heating energy. Rather, the blobs appear to be carried along with the surrounding solar wind plasma as “leaves in a stream,” continuously accelerating for many solar radii after the reconnection occurs (Sheeley et al., 2009). This implies that even though magnetic reconnection is important for the release of the solar wind, a different physical mechanism than reconnection is responsible for the acceleration.

The second example is outflows (blueshifts) from the so-called “fan loops” that are observed on the periphery of active regions (ARs) in Hinode/EIS. The field lines associated with the fan loops and magnetic field of ARs are often open to the heliosphere, so the blue shifts have been interpreted as the nascent solar wind flow. However, many of these fan loops close at other locations on the Sun (Schrijver & DeRosa, 2003), and the blue shifted outflows, as well as the temperatures of the fan loops, are independent of whether or not the field lines are open to heliosphere (van Driel-Gesztelyi et al., 2012). Therefore, the coronal heating (i.e., the energization mechanism low in the corona) is independent of whether or not the plasma is released into the solar wind and must be a separate physical step from acceleration.

The third example is the discovery of the Type II spicule phenomena low in the solar atmosphere; it has been postulated that they could be formed as the result of reconnection (Samanta et al., 2019) and may contribute plasma to the corona and solar wind (De Pontieu et al., 2011). However, Type II spicules are observed throughout the Sun, independent of their connection to the heliosphere, as was the case in the fan loop example. In the case of type II spicules, if the plasma is on a field line connected the heliosphere, the plasma must receive additional energy to prevent it from adiabatically cooling and falling back down to Sun (Klimchuk, 2012). The acceleration is a different physical step in the energization of the plasma and could be from a different source than that which initially created the Type II spicule.

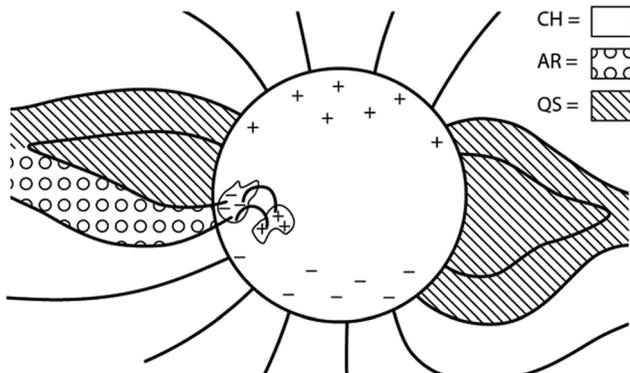
We show in Figure 3 the proposed new framework with multiple pathways to the solar wind. The framework separates the formation of the solar wind into three steps that correspond to the time history of the plasma parcel. The steps correspond to the three questions in this question group: (1) From where on the Sun does the solar wind originate? (2) How is the solar wind released? (3) How is the solar wind accelerated? A



**Figure 3.** Pathways to the solar wind. Q1, source is the top line; there are three general options. Q2 is how the plasma parcel is released. Q3 is how the plasma is accelerated. The type of solar wind parcel that results will depend on which path it followed.

significant difference from the old paradigm is that there is no presorting of the wind into fast and slow. Instead, we now link the solar wind to qualifiers that correspond to the initial physical steps that the solar wind plasma parcel undergoes as it leaves the Sun. Separating the questions by these three steps is particularly important if interchange reconnection is the release mechanism. In these cases, the initial state of the plasma (Q1) and the acceleration (Q3) occurs on different flux tubes and may be due to different physical mechanisms, or at least the mechanism operating in different physical regimes.

For convenience, we conceptualize a parcel of solar wind plasma near the Sun to be a mesoscale structure for which the frozen-in plasma properties of charge state, FIP abundance, and alpha/proton ratio are approximately homogenous. We return to frozen-in plasma properties in more detail in Question 4 and interpreting observations on mesoscale structures in the solar wind in Question 5. A particular parcel of solar wind could have taken any of the paths in Figure 3. The goal is to determine how much each pathway contributes to the global solar wind and under what conditions.



**Figure 4.** Cartoon of different source locations on the Sun, with black lines representing magnetic fields. 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.

The new framework of Figure 3 does not imply that the three questions cannot be linked as they were in the historical paradigm of Figure 2. The point is that it is not a foregone conclusion that they are linked. The state of the global solar wind is determined by combining the statistics of all of the solar wind parcels. The four pathways from the historical paradigm are still contained within the new framework. For example, wind that comes from corona holes (Q1), along open flux (Q2), and accelerated through wave turbulence (Q3) could produce fast wind in the same way that wave turbulence produced fast wind from CHs in the historical paradigm. Open fields in CHs (Q1) can have local magnetic field concentrations, resulting in interchange reconnection, wherein reconnection releases the plasma (Q2) and accelerates the plasma (Q3). Figure 3 indicates the many new possible paths to solar wind in the new framework to explain solar wind observations that did not fit the historical framework. We discuss each physical step (question) in more detail in sections 2.1.1–2.1.3.

### **2.1.1. Question 1: From Where on the Sun Does the Solar Wind Originate?**

To scientists outside the solar wind community, it is surprising that the location on the Sun from which the slow wind originates is unknown (solar wind researchers might be likewise surprised to know that the magnetospheric community does not know what powers the aurora; Borovsky et al., 2019). From where does the solar wind originate is a fundamental physics question that impacts how the Sun and stars get rid of stressed magnetic fields and is important for true predictability of the solar wind environment.

All solar wind originates from the solar corona, the atmosphere of the Sun. The solar corona can be separated into three broad categories: ARs, quiet Sun (QS), and CHs, as shown in Figure 4. These are measured in remote observations based on their radiative output and temperatures, which themselves are determined by the solar atmospheric heating, that is, the so-called coronal heating problem. ARs are the hottest and densest, and therefore brightest in EUV and X-ray emissions, while CHs are the coolest and most tenuous, and therefore dimmest in EUV and X-ray emission. QS regions fall in the middle in terms of temperatures, densities, and emission. The strength and topology of the magnetic field are different in each and determine the coronal heating, or how much thermal energy is deposited to the plasma. Note that streamers, which were part of the original framework, are not explicitly named here. Streamers can be associated with either AR or QS magnetic field, and therefore the state of the plasma and the atmospheric heating within streamers will be dependent on the underlying magnetic field.

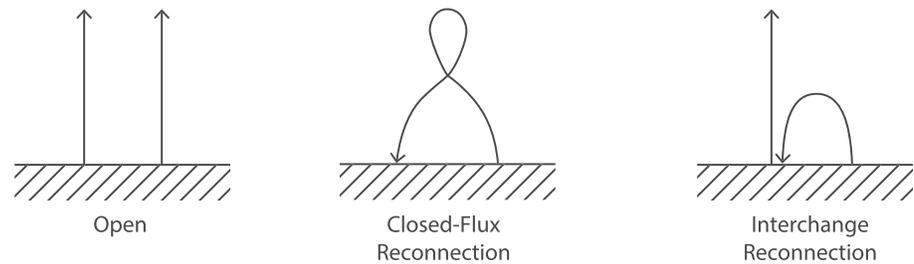
Note also that the term “coronal hole” is sometimes used synonymously to mean “locations where field lines are open to the heliosphere.” Though CHs are generally associated with open field lines to the heliosphere, the correspondence between the brightness boundary determined in EUV measurements and the boundary between magnetically open and closed fields is not well quantified (De Toma & Arge, 2005). The corollary to this is how much magnetic flux is open to the heliosphere. The amount of open flux inferred from in situ magnetic field measurements are much larger than that estimated in coronal models driven by photospheric magnetic flux (Linker et al., 2017). Uncertainty in the correspondence of CH EUV boundary detection methods (e.g., Caplan et al., 2016; Krista & Gallagher, 2009) with open flux still cannot account for the bulk of the discrepancy (Wallace et al., 2019), and it may be due to open flux at the poles that is likely systematically underestimated (Linker et al., 2017; Tsuneta et al., 2008).

We chose AR, QS, and CH as the three options because the temperature and density are similar within each, suggesting a similar heating mechanism. However, there is some temporal and spatial variability within each type of source, indicating local changes in coronal heating, and it may prove useful to subdivide the sources. Examples of possible subdivisions in ARs are “fan loops” located on the periphery of ARs, which are cooler and have a different FIP abundances than the cores of ARs, and AR age, since older ARs tend to be fainter in EUV and steadier than younger ARs (e.g., Ugarte-Urra & Warren, 2012). The QS includes all locations of the closed-field corona without large enough concentrations of magnetic field to be ARs. Both newly emerged magnetic concentrations in the QS and QS locations that are remnants of old ARs likely experience different coronal heating mechanisms than other locations of QS and are possible subdivisions. In CHs, a possible subdivision is between jets and their associated plumes versus interplume locations. Jets and plumes are dynamic, brighter, and hotter, suggesting a different coronal heating mechanism or manifestation than the interplume locations.

Excellent reviews about the origin locations for the solar wind (e.g., Cranmer et al., 2017; Feldman et al., 2005; Luhmann et al., 2013; Poletto, 2013) and the related question of coronal heating (e.g., Klimchuk, 2015; Viall et al., 2020) can be found. Answering the question of the solar locations of origin of different types of solar wind involves linking the flow of plasma and the magnetic connectivity from the low corona through the high corona and out into the solar wind. The atmospheric (coronal) heating that occurs leaves imprints in the resulting solar wind, which we discuss in Q4 and Q5. The near-Sun observations of Daniel K. Inouye Solar Telescope (DKIST), Parker Solar Probe, and Solar Orbiter will be immensely valuable to the question of the origin location of the solar wind.

### **2.1.2. Question 2: How Is the Solar Wind Released?**

Once the initial state of the plasma parcel is determined (Q1), the next step in the life of a solar wind plasma parcel is how the plasma gets out into the heliosphere, that is, how it is released. Put simply, is it already on a flux tube that is open to the heliosphere, or is reconnection required to open up the flux tube? Figure 3 shows



**Figure 5.** Cartoon of the three options for Q2 (How is the solar wind released?): open fields, closed-flux reconnection, interchange reconnection.

that plasma from all three locations on the Sun can be released either through open flux or through reconnection. Reconnection of closed flux primarily occurs at the HCS, which is the global polarity inversion line (note that explosive events such as filament eruptions and CMEs involve closed-flux reconnection at their local polarity inversion line, which does not have to be at the HCS).

Magnetic reconnection at the boundary between open and closed magnetic fields is predicted to occur on many different spatial and temporal scales due to the complex, multiscale evolution of the magnetic field (e.g., Higginson et al., 2017a, 2017b; Higginson & Lynch, 2018; Lionello et al., 2005; Lynch et al., 2014; Masson et al., 2014; Pontin & Wyper, 2015; Rappazzo et al., 2012; Török et al., 2009). On smaller scales, flux-replacement (recycling) estimates for the chromosphere and corona vary from 1.4–3 hr (Close et al., 2004, 2005) to ~40 hr (Schrijver et al., 1997). On larger scales, the equatorial extensions of CHs (associated with open fields) tend to exhibit rigid rotation (e.g., Adams, 1976; Hiremath & Hedge, 2013; Timothy et al., 1975) in contrast to the photosphere, which rotates differentially as a function of latitude; together, these observations can be understood as the result of interchange reconnection (Fisk et al., 1999; Nash et al., 1988).

The three general options for Q2 are illustrated in Figure 5 as a continuously open-flux tube, closed-flux reconnection, and interchange reconnection. Closed-flux reconnection or pinch-off at the helmet streamer (HCS) is predicted to have different magnetic field signatures than interchange reconnection at other locations along the open-closed boundary, with pinch-off (closed-flux) reconnection leading to flux ropes and interchange reconnection leading to torsional Alfvénic fluctuations (Higginson & Lynch, 2018). Pinch-off reconnection is the only reconnection that produces solar wind that is entirely magnetically disconnected from the Sun, indicated by an absence of the strahl. Pinch-off reconnection does not have to disconnect the plasma entirely from the Sun if there is an axial magnetic field component still connected to the Sun; in fact, if both magnetic foot points remain connected to the Sun, a bidirectional electron strahl can be present (Gosling et al., 1987). The height at which reconnection occurs might affect how

much plasma escapes and the gravitational settling signatures that survive into the heliosphere (Weberg et al., 2012).

Many observations indicate that interchange reconnection occurs at the edges of CHs (Baker et al., 2007; Krista et al., 2011; Subramanian et al., 2010) and generally at the open-closed boundaries (Kepko et al., 2016; Mason et al., 2019; Owens et al., 2013, 2018; Sanchez-Diaz et al., 2016, Sanchez-Diaz, Rouillard, Davies, Lavraud, Pinto, et al., 2017; Sanchez-Diaz, Rouillard, Davies, Lavraud, Sheeley, et al., 2017). Reconnection is expected to produce time dynamics in the solar wind. Quasiperiodic trains of density structures (so-called “blobs”) are observed at helmet streamers (Rouillard et al., 2010, 2010; Sheeley et al., 2009; Viall et al., 2010; Viall & Vourlidas, 2015; Wang et al., 1998). The in situ signatures of solar wind plasma near the HCS are also consistent with closed field plasma released through reconnection (Suess et al., 2009; Xu & Borovsky, 2015) (see summary in the right column of Table 2): At 1 AU, (1) the magnetic field in this type of plasma is statistically not Parker-spiral oriented, indicating it is not released continuously, (2) the HCS plasma has an absence of an

**Table 2**  
*A Comparison Between Streamer-Belt-Origin Plasma (Alfvénic Slow Wind) and Sector-Reversal-Region Plasma (Streamer-Stalk Wind)*

Property	Alfvénic slow wind	Sector-reversal-region plasma
Speed	Slow	Very slow
Proton specific entropy	Medium	Very low
Alfvénic	Yes	No
Parker-spiral-field orientation	Yes	No
$\alpha/p$ density ratio	Normal	Very low
Inhomogeneous	Yes	Very
Strahl	Yes	No
$C^{6+}/C^{5+}$ versus $O^{7+}/O^{6+}$ pattern	Like coronal-hole plasma	Like ejecta

electron strahl, indicating that it lacks a magnetic connection to the Sun, and (3) when  $C^{6+}/C^{5+}$  is plotted as a function of  $O^{7+}/O^{6+}$ , this HCS plasma follows the same pattern as ejecta does (cf. Figure 10 of Xu and Borovsky (2015)) and not the pattern of the continuously emitted CH and streamer-belt plasma.

The web of separatrices (S-web) throughout the corona that defines the open-closed boundary is predicted to be dynamic, with magnetic fields opening and closing, pinch-off as well as interchange reconnection occurring (e.g., Antiochos et al., 2012). Bright helmet streamers and pseudostreamers seen in EUV and white light observations of the solar corona are observational examples of the manifestations of the open-closed boundary. The S-web is subject to dynamics and reconnection from driving from the photosphere or from instabilities. Pseudostreamers and null point topologies are examples of S-web arcs that are observed to reconnect and release plasma into the heliosphere (Di Matteo et al., 2019; Mason et al., 2019; Stansby et al., 2018). The magnetic field concentrations from ARs are often involved in the creation of S-web arcs, and there are observational signatures of interchange reconnection associated with ARs (Del Zanna et al., 2011). However, it could take more than one reconnection exchange of plasma for the AR plasma to access open field lines and the heliosphere (Mandrini et al., 2014). We indicate such a series of reconnection events with a horizontal arrow from interchange reconnection to closed-flux reconnection in Figure 3 (pathways to the solar wind).

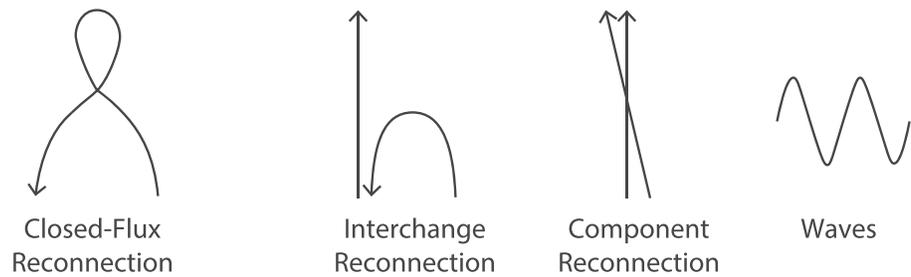
CH jets are another example in which reconnection events occur between localized concentrations of closed magnetic flux within open field CHs and release mass into the solar wind (see reviews by Innes et al., 2016 and Raouafi et al., 2016). Microstreams (Neugebauer et al., 1995, 1997), which are observed in the fast wind associated with polar CHs, have velocity fluctuations of  $\pm 35$  km/s and last 6 hr or longer in the solar wind time series at 1 AU. They are thought to be the in situ signature of these reconnection jets (Neugebauer, 2012) due to the compositional changes and large angle magnetic discontinuities associated with them. Similar  $\sim 6$ -hr structuring is seen in the properties of the proton plasma and in the Alfvénicity (Borovsky, 2016). Velocity spikes seen in Helios data close to the Sun may be related phenomena (Horbury et al., 2018). Simulations support the connection between CH jets and microstream/Alfvén waves (Karpen et al., 2017).

See Cranmer et al. (2017) for an excellent recent review of release mechanisms involved in the formation of the solar wind. The distinguishing observables for Q2 can be generally summarized as changes in plasma and magnetic field properties, because reconnection is an inherently time-dynamic process that produces parcels of solar wind with different plasma properties from each other and from surrounding wind produced in other ways. Time-stationary, open-flux tubes can create solar wind parcels (structure) in the heliosphere as well. Solar rotation will rotate these different sources past an in situ spacecraft or planet, leading to changes in the in situ plasma, as the different solar wind streams advect past the spacecraft. This time/space ambiguity can be addressed in remote images or with multipoint in situ measurements. We return to this topic in Q5: “What is the origin and evolution of the mesoscale plasma and magnetic field structure of the solar wind?” In the future, it will be important to have time-dependent modeling of the corona and solar wind that captures the dynamics necessary to produce the different types and time scales of reconnection-released solar wind.

### 2.1.3. Question 3: How Is the Solar Wind Accelerated?

The third step in the life of a solar wind parcel is its acceleration to the terminal speed it reaches in the heliosphere. It is well known that a heated corona on open magnetic field lines will produce a supersonic solar wind (Parker, 1958). An important point is that in the Parker solar wind solution, the plasma is held at a constant temperature and not allowed to cool adiabatically and so implicitly assumes energy deposition as the plasma flows away from the Sun. The goal now is to figure out what that energy deposition mechanism is. It has been 60 years since the Parker solution, and we know that the kinetic physics involved in two-fluid solutions is likely important. Especially in the fast wind, electron conduction and heating of protons is necessary to get the very high speeds observed of 800 km/s. However, there are a number of unsolved issues about the acceleration of the solar wind: (1) How much does reconnection directly energize the solar wind, (2) how is the Alfvénic turbulence cascade initiated and how is it dissipated (damping, parametric decay, phase mixing, and ion cyclotron waves), and (3) what is the role of the electron-driven ambipolar electric field.

In the new framework, acceleration could be directly tied to Q1, the heating occurring in the lower corona. This will be true for the case of a time-stationary, open-flux tube with waves and turbulence (e.g.,



**Figure 6.** Q3 (How is the solar wind accelerated?) cartoon of the four different mechanisms of acceleration: closed-flux reconnection, interchange reconnection, component reconnection, and wave/turbulence heating.

Velli, 1993). In this acceleration, the amount of energy deposited below or above the sonic transition point determines whether the energy is deposited as heat or flow energy and is related to the expansion of the magnetic field. Empirical studies showed that this “expansion factor” is correlated with the wind speed (Wang & Sheeley, 1990) and may be evidence of wave/turbulence acceleration. Likewise, the reconnection that releases the plasma (Q2) could also provide all of the acceleration energy to the plasma, in which case Q2 and Q3 are linked. Empirically, distance from the CH boundary is also correlated solar wind speed (Riley et al., 2015), which may be evidence of reconnection acceleration. However, Q1, Q2, and Q3 are not necessarily directly connected. We illustrate this in Figures 3 and 6. If the answer to Q2 is magnetic reconnection, then it may not be until the plasma is on the open-flux tube that it experiences the physics that produces acceleration.

Reconnection may release plasma (Q2) but not provide much direct energization of the wind, in which case the reconnection is crucial for Q2 but not important for Q3. Conversely, component reconnection may be occurring in the open fields of CHs (Tenerami et al., 2016). This reconnection would not be important for plasma release (Q2), since the reconnection is between two open field lines, but could play a role in accelerating the solar wind (Q3). Horizontal lines in Figure 3 on the acceleration row indicate that waves can lead to reconnection and vice versa, and both can be involved in the energization of the plasma.

It is inevitable that ambipolar electric fields will contribute to the acceleration of the solar wind. Indeed, there is evidence that the slow wind continues to accelerate beyond Mercury (Arya & Freeman, 1991; Schwenn et al., 1981) as the electron heat flux decays with distance from the Sun (Stverak et al., 2009). Because of the vastly different parallel-to-B mobilities of low-mass electrons and high-mass protons, on open field lines, there must be an ambipolar electric field that retards the outward motion of electrons from the Sun. This ambipolar electrostatic field is the core of exobase models of the solar wind evolution (e.g., Lemaire, 2012; Pierrard et al., 2004) where an interplanetary electric field acts to accelerate solar wind protons outward at the expense of an electron pressure gradient (Lie-Svendsen & Leer, 2000; Meyer-Vernet et al., 2003). An analogous ambipolar electric field also exists in the outward “polar wind” from the high-latitude ionosphere of the Earth: In this case, the situation is well diagnosed with in situ spacecraft measurements, and there is no doubt that the ambipolar field is present (Winningham & Gurgiolo, 1982; Yau et al., 2007) and the outward-accelerated ions from this electrostatic field are observed (Haaland et al., 2012; Welling et al., 2015). The observation of weak electrostatic double layers in the solar wind (Lacombe et al., 2002; Mangeney et al., 1999) has strong implications for solar exosphere models: As pointed out by Borovsky and Gary (2014), double layers (which move with respect to the plasma) can be much more efficient at transferring momentum to ions (and heating the ions) than the static (nonmoving) potential structure assumed in the existing exosphere models.

There are at least two distinctly different types of “slow wind,” here denoted as the “Alfvénic slow wind” (D’Amicis et al., 2019; D’Amicis & Bruno, 2015) and the plasma associated with the sector-reversal region around the HCS, which is accelerated to even slower speeds and often called the “very slow wind” (Sanchez-Diaz et al., 2016). This may indicate different acceleration mechanisms at work. The wind at the HCS is also sometimes called “streamer-stalk wind” (Susino et al., 2008), due to the fact that the HCS is directly tied to helmet streamers observed in white light images, though precisely which part of the streamer reconnects is still under active investigation and is part of Q2. In Table 2, the properties of the two types are

**Table 3**  
*Physical Questions for Each Step in the Pathway to a Solar Wind Parcel*

Physical questions	Q1: From where on the Sun does the parcel of solar wind originate?	Q2: How and at what height was it released to the heliosphere?	Q3: How was it accelerated?
Categories of theories	coronal hole; active region; quiet Sun	reconnection; continuously open field	reconnection energization; waves/turbulence
Distinguishing observational signatures	<i>near Sun only</i> : flow tracks in images; T  <i>conserved quantities</i> : FIP; alpha/proton; heat flux intensity; specific entropy <sup>a</sup>	<i>near Sun only</i> : flow tracks in images; flux ropes; changes in T; changes in $T_{\text{par}}/T_{\text{perp}}$ <i>conserved quantities</i> : 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 <sup>a</sup>	<i>near Sun only</i> : velocity; T; $T_{\text{par}}/T_{\text{perp}}$ ; $T_{\text{ions}}$ ; Alfvénicity <i>conserved quantities</i> : alpha/proton; charge states; specific entropy <sup>a</sup>
Space weather contribution to the heliosphere.	mass; magnetic flux	structure; variability; helicity	flow energy; stream interaction regions

*Note.* Theories and options for each question (first row) with distinguishing observations and indicators (second row), separated by signatures that are only valid close to the sun and those that are conserved and can be used throughout the heliosphere. The third row indicates how each physical step has a space weather impact.

<sup>a</sup>Specific entropy is not a conserved quantity but is correlated with those that are.

compared. Charge state measurements, which are an indication of the acceleration history (see description in Q4), are different for the two types of slow solar wind (Xu & Borovsky, 2015).

One hint about acceleration mechanisms (and source regions) lies in the fact that corotating interaction regions (CIRs) and the trailing edges of high-speed streams exhibit both gradual changes and abrupt changes in the plasma flow velocity, the proton specific entropy, and the heavy-ion charge states (Borovsky & Denton, 2010, 2016a). The CIR stream interface between CH (fast) wind and streamer-belt (slow) wind is often very sharp and very distinct, with the Alfvénicity of the plasma transitioning at 1 AU in an hour or two. If the “Alfvénic slow wind” was the result of a mix of mechanisms, that should result in a gradual shift in the Alfvénicity. If the Alfvénic slow wind plasma were caused by a speed-versus-expansion relation, indicating wave/turbulence acceleration, with increasing flux expansion at the edge of the CH, that should result in only gradual speed transitions from little expansion at the center of a CH to the highest expansion in the slow wind. Particularly if the velocity measurements are rotated into a local-Parker-spiral coordinate system, the stream interface exhibits a strong abrupt change in the flow velocity along the Parker-spiral direction (a vorticity layer).

Modeling capabilities of the solar wind continue to improve; see MacNeice et al. (2018) for a recent review. Solar wind models that include multifluid effects are now coming online (Ofman et al., 2015; Usmanov et al., 2018), which is important for understanding the evidence of ion-cyclotron energization (Cranmer, 2009). Additionally, the details of the magnetic topology can greatly affect acceleration and are important for understanding. Magnetic funnels at pseudostreamers are one example of such magnetic field topologies (Panasenco & Panasenco, 2019). The Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model is a sophisticated surface flux transport model which assimilates full disk magnetograms on an hourly time scale (Arge et al., 2013; Hickman et al., 2015) and is the current state-of-the-art in providing observed time-dependent global surface field input to coronal models, which can then be used to drive the solar wind (e.g., Linker et al., 2016).

#### 2.1.4. Applying the New Framework

We summarize the new framework for understanding the formation of the solar wind in Table 3. The headers are the three questions from this overarching theme. The first row lists the theoretical categories to explain each physical step, described above in their respective questions. The second row lists the observational signatures to distinguish between the theoretical categories, separated into those that are conserved and can be used in in situ measurements throughout the heliosphere, and those that can only be used close to the Sun, for example, in remote images and the in situ measurements of Parker Solar Probe, Helios and Solar Orbiter. Specific entropy is denoted with a superscript letter to indicate that it actually is not a

conserved quantity but is correlated with those that are; we revisit this and the other conserved quantities in Q4. The ultimate goal is to determine how much solar wind each of the possible theories contributes to the heliosphere and how that varies with solar cycle. The third row lists the aspect of each step of formation that is important for space weather, both in terms of impact on planetary bodies and in forming the medium through which interplanetary CMEs (ICMEs) and energetic particles propagate through.

For Q1, the main observable near the Sun that may be able to distinguish between AR, CH, and QS plasma is flows in remote imagery that have coverage from the low corona up through to the solar wind. Flows can be measured using optical flow tracks or mass flux estimates (e.g., DeForest et al., 2018), doppler dimming of spectral lines (Bemporad, 2017), or white light filters at temperature and speed-sensitive wavelengths (Reginald et al., 2018). Coverage from the low corona to the high corona is crucial for this question. Such a combined, continuous field of view coverage with adequate time coverage and resolution to track flows from the low to high corona is rare, due to instrumentation limitations. EUV and X-ray emissions are dependent on density squared, and so images of the corona in those emissions fall rapidly with height above the photosphere. White light coronagraph images are subject to strong scattering, making their relative noise increase in the low corona. Temperature measurements very close to the Sun, especially in combination with flow tracks, are also an indicator of source, since ARs can be several times hotter than CH plasma. Observables that are conserved quantities and can be used throughout the heliosphere are FIP abundances, alpha/proton ratios, heat flux intensity (the strahl), and specific entropy.

From where the solar wind originates determines how much solar wind mass and magnetic flux fills the heliosphere, and where in the heliosphere each type of wind goes is important pieces of information for space weather. For this question, CHs are already agreed upon to be a major contributor. The relative contribution of QS and AR plasma is the remaining uncertainty. Additionally, there are times in the solar cycle at which there are no ARs on the Sun, and so only QS and CH wind is possible.

For Q2, the observables that may be able to distinguish between magnetic reconnection or continuously open field lines near the Sun are flow tracks in images, flux ropes, changes in temperature, and changes in  $T_{\text{par}}/T_{\text{perp}}$ . Flow tracks for answering Q2 have similar benefits and challenges to those described for Q1. In this case, in-out pairs of flows indicate magnetic reconnection, and the height of reconnection can be localized in the images. Flux ropes are a consequence of reconnection; however, they can also be made at the HCS in the heliosphere. Further from the Sun, flux ropes in conjunction with a conserved quantity indicates reconnection as the release mechanism. Temperature and temperature anisotropy changes to the plasma are expected if reconnection releases the plasma. Of the conserved quantities, heavy ion dropouts indicate gravitational settling and are a unique indicator of the height at which reconnection occurred. For reasons described in Q4, sulfur may be a unique indicator of plasma from closed field lines that then undergo reconnection. The other conserved quantities that indicate reconnection-released wind are FIP abundances, specific entropy, and alpha/proton number-density ratios, particularly when they change in conjunction with changes in magnetic field, heat flux, or density. Waves across plasma boundaries, such as Kelvin Helmholtz at the HCS, which could also produce correlated magnetic field changes with compositional changes, are theoretically possible. In such cases, the magnetic field rotations have a precise relationship with composition and plasma boundaries and can easily be identified or ruled out (Crooker et al., 1996).

The space weather contribution to the heliosphere is how much structure, variability, and helicity is created through each type of release. If reconnection occurs and results in flux ropes, helicity could also be injected. Taking CH jets as an example, the presence of microstreams is an indication of the variability that the jets contribute to the heliosphere. As for the mass that the jets contribute, observational estimates range from mass 10% of solar wind (Cirtain et al., 2007) to 4% (Young, 2015) to 3.2% (Jackson et al., 2004); Lionello et al. (2016) used MHD simulations to estimate the contribution of the jets and concluded that CH jets contribute 0.4–3.0% of mass to solar wind. As another example, helmet streamer-tip reconnection wind can only fill the region of the heliosphere immediately adjacent to the HCS. Yet slower solar wind is observed at 30° and more above the HCS (Burlaga & Forman, 2002), a much larger volume than streamer-tip reconnection can account for. The predicted S-web arcs allow such a large solid angle (volume) of slow wind into the heliosphere (Crooker et al., 2012; Titov et al., 2011), and observations of reconnection-released plasma far away from the HCS support this (Di Matteo et al., 2019; Stansby et al., 2018).

For Q3, the observables that may be able to distinguish between acceleration theories near the Sun are velocity, temperature, and temperature anisotropies, ion temperature, and Alfvénicity. Conserved quantities that can be used throughout the heliosphere are alpha/proton ratios, charge states of heavy ions, and specific entropy. The space weather contribution is the dynamic pressure from the flow energy as well as the stream interaction regions formed between flows of different speeds.

We stress that Table 3 is based on the state of the field today, and we have every expectation that with DKIST, Parker Solar Probe, Solar Orbiter, PUNCH, and modeling and theoretical advances, the community will provide new measurements and understanding that fill in this table more accurately.

## 2.2. Theme 2, Interpreting Observations of Solar Wind Parcels

In this group of outstanding questions, we discuss the two outstanding questions (Q4 and Q5) regarding the physics of the properties of the solar wind and how to interpret the plasma signatures of solar wind plasma parcels. We provide the rationale for the defining observables presented in Table 3, namely, that some quantities in the solar wind evolve as the solar wind advects outwards, while others are conserved, and are imprints of coronal heating and solar wind formation. Some aspects of what determines the conserved plasma signatures are understood, while others are not.

### 2.2.1. Question 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?)

As a solar wind parcel advects through the heliosphere, it experiences expansion, compression, rarefaction, wave-particle interactions, instabilities, reconnection, etc., which alter its density, temperature, velocity, heat flux, and magnetic field. Ionic charge states, the abundance enhancement of elements with low FIP (first-ionization potentials), and the alpha/proton density ratio follow well-known trends. Ionic charge states are inversely correlated with solar wind speed (cf. Table 2 of Borovsky, 2012c), such that slower winds are associated with higher charge states and faster winds are associated with lower charge states. FIP abundances follow a trend with slow wind having enhanced abundances of low-FIP elements and fast wind having only a slight enhancement of low-FIP elements (Pilleri et al., 2015). Elements with a FIP below about 10 eV, such as Mg, Si, and Fe, are low FIP, while elements with a FIP above 10 eV, such as O, Ne, and He, are high FIP. Alpha-to-proton number-density ratios are positively correlated with solar wind speed (Kasper et al., 2007; Ogilvie & Hirshberg, 1974). The abundance of heavy elements in general increases during solar maximum and decreases during solar minimum but in proportion to each other so that the relative FIP patterns are not solar cycle dependent. The solar wind ionic charge states are higher (hotter) toward solar maximum (Lepri et al., 2013), and over a solar cycle, the global alpha/proton number-density ratio increases during solar maximum (Kasper et al., 2012).

Spectroscopic measurements show that the ratio of number densities of low FIP to high FIP elements is higher in the corona relative to the photosphere; this enhancement is small in CHs and fast wind and larger in the slow wind and closed-field areas of the solar corona (Feldman & Widing, 2002; Heidrich-Meisner et al., 2018). The overabundance of elements with low FIP is set in the chromosphere (Peter, 1998). A thorough description of the possible physical mechanisms at work is reviewed by Laming (2015). The chromosphere has substantial populations of both ions and neutrals due to its relatively low temperatures. This is in contrast to the mega-Kelvin corona where the plasma reaches a highly ionized state. When plasma is in the partially ionized chromosphere, elements with low FIP will be preferentially ionized while high-FIP elements will still be neutral. Electromagnetic forces act on the ionized species and not the neutral species, leading to an elemental fractionation with an overabundance of low-FIP ions transported from the chromosphere into the corona. For plasma on field lines open to the heliosphere, this elemental fractionation is “frozen in” to the plasma; that is, it remains unchanged as it fills the corona and advects with the solar wind. A closed loop in the corona has FIP elemental abundances that are time dependent, as cycles of coronal heating and cooling and associated mass exchange with the chromosphere occur. In new theoretical work extending our understanding of the FIP effect (Laming et al., 2019), sulfur seems to be a key for Q2 about the release of the solar wind from the corona (as noted in Table 3), due to its FIP being between high-FIP and low-FIP elements. The result is that sulfur can behave as either a low- or high-FIP element, depending explicitly on whether or not the flux tube is open to the heliosphere. Based on measurements of the abundance of sulfur,

the average solar wind exhibits evidence for a mixture of solar wind from both open and closed fields (Laming et al., 2019).

Ionic charge states are determined by (1) electron temperatures, (2) electron number densities, and (3) the amount of time the ions spend with the electrons. The time scale for heating the high hot (1–2 MK) closed loops is in the range of 1–6 hr (Kopp et al., 1985; Reale, 2014; Sheeley, 1980; Viall & Klimchuk, 2017). The time scale for carbon and oxygen to reach charge-state equilibria by progressive ionization in the hot (1–2 MK) high loops is in the range of  $10^4$  s (for  $n_e = 10^8 \text{ cm}^{-3}$ ) to  $10^6$  s (for  $n_e = 10^6 \text{ cm}^{-3}$ ) (cf. Figure 1 of Smith and Hughes, 2010 or Figure 3 of Landi et al., 2012). To a large degree, the ionic charge states are set by the electron temperature at the height at which the charge states are frozen in, which is the height at which the plasma flows away from the Sun fast enough in low-enough electron density so that the charge states no longer evolve. This is because charge-state evolution is faster at lower altitudes where the electron density is higher, and the evolution is very slow at higher altitudes where the electron density is low. Traditionally, since loop height corresponds to the electron temperature, the solar wind ionic charge-state ratio was related to loop height (Feldman et al., 1999; Gloeckler et al., 2003). While the FIP abundances are set in the chromosphere before the heavy ions reach the corona, the ionic charge states are set a solar radii or more above the photosphere; this is a greater height than most coronal loops reach. Landi et al. (2012) showed the charge-state freezing in typically occurs at heights of 1.5 and 3.0 solar radii above the photosphere. Oran et al. (2015) showed that most, but not all, of the observed charge states can be reproduced with time-stationary open fields. Therefore (cf. Table 3), charge state is a tracer of Q3 (acceleration) and possibly Q1 (the initial thermal state) but not likely a direct test of Q2 (release).

The solar wind alpha particle abundance relative to protons probably has its roots in part in the fractionation processes in the partially ionized chromosphere (Peter & Marsch, 1998), with helium having the highest FIP of any element. In the solar wind, the alpha/proton number-density ratio is positively correlated with wind speed (Ogilvie & Hirshberg, 1974); however, in CH-origin solar wind observed at 1 AU, that correlation is weak. The ecliptic alpha/proton number-density ratio increases during solar maximum (Kasper et al., 2012); some of this alpha/proton solar cycle variation can be explained by the prevalence of ejecta plasma and absence of sector-reversal-region plasma in the ecliptic during solar maxima, with ejecta having high alpha/proton ratios and sector-reversal-region plasma having very low ratios (Xu & Borovsky, 2015). The alpha/proton density ratio exhibits sudden changes across magnetic discontinuities in the solar wind (Borovsky, 2020b): Since a boundary in the alpha abundance can only be created at the Sun, measurements of the alpha/proton density ratio in the solar wind are potential tracers of flux-tube dynamics at the Sun (cf. Table 3) (the abundances and charge states of heavy ions might also exhibit sudden changes across magnetic discontinuities, but the time resolution of current heavy-ion data sets is too poor to determine this). In the heliosphere, the alpha particles move outward from the Sun faster than the protons (Asbridge et al., 1976; Marsch et al., 1982), traveling with the mesoscale magnetic structure rather than with the proton plasma (Němeček et al., 2020). The differential flow between the alphas and protons is proportional to the bulk velocity (Steinberg et al., 1996). This proton-alpha velocity difference may provide clues to the mechanisms that accelerate the solar wind.

The proton specific entropy  $S_p = T_p/n_p^{2/3}$  of the solar wind follows similar trends to that of charge states; the proton specific entropy is correlated with speed and anticorrelated with heavy-ion charge states (Pagel et al., 2004). The proton specific entropy has been used as an identifier of solar wind at 1 AU (Camporeale et al., 2017; Xu & Borovsky, 2015). However, proton specific entropy is not a conserved quantity (Freeman, 1988), and it evolves with distance from the Sun. It is still unknown what mechanism(s) back at the Sun it is a proxy for, although (as noted in Table 3) it may provide useful high-time-resolution information for Q1 to Q3 solar wind formation.

Reading the solar wind time sequence data of FIP abundances, ionic charge states, and alpha-to-proton density ratios yields clues to the time and space dependence of coronal structure and processes (cf. Q1 and Q2 in Table 3). These properties are “frozen in” and do not evolve with distance from the Sun (but see Hollweg et al., 2014 and Durovcova et al., 2019 for particular situations in which the alpha/proton ratio can be altered). The alpha streaming relative to protons in the solar wind may hold clues to the acceleration mechanisms (Q3) of the solar wind. To exploit this information, better understanding of the connection of these solar wind measurements to physical processes at the Sun is

needed as well as higher-time-resolution, higher-accuracy solar wind measurements of heavy ions and alpha particles.

As noted in Table 3, FIP elemental abundance relates to Q1 (location on the Sun) and Q2 (release). FIP abundances provide no direct information about Q3 (acceleration). Future high temporal and spatial resolution sulfur measurements in remote spectroscopy off the limb and sulfur measurements in situ would be very useful (see Del Zanna & Mason, 2018 for a thorough review of spectral line measurements). Future models that include the crucial physics of chromosphere-to-coronal transport to reproduce the FIP effect simultaneously with dynamic opening and closing of loops will be important for understanding how the time scales of release effect the plasma parcel that is in the solar wind. For example, if the loop undergoes a new reconnection event too rapidly after closing down, it may not have had time for fractionation to occur.

The heavy ion abundance and alpha/proton density can generally be determined by the FIP mechanism, but it could also be determined by gravitational settling (Endeve et al., 2005; Raymond et al., 1998; Weberg et al., 2012). In principle, in situ data can distinguish between these, but they require data from enough elements to sort by FIP and also by mass, which in practice exist but are rare. Alpha behavior in the corona is especially difficult to determine due to the lack of spectral lines (helium is fully ionized in the corona and so there are no electron transitions to image).

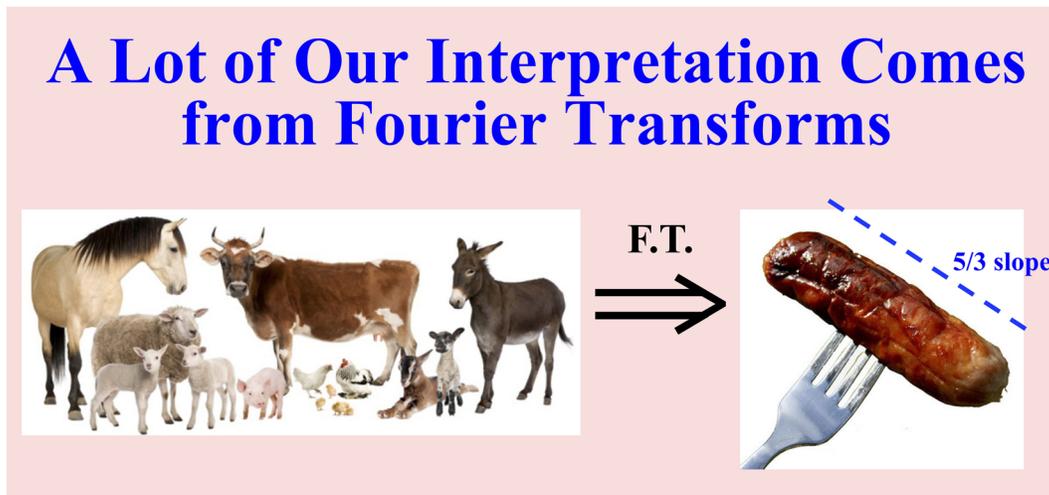
The alpha-to-proton density ratio provides the highest-time-resolution method to study the magnetic structure of the corona using solar wind measurements (e.g., Safrankova et al., 2013). Close-to-the-Sun alpha/proton measurements by Parker Solar Probe will greatly advance this connection. Solar Orbiter will have heavy-ion abundance and charge-state measurements at much higher time resolution than has been available so far, fast enough to differentiate boundaries of individual flux tubes.

### 2.2.2. Question 5: What Is the Origin and Evolution of the Mesoscale Plasma and Magnetic Field Structure of the Solar Wind?

A major question concerns the structure and dynamics of the heliospheric plasma and magnetic field and its connections back to the Sun. This relates to the relative roles of active MHD turbulence, dead turbulence (turbulence that has exhausted its energy and left behind a structured magnetic field), nonlinear Alfvén waves, advected pressure-balance structures, fossil coronal flux tubes, magnetic holes, mirror modes, etc. (Li & Qin, 2011; Neugebauer & Giacalone, 2010, 2015; Owens et al., 2011; Tu et al., 2016).

Solar wind structure comes from three sources: (1) spatial structures on the Sun, plus the solar rotation and the expansion of the wind away from the Sun, (2) time dynamics at the Sun, including reconnection of magnetic fields, spicules, and jets, and (3) evolution in the heliosphere, for example, turbulence, which destroys structure originating from the Sun and continually creates and destroys new structure. The question is what are the relative contributions of sources (1), (2), and (3): when, where, and what do they look like. Very large scale structure with time scales of a day or so (CIRs, high-speed streams, trailing edges, HCSs, heliospheric plasma sheets, CMEs, ...) are created by identifiable magnetic and velocity features in the corona of the rotating Sun. On mesoscales (time scales in the range of minutes up to a few hours), determining the origin of the structure is difficult due to observational limits, modeling limits, and an incomplete understanding of all of the competing physical processes that can act, making it difficult to model the connection between the solar wind and the solar source. These mesoscales are much larger than kinetic scales (microscales).

As the solar wind plasma advects past a spacecraft, fluctuations in all quantities at all time scales are seen. At time scales of seconds and longer, it is safe to assume that the temporal fluctuations largely represent spatial structure of the plasma and magnetic field. There are robust velocity and magnetic field fluctuations in the plasma (with changes  $\langle |\Delta B|/|B| \rangle \sim 0.5$  and  $\langle |\Delta v|/v_A \rangle \sim 0.35$  at 30-min time scales) and the estimated Reynold's numbers of these fluctuations are extremely high (Borovsky & Gary, 2009), so it makes sense that the velocity and magnetic field fluctuations are turbulence (Coleman, 1968; Matthaeus & Goldstein, 1982). Observed magnetic and velocity power spectral densities are consistent with expectations for MHD turbulence (Boldyrev et al., 2011; Perez & Boldyrev, 2010; Podesta et al., 2007; Wicks et al., 2010), and higher-order moment calculations are also consistent with dissipating turbulence (Hadid et al., 2017; Smith et al., 2018). Some solar wind statistical analyses aim to quantify the effects of “coherent structures” or “intermittent structures” in the statistical transformations of solar wind time series data (e.g., Bruno, 2019; Bruno et al., 1999; Greco et al., 2010; Salem et al., 2009). Nonetheless, there



**Figure 7.** A comical depiction of the transformation (blending) of information from the solar wind time series (left) to a Fourier power spectrum or other statistical reduction (right).

are issues as to the role of nonturbulent structures in the solar wind measurements. Analyses of turbulence in the solar wind are statistical analyses, typically in frequency space, and often without consideration of what specific types of structures (i.e., current sheets, plasma boundaries, magnetic holes, pressure-balance structures, and mirror modes) are in the solar wind time series. As depicted in Figure 7, looking at the output of a statistical (e.g., Fourier or structure-function) analysis, it is difficult to discern what was in the time series: for example, magnetic decreases, pressure balance structures, flux ropes, plasma boundaries, and plasma blobs.

Understanding the nature and dynamics of the mesoscale structure is important for the transport of energetic particles in the heliosphere, for the propagation and evolution of CMEs, for processes at interplanetary shocks, and for solar heat-flux transport. The mesoscale structure of the magnetic field is largely structured into magnetic flux tubes (Bruno et al., 2001; McCracken & Ness, 1966; Michel, 1967). The origin of the flux-tube structure is debatable and probably mixed (turbulence, dead turbulence, solar coronal structure, Alfvén wave dynamics, etc.), but the high level of intermittency associated with coherent structure is not debatable.

The mesoscale structure of the solar wind is also an important part of the Sun-Earth connection (Borovsky, 2020c). The temporal changes in the magnetic field associated with the passage of flux tubes results in sudden changes in the rate of dayside reconnection and the driving of the magnetosphere: Depending primarily on the local orientation of each tube, some flux tubes are geoeffective, some are not. Some flux tubes will be capable of driving a magnetospheric substorm (Freeman & Morley, 2009; Newell & Liou, 2011) as they pass. When the current sheets that form the walls of the flux tubes come into contact with the Earth's bow shock, the current sheets can produce hot-flow anomalies upstream of the Earth (Schwartz et al., 2000). Ambient solar wind mesoscale structures also drive ultra-low frequency (ULF) wave dynamics in the magnetosphere (Kessel, 2008; Wang et al., 2017). Large-amplitude ( $>2X$ ) solar wind density structures produce sudden changes in dynamic pressure that compress and relax the entire magnetosphere, causing globally coherent compressional oscillations (Borovsky & Denton, 2016b; Cahill & Winckler, 1992; Korotova & Sibeck, 1995; Matsuoka et al., 1995; Sarafopoulos, 1995). One type of mesoscale solar wind structure occurs as quasiperiodic enhancements of density optically observed at the Sun and throughout the inner heliosphere (Di Matteo et al., 2019; Kepko et al., 2016; Viall et al., 2009) and detected in situ at the Earth's magnetosphere (Viall et al., 2008, 2010; Di Matteo & Villante, 2018). The quasiperiodic dynamic-pressure enhancements drive globally coherent ULF waves inside the magnetosphere at the same frequencies (Kepko et al., 2002; Viall et al., 2009): The ULF waves are observed by ground magnetometers (Villante et al., 2016), as radar oscillations in the high latitude ionosphere (Fenrich & Waters, 2008), in polar UV imaging data (Liou et al., 2008), in the radiation-belt dynamics (Kepko & Viall, 2019), and even the

equatorial ionosphere (Dyrud et al., 2008). MHD simulations capture this interaction and show that locations of field line resonance will even amplify the waves (Claudepierre et al., 2010; Hartinger et al., 2014). Finally, the current sheets of the solar wind are often the sites of strong ( $\sim 80$  km/s) wind shears that disrupt the Earth's magnetotail as they advect past (Borovsky, 2012a).

In the highly Alfvénic solar wind, variations in the proton flow vector and the magnetic field vector seen by a spacecraft are highly time correlated with  $\Delta \underline{v} \approx \pm \Delta \underline{B} / (4\pi\rho)^{1/2}$ : The changes in  $\underline{v}$  are parallel (or antiparallel) to the changes in  $\underline{B}$ . This means that if you shift into the reference frame that moves with the magnetic structure, you see a network of flux tubes, with each flux tube having a parallel proton plasma flow inside of it at a fraction of the Alfvén speed (Borovsky, 2020a). The correlations are such that the plasma flow relative to the structure is toward the Sun, hence the structure is moving outward along the Parker spiral relative to the proton plasma at a fraction of the Alfvén speed. In the reference frame of the magnetic structure, the flow is everywhere parallel to the magnetic field; any plasma flow velocity perpendicular to the local magnetic field is below the noise of the measurements. This includes the very large velocity shears across the current sheets at the flux-tube walls: the rotating plasma flow is parallel to the rotating magnetic field. This lack of a perpendicular-to- $\underline{B}$  flow in the reference frame of the magnetic structure indicates that the magnetic structure is not evolving as it moves outward from the Sun (Němeček et al. (2000) refer to the frame that move outward with the magnetic structure as the de Hoffmann-Teller frame of the solar wind: They find that the alpha particles of the solar wind tend to move with this frame).

Some clues to the nature of the nonturbulence mesoscale structure of the solar wind are the following. (1) Solar wind flux tubes can have a long-distance coherence from the Earth to near the Sun (Borovsky, 2020b; Gosling et al., 2004; Trenchi et al., 2013). (2) Some flux-tube walls are also plasma boundaries (e.g., they exhibit changes in the proton specific entropy, the density, the ionic composition, the field strength, the electron heat flux, and the plasma  $\beta$ ) (Borovsky, 2008; Borovsky, 2020b). (3) Tube cross sections squash and stretch under the action of compression (CIRs) and rarefaction (trailing edges), respectively: The statistical amount of squashing and stretching matches theoretical predictions for static structures (Borovsky & Denton, 2016a). (4) In the Alfvénic solar wind in the reference frame of the magnetic structure, there are parallel plasma flows in each flux tube, with the flow vector changing from tube-to-tube because the field direction changes from tube-to-tube. (5) There is a lack of evidence of turbulent mixing in the slow solar wind (Borovsky, 2012b). (6) Some solar wind structures survive from the Sun to 1 AU. One example of surviving structure is the periodic density structures imaged at streamer stalks (Viall & Vourlidas, 2015) and detected upstream of Earth's magnetosphere (Kepko & Viall, 2019). A second example is the narrow ( $\sim 10^4$  km at 1 AU) CIR stream interface between fast and slow wind (Borovsky, 2006), whose thickness is consistent with Bohm diffusion acting over the  $\sim 100$ -hr lifetime of the solar wind plasma advecting from the Sun to 1 AU.

White light images provide important information regarding two sources of mesoscale structures: coronal structure versus turbulence evolution. Mesoscale structures coming directly from the upper corona as the solar wind is formed are observed using STEREO/SECCHI HI1 white light imaging (FOV is 15–90 Solar radii); and as the solar wind advects out, turbulent fluctuations on mesoscales appear in the images, which coexist with the mesoscale structures that came directly from the Sun (DeForest et al., 2016). In rare circumstances, mesoscale structures can be followed from their release at the Sun, through the heliosphere, to Earth impact in the STEREO/SECCHI heliospheric imagers (Rouillard et al., 2010; Rouillard, Davies, Lavraud, et al., 2010; Rouillard, Lavraud, Sheeley, et al., 2010). However, the direct Sun-Earth connection in white light is biased to mesoscale structures with density enhancements (white light image intensity is proportional to the electron density). Additionally, current heliospheric imagers are resolution and noise limited, and most mesoscale structures fall below the noise floor well before they get to Earth. Lastly, though distinguishing the development of dynamics en route from solar structures is relatively straightforward in imaging data, using ecliptic-viewpoint measurements, it is however difficult to tell (a) time stationary spatial structures from the Sun from (b) time-dynamic released structures. A polar view is better suited, since the line of sight is parallel to the rotational axis of the Sun. Solar Orbiter's extended phase with its  $30^\circ$  orbit inclination will get a peek. For understanding the origin of mesoscale structures impacting the Earth, we are currently limited to single point, in situ measurements, with a few rare intervals with multiple spacecraft measurements (e.g., Thieme et al., 1989). In situ measurements of plasma parameters of mesoscale

structures at distributed longitudes upstream of Earth could decouple solar sources (a) and (b) due to the rotational offset in longitude expected for structures from source (a).

Excellent reviews of the issues associated with mesoscale structure can be found (Bruno & Carbone, 2013, 2016; Neugebauer & Giacalone, 2010; Owens et al., 2011; Schatten, 1971).

Future progress will be helped by higher sensitivity and resolution white light imagers, such as those of PUNCH, and by higher-accuracy higher-time-resolution measurements of the magnetic field, plasma flow, heavy ions, and electron strahl. Investigations of strahl statistics can reveal details of the magnetic field structure between the Sun and the measuring spacecraft. Innovative methods to trace field lines in the solar wind could be greatly helpful.

### 2.3. Theme 3, Physical Mechanisms Operating on Solar Wind Formation and Evolution

In this group of questions, we discuss the four outstanding questions (Q6–9) regarding the physical mechanisms that operate on solar wind formation and evolution. Answering these questions involves understanding fundamental physical processes. These processes change the solar wind plasma and particle populations as the solar wind advects outward and provides the rationale for the defining observables that are not conserved in Table 3.

#### 2.3.1. Question 6: What Is the Origin of the Alfvénic Fluctuations in the Solar Wind?

In fast CH-origin plasma and, to a lesser degree, in intervals of slower speed wind, the fluctuations are dominated by outward-propagating Alfvénic fluctuations (Belcher & Davis, 1971; D’Amicis et al., 2019) with strong correlations between the vector changes  $\Delta \mathbf{v}$  and  $\Delta \mathbf{B}$ . Strong Alfvénic fluctuations are also observed in the transition region and corona (McIntosh et al., 2011). In the solar wind, the Alfvénic fluctuations are seen on time scales from seconds to days. The Alfvénic correlations are particularly strong across strong current sheets (directional discontinuities) in the solar wind plasma (Neugebauer, 1985), with these current sheets having normals that are essentially perpendicular to the local magnetic field (Knetter et al., 2004). The velocity shear across the current sheets can be greater than the Alfvén speed and can approach the magnetosonic speed (Borovsky, 2012a); hence, the shears can have magnetosonic Mach numbers  $\sim 1$ . Borovsky (2020a) has argued that the Alfvénic fluctuations look like a nonevolving heliospheric magnetic structure propagating outward at  $0.7v_A$ .

If the  $\mathbf{k}$  vector of the Alfvénic fluctuation is purely perpendicular to  $\mathbf{B}$ , then the fluctuation has no group velocity: In that case, is the Alfvénic fluctuation an Alfvén wave? A longstanding question is whether these Alfvénic current sheets (Elsasser sheets) are rotational discontinuities propagating through the plasma or tangential discontinuities (plasma boundaries). Burkholder et al. (2019) point out that the Alfvénic signatures on the two sides of a discontinuity have their origins at different times from different locations in the corona. The outward Alfvénic correlations in the solar wind statistically decay with distance from the Sun: It is an issue whether the decay is caused by the destruction of the outward Alfvénic fluctuations or by the addition of inward Alfvénic fluctuations (Bruno & Bavassano, 1991).

Understanding the outward-traveling Alfvén waves is important for a number of reasons: (1) They may be integral to the acceleration of the solar wind, (2) they may power the turbulence in the solar wind which alters the evolution of the solar wind, (3) they affect the propagation and scattering of energetic particles throughout the inner heliosphere, and (4) their magnetic-field-direction fluctuations produce intermittent intervals of on-off driving of the Earth’s magnetosphere by intermittently altering the dayside reconnection rate (an “on” interval can produce a magnetospheric substorm).

A number of sources for the Alfvénic fluctuations in the solar wind have been considered. Because of the dominance of outward propagation, it is likely that a major source is at the Sun. The magnetic flux of the CH solar wind connects to the Sun via open-flux funnels that are caught in the downflow lanes at the edges of supergranules (Dowdy et al., 1987). Only a small fraction of the photospheric flux connects to the corona above. Most of the flux resides in low-lying loops that close before reaching coronal heights and temperatures. Photospheric motion jiggling the base of the open-flux funnels is one source of Alfvén waves; however, the motion of the funnel in the downflow lane is probably more restrictive than the Leighton random walk in two dimensions. Jiggling of the closed chromospheric magnetic carpet and leakage of wavemodes from the chromosphere into the open funnels has also been considered (Cranmer & van Ballegooijen, 2005). Reconnection of low-lying loops with the open-flux funnels (one possible source of plasma to the funnels)

also will produce outward-Alfvénic perturbations (Burkholder & Otto, 2019; Fisk et al., 1999; Tu et al., 2005). Similarly, near the edges of CHs, reconnection of the open flux with the magnetic canopy of the corona will produce Alfvén waves. Another possibility is that turbulence near the Sun decays into a dynamic-alignment state, leaving one-side Alfvén waves (Dobrowolny et al., 1980; Matthaeus et al., 1983; Telloni, Perri, et al., 2016).

Away from the Sun, the driving of inward and outward Alfvén waves by instabilities at velocity shears has been considered, in particular at CIR stream interfaces (Smith et al., 2011) and at the edges of coronal-plasma microstreams (Goldstein et al., 2003). Parametric instabilities have been invoked to create lower-frequency Alfvén waves in the solar wind from solar-origin higher-frequency Alfvén waves and to create inward-propagating Alfvén waves (Bruno & Carbone, 2016). Higher-frequency Alfvén waves can be driven by various kinetic instabilities in the proton-alpha-electron solar wind plasma (Gary, 1993).

Excellent reviews of the origin of the Alfvénic fluctuations can be found (e.g., Cranmer & van Ballegoijen, 2005; Marsch, 2018; Velli & Pruneti, 1997). The near-Sun observations of Parker Solar Probe will provide valuable observations of a less evolved Alfvén-wave spectrum from the Sun (e.g., Bale et al., 2019) and perhaps direct clues to the mechanisms producing the Alfvénic fluctuations. Future progress on this question will be helped by higher-resolution observations and simulations of open-flux funnels interacting with low and high closed loops, with simulations taking account of the granular and supergranular convection of closed flux.

### **2.3.2. Question 7: How Is Solar Wind Turbulence Driven, What Are Its Dynamics, and How Is it Dissipated?**

Active turbulence produces an energy transfer from large-scale fluctuations into smaller-scale fluctuations and then into the particle distribution functions in the form of heating. Fourier (advected) time scales of seconds to about an hour are believed to represent the spatial scales of active MHD turbulence in the solar wind (note, however, that the Fourier power in those frequencies comes dominantly from strong small-scale current sheets [directional discontinuities] in the solar wind plasma; Borovsky, 2010; Siscoe et al., 1968; and since the correlation function is the Fourier transform of the power spectral density, correlation functions are also expected to be dominated by the small-scale current sheets). To understand the turbulence of the solar wind and its impact on the heliosphere, its driving, dynamics, and dissipation must be understood. How the turbulence is driven affects the evolution of the solar wind; how the turbulence is dissipated affects the evolution of the solar wind particle distribution functions; the dynamical nature of the turbulent fluctuations affects the scattering and transport of energetic particles in the heliosphere.

Ideas about the driving of the turbulence involve extracting energy from outward-propagating Alfvén waves (Goldstein et al., 1995) or from large-scale or mesoscale velocity shears (Roberts et al., 1987). It is well known that to produce a turbulent cascade of Alfvénic fluctuations to smaller spatial scales, counter-propagating Alfvénic fluctuations are needed (Kraichnan, 1965): To tap the energy of outward-propagating Alfvén waves, inward-propagating Alfvén waves must first be created. Ideas to produce inward Alfvén waves include (a) the reflection of outward waves (Chandran & Hollweg, 2009; Verdini et al., 2009), (b) parametric-decay instabilities (Tu et al., 1989), and (c) the production of both inward and outward Alfvén waves at velocity shears (Breech et al., 2008). Prominent solar wind shears include CIRs and the edges of microstreams. Recent observations of optical flows in white light images (i.e., measuring the motion of density features as a function of time) between 5 and 15 solar radii suggest that the solar wind may begin in a highly filamentary state, with an abundance of mesoscale flow shears (DeForest et al., 2018).

In the MHD range of spatial scales, the study of the dynamics of the turbulence focuses on the nature of the fluctuations, the nature of the interactions between fluctuations, and on the physics of the energy transfer to smaller scales. Major models of the MHD dynamics of the magnetic field and velocity fluctuations include the Maltese cross (Matthaeus et al., 1990), critical balance (Goldreich & Sridhar, 1997), and scale-dependent dynamic alignment (Boldyrev, 2006), each with different distributions of amplitude and spectral anisotropy of the fluctuations as functions of scale size. Issues about the nonlinear interactions between fluctuations include selective decay versus dynamic alignment, which evolve the turbulence toward different final states (Dobrowolny et al., 1980; Matthaeus et al., 2008; Telloni, Carbone, et al., 2016). Compressibility of the turbulence is another dynamic issue, as is the origin and role of pressure-balance structures in the solar wind plasma. In the spatial scales smaller than the MHD regime, the nature of the kinetic fluctuations (e.g.,

whistler versus kinetic Alfvén wave versus inertial kinetic Alfvén wave) is not fully understood (Carbone, 2012; Gary & Smith, 2009). The dynamics of the turbulence in the faster, highly Alfvénic, quasi-homogeneous CH-origin solar wind is probably different from the dynamics in slower, weakly Alfvénic or non-Alfvénic, inhomogeneous non-CH wind (Tu et al., 2016). One universal consequence of the dynamics of active turbulence is “mixing”: An attempt to quantify the amount of mixing occurring in the solar wind plasma between 0.3 and 1 AU found none (Borovsky, 2012b).

In going from MHD spatial scales to kinetic spatial scales, there is a breakpoint in the Fourier power spectrum of solar wind fluctuations, with the Fourier power being substantially reduced on the kinetic side of the spectral break. This breakpoint is taken as evidence of energy dissipation or mode conversion of MHD fluctuations at kinetic scales (Goldstein et al., 2015). At these kinetic spatial scales, investigators have focused on Landau damping and mode conversion of Alfvén and kinetic-Alfvén waves with quasi-perpendicular wavevectors (Leamon et al., 1999), on ion-cyclotron damping and mode conversion of Alfvén waves with quasi-parallel wavevectors (Gary & Borovsky, 2004), on mode conversion of kinetic Alfvén waves (Podesta, 2012), and on magnetic field reconnection across thin current sheets (Loureiro & Boldyrev, 2017). On the dissipation of the turbulence, the parametric instability of Alfvén waves can produce dissipation at all spatial scales (Shi et al., 2017). A data analysis argument has been made that the physics of what determines the location of the spectral breakpoint is the physics of what determines the thicknesses of strong current sheets (directional discontinuities) in the solar wind plasma (Borovsky & Podesta, 2015); another argument has been made that the properties of the power spectrum above the breakpoint is owed to processes acting within the current sheets (Borovsky & Burkholder, 2020).

Relevant to this outstanding question, there are many excellent brief review articles (Carbone, 2012; Goldstein et al., 1995, 2015; Horbury et al., 2005; Howes, 2015; Matthaeus & Velli, 2011; Oughton et al., 2015; Podesta, 2010) and extensive review articles (e.g., Bruno & Carbone, 2013, 2016; Schekochihin et al., 2009; Tu & Marsch, 1995).

For future progress in understanding the nature of the MHD turbulence, the kinetic-scale fluctuations, the physics of current sheets, and the physics of dissipation, high-time-resolution very accurate multipoint measurements of the solar wind are badly needed (cf. Cara et al., 2017; De Keyser et al., 2018; Howes, 2017; Podesta, 2015; Vaivads et al., 2016), including separate measures of the ion velocities and the electron velocities.

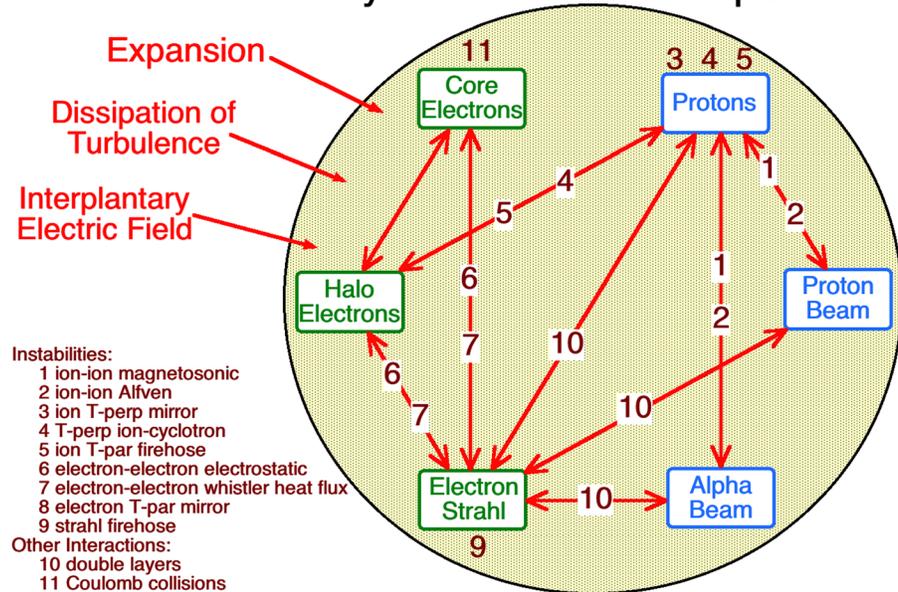
### 2.3.3. Question 8: How Do the Kinetic Distribution Functions of the Solar Wind Evolve?

The solar wind plasma is comprised of multiple particle populations: protons, an antisunward proton beam, an antisunward alpha-particle beam, core (cool) electrons, halo (hot) electrons, an antisunward electron strahl, and small numbers of highly ionized heavy ions. As the solar wind moves outward from the Sun, the particle populations evolve: The protons and alphas increase in temperature and specific entropy (Gary et al., 2000; Hellinger et al., 2011), the strahl intensity decreases (Maksimovic et al., 2005), the halo intensity increases (Maksimovic et al., 2005), and the proton and alpha beam speeds decrease (Marsch et al., 1982).

Note that the various particle distributions do not travel together: The proton distribution moves outward from the Sun at the “solar wind speed,” the alpha particles and heavy ions stream through the protons moving outward along the local-magnetic-field direction at a fraction of the Alfvén speed faster than the protons, and electrons rapidly move along magnetic field lines sunward and antisunward at the individual electron speed. Driven by the free energy in beams and temperature anisotropies, there are multiple plasma wave instabilities that couple the populations (Gary, 1993; Verscharen et al., 2015): The web of known interaction processes is sketched in Figure 8. The processes listed include weak double layers with antisunward-pointing electric fields that have been found in the solar wind plasma (LaCombe et al., 2002): Double layers can transfer energy and momentum between electrons and ions while most solar wind wave instabilities cannot.

Understanding the nature and evolution of the multiple particle populations of the solar wind is important for several reasons: These populations carry the signatures of coronal and solar wind physics, they drive the interplanetary electric field that contributes to solar wind acceleration, they affect the manner in which solar wind turbulence is dissipated, they are the energy sink for that turbulence, and they are the carriers of solar wind heat flux and the determiners of where that power is deposited. The field-aligned strahl population is also important as a tracer of the local magnetic connectivity to the Sun (see Q9) and as a probe of processes acting beyond the observing spacecraft.

## The Solar Wind's System of Particle Populations



**Figure 8.** A systems science view of the solar wind comprised of distinct particle populations interacting via plasma instabilities. The black circle is the system, driven by (1) solar wind expansion, (2) energy input from the dissipation of MHD turbulence, and (3) the interplanetary electric field. The green double arrows denote interactions between the populations (with special thanks to Peter Gary).

The solar wind plasma can be thought of as a complex system wherein the various particle populations are the components (subsystems) of the system, with these components coupling to each other via plasma waves (cf. Figure 8): As is typical of a complex system, the natures of the couplings change as the subsystems co-evolve. A complex system (Lin et al., 2013) has multiple components, components that are not homogeneous, complicated interactions, and interactions that are nonlinear: The solar wind fits this definition. Adjectives describing the behavior of complex systems can be applied to a parcel of solar wind: driven (by expansion of the solar wind and by the dissipation of solar wind turbulence), dissipative (via Coulomb scattering), adaptive (by the evolution of the populations and their changing interactions), irreversible (because of Coulomb scattering), and open (energy is transferred to the plasma by the dissipation of turbulence and by electron heat flux from the Sun). A complex system also exhibits “emergence”: One emergent phenomenon in the solar wind may be the formation of a myriad of weak double layers to collectively produce the large-scale interplanetary potential (Lacombe et al., 2002; Lamy et al., 2003; Salem et al., 2003).

Excellent reviews of the kinetic evolution of the solar wind are available (Echim et al., 2011; Feldman & Marsch, 1997; Maksimovic et al., 2005; Marsch, 2006, 2018; Matteini, 2016; Matteini et al., 2012; Pierrard et al., 2016).

The velocity distribution functions of the particle populations at the Sun are not known: Parker Solar Probe’s measurements should provide key information about distributions at the Sun. Parker Solar Probe has exceptionally good instrumentation, and the community looks forward to future data analysis efforts to further understand the physics of and evolution of the particle populations of the solar wind. Beyond Parker Solar Probe, future progress in understanding the evolution of the particle populations in the heliosphere needs more accurate and faster particle-distribution-function measurements (including heavy ions) correlated with high-quality plasma wave measurements: Such measurements may reveal active or past Landau resonances and active or past cyclotron resonances that are the fingerprints on the distribution functions of various wave-particle interactions.

### 2.3.4. Question 9: What Are the Roles of Solar Wind Structure and Turbulence on the Transport of Energetic Particles in the Heliosphere?

Steady progress is being made on the understanding and calculation of the transport of energetic particles through the solar wind, but it is still a major outstanding issue. Various particle populations are considered:

**Table 4**

*The Scale Size of Typical Magnetic Structures in the Solar Wind at 1 AU and the Energies of Particles With an Equivalent Gyroradius Assuming  $B = 5$  nT*

	Advection time scale	Thickness	Proton energy	Electron energy	Proton gyroperiod	Electron gyroperiod
Current sheet	6 s	3,000 km	11 keV	4 MeV	13 s	0.063 s
Flux tube	15 min	$4.4 \times 10^5$ km	210 MeV	660 MeV	16 s	9.2 s
Outer scale	2 hr	$3.6 \times 10^6$ km	4.5 GeV	5.8 GeV	77 s	75 s

electrons, protons, and heavy ions from solar flares and CME shocks, electrons and protons from CIR shocks, protons and electrons from Jupiter, cosmic rays from the outer heliosphere and beyond, and at lower energies, the electron strahl from the Sun.

Understanding the transport of energetic particles is important (1) for planning manned space exploration away from Earth, (2) for enabling energetic-particle measurements to be used for the understanding of the physics of particle acceleration, (3) for providing information about the structure of the heliosphere and its turbulence, and (4) for providing an understanding of particle transport in astrophysical plasmas.

To understand the transport of energetic particles in the heliosphere, two things are needed. First, knowledge of the magnetic structure and magnetic connectedness of the heliosphere is needed (cf. Kahler et al., 2016; Schatten, 1971). Often, this comes from heliospheric MHD simulations. Second, the scattering physics of particles in the heliospheric magnetic field needs to be understood. This might be as simple as obtaining perpendicular and parallel mean free paths to construct pitch-angle, parallel, and perpendicular diffusion coefficients to use in a diffusive transport equation (Li, 2017; Zimbardo et al., 2012). Increasingly sophisticated modeling is being used to estimate these values, including dynamic modeling with waves (Gammon et al., 2019; Tautz & Shalchi, 2011), and the modeling is producing increasingly better matches with observations.

On the issue of magnetic connectedness, there are some types of solar wind plasma that lack electron strahls: One such plasma type is the plasma associated with the sector-reversal region around the HCS (Xu & Borovsky, 2015), also known as the very slow solar wind. This plasma originates as blobby impulsive emissions (a.k.a. puffs or plasmoids) from streamer-stalk regions (Foullon et al., 2011; Suess et al., 2009; Viall & Vourlidas, 2015). The magnetic field in this type of plasma is not Parker-spiral oriented, and, as indicated by the absence of a strahl, it is unlikely that there is much contiguous magnetic flux that connects the Sun to this plasma in the heliosphere. Magnetic reconnection (Suess et al., 2009) at the top of the helmet streamer magnetic structure is the cause of the strahl dropouts (Kepko et al., 2016); counterflowing plasma structures from the reconnection site are observed in the white light images around 5 solar radii (Sanchez-Diaz, Rouillard, Davies, Lavraud, Sheeley, et al., 2017). The Earth is in this sector-reversal-region plasma about 20% of the time. When the Earth (or a measuring spacecraft) is in this type of plasma, solar energetic particle events (and lower-energy cosmic-ray fluxes) may be weaker than anticipated because of the lack of long-distance magnetic connections.

For the ducting of energetic particles in the heliosphere, the mesoscale structure of the solar wind magnetic field is very important. As discussed in Q5, the heliospheric field is largely structured into magnetic flux tubes separated by current sheets (Bruno et al., 2001); the magnetic tubes have narrow walls (current sheets, directional discontinuities) with large-angle changes in the magnetic field direction across the walls with the interiors of the tubes having much lower levels of magnetic fluctuation. This produces an observed long-distance ducting of energetic particles (Bartley et al., 1966; Borovsky, 2020b; Gosling et al., 2004; Kocharov et al., 2014; McCracken et al., 1968; Trenchi et al., 2013; Zimbardo, 2005) consistent with the magnetic field lines being confined inside the tubes.

The flux-tube nature of the heliospheric magnetic field can also impact the physics of particle scattering (Michel, 1967; Qin & Li, 2008), with less scattering in the lower levels of fluctuations within the tubes. However, particles with finite gyroradii passing close to the tube walls will suffer large-angle scattering. In Table 4, some typical scale sizes of the solar wind magnetic structure at 1 AU are listed: current sheets (tube walls), tube diameters, and the integral scale of the magnetic power spectral density. At 1 AU (taking  $B = 5$  nT), current sheets are about as thick as the gyroradius of an 11-keV proton. Hence, protons with energies above  $\sim 11$  keV (or electrons above  $\sim 4$  MeV) could suffer sudden strong ( $\sim 90^\circ$ ) changes in their pitch

angles in less than a gyroperiod. At 1 AU, flux tubes have diameters on the order of the gyroradius of 210-MeV protons. Protons with energies well below 210 MeV can be ducted in the relatively quiet tubes; for protons with energies much greater than  $\sim 210$  MeV, the tubes would act as scatterers, since adjacent tubes can have magnetic field orientations that significantly differ. Using pitch-angle-diffusion coefficients based on the amplitude of a Power spectra and the assumption of random phases in the spectra may not capture the strong scattering of the intermittent structures (walls) and the long mean-free-paths of the tube interiors. Additionally, the flux tubes at 1 AU have local curvatures with wandering wavelengths that are on the order of 0.07 AU along the Parker-spiral direction (Tong et al., 2016), which may play a role in the scattering of very energetic particles (e.g., Webb et al., 2006).

Excellent reviews of the transport of energetic particles in the solar wind can be found (e.g., Cliver, 2001; Cohen, 2016; Giacalone & Jokipii, 2001; Li, 2017; Malandraki, 2015; Reames, 2013; Richardson, 2004; Zimbardo et al., 2012), as well as explorations of the effects of intermittency on the transport (Borovsky, 2008; Droge et al., 2018; Fisk & Sari, 1973; Michel, 1967; Pucci et al., 2016; Qin & Li, 2008; Trenchi et al., 2013).

For future progress on this question, more multipoint observations are crucial. The in situ measurements of Parker Solar Probe and Solar Orbiter near the Sun combined with energetic-particle measurements at STEREO and at Earth will be particularly valuable. Exploration of the properties of the electron strahl to reveal the properties of the structure and connectivity of the heliospheric magnetic field could be fruitful. Advancing our understanding of the nature and dynamics of the mesoscale structure of the solar wind plasma via faster and more accurate in situ measurements combined with more advanced plasma simulations will also be productive.

### 3. Discussion: Other Important Questions

To develop the list of nine solar wind questions (Table 1), dozens of heliospheric researchers were polled. From the contributed lists of questions from many heliospheric scientists, a few that were repeatedly mentioned were not discussed in this commentary. One dealt with CME creation, evolution, and impact on the global structure of the heliosphere (see Burkepile et al., 2004; Gopalswamy (2016); Kilpua et al., 2017, 2019 and Thompson et al., 2020 for reviews of the research and outstanding questions). A second dealt with the interaction of the solar wind with the interstellar medium: Excellent reviews on that topic can be found (Burlaga, 2015; Burlaga et al., 2018; Zank, 2015). Other topics less extensively mentioned were about shock physics, seed-particle populations, dust, and pickup ions.

Finally, an important question related to space weather and the Sun-Earth connection is where to locate a single solar wind monitor or a network of monitors for the Earth (Ashour-Abdalla et al., 2008; Biesecker et al., 2007; Sandahl et al., 1996). The activity and evolution of the Earth's magnetosphere is driven (a) chiefly by magnetic field reconnection with the shocked solar wind plasma on the dayside edge of the magnetosphere (Dungey, 1961) and (b) to a minor extent by a "viscous interaction" with the solar wind (Axford & Hines, 1961), the physics of the latter being little understood. In the dayside-reconnection driving, it is not the energy release of reconnection that does the driving; rather, it is the fact that dayside reconnection magnetically connects the magnetosphere to the moving solar wind. The rate of dayside reconnection, which largely controls the rate of driving, depends on the orientation of the solar wind magnetic field and on the speed, density, magnetic field strength, and Mach number of the solar wind (Borovsky & Birn, 2014). The reconnection rate is very sensitive to the clock angle of the solar wind magnetic field vector as seen from Earth (Komar et al., 2015), on time scales of less than 1 min.

The standard practice has been to put a solar wind monitor in orbit around the L1 point,  $230 R_E \approx 0.01$  AU upstream of the Earth (King & Papitashvili, 2005; Weimer & King, 2008). A problem with this is that the solar wind that hits the monitor is not the solar wind that hits the Earth: Owing to the high variability of the direction of the solar wind flow vector and to aberration of the solar wind flow by the Earth's orbital motion about the Sun, an L1 monitor is rarely on a flow streamline that connects to the Earth (Borovsky, 2018; Walsh et al., 2019). Correlation scales of the solar wind magnetic field direction transverse to its flow are on the order of  $50 R_E$  (Richardson & Paularena, 2001; Zastenker et al., 2000), and the L1 monitor's streamline can easily miss the Earth by that amount. The space weather community and a large part of the magnetospheric research community both rely on accurate solar wind information, and improvements over single monitors located at L1 are needed. One solution that preserves some space-weather warning time

is a swarm of monitors about the L1 point; one solution that yields more accuracy as to what is hitting the magnetosphere is a set of monitors in  $\sim 30 R_E$  circular orbits about the Earth, similar to the NASA Interplanetary Monitoring Platform (IMP) constellation of the 1970s (Butler, 1980; Feldman et al., 1978). Alternatives to an L1 monitor are spacecraft with imaging suites located over the poles of the Sun, or at L5 (Vourlidas, 2015; Gibney, 2017; Thomas et al., 2018).

#### 4. Outlook—What Are the Needs and Prospects for Future Progress?

In discussing the individual outstanding questions in section 2, specific needs for the future were called out. There are common themes to these needs.

Certainly, solar wind physics needs accurate solar models and accurate solar wind propagation models that can resolve mesoscale structures. At the Sun, fully 3-D, time-dependent models of solar wind sources and acceleration are needed. The time dependence must at the least include the differential rotation of the photosphere, supergranulation, and the evolving magnetic field. Away from the Sun, reliable modeling of quiescent background solar wind is needed. The solar wind plasma and the heliospheric magnetic field, with compressions, rarefactions, and fluctuations, are the ground state of space weather. The quiescent solar wind preconditions the magnetosphere before major storms and that preconditioning changes the manner in which the magnetosphere reacts during the storm. The quiescent solar wind is the medium through which CMEs propagate and from which CIRs form. The quiescent solar wind is also the medium through which solar energetic particles are transported. Future modeling needs to go beyond the large-scale no-detail fast-versus-slow level to capture mesoscale structure, microstreams, and fluctuation amplitudes. Another need for future progress is advancements in plasma physics pertaining to the weakly collisional solar wind: treatments of collisionless viscosity, non-Maxwellian thermodynamics, heating without collisions, and the origin of suprathermal populations.

Solar observations needed for future progress include regular backside magnetograms and polar magnetograms. The location of the HCS and the region on the Sun that Earth or a spacecraft is connected to are not well determined, largely as a result of the lack of information on the polar magnetic field and time-evolving magnetic field on the backside that we currently do not observe. EUV imagers are limited to the low corona, while white light imagers are currently limited to the outer corona and heliosphere, due to the need to block out the bright photosphere below and the scattered light associated with that. Natural solar eclipses are exceptions to this requirement but provide little time coverage. The region in between these two instrumental regimes is sometimes called the “middle corona” and spans the region up to a few solar radii. This is the region in which many of the processes described in Q1, Q2, and Q3 occur, and it is the region where the magnetic fields and connectivity are highly nonradial. Continuous measurements of temperature, flow velocity, and magnetic field in the middle corona would provide the link from the low corona to the solar wind. Spectroscopy on disk and off disk, especially with sulfur and elements of different FIP, will be important for direct relation with in situ tracers.

Parker Solar Probe is yielding (e.g., Parker, 2020; Verscharen, 2019), and DKIST and Solar Orbiter are going to yield unprecedented high-quality plasma and field measurements close to the Sun, revealing some of the plasma physics of the transition from corona to solar wind. Solar Orbiter will get some backside magnetograms and a polar view of the magnetic field. The solar wind measurements most needed for the future will be high-time-resolution high-accuracy multipoint measurements of the plasma, flow, magnetic field, and ion composition to discern the nature and physics of the solar wind’s ubiquitous fluctuations.

#### References

Adams, W. M. (1976). Differential rotation of photospheric magnetic fields associated with coronal holes. *Solar Physics*, 47(2), 601–605. <https://doi.org/10.1007/BF00154768>

Antiochos, S. K., Linker, J. A., Lionello, R., Mikic, Z., Titov, V., & Zurbuchen, T. H. (2012). The structure and dynamics of the corona-heliosphere connection. *Space Science Reviews*, 172(1–4), 169–185. <https://doi.org/10.1007/s11214-011-9795-7>

Arge, C. N., Henney, C. J., Gonzalez Hernandez, I., Toussaint, W. A., Koller, J., & Godinez, H. C. (2013). Modeling the corona and solar wind using ADAPT maps that include far-side observations. In *AIP Conference Proceedings*. 1539, 11. <https://doi.org/10.1063/1.4810977>

Arge, C. N., Luhmann, J. G., Odstrcil, D., Schrijver, C. J., & Li, Y. (2004). Stream structure and coronal sources of the solar wind during the May 12th, 1997 CME. *Journal of Atmospheric and Solar-Terrestrial Physics*, 66(15–16), 1295–1309. <https://doi.org/10.1016/j.jastp.2004.03.018>

#### Acknowledgments

To initiate this commentary, dozens of scientists in the solar wind research community were individually asked to create a list of what they thought were the outstanding questions in solar wind physics. We chose to comment on nine questions from the full list of suggestions. The authors thank Nick Arge, Doug Biesecker, Joan Burkepile, Ben Chandran, Ed Cliver, Christina Cohen, Georgia de Nolfo, Craig DeForest, Mihir Desai, Bill Feldman, Peter Gary, Joe Giacalone, Nat Gopalswamy, Aleida Higginson, Tim Horbury, Bernie Jackson, Steve Kahler, Harald Kucharek, Jon Linker, Janet Luhmann, Benjamin Lynch, Peter MacNeice, Bob McPherron, John Podesta, Ian Richardson, Aaron Roberts, Nathan Schwadron, Chuck Smith, Angelos Vourlidas, Peter Young, Samantha Wallace, Rob Wicks, and Dan Weimer for their help. J.B. was supported by the National Science Foundation (NSF) SHINE program via Award AGS-1723416, by the National Aeronautics and Space Administration (NASA) Heliophysics Guest Investigator Program via Grant NNX17AB71G, by the NASA Heliophysics LWS program via Grants NNX16AB75G and NNX14AN90G, and by the NSF GEM Program. N.M.V. is supported by the NASA Heliophysics Internal Scientist Funding Model. No data were used in the preparation of this manuscript. The authors thank the two reviewers, Susan Lepri and Marco Velli, for their thoughtful and constructive comments on this manuscript.

- Arya, S., & Freeman, J. W. (1991). Estimates of solar wind velocity gradients between 0.3 and 1 AU based on velocity probability distributions from Helios 1 at perihelion and aphelion. *Journal of Geophysical Research*, *96*(A8), 14,183–14,187. <https://doi.org/10.1029/91JA01135>
- Asbridge, J. R., Bame, S. J., Feldman, W. C., & Montgomery, M. D. (1976). Helium and hydrogen velocity differences in the solar wind. *Journal of Geophysical Research*, *81*(16), 2719–2727. <https://doi.org/10.1029/JA081i016p02719>
- Ashour-Abdalla, M., Walker, R. J., Peromian, V., & El-Alaoui, M. (2008). On the importance of accurate solar wind measurements for studying magnetospheric dynamics. *Journal of Geophysical Research*, *113*, A08204. <https://doi.org/10.1029/2007JA012785>
- Axford, W. I., & Hines, C. O. (1961). A unifying theory of high-latitude geophysical phenomena and geomagnetic storms. *Canadian Journal of Physics*, *39*(10), 1433–1464. <https://doi.org/10.1139/p61-172>
- Baker, D., van Driel-Gesztelyi, L., & Attrill, G. R. R. (2007). Evidence for interchange reconnection between a coronal hole and an adjacent emerging flux region. *Astronomische Nachrichten*, *328*, 773. <https://doi.org/10.1002/asna.200710787>
- Bale, S. D., Badman, S. T., Bonnell, J. W., Bowen, T. A., Burges, D., Case, A. W., et al. (2019). Highly structured slow solar wind emerging from an equatorial coronal hole. *Nature*, *576*(7786), 237–242. <https://doi.org/10.1038/s41586-019-1818-7>
- Bame, S. J., Asbridge, J. R., Feldman, W. C., & Gosling, J. T. (1976). Solar cycle evolution of high-speed solar wind streams. *The Astrophysical Journal*, *207*, 977. <https://doi.org/10.1086/154566>
- Bartley, W. C., Bakata, R. P., McCracken, K. G., & Rao, U. R. (1966). Anisotropic cosmic radiation fluxes of solar origin. *Journal of Geophysical Research*, *71*, 3297–3304. <https://doi.org/10.1029/JZ071i013p03297>
- Belcher, J. W., & Davis, L. (1971). Large amplitude Alfvén waves in the interplanetary medium, 2. *Journal of Geophysical Research*, *76*, 3534–3563. <https://doi.org/10.1029/JA076i016p03534>
- Bemporad, A. (2017). Exploring the inner acceleration region of solar wind: A study based on coronagraphic UV and visible light data. *The Astrophysical Journal*, *846*, 86. <https://doi.org/10.3847/1538-4357/aa7de4>
- Biesecker, D. A., Webb, D. F., & St. Cyr, O. C. (2007). STEREO space weather and the Space Weather Beacon. *Space Science Reviews*, *136*, 45. <https://doi.org/10.1007/s11214-007-9165-7>
- Boldyrev, S. (2006). Spectrum of magnetohydrodynamic turbulence. *Physical Review Letters*, *96*, 115,002. <https://doi.org/10.1103/physrevlett.96.115002>
- Boldyrev, S., J. Perez, J. C., Borovsky, J. E., & Podesta, J. J. (2011). Spectral scaling laws in magnetohydrodynamic turbulence simulations and in the solar wind. *The Astrophysical Journal Letters*, *741*, L19. <https://doi.org/10.1088/2041-8205/741/1/L19>
- Borovsky, J. E. (2006). Eddy viscosity and flow properties of the solar wind: Co-rotating interaction regions, coronal-mass-ejection sheaths, and solar-wind/magnetosphere coupling. *Physics of Plasmas*, *13*, 056505. <https://doi.org/10.1063/1.2200308>
- Borovsky, J. E. (2008). The flux-tube texture of the solar wind: Strands of the magnetic carpet at 1 AU? *Journal of Geophysical Research*, *113*, A08110. <https://doi.org/10.1029/2007JA012684>
- Borovsky, J. E. (2010). On the contribution of strong discontinuities to the power spectrum of the solar wind. *Physical Review Letters*, *105*, 111,102. <https://doi.org/10.1103/physrevlett.105.111102>
- Borovsky, J. E. (2012a). The effect of sudden wind shear on the Earth's magnetosphere: Statistics of wind-shear events and CCMC simulations of magnetotail disconnections. *Journal of Geophysical Research*, *117*, A06224. <https://doi.org/10.1029/2012JA017623>
- Borovsky, J. E. (2012b). Looking for evidence of mixing in the solar wind from 0.31 to 0.98 AU. *Journal of Geophysical Research*, *117*, A06107. <https://doi.org/10.1029/2012JA017525>
- Borovsky, J. E. (2012c). The velocity and magnetic-field fluctuations of the solar wind at 1 AU: Statistical analysis of Fourier spectra and correlations with plasma properties. *Journal of Geophysical Research*, *117*, A05104. <https://doi.org/10.1029/2011JA017499>
- Borovsky, J. E. (2016). Plasma structure of the coronal-hole solar wind: Origins and evolution. *Journal of Geophysical Research*, *121*, 5055–5087. <https://doi.org/10.1002/2016JA022686>
- Borovsky, J. E. (2018). The spatial structure of the oncoming solar wind at Earth. *Journal of Atmospheric and Solar-Terrestrial Physics*, *177*, 2. <https://doi.org/10.1016/j.jastp.2017.03.014>
- Borovsky, J. E. (2020a). On the motion of the heliospheric magnetic structure through the solar wind plasma. *Journal of Geophysical Research*, *125*, 2019JA027377. <https://doi.org/10.1029/2019JA027377>
- Borovsky, J. E. (2020b). The magnetic structure of the solar wind: Ionic composition and the electron strahl. *Geophysical Research Letters*, *47*, e2019GL084586. <https://doi.org/10.1029/2019GL084586>
- Borovsky, J. E. (2020c). What magnetospheric and ionospheric researchers should know about the solar wind. *Journal of Atmospheric and Solar-Terrestrial Physics*, *204*, 105271. <https://doi.org/10.1016/j.jastp.2020.105271>
- Borovsky, J. E., & Birn, J. (2014). The solar-wind electric field does not control the dayside reconnection rate. *Journal of Geophysical Research: Space Physics*, *119*, 751–760. <https://doi.org/10.1002/2013JA019193>
- Borovsky, J. E., Birn, J., Echim, M. M., Fujita, S., Lysak, R. L., Knudsen, D. J., et al. (2019). Quiescent discrete auroral arcs: A review of magnetospheric generator mechanisms. *Space Science Reviews*, *216*. <https://doi.org/10.1007/s11214-019-0619-5> SPAC-D-19-00040
- Borovsky, J. E., & Burkholder, B. L. (2020). On the Fourier contribution of strong current sheets to the high-frequency magnetic power spectral density of the solar wind. *Journal of Geophysical Research: Space Physics: Space Physics*, *125*, 2019JA027307. <https://doi.org/10.1029/2019JA027307>
- Borovsky, J. E., & Denton, M. H. (2010). Solar-wind turbulence and shear: A superposed-epoch analysis of corotating interaction regions at 1 AU. *Journal of Geophysical Research*, *115*, A10101. <https://doi.org/10.1029/2009JA014966>
- Borovsky, J. E., & Denton, M. H. (2016a). The trailing edges of high-speed streams at 1 AU. *Journal of Geophysical Research: Space Physics*, *121*, 6107–6140. <https://doi.org/10.1002/2016JA022863>
- Borovsky, J. E., & Denton, M. H. (2016b). Compressional perturbations of the dayside magnetosphere during high-speed-stream-driven geomagnetic storms. *Journal of Geophysical Research: Space Physics*, *121*, 4569–4589. <https://doi.org/10.1002/2015JA022136>
- Borovsky, J. E., & Gary, S. P. (2009). On viscosity and the Reynolds number of MHD turbulence in collisionless plasmas: Coulomb collisions, Landau damping, and Bohm diffusion. *Physics of Plasmas*, *16*, 082307. <https://doi.org/10.1063/1.3155134>
- Borovsky, J. E., & Gary, S. P. (2014). How important are the alpha-proton relative drift and the electron heat flux for the proton heating of the solar wind in the inner heliosphere? *Journal of Geophysical Research: Space Physics*, *119*, 5210–5219. <https://doi.org/10.1002/2014JA019758>
- Borovsky, J. E., & Podesta, J. J. (2015). Exploring the effect of current-sheet thickness on the high-frequency Fourier spectrum of the solar wind. *Journal of Geophysical Research: Space Physics*, *120*, 9256–9268. <https://doi.org/10.1002/2015JA021622>
- Breech, B., Matthaeus, W. H., Minnie, J., Bieber, J. W., Oughton, S., Smith, C. W., & Isenberg, P. A. (2008). Turbulence transport throughout the heliosphere. *Journal of Geophysical Research*, *113*, A08105. <https://doi.org/10.1029/2007JA012711>

- Bruno, R. (2019). Intermittency in solar wind turbulence from fluid to kinetic scales. *Earth and Space Science*, 6, 656–672. <https://doi.org/10.1029/2018ea000535>
- Bruno, R., & Bavassano, B. (1991). Origin of low cross-helicity regions in the inner solar wind. *Journal of Geophysical Research*, 96, 7841–7851. <https://doi.org/10.1029/91JA00144>
- Bruno, R., Bavassano, B., Bianchini, L., Pietropaolo, E., Villante, U., Carbone, V., & Veltri, P. (1999). Solar wind intermittency studied via local intermittency measure. *ESA Special Publications*, 448, 1147.
- Bruno, R., & Carbone, V. (2013). The solar wind as a turbulence laboratory. *Living Reviews of Solar Physics*, 10, 2. <http://www.livingreview.org/lrsp-2013-2>. <https://doi.org/10.12942/lrsp-2013-2>
- Bruno, R., & Carbone, V. (2016). Turbulence in the solar wind. *Lecture Notes in Physics*, 928, 1. <https://doi.org/10.1007/978-3-319-43440-7>
- Bruno, R., Carbone, V., Veltri, P., Pietropaolo, E., & Bavassano, B. (2001). Identifying intermittency events in the solar wind. *Planetary and Space Science*, 49, 1201. [https://doi.org/10.1016/s0032-0633\(01\)00061-7](https://doi.org/10.1016/s0032-0633(01)00061-7)
- Burkpile, J. T., Hundhausen, A. J., Stranger, A. L., St. Cyr, O. C., & Seiden, J. A. (2004). Role of projection effects on solar coronal mass ejection properties: 1. A study of CMEs associated with limb activity. *Journal of Geophysical Research*, 109, A03103. <https://doi.org/10.1029/2003JA010149>
- Burkholder, B., Otto, A., Delamere, P., & Borovsky, J. E. (2019). Magnetic connectivity in the corona as a source of structure in the solar wind. *Journal of Geophysical Research: Space Physics*, 124, 32–49. <https://doi.org/10.1029/2018JA026132>
- Burkholder, B. L., & Otto, A. (2019). Magnetic reconnection of solar flux tubes and coronal reconnection signatures in the solar wind at 1 AU. *Journal of Geophysical Research: Space Physics*, 124, 8227–8254. <https://doi.org/10.1029/2019JA027114>
- Burlaga, L. (2015). Voyager observations of the magnetic field in the heliosheath and the local interstellar medium. *Journal of Physics: Conference Series*, 642, 012003. <https://doi.org/10.1088/1742-6596/642/1/012003>
- Burlaga, L. F., Florinkski, V., & Ness, N. F. (2018). Turbulence in the outer heliosheath. *The Astrophysical Journal*, 854, 20. <https://doi.org/10.3847/1538-4357/aaa45a>
- Burlaga, L. F., & Forman, M. A. (2002). Large-scale speed fluctuations at 1 AU on scales from 1 hour to  $\approx 1$  year: 1999 and 1995. *Journal of Geophysical Research*, 107(A11), 1403. <https://doi.org/10.1029/2002JA009271>
- Butler, P. (1980). Interplanetary Monitoring Program engineering history and achievement. In *NASA TM-80758. Greenbelt, Maryland: NASA Goddard Space Flight Center*. <https://repository.exst.jaxa.jp/dspace/handle/a-is/172884>, <http://hdl.handle.net/2060/19800012928>
- Cahill, L. J. Jr., & Winckler, J. R. (1992). Periodic magnetopause oscillations observed with the GOES satellites on March 24, 1991. *Journal of Geophysical Research*, 97, 8239. <https://doi.org/10.1029/92JA00433>
- Camporeale, E., Care, A., & Borovsky, J. E. (2017). Classification of solar wind with machine learning. *Journal of Geophysical Research: Space Physics*, 122, 10,910–10,920. <https://doi.org/10.1002/2017JA024383>
- Caplan, R. M., Downs, C., & Linker, J. A. (2016). Synchronic coronal hole mapping using multi-instrument EUV images: Data preparation and detection method. *The Astrophysical Journal*, 823, 53. <https://doi.org/10.3847/0004-637x/823/1/53>
- Cara, A., Lavraud, B., Fedorov, A., De Keyser, J., DeMarco, R., Marcucci, M. F., et al. (2017). Electrostatic analyzer design for solar wind proton measurements with high temporal, energy, and angular resolutions. *Journal of Geophysical Research: Space Physics*, 122, 1439–1450. <https://doi.org/10.1002/2016JA023269>
- Carbone, V. (2012). Scalings, cascade and intermittency in solar wind turbulence. *Space Science Reviews*, 172, 343. <https://doi.org/10.1007/s11214-012-9907-z>
- Chandran, B. D. G., & Hollweg, J. V. (2009). Alfvén wave reflection and turbulent heating in the solar wind from 1 solar radius to 1 AU: An analytical treatment. *The Astrophysical Journal*, 707, 1659. <https://doi.org/10.1088/0004-637x/707/2/1659>
- Cirtain, J. W., Golub, L., Lundquist, L., van Ballegoijen, A., Savcheva, A., Shimojo, M., et al. (2007). Evidence for Alfvén waves in solar X-ray jets. *Science*, 318, 1580. <https://doi.org/10.1126/science.1147050>
- Claudepierre, S. G., Hudson, M. K., Lotko, W., Lyon, J. G., & Denton, R. E. (2010). Solar wind driving of magnetospheric ULF waves: Field line resonances driven by dynamic pressure fluctuations. *Journal of Geophysical Research*, 115, A11202. <https://doi.org/10.1029/2010JA015399>
- Cliver, E. W. (2001). Solar energetic particles: Acceleration and transport. *AIP Conference Proceedings*, 516, 103. <https://doi.org/10.1063/1.1291471>
- Close, R. M., Parnell, C. E., Longcope, D. W., & Priest, E. R. (2004). Recycling of the solar corona's magnetic field. *The Astrophysical Journal*, 612, 81. <https://doi.org/10.1086/424659>
- Close, R. M., Parnell, C. E., Longcope, D. W., & Priest, E. R. (2005). Coronal flux recycling times. *Solar Physics*, 231, 45. <https://doi.org/10.1007/s11207-005-6878-1>
- Cohen, C. M. S. (2016). Current understanding of SEP acceleration and transport. *AIP Conference Proceedings*, 1720, 060001. <https://doi.org/10.1063/1.4943836>
- Coleman, P. J. (1968). Turbulence, viscosity, and dissipation in the solar-wind plasma. *The Astrophysical Journal*, 153, 371. <https://doi.org/10.1086/149674>
- Cranmer, S. R. (2009). Coronal holes. *Living Reviews in Solar Physics*, 6, 3. <https://doi.org/10.12942/lrsp-2009-3>
- Cranmer, S. R., Gibson, S. E., & Riley, P. (2017). Origins of the ambient solar wind: Implications for space weather. *Space Science Reviews*, 212, 1345. <https://doi.org/10.1007/s11214-017-0416-y>
- Cranmer, S. R., & van Ballegoijen, A. A. (2005). On the generation, propagation, and reflection of Alfvén waves from the solar photosphere to the distant heliosphere. *The Astrophysical Journal Supplement Series*, 156, 265. <https://doi.org/10.1086/426507>
- Cranmer, S. R., van Ballegoijen, A. A., & Edgar, R. J. (2007). Self-consistent coronal heating and solar wind acceleration from anisotropic magnetohydrodynamic turbulence. *The Astrophysical Journal Supplement Series*, 171, 520. <https://doi.org/10.1086/518001>
- Crooker, N. U., Antiochos, S. K., Zhao, X., & Neugebauer, M. (2012). Global network of solar wind. *Journal of Geophysical Research*, 117, A04104. <https://doi.org/10.1029/2011JA017236>
- Crooker, N. U., Burton, M. E., Siscoe, G. L., Kahler, S. W., Gosling, J. T., & Smith, E. J. (1996). Solar wind streamer belt structure. *Journal of Geophysical Research*, 101(A11), 24,331–24,341. <https://doi.org/10.1029/96JA02412>
- Crooker, N. U., Gosling, J. T., & Kahler, S. W. (2002). Reducing heliospheric magnetic flux from coronal mass ejections without disconnection. *Journal of Geophysical Research*, 107, 1028. <https://doi.org/10.1029/2001JA000236>
- D'Amicis, R., & Bruno, R. (2015). On the origin of highly Alfvénic slow solar wind. *The Astrophysical Journal*, 805, 84. <https://doi.org/10.1088/0004-637x/805/1/84>
- D'Amicis, R., Matteini, L., & Bruno, R. (2019). On the slow solar wind with high Alfvénicity: From composition and microphysics to spectral properties. *Monthly Notices of the Royal Astronomical Society*, 483, 4665. <https://doi.org/10.1093/mnras/sty3329>

- De Keyser, J., Lavraud, B., Prech, L., Neefs, E., Berkenbosch, S., Beeckman, B., et al. (2018). Beam tracking strategies for fast acquisition of solar wind velocity distribution functions with high energy and angular resolutions. *Annales Geophysicae*, 36, 1285. <https://doi.org/10.5194/angeo-36-1285-2018>
- De Pontieu, B., McIntosh, S. W., Carlsson, M., Hansteen, V. H., Tarbell, T. D., Boerner, P., et al. (2011). The origins of hot plasma in the solar corona. *Science*, 331, 55. <https://doi.org/10.1126/science.1197738>
- De Toma, G., & Arge, C. N. (2005). Multi-wavelength observations of coronal holes, Large-scale structures and their role in solar activity, ASP Conference Series. In K. Sankarasubramanian, M. Penn, & A. Pevtsov (Eds.), *Proceedings of the Conference Held 18–22 October, 2004 in Sunspot, New Mexico, USA* (Vol. 346, p. 251). Astronomical Society of the Pacific. <http://aspbooks.org/custom/publications/paper/346-0251.html>
- DeForest, C. E., Howard, R. A., Velli, M., Viall, N., & Vourlidis, A. (2018). The highly structured outer solar corona. *The Astrophysical Journal*, 862, 18. <https://doi.org/10.3847/1538-4357/aac8e3>
- DeForest, C. E., Matthaeus, W. H., Viall, N. M., & Cramer, S. R. (2016). Fading coronal structure and the onset of turbulence in the young solar wind. *The Astrophysical Journal*, 828, 66. <https://doi.org/10.3847/0004-637x/828/2/66>
- Del Zanna, G., Aulanier, G., Klein, K.-L., & Török, T. (2011). A single picture for solar coronal outflows and radio noise storms. *Astronomy and Astrophysics*, 526, A137. <https://doi.org/10.1051/0004-6361/201015231>
- Del Zanna, G., & Mason, H. E. (2018). Solar UV and X-ray spectral diagnostics. *Living Reviews in Solar Physics*, 15(1), 5. <https://doi.org/10.1007/s41116-018-0015-3>
- Di Matteo, S., Viall, N. M., Kepko, L., Wallace, S., Arge, C. N., & MacNeice, P. (2019). Helios observations of quasiperiodic density structures in the slow solar wind at 0.3, 0.4, and 0.6 AU. *Journal of Geophysical Research: Space Physics*, 124, 837–860. <https://doi.org/10.1029/2018JA026182>
- Di Matteo, S., & Villante, U. (2018). The identification of waves at discrete frequencies at the geostationary orbit: The role of the data analysis techniques and the comparison with solar wind observations. *Journal of Geophysical Research: Space Physics*, 123, 1953–1968. <https://doi.org/10.1002/2017JA024922>
- Dobrowolny, M., Mangeney, A., & Veltri, P. (1980). Fully developed anisotropic turbulence in interplanetary space. *Physical Review Letters*, 45, 144. <https://doi.org/10.1103/physrevlett.45.144>
- Dowdy, J. F., Emslie, A. G., & Moore, R. L. (1987). On the inability of magnetically constricted transition regions to account for the  $10^5$  to  $10^5$  K plasma in the quiet solar atmosphere. *Solar Physics*, 112, 255. <https://doi.org/10.1007/bf00148781>
- Droge, W., Kartavykh, Y. Y., Wang, L., Telloni, D., & Bruno, R. (2018). Transport modeling of interplanetary electrons in the 2002 October 20 solar particle event. *The Astrophysical Journal*, 869, 168. <https://doi.org/10.3847/1538-4357/aaec6c>
- Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Physical Review Letters*, 6, 47. <https://doi.org/10.1103/physrevlett.6.47>
- Durovcova, T., Nemecek, Z., & Safrankova, J. (2019). Evolution of the  $\alpha$ -proton differential motion across stream interaction regions. *The Astrophysical Journal*, 873, 24. <https://doi.org/10.3847/1538-4357/ab01c8>
- Dyrud, L. P., Behnke, R., Kepko, E. L., Sulzer, M., & Zafke, S. (2008). Ionospheric ULF oscillations driven from above Arecibo. *Geophysical Research Letters*, 35, L14101. <https://doi.org/10.1029/2008GL034073>
- Echim, M. M., Lemaire, J., & Lie-Svendsen, O. (2011). A review on solar wind modeling: Kinetic and fluid aspects. *Surveys of Geophysics*, 32, 1. <https://doi.org/10.1007/s10712-010-9106-y>
- Endeve, E., Lie-Svendsen, O., Hansteen, V. H., & Leer, E. (2005). Release of helium from closed-field regions of the Sun. *The Astrophysical Journal*, 624, 402–413. <https://doi.org/10.1086/428938>
- Feldman, U., Landi, E., & Schwadron, N. A. (2005). On the sources of fast and slow solar wind. *Journal of Geophysical Research*, 110, A07109. <https://doi.org/10.1029/2004JA010918>
- Feldman, U., & Widing, K. C. (2002). A review of the first ionization potential effects on elemental abundances in the solar corona and in flares. *Physics of Plasmas*, 9, 629. <https://doi.org/10.1063/1.1435000>
- Feldman, U., Widing, K. G., & Warren, H. P. (1999). Morphology of the quiet solar upper atmosphere in the  $4 \times 10^4 < T_e < 1.4 \times 10^6$  K temperature regime. *The Astrophysical Journal*, 522, 1133. <https://doi.org/10.1086/307682>
- Feldman, W. C., Anderson, J., Bohlin, J. D., Bulaga, L. F., Farquhar, R., Gloeckler, G., et al. (1990). The Solar Probe mission. In *AIP Conference Proceedings* (Vol. 203, pp. 101–110). American Institute of Physics. <https://doi.org/10.1063/1.39167>
- Feldman, W. C., Asbridge, J. R., Bame, S. J., & Gosling, J. T. (1978). Long-term variations of selected solar wind properties: Imp 6, 7, and 8 results. *Journal of Geophysical Research*, 83(A5), 2177–2189. <https://doi.org/10.1029/JA083IA05p02177>
- Feldman, W. C., & Marsch, E. (1997). Kinetic phenomena in the solar wind. In J. R. Jokipii, C. P. Sonett, & M. S. Giampapa (Eds.), *Cosmic winds and the heliosphere*, (pp. 617–676). Tucson: University of Arizona Press.
- Fenrich, F. R., & Waters, C. L. (2008). Phase coherence analysis of a field line resonance and solar wind oscillation. *Geophysical Research Letters*, 35, L20102. <https://doi.org/10.1029/2008gl035430>
- Fisk, L., & Sari, J. W. (1973). Correlation length for interplanetary magnetic field fluctuations. *Journal of Geophysical Research*, 78, 6729. <https://doi.org/10.1029/JA078i028P06729>
- Fisk, L. A. (2003). Acceleration of the solar wind as a result of the reconnection of open magnetic flux with coronal loops. *Journal of Geophysical Research*, 108, 1157. <https://doi.org/10.1029/2002JA009284>
- Fisk, L. A., Schwardron, N. H., & Zurbuchen, T. H. (1999). Acceleration of the fast solar wind by the emergence of new magnetic flux. *Journal of Geophysical Research*, 104(A9), 19,765–19,772. <https://doi.org/10.1029/1999JA000256>
- Foullon, C., Lavraud, B., Luhmann, J. G., Farrugia, C. J., Retino, A., Simunac, K. D. C., et al. (2011). Plasmod releases in the heliospheric current sheet and associated coronal hole boundary layer evolution. *The Astrophysical Journal*, 737, 1. <https://doi.org/10.1088/0004-637x/737/1/16>
- Fox, N. J., Velli, M. C., Bale, S. D., Decker, R., Driesman, A., Howard, R. A., et al. (2016). The Solar Probe Plus mission: Humanity's first visit to our star. *Space Science Reviews*, 204, 7. <https://doi.org/10.1007/s11214-015-0211-6>
- Freeman, J. W. (1988). Estimates of solar wind heating inside 0.3 AU. *Geophysical Research Letters*, 15, 88. <https://doi.org/10.1029/gl015i001p00088>
- Freeman, M. P., & Morley, S. K. (2009). No evidence for externally triggered substorms based on superposed epoch analysis of IMF Bz. *Geophysical Research Letters*, 36, L21101. <https://doi.org/10.1029/2009gl040621>
- Gammon, M., Heusen, M., & Shalchi, A. (2019). Comparison between test-particle simulations and test-particle theories for cosmic ray transport: III. Dynamical turbulence. *Journal of Physics Communications*, 3, 015016. <https://doi.org/10.1088/2399-6528/aaff26>
- Gary, S. P. (1993). *Theory of space plasma microinstabilities*. New York: Cambridge Univ. Press.

- Gary, S. P., & Borovsky, J. E. (2004). Alfvén-cyclotron fluctuations: Linear Vlasov theory. *Journal of Geophysical Research*, *109*, A06105. <https://doi.org/10.1029/2004JA010399>
- Gary, S. P., & Smith, C. W. (2009). Short-wavelength turbulence in the solar wind: Linear theory of whistler and kinetic Alfvén fluctuations. *Journal of Geophysical Research*, *114*, A12105. <https://doi.org/10.1029/2009JA014525>
- Gary, S. P., Yin, L., Winske, D., & Reisenfeld, D. B. (2000). Electromagnetic alpha/proton instabilities in the solar wind. *Geophysical Research Letters*, *27*, 1355. <https://doi.org/10.1029/2000gl000019>
- Giacalone, J., & Jokipii, J. R. (2001). The transport of energetic particles and cosmic rays in the heliosphere. *Advances in Space Research*, *27*(3), 461. [https://doi.org/10.1016/s0273-1177\(01\)00075-8](https://doi.org/10.1016/s0273-1177(01)00075-8)
- Gibney, E. (2017). Europe lines up for solar-storm view. *Nature*, *541*, 271. <https://doi.org/10.1038/541271a>
- Gloeckler, G., Zurbuchen, T. H., & Geiss, J. (2003). Implications of the observed anticorrelation between solar wind speed and coronal electron temperature. *Journal of Geophysical Research*, *108*, 1158. <https://doi.org/10.1029/2002JA009286>
- Goldreich, P., & Sridhar, S. (1997). Magnetohydrodynamic turbulence revisited. *The Astrophysical Journal*, *485*, 680. <https://doi.org/10.1086/304442>
- Goldstein, M. L., Roberts, D. A., & Deane, A. (2003). The effect of microstreams on Alfvénic fluctuations in the solar wind. In *AIP Conference Proceedings* (Vol. 679, pp. 405–408). American Institute of Physics. <https://aip.scitation.org/doi/abs/10.1063/1.1618622>
- Goldstein, M. L., Roberts, D. A., & Matthaeus, W. H. (1995). Magnetohydrodynamic turbulence in the solar wind. *Annual Review of Astronomy and Astrophysics*, *33*, 283. <https://doi.org/10.1146/annurev.aa.33.090195.001435>
- Goldstein, M. L., Wicks, R. T., Perri, S., & Sahraoui, F. (2015). Kinetic scale turbulence and dissipation in the solar wind: Key observational results and future outlook. *Philosophical Transactions of the Royal Society*, *A373*, 20,140,147. <https://doi.org/10.1098/rsta.2014.0147>
- Gopalswamy, N. (2016). History and development of coronal mass ejections as a key player in solar terrestrial relationship. *Geoscience Letters*, *3*, 8. <https://doi.org/10.1186/s40562-016-0039-2>
- Gosling, J. T., Baker, D. N., Bame, S. J., Feldman, W. C., Zwickl, R. D., & Smith, E. J. (1987). Bidirectional solar wind electron heat flux events. *Journal of Geophysical Research*, *92*, 8519. <https://doi.org/10.1029/JA092Ia08P08519>
- Gosling, J. T., Skoug, R. M., McComas, D. J., & Mazur, J. E. (2004). Correlated dispersionless structure in suprathermal electrons and solar energetic ions in the solar wind. *The Astrophysical Journal*, *614*, 412. <https://doi.org/10.1086/423368>
- Greco, A., Servidio, S., Matthaeus, W. H., & Dmitruk, P. (2010). Intermittent structures and magnetic discontinuities on small scales in MHD simulations and solar wind. *Planetary and Space Science*, *58*, 1895. <https://doi.org/10.1016/j.pss.2010.08.019>
- Haaland, A., Eriksson, A., Engwall, E., Lybekk, B., Nilsson, H., Pedersen, A., et al. (2012). Estimating the capture and loss of cold plasma from ionospheric outflow. *Journal of Geophysical Research*, *117*, A07311. <https://doi.org/10.1029/2012JA017679>
- Hadid, L. Z., Sahraoui, F., & Galtier, S. (2017). Energy cascade rate in compressible fast and slow solar wind turbulence. *The Astrophysical Journal*, *838*, 9. <https://doi.org/10.3847/1538-4357/aa603f>
- Hartinger, M. D., Welling, D., Viall, N. M., Moldwin, M. B., & Ridley, A. (2014). The effect of magnetopause motion on fast mode resonance. *Journal of Geophysical Research: Space Physics*, *119*, 8212–8227. <https://doi.org/10.1002/2014JA020401>
- Heidrich-Meisner, V., Berger, L., & Wimmer-Schweingruber, R. F. (2018). Disparity among low first ionization potential elements. *Astronomy & Astrophysics*, *619*, A79. <https://doi.org/10.1051/0004-6361/201833454>
- Hellinger, P., Matteini, L., Stverak, S., Travnicek, P. M., & Marsch, E. (2011). Heating and cooling of protons in the fast solar wind between 0.3 and 1 AU: Helios revisited. *Journal of Geophysical Research*, *116*, A09105. <https://doi.org/10.1029/2011JA016674>
- Hesse, M., & Cassak, P. A. (2020). Magnetic reconnection in the space sciences: Past, present, and future. *Journal of Geophysical Research: Space Physics*, *125*. <https://doi.org/10.1029/2018JA025935>
- Hickman, K. S., Godinez, H. C., Henney, C. J., & Arge, C. N. (2015). Data assimilation in the ADAPT photospheric flux transport model. *Solar Physics*, *290*, 1105. <https://doi.org/10.1007/s11207-015-0666-3>
- Higginson, A. K., Antiochos, S. K., DeVore, C. R., Wyper, P. F., & Zurbuchen, T. H. (2017a). Formation of heliospheric arcs of slow solar wind. *The Astrophysical Journal Letters*, *840*, L10. <https://doi.org/10.3847/2041-8213/aa6d72>
- Higginson, A. K., Antiochos, S. K., DeVore, C. R., Wyper, P. F., & Zurbuchen, T. H. (2017b). Dynamics of coronal hole boundaries. *The Astrophysical Journal*, *837*, 113. <https://doi.org/10.3847/1538-4357/837/2/113>
- Higginson, A. K., & Lynch, B. J. (2018). Structured slow solar wind variability: Streamer-blob flux ropes and torsional Alfvén waves. *The Astrophysical Journal*, *859*, 6. <https://doi.org/10.3847/1538-4357/aabc08>
- Hiremath, K. M., & Hedge, M. (2013). Rotation rates of coronal holes and their probable anchoring depths. *The Astrophysical Journal*, *763*(137), 2013. <https://doi.org/10.1088/0004-637x/763/2/137>
- Hollweg, J. V., Verscharen, D., & Chandran, B. D. G. (2014). Magnetohydrodynamic slow mode with drifting He<sup>++</sup>: Implications for coronal seismology and the solar wind. *The Astrophysical Journal*, *788*, 35. <https://doi.org/10.1088/0004-637x/788/1/35>
- Horbury, T. S., Forman, M. A., & Oughton, S. (2005). Spacecraft observations of solar wind turbulence: An overview. *Plasma Physics and Controlled Fusion*, *47*, B703. <https://doi.org/10.1088/0741-3335/47/12b/s52>
- Horbury, T. S., Matteini, L., & Stansby, D. (2018). Short, large-amplitude speed enhancements in the near-Sun fast solar wind. *Monthly Notices of the Royal Astronomical Society*, *478*, 1980. <https://doi.org/10.1093/mnras/sty953>
- Howard, R. A., Moses, J. D., Socker, D. G., Dere, K. P., & Cook, J. W. (2008). Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI). *Space Science Reviews*, *136*, 67. [https://doi.org/10.1016/s0273-1177\(02\)00147-3](https://doi.org/10.1016/s0273-1177(02)00147-3)
- Howard, R. A., Vourlidas, A., Korendyke, C., Plunkett, S. P., Carter, M. T., Wang, D., et al. (2013). The solar orbiter imager (SoloHI) instrument for the Solar Orbiter mission. In *Proceedings of the SPIE* (Vol. 8862, pp. 1–13). SPIE. [https://spie.org/Publications/Proceedings/Paper/10.1117/12.2027657?origin\\_id=x4325%26start\\_volume\\_number=08800](https://spie.org/Publications/Proceedings/Paper/10.1117/12.2027657?origin_id=x4325%26start_volume_number=08800), <https://doi.org/10.1117/12.2027657>
- Howes, G. G. (2015). A dynamical model of plasma turbulence in the solar wind. *Philosophical Transactions of the Royal Society*, *A373*, 20,140,145. <https://doi.org/10.1098/rsta.2014.0145>
- Howes, G. G. (2017). A prospectus on kinetic heliophysics. *Physics of Plasmas*, *24*, 055907. <https://doi.org/10.1063/1.4983993>
- Innes, D. E., Bučik, R., Guo, L.-J., & Nitta, N. (2016). Observations of solar X-ray and EUV jets and their related phenomena. *Astronomische Nachrichten*, *337*(10), 1024.
- Jackson, B. V., Buffington, A., Hick, P. P., Altrock, R. C., Figueroa, S., Holladay, P. E., et al. (2004). The Solar Mass-Ejection Imager (SMEI) mission. *Solar Physics*, *225*, 177. <https://doi.org/10.1007/s11207-004-2766-3>
- Kahler, S. W., Arge, C. N., & Smith, D. A. (2016). Using the WSA model to test the Parker spiral approximation for SEP event magnetic connections. *Solar Physics*, *291*, 1829. <https://doi.org/10.1007/s11207-016-0934-x>
- Karpen, J. T., DeVore, C. R., Antiochos, S. K., & Pariat, E. (2017). Reconnection-driven coronal-hole jets with gravity and solar wind. *The Astrophysical Journal*, *834*, 62. <https://doi.org/10.3847/1538-4357/834/1/62>

- Kasper, J. C., Bale, S. D., Belcher, J. W., Bertomier, M., Case, A. W., Chandran, B. D. G., et al. (2019). Alfvén velocity spikes and rotational flows in the near-Sun solar wind. *Nature*, *576*, 228. <https://doi.org/10.1038/s41586-019-1813-z>
- Kasper, J. C., Stevens, M. L., Korreck, K. E., Maruca, B. A., Kiefer, K. K., Schwadron, N. A., & Lepri, S. T. (2012). Evolution of the relationships between helium abundance, minor ion charge state, and solar wind speed over the solar cycle. *The Astrophysical Journal*, *745*, 162. <https://doi.org/10.1088/0004-637x/745/2/162>
- Kasper, J. C., Stevens, M. L., Lazarus, A. J., Steinberg, J. T., & Ogilvie, K. W. (2007). Solar wind helium abundance as a function of speed and heliographic latitude: Variation through the solar cycle. *The Astrophysical Journal*, *660*, 901. <https://doi.org/10.1086/510842>
- Kepko, L., Spence, H. E., & Singer, H. J. (2002). ULF waves in the solar wind as direct drivers of magnetospheric pulsations. *Geophysical Research Letters*, *29*, 1197. <https://doi.org/10.1029/2001gl014405>
- Kepko, L., & Viall, N. M. (2019). The source, significance, and magnetospheric impact of periodic density structures within stream interaction regions. *Journal of Geophysical Research: Space Physics*, *124*, 7722–7743. <https://doi.org/10.1029/2019JA026962>
- Kepko, L., Viall, N. M., Antiochos, S. K., Lepri, S. T., Kasper, J. C., & Weberg, M. (2016). Implications of L1 observations for slow solar wind formation by solar reconnection. *Geophysical Research Letters*, *43*, 4089. <https://doi.org/10.1002/2016gl068607>
- Kessel, R. L. (2008). Solar wind excitation of Pc5 fluctuations in the magnetosphere and on the ground. *Journal of Geophysical Research*, *113*, A04202. <https://doi.org/10.1029/2007JA012255>
- Kilpua, E., Koskinen, H. E. J., & Pulkkinen, T. I. (2017). Coronal mass ejections and their sheath regions in interplanetary space. *Living Reviews in Solar Physics*, *14*, 5. <https://doi.org/10.1007/s41116-017-0009-6>
- Kilpua, E. K. J., Lugaz, N., Mayx, M. L., & Temmer, M. (2019). Forecasting the structure and orientation of earthbound coronal mass ejections. *Space Weather*, *17*, 498–526. <https://doi.org/10.1029/2018sw001944>
- King, J. H., & Papitashvili, N. E. (2005). Solar wind spatial scales in and comparisons of hourly wind and ACE plasma and magnetic field data. *Journal of Geophysical Research*, *110*, 2104. <https://doi.org/10.1029/2004JA010649>
- Klimchuk, J. A. (2012). The role of type II spicules in the upper solar atmosphere. *Journal of Geophysical Research*, *117*, A12102. <https://doi.org/10.1029/2012JA018170>
- Klimchuk, J. A. (2015). Key aspects of coronal heating. *Philosophical Transactions of the Royal Society A*, *373*, 20140256. <https://doi.org/10.1098/rsta.2014.0256>
- Knetter, T., Neubauer, F. M., Horbury, T., & Balogh, A. (2004). Four-point discontinuity observations using Cluster magnetic field data: A statistical survey. *Journal of Geophysical Research*, *109*, A06102. <https://doi.org/10.1029/2003JA010099>
- Kocharov, L., Laitinen, T., Usoskin, I., & Vainio, R. (2014). Transmission and emission of solar energetic particles in semi-transparent shocks. *The Astrophysical Journal Letters*, *787*, L21. <https://doi.org/10.1088/2041-8205/787/2/L21>
- Komar, C. M., Fermo, R. L., & Cassak, P. A. (2015). Comparative analysis of dayside magnetic reconnection models in global magnetosphere simulations. *Journal of Geophysical Research: Space Physics*, *120*, 276–294. <https://doi.org/10.1002/2014JA020587>
- Kopp, R. A., Poletto, G., Noci, G., & Bruner, M. (1985). Analysis of loop flows observed on 27 March, 1980 by the UVSP instrument during the Solar Maximum Mission. *Solar Physics*, *98*, 91. <https://doi.org/10.1007/bf00177201>
- Korotova, G. I., & Sibeck, D. G. (1995). A case study of transient event motion in the magnetosphere and in the ionosphere. *Journal of Geophysical Research*, *100*, 35. <https://doi.org/10.1029/94JA02296>
- Kraichnan, R. H. (1965). Inertial-range spectrum of hydromagnetic turbulence. *Physics of Fluids*, *8*, 1385. <https://doi.org/10.1063/1.1761412>
- Krieger, A. S., Timothy, A. F., & Roelof, E. C. (1973). A coronal hole and its identification as the source of a high velocity solar wind stream. *Solar Physics*, *29*, 505. <https://doi.org/10.1007/bf00150828>
- Krista, L. D., & Gallagher, P. T. (2009). Automated coronal hole detection using local intensity thresholding techniques. *Solar Physics*, *256*, 87. <https://doi.org/10.1007/s11207-009-9357-2>
- Krista, L. D., Gallagher, P. T., & Bloomfield, D. S. (2011). Short-term evolution of coronal hole boundaries. *The Astrophysical Journal Letters*, *731*, L26. <https://doi.org/10.1088/2041-8205/731/2/L26>
- Lacombe, C., Salem, C., Mangeney, A., Hubert, D., Perche, C., Bougeret, J.-L., et al. (2002). Evidence for the interplanetary electric potential? WIND observations of electrostatic fluctuations. *Annales Geophysicae*, *20*, 609. <https://doi.org/10.5194/angeo-20-609-2002>
- Laming, J. M., Vourlidas, A., Korendyke, C., Chua, D., Cranmer, S. R., Ko, Y.-K., et al. (2019). Element abundances: A new diagnostic for the solar wind. *The Astrophysical Journal*, *879*, 124. <https://doi.org/10.3847/1538-4357/ab23f1>
- Laming, J. M. (2015). The FIP and inverse FIP effects in solar and stellar coronae. *Living Reviews in Solar Physics*, *12*, 2. <https://doi.org/10.1007/lrsp-2015-2>
- Lamy, H., Maksimovic, M., Pierrard, V., & Lemaire, J. (2003). Solar wind kinetic exospheric models with typical coronal holes exobase conditions. In *AIP Conference Proceedings* (Vol. 679, pp. 367–370). American Institute of Physics. <https://doi.org/10.1063/1.1618615>
- Landi, E., Alexander, R. L., Gruesbeck, J. R., Gilbert, J. A., Lepri, S. T., Manchester, W. B., & Zurbuchen, T. H. (2012). Carbon ionization stages as a diagnostic of the solar wind. *The Astrophysical Journal*, *744*, 100. <https://doi.org/10.1088/0004-637x/744/2/100>
- Landi, E., Gruesbeck, J. R., Lepri, S. T., Zurbuchen, T. H., & Fisk, L. A. (2012). Charge state evolution in the solar wind. II. Plasma charge state composition in the inner corona and accelerating fast solar wind. *The Astrophysical Journal*, *761*, 48. <https://doi.org/10.1088/0004-637x/761/1/48>
- Leamon, R. J., Smith, C. W., Ness, N. F., & Wong, H. K. (1999). Dissipation range dynamics: Kinetic Alfvén waves and the importance of  $\beta_e$ . *Journal of Geophysical Research*, *104*, 22331. <https://doi.org/10.1029/1999JA900158>
- Lemaire, J. (2012). Half a century of kinetic solar wind models. In *AIP Conference Proceedings* (Vol. 1216, pp. 8–13). American Institute of Physics. <https://doi.org/10.1063/1.3395971>
- Lepri, S. T., Landi, E., & Zurbuchen, T. H. (2013). Solar wind heavy ions over solar cycle 23: ACE/SWICS measurements. *The Astrophysical Journal*, *768*, 94. <https://doi.org/10.1088/0004-637x/768/1/94>
- Li, G. (2017). Particle acceleration and transport in the inner heliosphere. *Science China Earth Sciences*, *60*, 1440. <https://doi.org/10.1007/s11430-017-9083-y>
- Li, G., & Qin, G. (2011). A solar wind model with current sheets. In *ASP Conference Series* (Vol. 444, p. 117). Astronomical Society of the Pacific Conference Series. <http://aspbooks.org/custom/publications/paper/444-0117.html>, <https://myasp.astronomy.org/product/CS444/vol-444-5th-international-conference-of-numerical-modeling-of-space-plasma-flows-astronom-2010>
- Lie-Svendsen, O., & Leer, E. (2000). The electron velocity distribution in the high-speed solar wind: Modeling the effects of protons. *Journal of Geophysical Research*, *105*, 35. <https://doi.org/10.1029/1999JA900438>
- Lin, Y., Duan, X., Zhao, C., & Xu, L. (2013). *Systems Science Methodological Approaches*. Sect. 7.2.2. Boca Raton, Florida: CRC Press.
- Linker, J. A., Caplan, R. M., Downs, C., Lionello, R., Riley, P., Mikic, Z., et al. (2016). An empirically driven time-dependent model of the solar wind. *Journal of Physics: Conference Series*, *719*, 012012. <https://doi.org/10.1088/1742-6596/719/1/012012>

- Linker, J. A., Caplan, R. M., Downs, C., Riley, P., Mikić, Z., Lionello, R., et al. (2017). The open flux problem. *The Astrophysical Journal*, *848*, 70. <https://doi.org/10.3847/1538-4357/aa8a70>
- Lionello, R., Riley, P., Linker, J. A., & Mikić, Z. (2005). The effects of differential rotation on the magnetic structure of the solar corona: Magnetohydrodynamic simulations. *The Astrophysical Journal*, *625*, 463. <https://doi.org/10.1086/429268>
- Lionello, R., Török, T., Titov, V. S., Leake, J. E., Mikić, Z., Linker, J. A., & Linton, M. G. (2016). The contribution of coronal jets to the solar wind. *The Astrophysical Journal Letters*, *831*, L2. <https://doi.org/10.3847/2041-8205/831/1/L2>
- Liou, K., Takahashi, K., Newell, P. T., & Yumoto, K. (2008). Polar Ultraviolet Imager observations of solar wind-driven ULF auroral pulsations. *Geophysical Research Letters*, *35*, L16101. <https://doi.org/10.1029/2008GL034953>
- Loureiro, N., & Boldyrev, S. (2017). Collisionless reconnection in magnetohydrodynamic and kinetic turbulence. *The Astrophysical Journal*, *850*, 182. <https://doi.org/10.3847/1538-4357/aa9754>
- Luhmann, J. C., Petrie, G., & Riley, P. (2013). Solar origins of solar wind properties during the cycle 23 solar minimum and rising phase of cycle 24. *Journal of Advanced Research*, *4*, 221. <https://doi.org/10.1016/j.jare.2012.08.008>
- Lynch, B. J., Edmondson, J. K., & Li, Y. (2014). Interchange reconnection Alfvén wave generation. *Solar Physics*, *289*, 3043. <https://doi.org/10.1007/s11207-014-0506-x>
- MacNeice, P., Jian, L. K., Antiochos, S. K., Arge, C. N., Bussy-Virat, C. D., De Rosa, M. L., et al. (2018). Assessing the quality of models of the ambient solar wind. *Space Weather*, *16*, 1644–1667. <https://doi.org/10.1029/2018sw002040>
- Maksimovic, M., Zouganelis, I., Chaufray, J.-Y., Issautier, K., Scime, E. E., Littleton, J. E., et al. (2005). Radial evolution of the electron distribution functions in the fast solar wind between 0.3 and 1.5 AU. *Journal of Geophysical Research*, *110*, A09104. <https://doi.org/10.1029/2005JA011119>
- Malandraki, O. (2015). Heliospheric energetic particles and galactic cosmic ray modulation. *Journal of Physics: Conference Series*, *632*, 012070. <https://doi.org/10.1088/1742-6596/632/1/012070>
- Mandrini, C. H., Nuevo, F. A., Vázquez, A. M., Démoulin, P., van Driel-Gesztelyi, L., Baker, D., et al. (2014). How can active region plasma escape into the solar wind from below a closed helmet streamer? *Solar Physics*, *289*, 11. <https://doi.org/10.1007/s11207-014-0582-y>
- Mangency, A., Salem, C., Lacombe, C., Bougeret, J.-L., Perche, C., Manning, R., et al. (1999). WIND observations of coherent electrostatic waves in the solar wind. *Annales Geophysicae*, *17*, 307. <https://doi.org/10.1007/s00585-999-0307-y>
- Marsch, E. (2006). Kinetic physics of the solar corona and solar wind. *Living Reviews in Solar Physics*, *3*. <https://doi.org/10.12942/lrsp-2006-1>
- Marsch, E. (2018). Solar wind and kinetic heliophysics. *Annales Geophysicae*, *36*, 1607. <https://doi.org/10.5194/angeo-36-1607-2018>
- Marsch, E., Muhlhauer, K.-H., Rosenbauer, H., Schwenn, R., & Neubauear, F. M. (1982). Solar wind helium ions: Observations of the Helios solar probes between 0.3 and 1 AU. *Journal of Geophysical Research*, *87*, 35. <https://doi.org/10.1029/JA087IA01P00035>
- Mason, E. I., Antiochos, S. K., & Viall, N. M. (2019). Observations of solar coronal rain in null point topologies. *The Astrophysical Journal*, *874*, L33. <https://doi.org/10.3847/2041-8213/ab0c5d>
- Masson, S., McCauley, P., Golub, L., Reeves, K. K., & DeLuca, E. E. (2014). Dynamics of the transition corona. *The Astrophysical Journal*, *787*, 145. <https://doi.org/10.1088/0004-637x/787/2/145>
- Matsuoka, H., Takahashi, K., Yumoto, K., Anderson, B. J., & Sibeck, D. G. (1995). Observation and modeling of compressional Pi 3 magnetic pulsations. *Journal of Geophysical Research*, *100*(A7), 12,103–12,115. <https://doi.org/10.1029/94JA03368>
- Matteini, L. (2016). Kinetic instabilities in the solar wind: A short review. *AIP Conference Proceedings*, *1720*, 030003. <https://doi.org/10.1063/1.4943811>
- Matteini, L., Hellinger, P., Landi, S., Travnicek, P. M., & Velli, M. (2012). Ion kinetics in the solar wind: Coupling global expansion to local microphysics. *Space Science Reviews*, *172*, 373. <https://doi.org/10.1007/s11214-011-9774-z>
- Matthaeus, W. H., & Goldstein, M. L. (1982). Measurement of the rugged invariants of magnetohydrodynamic turbulence in the solar wind. *Journal of Geophysical Research*, *87*, 6011. <https://doi.org/10.1029/JA087IA08P06011>
- Matthaeus, W. H., Goldstein, M. L., & Montgomery, D. C. (1983). Turbulent generation of outward-traveling interplanetary Alfvénic fluctuations. *Physical Review Letters*, *51*, 1484. <https://doi.org/10.1103/physrevlett.51.1484>
- Matthaeus, W. H., Goldstein, M. L., & Roberts, D. A. (1990). Evidence for the presence of quasi-two-dimensional nearly incompressible fluctuations in the solar wind. *Journal of Geophysical Research*, *95*(A12), 20,673–20,683. <https://doi.org/10.1029/JA095IA12P20673>
- Matthaeus, W. H., Pouquet, A., Mininni, P. D., Dmitruk, P., & Breech, B. (2008). Rapid alignment of velocity and magnetic field in magnetohydrodynamic turbulence. *Physical Review Letters*, *100*. <https://doi.org/10.1103/physrevlett.100.085003>
- Matthaeus, W. H., & Velli, M. (2011). Who needs turbulence? A review of turbulence effects in the heliosphere and on the fundamental process of reconnection. *Space Science Reviews*, *160*, 145. <https://doi.org/10.1007/s11214-011-9793-9>
- McComas, D. J., Bame, S. J., Barraclough, B. L., Feldman, W. C., Funsten, P. H., Gosling, J. T., et al. (1998). Ulysses' return to the slow solar wind. *Geophysical Research Letters*, *25*, 1. <https://doi.org/10.1029/97gl03444>
- McComas, D. J., Chritian, E. R., Cohen, C. M. S., Cummings, A. C., Davis, A. J., Desai, M. I., et al. (2019). Probing the energetic particle environment near the Sun. *Nature*, *576*, 223. <https://doi.org/10.1038/s41586-019-1811-1>
- McCracken, K. G., & Ness, N. F. (1966). The collimation of cosmic rays by the interplanetary magnetic field. *Journal of Geophysical Research*, *71*, 3315. <https://doi.org/10.1029/JZ071I01P03315>
- McCracken, K. C., Rao, U. R., & Ness, N. F. (1968). Interrelationship of cosmic-ray anisotropies and the interplanetary magnetic field. *Journal of Geophysical Research*, *73*, 4159. <https://doi.org/10.1029/JA073I01P04159>
- McIntosh, S. W., De Pontieu, B., Garlsson, M., Hansteen, V., Boerner, P., & Goossens, M. (2011). Alfvén waves with sufficient energy to power the quiet solar corona and fast solar wind. *Nature*, *475*, 477. <https://doi.org/10.1038/nature10235>
- Meyer-Vernet, N., Mangency, A., Maksimovic, M., Pantellini, F., & Issartier, K. (2003). Some basic aspects of solar wind acceleration. *AIP Conference Proceedings*, *679*, 263. <https://doi.org/10.1063/1.1618591>
- Michel, F. C. (1967). Model of solar wind structure. *Journal of Geophysical Research*, *72*, 1917. <https://doi.org/10.1029/JZ072i007p01917>
- Muller, D., Marsden, R. G., St. Cyr, O. C., & Gilbert, H. R. (2013). Solar Orbiter exploring the Sun-heliosphere connection. *Solar Physics*, *285*, 25. <https://doi.org/10.1007/s11207-012-0085-7>
- Nash, A. G., Sheeley, N. R., & Wang, Y.-M. (1988). Mechanisms for the rigid rotation of coronal holes. *Solar Physics*, *117*(359), 1988. <https://doi.org/10.1007/bf00147253>
- Němeček, Z., Ďurovcová, T., Šafránková, J., Němec, F., Matteini, L., Stansby, D., et al. (2020). What is the solar wind frame of reference? *The Astrophysical Journal*, *889*(2). <https://doi.org/10.3847/1538-4357/ab65f7>, <https://iopscience.iop.org/article/10.3847/1538-4357/ab65f7>
- Ness, N. F. (1996). Pioneering the swinging 1960s into the 1970s and 1980s. *Journal of Geophysical Research*, *101*(A5), 10497–10509. <https://doi.org/10.1029/96JA00138>

- Neugebauer, M. (1985). Alignment of velocity and field changes across tangential discontinuities in the solar wind. *Journal of Geophysical Research*, *90*, 6627. <https://doi.org/10.1029/JA090IA07P06627>
- Neugebauer, M. (1997). Pioneers of space physics: A career in the solar wind. *Journal of Geophysical Research*, *102*, 26887. <https://doi.org/10.1029/97JA02444>
- Neugebauer, M. (2012). Evidence for polar X-ray jets as sources of microstream peaks in the solar wind. *The Astrophysical Journal*, *750*, 50. <https://doi.org/10.1088/0004-637x/750/1/50>
- Neugebauer, M., & Giacalone, J. (2010). Progress in the study of interplanetary discontinuities. *AIP Conference Proceedings*, *1216*, 194. <https://doi.org/10.1063/1.3395834>
- Neugebauer, M., & Giacalone, J. (2015). Energetic particles, tangential discontinuities, and solar flux tubes. *Journal of Geophysical Research: Space Physics*, *120*, 8281–8287. <https://doi.org/10.1002/2015JA021632>
- Neugebauer, M., Goldstein, B. E., McComas, D. J., Suess, S. T., & Balogh, A. (1995). Ulysses observations of microstreams in the solar wind from coronal holes. *Journal of Geophysical Research*, *100*, 23389. <https://doi.org/10.1029/95JA02723>
- Neugebauer, M., Ruzmaikin, A., & McComas, D. J. (1997). Wavelet analysis of the structure of microstreams in the polar solar wind. *AIP Conference Proceedings*, *385*, 41. <https://doi.org/10.1063/1.51765>
- Newell, P. T., & Liou, K. (2011). Solar wind driving and substorm triggering. *Journal of Geophysical Research*, *116*, A03229. <https://doi.org/10.1029/2010JA016139>
- Obridko, V. N., & Vaisberg, O. L. (2017). On the history of the solar wind discovery. *Solar System Research*, *51*, 165. <https://doi.org/10.1134/s0038094617020058>
- Ofman, L., Provornikova, E., Abbo, L., & Giordano, S. (2015). Three-dimensional multi-fluid model of a coronal streamer belt with a tilted magnetic dipole. *Annales Geophysicae*, *33*, 47. <https://doi.org/10.5194/angeo-33-47-2015>
- Ogilvie, K. W., & Hirshberg, J. (1974). The solar cycle variation of the solar wind helium abundance. *Journal of Geophysical Research*, *79*, 4595. <https://doi.org/10.1029/JA079i031p04595>
- Oran, R., Landi, E., van der Holst, B., Lepri, S. T., Vázquez, A. M., Nuevo, F. A., et al. (2015). A steady-state picture of solar wind acceleration and charge state composition derived from a global wave-driven MHD model. *The Astrophysical Journal*, *806*, 55. <https://doi.org/10.1088/0004-637x/806/1/55>
- Oughton, S., Matthaeus, W. H., Wan, M., & Osman, K. T. (2015). Anisotropy in solar wind plasma turbulence. *Philosophical Transactions of the Royal Society*, *A373*, 20,140,152. <https://doi.org/10.1098/rsta.2014.0152>
- Owens, M. J., Crooker, N. U., & Lockwood, M. (2013). Solar origin of heliospheric magnetic field inversions: Evidence for coronal loop opening with pseudostreamers. *Journal of Geophysical Research*, *118*, 1868–1879. <https://doi.org/10.1002/jgra.50259>
- Owens, M. J., Lockwood, M., Barnard, L. A., & MacNeil, A. R. (2018). Generation of inverted heliospheric magnetic flux by coronal loop opening and slow solar wind release. *The Astrophysical Journal Letters*, *868*, L14. <https://doi.org/10.3847/2041-8213/a8e82>
- Owens, M. J., Wicks, R. T., & Horbury, T. S. (2011). Magnetic discontinuities in the near-Earth solar wind: Evidence of in-transit turbulence or remnants of coronal structure? *Solar Physics*, *269*, 411. <https://doi.org/10.1007/s11207-010-9695-0>
- Pagel, A. C., Crooker, N. U., Zurbuchen, T. H., & Gosling, J. T. (2004). Correlation of solar wind entropy and oxygen ion charge state ratio. *Journal of Geophysical Research*, *109*, A01113. <https://doi.org/10.1029/2003JA010010>
- Panasenco, V., & Panasenco, A. (2019). Large-scale magnetic funnels in the solar corona. *The Astrophysical Journal*, *873*. <https://doi.org/10.3847/1538-4357/ab017c>
- Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. *Astrophysical Journal*, *128*, 664. <https://doi.org/10.1086/146579>
- Parker, E. N. (2020). Exploring the innermost solar atmosphere. *Nature Astronomy*, *4*(1), 19–20. <https://doi.org/10.1038/s41550-019-0985-7>
- Paz Miralles, M., & Sanchez Alveida, J. (2011). *The Sun, the solar wind, and the heliosphere*. Dordrecht: Springer.
- Perez, J. C., & Boldyrev, S. (2010). Numerical simulations of imbalanced strong magnetohydrodynamic turbulence. *The Astrophysical Journal Letters*, *710*, L63. <https://doi.org/10.1088/2041-8205/710/1/L63>
- Peter, H. (1998). Element fractionation in the solar chromosphere driven by ionization-diffusion processes. *Astronomy & Astrophysics*, *335*, 691.
- Peter, H., & Marsch, E. (1998). Hydrogen and helium in the solar chromosphere: A background model for fractionation. *Astronomy & Astrophysics*, *335*, 1069.
- Pierrard, V., Lamy, H., & Lemaire, J. (2004). Exospheric distributions of minor ions in the solar wind. *Journal of Geophysical Research*, *109*. <https://doi.org/10.1029/2003JA010069>
- Pierrard, V., Moschou, S. P., Lazar, M., Borremans, K., & Lopez Rosson, G. (2016). Kinetic models for space plasmas: Recent progress for the solar wind and the Earth's magnetosphere. *AIP Conference Proceedings*, *1786*, 160,001. <https://doi.org/10.1063/1.4967658>
- Pilleri, P., Reisenfeld, D. B., Zurbuchen, T. H., Lepri, S. T., Shearer, P., Gilbert, J. A., et al. (2015). Variations in solar wind fractionation as seen by AC/SWICS and the implications for GENESIS mission results. *The Astrophysical Journal*, *812*, 1. <https://doi.org/10.1088/0004-637x/812/1/1>
- Podesta, J. J. (2010). Solar wind turbulence: Advances in observations and theory. *Proceedings of the International Astronomical Union*, *6*(S274), 295. <https://doi.org/10.1017/s1743921311007162>
- Podesta, J. J. (2012). The need to consider ion Bernstein waves as a dissipation channel of solar wind turbulence. *Journal of Geophysical Research*, *117*, A07101. <https://doi.org/10.1029/2012JA017770>
- Podesta, J. J. (2015). On the resolution of the phase space density required to obtain a specified accuracy of the solar wind bulk velocity. *Journal of Geophysical Research: Space Physics*, *120*, 3350–3365. <https://doi.org/10.1002/2015JA021010>
- Podesta, J. J., Roberts, D. A., & Goldstein, M. L. (2007). Spectral exponents of kinetic and magnetic energy spectra in solar wind turbulence. *The Astrophysical Journal*, *664*, 543. <https://doi.org/10.1086/519211>
- Poletto, G. (2013). Sources of solar wind over the solar activity cycle. *Journal of Advanced Research*, *4*, 215. <https://doi.org/10.1016/j.jare.2012.08.007>
- Pontin, D. I., & Wyper, P. F. (2015). The effect of reconnection on the structure of the Sun's open-closed flux boundary. *The Astrophysical Journal*, *805*, 39. <https://doi.org/10.1088/0004-637x/805/1/39>
- Pucci, F., Malara, F., Perri, S., Zimbardo, G., Sorrio-Valvo, L., & Valentini, F. (2016). Energetic particle transport in the presence of magnetic turbulence: Influence of spectral extension and intermittency. *Monthly Notices of the Royal Astronomical Society*, *459*, 3395. <https://doi.org/10.1093/mnras/stw877>
- Qin, G., & Li, G. (2008). Effect of flux tubes in the solar wind on the diffusion of energetic particles. *The Astrophysical Journal*, *682*, L129. <https://doi.org/10.1086/591229>

- Randolph, J. E. (1996). NASA solar probe mission and system concepts. *Advances in Space Research*, 17(3), 3. [https://doi.org/10.1016/0273-1177\(95\)00491-v](https://doi.org/10.1016/0273-1177(95)00491-v)
- Raouafi, N. E., Patsourakos, S., Pariat, E., Young, P. R., Sterling, A. C., Savcheva, A., et al. (2016). Solar coronal jets: Observations, theory, and modeling. *Space Science Reviews*, 201, 1. <https://doi.org/10.1007/s11214-016-0260-5>
- Rappazzo, A. F., Matthaeus, W. H., Ruffolo, D., Servidio, S., & Velli, M. (2012). Interchange reconnection in a turbulent corona. *The Astrophysical Journal Letters*, 758, L14. <https://doi.org/10.1088/2041-8205/758/1/L14>
- Rappazzo, A. F., Velli, M., Einaudi, G., & Dahlburg, R. B. (2005). Diamagnetic and expansion effects on the observable properties of the slow solar wind in a coronal streamer. *The Astrophysical Journal*, 633, 474. <https://doi.org/10.1086/431916>
- Raymond, J. C., Suleiman, R., Kohl, J. L., & Noci, G. (1998). Elemental abundances in coronal structures. In *Space Science Reviews* (Vol. 85, pp. 283–289). <https://link.springer.com/article/10.1023%2FA%3A1005162803316>
- Reale, F. (2014). Coronal loops: Observations and modeling confined plasmas. *Living Reviews of Solar Physics*, 11, 4. <https://doi.org/10.12942/lrsp-2014-4>
- Reames, D. V. (2013). The two sources of solar energetic particles. *Space Science Reviews*, 175, 53. <https://doi.org/10.1007/s11214-013-9958-9>
- Reginald, N., St. Cyr, O., Davilla, J., Rastaetter, L., & Torok, T. (2018). Evaluating uncertainties in coronal electron temperature and radial speed measurements using a simulation of the Bastille Day eruption. *Solar Physics*, 293, 82. <https://doi.org/10.1007/s11207-018-1301-x>
- Richardson, I. G. (2004). Energetic particles and corotating interaction regions in the solar wind. *Space Science Reviews*, 111, 267. <https://doi.org/10.1023/b:spac.0000032689.52830.3e>
- Richardson, J. D., & Paularena, K. I. (2001). Plasma and magnetic field correlations in the solar wind. *Journal of Geophysical Research*, 106, 239. <https://doi.org/10.1029/2000JA000071>
- Riley, P., Linker, J. A., & Arge, C. N. (2015). On the role played by magnetic expansion factor in the prediction of solar wind speed. *Space Weather*, 13, 154–169. <https://doi.org/10.1002/2014sw001144>
- Roberts, D. A., Goldstein, M. L., Klein, L. W., & Matthaeus, W. H. (1987). Origin and evolution of fluctuations in the solar wind: Helios observations and Helios-Voyager comparisons. *Journal of Geophysical Research*, 92(A11), 12,023–12,035. <https://doi.org/10.1029/JA092ia11p12023>
- Rouillard, A. P., Davies, J. A., Lavraud, B., Forsyth, R. J., Savani, N. P., Bewsher, D., et al. (2010). Intermittent release of transients in the slow solar wind: 1. Remote sensing observations. *Journal of Geophysical Research*, 115, A04103. <https://doi.org/10.1029/2009JA014471>
- Rouillard, A. P., Lavraud, B., Davies, J. A., Savani, N. P., Burlaga, L. F., Forsyth, R. J., et al. (2010). Intermittent release of transients in the slow solar wind: 2. In situ evidence. *Journal of Geophysical Research*, 115, A04104. <https://doi.org/10.1029/2009JA014472>
- Rouillard, A. P., Lavraud, B., Sheeley, N. R., Davies, J. A., Burlaga, L. F., Savani, N. P., et al. (2010). A white light and in situ comparison of a forming merged interaction region. *The Astrophysical Journal*, 719, 1385. <https://doi.org/10.1088/0004-637x/719/2/1385>
- Safrankova, J., Nemecek, Z., Cagas, P., Prech, L., Pavlu, J., Zastenker, G. N., et al. (2013). Short-scale variations of the solar wind helium abundance. *The Astrophysical Journal*, 778, 25. <https://doi.org/10.1088/0004-637x/778/1/25>
- Salem, C., Lacombe, C., Mangeney, A., Kellogg, P. J., & Bougeret, J.-L. (2003). Weak double layers in the solar wind and their relation to the interplanetary electric field. *AIP Conference Proceedings*, 679, 513. <https://doi.org/10.1063/1.1618647>
- Salem, C., Mangeney, A., Bale, S. D., & Veltri, P. (2009). Solar wind magnetohydrodynamics turbulence: Anomalous scaling and role of intermittency. *The Astrophysical Journal*, 702, 553. <https://doi.org/10.1088/0004-637x/702/1/537>
- Samanta, T., Tian, H., Yurchyshyn, V., Peter, H., Cao, W., Sterling, A., et al. (2019). Generation of solar spicules and subsequent atmospheric heating. *Science*, 366, 890. <https://doi.org/10.1126/science.aaw2796>
- Sanchez-Diaz, E., Rouillard, A. P., Davies, J. A., Lavraud, B., Pinto, R. F., & Kilpua, E. (2017). The temporal and spatial scales of density structures released in the slow solar wind during solar activity maximum. *The Astrophysical Journal*, 851, 32. <https://doi.org/10.3847/1538-4357/aa98e2>
- Sanchez-Diaz, E., Rouillard, A. P., Davies, J. A., Lavraud, B., Sheeley, N. R., Pinto, R. F., et al. (2017). Observational evidence for the associated formation of blobs and raining inflows in the solar corona. *The Astrophysical Journal Letters*, 835, L7. <https://doi.org/10.3847/2041-8213/835/1/L7>
- Sanchez-Diaz, E., Rouillard, A. P., Lavraud, B., Segura, K., Tao, C., Pinto, R., et al. (2016). The very slow solar wind: Properties, origin and variability. *Journal of Geophysical Research: Space Physics*, 121, 2830–2841. <https://doi.org/10.1002/2016JA022433>
- Sandahl, I., Lundstedt, H., Koskinen, H., & Glassmeir, K.-H. (1996). On the need for solar wind monitoring close to the magnetosphere. *ASP Conference Series*, 95, 300. <http://articles.adsabs.harvard.edu/pdf/1996ASPC...95..300S>
- Sarafopoulos, D. V. (1995). Long duration Pc 5 compressional pulsations inside the Earth's magnetotail lobes. *Annales Geophysicae*, 13, 926. <https://doi.org/10.1007/s00585-995-0926-x>
- Schatten, K. H. (1971). Large-scale properties of the interplanetary magnetic field. *Reviews of Geophysics and Space Physics*, 9, 773. <https://doi.org/10.1029/rg009i003p00773>
- Schekochihin, A. A., Cowley, S. C., Dorland, W., Hammett, G. W., Howes, G. G., Quataert, E., & Tatsuno, T. (2009). Astrophysical gyrokinetics: Kinetic and fluid turbulent cascades in magnetized weakly collisional plasmas. *The Astrophysical Journal Supplement Series*, 182, 310. <https://doi.org/10.1088/0067-0049/182/1/310>
- Schrijver, C. J., & DeRosa, M. L. (2003). Photospheric and heliospheric magnetic fields. *Solar Physics*, 212, 165. <https://doi.org/10.1023/A:1022908504100>
- Schrijver, C. J., & Siscoe, G. L. (Eds) (2009). *Heliophysics: Plasma physics of the local cosmos*. Academic, New York: Cambridge University Press.
- Schrijver, C. J., Title, A. M., van Ballegoijen, A. A., Hagenaar, H. J., & Shine, R. A. (1997). Sustaining the quiet photospheric network: The balance of flux emergence, fragmentation, merging, and cancellation. *The Astrophysical Journal*, 487, 424. <https://doi.org/10.1086/304581>
- Schwadron, N. A., & McComas, D. J. (2003). Solar wind scaling law. *The Astrophysical Journal*, 599, 1395. <https://doi.org/10.1086/379541>
- Schwartz, S. J., Paschmann, G., Sckopke, N., Bauer, T. M., Dunlop, M., Fazakerley, A. N., & Thomsen, M. F. (2000). Conditions for the formation of hot flow anomalies at Earth's bow shock. *Journal of Geophysical Research*, 105, 12,639–12,650. <https://doi.org/10.1029/1999JA000320>
- Schwenn, R., & Marsch, E. (Eds) (1991a). Physics of the inner heliosphere 1. In *Large-scale structure*. Berlin: Springer-Verlag. <https://ui.adsabs.harvard.edu/abs/1990PCSS...20.....S/abstract>
- Schwenn, R., & Marsch, E. (Eds) (1991b). *Physics of the inner heliosphere 2. Particles, waves, and turbulence*. Berlin: Springer-Verlag.
- Schwenn, R., Muhlhäuser, K.-H., Marsch, E., & Rosenbauer, H. (1981). Two states of the solar wind at the time of solar activity minimum II. Radial gradients of plasma parameters in fast and slow streams. In *Solar Wind Four, MPAE-W-100-81-31* (pp. 126–130). Lindau, Germany: Max Planck Institut für Aeronomie. <http://hdl.handle.net/11858/00-001M-0000-000E-EAB9-F>

- Sheeley, N. R. Jr. (1980). Temporal variation of loop structures in the solar atmosphere. *Solar Physics*, 66, 79. <https://doi.org/10.1007/bf00150520>
- Sheeley, N. R. Jr., Lee, D. D. -H., Casto, K. P., Wang, Y. -M., & Rich, N. B. (2009). The structure of streamer blobs. *The Astrophysical Journal*, 694, 1471. <https://doi.org/10.1088/0004-637x/694/2/1471>
- Shi, M., Li, H., Xiao, C., & Wang, X. (2017). The parametric decay instability of Alfvén waves in turbulent plasmas and the applications in the solar wind. *The Astrophysical Journal*, 842, 63. <https://doi.org/10.3847/1538-4357/aa71b6>
- Siscoe, G. L., Davis, L., Coleman, P. J., Smith, E. J., & Jones, D. E. (1968). Power spectra and discontinuities of the interplanetary magnetic field: Mariner 4. *Journal of Geophysical Research*, 73, 61–82. <https://doi.org/10.1029/JA073i001p00061>
- Smith, C. W., Tessein, J. A., Vasquez, B. J., & Skoug, R. M. (2011). Turbulence associated with corotating interaction regions at 1 AU: Inertial range cross-helicity spectra. *Journal of Geophysical Research*, 116, A10103. <https://doi.org/10.1029/2011JA016645>
- Smith, C. W., Vasquez, B. J., Coburn, J. T., Forman, M. A., & Stawarz, J. E. (2018). Correlation scales of the turbulent cascade at 1 AU. *The Astrophysical Journal*, 858, 21. <https://doi.org/10.3847/1538-4357/aabb00>
- Smith, R. K., & Hughes, J. P. (2010). Ionization equilibrium timescales in collisional plasmas. *The Astrophysical Journal*, 718(583), 2010. <https://doi.org/10.1088/0004-637x/718/1/583>
- Stakhiv, M., Landi, E., Lepri, S. T., Oran, R., & Zurbuchen, T. H. (2015). On the origin of mid-latitude fast wind: Challenging the two-state solar wind paradigm. *The Astrophysical Journal*, 801, 100. <https://doi.org/10.1088/0004-637x/801/2/100>
- Stansby, D., Horbury, T. S., & Matteini, L. (2018). Diagnosing solar wind origins using in situ measurements in the inner heliosphere. *Monthly Notices of the Royal Astronomical Society*, 482(2), 1706–1714. <https://doi.org/10.1093/mnras/sty2814>
- Steinberg, J. T., Lazarus, A. J., Ogilvie, K. W., Lepping, R., & Byrnes, J. (1996). Differential flow between solar wind protons and alpha particles: First WIND observations. *Geophysical Research Letters*, 23, 1183. <https://doi.org/10.1029/96GL00628>
- Stverak, S., Maksimovic, M., Travnicek, P. M., Marsch, E., Fazakerley, A. N., & Scime, E. E. (2009). Radial evolution of nonthermal electron populations in the low-latitude solar wind: Helios, Cluster, and Ulysses observations. *Journal of Geophysical Research*, 114, A05104. <https://doi.org/10.1029/2008JA013883>
- Subramanian, S., Madjarska, M. S., & Doyle, J. G. (2010). Coronal hole boundaries evolution at small scales II. XRT view. Can small-scale outflows at CHBs be a source of the slow wind? *Astronomy & Astrophysics*, 516. <https://doi.org/10.1051/0004-6361/200913624>
- Suess, S. T., Ko, Y.-K., von Steiger, R., & Moore, R. L. (2009). Quiescent current sheets in the solar wind and origins of slow wind. *Journal of Geophysical Research*, 114, A04103. <https://doi.org/10.1029/2008JA013704>
- Susino, R., Ventura, R., Spadaro, D., Vourlidis, A., & Landi, E. (2008). Physical parameters along the boundaries of a mid-latitude streamer and its adjacent regions. *Astronomy & Astrophysics*, 488, 303. <https://doi.org/10.1051/0004-6361:200809713>
- Tautz, R. C., & Shalchi, A. (2013). Simulated energetic particle transport in the interplanetary space: The Palmer consensus revisited. *Journal of Geophysical Research*, 118, 642–647. <https://doi.org/10.1002/jgra.50155>
- Telloni, D., Carbone, V., Perri, S., Bruno, R., Lepreti, F., & Veltri, P. (2016). Relaxation processes within flux ropes in solar wind. *The Astrophysical Journal*, 826, 205. <https://doi.org/10.3847/0004-637x/826/2/205>
- Telloni, D., Perri, S., Carbone, V., & Bruno, R. (2016). Selective decay and dynamic alignment in the MHD turbulence: The role of the rugged invariants. *AIP Conference Proceedings*, 1720. <https://doi.org/10.1063/1.4943826>
- Tenerami, A., Velli, M., & DeForest, C. (2016). Inward motions in the outer solar corona between 7 and 12 Rs: Evidence for waves or magnetic reconnection jets? *The Astrophysical Journal Letters*, 825, L3. <https://doi.org/10.3847/2041-8205/825/1/L3>
- Thieme, K. M., Schwenn, R., & Marsch, E. (1989). Are structures in high-speed streams signatures of coronal fine structures? *Advances in Space Research*, 9(4), 127. [https://doi.org/10.1016/0273-1177\(89\)90105-1](https://doi.org/10.1016/0273-1177(89)90105-1)
- Thomas, S. R., Fazakerley, A., Wicks, R. T., & Green, L. (2018). Evaluating the skill of forecasts of the near-earth solar wind using a space weather monitor at L5. *Space Weather*, 16, 814–828. <https://doi.org/10.1029/2018SW001821>
- Thompson, B., Lugaz, N., Qiu, J., & Webb, D. F. (2020). Solar flares and coronal mass ejections. In N. Raouafi, & A. Vourlidis (Eds.), *book chapter accepted for publication in "The sun and solar wind"* (Chap. 4). AGU; Wiley. <https://doi.org/10.1002/essoar.10502681.1>
- Timothy, A. F., Krieger, A. S., & Vaiana, G. S. (1975). The structure and evolution of coronal holes. *Solar Physics*, 42(135), 1975. <https://doi.org/10.1007/bf00153291>
- Titov, V. S., Mikic, Z., Linker, J. A., Lionello, R., & Antiochos, S. K. (2011). Magnetic topology of coronal hole linkages. *The Astrophysical Journal*, 731, 111. <https://doi.org/10.1088/0004-637x/731/2/111>
- Tong, Y., Borovsky, J. E., & Steinberg, J. T. (2016). Using ACE-Earth magnetic connection events to measure wandering length scale of interplanetary magnetic field in the solar wind. In *2016 Los Alamos Space Weather Summer School Research Reports* (Chap. 7, pp. 55–62). Los Alamos, New Mexico: Report LA-UR-16-29471, Los Alamos National Laboratory.
- Török, T., Aulanier, G., Schmieder, B., Reeves, K. K., & Golub, L. (2009). Fan-spine topology formation through two-step reconnection driven by twisted flux emergence. *The Astrophysical Journal*, 704, 485. <https://doi.org/10.1088/0004-637x/704/1/485>
- Trenchi, L., Bruno, R., Telloni, D., D'Amicis, R., Marcucci, M. F., Zurbuchen, T. H., & Weberg, M. (2013). Solar energetic particle modulation associated with coherent magnetic structures. *The Astrophysical Journal*, 770, 11. <https://doi.org/10.1088/0004-637x/770/1/11>
- Tsuneta, S., Ichimoto, K., Katsukawa, Y., Lites, B. W., Matsuzaki, K., Nagata, S., et al. (2008). The magnetic landscape of the Sun's polar region. *The Astrophysical Journal*, 688, 1374. <https://doi.org/10.1086/592226>
- Tu, C.-Y., & Marsch, E. (1995). MHD structures, waves and turbulence in the solar wind. *Space Science Reviews*, 73, 1. <https://doi.org/10.1007/bf00748891>
- Tu, C.-Y., Marsch, E., & Thieme, K. M. (1989). Basic properties of solar wind MHD turbulence near 0.3 AU analyzed by means of Elasser variables. *Journal of Geophysical Research*, 94, 11,739–11,759. <https://doi.org/10.1029/JA094ia09p11739>
- Tu, C.-Y., Wang, X., He, J., Marsch, E., & Wang, L. (2016). Two cases of convecting structure in the slow solar wind turbulence. *AIP Conference Proceedings*, 1720, 040017. <https://doi.org/10.1063/1.4943828>
- Tu, C.-Y., Zhou, C., Marsch, E., Xia, L.-D., Zhao, L., Wang, J.-X., & Wilhelm, K. (2005). Solar wind origin in coronal funnels. *Science*, 308, 519. <https://doi.org/10.1126/science.1109447>
- Ugarte-Urra, I., & Warren, H. P. (2012). Is active region core variability age dependent? *The Astrophysical Journal*, 761, 21. <https://doi.org/10.1088/0004-637x/730/1/37>
- Usmanov, A. V., Matthaeus, W. H., Goldstein, M. L., & Chhiber, R. (2018). The steady global corona and solar wind: A three-dimensional MHD simulation with turbulence transport and heating. *The Astrophysical Journal*, 865, 25. <https://doi.org/10.3847/1538-4357/aad687>
- Vaivads, A., et al. (2016). Turbulence Heating Observer—Satellite mission proposal. *Journal of Plasma Physics*, 82, 905,820,501. <https://doi.org/10.1017/s0022377816000775>

- van Driel-Gesztelyi, L., Culhane, J. L., Baker, D., Démoulin, P., Mandrini, C. H., DeRosa, M. L., et al. (2012). Magnetic topology of active regions and coronal holes: Implications for coronal outflows and the solar wind. *Solar Physics*, *281*, 1. <https://doi.org/10.1007/s11207-012-0076-8>
- Velli, M. (1993). On the propagation of ideal, linear Alfvén waves in radially stratified stellar atmospheres and winds. *Astronomy & Astrophysics*, *270*, 304.
- Velli, M., & Pruneti, F. (1997). Alfvén waves in the solar corona and solar wind. *Plasma Physics and Controlled Fusion*, *39*, B317. <https://doi.org/10.1088/0741-3335/39/12b/024>
- Verdini, A., Velli, M., & Buchlin, E. (2009). Reflection driven MHD turbulence in the solar atmosphere and wind. *Earth, Moon, and Planets*, *104*, 121. <https://doi.org/10.1007/s11038-008-9250-2>
- Verscharen, D. (2019). A step closer to the Sun's secrets. *Nature*, *576*, 219. <https://doi.org/10.1038/d41586-019-03665-3>
- Verscharen, D., Chandran, D. G., Bourouaine, S., & Hollweg, J. V. (2015). Deceleration of alpha particles in the solar wind by instabilities and the rotational force: Implications for heating, azimuthal flow, and the Parker spiral magnetic field. *The Astrophysical Journal*, *806*, 157. <https://doi.org/10.1088/0004-637x/806/2/157>
- Viall, N. M., De Moortel, I., Downs, C., Klimchuk, J. A., Parenti, S., & Reale, F. (2020). Coronal heating, book chapter accepted for publication. In N. Raouafi, & A. Vourlidas (Eds.), *The sun and solar wind* (Chap. 6). AGU; Wiley. <https://doi.org/10.1002/essoar.10502697.1>
- Viall, N. M., Kepko, L., & Spence, H. E. (2008). Inherent length-scales of periodic solar wind number density structures. *Journal of Geophysical Research*, *113*, A07101. <https://doi.org/10.1029/2007JA012881>
- Viall, N. M., Kepko, L., & Spence, H. E. (2009). Relative occurrence rates and connection of discrete frequency oscillations in the solar wind density and dayside magnetosphere. *Journal of Geophysical Research*, *114*, A01201. <https://doi.org/10.1029/2008JA013334>
- Viall, N. M., & Klimchuk, J. A. (2017). A survey of nanoflare properties in active regions observed with the Solar Dynamics Observatory. *The Astrophysical Journal*, *842*, 108. <https://doi.org/10.3847/1538-4357/aa7137>
- Viall, N. M., Spence, H. E., & Kasper, J. (2009). Are periodic solar wind number density structures formed in the solar corona? *Geophysical Research Letters*, *36*, L23102. <https://doi.org/10.1029/2009GL041191>
- Viall, N. M., Spence, H. E., Vourlidas, A., & Howard, R. (2010). Examining periodic solar-wind density structures observed in the SECCHI heliospheric imagers. *Solar Physics*, *267*(1), 175–202. <https://doi.org/10.1007/s11207-010-9633-1>
- Viall, N. M., & Vourlidas, A. (2015). Periodic density structures and the origin of the slow solar wind. *The Astrophysical Journal*, *807*, 176. <https://doi.org/10.1088/0004-637x/807/2/176>
- Villante, U., Di Matteo, S., & Piersanti, M. (2016). On the transmission of waves at discrete frequencies from the solar wind to the magnetosphere and ground: A case study. *Journal of Geophysical Research: Space Physics*, *121*, 380–396. <https://doi.org/10.1002/2015JA021628>
- von der Luhe, O. (2009). History of solar telescopes. *Experimental Astronomy*, *25*, 197. <https://doi.org/10.1007/s10686-009-9173-6>
- von Steiger, R. (2008). The solar wind throughout the solar cycle. In A. Balogh, L. J. Lanzerotti, & S. T. Suess (Eds.), *The heliosphere through the solar activity cycle* (Chap. 3, pp. 41–78). Chichester, UK: Springer Praxis.
- Vourlidas, A. (2015). Mission to the Sun-Earth L5 Lagrangian Point: An Optimal Platform for Space Weather Research. *Journal of Geophysical Research: Space Physics*, *13*, 197–201. <https://doi.org/10.1002/2015SW001173>
- Wallace, S., Arge, C. N., Patytichis, M., Hock-Mysliwiec, R. A., & Henney, C. J. (2019). Estimating total open heliospheric magnetic flux. *Solar Physics*, *294*, 19. <https://doi.org/10.1007/s11207-019-1402-1>
- Walsh, B. M., Bhakyaipabul, T., & Zou, Y. (2019). Quantifying the uncertainty of using solar wind measurements for geospace inputs. *Journal of Geophysical Research: Space Physics*, *124*, 3291–3302. <https://doi.org/10.1029/2019JA026507>
- Wang, C.-P., Thorne, R., Liu, T. Z., Hartinger, M. D., Nagai, T., Angelopoulos, V., et al. (2017). A multispacecraft event study of Pc5 ultralow-frequency waves in the magnetosphere and their external drivers. *Journal of Geophysical Research: Space Physics*, *122*, 5132–5147. <https://doi.org/10.1002/2016JA023610>
- Wang, Y.-M., & Sheeley, N. R. Jr. (1990). Solar wind speed and coronal flux-tube expansion. *The Astrophysical Journal*, *355*, 726. <https://doi.org/10.1086/168805>
- Wang, Y. M., Sheeley, N. R., Walters, J. H., Brueckner, G. E., Howard, R. A., Michels, D. J., et al. (1998). *The Astrophysical Journal*, *498*, L165. <https://doi.org/10.1086/311321>
- Webb, G. M., Zank, G. P., Kaghshvili, E. K., & le Roux, J. A. (2006). Compound and perpendicular diffusion of cosmic rays and random walk of the field lines. I. Parallel particle transport models. *The Astrophysical Journal*, *651*, 211. <https://doi.org/10.1086/507415>
- Weberg, M., Zurbuchen, T., & Lepri, S. (2012). ACE/SWICS observations of heavy ion dropouts within the solar wind. *The Astrophysical Journal*, *760*, 1. <https://doi.org/10.1088/0004-637x/760/1/30>
- Weimer, D. R., & King, J. H. (2008). Improved calculations of IMF phase-front angles and propagation time delays. *Journal of Geophysical Research*, *113*, A01105. <https://doi.org/10.1029/2007JA012452>
- Welling, D. T., Andre, M., Dandouras, I., Delcourt, D., Fazakerley, A., Fontaine, D., et al. (2015). The Earth: Plasma sources, losses, and transport processes. *Space Science Reviews*, *192*, 145. <https://doi.org/10.1007/s11214-015-0187-2>
- Wicks, R. T., Horbury, T. S., Chen, C. H. K., & Schekochihin, A. A. (2010). Power and spectral index anisotropy of the entire inertial range of turbulence in the fast solar wind. *Monthly Notices of the Royal Astronomical Society*, *407*, L31. <https://doi.org/10.1111/j.1745-3933.2010.00898.x>
- Winningham, J. D., & Gurgiolo, C. (1982). DE-2 photoelectron measurements consistent with a large scale parallel electric field over the polar cap. *Geophysical Research Letters*, *9*, 977. <https://doi.org/10.1029/GL009i009p00977>
- Xu, F., & Borovsky, J. E. (2015). A new 4-plasma categorization scheme for the solar wind. *Journal of Geophysical Research*, *120*, 70–100. <https://doi.org/10.1002/2014JA020412>
- Yau, A. W., Abe, T., & Peterson, W. K. (2007). The polar wind: Recent observations. *Journal of Atmospheric and Solar-Terrestrial Physics*, *69*, 1936. <https://doi.org/10.1016/j.jastp.2007.08.010>
- Young, P. R. (2015). Dark jets in solar coronal holes. *The Astrophysical Journal*, *801*(2), 124. <https://doi.org/10.1088/0004-637x/801/2/124>
- Zank, G. P. (2015). Faltering steps into the galaxy: The boundary regions of the heliosphere. *Annual Reviews of Astronomy and Astrophysics*, *53*, 449. <https://doi.org/10.1146/annurev-astro-082214-122254>
- Zastenker, G. N., Dalin, P. A., Petrukovich, A. A., Nozdrachev, M. N., Romanov, S. A., Paularena, K. I., et al. (2000). Solar wind structure dynamics by multipoint observations. *Physics and Chemistry of the Earth—Part C*, *25*, 137. [https://doi.org/10.1016/s1464-1917\(99\)00055-0](https://doi.org/10.1016/s1464-1917(99)00055-0)
- Zimbardo, G. (2005). Anomalous particle diffusion and Levy random walk of magnetic field lines in three-dimensional solar wind turbulence. *Plasma Physics and Controlled Fusion*, *47*, B755. <https://doi.org/10.1088/0741-3335/47/12b/s57>

- Zimbardo, G., Perri, S., Pommois, P., & Veltri, P. (2012). Anomalous particle transport in the heliosphere. *Advances in Space Research*, 49, 1633. <https://doi.org/10.1016/j.asr.2011.10.022>
- Zurbuchen, T. H., Hefli, S., Fisk, L. A., Gloeckler, G., & Von Steiger, R. (1999). The transition between fast and slow solar wind from composition data. *Space Science Reviews*, 87, 353. <https://doi.org/10.1023/a:1005126718714>