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Switchbacks, microstreams, and broadband turbulence in the solar wind

Special Collection: Plasma Physics of the Sun in Honor of Eugene Parker

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ABSTRACT

Switchbacks are a striking phenomenon in near-Sun coronal hole flows, but their origins, evolution, and relation to the broadband fluctuations seen farther from the Sun are unclear. We use the near-radial lineup of Solar Orbiter and Parker Solar Probe during September 2020 when both spacecraft were in wind from the Sun's Southern polar coronal hole to investigate if switchback variability is related to large scale properties near 1 au. Using the measured solar wind speed, we map measurements from both spacecraft to the source surface and consider variations with source Carrington longitude. The patch modulation of switchback amplitudes at Parker at 20 solar radii was associated with speed variations similar to microstreams and corresponds to solar longitudinal scales of around 5°–10°. Near 1 au, this speed variation was absent, probably due to interactions between plasma at different speeds during their propagation. The alpha particle fraction, which has recently been shown to have spatial variability correlated with patches at 20 solar radii, varied on a similar scale at 1 au. The switchback modulation scale of 5°–10°, corresponding to a temporal scale of several hours at Orbiter, was present as a variation in the average deflection of the field from the Parker spiral. While limited to only one stream, these results suggest that in coronal hole flows, switchback patches are related to microstreams, perhaps associated with supergranular boundaries or plumes. Patches of switchbacks appear to evolve into large scale fluctuations, which might be one driver of the ubiquitous turbulent fluctuations in the solar wind.

I. INTRODUCTION

Eugene Parker's conceptual model of the generation of the solar wind[1] has been amply verified by observations over the past six decades. Nevertheless, major open questions remain about the energization and acceleration of the wind, and it has become clear that even within apparently smooth flows from coronal holes, there is considerable dynamics that contain a non-trivial fraction of the total kinetic energy and momentum. The most dramatic of these are switchbacks, which are discrete, impulsive, anti-Sunward propagating Alfvénic fluctuations. At tens of solar radii ($1R_S = 7 \times 10^5$ km), the amplitude of the magnetic field deflection can be larger than the field magnitude and, hence, the magnetic field can fully reverse, leading to bulk speed enhancements of up to twice the local Alfvén speed, V_A; therefore, switchbacks carry significant momentum and kinetic energy and appear to be an important aspect of the solar wind, at least from coronal holes, and perhaps more widely. Early observations of switchbacks[2,3] by Parker Solar Probe (PSP) at $\approx 36\, R_S$ revealed them to be short, on timescales of seconds to minutes, to generally occur in "patches" lasting several hours that are separated by quieter regions of near-radial magnetic field, for nearby structures to be statistically correlated,[4] and to be long, thin structures aligned along the magnetic field.[5,6]

Despite the clear importance of switchbacks to the energetics of the solar wind, their origin is unclear, with two general classes of theory: that they spontaneously generate from a wave field[7,8] or flow shear[9,10] or that they are the result of discrete reconnection events, for example, interchange reconnection or nano-scale jets[11,12] near the Sun. There is extensive evidence of near-Sun reconnection, over a broad range of spatial and temporal scales: individual jets can be resolved on scales of hundreds of kilometers and hundreds of seconds.[13] On far larger scales, coronal jets can last hours[14,15] and plumes—larger scale patches of enhanced emission in coronal holes, often associated with the supergranular network[16]—can last hours to days.[15]

Waves pervade the corona and solar wind and as Alfvén waves propagate from the Sun to the Alfvén critical point (at $r \sim 10$–$15R_\odot$) and beyond, the conservation of wave action causes their amplitudes to increase, and the fractional magnetic-field fluctuation $\delta B/B_0$ to grow to values comparable to unity. However, it does not appear possible for a magnetic field that depends on three spatial coordinates to satisfy both $|\mathbf{B}| =$ constant and $\delta B/B_0 \sim 1$ without developing discontinuities.[17,18] As a consequence, the growth in wave amplitudes combined with the nonlinear drive toward spherical polarization is a possible mechanism for producing abrupt magnetic-field rotations, which might explain the switchbacks observed by Parker Solar Probe: expanding-box numerical simulations designed to emulate the expanding solar wind[2,7,8,19,20] showed that this mechanism does indeed produce abrupt field rotations and B_r reversals out of an initially smooth Alfvén-wave field near the Sun.

Since reconnection exhausts also generate Alfvénic fluctuations that could themselves evolve,[7] it appears difficult from the available evidence unambiguously to distinguish a reconnection or wave-driven origin for individual switchbacks at this time. Their occurrence in patches, however, is important additional evidence for their origin, since it suggests that the source of energy for the switchbacks itself varies within an individual stream. It has previously been argued[21,22] that structures within solar wind streams between 0.3 and 1 au could be signatures of coronal structures such as supergranules: in this work, we attempt to link switchbacks and patches observed by PSP within 20 R_S to those seen farther from the Sun.

Beyond their origin, the relationship of switchbacks to the broadband waves and turbulence routinely observed farther from the Sun[23,24] is not well established, even though the energy associated with near-Sun switchbacks must, in some way, ultimately reside in the observed fluctuations and plasma farther from the Sun. While turbulence evolves with distance[25] and switchbacks can certainly be observed farther from the Sun, at tens of R_S,[12] near Earth[26] and even beyond,[27] they are typically longer duration and far less numerous farther from the Sun[28,29] and so the fate of the majority of these structures, and indeed the patch structure itself, is not clear.

The sixth PSP encounter (E6) in September 2020 provided an unprecedented opportunity to shed light on the questions above. Perihelion was at 20 R_S; PSP was at around 4°S heliolatitude at perihelion and stayed within wind from the Sun's Southern polar coronal hole for several days. Recently, Ref. 30 has shown that near the E6 perihelion, quasi-periodic enhancements in the solar wind speed were associated with patches of switchbacks and, crucially, an increase in the alpha particle fraction. Since the alpha particle fraction is fixed at the Sun and does not change as the wind propagates, this demonstrates unambiguously that the switchback patches are associated with regions near the Sun with different properties to those elsewhere. References 30 and 31 argued that their longitudinal scale, of around 5°, is consistent with that of the supergranular network. Reference 30 also argued that the presence of suprathermal ions within patches suggested a reconnection-based origin for switchbacks.

At the same time as PSP's E6 perihelion, Solar Orbiter was at 208 R_S and 7°S at a similar inertial longitude and measured wind from the same coronal hole. Although they did not generally measure the same parcel of solar wind, both spacecraft encountered wind from almost the same solar source. In this paper, we consider the variations in solar wind properties measured at both PSP and Orbiter in order to understand more about the spatial variability of patches, switchbacks, and solar wind structure and how they evolve with solar distance.

II. MEASUREMENTS AT 20 AND 200 SOLAR RADII

Parker Solar Probe measurements during the encounter are shown in Fig. 1, with magnetic field data from the FIELDS instrument[32] and ion data from the SWEAP SPAN-I ion sensor.[33] Many switchbacks were present in this period[30] and they can be seen here as short sharp enhancements in the solar wind speed and radial magnetic field component, although on this scale, many events are not resolved. Of note for this work is the quasi-periodic variation in wind speed on scales of a few hours between the 26th and 29th of September, with speed increases being associated with enhancements in the amplitude of switchbacks, most visible in the V_R time series (top panel) and also slight $|B|$ decreases (fifth panel). These periods of enhanced switchback amplitude, associated with overall higher speed, as often referred to as patches. This overall structure is not radically different to earlier perihelia,[2,3] but here the correlation between switchback amplitude and speed is clearer than in those encounters. This might be the result of the closer perihelion distance in this encounter, the sampling of a rather different solar wind stream, the more rapid spacecraft motion in this encounter, or a combination of the three.

Reference 30 has shown that these speed enhancements are also associated with increases in alpha particle fraction. These speed variations are similar to "microstreams" seen in coronal hole flows over the Sun's poles[34] and also in Helios data at 0.3 au, where alpha particle fraction was also seen to vary.[21]

Solar Orbiter data are shown in Fig. 2: for clarity, blue is used for Orbiter data, and red for PSP, throughout this paper. Magnetic field[35]

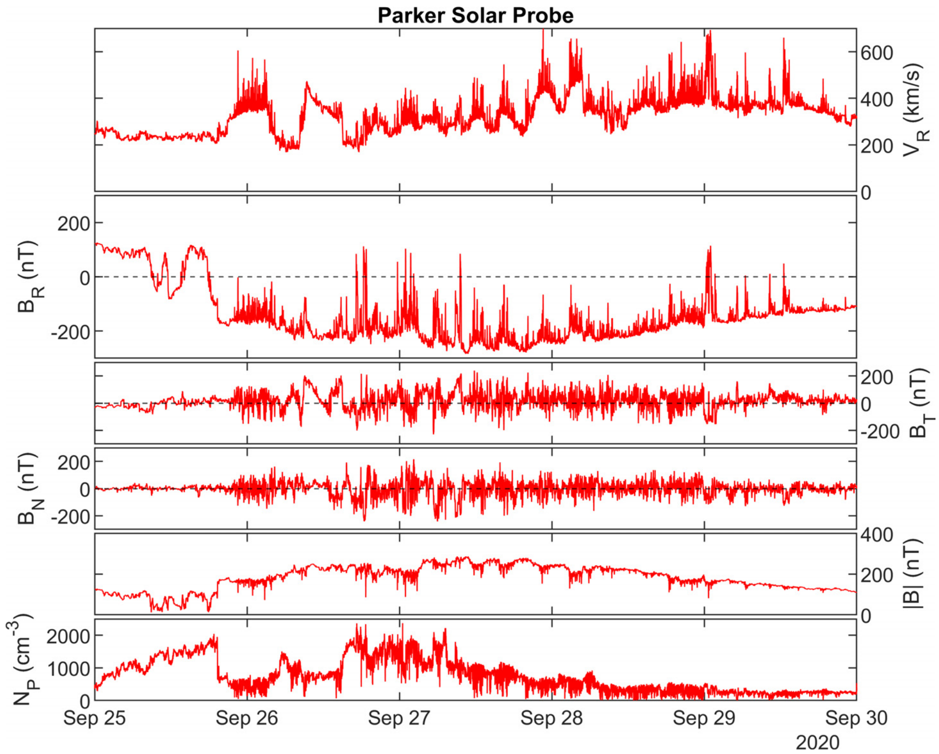

FIG. 1. Magnetic field and plasma measurements from Parker Solar Probe during encounter 6. From top to bottom, panels are radial proton speed; radial, tangential, and normal magnetic field components; field magnitude; and proton number density.

and SWA PAS sensor proton[36] measurements are shown. The Orbiter measurements are generally unremarkable for 1 au data, showing a medium speed solar wind stream with large amplitude Alfvénic fluctuations. From the middle of the 26th of September, Orbiter was in a "trailing edge," with a slowly decreasing solar wind speed. During this time, there were distinct large scale field fluctuations on scales of 6–12 h.

III. SPATIAL SCALES IN THE SOLAR WIND

Movement of the source region due to rotation of the Sun, combined with finite plasma propagation speeds, non-zero spacecraft motion and en route dynamics, makes it challenging to determine the origin of a solar wind parcel. Here we make a simple attempt, using "ballistic mapping,"[37] as has previously been used for this encounter:[25,30] for each spacecraft data point taken at a time t, distance r, and instantaneous Carrington longitude ϕ_C, we assume radial solar wind propagation and, using the (15 min smoothed) measured radial wind speed V, calculate the time taken to propagate from a $r_0 = 2.5\,R_S$ source surface and using the solar rotation rate Ω, we calculate the corresponding source longitude

$$\phi_S(t) = \phi_C(t) + \Omega \times (r(t) - r_0)/V(t). \quad (1)$$

The results of this procedure are shown in Fig. 3: unlike all previous spacecraft, PSP supercorotates near perihelion and so sampled longitude in the opposite sense to Orbiter. Small changes in the rate of change of ϕ_S, due to speed changes, are visible at both spacecraft and can lead to "dwells"—periods when the source longitude does not vary over 1 h or more—and also occasional short reversals in the sense of the mapping, which are due to relatively sharp velocity declines. Such features, at larger scale, are long established in the solar wind.[37]

While this mapping procedure is very crude, it is adequate for our purposes, which is to compare scales between the two spacecraft: we are not attempting to match particular features. As we will see, there is evidence for significant acceleration of the wind between the two spacecraft and the simple mapping we use assumes a constant speed, so there will be additional systematic errors in our source longitude estimates. This is likely to be a few degrees: for example, a 50 km/s error in the Orbiter wind speed leads to a $\approx 5°$ error in ϕ_S.

Both spacecraft measured wind from the same source longitudes over a period of a few days; here we consider source Carrington longitudes between 245° and 290°, a period when the two spacecraft were also separated by just a few degrees in latitude. Note that although both spacecraft measured wind from approximately the same source Carrington longitude (and very similar latitude) at the start of the 28th of September, because of their different solar distances and hence wind travel times, the plasma that arrived at Orbiter left the Sun around 3 days earlier than that at PSP so we rely on the statistical properties of source features not changing over the period of the encounter by both spacecraft.

While the source region was not visible from Earth during this encounter and the Solar Orbiter telescopes were not operating, SDO/AIA data from earlier in September show a stable Southern polar coronal hole at these longitudes, with multiple plumes and jets visible. Given the lifetimes of such structures of hours to days,[14,38] we would therefore not necessarily expect to be able match anything measured at PSP or Orbiter to an individual structure for this encounter. Indeed, it has recently been argued[39] that switchback patches might also have

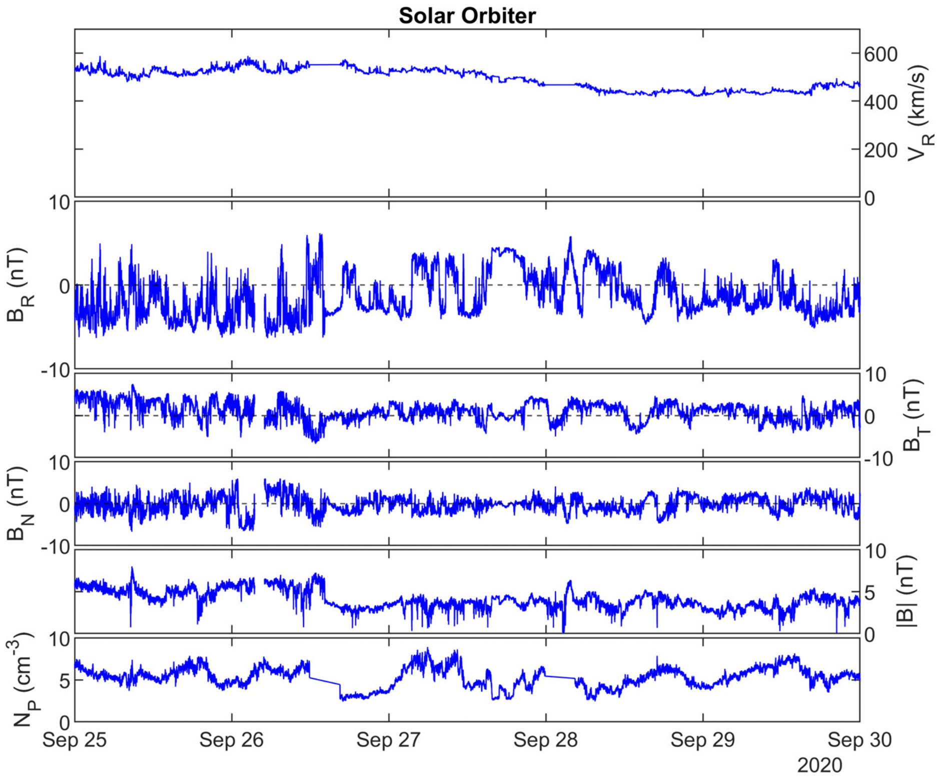

FIG. 2. Magnetic field and plasma measurements from Solar Orbiter in the same format as Fig. 1.

similar lifetimes, again suggesting that we should also not expect to match individual structures between the two spacecraft.

Data from both spacecraft, plotted with respect to ϕ_S, are shown in Fig. 4: the sub-corotating Orbiter data are effectively reversed compared to the time series, while that from PSP are not. Again, we are not trying to match individual features between the two data sets, but rather to consider the spatial scales in each. The regions of enhanced speed at PSP (e.g., from 263° to 267°) have, if anything, sharper edges than in the time series (cf. Fig. 1) as a result of the smooth speed variation at their edges, similar to that of trailing edges of high speed stream at larger distances.[40] These higher speed regions at PSP have scales of a few degrees in longitude, consistent with earlier observations of microstreams in coronal hole flows[34] and, indeed, of the typical separation of plumes in coronal holes.[15]

The speed variations at PSP are not present at Orbiter, presumably due to the interaction of the varying speed wind parcels as they travel to 1 au. There is more large scale density and field magnitude variation at Orbiter than at PSP, perhaps for this reason.

Strikingly, the switchback patches present at PSP are not, in general, visible at Orbiter. Instead, the switchback modulation associated with speed variations seen at PSP is replaced at Orbiter by systematic large amplitude variations in the field components, on a similar scale to the PSP patch modulation. Note that it is not simply that case that the switchbacks are less visible in the radial magnetic field due to the larger Parker spiral angle at Orbiter,[29] there are fewer of the structures present.

All of these variations can be seen in spectra of the Carrington series of the parameters (Fig. 5, where the data in Fig. 4 are interpolated onto a 0.02° grid from which multitaper[41] spectra are calculated); this is a similar presentation to that previously used[21] for Helios data. Vertical lines delineate the approximate range of scales on which the spatial variation can be seen in Fig. 4 which also correspond to supergranular, or plume, scales. As one would expect, there is generally a

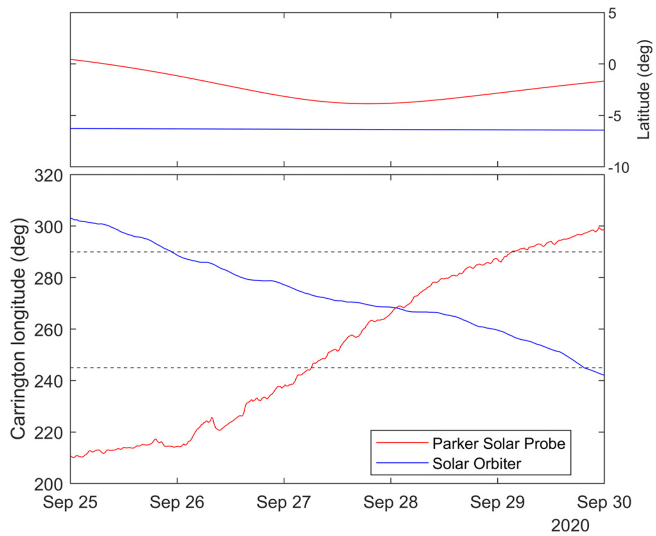

FIG. 3. Solar source latitude and Carrington longitude as a function of the time measured at Parker Solar Probe and Solar Orbiter.

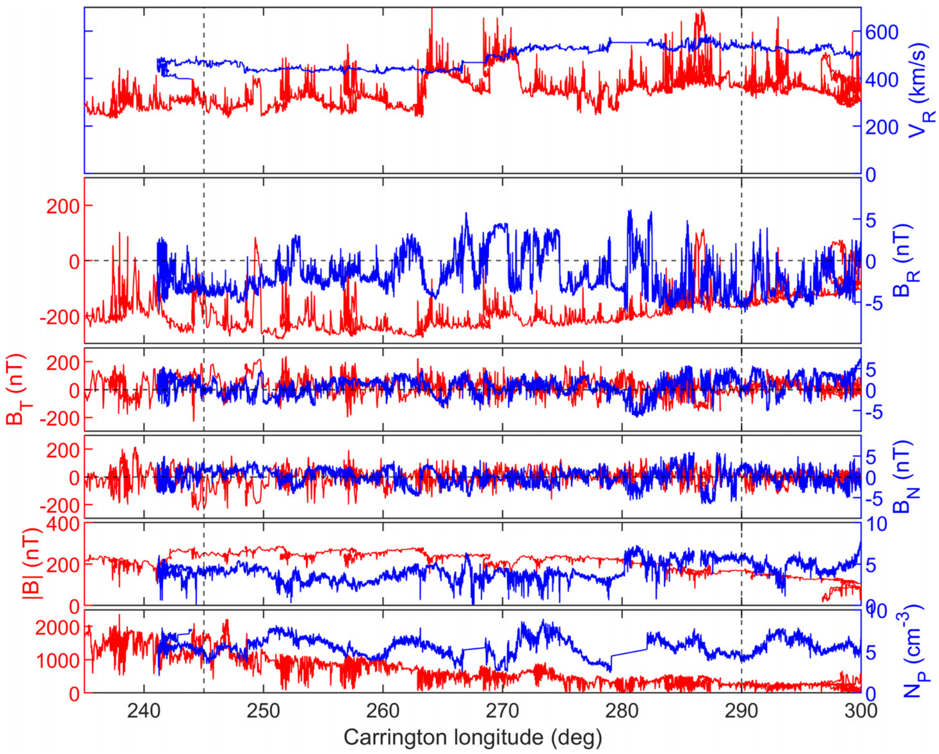

FIG. 4. Parker (red) and Solar Orbiter (blue) data plotted with respect to source Carrington longitude, assuming ballistic constant speed propagation from a source surface at 2.5 R_S. Spectra in Fig. 5 are calculated over the range of longitudes denoted by dashed lines.

lower amplitude of velocity and magnetic field fluctuations at Orbiter, which was farther from the Sun than PSP.

The time series in Fig. 4 show that speed variations on supergranular scales were present at PSP but not Orbiter and this can be seen clearly in the top panel of Fig. 5, where the peak in the V_R spectrum at Parker on supergranule scales, and its absence at Orbiter, is clear. Conversely, there is no peak in the density spectrum (second panel) at PSP, but a peak is present at Orbiter. At PSP, the trace spectrum of the magnetic field (sum of power in the components) has a sharp peak on these scales; this is less clear at Orbiter, where it is replaced by a break in the spectrum. The relationship between the trace spectrum and turbulence is discussed in more detail in Sec. V.

Since switchbacks are generally deflections away from the background (Parker spiral) direction,[29] we have attempted to isolate the power from these, or other Alfvénic fluctuations, independently of any compressive fluctuations. We have done this by calculating the background Parker spiral direction at each spacecraft as a function of time, based on the solar distance and plasma speed, and then calculating the time series of the angle of the magnetic field vector from the Parker spiral unit vector. We term this angle θ_{BP} and it provides information on the amplitude of the fluctuations relative to the nominal background field direction. Unlike the case for the trace magnetic field spectrum, a peak is visible in the spectra of θ_{BP} at both spacecraft on the supergranular scale, showing that magnetic field fluctuations were present on this scale at both spacecraft, even though they appear very different in the time series.

The peaks in the Orbiter and PSP spectra in Fig. 5 confirm what is visible in Fig. 4: that if we interpret the variations on the scales of hours as spatial, they correspond to broadly the same longitudinal scale size, of around 5°, at both spacecraft. We note that this is actually larger than the latitudinal separation of the spacecraft over much of this period, so if these are indeed spatial scales in the solar wind, then the two spacecraft were sampling latitudes within one scale size of each other. This reinforces the value of this particular lineup, since such close latitudinal alignments between spacecraft are rare, although we again emphasize that this we are making a statistical comparison, rather than identifying the same structures at each spacecraft, in this work.

IV. COMPOSITION

The discovery by Ref. 30 of variations in the alpha–proton ratio with switchback patch structure, with higher values within the patches, demonstrates that the patches have a solar origin. Since patches have a similar longitudinal scale, of a few degrees, to the supergranular network, the two may well be related.

We have seen that the variation in fluctuation power associated with patches becomes hard to identify, at least by eye, as the solar wind propagates to 1 au, but a composition signature should remain in the plasma. Figure 6 shows the alpha to proton ratio calculated from SPAN and PAS data, as a function of source longitude. We note that this is a challenging measurement and with both instruments early in their mission lifetimes, these data should be treated with caution. As a result, we have smoothed the data, and we aim only to identify the scale of any variations in the alpha fraction, rather than the details of these changes and their absolute value.

The previously reported[30] enhancement of the alpha fraction within the faster switchback patches at PSP is clear in Fig. 6 although it is highly structured—note that here we are plotting the

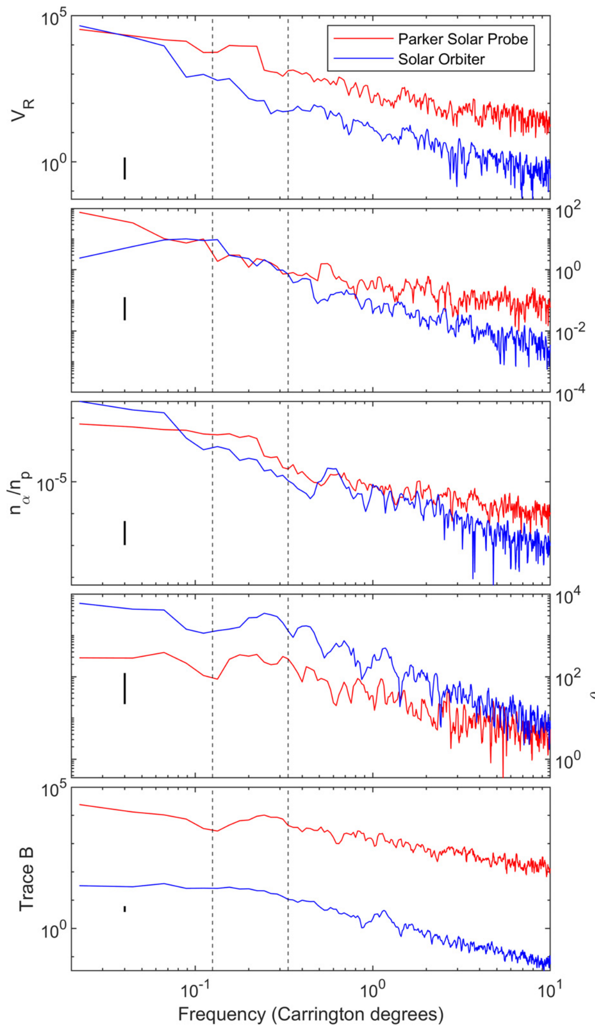

FIG. 5. Parker (red) and Solar Orbiter (blue) power spectra, with respect to source Carrington longitude, for data from 240° to 280°. Panels are as follows, from top to bottom with time series units in parenthesis: radial speed (km/s), ion number density (cm^{-3}), alpha/proton ratio, angle of the field to the nominal Parker spiral (°), and magnetic field trace spectrum (nT). Vertical lines are marked at scales of 3° and 8°. Errors in the power spectra are shown as vertical bars in the bottom left of each panel.

alpha–proton ratio, rather than the alpha fraction, which gives slightly different absolute values but qualitatively similar results. At Orbiter, where speed variations are largely absent, some composition variation can still be seen. Despite some significant systematic differences (which are partly expected due to the changing relative speeds of the protons and alphas) variations can be seen on $\approx 5°$ scales, and indeed at similar apparent source longitudes, at both spacecraft. This can also be seen in the spectra of the alpha/proton ratio in Fig. 5, which are similar, with a break at around the expected scale of several degrees.

These data are consistent with composition signatures of switchback patches persisting into the heliosphere, even when there is no obvious signature in other macroscopic parameters such as plasma speed, and suggest that composition might prove to be an important diagnostic for determining the evolution of mesoscale structure in the solar wind and linking it to its source.

V. DISCUSSION

Measurement of the same solar wind stream at multiple distances makes it possible to study, statistically, the evolution of fluctuations as well as the spatial structure within it. Parker Solar Probe's sixth perihelion, at just 20 R_S, provides just such an opportunity when combined with Solar Orbiter data from near 1 au and a very similar latitude.

The Parker data reveal, more clearly than in earlier more distant encounters, that the "patch" modulation of switchback amplitude is strongly correlated with variations in wind speed which last just a few hours in the spacecraft frame. This clearer signature might be due to the particular characteristics of the polar coronal hole stream which the spacecraft sampled; an additional effect, though, was the much more rapid longitudinal speed of the spacecraft at perihelion due to its more eccentric orbit. If the spacecraft takes longer to pass across structures than their typical lifetime, then such a clear signature would not be visible. It might, therefore, be the combination of sampling a coronal hole flow, with this more rapid relative longitudinal motion, that makes these structures so clear in this encounter. Coronal jets are known to typically last hours, and plumes up to several days: therefore, if we interpret these speed variations to be spatial, with Parker passing through them more quickly than their lifetime, then they correspond to longitudinal scales of around 5°, as previously inferred by Refs. 30 and 31. Indeed, Helios measurements from 0.3 au and above revealed corotating longitudinal structures in coronal hole flows with scales of $\approx 5°$, similar to that seen here in the PSP data, which were interpreted[21] as possible signatures of plumes or macrospicules. A similar spatial scale is seen in the Orbiter data, where although the speed variations had smoothed out by the time the plasma arrived at 1 au, large scale magnetic field fluctuations were present, corresponding to temporal scales at the spacecraft of several hours, along with density variations and changes in the alpha–proton ratio.

Based on these observations, it seems likely that the velocity variations associated with switchback patch structure on $\approx 5°$ scale at PSP generated the observed density structure at 1 au, while the associated velocity shear produced the magnetic field variations on the same scale, perhaps by a similar mechanism to that proposed at a smaller scale for switchbacks themselves.[42] Microstreams, therefore, generate large scale mixing within solar wind streams and indeed on these scales $\delta\mathbf{B}/|\mathbf{B}|$ is larger at Orbiter than PSP (see, for example, the θ_{BP} spectrum in Fig. 5). The original microstreams can sometimes be identified using composition data but are otherwise hard to detect. PSP data have revealed that between patches, the magnetic field is quiet and near-radial.[2,43] These periods are effectively eliminated by 1 au, perhaps by the propagation of Alfvénic fluctuations from nearby plasma.

At 1 au and beyond, fluctuations are generally considered within a paradigm of broadband, space-filling turbulence. Isolated, discrete switchbacks seem to be very different in character, but the interval considered here provides a clear demonstration that the former evolves from the latter. The trace spectrum in Fig. 5, calculated over the entire interval of interest, shows a clear peak at PSP at the patch

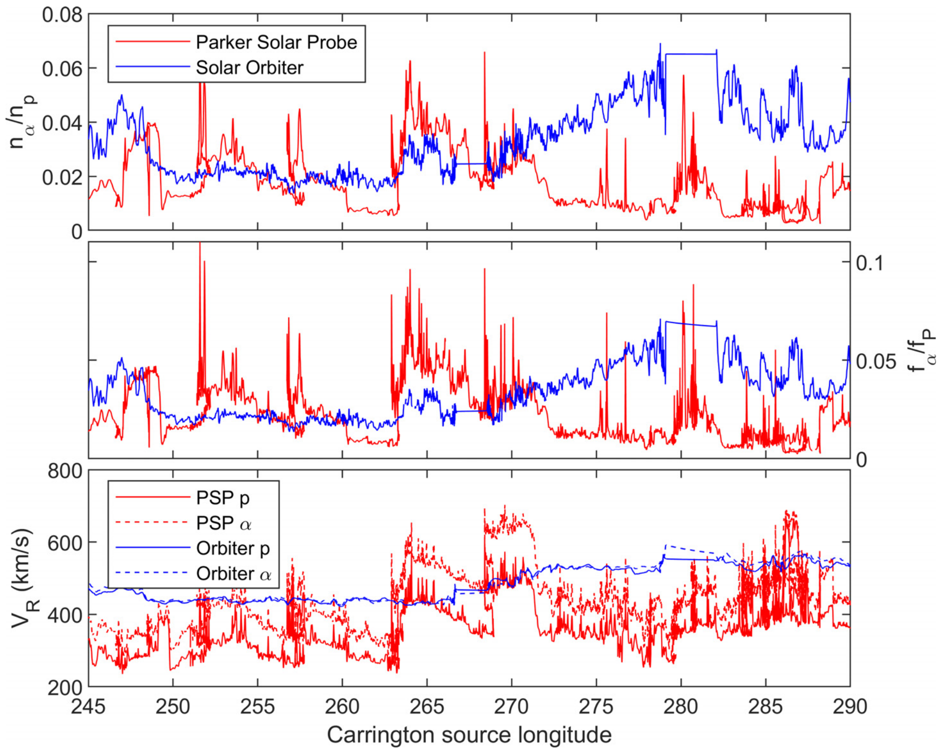

FIG. 6. Variation of alpha–proton ratio with source Carrington longitude. Top: ratio of alpha to proton number density. Middle: ratio of alpha and proton fluxes. Bottom: alpha (dashed) and proton (solid) radial speeds.

scale, with a 1/f spectrum at smaller scales. At Orbiter, in contrast, there is a break in the spectrum at these scales with a steeper, −5/3 spectrum above it. Gradients of spacecraft-frequency power spectra (see Fig. 7: Ref. 25 have recently performed a more detailed spectral analysis on part of this interval) also show this, with a −1 spectral index at PSP and a transition to a −3/2 value at the highest frequencies.[24] At Orbiter, with a −5/3 turbulent spectrum, the transition to a −1 index occurs at spacecraft frequencies of around 5×10^{-4} Hz, around 1 h, as is usual at 1 au. This is a significantly higher frequency than the time taken for Orbiter to cross a microstream (around 12 h) so it does not seem to be as if the large scale mixing is the direct cause of the 1/f break scale at 1 au. It remains unclear, therefore, how switchbacks evolve and decay into broadband turbulence. The importance of turbulent fluctuations for energetic particle propagation throughout the heliosphere means that this is an important question that deserves future study and is only likely to be fully resolved with measurements at intermediate distances, perhaps with later radial alignments with Orbiter and Parker such as that in early 2022, or during a PSP fast radial scan.

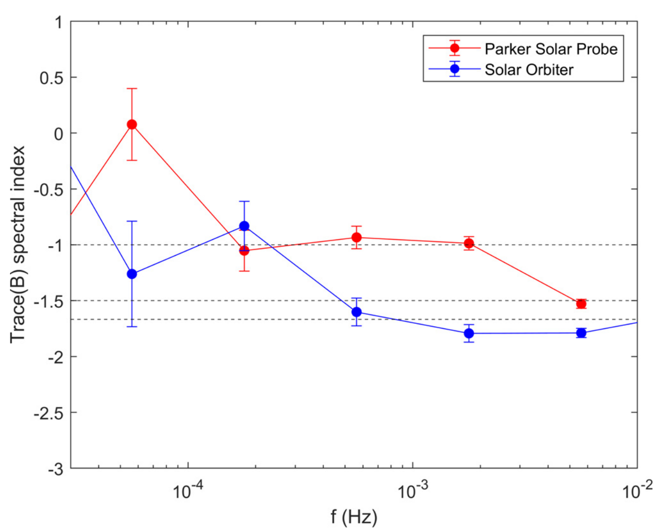

FIG. 7. Parker (red) and Solar Orbiter (blue) spectral index values for the magnetic field trace power spectra. These spectra are calculated in each spacecraft frame, using all the data that correspond to source Carrington longitudes between 245° and 290°.

One glaring difference between PSP and Orbiter measurements of this stream is the nearly 200 km/s increase in the background proton speed between the two spacecraft, which is clear in Fig. 4. Some of this is presumably due to the ongoing acceleration of the wind even at 20 au, but we also note that the deceleration of alphas and proton beams relative to the proton core, as a result of the decreasing Alfvén speed with distance, combined with momentum conservation will also act to accelerate the core. A detailed multi-species analysis of the plasma, in a similar manner to Ref. 44 with Helios data, would help to quantify the relative amplitude of these effects. We note in passing that while the proton core speeds at the two spacecraft are very different, the deHoffman–Teller speeds[5] are remarkably similar which might be an important piece of evidence as to the acceleration mechanism of the wind and we will return to this in a future paper.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Timothy S. Horbury: Conceptualization (lead); Data curation (supporting); Formal analysis (lead); Funding acquisition (equal); Investigation (lead); Methodology (lead); Writing – original draft (equal); Writing – review & editing (equal). **Lloyd D. Woodham:** Investigation (supporting). **Thomas Woolley:** Investigation (supporting). **Andrey FEDOROV:** Data curation (supporting). **Philippe Louarn:** Data curation (supporting). **Rungployphan Kieokaew:** Data curation (supporting). **Tereza Durovcova:** Data curation (supporting). **Benjamin Chandran:** Investigation (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Christopher J Owen:** Data curation (supporting). **Stuart D. Bale:** Data curation (supporting); Investigation (supporting). **Michael McManus:** Data curation (supporting). **Davin Larson:** Data curation (supporting). **Justin C. Kasper:** Data curation (supporting). **Ronan Laker:** Investigation (supporting); Writing – review & editing (supporting). **Lorenzo Matteini:** Conceptualization (supporting); Investigation (supporting); Writing – review & editing (supporting). **Nour Raouafi:** Investigation (supporting). **Marco Velli:** Investigation (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The Parker Solar Probe data that support this study are openly available at https://doi.org/10.48322/0yy0-ba92 (FIELDS), https://doi.org/10.48322/ypyh-s325 (SPAN protons) and https://doi.org/10.48322/ke19-2789 (SPAN alphas). The Solar Orbiter data that support this study are openly available at https://doi.org/10.5270/esa-ux7y320 (MAG) and https://doi.org/10.5270/esa-ahypgn6 (SWA/PAS). One exception is the PAS alpha particle data which are not yet publicly available.

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