Solar-Wind Structures That Are Not Destroyed by the Action of Solar-Wind Turbulence

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If MHD turbulence is a dominant process acting in the solar wind between the Sun and 1 AU, then the destruction and regeneration of structure in the solar-wind plasma is expected. Six types of solar-wind structure at 1 AU that are not destroyed by turbulence are examined: 1) corotating-interaction-region stream interfaces, 2) periodic density structures, 3) magnetic structure anisotropy, 4) ion-composition boundaries and their co-located current sheets, 5) strahl-intensity boundaries and their co-located current sheets, and 6) non-evolving Alfvénic magnetic structure. Implications for the solar wind and for turbulence in the solar wind are highlighted and a call for critical future solar-wind measurements is given.

Keywords: solar wind, turbulence, current sheets, discontinuities, magnetic structure

INTRODUCTION

Turbulence in the solar wind should have multiple impacts on the plasma and magnetic structure between the Sun and 1 AU: heating of the particle populations, mixing (chunk-size evolution followed by homogenization), flux-tube shredding, destruction of structure from the Sun, and a constant annihilation and recreation of its own structures.

The quasi-two-dimensional component of MHD turbulence is eddy like in its fluid motion and it is anticipated that this will give rise to eddy transport in the plasma (Matthaeus et al., 1995; Pucci et al., 2016). Much of the action of turbulence should occur on a nonlinear or eddy-turnover timescale \( \tau_{\text{eddy}} \) and much of the action is manifested by eddy diffusion or eddy viscosity with coefficients \( D_{\text{eddy}} \). Simple estimates using the rms velocity-fluctuation amplitude \( \delta v \) of the solar wind and the fluctuation correlation length \( L_{\text{corr}} \) (Matthaeus et al., 1994; Borovsky, 2006) yield (for \( \delta v \sim 10 \text{ km/s} \) and \( L_{\text{corr}} \sim 1 \times 10^6 \text{ km at 1 AU} \)) \( \tau_{\text{eddy}} = L_{\text{corr}}/\delta v \sim 30 \text{ h} \) and \( D_{\text{eddy}} = L_{\text{corr}} \delta v \sim 1 \times 10^7 \text{ km}^2/\text{s} \). If the magnetic-fluctuation energy is also accounted for (e.g. Yoshizawa and Yokoi, 1996; Yokoi and Hamba, 2007; Yokoi et al., 2008), then faster nonlinear timescales and stronger eddy diffusion are estimated. In the highly Alfvénic regions of the solar wind more-proper estimates replace \( \delta v \) with the rms amplitude of inward-Elsasser fluctuations \( \delta Z^{\text{in}} \) (Dobrowolny et al., 1980).

There have been a few indications that the action of turbulence in the solar wind is not as robust as expected. 1) Mixing is a universal process in turbulence (Liepmann, 1979; Ottino, 1990; Paul et al., 2003; Dimotakis, 2005) involving first the stretching and folding of structure (mesomixing) and then the homogenization of the medium (micromixing). By statistically comparing the plasma “chunk” sizes near 0.3 AU with the plasma chunk sizes near 1 AU, an analysis (Borovsky, 2012a) to quantify the amount of mixing of the solar wind plasma under the action of stretching and folding found no evidence for mixing by stretching and folding. (“Stretching and folding” is the evolution of passive structures in an irregular turbulent flow field that is the stretching of the structure by the action of the strain field and the folding of the structure by gradients in the vorticity field (Ottino, 1990;
Muzzio et al., 1991; Buch and Dahm, 1996); cf. Figure 9 of Corrsin (1959) The same study found no evidence for homogenization of the solar-wind plasma by turbulence. Hence, no evidence for the action of mixing by turbulence. 2) Numerical investigations into MHD turbulence find concentrated dissipation of energy occurring at intermittent current-sheet structures in the turbulent plasma (Servidio et al., 2011; Karimabadi et al., 2013). Searches for proton heating at solar-wind current sheets (Borovsky and Denton, 2011) and at solar-wind velocity shears (Borovsky and Steinberg, 2014), as measured by an increase in the proton specific entropy, found no evidence for localized heating. (Note that this result is contradicted by studies using the proton temperature instead of entropy as an indication for localized heating (Osman et al., 2011, 2012; Wang et al., 2013)) . 3) For an MHD-turbulence energy cascade to occur, the presence of both inward and outward propagating Alfvén waves must be present (Verdini et al., 2009; Perez and Boldyrev, 2010; Stawarz et al., 2010), with the amplitudes of the inward waves characterized by the inward Elsasser variable $Z^\text{in}$. The solar-wind data analysis of Wang et al. (2018) finds that two dominant sources of $Z^\text{in}$ in solar-wind measurements are 1) measurement noise and 2) non-propagating convective structures in the plasma. The implications of these three findings are collected into Table 1.

If turbulence is the dominant physical process occurring in the solar wind, then one should expect to find a generalized destruction of solar-origin structure between the Sun and 1 AU and a constant destruction and regeneration of turbulence-origin structure. In this report examples will be given of six types of structures in the solar wind that are not destroyed by turbulence. These structures are 1) CIR stream interfaces, 2) periodic density structures, 3) compression- and rarefaction-driven magnetic-structure anisotropies, 4) alpha-to-proton ion-composition boundaries and their current sheets, 5) electron-strahl-intensity boundaries and their current sheets, and 6) non-evolving Alfvénic magnetic structure. The survival of these various types of structures should raise questions about turbulence in the solar wind and about the impact of turbulence on the evolution of the solar wind.

In the next section six types of structure that are not destroyed by turbulence are examined and in the final section questions about the nature of the solar wind are raised and a call is made for critical solar-wind measurements.

### EXAMPLES OF STRUCTURE THAT SURVIVES TO 1 AU

Six types of structures that survive to 1 AU are examined using measurements from the 3DP (Lin et al., 1995), SWE (Ogilvie et al., 1995), and MFI (Lepping et al., 1995) instruments on the WIND spacecraft and the SWEPAM (McComas et al., 1998) and MAG (Smith et al., 1998) instruments on the ACE spacecraft. Structure beyond 1 AU is examined using the VHM (Vector Helium Magnetometer) (Balogh et al., 1992) instrument on the Ulysses spacecraft. The implications of these structures surviving to 1 AU are summarized in Table 1.

### CIR Stream Interfaces

At the edge of a coronal hole or coronal hole extension, there is a boundary at the Sun between fast coronal-hole-origin plasma and slower streamer-belt-origin plasma (Crooker and Gosling, 1999;

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**TABLE 1** | Implications for solar-wind turbulence raised by the findings of the non-destruction of solar-wind structures.

| Finding | Possible Implications | Discussed |
|---------|-----------------------|-----------|
| No evidence of mixing | No stretching and folding by turbulence | Borovsky (2012a) |
| No proton heating at current sheets and at velocity shears | Energy cascade is weak. Sheets are not part of turbulence | Borovsky and Denton (2011) |
| Measured $Z^\text{in}$ is not from inward Alfvén waves |  | Borovsky and Steinberg (2014) |
| Thin stream interfaces survive to 1 AU | Energy cascade is weak | Wang et al. (2018) |
| Periodic density structures survive to 1 AU | No eddy viscosity | This paper |
| Ion-composition-boundary current sheets survive to 1 AU | No stretching and folding | This paper |
| Strahl-boundary current sheets survive to 1 AU | Current sheets are not being destroyed and regenerated by turbulence | This paper |
| Compressed/rarefacted magnetic structure does not return to isotropy | Current sheets are not being destroyed and regenerated by turbulence | This paper |
| Proton flow $v_\parallel = 0$ in reference frame of Alfvénic magnetic structure | Propagation of structure without time evolution. Absence of inward Alfvén waves | This paper |
Gosling and Pizzo, 1999; Krista et al., 2011). This is a vorticity boundary. Away from the Sun, on the leading edge of the coronal hole the faster solar wind moving radially outward from the coronal hole overtakes the slower solar wind from the streamer belt and forms a region of plasma compression: a corotating interaction region (CIR). At 1 AU the duration of the CIR compression as it advects past a spacecraft is about 1 day. In a CIR at 1 AU there is typically a well-known sharp boundary making the transition from streamer-belt-origin plasma to coronal-hole-origin plasma known as the CIR stream interface, and this boundary is typically co-located with an abrupt vorticity layer. In time-series solar-wind measurements, the locations of stream interfaces can be identified by various signatures: the reversal of the East-West compressional flow deflection of the solar wind (McPherron and Weygand, 2006), the peak of the total (particle plus magnetic field) pressure (Jian et al., 2006), a sudden increase in the proton specific entropy (Siscoe and Intriligator, 1993; Lazarus et al., 2003), a sudden change in the heavy-ion charge-state composition (Wimmer-Schweingruber et al., 1997; Crooker and McPherron, 2012), or the peak in the plasma vorticity (velocity shear) (Borovsky and Denton, 2010). Note that some CIRs have more than one abrupt step in velocity: for example the CIR shown in Figure 1 of Borovsky (2006) has two large abrupt steps in velocity rather than a single step. The single, double, or multiple shear cases might be owed to the morphology of the boundary on the Sun between the fast-wind coronal hole and the solar region producing slower wind. In the discussion of this subsection, only CIRs with a single step are considered.

Rotating into the local Parker-spiral coordinate system (Borovsky, 2006) which, at 1 AU, is at an angle \( \theta = \arctan(405 \text{ km/s}/v_r) \) with respect to the radial direction, the vorticity component of interest is \( \omega = \partial v_r / \partial x_\perp \), where \( v_r \) is the flow component along the Parker-spiral direction and \( x_\perp \) is the...
distance perpendicular to the Parker-spiral direction. At 1 AU the CIR vorticity layer is often less than 1 min thick as seen by a spacecraft, and sometime much thinner. The age of that shear layer at 1 AU is about \((1.5 \times 10^6 \text{ km})/(400 \text{ km/s}) = 10^4 \text{ h}\), with the plasma in the slow-wind side of the shear being older than 104 h and the plasma on the fast-wind side of the shear being younger than 104 h. An example of a very thin stream-interaction vorticity layer at 1 AU observed by the WIND spacecraft is shown in Figure 2. The small points are 3-s resolution measurements and the large points are 24-s measurements from the WIND 3DP instrument and the WIND MFI instrument. Plotted in blue (logarithmically, left axis) is the proton specific entropy \(S_p = T_p/n_p^{2/3}\) of the solar wind. At 18.514 UT (18:31 UT) an abrupt jump in \(S_p\) is seen. Simultaneously an abrupt increase in the proton flow velocity \(v||\) along the Parker-spiral direction is seen (red, right axis). The widths of the shear layer and entropy boundary are about 1000 km in the direction perpendicular to the Parker spiral. Note that the magnetic field strength (green, left axis) does not change across this velocity shear.

In Figure 3 a less-abrupt stream interface is examined, again with 3-s and 24-s measurements from the WIND spacecraft. The black vertical dashed lines demark the width of the stream interface, as measured by the transition of the proton specific entropy between the plasmas. Here the stream-interface width is about \(2 \times 10^4 \text{ km}\) perpendicular to the Parker-spiral direction.

In Figures 2, 3, the vorticity layers that are thought to originate at the Sun as the fast-slow wind boundary are intact at 1 AU, with no substantial spreading, and with no evidence of \(S_p\) being transported from one side of the velocity shear to the other. Borovsky (2006) in examining the minute-or-so thickness of stream-interface shear layers noted that thicknesses of \(\sim 10^4 \text{ km}\) are consistent with Bohm diffusion acting over the \(\sim 100\)-h lifetime of the solar-wind plasma. Arguments presented in Borovsky (2006) for MHD eddy viscosity (using the full fluctuation amplitude of the solar wind velocity and magnetic field and the typical correlation timescales) would produce spreading of the shear layers that are several orders of magnitude larger than \(10^4 \text{ km}\) in the 100-h lifetime of the solar wind. Similarly, Borovsky and Denton (2010) estimated the eddy-diffusion spreading width \(W_\perp\) in CIRs corresponding to the age of the solar wind at 1 AU and found that spreading width to be \(W_\perp \sim 2 \times 10^4 \text{ km}\) (about 2 h in duration in the solar-wind time series), which is two orders of magnitude wider than the \(1\)-min-thick vorticity layers.

Borovsky and Denton (2010) in examining the statistical properties of the solar-wind fluctuations across CIRs found that there was no systematic enhancement in the fluctuation amplitude within CIRs as might be expected if large-scale velocity shear was driving solar-wind turbulence. Rather, they found a quasi-monotonic transition of the fluctuation properties (amplitude, spectral indices, Alfvénicity, inward and outward \(Z^\text{in}\) and \(Z^\text{out}\) Elsasser properties, etc.) across CIRs from the characteristic properties of slow wind to the characteristic properties of the coronal-hole-origin fast wind. They concluded that there was not evidence for the driving of solar-wind turbulence in CIRs. Note that Borovsky and Denton (2010) only examined CIRs with a single prominent velocity shear so that they had no ambiguity in choosing a vorticity signature for the zero epoch of their superposed epoch analysis. In contrast to the Borovsky and Denton (2010) findings of no turbulence driving, Smith et al. (2011), based on an analysis of a quasi-equal balance of \(Z^\text{in}\) and \(Z^\text{out}\) inside of a CIR in comparison with the dominance of \(Z^\text{out}\) outside of the CIR, concluded that there is driving of turbulence within CIRs. (For MHD turbulence to be occurring both inward \(Z^\text{in}\) and outward \(Z^\text{out}\) Alfvén waves must be present (e.g. Kraichnan, 1965; Dubrowolny et al., 1980): normally in the solar wind the amplitude of inward Alfvén waves are weak, even in the noise of the measurements (e.g. Wang et al., 2018), and so an equal balance of inward and outward Alfvén waves would indicate robust turbulence.) (See also Bavassano and Bruno (1992) on \(Z^\text{in}\) in CIRs.) Borovsky and Denton (2010) (Fig. 16) also examined the \(Z^\text{in}\) and \(Z^\text{out}\) amplitudes across CIRs and, in contrast, found smooth transitions in the amplitudes across the CIRs from the systematic values in slow wind to the systematic values in fast wind; they found no enhancement of \(Z^\text{in}\) within the CIRs.

A question to consider is: If solar-wind turbulence is driven by large-scale shears in the solar wind (Bavassano and Bruno, 1989; Roberts et al., 1992; Goldstein et al., 1995) then why do these classic prominent shears survive to 1 AU? Note that an argument the shear is thinning because of compression is probably invalid since it will be shown later in this Section that the CIR volume compression is only about a factor of 2 and 2) the net expansion of the solar wind still overpowers the CIR compression of the solar-wind plasma (cf. Figure 4 of Hundhausen (1973)).

**Periodic Density Structures**

Periodic solar-wind structures with wavelengths in the “inertial subrange” of spatial structures survive to 1 AU without being...
destroyed by turbulence (Kepko et al., 2002; Kepko and Spence, 2003; Viall et al., 2009a; Di Matteo et al., 2019; Kepko and Viall, 2019; Birch and Hargreaves, 2020a,b).

These periodic solar-wind structures were first identified by examining the solar wind at Earth when spacecraft in the magnetosphere indicated that the magnetosphere was undergoing periodic compressions (Kepko et al., 2002); the solar-wind periodic structures are also responsible for periodic variations of the total electron content of the Earth’s ionosphere (Birch and Hargreaves, 2020a). Periodic density oscillations are found typically in slow solar wind with periods in the range of 4–140 min, corresponding to radial wavelengths of 8 × 10^5–3 × 10^6 km (Viall et al., 2008; Kepko et al., 2020), which are in the inertial range of scalesizes. Viall et al. (2009b) reports a periodic-structure interval wherein the alpha-to-proton number-density ratio α/p oscillates with the proton number density: the ion composition α/p variation is a firm indication that the number-density oscillation has its origin at the Sun. Indeed, the emission from the Sun of periodic density structures has been white-light imaged above the corona and out into the inner heliosphere (Viall et al., 2010; Viall and Vourlidas, 2015; DeForest et al., 2018). Proton number-density periodic structures are seen to persist in the solar wind well past 1 AU (Birch and Hargreaves, 2020b).

Three examples of periodic density structures in the solar wind at 1 AU (from the collection of events in Kepko and Spence (2003)) are plotted in Figure 4. In each panel the detrended proton number density n_p as measured by the 3DP instrument on the WIND spacecraft is plotted, with detrending performed by subtracting off a running average from the time series n_p(t). The detrending gives the density oscillation a zero mean makes the plotted periodicity and amplitude easier to see. The three events are from three different days. In Figure 4A a low-frequency periodic structure with a period of ∼70 min is seen (13 h plotted and density peaks marked with vertical red dashed lines), in Figure 4B a higher-frequency periodic structure with a period of ∼18 min is seen (11 h plotted), and in Figure 4C an even higher-frequency periodic structure with a period of ∼7 min is seen (2.5 h plotted). For each of the three panels of Figure 4 the observed periods were also identified by Kepko and Spence (2003) as localized peaks in the temporal Fourier transform of the non-detrended time series n_p(t).

Viall et al. (2021) review observations of periodic density structure moving outward from the corona into the inner heliosphere and review ideas about the solar origin of the periodic structure. They argue that various periodic (in space and in time) reconnection processes in the corona could be responsible for the creation of the density structures with various temporal periods: e.g. tearing instabilities (Revil et al., 2020), coronal acoustic oscillations driving reconnection (Pylaev et al., 2017), and growth-instability-release cycles for helmet streamers (Allread and MacNeice, 2015).

**Magnetic Structure Anisotropy**

Examination has found that when the solar-wind plasma is unidirectionally compressed or rarefied the magnetic structure takes on an anisotropy and that anisotropy does not appear to evolve back to isotropy as it should if turbulence was destroying and re-creating the magnetic structure. This is seen by analyzing the current-sheet orientations in the magnetic structure.

Figure 5 depicts the compression of the magnetic structure of the solar wind, with a Voronoi tessellation (Okabe et al., 2000) representing a cut through the spaghetti of magnetic flux tubes in the solar wind plasma. On the left is the Voronoi pattern representing the magnetic structure before the plasma is compressed, with the various flux-tube interiors shaded in different colors and with the current-sheet walls of the flux tubes denoted in black. The right panel of Figure 5 depicts the Voronoi pattern after it is compressed in the horizontal direction by a factor of 4. Note the systematic flattening of the flux tubes by the compression and the systematic change in the orientations of the current sheets.

When a spacecraft crosses a current sheet in the solar wind, the time series of magnetic-field measurements can be used to determine the orientation of the sheet using the cross-product method (Burlaga and Ness, 1969; Knetter et al., 2004; Borovsky, 2008). At 1 AU the orientations of the normals to the strong current sheets of the solar wind are approximately isotropic perpendicular to the Parker-spiral direction (Borovsky, 2008). (Here, “strong” means that the magnetic-field rotation angle across the current sheet is about 30° or larger (cf. Borovsky, 2008)). This is consistent with cylindrical-shaped magnetic flux tubes that are approximately aligned with the Parker-spiral direction (Borovsky, 2010), although the flux-tube cross sections should look more like a Voronoi cell rather than being circular. In compressed or rarefied solar wind at 1 AU, the current-sheet orientations are no longer consistent with cylinders, but show a flattening of the flux-tube cross...
sections. Using a cylindrical-tube model, Figure 6 shows the expected anisotropy of the current sheets as a function of the amount of compression or rarefaction. If in the absence of compression or rarefaction the flux tubes are cylindrical (round), then a spacecraft going through these tubes would find that the mean angle between the current-sheet normals and the ecliptic plane would be 32.7° (cf. Fig. A1 of Borovsky and Denton, 2016). This value is plotted in Figure 6 for the volume compression or volume rarefaction factor being 1. The red curve in Figure 6 for compression shows that as the amount of compression increases the mean angle of the current-sheet normals from the ecliptic plane for squashed cylinders becomes less as the flux tubes flatten. The blue curve in Figure 6 for rarefaction shows that the greater the amount of rarefaction the greater the mean angle is from the ecliptic plane as the cross sections of the flux tubes are stretched.

Figures 7, 8 demonstrate this effect for compressions and rarefactions of the solar wind. Figure 7 plots superposed-epoch averages for 27 corotating interaction regions as measured by the SWEPAM and MAG instruments on the ACE spacecraft. The zero epoch (vertical dashed line) in Figure 7 is the time that the CIR stream interface (located by the peak in the vorticity) passes ACE. The CIR spans the time from about −1 day to about +1 day. Figure 7A plots the radial flow velocity of the solar wind: a transition is made from slow solar wind on the left to fast (coronal hole) solar wind on the right. Figure 7B plots the superposed average of the magnetic-field strength $B_{\text{mag}}$. $B_{\text{mag}}$ can be used as a measure of the compression normal to the Parker-spiral direction in the CIR. Comparing $B_{\text{mag}}$ in the uncompressed slow solar wind about 1 day before the passage of the stream interface (lower red dashed curve) to the peak value of $B_{\text{mag}}$ in the CIR (upper red dashed curve) yields an amplification of $B_{\text{mag}}$ by a factor of 2.0, which corresponds to a volume compression factor of 2.0. This value is marked in Figure 6 by a large red point, which corresponds to a predicted mean angle of current-sheet normals of 20.7°. In Figure 7C the superposed average of the measured current-sheet orientations in the solar wind is plotted. Before the CIR compression and after the CIR compression the mean angle is in the ballpark of 32°, as expected for isotropic orientations of the current sheets. At the center of the CIR where the plasma has been compressed by a volume compression factor of about 2.0, the mean angle has decreased from about 32° to about 26°.

Figure 8 plots superposed-epoch averages for 54 high-speed-stream trailing-edge rarefaction regions as measured by the SWEPAM and MAG instruments on the ACE spacecraft. The zero epoch (vertical dashed line) in Figure 7 is the time that the trailing-edge stream interface (located by the inflection point in the solar-wind speed) passes ACE. The trailing-edge rarefaction
spans the time from about \(-2\) day to \(+2\) day. Figure 8A plots the radial flow velocity of the solar wind: the infection point of the velocity curve at time \(t = 0\) marks the actual boundary between coronal-hole-origin plasma before the infection point and streamer-belt-origin plasma after the infection point (Borovsky and Denton, 2016). Figure 8B plots the superposed average of the magnetic-field strength \(B_{\text{mag}}\). Comparing \(B_{\text{mag}}\) in the unrarefacted fast solar wind about 2 days before the passage of the stream interface (upper blue dashed curve) to the minimum value of \(B_{\text{mag}}\) in the rarefaction (lower blue dashed curve) yields a reduction of \(B_{\text{mag}}\) by a factor of 1.9, which corresponds to a volume rarefaction factor of 1.9. This is marked in Figure 6 by a large blue point, which corresponds to a predicted mean angle of current-sheet normals of 45°. Figure 8C plots the superposed average of the measured current-sheet orientations in the solar wind. Before the rarefaction and after the rarefaction the mean angle is in the ballpark of 32°, as expected for isotropic orientations of the current sheets. At the center of the rarefaction where the plasma has been rarefied by a volume rarefaction factor of about 1.9, the mean angle has increased from about 32° to about 40°.

In Figures 7, 8 the change in the mean current-sheet-normal angle from the ecliptic plane was not as much as predicted for the estimated amount of compression or rarefaction: for compression the mean angle change was 32°→26° while the prediction was 32°→21° and for the rarefaction the mean change was 32°→40° while the prediction was 32°→45°. But the predictions were for
compressions and rarefactions in the ecliptic plane without north-south components, whereas typical CIRs have tilted fronts with strong north-south components to the compression (e.g. Pizzo, 1991; Gosling and Pizzo, 1999). Thus the predicted changes in the mean angle from the ecliptic plane are too strong.

Another generator of anisotropy of the magnetic structure occurs as the Parker-spiral becomes strongly wound past ~1 AU and the solar-wind expansion is anisotropic with respect to the Parker-spiral direction. The steady-speed solar-wind plasma expands poloidally and toroidally but not radially. Near the Sun the plasma expands in both directions that are perpendicular to the near-radial Parker-spiral direction (poloidal and toroidal), but beyond 1 AU the Parker-spiral direction is nearly toroidal and there is expansion in one perpendicular direction (poloidal) but not the other (radial). The resulting flux-tube cross-section evolution (for passive flux tubes in the equatorial plane) is sketched in Figure 9A for a flux tube that has a circular cross section near the Sun. In Figure 9B the vector tips of the unit normals of current sheets observed at 1 AU by ACE MAG are plotted on the unit sphere viewed along the nominal Parker-spiral direction. A quasi-isotropic distribution perpendicular to the Parker-spiral direction is seen. In Figure 9C the unit normals of current sheets observed at 5.2–5.4 AU (but within 5° of latitude of the solar equator) by Ulysses VHM are plotted on the unit sphere viewed along the nominal Parker-spiral direction, showing the evolution from quasi-isotropy at 1 AU to strong anisotropy at 5 AU, as predicted in the top panel for the mapping of passive magnetic structure in the solar-wind expansion. Figure 9D plots the normalized occurrence distribution of the angles between each current-sheet normal and the solar equatorial plane: the concentration of normals parallel to the equatorial plane at 5 AU is clearly seen. If the ubiquitous current sheets of the solar wind beyond 1 AU were created by the action of MHD turbulence, then the current-sheet normals should be distributed isotropically about the mean-field direction (i.e. about the Parker-spiral direction).

Finally, a similar persisting anisotropy is measured when interplanetary shocks compress the solar-wind plasma (Borovsky, 2020a). The systematic anisotropy is difficult to measure using the average orientation of the current sheets because the direction of the compression is difficult to determine for the interplanetary shocks. Instead, flux-tube flattening can be quantified by looking at the change in direction of the current sheet normal from one current-sheet crossing to the next current-sheet crossing. If flux tubes become flattened, then the two normals will be similarly aligned. The angular change $\Delta \alpha$ from one unit normal $\mathbf{n}_1$ to the next unit normal $\mathbf{n}_2$ is given by the dot product between the two normals: $\Delta \alpha = \arccos(\mathbf{n}_1 \cdot \mathbf{n}_2)$. In Figure 1 the statistical trends for the $\Delta \alpha$ values upstream and downstream of 109 interplanetary shocks are examined as a function of the time since the plasma was shocked $\tau_{age}$. The green curve is a 600 point running average of the $\Delta \alpha$ values for all of the collected current-sheet pairs and the red curve is a 600-point running median of the $\Delta \alpha$ values for all of the collected pairs. As can be seen, the mean and median values of $\Delta \alpha$ make transitions to lower values going from the upstream (uncompressed) plasma to the downstream (compressed) plasma. Note that with time in the downstream plasma the $\Delta \alpha$ values do not return to the upstream values. I.e. the anisotropy of the magnetic structure produced by shock compression does not return toward isotropy in the 10’s of hours after the plasma gets its compression. These times are much longer than the few-hour estimate of the lifetime of solar-wind-turbulence-produced current sheets (Yang et al., 2017), which would show an isotropy after a few hours.

### Ion-Composition Boundaries and Their Co-Located Current Sheets

Borovsky (2020b) examined 637 boundaries of the alpha-to-proton number-density ratio $a/p$ at 1 AU using the SWEPAM and MAG instruments on ACE and the SWE and MFI instruments on WIND, with a $a/p$ boundary defined as a distinct (well above the measurement noise level) temporal step in the $a/p$ time series. In the two panels of Figure 10 the superposed epoch average of the angular change $\Delta \theta$ of the magnetic-field direction is plotted with the zero epoch (vertical dashed line) being the crossing of the $a/p$ ion-composition boundary. Figure 10A plots the superposed average of the 315 boundary crossings measured by ACE in green and the 322
boundary crossings measured by WIND in red. For both sets of ion-composition boundaries, the temporal change in the field direction $\Delta \theta$ is much greater at the time of the boundary crossing than it is away from the boundary crossing. This indicates the statistical co-location of strong current sheets in the solar wind at the locations of the ion-composition boundaries. This is explored in Figure 11, where the distribution of magnetic-field angular-change values $\Delta \theta$ at the locations of the a/p boundaries is plotted in red and the distribution of $\Delta \theta$ values two data points before and after the a/p boundaries and two data points after is plotted in blue. The red curves in Figure 11 represent a population of strong (large-angular-change) current sheets and the curves in blue represent random locations in the solar wind, where occasionally there can be a strong current sheet (cf. Figure 3 of Borovsky (2008) or Figure 4 of Borovsky (2020b)). In Figure 10B the superposed epoch average of the magnetic-field direction is plotted separated into the type of solar-wind plasma in which each boundary was found using the Xu and Borovsky (2015) solar-wind categorization scheme. The superposed average for the boundaries in coronal-hole-origin plasma are plotted in blue, boundaries in streamer-belt-origin plasma are plotted in red, and boundaries in sector-reversal-region plasma are plotted in purple. All three plasmas show that a/p ion-composition boundaries are statistically co-located with strong current sheets in the solar wind.

Each alpha-to-proton composition boundary comes from the corona: such ion-composition boundaries cannot be formed in the solar wind away from the Sun. The ion-composition boundaries seen at 1 AU are co-located with strong current sheets (flux-tube walls). Unless there is a mechanism to form current sheets on ion-composition boundaries, those co-located current sheets seen at 1 AU also came from the corona. The ion-composition boundary and current sheet could be subject to stretching and folding by turbulence in the solar wind, but not in a manner that would destroy the current sheet. Note however, a study to specifically quantify the amount of stretching and folding that occurs between 0.3 and 1 AU (Borovsky, 2012a) found no evidence for any stretching and folding.

**Strahl-Intensity Boundaries and Their Co-Located Current Sheets**

Borovsky (2020b) examined 351 boundaries in the intensity of the electron strahl at 1 AU using the SWE and MFI instruments on WIND, with a strahl boundary defined as a distinct (well above the measurement noise level) temporal step in the logarithm of the flux of the electron strahl measured at 203 eV. In Figure 12 the superposed epoch average of the angular change $\Delta \theta$ in the magnetic-field direction is plotted for the 351 strahl-intensity boundaries, with the zero epoch (vertical dashed line) being the crossing of the strahl boundary. The temporal change in the field direction $\Delta \theta$ is much greater at the time of the strahl boundary crossing than it is away from the boundary crossing. This indicates the statistical co-location of strong current sheets in the solar wind at the positions of the strahl-intensity boundaries. A figure revealing the strong-current-sheet population seen at the strahl-intensity boundaries (equivalent to Figure 11 for the a/p boundaries) can be seen in Figure 7 of Borovsky (2020b).

If the change in strahl intensity at 1 AU is caused by a change in the magnetic connection location back into the corona, then the observation of current sheets co-located with the strahl change is consistent with the current sheet at 1 AU being coherent (intact) all the way back to the Sun.

If the change in strahl intensity at 1 AU is caused by a change in the amount of scattering of the strahl electrons between the Sun...
and 1 AU (cf. Borovsky, 2021), and the current sheet seen at 1 AU is not coherent back to the Sun, then a mechanism is needed that would cause a current sheet to form at the location of the strahl-intensity change.

**Non-Evolving Alfvénic Magnetic Structure**

In the fast and slow Alfvénic solar wind, it is observed that the magnetic structure moves en masse relative to the proton plasma at a speed of about 0.7 $v_A$, where $v_A$ is the measured Alfvén speed. In the Alfvénic regions, one can analyze an hour or so of measurements at 1 AU and find a single reference frame for that hour or so of solar wind that has the proton flow vector everywhere parallel to the local magnetic field vector (Borovsky, 2020c; Nemecek et al., 2020). This is the reference frame moving with the magnetic structure. In the reference frame of the magnetic structure, to within measurement error all proton flows $v$ are parallel to the local magnetic-field direction $B$. With $v_L = 0$ there is (to within measurement error) no time evolution of the structure. Seeing $v_L = 0$, when riding in the reference frame of outward-propagating Alfvénic structure also means that no inward-propagating Alfvén waves are seen, consistent with $Z^{th} = 0$ (e.g. Wang et al., 2018), where $Z^{th}$ is the amplitude of the inward Elsasser variable.

A 2-h-long example is shown in Figure 13 where 3-s-resolution velocity measurements from WIND 3DP are shifted into the reference frame of the magnetic structure, which for this time interval was found to move at the constant velocity $v_{mag} = (708.27, -19.54, -10.78)$ km/s (in RTN coordinates) with respect to the frame of the Sun. In Figure 13A the RTN velocity of the proton flow $v^*$ is plotted for the 2 h in the reference frame of the magnetic structure, where $v^*(t) = v(t) - v_{mag}$ with $v(t)$ being the measurements from WIND 3DP. Using 3-s-averaged magnetic-field measurements $B(t)$ from WIND MFI, a 3-s time-resolution unit vector of the magnetic field direction $b(t) = B(t)/B_{mag}(t)$ is created. In Figure 13B the proton flow velocity parallel and perpendicular to the local magnetic-field direction is plotted, where $v_{||}(t) = v^*(t) \cdot b(t)$ and $v_{\perp}(t) = v^*(t) - v_{||}(t) b(t)$. For this 2-h interval, the mean value of $v_{||}$ is 54.6 km/s and the mean value of $v_{\perp}$ is 4.7 km/s. The parallel-to-$B$ flow is everywhere Sunward in the reference frame of the magnetic structure. (Note in magnetic switchbacks in the Alfvénic structure that this Sunward flow is maintained, where “Sunward” means “in the direction along the magnetic field that leads to the Sun” (cf. Figure 7 of Borovsky, 2020d)).

In Figure 13B a large source of the $v_{\perp}$ measured in the reference frame of the magnetic structure comes from the fact that the magnetic-field direction varies during the 3-s 3DP measurement of the flow vector confusing parallel and perpendicular with respect to $B$. If the actual flow was strictly parallel to $B$, the measurements of the flow will pick up a perpendicular component owing to the error in knowing the direction of $B$ through the 3-s particle measurement interval. For the 2-h interval of Figure 13B the rms value of the 3-s angular change in the magnetic-field direction is $\Delta \theta_{3-s} = 5.9^\circ$: taking the $v_{\perp}$ error to be $v_{||}\sin(\Delta \theta_{3-s})$ with $\Delta \theta_{3-s} = 5.9^\circ$ and with $v_{||} = 54.6$ km/s yields 5.6 km/s as an estimate of the amount of $v_{\perp}$ coming from a projection of $v_{||}$ attributable to the motion of the field direction during the collection of the proton distribution function to obtain a velocity measurement. This is comparable to the rms value of $v_{\perp}$ plotted in Figure 13B.

Note that the error estimate for a large actual $v_{||}$ going into a false $v_{\perp}$, plus an error estimate for the accuracy of the proton flow vector measurements, may be a method to determine the errors in the measured values of the inward Elsasser variable $Z^{th}$ of the solar wind (cf. Wang et al., 2018).

The analyses of Borovsky (2020c) and Nemecek et al. (2020) find that a large-spatial-scale region of the Alfvénic solar wind has a magnetic structure that propagates at a single vector velocity without evolution. Hence, the magnetic structure in the Alfvénic solar wind is an example of the Chandrasekhar dynamic equilibrium (CDE) (cf. Fig. 7.1 of Parker (1979)) where a nonlinear tangle of magnetic field will propagate en masse without evolution provided that the flow is everywhere parallel to the local field (See also Birn (1991) and Tenerani et al. (2020)). In the case of the solar wind the nonlinear tangle of field is a spaghetti flux-tube magnetic structure with current sheets. The large abrupt velocity shears that are ubiquitous in the Alfvénic solar wind (Borovsky, 2012a) are parallel-to-$B$ flows in a magnetic structure with sudden changes in the field direction from tube to tube.
Note that the alpha particles (and probably the heavy ions) in the solar wind are approximately at rest in the reference frame of the magnetic structure (Nemecek et al., 2020) that moves at a speed of less than $v_A$ through the proton plasma.

**DISCUSSION**

Questions are raised about the nature of the solar wind in the inner heliosphere and a call is made for future solar-wind measurements.

**Turbulence and Non Turbulence in the Solar Wind**

There are many indications that the $v$ and $B$ fluctuations observed in the solar wind are manifestations of turbulence: notably the observed Fourier spectra (Tu and Marsch, 1995; Podesta, 2010), the fact that the fluctuations have extremely high Reynolds numbers (Neugebauer and Snyder, 1966; Borovsky and Gary, 2009), the results of third-order-moment analysis (Smith et al., 2009; Hadid et al., 2017), and evolution with distance of the low-frequency Fourier breakpoint (Feynman et al., 1996; Bruno et al., 2005; Bruno and Carbone, 2013). Table 1 summarizes various types of structures in the solar wind that are not destroyed by turbulence: the implications of the survival of structure are that turbulence is not always the dominant mechanism operating in the solar wind between the Sun and 1 AU. Some questions are raised. Why is turbulence not destroying and regenerating structure? What is the nature of the solar-wind fluctuations and why do they look like turbulence? A possibility is that the fluctuations seen at 1 AU are fossils of turbulence from near the Sun that has relaxed (Dobrowolny et al., 1980; Matthaeus et al., 2008, 2012; Servidio et al., 2014; Telloni et al., 2016) either to a non-Alfvénic state that is advecting with the solar-wind plasma or to a $v=B$ aligned Alfvénic state that is propagating outward from the Sun. Another possibility (cf. Sect. 7.2 of Parker, 1979) is that there is a region near the Sun where turbulence is being driven and some of the outward-Alfvénic components of the turbulence are radiating out from the driving region to escape into the solar wind, carrying statistical properties of the driven near-Sun turbulence.

Borovsky et al. (2021) found that the core-electron temperature of the solar wind is structured with the magnetic structure of the solar wind for all major types of solar-wind plasma. Thus it is seen that differing magnetic flux tubes have differing core-electron temperatures, with temperature jumps from tube to tube. A common interpretation of the core-electron temperature is that it is a direct measure of the local interplanetary electric potential (Feldman et al., 1975; Boldyrev et al., 2020; Moncuquet et al., 2020). This being the case along with the electron-temperature differences, individual flux tubes would have independent exospheric models operating inside of them driving solar-wind acceleration. If a plasma system is defined as multiple subsystems of interacting particle populations (such as the Earth’s magnetosphere (Borovsky and Valdivia, 2018)), then each solar-wind flux tube seen at 1 AU is an independent system and the measured parameters from flux tube to flux tube are independent realizations of system evolution.

Many features (e.g. Table 1) in the solar wind time series are inconsistent with turbulence. Hence, there might be some caution in taking a statistical description of the solar-wind time series (i.e. a Fourier power spectral density, an autocorrelation function, third-order moments, etc.) and interpreting the entirety of the statistical description as a measures of the properties of turbulence. (Cf. Figure 8 of Viall and Borovsky (2020).) At least, the effects of the “definitely-not-turbulence” features in the time series on the statistical picture should be understood and not interpreted as turbulence.

**Future Studies**

Another solar-wind feature that can be examined with existing data sets are proton-number-density boundaries and their co-located strong current sheets (Razantseva et al., 2005; Safrankova et al., 2013a; Zastenker et al., 2014). A statistical examination of their thickness versus distance from the Sun in comparison with the expected action of Bohm and gyro-Bohm diffusion (Perkins et al., 1993; Hannum et al., 2001; Borovsky, 2006) can yield indications of their age compared with the age of the solar-wind plasma.

A major impediment to identifying at 1 AU structure that has it origin in the corona is a lack of accuracy of solar-wind measurements. It is critical to be able to unambiguously detect subtle changes in the particle populations (protons, heavy ions, electrons) across solar-wind current sheets. In this manner every current sheet can be assessed as to it possible origins. As it is now, only current sheets with strong changes (above the instrument noise) in the particle populations can be identified as solar origin. Future progress on understanding the nature of the structure of the solar wind calls for the deployment of low-noise, high-accuracy, high-time resolution particle measurements on a single spacecraft in the solar wind. Coordinating plasma, ion-composition, and electron boundaries with the magnetic structure of the solar wind is at present difficult owing to counting-statistics noise in the existing particle measurements. In the available solar-wind data sets only the most-robust particle boundaries can be identified, the majority of boundaries are lost in the noise of the measurements. Improved instruments with large geometric factors are needed to obtain sufficient counting statistics to make low-noise measurements in short measuring times. Breakthroughs in the observation of the structure of the solar wind will be possible with such precision measurements of the a/p ion composition, the heavy-ion charge-state composition, and the electron strahl intensity.

Similarly, large-geometric-factor proton measurements would enable faster resolution of proton velocity vectors with less movement of the magnetic-field vector during a measurement sequence, resulting in flow proton vectors that are sufficiently accurate to determine whether inward Elsasser variables represent inward Alfvén waves versus noise. In the standard model of solar-wind turbulence (e.g. Matthaeus et al., 1994, 2020; Goldstein et al., 1995; Horbury et al., 1996; Bruno et al., 2005; Petrosyant et al., 2010) large-scale static (non-evolving) structures in the energy-containing scales of the solar wind transfer energy.
across the low-frequency Fourier breakpoint to dynamic (interacting, evolving) structures in the inertial range of the solar wind. An outstanding question asks whether the structures in the inertial range are dynamic (evolving) or static (non-evolving), and under what conditions? Much needed accurate measurements of the inward-Elssasser amplitudes could answer this. For the proton measurements, multi-instrument techniques such as the Spektr-R BMSW instrument (Safrankova et al., 2013b; Zastenker et al., 2013) that reduce energy sweep time may be a path forward.

The solar wind is a scientifically invaluable astrophysical plasma. A main difficulty is that it the plasma passes a spacecraft at an extremely high velocity making measurements of the detailed structure challenging. The scientific community needs to focus on fast accurate measurements to take advantage of this unique opportunity.

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AUTHOR CONTRIBUTIONS

JB initiated this project, performed the analysis, and wrote the manuscript.

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