

Origins of the Ambient Solar Wind: Implications for Space Weather

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Received: 2 June 2017 / Accepted: 30 August 2017 / Published online: 2 October 2017
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Abstract The Sun’s outer atmosphere is heated to temperatures of millions of degrees, and solar plasma flows out into interplanetary space at supersonic speeds. This paper reviews our current understanding of these interrelated problems: coronal heating and the acceleration of the ambient solar wind. We also discuss where the community stands in its ability to forecast how variations in the solar wind (i.e., fast and slow wind streams) impact the Earth. Although the last few decades have seen significant progress in observations and modeling, we still do not have a complete understanding of the relevant physical processes, nor do we have a quantitatively precise census of which coronal structures contribute to specific types of solar wind. Fast streams are known to be connected to the central regions of large coronal holes. Slow streams, however, appear to come from a wide range of sources, including streamers, pseudostreamers, coronal loops, active regions, and coronal hole boundaries. Complicating our understanding even more is the fact that processes such as turbulence, stream-stream interactions, and Coulomb collisions can make it difficult to unambiguously map a parcel measured at 1 AU back down to its coronal source. We also review recent progress—in theoretical modeling, observational data analysis, and forecasting techniques that sit at the interface between data and theory—that gives us hope that the above problems are indeed solvable.

Keywords Coronal holes · Coronal streamers · Heliosphere · Solar corona · Solar wind

The Scientific Foundation of Space Weather
Edited by Rudolf von Steiger, Daniel Baker, André Balogh, Tamás Gombosi, Hannu Koskinen
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1 Introduction

This paper surveys the current state of understanding about how the solar wind is accelerated along magnetic field lines rooted in the Sun's hot corona. It is based on talks and discussions that took place at a June 2016 workshop devoted to *The Scientific Foundations of Space Weather* at the International Space Science Institute (ISSI) in Bern, Switzerland. A primary goal of this interdisciplinary workshop was to review the causal chain of events that link the Sun and the terrestrial environment, and thus to assess where we stand in our basic physical understanding of this complex system. This paper focuses on the origins of the “ambient” solar wind, by which we mean to exclude eruptive events like coronal mass ejections (CMEs), but to include a wide range of stochastic processes that produce global-scale structure in the heliosphere. This global-scale structure (consisting mainly of fast and slow streams that interact with one another as they expand out from the Sun) evolves on timescales from minutes to years, so it is clear that the term “ambient” is not equivalent to “time-steady.”

The ambient solar wind is known to be a driver of geoeffective space weather activity. There are three main ways in which this driving occurs:

1. CMEs, the most dramatic source of space weather, accelerate through a background flow consisting of fast and slow wind streams. CME flux ropes can be accelerated or decelerated by drag-like interactions with the surrounding solar wind (Gopalswamy et al. 2000; Vršnak et al. 2010; Temmer et al. 2011). Large-scale spatial structures in the wind can also distort CMEs, deflect their trajectories, and affect their overall strengths (Riley et al. 1997; Odstrčil and Pizzo 1999; Wang et al. 2004; Isavnin et al. 2014; Zhou and Feng 2017). Thus, being able to predict the properties of the ambient solar wind appears to be a necessary component of predicting CME geoeffectiveness. In this issue, related reviews of the space weather impacts of CMEs and other transient forcing events include Manchester et al. (2017), Green et al. (2017), Eastwood et al. (2017), McPherron et al. (2017), Lester et al. (2017), and Sojka et al. (2017).
2. Sustained high-speed wind streams that intersect the Earth's magnetosphere have been shown to drive geomagnetic activity (see, e.g., Tsurutani et al. 2006; Baker et al. 2017; Ganushkina and Jaynes 2017). The primary impact of a fast stream appears to be the acceleration of additional energetic electrons in the radiation belts (e.g., Iles et al. 2002; Reeves et al. 2003; Jaynes et al. 2015; Kilpua et al. 2015). High-speed streams usually also contain stronger Alfvén waves than the slow wind, and these have been shown (McGregor et al. 2014) to enhance magnetospheric ultralow frequency (ULF) fluctuations associated with storms and radiation belt dynamics.
3. The apparently bimodal structure of the solar wind—i.e., its tendency to produce fast and slow streams—leads to the production of compressions, rarefactions, and shocks when the streams interact with one another. The passage of such corotating interaction regions (CIRs) past the Earth's magnetosphere is known to contribute to geomagnetic storm activity (in this issue, see Kilpua et al. 2017; Klein and Dalla 2017). Although only a small fraction of the most intense storms appear to come from CIRs alone (Gosling et al. 1991; Huttunen et al. 2002; Zhang et al. 2007), they are responsible for the majority of moderate-strength storms, especially at solar minimum (Verbanac et al. 2011; Echer et al. 2013). CIR events, in combination with high-speed wind streams, also provide extra heat to the Earth's ionosphere/thermosphere layers (Sojka et al. 2009), which can enhance spacecraft drag and alter its infrared energy budget.

Despite the apparently modest space-weather impacts from fast streams and CIRs (compared to CMEs) they have the potential for increased significance because they can persist

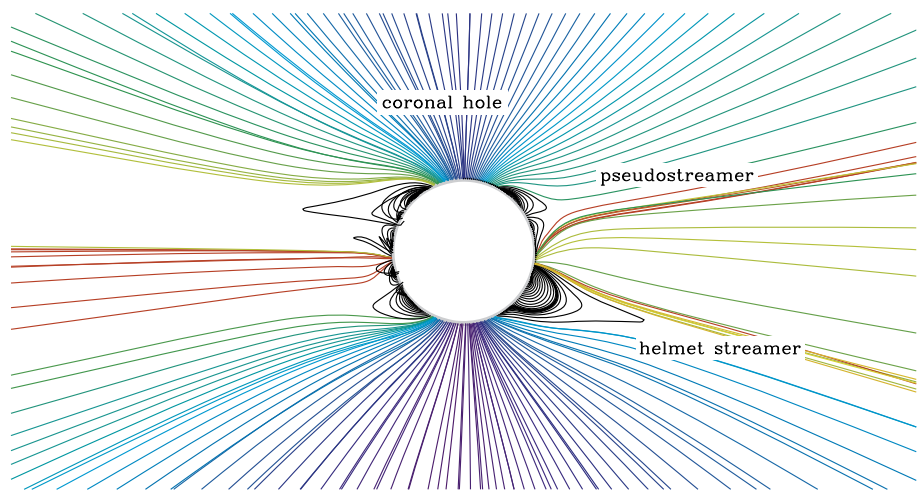


Fig. 1 Closed (*black*) and open (*multi-color*) magnetic field lines traced from a time-steady solution of the polytropic MHD conservation equations, computed by the Magnetohydrodynamics Around a Sphere (MAS) code (Linker et al. 1999). Photospheric boundary conditions were from Carrington Rotation 2058 (June–July 2007). Colors of open field lines correspond to the Wang and Sheeley (1990) expansion factor: $f \leq 4$ (*violet*), $f \sim 6$ (*blue*), $f \sim 10$ (*green*), $f \sim 15$ (*gold*), $f \geq 40$ (*red*). Labeled structures are discussed in more detail in Sect. 2.2

over long times and are likely to repeat over multiple solar rotations (see, e.g., Sibeck and Richardson 1997; Borovsky and Denton 2006).

An ongoing topic of debate is whether the solar wind is truly bimodal (i.e., cleanly separable into two distinct source regions). In the half-dozen years around each minimum in the Sun’s 11-year activity cycle, there are large unipolar coronal holes at the north and south poles, with mostly closed fields at low latitudes. Figure 1 shows extrapolated field lines from a rotation-averaged magnetohydrodynamic (MHD) model constructed for a representative solar-minimum time period. We have high confidence that the fast solar wind is rooted in the central regions of coronal holes. The slow solar wind appears to be associated with “everywhere else” on the Sun that connects out to the distant heliosphere. Some slow-wind source regions may start as closed magnetic loops and undergo jet-like magnetic reconnection. Other regions may be topologically similar to fast-wind source regions, but with lower levels of momentum and energy deposition. This paper will discuss several unanswered questions about the solar wind’s bimodality, magnetic topology, and radial evolution.

The remainder of this paper is organized as follows. Section 2 provides a review of solar wind observations, both remote and *in situ*, as well as a discussion of how coronal structures appear to be connected to their counterparts in the heliosphere. In Sect. 3 we summarize the current state of theoretical solar wind modeling. Section 4 gazes into the crystal ball to speculate about what future improvements are needed, and Sect. 5 concludes with some broader context about the impact of this work on other fields. Because the solar wind has been studied by hundreds of researchers for more than a half-century, this paper cannot be truly comprehensive in its review of the literature. Interested readers are urged to fill in the gaps by surveying other reviews, such as those by Dessler (1967), Holzer and Axford (1970), Hundhausen (1972), Leer et al. (1982), Barnes (1992), Parker (1997), Cranmer (2002, 2009), Marsch (2006), Velli (2010), Abbo et al. (2016), and Chen (2016).

2 Observations of Solar Wind Origins

In order to identify the physical processes responsible for producing the solar wind, we must have accurate empirical measurements of the plasma and field properties. Section 2.1 summarizes *in situ* interplanetary measurements, and Sect. 2.2 describes remote-sensing observations of the coronal origin regions near the Sun. Section 2.3 discusses how periodicities and other correlations between data sets have been used to improve our understanding of “what connects to what” between the corona and heliosphere.

2.1 Interplanetary Measurements

Evidence for the existence of an outflow of “corpuscular radiation” (i.e., charged particles) from the Sun accumulated gradually throughout the early 20th century (see historical reviews by Dessler 1967; Hundhausen 1972). Early *in situ* detections of solar wind particles were made between 1959 and 1961 by Russian and American spacecraft that left Earth’s magnetosphere. The continuous, supersonic, and possibly bimodal nature of the solar wind was confirmed by *Mariner 2* on its journey to Venus (Neugebauer and Snyder 1962). Those early data indicated a range of outflow speeds (roughly from 250 to 800 km s⁻¹) that seem to act as an organizing quantity. In other words, many of the other plasma and field quantities measured at 1 AU appear to be correlated with whether one is in a fast or slow stream.

Table 1 summarizes some representative properties of the fast and slow wind regimes as revealed over the past half-century of exploration (see also Schwenn 2006). There is still substantial debate about whether the solar wind plasma can be classified into more than two distinct types—based on, e.g., source regions, acceleration mechanisms, or local plasma physics—and whether or not the wind speed is in fact a reliable indicator of which type is being detected (see, e.g., Wang et al. 2009; Zurbuchen et al. 2012; Stakhiv et al. 2015; Neugebauer et al. 2016). Difficulties arise because much of the solar wind at 1 AU has undergone some kind of processing or mixing (see Sect. 2.3), such that the global magnetic topology and coronal connections are not easy to determine.

Despite the above difficulties, there are many regularities in the *in situ* data. The raw probability distribution of wind speeds u in the ecliptic is usually single-peaked around

Table 1 Properties of slow and fast solar wind streams

Quantity	Slow wind	Fast wind
Radial flow speed	250–450 km s ⁻¹	450–800 km s ⁻¹
Proton density (1 AU)	5–20 cm ⁻³	2–4 cm ⁻³
Proton temperature (1 AU)	0.03–0.1 MK	0.1–0.3 MK
Electron temperature (1 AU)	0.1–0.15 MK	~0.1 MK
Freezing-in temperature (corona)	1.4–1.7 MK	1.0–1.3 MK
Helium abundance	0.5–4%	3–5%
Heavy ion abundances	low-FIP enhanced	~photospheric
Ion/proton temperature ratio	< m_{ion}/m_p	> m_{ion}/m_p
Coulomb collisional age (1 AU)	0.1–10	0.001–0.1
Coronal WSA expansion factor	15–100	3–10
Coronal sources (Sects. 2.2–2.3)	streamers, quiet loops, active regions, coronal hole boundaries, separatrices	coronal hole cores

400 km s⁻¹, with a relatively sharp cutoff below about 250 km s⁻¹ and a skewed tail toward higher speeds (e.g., Gosling et al. 1971; McGregor et al. 2011b). An interesting exception was in 2008 during the “peculiar solar minimum” when the presence of long-lived, low-latitude coronal holes led to a truly bimodal distribution of solar wind speed at 1 AU (de Toma 2011). Proton and electron densities n are negatively correlated with speed, but the mass flux (i.e., the product nu) has a slight residual trend toward higher values in the slow wind. Le Chat et al. (2012) found that the kinetic energy flux (proportional to nu^3) is very nearly constant as a function of wind speed, latitude, and solar cycle. The radial magnetic flux also tends to be reasonably constant throughout the low- and high-latitude heliosphere (Smith and Balogh 1995), but its overall value does change as a function of global solar activity (Svalgaard and Cliver 2007). Any theoretical model of the solar wind must reproduce these trends and quasi-invariants.

Heliospheric measurements in the ecliptic plane tend to show a preponderance of slow solar wind, with high-speed streams being occasional interlopers. This led to early widespread identification of the slow wind as the “ambient” background state (e.g., Hundhausen 1972). However, there were hints—going back to at least Bame et al. (1977)—that the fast wind was a much better candidate for being the most time-steady and quiescent type of solar wind. The *Ulysses* probe confirmed this picture when it left the ecliptic plane and showed that the fast wind is ubiquitous over large polar coronal holes, which (1) persist over more than half of each solar cycle, and (2) expand out to fill the majority of the heliospheric volume (Goldstein et al. 1996; Marsden 2001; McComas et al. 2008).

In the 1990s, *Ulysses* and *ACE* also began to show that ion composition measurements (i.e., both elemental abundances and ionization states) can be used to reliably distinguish slow and fast wind streams from one another. These composition signatures are established close to the Sun and are subsequently “frozen in” along most of the extent of each wind stream. On the other hand, the wind speed itself continues to evolve dynamically between the Sun and 1 AU as streams interact with one another. Thus, ion composition is suspected to be more reliable as a wind-stream identification tag than the flow speed (see, e.g., Neugebauer et al. 2016; Fu et al. 2017). The ratio of O⁺⁷ to O⁺⁶ charge-state number densities tends to be the most widely reported composition signature, mainly because the large oxygen abundance allows for good measurement statistics. However, Landi et al. (2012a) suggested that the relative fractions of carbon ions C⁺⁴, C⁺⁵, and C⁺⁶ may be more precise probes of the plasma conditions in the low corona ($r \approx 1.2 R_{\odot}$) where the freezing-in occurs.

Figure 2 shows data from the *Ulysses* SWICS (Solar Wind Ion Composition Spectrometer) instrument final archive to illustrate how the traditional O⁺⁷/O⁺⁶ charge-state ratio varies as a function of solar wind speed (Gloeckler et al. 1992; von Steiger et al. 2000). The polar plots show (a) wind speed in km s⁻¹, and (b) a scaled ratio with magnitude $3.4 + \log_{10}(\text{O}^{+7}/\text{O}^{+6})$, as a function of latitude during an orbit near solar minimum. In panels (c)–(d), the equivalent O⁺⁷/O⁺⁶ freezing-in temperature (i.e., the electron temperature corresponding to a given charge-state ratio in coronal equilibrium) was computed from ionization balance curves provided in version 7.1 of CHIANTI (Landi et al. 2012b). Note that panel (c) sometimes indicates abrupt changes in the ionization state at intermediate wind speeds, but panel (d) shows that, statistically speaking, the trend is rather gradual.

Additional clues about the physical origins of fast and slow wind streams come from the kinetic properties of the plasma. It has been known since the first decade of interplanetary exploration (e.g., Sturrock and Hartle 1966) that solar wind parcels are not just expanding adiabatically, but are continuing to undergo changes in their energy budgets at 1 AU and beyond. The relatively slow radial decline in particle temperature $T(r)$ indicates some combination of sustained thermal energy input (a continuation of coronal heating) and strong

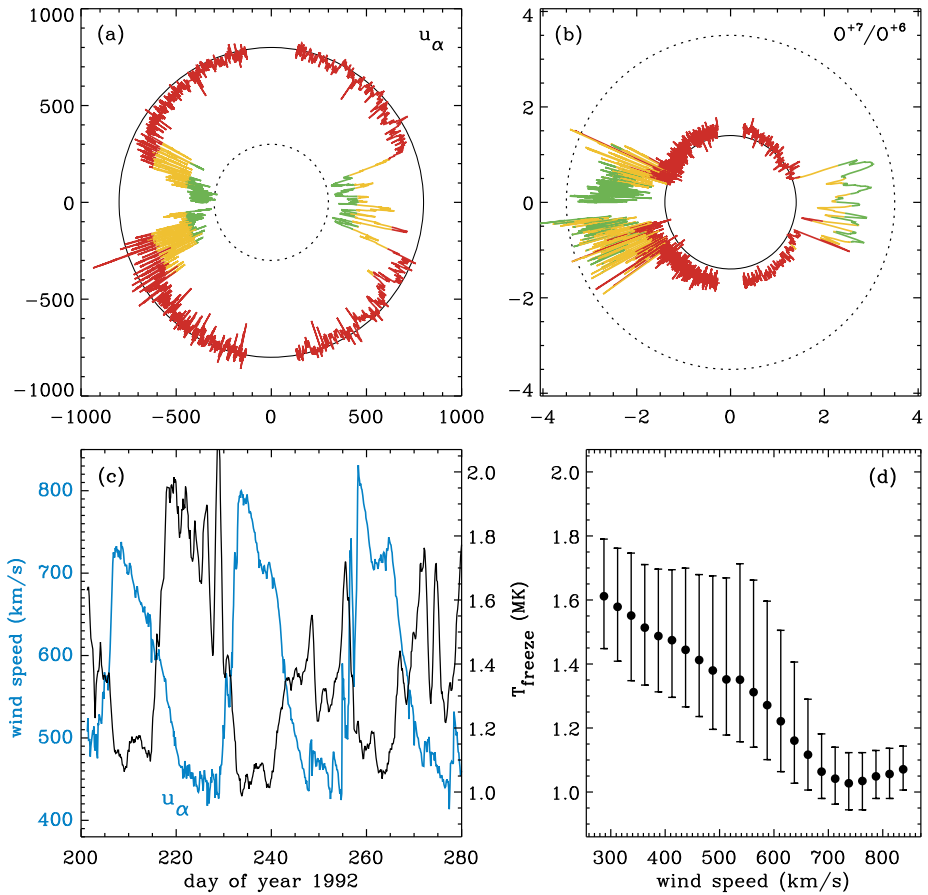


Fig. 2 Polar plots of (a) alpha particle wind speeds, and (b) ratios of O^{+7} to O^{+6} ion number densities from *Ulysses*/SWICS during its first high-latitude orbit in 1992–1997. Parcels are color-coded by wind speed (green: $u < 450$ km s⁻¹, red: $u > 650$ km s⁻¹, yellow: intermediate) with the same labels applied to data points in panel (b). The speed/ion-ratio anticorrelation is also shown in (c) as a function of time for several solar rotations in 1992 (i.e., the same period analyzed by Geiss et al. 1995). Panel (d) shows the same anticorrelation, collected into 25 km s⁻¹ bins over the entire *Ulysses* mission, with each bin’s median (filled circles) and $\pm 1\sigma$ error bars. In (c) and (d) the ion ratio was converted to freezing-in temperature (see text)

heat conduction due to the presence of skewness in the velocity distributions. The latter is certainly true for electrons (e.g., Bale et al. 2013), and it has been recently argued to be an important contributor to proton thermodynamics as well (Scudder 2015).

Coulomb collisions in the solar wind appear to be infrequent enough to allow the protons and electrons to evolve away from a common thermal state. Figure 3 illustrates this by showing the dominant trends of proton temperature T_p and electron temperature T_e versus wind speed at 1 AU. The protons appear to be strongly correlated with wind speed (see also Elliott et al. 2012) while the electrons are much less sensitive to local conditions. In the slow wind, it seems possible that stronger electron conduction keeps the coronal T_e high for a larger range of distance, while weaker proton conduction (and a lack of equilibrating collisions) allows the protons to cool off more rapidly (see, e.g., Freeman 1988). In the fast wind, the data show $T_p > T_e$, which suggests sustained heating for the protons. There have

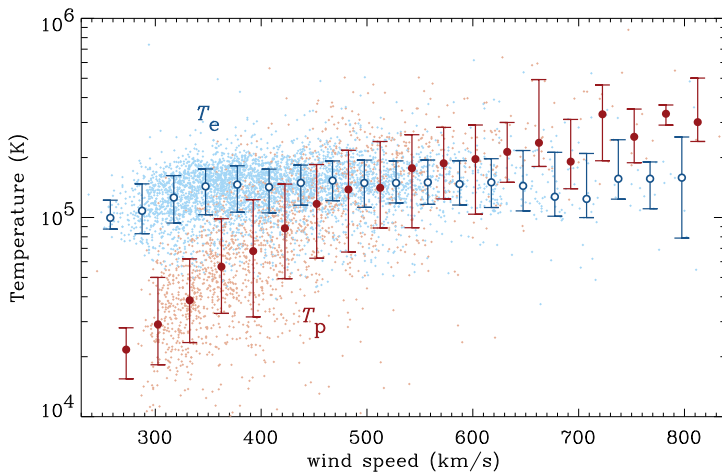


Fig. 3 Hourly averaged proton (red) and electron (blue) temperatures measured at 1 AU by *ISEE-3* (Newbury et al. 1998) between January 1980 and October 1982. Small points indicate individual measurements, and large symbols with error bars show median and $\pm 1\sigma$ values within 30 km s^{-1} bins of solar wind speed

been several empirical estimates of heat input rates that indicate the protons receive more “extended coronal heating” than do the electrons (Stawarz et al. 2009; Cranmer et al. 2009; Štverák et al. 2015).

Protons in the inner heliosphere also tend to exhibit thermal anisotropies, with unequal temperatures measured perpendicular and parallel to the background magnetic field (Marsch 2006). In the fast solar wind, the proton magnetic moment $\mu \propto T_{\perp}/B$ has been seen to increase with increasing heliocentric distance (Marsch et al. 1983). This suggests the existence of kinetic wave-particle interactions that transfer thermal energy to only *some* of the proton degrees of freedom. When the proton data at 1 AU are plotted in a two-dimensional plane of the anisotropy ratio ($\mathcal{R} = T_{\perp}/T_{\parallel}$) versus the parallel plasma beta parameter (β_{\parallel} , parallel gas pressure divided by magnetic pressure), the resulting distribution of data points (see Hellinger et al. 2006; Maruca et al. 2012) provides additional constraints on the nature of wave-particle interactions that energize the protons. Some kinds of simple linear theory—i.e., the damping of a cascading spectrum of ion cyclotron waves (Cranmer 2014b)—predict reasonably correct shapes for the populated region in $(\mathcal{R}, \beta_{\parallel})$ parameter space. However, more physically realistic numerical simulations (e.g., Servidio et al. 2015; Hellinger et al. 2017) may be needed to reproduce all of the relevant details of this region.

Ions heavier than hydrogen are also useful probes of kinetic physics in the collisionless solar wind. Both alpha particles and other minor ion species are heated and accelerated preferentially in comparison to the protons. At 1 AU, these differences appear to be organized by the Coulomb collisional “age” of the solar wind parcel; i.e., parcels that experience the fewest number of collisions between the Sun and 1 AU show the strongest departures from thermal equilibrium (e.g., Kasper et al. 2008). Preferential ion heating appears to be necessary condition for preferential ion acceleration. Geiss et al. (1970) investigated models without extra heating and found that ions tend to flow out more slowly than the protons; in fact, in those models Coulomb friction may help bring ions up to the proton outflow speed, but no faster. Ryan and Axford (1975) and others realized that heating the ions more strongly than the protons—at least proportionally to their masses (to provide comparable

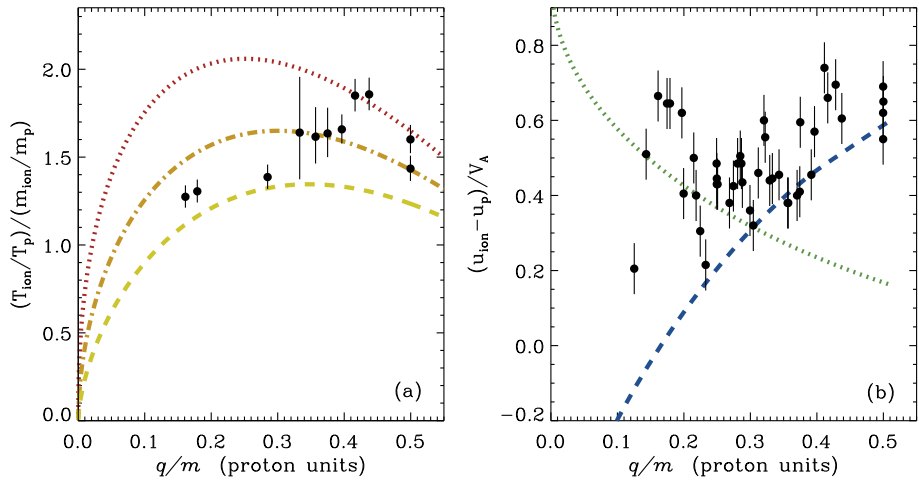


Fig. 4 Heavy-ion preferential heating (a) and acceleration (b) with respect to solar wind protons at 1 AU. Both panels show relative ion-proton quantities versus the charge/mass ratio (q/m) in units of proton charge/mass. (a) Points show the ratio of ion to proton squared thermal speeds ($v_{\text{th}}^2 \propto T/m$) from ACE/SWICS (Tracy et al. 2016). (b) Points show the difference between ion and proton bulk flow speeds in units of the local Alfvén speed, as measured by SWICS and SWEPM on ACE (Berger et al. 2011). For discussion of the model curves, see text

pressure gradients) or even more than that (to accelerate them even faster)—was a natural explanation for the data.

Figure 4 shows recent measurements of preferential ion heating (Tracy et al. 2016) and preferential ion acceleration (Berger et al. 2011) measured at 1 AU for collisionally young plasma that tends to be dominant in the fast wind. The particles measured by ACE include multiple ionization stages of He, C, N, O, Ne, Mg, Si, S, Ca, and Fe. Each ion temperature is shown as a squared thermal speed (i.e., T_i/m_i) in units of a similar quantity corresponding to the protons. The ion bulk flow speeds are shown as differences ($u_i - u_p > 0$) in units of the local Alfvén speed V_A .

There is still no consensus about the identity of the physical processes responsible for the observed ion properties. The model curves shown in Fig. 4 are meant to illustrate the challenges inherent in explaining the data with a single kinetic theory. Curves in Fig. 4a are predictions from ion cyclotron resonance excited by MHD turbulence (see equation 26 of Cranmer 2002). These curves correspond to a turbulent power-law spectrum $P \propto k_{\parallel}^{-\eta}$ with $\eta = 1.57$ (red dotted curve), $\eta = 1.47$ (orange dot-dashed curve), and $\eta = 1.37$ (yellow dashed curve), where k_{\parallel} is the wavenumber of cyclotron resonant fluctuations in the direction parallel to the background magnetic field. The model curves in Fig. 4b are upper and lower limits on the differential ion flow speeds compatible with ion cyclotron resonance. The cyclotron waves were assumed to obey a cold-plasma dispersion relation (e.g., Hollweg and Isenberg 2002) with alpha particles flowing $0.55V_A$ faster than protons, as measured by Berger et al. (2011). The blue dashed curve shows minimum resonant ion speeds for $k_{\parallel} < 0$, and the green dotted curve shows maximum resonant ion speeds for $k_{\parallel} > 0$ (see also McKenzie and Marsch 1982). It is important to note that the relevance of these ion-cyclotron curves to the data has not yet been demonstrated conclusively. However, it may be noteworthy that the rightmost “wedge” region of the plot (below the blue curve and above the green curve, for $q/m > 0.3$) is firmly excluded by both curves and is also more or less empty of data points.

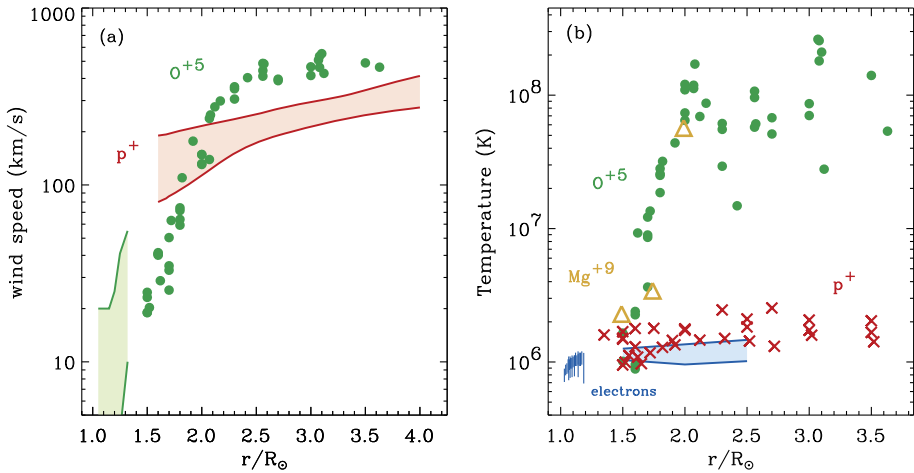


Fig. 5 Off-limb measurements of (a) outflow speeds and (b) temperatures above polar coronal holes. *Red*: proton flow speeds (Cranmer et al. 1999) and temperatures assembled from various sources (e.g., Antonucci et al. 2000; Cranmer 2009). *Green*: O^{+5} data points from Cranmer et al. (2008), and near-Sun bounded region in outflow speed from Teriaca et al. (2003). *Gold*: Mg^{+9} ion temperatures (Kohl et al. 1999). *Blue*: electron temperatures at $r < 1.3 R_{\odot}$ (Landi 2008) and $r > 1.5 R_{\odot}$ (Cranmer 2017, in prep). See text for details, and original sources for error bars

2.2 Coronal Measurements

A wide variety of remote observation techniques—direct imaging, spectroscopy, radio sounding, and coronagraphic occultation—have been used to put useful constraints on solar wind origins (Bird and Edenhofer 1990; Kohl et al. 2006; Habbal et al. 2013; Judge et al. 2013; Slemzin et al. 2014). These techniques have been implemented on a number of different platforms—spacecraft, rockets, ground-based observatories, and movable “eclipse-chasing” instruments—each with its own unique advantages and challenges. The combined analysis of data from these different platforms (also including *in situ* particle and field detection) has been a crucial ingredient in the advances made so far in our knowledge about the complex Sun-heliosphere system.

The solar disk contains small-scale features (e.g., bright points, faculae, ephemeral regions) and medium-scale structures (e.g., active regions, filaments) that are associated mainly with closed magnetic loops. Because these features do not appear to be connected continuously to the open heliosphere, much of the work in studying solar wind origins has focused on *large-scale* features such as coronal holes and streamers. The remainder of this subsection describes these features. However, Sect. 3.2 discusses a range of proposed coronal heating processes that includes the dynamical evolution of (temporarily) closed magnetic regions.

Coronal holes are low-density patches of nearly unipolar magnetic flux on the surface that appear to expand out superradially into the heliosphere. The central regions of large coronal holes are known sources of fast solar wind (Wilcox 1968; Krieger et al. 1973; Noci 1973). Because they are associated with tenuous, collisionless plasmas and are long-lived time-steady structures, coronal holes have been ideal hunting grounds for similar kinetic effects as seen in fast wind streams at 1 AU. Figure 5 summarizes the evidence found by the Ultraviolet Coronagraph Spectrometer (UVCS) instrument on the *Solar and Heliospheric*

Observatory (SOHO) for preferential ion heating and acceleration above coronal holes (see, e.g., Kohl et al. 2006). Most of this evidence comes from the comparison of proton properties (measured by proxy using the neutral hydrogen H I Ly α line) and O⁺⁵ ions (similarly probed by the O VI 103.2–103.7 nm resonance doublet).

The flow speeds in Fig. 5a were derived from the so-called “Doppler dimming” technique, which takes advantage of the fact that fewer solar-disk photons are scattered into our line of sight when the atoms (i.e., the coronal scattering centers) are Doppler shifted away from the narrow spectral window of the available photons. The ion temperatures in Fig. 5b were derived from spectral line widths and associated modeling, and are mainly probes of T_{\perp} . These temperatures were corrected to remove nonthermal line widths associated with MHD waves and turbulence. This is a model-dependent correction, but it is based on additional observational data (see below). The electron temperatures at $r > 1.5 R_{\odot}$ are preliminary results from an empirical generalization of older hydrostatic scale-height techniques (see, e.g., Lemaire and Stegen 2016) using the UVCS visible-light and Ly α data as constraints. These estimates of T_e generally agree with existing visible-light Thomson scattering results (Reginald et al. 2011).

The remote-sensing data provide evidence for $T_{\text{ion}} \gg T_p > T_e$ in the source regions of fast solar wind, which is reminiscent of the heliospheric data at distances greater than 0.3 AU. The initial reports of heavy ions with temperatures of order 10^8 K (i.e., even hotter than in the solar core), together with $T_{\perp} > T_{\parallel}$ and ion flow speeds roughly double those of the protons at $r \approx 3 R_{\odot}$, were surprising. There was some skepticism about the uniqueness of these interpretations of the data (e.g., Raouafi and Solanki 2004). However, more rigorous data analysis (Cranmer et al. 2008) has generally upheld those initial results, albeit with some tempering (i.e., the O⁺⁵ anisotropy ratio T_{\perp}/T_{\parallel} was found to be more like 3–10, instead of the earlier claim of ~ 100).

In addition to coronal holes, the large-scale corona contains a variety of other magnetic features that appear to be connected to the slow solar wind (see Sect. 2.3). When observing above the solar limb, the most striking of these are the bright streamers illustrated in Fig. 1. The magnetic field in streamers appears to be closed at low heights, with surrounding open field lines converging above a cusp-like point at the top. The helmet-like appearance of many streamers has been compared to the 19th century Prussian *pickelhaube*, and it is clear that the solar wind acts to open up the magnetic field above these structures. Streamers are generally assumed to be sources of low-speed solar wind, but the precise topological connections (Sect. 2.3) and mass-release mechanisms (Sect. 3.2) are still being debated.

In recent years, distinctions have been made between: (1) helmet streamers that expand up from a bipolar loop, and thus have a large current sheet between the two opposite-polarity legs, and (2) “pseudostreamers” that are connected to an even number of bipoles, and thus have legs with the same polarity (e.g., Wang et al. 2007; Riley and Luhmann 2012; Rachmeler et al. 2014). There are also differences in the plasma properties between large quiescent equatorial streamers and the brighter, more compact streamers associated with active regions (Liewer et al. 2001; Ko et al. 2002). The relatively high densities seen in all coronal streamers (Gibson et al. 1999; Strachan et al. 2002) appear to indicate rapid Coulomb collisions that generally lead to temperature equilibration ($T_p \approx T_e$). However, the largest streamers do start to exhibit collisionless kinetic effects, such as high O⁺⁵ temperatures similar to what is seen in coronal holes, above their cusps (Frazin et al. 2003).

Both coronal holes and streamers are intrinsically time-variable. In addition to changes in connectivity that occur as the Sun’s magnetic field evolves over multiple solar rotations, the corona is also observed to be full of large-amplitude oscillations (e.g., waves, shocks, and transient eddies). A comprehensive review of oscillation measurement techniques is

beyond the scope of this paper (see, e.g., Cranmer 2002, 2004; Nakariakov 2006), but there are several aspects that are relevant to solar wind origins:

1. Sensitive measurements of the off-limb coronal intensity allow *low-frequency density fluctuations* to be tracked in space and time. The tips of most helmet streamers appear to be unstable to the production of blob-like plasmoids that flow out with the slow solar wind (Sheeley et al. 1997, 2009; Wang et al. 2000; Plotnikov et al. 2016). Similar features continue to be detected as 1–2 hour density modulations at larger distances (Viall and Vourlidis 2015), and they appear to be most intense in the heliospheric current sheet (HCS). Above coronal holes, there are appear to be weak, but ubiquitous field-aligned compressive waves with periods of order 10–20 minutes (Ofman et al. 1999; Threlfall et al. 2013; Liu et al. 2015).
2. Radio telescopes probe plasma properties near the Sun by measuring how signals are distorted by changes in the refractive index as they pass through the corona (e.g., Bastian 2001). Interplanetary scintillation (IPS) measurements are sensitive to *high-frequency density fluctuations* (i.e., millisecond timescales), and additional information can be extracted about the coronal magnetic field and the solar wind speed. Global IPS maps of solar wind acceleration show the presence of fast and slow streams (Kojima and Kakimura 1990; Grall et al. 1996; Imamura et al. 2014), but some information is lost by the integration over long lines of sight. Efimov et al. (2010) detected spatial anisotropy in radio-detected turbulent eddies at heliocentric distances smaller than $\sim 25 R_{\odot}$, and isotropy above $\sim 30 R_{\odot}$. This is a similar qualitative transition as the one seen in the shapes of larger visible-light structures resolved by heliospheric imagers. However, for the latter, DeForest et al. (2016) found that the transition to isotropy does not occur until at least $60\text{--}80 R_{\odot}$.
3. A combination of motion-tracking and spectroscopic Doppler-shift techniques allows *transverse Alfvénic fluctuations* to be detected in the solar wind. It is suspected (see Sect. 3.2) that Alfvén waves and turbulence are major players in heating the extended corona and solar wind. Figure 6 shows a summary of inferred velocity amplitudes over polar coronal holes. The associated model curves show predictions for undamped and damped Alfvénic turbulence from Cranmer and van Ballegooijen (2005). Measured amplitudes derived from nonthermal line widths are shown from SUMER/SOHO (Banerjee et al. 1998, orange crosses), near-limb EIS/Hinode data (Landi and Cranmer 2009, red diamonds), and UVCS/SOHO (Esser et al. 1999, green region). Taken together, those data appeared to agree well with the predictions for Alfvén waves that dissipate and heat the corona. More recently, however, the EIS instrument has been used to probe larger heights above the poles; magenta points show data from Hahn and Savin (2013) (see also Hahn et al. 2012; Bemporad and Abbo 2012; Gupta 2017). There is now clearly some “tension” with the model curves and with the inferred UVCS result from Esser et al. (1999).

Figure 6 makes it clear that our knowledge of the global evolution of waves and turbulence in the solar wind is still lacking. The recent EIS data call into question our understanding of where Alfvén waves are damped and how their energy is converted to heat. There is also some inherent uncertainty in interpreting the properties of off-limb emission lines, especially when observing diffuse areas such as coronal holes. If the line of sight contains N independently fluctuating flux tubes, with $N \gg 1$, then many of the desired diagnostics (e.g., Doppler shifts or plane-of-sky swaying motions) are reduced in amplitude by roughly $1/\sqrt{N}$. Monte Carlo forward models (De Pontieu et al. 2007; McIntosh et al. 2011) have proven to be helpful in estimating the magnitude of this effect, but definitive “inversions”

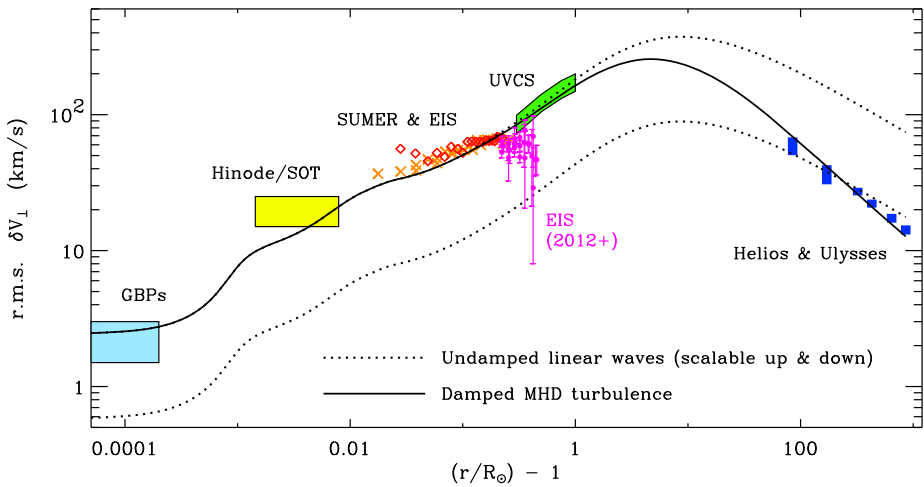


Fig. 6 Height dependence of transverse velocity amplitudes of MHD fluctuations in coronal holes and the fast solar wind. Model curves and the photospheric G-band Bright Point (GBP) data are from Cranmer and van Ballegoijen (2005). Other data, from left to right, are from Type II spicule motions observed by *Hinode*/SOT (De Pontieu et al. 2007), nonthermal line broadening from SUMER, EIS, and UVCS (see text), and direct *in situ* measurement from *Helios* and *Ulysses* (Bavassano et al. 2000)

are not yet possible. In Sect. 4, we discuss future efforts to improve upon the existing measurements.

2.3 Periodicities Linking the Sun and Heliosphere

There is not yet a fully-understood one-to-one mapping between observed features in the corona and *in situ* detected structures in the heliosphere. Multi-point measurements made over multiple solar rotations—sometimes extending to multiple solar cycles—have helped us find correlations between large, long-lived structures on the Sun and in the solar wind. Whether or not these correlations are related to physics-based causations is a separate issue, but good correlations provide good starting points for space weather prediction.

For example, the half-century long OMNI database of plasma and field measurements at 1 AU has been shown to be useful for long-baseline studies of all kinds (e.g., O’Brien and McPherron 2000; King and Papitashvili 2005; Lee et al. 2009). Analogous databases for regions near the Sun have run the gamut from careful hand-drawings based on daily images (Harvey and Recely 2002; McIntosh 2003) to automated “big data” feature-extraction systems (Martens et al. 2012; Bobra et al. 2014). Taking inspiration from worldwide events like the 1957 International Geophysical Year, multiple communities came together in coordinated projects—e.g., three “Whole Sun Months” in 1996, 1998, and 1999 (Galvin and Kohl 1999; Riley et al. 1999; Breen et al. 2000) and a “Whole Heliosphere Interval” in 2008 (Gibson et al. 2009, 2011; Riley et al. 2011; Thompson et al. 2011)—to improve our understanding of Sun-heliosphere connectivity.

Figure 7 illustrates the synergistic power of combining multiple databases. Stacking up a solar cycle’s worth of OMNI wind speeds versus Carrington longitude reveals the presence of high-speed streams that recur over multiple rotations and fade in and out over time (see also Lee et al. 2009). The occurrences of these streams line up quite well with the presence of

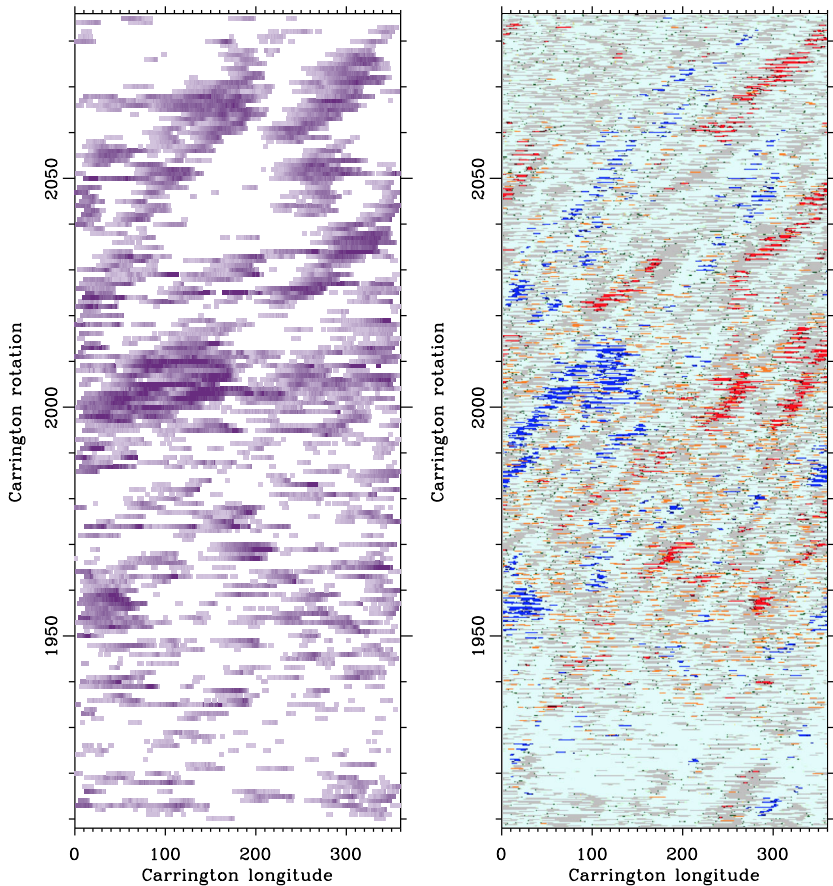


Fig. 7 Carrington rotation stack plots showing (a) in-ecliptic OMNI wind speeds and (b) surface features from the McIntosh archive, both for the duration of solar cycle 23 (June 1996 to July 2009). In panel (a), white denotes $u \leq 450 \text{ km s}^{-1}$ and increasingly darker shades of purple eventually saturate at the darkest color for $u \geq 750 \text{ km s}^{-1}$. Longitudes have been offset by 50.55° , or 3.83 days, to account for propagation from the Sun to 1 AU at a mean speed of 450 km s^{-1} . Panel (b) shows equatorial ($\pm 20^\circ$ from equator) features, with blue [red] showing coronal holes of positive [negative] polarity, cyan [gray] showing quiet regions with predominantly positive [negative] polarity, orange indicating sunspots, and green indicating filaments

large equatorial coronal holes as recorded in the McIntosh synoptic image archive (Gibson et al. 2017b). The long-lived coronal holes (blue/red) seen in panel (b) are rotating at a rate somewhat faster than the 27.275 day Carrington rotation, and thus they have a positive slope in this plot. This correlates well with the slopes seen in the fast wind streams indicated in panel (a).

The correlations shown in Fig. 7 do not stop at the solar wind, but indeed extend to the Earth's space environment and upper atmosphere. Clear connections can be found between high-speed solar wind streams and modulations of the aurora and geomagnetic indices, radiation belts, ionosphere, and thermosphere (Gibson et al. 2009; Solomon et al. 2010; Lei et al. 2011). Long-time series analyses over years and decades show periodicities in all of these quantities that may be associated with periodicities in the fast solar wind, and consequently

the distribution of open magnetic flux at the Sun in the form of coronal holes (Emery et al. 2011; Love et al. 2012).

The connection between large coronal holes and the fast wind is clear, but the remaining connections between other coronal structures and the slow wind are less well understood. An exact census or mass budget of slow-wind source regions has not yet been constructed (see also Poletto 2013; Kilpua et al. 2016; Abbo et al. 2016), but the following contributors may be significant:

1. Steady flows from the *boundaries of coronal holes* are often viewed as the open-field “legs” of helmet streamers (Wang and Sheeley 1990; Strachan et al. 2002). When the axis of the streamer belt is oblique to the line of sight, these structures may be identifiable in coronagraph images merely as diffuse patches of Quiet Sun. In either case, the open field lines in these regions tend to expand more superradially than the central regions of the large coronal holes. Stakhiv et al. (2015) coined the phrase “boundary wind” for this component, which tends to be compositionally similar to the fast wind despite its lower asymptotic speed. The smallest coronal holes, which are known to be correlated with slow wind speeds at 1 AU (Nolte et al. 1976), may also be close cousins of these boundary-layer type flows.
2. A more time-variable component of the slow wind may be the result of *multi-scale magnetic reconnection* in the corona; i.e., the opening up of previously closed magnetic loops. Theoretical arguments for this scenario are discussed below in Sect. 3.2. Evidence for large-scale intermittent mass loss in the HCS (in the form of low-frequency density fluctuations) was summarized above. In addition, smaller jet-like reconnection events have been suggested to feed mass into the solar wind (Moore et al. 2011; Madjarska et al. 2012; Raouafi et al. 2016), especially when they occur near topological boundaries of magnetic connectivity. However, Paraschiv et al. (2015) concluded that the hot jets seen in X-ray images convert most of their magnetic energy into heat and not kinetic energy. Thus, it is unclear whether these reconnection events are powerful or numerous enough to make a major contribution to the solar wind (see also Lionello et al. 2016).
3. Images and spectra of *active regions* show rapid flows with speeds of at least 100 km s^{-1} along their fanned-out edges (e.g., Harra et al. 2008; Brooks and Warren 2011; Morgan 2013; Zangrilli and Poletto 2016). The slow solar wind associated with these structures may come from small, short-lived coronal holes adjacent to the active regions themselves (Wang et al. 2009). Active-region slow wind tends to be associated with larger expansion factors, stronger magnetic fields, higher mass fluxes, higher $\text{O}^{+7}/\text{O}^{+6}$ ratios, and larger abundance enhancements of low first ionization potential (FIP) elements than the slow wind associated with streamers.
4. Although there is still some debate, it is becoming increasingly clear that *pseudostreamers* are sources of slow solar wind (Riley and Luhmann 2012; Crooker et al. 2014; Owens et al. 2014). Open field lines near pseudostreamers are topologically complex and “squashed,” and the asymptotic speed of their solar wind may depend on small details of their geometric expansion (Wang et al. 2012; Panasenco and Velli 2013; Gibson et al. 2017a). Nevertheless, the narrow HCS generally appears to be surrounded by a web-like band of pseudostreamer separatrix surfaces (Antiochos et al. 2011), and the 20° to 30° width of this band in latitude corresponds closely to the zone of slow solar wind seen by *Ulysses* (see Fig. 2). Wind streams associated with pseudostreamers tend to have charge states and kinetic properties intermediate between those typical of fast and slow wind (Wang et al. 2012; Abbo et al. 2015) and extreme values of the proton mass flux (Zhao et al. 2013).

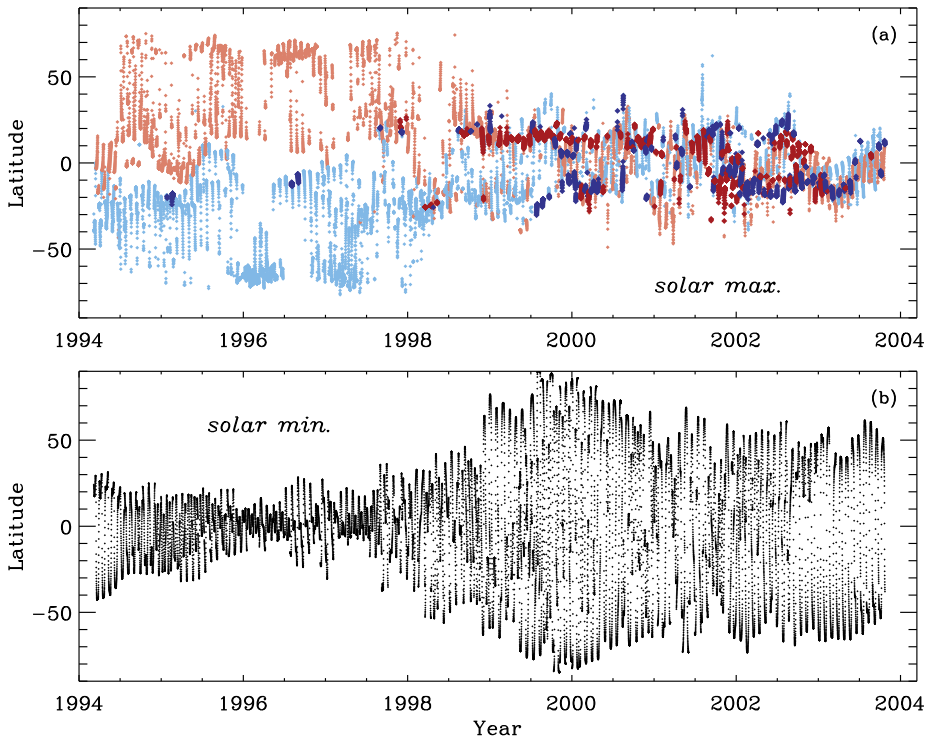


Fig. 8 (a) Latitudes of photospheric footpoints of open field lines that connect to the ecliptic plane. The PFSS technique was used to extrapolate synoptic magnetogram data from the Wilcox Solar Observatory (Hoeksema and Scherrer 1986), and a series of 133 sequential Carrington rotations was stacked together in time. Red [blue] points show footpoints with positive [negative] polarities. Large points with darker colors indicate strong photospheric fields ($|B_r| > 5$ G), and small points with lighter colors indicate weak fields below this threshold. (b) Latitude of the HCS neutral line at the source surface, mapped from the same set of PFSS models as in panel (a)

Although the coronal magnetic field is not yet measurable in a routine way, there are several semi-empirical extrapolation models that have been successful in estimating how the photospheric field maps out into the heliosphere. The community's workhorse is the potential-field source-surface (PFSS) technique, which assumes the corona is current-free between the photosphere and a spherical surface in the mid-corona, typically at $r = 2.5 R_{\odot}$ (Schatten et al. 1969; Altschuler and Newkirk 1969). Above the so-called source surface, the magnetic field is assumed to be stretched out by the solar wind into a radially-pointing "split monopole" configuration.

The PFSS technique is computationally efficient to implement, and it reproduces a number of large-scale features of the corona as seen with coronagraphs and during eclipses (Riley et al. 2006). Figure 8 shows how PFSS models can also be useful tools for mapping the origins of solar wind streams (see also Luhmann et al. 2002; Liewer et al. 2004; Fazakerley et al. 2016). At solar minimum, it is clear that high-latitude coronal holes have significant "reach" down into the ecliptic plane. However, the persistently low latitude of the HCS also means that slow wind from equatorial streamers must also contribute to the measurement record at 1 AU. At solar maximum, the Sun's dominant dipole field is in the process of being destroyed and reconstituted with opposite polarity, so the tilted HCS tends

to spend time at nearly all latitudes (see also Riley et al. 2001). Interestingly, the distribution of photospheric footpoints of open field appears to trace out the well-known butterfly diagram of active regions (see also Gibson et al. 2017b, and references therein, for discussions of similar patterns observed in the long-term evolution of coronal holes).

Levine et al. (1977) and Wang and Sheeley (1990) found that the asymptotic solar wind speed along a field line tends to be inversely correlated with the amount of transverse flux-tube expansion between the photosphere and a reference point in the mid-corona. This has been subsequently formalized using the PFSS source surface at $r = 2.5 R_{\odot}$ as the reference point. The anticorrelation between the wind speed u and the flux-tube expansion factor f is most evident for the largest structures like polar coronal holes and low-latitude streamers. Further refinement in the exact functional dependence of u on f and other parameters has led to the widely-used Wang-Sheeley-Argé (WSA) empirical model (see also Arge and Pizzo 2000; Arge et al. 2003; Wang and Sheeley 2006; Riley et al. 2015).

It should be noted that the PFSS technique is only an approximation to the true three-dimensional structure of the coronal magnetic field. Stopping short of performing fully global MHD simulations (see below), there have been a number of attempts to improve on the accuracy of PFSS-like extrapolation methods. Many of these methods, along with their alphabet soup of acronyms, have been reviewed comprehensively by Sun (2012). One noteworthy technique is the so-called current-sheet source-surface (CSSS) model, which adds some complexity by inserting another spherical surface between the Sun and the source surface (Zhao and Hoeksema 1995), but also may provide improvement to solar wind stream prediction (Poduval and Zhao 2014).

There has also been substantial effort devoted to improving the ability of the WSA method to predict the wind speed at 1 AU. Despite its successes, the time-averaged correlation coefficient between the predicted and measured wind speed tends to never exceed $\sim 50\%$ (e.g., McGregor et al. 2011b; Gressl et al. 2014; Riley et al. 2015). Statistical comparisons between multiple models and the observed solar wind (Jian et al. 2015, 2016) show generally similar results for other quantities such as density, temperature, and the magnetic field. Improvements to the original Wang and Sheeley (1990) anticorrelation have been found by including a second parameter, such as the angular distance θ between each field-line footpoint and the nearest coronal hole edge (Arge et al. 2003; Owens et al. 2008; Shen et al. 2012; Riley and Luhmann 2012) or the magnetic field magnitude at the source surface (Suzuki 2006; Fujiki et al. 2015; Wang 2016). In addition to magnetic-field parameters, it is possible that data from EUV images of the chromosphere and low corona can be used to improve these kinds of empirical predictions (Leamon and McIntosh 2007; Luo et al. 2008; Rotter et al. 2015).

Lastly, it is important to note that there is a difference between the largest-scale stream structure of the solar wind, which clearly survives the journey to 1 AU, and smaller-scale structure, which may or may not have a one-to-one correspondence with features on the Sun. There have been many reports of *in situ* “microstreams” that may be the imprints or relics of coronal structures (Thieme et al. 1990; Reisenfeld et al. 1999; Borovsky 2008, 2016). However, there are several stochastic processes that appear to vigorously blend or scramble the plasma and magnetic flux tubes to such a degree that deterministic mappings may not be possible. Section 3.3 discusses these processes in more detail.

3 Physical Processes that Produce the Solar Wind

Empirically based prediction techniques have been successful, but it can be argued that moving beyond correlations into the realm of fundamental physics is required to make sub-

stantial new gains in predictive accuracy. Once the key physical processes are identified and characterized, it will be much more straightforward to benchmark, assess, and refine the simulations used for predicting heliospheric conditions at 1 AU. This section reviews recent work along these lines. Section 3.1 begins by outlining the ideas about which most researchers agree, and Sect. 3.2 describes the areas of active debate. Section 3.3 discusses one notable difficulty in choosing between the various model proposals: the fact that wind streams tend to lose their unique connections back to the corona due to a range of dynamical effects.

3.1 Uncontroversial Fundamentals

The Sun's corona is hot. Although Grotrian, Edlén, and others began to understand the high ionization state of coronal emission lines in the 1930s, it was left to Alfvén (1941) to assemble additional lines of evidence and make the definitive case that the corona is comprised of plasma with $T \approx 10^6$ K (see also Peter and Dwivedi 2014). The high gas pressure gradient in such an extended atmosphere led Parker (1958) to determine that the most likely steady state would be a supersonic outflow. This is still the dominant idea in solar wind theory, but there may be other supplementary sources of radial acceleration in addition to the gas pressure gradient (see, e.g., Jacques 1977; Hollweg and Isenberg 2002).

The mechanism by which the coronal plasma is heated is not yet known, but its ultimate energy source is universally understood to be the convection zone. Photospheric granulation enables some kind of upward Poynting flux that delivers kinetic and magnetic energy to the higher layers of the atmosphere. After an undetermined time over which much of this energy is “stored” in the magnetic field, it is converted irreversibly to heat. Some of that thermal energy conducts back down to the chromosphere, and some is extracted by the Parker (1958) mechanism to do work against the Sun's gravitational potential. In steady-state, the power input at the base (i.e., energy flux multiplied by available surface area) should equal the solar wind's kinetic power far above the solar surface,

$$\left[4\pi r^2 f \left(F_{\text{heat}} - F_{\text{cond}} + \frac{1}{2} \rho u_r^3 - \rho u_r \frac{GM_{\odot}}{r} \right) \right]_{\text{base}} \approx \left[4\pi r^2 \left(\frac{1}{2} \rho u_r^3 \right) \right]_{r \gg R_{\odot}} \quad (1)$$

where f is the surface filling factor of magnetic field lines that eventually reach the solar wind, F_{heat} is the energy flux deposited by the still-unidentified source of coronal heating, and F_{cond} is the energy flux conducted back down to the chromosphere (see also Hammer 1982; Hansteen and Leer 1995; Schwadron and McComas 2003; Cranmer and Saar 2011). The equation above neglects enthalpy fluxes and radiative losses, both of which are usually negligible above the transition region. From the standpoint of the supersonic solar wind, the high coronal temperature is only a kind of temporary holding area; i.e., a stopover between the original source of the energy and its eventual destiny as outflowing kinetic energy.

The energy balance shown in Eq. (1) sets the mass loss rate \dot{M} of the wind, but the relative magnitudes of the terms on the left-hand side are still not known. This is an analogous situation to the long-studied problem of heating in static coronal loops (e.g., Rosner et al. 1978), in which the “base pressure” is determined by time-steady energy conservation. Both the wind's \dot{M} and a loop's pressure are measures of how much plasma is drawn up from the relatively vast chromospheric reservoir. A key point is that the mass loss rate is *not* determined by the Parker (1958) solution of the momentum equation. The accelerating flow through the Parker critical point (i.e., the radius at which the wind speed exceeds the sound

speed) merely takes whatever mass is supplied at the coronal base and draws it out. Wang (1998) estimated the sphere-averaged value of \dot{M} varies between about $2 \times 10^{-14} M_{\odot} \text{yr}^{-1}$ (at solar minimum) to $3 \times 10^{-14} M_{\odot} \text{yr}^{-1}$ (at solar maximum).

In the past, theorists have disagreed about whether the solar wind is more properly described using fluid or kinetic equations (Chamberlain 1960; Jockers 1970; Lemaire and Scherer 1971). The consensus now is that both pictures agree on the basic properties of the outflow (Lemaire and Pierrard 2001; Parker 2010). To some extent, this ought to be the case, because the conservation equations based on fluid moments are derived directly from Liouville's theorem and the associated kinetic transport equations. However, the fluid picture does make closure assumptions about the shapes of the velocity distribution functions, and there remain disagreements about, e.g., the validity of classical heat conduction (Landi and Pantellini 2003) and the available linear wave modes (Verscharen et al. 2017).

It has also been proposed that there are suprathermal particles (i.e., power-law tails that augment the normally Maxwellian velocity distributions) in the solar atmosphere, and that these particles escape preferentially to produce high coronal temperatures (Levine 1974; Scudder 1992). This “velocity filtration” idea has been implemented in kinetic exobase-type models that successfully predict some aspects of the particle measurements at 1 AU (e.g., Meyer-Vernet 1999; Zouganelis et al. 2004; Pierrard and Pieters 2014). Despite this idea being somewhat outside the mainstream of research, we list it here in the subsection about uncontroversial physics. It may or may not be important on the Sun, but it is similar to any other coronal heating theory in that it requires converting some other form of energy (i.e., kinetic or magnetic) into thermal energy. The difference is that this conversion would have to occur down in the chromosphere, where a combination of Coulomb collisions and radiative losses would keep the majority of particles cool.

A final uncontroversial statement to make about the solar wind is that its fluctuations (e.g., waves, turbulence, shocks, and end-products of magnetic reconnection) are likely to both affect and be affected by the time-averaged properties of the flow. There do not seem to be any theories of coronal heating and solar wind acceleration that do *not* ultimately involve the summed impact from multiple transient or oscillating events. The extent to which terms like “waves” and “turbulence” are useful descriptors of the physics is still being debated, but the variability is ubiquitous and important.

3.2 Controversial Alternatives

The exact chain of events by which the corona is heated and the solar wind is accelerated is not yet known. It has proven exceedingly difficult to distinguish between competing theoretical models because the basic energy conversion processes appear to be acting on spatial and time scales unresolved by existing observations. It is also probably the case that different mechanisms are dominant in different source-regions of the solar wind (e.g., active regions versus coronal holes), and that in some regions multiple mechanisms may be contributing at comparable levels.

With the above caveats in mind, we have sorted the proposed physical models into three broad categories:

1. If solar wind field lines are open to interplanetary space—and if they remain open on timescales comparable to the time it takes plasma to accelerate into the corona—then the main sources of energy must be injected at the footpoints. Thus, in *wave/turbulence-driven (WTD) models*, the convection-driven jostling of the flux-tube is assumed to gen-

- erate wave-like fluctuations that propagate up into the extended corona (Coleman 1968; Hollweg 1986; Velli et al. 1991; Matthaeus et al. 1999; Suzuki and Inutsuka 2006; Cranmer et al. 2007; Ofman 2010; van Ballegoijen et al. 2011; Chandran et al. 2011; Matsumoto and Suzuki 2012; Perez and Chandran 2013; Lionello et al. 2014; Tenerani and Velli 2017; van Ballegoijen and Asgari-Targhi 2017). The coronal heating comes from wave dissipation, whose physical origin is still a subject of debate. Fast and slow wind streams come from the fact that flux tubes with different expansion factors have different radial distributions of the heating rate and different locations of the Parker critical point (see, e.g., Leer and Holzer 1980; Cranmer 2005).
2. Near the Sun, all open magnetic flux tubes are observed to exist in the vicinity of closed loops. The complex distribution of mixed-polarity loop footpoints—which is evolving continuously via emergence, cancellation, diffusion, splitting, and merging—has been called the Sun’s “magnetic carpet” (Title and Schrijver 1998). It is natural to propose a class of *reconnection/loop-opening (RLO) models*, in which the mass and energy in some coronal loops is fed into the open regions that connect to the solar wind. Some have suggested that RLO-type energy interchange primarily occurs at the scale of the supergranular network (Axford and McKenzie 1992; Fisk et al. 1999; Fisk 2003; Schwadron et al. 2006; Yang et al. 2013; Karpen et al. 2017), and others favor larger-scale reconnection events near global null points and streamer cusps (Suess et al. 1996; Einaudi et al. 1999; Wang et al. 2000). The idea of a so-called S-web, or separatrix-web (Antiochos et al. 2011; Edmondson 2012; Higginson et al. 2017) involves a continuous range of scales between the two, with the complex topological rearrangement helping to energize the slow wind.
 3. The upper chromosphere is filled with a range of narrow features known variously as spicules, jets, fibrils, surges, and mottles. Some have suggested that much of the corona’s mass and energy may be injected directly from these structures (Pneuman 1986; Loucif 1994; De Pontieu et al. 2009; Moore et al. 2011; Tian et al. 2014; Raouafi et al. 2016). Strictly speaking, this idea could be considered a subset of either the WTD or RLO models, depending on whether the spicules and jets are driven by waves (Sterling and Hollweg 1984; Kudoh and Shibata 1999; Cranmer and Woolsey 2015) or by reconnection (e.g., Uchida 1969; Parlat et al. 2016). Still, the direct chromospheric source of the mass appears to distinguish this idea—here called *chromospheric mass supply (CMS)*—from the other two, in which the processes giving rise to the corona and solar wind are generally located up in the corona itself.

The above list of processes does not include some that have been applied mostly to closed loops that do not connect directly to the solar wind. For example, the classical idea of direct-current (DC) heating—in which the corona evolves in a succession of twisted and quasi-static states via small-scale current dissipation events (Parker 1972; Heyvaerts and Priest 1984; van Ballegoijen 1986)—does not sit solidly within the WTD, RLO, or CMS categories. These DC mechanisms are often associated with *nanoflares*: tiny episodic bursts of energy that may dominate the coronal heating (Parker 1988; Parnell and Jupp 2000; Joulain et al. 2016). It is fair to say that all three of the above model categories can produce nanoflare-like intermittent heating. In many cases, however, the predicted small-scale bursts are expected to be highly dynamic and not quasi-static; this is consistent with observations of “braiding” by high-resolution imagers (e.g., Cirtain et al. 2013; van Ballegoijen et al. 2014). No matter the source of these bursts, they may generate nonthermal electrons that propagate out into the heliosphere (e.g., Che and Goldstein 2014).

Observations have been used to attempt to support or rule out the above processes, but no consensus has been reached. For example, Roberts (2010) claimed there to be insufficient WTD energy present to heat the corona. Cranmer and van Ballegooijen (2010) similarly claimed the RLO model cannot energize the plasma in open-field regions (see also Karachik and Pevtsov 2011; Lionello et al. 2016). Klimchuk and Bradshaw (2014) concluded that CMS-type processes cannot produce sufficient heat to power the corona. However, none of these ideas has been ruled out conclusively because (1) the relevant energy-release events cannot yet be measured directly, and (2) most models still employ free parameters that can be adjusted to improve agreement with the existing data.

As mentioned above, it may also be possible for aspects of more than one model to be present. Stakhiv et al. (2016) suggested that both closed loops and open flux tubes produce solar wind—with closed loops contributing more to the slow wind and open flux tubes contributing more to the fast wind—and that once the plasma is released, both types share a single WTD acceleration mechanism. There are other ways that the WTD, RLO, or CMS models can exhibit intermingled characteristics. If there is a turbulent cascade that produces WTD-type heating, the ultimate energy dissipation may be best describable by small-scale reconnection events that reconfigure the magnetic topology (e.g., Matthaeus and Velli 2011). On the other hand, the proposed RLO reconnection events in the magnetic carpet may generate MHD waves (Lynch et al. 2014; Karpen et al. 2017) that go on to dissipate and heat the plasma. Lastly, even if the evolving S-web does not produce sufficient reconnection to heat the global corona, it may be that the mere presence of the sharp transverse gradients and separatrices can act as an additional source of shear-driven waves (see, e.g., Lee and Roberts 1986; Kaghashvili 1999, 2007; Evans et al. 2012).

How can we as a community progress toward the goal of identifying and characterizing the physical processes at work in the solar corona? It is worthwhile listing some promising paths forward (see Sect. 4), but there have also been unsuccessful attempts to rule out models. For example, the prevalence of enhanced low-FIP elements and high freezing-in temperatures (e.g., high O^{+7}/O^{+6} ratios) in the slow wind has been used as evidence for RLO-type processes. Closed coronal loops exhibit similar composition patterns to the slow wind, so it is natural to connect them together. However, time-steady WTD models have been shown to predict variations with wind speed in abundances and charge states that follow the measured patterns in interplanetary space (Cranmer et al. 2007; Jin et al. 2012; Cranmer 2014a; Oran et al. 2015). Thus, for now, it appears that solar wind composition is not a useful discriminator between the main theoretical categories.

3.3 Does Radial Evolution Mask Bimodality?

It is still not clear whether the dominant acceleration processes in the corona produce *bimodal* (i.e., cleanly separated) fast and slow wind streams, or if they produce a continuous distribution of states by varying one of more parameters. In some versions of the WTD model, a slow variation of the superradial flux-tube expansion factor can produce a bimodal jump in the wind speed (Cranmer 2005). This occurs because there are often multiple possible radii for the Parker (1958) critical point, and the global time-steady solution can undergo a rapid transition from one of those radii to another, depending on small changes in the expansion factor (see also Kopp and Holzer 1976). If the overall radial distribution of coronal heating remains more or less unchanged, a wind with a lower critical point tends to have a higher asymptotic speed, and a wind with a higher critical point tends to have a lower speed (Leer and Holzer 1980; Pneuman 1980).

Whether or not the corona produces a bimodal or broad/continuous distribution of wind speeds, it remains difficult to use *in situ* interplanetary data to make definitive conclusions

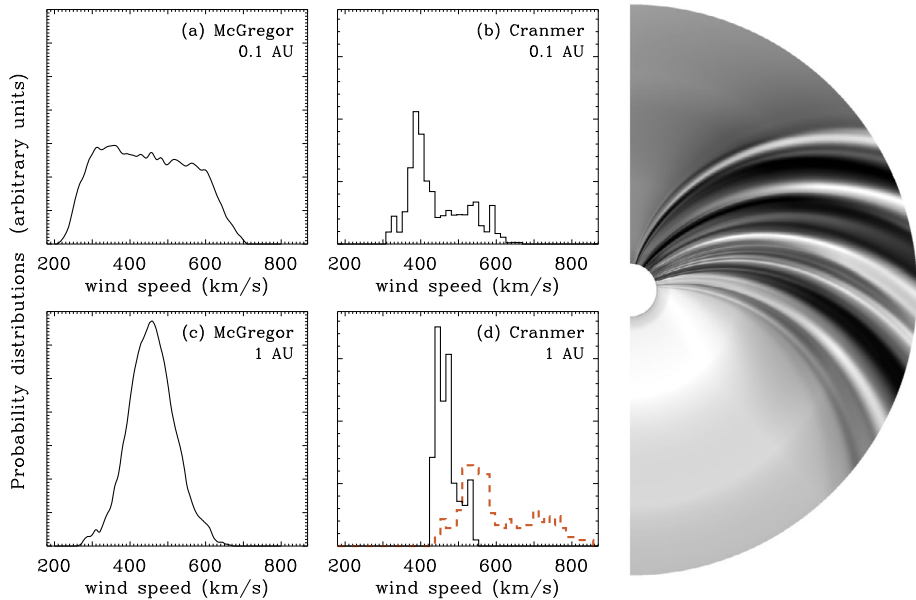


Fig. 9 Comparison of solar wind-speed probability distributions in near-ecliptic regions of semi-empirical three-dimensional models: (a), (c) WSA-ENLIL models (McGregor et al. 2011a) assembled over 3 years during the 1995–1997 solar minimum, sampled at 0.1 AU and 1 AU; (b), (d) coordinated set of ZEPHYR models (Cranmer et al. 2013) for a quiet region observed with SOLIS in 2003, sampled at 0.1 AU and 1 AU. The red dashed curve is the distribution of wind speeds at 1 AU for separate ZEPHYR-model flux tubes computed *without* stream interactions in the ecliptic plane. Right-hand panel shows the simulated CIR pattern for the 2003 quiet region. Grayscale levels correspond to density variations, with the large-scale radial dropoff removed

about this issue. In the ecliptic plane, the solar wind becomes mixed—in ways that usually increase its randomness and stochasticity—in at least three distinct ways. (1) MHD turbulence gives rise to an effective random walk of field lines and a potential loss of identity for initial plasma parcels that become shredded in space and time (Matthaeus et al. 1998; Greco et al. 2012). (2) The Sun’s rotation produces stream-stream interactions that create CIR spiral structures and ever-greater longitudinal blending with increasing distance (Burlaga and Szabo 1999; Riley 2007). (3) Coulomb collisions, whose randomizing effects accumulate with radial distance, tend to erase the field-aligned kinetic effects discussed in Sect. 2 (e.g., Kasper et al. 2008). The main impact of these processes is to produce ambiguity when mapping wind streams back from interplanetary space to the Sun. This ambiguity becomes more apparent for smaller scales in longitude and latitude, and for more distant mappings from the outer heliosphere (e.g., Elliott et al. 2012).

Figure 9 illustrates the second of the three mixing processes listed above. Model-based reconstructions of radial and longitudinal evolution of the solar wind are shown from McGregor et al. (2011a) and Cranmer et al. (2013). High-contrast flux-tube structure near the Sun appears to be eroded rapidly by CIR stream interactions. The most extreme solar wind parcels (e.g., the highest and lowest speeds) tend to disappear and leave behind a single-peaked distribution dominated by moderate speeds of order $400\text{--}450\text{ km s}^{-1}$. The red dashed curve in Fig. 9d shows what the distribution of speeds would have been if stream-stream interactions in the ecliptic were ignored (i.e., the slight bimodality at 0.1 AU would have

been preserved at 1 AU). Thus, the presence of stream-stream interactions tends to make any intrinsic coronal bimodality extremely difficult to detect at 1 AU.

4 Paths Forward to Improved Space Weather Prediction

Although past observational and theoretical work has improved our understanding of the basic processes at work in generating the solar wind, much more needs to be done. The subsections below describe some of what is on the horizon for pure theory (Sect. 4.1), observations and *in situ* measurements (Sect. 4.2), and empirical prediction tools that attempt to make use of the best of what models and data have to offer (Sect. 4.3).

4.1 Theoretical Improvements

In order to determine the quantitative contributions of WTD, RLO, and CMS processes to accelerating the solar wind, each of these models must be developed to the point of eliminating their free parameters. The difficulty in doing this lies in the large range of relevant spatial and time scales important to the physics—e.g., the Sun can exhibit wavelike variability with periods from milliseconds (Bastian et al. 1998) to years (McIntosh et al. 2017). This reality demands adaptive, multi-scale modeling techniques that go beyond many traditional plasma-in-a-box type simulations. These models must also strive to contain as many of the proposed physical processes as possible. The true impact of any one process on the system may not be made clear until it is allowed to interact with the others in a realistic way.

Although there are still many physics questions that can be answered by models with limited spatial extent, the community's ultimate goal is to develop and improve *global three-dimensional simulations* of the entire corona and heliosphere. In the last decade, several of these models have made the transition from polytropic energy equations and prescribed heating functions to more physics-based (usually WTD) ways of computing the coronal heating. Additional recent developments include solving multi-fluid energy equations instead of single-fluid MHD (Usmanov et al. 2012, 2016; van der Holst et al. 2014; Oran et al. 2015) and assimilating time-dependent photospheric data instead of using static synoptic maps (Feng et al. 2015; Linker et al. 2016; Yalim et al. 2017). Aspects of the simulations that have been shown to be especially important for space weather prediction include resolving the sharp HCS (i.e., avoiding unphysical diffusion associated with too coarse a grid; Stevens et al. 2012) and using Monte Carlo ensembles instead of single models (Riley et al. 2013; Owens et al. 2017).

Because of the need to compare model predictions with actual observational data (see below), it is important to include *forward modeling* in the theorist's toolbox. It has long been a goal to "invert" the data; i.e., to extract information from images and spectra that allow us to solve for the three-dimensional distributions of plasma parameters such as temperature and density. However, the corona is optically thin, highly structured, and time-variable. Thus, attempts at data inversion are often nonunique and fraught with uncertainty (see, e.g., Judge and McIntosh 1999; De Moortel and Bradshaw 2008). It is a much safer procedure to take the theoretical model output, simulate what observers would see, and make direct comparisons at the level of the data. Several sets of sophisticated software tools are being developed to enable this kind of forward modeling (e.g., Nita et al. 2015; Gibson 2015; Gibson et al. 2016; Van Doorselaere et al. 2016). Methodologies are also being developed to iteratively optimize models to match observations, thus achieving the ultimate goal of inversion (e.g., Dalmasse et al. 2016). A benefit of these approaches is that they provide information about which observables are the most influential in validating or falsifying a given model.

4.2 Observational Improvements

Despite the difficulties described above regarding forward and inverse modeling, we need to remain on the lookout for new ways in which observations can put tight constraints on theory. A clear source of “low-hanging fruit” is to pursue better measurements of the ingredients of proposed physical mechanisms. For example, testing the WTD model requires knowing the amplitudes and damping rates of fluctuations that propagate along open field lines (i.e., filling in the gaps in Fig. 6). Testing the CMS model requires knowing how much mass and Poynting flux comes up through the photosphere, chromosphere, and transition region—and does not come back down again. Testing the RLO model requires measuring how much plasma and magnetic energy gets processed through magnetic reconnection events that convert closed to open field lines.

Global models of the solar wind depend on photospheric magnetic field maps as lower boundary conditions. Traditional synoptic maps, built up from longitudinal magnetograms, are problematic because (1) they do not contain information about magnetic currents in the solar atmosphere, (2) they ignore variability on timescales shorter than a solar rotation, and (3) the north and south poles are poorly resolved (Sun et al. 2011; Petrie 2017). Vector magnetograms are improving the situation (e.g., Liu et al. 2017), but it is still the case that magnetograms from different observatories tend to produce markedly different predictions for the ecliptic plane at 1 AU (Jian et al. 2011; Riley et al. 2014). The ideal solution would be to have telescopes on multiple spacecraft, positioned throughout the heliosphere, so that all 4π steradians of the Sun can be monitored continuously (Roelof et al. 2004; Liewer et al. 2008; Strong et al. 2012). A continuous view of the solar poles is particularly compelling, both for space-weather monitoring and for establishing the nature of the solar dynamo. There are also mission concepts that would provide new insights while stopping short of full 4π coverage, such as an early-warning system at the Earth-Sun L5 point (e.g., Lavraud et al. 2016; Pevtsov et al. 2016), or a two-spacecraft system that would improve upon *STEREO*'s initial exploration of stereoscopic imaging (Strugarek et al. 2015). Sustained multi-vantage observations of the photospheric magnetic field, the inner boundary of the heliosphere, has transformative potential.

Having the ability to make direct and routine measurements of the coronal magnetic field would complement the photospheric data (Lin et al. 2004; Judge et al. 2013). Most proposed coronal heating mechanisms are magnetic in nature, and they often depend on the properties of twisted, non-potential structures that are difficult to extrapolate up from photospheric boundary conditions. Indirect methods such as coronal seismology (e.g., De Moortel and Nakariakov 2012) have been helpful, but direct measurements of the field magnitude and direction could put more stringent constraints on models. Observations of linear polarization in infrared coronal emission lines by the *Coronal Multichannel Spectropolarimeter* (Tomczyk et al. 2008) have demonstrated the power of such observations for establishing the topologies of magnetic structures such as flux ropes and pseudostreamers (Dove et al. 2011; Bąk-Stęślicka et al. 2013; Rachmeler et al. 2013, 2014; Gibson et al. 2017a). The *Daniel K. Inouye Solar Telescope* (DKIST; Tritschler et al. 2016) will provide a more direct measure of the line-of-sight coronal field strength via high-precision measurements of circular polarization, and explore new regimes of coronal magnetometry. Future programs, such as the *Coronal Solar Magnetism Observatory* (COSMO; Tomczyk et al. 2016), would enable full-Sun, synoptic measurements of the coronal magnetic field. Ultimately, a vantage away from the Earth-Sun line would be beneficial for monitoring Earth-directed space weather; the proposed balloon-borne *Waves and Magnetism in the Solar Atmosphere* (WAMIS; Ko et al. 2016) and the *massively-multiplexed Coronal Spectropolarimetric Magnetometer* (mxCSM; Lin 2016) represent development in this direction.

Additional information about solar wind acceleration is likely to be learned by detecting scattered light from plasma parcels in the extended corona ($r \approx 2\text{--}30 R_{\odot}$). This range of heights is where coronal “structures” evolve into solar wind streams. It is also where the plasma becomes collisionless; i.e., where departures from thermal equilibrium (Fig. 5) start to become useful probes of the physics. It would be beneficial for next-generation ultraviolet coronagraph spectrometers (e.g., Kohl et al. 2008; Strachan et al. 2016) to be developed, in order to follow up on the successes of UVCS and extend the remote-sensing field of view to larger heights and more ions.

To monitor solar wind acceleration at slightly larger distances, there are opportunities for improving both the analysis techniques and instrumentation for space-based visible-light heliospheric imagers (Rouillard et al. 2011; DeForest et al. 2011, 2016; DeForest and Howard 2015) and ground-based radio arrays (Manoharan et al. 2017). Large-scale collaborations such as HELCATS (Heliospheric Cataloguing, Analysis, and Techniques Service; Plotnikov et al. 2016; Rouillard et al. 2017) are building a broad range of analysis tools and observational databases. New remote-sensing heliospheric observations have the potential to improve our knowledge of how parcels accelerate in both isolated wind streams and CIRs (as well as CMEs), and also to reveal how coronal waves evolve into turbulent eddies.

Of course, future improvements in solar wind measurements must also include *in situ* particle and field detection. We anticipate that the *Parker Solar Probe* (Fox et al. 2016) and *Solar Orbiter* (Müller et al. 2013), both scheduled for launch in 2018, will revolutionize our conception of the inner heliosphere. Specifically, these missions will explore regions in which all three mixing processes discussed in Sect. 3.3 have not yet had time to smear out the unique field-line mappings back to the corona. As these missions are starting to explore the inner heliosphere, India’s *Aditya-L1* mission is expected to launch around 2020. Its combination of remote-sensing and *in situ* instruments (Ghosh et al. 2016; Venkata et al. 2017) should extend the multi-diagnostic capabilities pioneered by *SOHO* and *ACE* at Earth-Sun L1. Lastly, the *Turbulence Heating Observer* (THOR; Vaivads et al. 2016) spacecraft is expected to launch in 2026, and it will be dedicated to a complete characterization of micro-scale turbulent dissipation in the solar wind and Earth’s magnetosphere.

4.3 Improvements in Empirical Prediction Tools

As discussed in Sect. 2.3, empirically based techniques to predict solar wind conditions at 1 AU (e.g., PFSS and WSA) continue to be tested and upgraded. Comparisons are being made between potential-based field extrapolations and global MHD models (Jian et al. 2015, 2016), but both techniques still have problems reproducing the full range of observed solar-wind variability. Ongoing improvements in model validation are being made by collaborative efforts such as the Community Coordinated Modeling Center (CCMC; Hesse et al. 2010), the Space Weather Modeling Framework (SWMF; Tóth et al. 2005), the European Heliospheric Forecasting Information Asset (EUHFORIA; Pomoell et al. 2017), and the NOAA Space Weather Prediction Center (SWPC; Berger et al. 2015).

Eventually, forecasts based on solutions to conservation equations ought to replace empirical recipes such as PFSS, but at present that appears to be too computationally expensive. A promising middle ground may be to use extrapolations based on *magnetofrictional evolution*, which stops short of full MHD but still manages to include the time-dependent development of non-potential coronal currents (Yeates 2014; Edwards et al. 2015; Fisher et al. 2015). For the actual prediction of solar wind properties along open field lines, there are new semi-empirical tools (see, e.g., Woolsey and Cranmer 2014; Pinto and Rouillard 2017) that use the output of physics-based models (rather than WSA-type correlations) but

are also designed for computational speed. For solar-cycle-length predictions, it may be important to couple corona/wind models to flux-transport models of the photospheric fields (e.g., Merkin et al. 2016; Weinzierl et al. 2016) or even to more self-consistent simulations of the interior dynamo.

Space weather forecasting also requires efficient *data assimilation* (or *data incorporation*, as discussed by Schrijver et al. 2015) for it to be accurate. Unfortunately, there is a stark contrast with terrestrial weather forecasting, in that (1) the space-based data are so sparse that the “upwind conditions” are not really known with sufficient precision, and (2) the corona/heliosphere physics that produces these upwind conditions is still not understood. There are also differences in how data products are used. Photospheric magnetograms are straightforward drivers of the models because they can be used as lower boundary conditions. However, it is more difficult to use data measured in the corona and inner heliosphere, because those regions are inside the computational grids of most MHD simulations. Just straightforwardly inserting newly measured plasma properties into an MHD model would overconstrain the equations and produce discontinuities in the conserved quantities. One promising path forward is to run multiple simulations in parallel—with randomly varied initial/boundary conditions or different choices for unknown coronal heating processes—and then to choose the model (or linear combination of models) that best matches the data (see Doxas et al. 2007). The optimization method of Dalmasse et al. (2016) discussed above also suggests possible solutions to this problem. This type of *ensemble modeling* is now being applied to a range of solar wind and ICME prediction methods (Lee et al. 2013; Riley et al. 2013; Cash et al. 2015; Owens et al. 2017).

5 Conclusions

The objective of this paper has been to review our present-day understanding of the origins of ambient solar wind streams. We also examined a wide range of possible ways to improve space-weather forecasts related to the ambient wind. There are still some fundamental questions about solar wind acceleration for which we do not yet have answers: What are the physical processes that dominate coronal heating? Where does most of the slow wind come from on the Sun? Do fast and slow wind streams originate from two separate mechanisms? However, it is nevertheless the case that forecasts are improving. This is due in part to the successes of empirical correlation techniques, which help point the way to identifying the “best” physical processes to include in simulations. As these processes are identified and characterized, we also expect improvements in models of CMEs, which have proposed heating mechanisms (see, e.g., Liu et al. 2006; Murphy et al. 2011) very similar to those discussed in Sect. 3 for the ambient wind.

Much of the discussion in this paper has been focused on the idea of applying insights from fundamental research to the practical goals of space weather forecasting. This phase of work has been called “research-to-operations” (R2O). However, there are also benefits that flow in the opposite direction; i.e., “operations-to-research” (O2R; Steenburgh et al. 2014). Increased knowledge about our well-studied Sun and heliosphere feeds back into astrophysical studies of Sun-like stars (e.g., Haisch and Schmitt 1996; Schmelz 2003; Brun et al. 2015) and even more distant objects such as supermassive black holes (Quataert and Gruzinov 1999; Li et al. 2017) and galaxy clusters (Parrish et al. 2012). For decades, the Sun has been considered a testbed for studying fundamental physical processes that cannot be reproduced in terrestrial laboratories. Because the solar wind unifies studies of waves, turbulence, and magnetic reconnection, it also feeds into interdisciplinary studies of universal processes in heliophysics (see Davila et al. 2009; Raulin et al. 2010).

Acknowledgements The authors would like to thank Ruedi von Steiger, André Balogh, Dan Baker, Tamás Gombosi, Hannu Koskinen, and Astrid Veronig for convening the fantastic 2016 ISSI workshop on the scientific foundations of space weather. SRC's work was supported by NASA grants NNX15AW33G and NNX16AG87G, NSF grants 1540094 (SHINE) and 1613207 (AAG), and start-up funds from the Department of Astrophysical and Planetary Sciences at the University of Colorado Boulder. PR's work was supported through a grant from NASA's Living With a Star (LWS) Program. The National Center for Atmospheric Research (NCAR) is supported by the National Science Foundation. This research made extensive use of NASA's Astrophysics Data System (ADS).

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