

Parker Solar Probe Observations of a Flux Rope Embedded in a Near-Sun Heliospheric Current Sheet Magnetic Reconnection Exhaust

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Abstract

In situ observations by Parker Solar Probe (PSP) suggest that the heliospheric current sheet (HCS) undergoes near-continuous magnetic reconnection close to the Sun, in stark contrast to scarce observations of this phenomenon in the HCS at 1 au. Situated at the boundary between sectors of opposite interplanetary magnetic field polarity, reconnection in the HCS has important consequences for magnetic topology and plasma dynamics in the slow solar wind. We report observations of a reconnection outflow in the HCS near the Alfvén transition region in PSP’s 17th solar encounter, featuring plasma jetting, proton temperature enhancement, and electron heat flux dropout. Embedded within the exhaust is a non-force-free flux rope plasmoid exhibiting counterstreaming strahl electrons, indicating connection at both ends to the Sun in an otherwise disconnected region of the magnetic field. The flux rope features diminished isotropic proton temperature and lower bulk speed compared to the remainder of the HCS exhaust. Its oblique orientation and different plasma properties imply that the flux rope originates from a different reconnection site to the HCS exhaust, suggesting PSP has intercepted a flux-rope-like streamer blob produced at the helmet streamer. Remote observations show several comparable blobs traveling in a distant coronal ray, demonstrating the possibility that the in situ flux rope is a streamer blob. The combination of in situ and remote observations demonstrates the role of magnetic reconnection in HCS dynamics, contributing to a growing understanding of this fundamental mechanism and its impact on the young solar wind.

Unified Astronomy Thesaurus concepts: [Heliophysics \(2373\)](#); [Interplanetary magnetic fields \(824\)](#); [Slow solar wind \(1873\)](#); [Solar wind \(1534\)](#); [Heliosphere \(711\)](#); [Space plasmas \(1544\)](#); [Magnetohydrodynamics \(1964\)](#)

1. Introduction

Since 2018, Parker Solar Probe (PSP; N. J. Fox et al. 2016) has used successive Venusian gravity assists to lower its perihelion to less than 10 solar radii (R_S), providing in situ measurements of the high solar corona and young solar wind for the first time. The first solar encounters by PSP demonstrated an abundance of magnetic reconnection in the near-Sun heliospheric current sheet (HCS; B. Lavraud et al. 2020; T. D. Phan et al. 2020; A. Szabo et al. 2020), in stark contrast to its scarcity at 1 au (e.g., J. T. Gosling et al. 2005a, 2005b, 2006; B. Lavraud et al. 2009; S. Du et al. 2025). This is unexpected (J. T. Gosling 2012) due to the HCS thickness of $\gtrsim 10^4 d_i$ (K. Liou & C.-C. Wu 2021; N. Fargette et al. 2026, where $d_i = \sqrt{m_i/e^2\mu_0\langle n_p \rangle}$ is the ion inertial length)—several orders of magnitude greater than the kinetic scales ($\lesssim 1 d_i$) typically required for collisionless reconnection onset near the Earth (J. Sanny et al. 1994; A. Runov et al. 2008; T. D. Phan et al. 2020). Subsequent HCS crossings (e.g., T. D. Phan et al. 2021, 2022, 2024, 2025; E. Berriot et al. 2025; M. I. Desai et al. 2025; J. P. Eastwood et al. 2026; N. Fargette et al. 2026) and remote observations (e.g., M. L. Ascione et al.

2024; P. C. Liewer et al. 2024, 2025) have reinforced the view that reconnection is prevalent in this region.

Magnetic reconnection influences current sheet topology, causing plasma jetting and heating (see, e.g., M. Hesse & P. A. Cassak 2020; J. L. Burch & R. Nakamura 2025 and references therein). In the HCS—which forms at the boundary between interplanetary magnetic field (IMF) sectors of opposite magnetic polarity (e.g., E. J. Smith et al. 1978; J. T. Gosling et al. 1981)—reconnection reorganizes the magnetic field, leading to regions disconnected from or connected at both ends to the Sun (J. T. Gosling et al. 2005a, 2006; T. D. Phan et al. 2022). The HCS is closely related to the origin and variability of the slow solar wind (A. K. Higginson et al. 2017), so heating, acceleration, and changes to its topology due to reconnection are of key importance for the dynamics of the inner heliosphere. Furthermore, the onset and extent of reconnection in the HCS are still topics of active investigation (e.g., S. Du et al. 2025; T. D. Phan et al. 2025; N. Fargette et al. 2026), with links to solar transients and their role in large-scale dynamics of the HCS (e.g., O. M. Romeo et al. 2023; R. Patel et al. 2025).

Reconnection has also been suggested (e.g., E. Sanchez-Diaz et al. 2019) as the origin of transient density enhancements in the slow solar wind (also known as “streamer blobs,” or just “blobs”), commonly observed by white-light remote coronal



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imagers (N. R. Sheeley et al. 1997, 2009; Y. Wang et al. 2000; C. E. DeForest et al. 2018). It has been suggested that these blobs are generated through pinch-off reconnection, which can occur where a closed solar loop is stretched until oppositely directed field lines undergo reconnection, or by interchange reconnection, which can liberate dense plasma from a closed loop when it reconnects with an open field line (see Figure 8 in Y. Wang et al. 2000; figures in E. Sanchez-Diaz et al. 2019 and B. Lavraud et al. 2020). There is a growing body of recent work utilizing new results from PSP to improve our understanding of the role of reconnection in the formation and evolution of streamer blobs (B. Lavraud et al. 2020; V. Réville et al. 2022; N. Poirier et al. 2023; P. C. Liewer et al. 2024, 2025), but the area remains an active field of research.

Here, we present in situ measurements of a flux rope plasmoid embedded in an outward-flowing HCS reconnection exhaust. Counterstreaming electron strahl populations are found inside the flux rope, despite the surrounding reconnection exhaust being disconnected from the Sun. This challenges traditional expectations of strahl signatures in an HCS crossing and suggests a complex magnetic topology, consisting of structures produced by distinct reconnection events at different origins. Contemporaneous remote observations of streamer blobs escaping the corona in a distant coronal ray provide valuable context to in situ measurements, demonstrating the role of reconnection in the formation and variability of the slow solar wind.

The structure of this paper is as follows. Section 2 introduces the PSP data used and the HCS crossing in solar encounter 17 (E17). Section 3 describes in situ measurements of a flux rope plasmoid contained within an HCS reconnection outflow. Section 4 contextualizes the in situ measurements with remote observations. Finally, Section 5 summarizes our findings.

2. Data and Event Context

The focus of this study is an HCS crossing that occurred on 2023 September 28 while PSP was situated at $12.3 R_S$, traveling prograde (in the Carrington frame) outbound from perihelion of E17. This HCS crossing is the second to occur in E17, but for brevity, we simply refer to it as the E17 HCS crossing. We utilize in situ and remote observations to investigate the properties of the HCS in this encounter. To include the context around this event, we use an in situ data window from 05:00 to 09:00 UTC on 2023 September 28.

For the in situ element of this study, we utilize 4.58 samples per second vector magnetic field measurements from the FIELDS fluxgate magnetometer (S. D. Bale et al. 2016), in addition to electron number density from the simplified quasi-thermal noise (SQTN) data product (M. Moncuquet et al. 2020). Ion spectrograms and moments (cadence up to ≈ 1.7 s) are provided by SWEAP/SPAN-Ion (R. Livi et al. 2022), and electron spectrograms and pitch angle distributions (PADs; cadence up to ≈ 7 s) come from SWEAP/SPAN-Electron (P. L. Whittlesey et al. 2020). Vector quantities are given in radial tangential normal coordinates (rtn, where we write the acronym in lower case to distinguish the normal direction, $\hat{n}$, from the current sheet normal, $\hat{N}$). In this coordinate system, $\hat{r}$ is directed along the Sun–spacecraft line, $\hat{t} = \hat{\Omega} \times \hat{r}$ is perpendicular to the solar rotation axis ($\hat{\Omega}$) and $\hat{r}$, and $\hat{n}$ is the normal direction, which completes the right-handed system.

Remote-sensing images from WISPR (A. Vourlidas et al. 2016) are used to contextualize the in situ observations. WISPR produces images of the solar corona by observing sunlight that has been Thomson-scattered by coronal electrons. The imager consists of two white-light telescopes oriented on the ram side of the spacecraft, referred to as the inner (WIS-I) and outer (WIS-O), with fields of view (FOVs) extending 13.5° – 53.0° and 50.5° – 108.5° from the Sun-centered near-equatorial plane, respectively. The transverse FOV is approximately 50° . As PSP lowers its perihelion, the size of the region of sensitivity (the Thomson sphere; see A. Vourlidas & R. A. Howard 2006) decreases proportionately, allowing WISPR to image the local environment almost exclusively. When PSP is located within $< 20 R_S$ of the Sun, the inner edge of WIS-I’s FOV corresponds to $< 5 R_S$, imaging electrons from a Thomson surface with diameter < 0.1 au (P. C. Liewer et al. 2023). We utilize the ~ 5 minute cadence so-called LW data product (Appendix of R. A. Howard et al. 2022), which is optimized to emphasize nonstationary features such as streamer blobs (P. C. Liewer et al. 2023) and magnetic islands (M. L. Ascione et al. 2024), rather than the L3 data, which represent a rough estimate of K-corona (electron-scattered) brightness.

2.1. Heliospheric Current Sheet and Surrounding Conditions

Figure 1 displays key variables for the in situ data window. Figures 1(a) and (b) show the omnidirectional proton and electron energy spectra, respectively, for context. PSP is crossing the HCS from 06:20 to 07:05, denoted by solid vertical lines, during which there is a large-scale reversal in the B_r component as shown in Figure 1(e). The reversal in B_r occurs because PSP passes between regions of opposite magnetic polarity (also known as an IMF sector boundary crossing). Another factor in identifying HCS crossings is a change in the pitch angle associated with the suprathermal electron strahl population (N. U. Crooker et al. 2004). Figure 1(c) shows the electron PAD averaged over the energy range 300–800 eV, in which the strahl appears as a collimated beam with a maximum pitch angle flux angle switching from 0° to 180° during the HCS crossing. To confirm this, Figure 1(d) shows the pitch angle fluxes averaged in the ranges $[0, 30]^\circ$ and $[150, 180]^\circ$, demonstrating a dropout of the former in exchange for the latter. As the strahl is thought to be a near-freely streaming electron beam traveling outward from its origin in the solar corona (e.g., K. Horaites et al. 2019; J. S. Halekas et al. 2021), the switch in pitch angle direction is attributed to the reversal of magnetic polarity (e.g., S. W. Kahler et al. 1996); i.e., it indicates that the strahl remains antisunward. The combination of signatures in Figures 1(c) and (e) confirms that an HCS crossing occurs in this interval.

The surrounding solar wind properties can be deduced from other panels, noting that conditions are similar on either side of the HCS. Figure 1(e) shows IMF strength $|B| \sim 700$ nT predominantly arising from the radial component ($B_r > 0$ before the crossing, and $B_r < 0$ after). Figure 1(f) shows that proton density n_p is consistent at around $5 \times 10^3 \text{ cm}^{-3}$. SQTN electron number density is consistent with n_p as determined by SPAN, although it has a data gap for the duration of the HCS itself. Figure 1(g) demonstrates largely radial solar wind outflow with proton bulk velocity reaching $v_p \sim 210 \text{ km s}^{-1}$ on either side of the HCS crossing, rising slightly with increasing

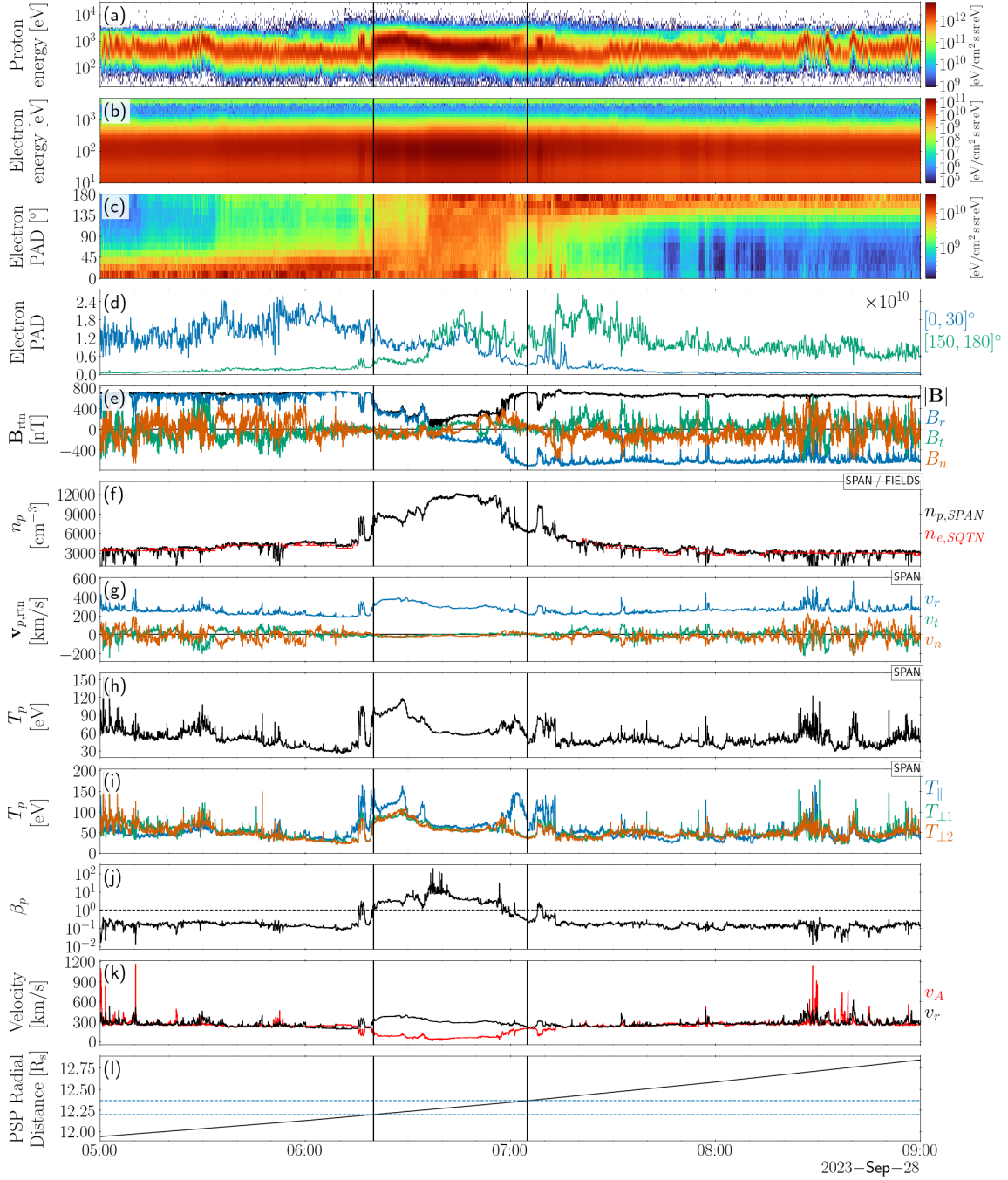


Figure 1. Key plasma parameters from around the E17 HCS crossing, showing 05:00 to 09:00 on 2023 September 28. Solid vertical lines denote the crossing period 06:20–07:05. (a) and (b) SPAN-Ion and SPAN-Electron omnidirectional energy spectra. (c) SPAN-Electron PAD in the energy range 300–800 eV. (d) Electron PAD channels in the ranges $[0, 30]^\circ$ and $[150, 180]^\circ$. (e) Magnitude and vector FIELDS magnetic field. (f) SPAN-Ion proton number density and SQTN electron number density, where available. (g)–(i) SPAN-Ion proton plasma moments. (j) Proton plasma beta. (k) Local Alfvén speed and radial proton speed. (l) Radial distance of PSP from the Sun, with horizontal dashed lines representing the start and end of the HCS crossing, 12.20 and 12.36 R_s , respectively.

distance from the HCS. Figures 1(h) and (i) show the proton temperature moment, which is generally isotropic and stable in the studied interval of solar wind, albeit subject to modulations in small structures. Figure 1(j) gives the proton plasma beta $\beta_p = n_p k_B T_p / (B^2 / 2\mu_0)$, which is dominated by magnetic pressure outside the HCS crossing. In Figure 1(k), it is seen that the local Alfvén speed $v_A = |B| / \sqrt{\mu_0 m_p n_p}$ is comparable to the radial solar wind speed, indicating that PSP is within the Alfvén transition region (also known as the Alfvén critical surface). Finally, Figure 1 shows the radial distance of PSP

from the Sun, which is increasing throughout this window, in particular from 12.20 to 12.36 R_s during the HCS crossing.

2.2. Current Sheet Coordinate System

It is helpful to define a current sheet coordinate system (*LMN*), where the current sheet is contained in the *L–M* plane and *N* is the current sheet normal. A schematic representation of the *LMN* coordinate axes within the HCS is discussed in Section 3.3. We determine *LMN* via the minimum variance

analysis (MVA) technique (B. U. Sonnerup & L. J. Cahill 1967), using the window 06:08:00–07:20:00 to encompass the main HCS crossing, partial crossings, and part of the surrounding IMF conditions. The resultant eigenvectors are $\hat{L} = [-0.99, 0.06, 0.02]_{\text{rtm}}$, $\hat{M} = [0.02, >0.01, 0.99]_{\text{rtm}}$, and $\hat{N} = [0.06, 0.99, >-0.01]_{\text{rtm}}$, with eigenvalues $\lambda_L = 225525.2$, $\lambda_M = 19015.0$, and $\lambda_N = 5777.3$, respectively. The results suggest a highly inclined HCS plane with a normal vector approximately aligned with the direction of PSP’s motion. The distinction between the maximum and intermediate directions is quite clear ($\lambda_L/\lambda_M \sim 10$), so the $\hat{L}$ direction can be trusted. However, the ratio of intermediate and minimum eigenvalues $\lambda_M/\lambda_N = 3.29$ is not large enough to be confident in the determination of the current sheet normal by MVA. This is likely a result of the high magnetic shear ($\approx 175^\circ$) across the HCS, in addition to the variety of magnetic variations within the HCS crossing.

As an alternative to traditional MVA, we try employing the Hybrid-MVA technique (J. T. Gosling & T. D. Phan 2013), which uses the average magnetic field on the edges, $\mathbf{B}_1$ and $\mathbf{B}_2$, to estimate $\hat{N} = \mathbf{B}_1 \times \mathbf{B}_2 / |\mathbf{B}_1 \times \mathbf{B}_2|$. However, we find Hybrid-MVA to be highly sensitive to the chosen $\mathbf{B}_1$ and $\mathbf{B}_2$, as a result of a degeneracy introduced because $\mathbf{B}_t$ and $\mathbf{B}_n$ are very small. As such, this method is unable to reliably distinguish $\hat{M}$ from $\hat{N}$ and is not appropriate for use on this HCS crossing.

To further explore the MVA properties of the HCS, we systematically vary the interval of $\mathbf{B}_{\text{rtm}}$ onto which MVA is applied. By evenly broadening the window outward from the HCS boundaries, a maximum $\lambda_M/\lambda_N = 3.48$ is found for the interval 06:11:14–07:29:46. A greater value is found by varying the start and end of the MVA interval separately, resulting in a maximum $\lambda_M/\lambda_N = 4.3$ for 05:55:02–07:14:50. Importantly, $\hat{M} \cdot \hat{n} \approx 1$ and $\hat{N} \cdot \hat{i} \approx 1$ are maintained regardless of MVA window, giving confidence that the principle components of LMN with respect to rtm are not subject to the same sensitivity as in Hybrid-MVA.

The high inclination of the HCS determined by MVA is consistent with a potential field source surface extrapolation (PFSS) model,⁹ which estimates the HCS normal to be closely aligned with the $\hat{i}$ direction. It should, however, be noted that PSP is on the opposite side of the Sun to Earth, so the magnetograms could be out of date. Based on the initial MVA results, the subsequent maximization of λ_M/λ_N , and the PFSS map, we adopt the LMN coordinate directions $\hat{L} = [1, 0, 0]_{\text{rtm}}$, $\hat{M} = [0, 0, -1]_{\text{rtm}}$, and $\hat{N} = [0, 1, 0]_{\text{rtm}}$. We acknowledge that it is possible that the true $\hat{N}$ direction has a nonzero $\pm \hat{n}_{\text{rtm}}$ component, but this would not significantly impact the qualitative results.

3. In Situ Measurements of HCS Crossing

3.1. Properties of HCS Crossing during Encounter 17

PSP crosses through the HCS over a 45 minute period from 06:20 to 07:05, which is comparable in duration to HCS crossings in other encounters, typically lasting from a few minutes to several hours (N. Fargette et al. 2026). The magnetic field rotation is $\sim 175^\circ$, constituting a polarity change of B_r from 700 to -600 nT. PSP transits through the current

sheet at an average spacecraft velocity $\langle \mathbf{v}_{\text{sc}} \rangle = [43, -3, 164]_{LMN} \text{ km s}^{-1}$, corresponding to motion primarily in the HCS normal direction. In the frame of the spacecraft, the average HCS flow is given by $\langle \mathbf{v}_{\text{sc}} - \mathbf{v}_p \rangle = [265, 12, -169]_{LMN} \text{ km s}^{-1}$, revealing a large $\hat{L} \sim \hat{r}$ outflow component. We use the component of this velocity along the HCS normal to estimate the current sheet thickness, $d_{\text{HCS}} = \Delta t |\langle \mathbf{v}_{\text{sc}} - \mathbf{v}_p \rangle \cdot \hat{N}| = 4.56 \times 10^5 \text{ km} = 0.66 R_S$, where $\Delta t = 2700 \text{ s}$ is the transit duration. The HCS thickness is of order $\sim 10^5 d_i$, larger than average but still within the typical range (N. Fargette et al. 2026).

We now describe the sequence of events as measured by PSP during this HCS crossing, shown in Figure 2. After a short partial crossing at 06:16, PSP enters the HCS at 06:20, encountering reduced $|\mathbf{B}|$, enhanced n_p and proton temperature (particularly $T_{\parallel}$), broadening of the 0° electron pitch angle flux, and velocity enhancement of v_L from 210 to 360 km s^{-1} . Because $\hat{L} \sim \hat{r}$, the positive increase in v_L signifies plasma jetting away from the Sun, indicating that the site of magnetic reconnection is sunward of the HCS crossing (e.g., T. D. Phan et al. 2022). At 06:28, there is a minor $\mathbf{B}$ rotation, which is the site of the peak in $T_{p,\parallel}$, slight velocity and density depletion, and an enhancement in $|\mathbf{B}|$. At 06:34, there is a similar feature, which occurs on the boundary of a change in the HCS properties near the true sector boundary where B_L ($\sim B_r$) reverses. These two features correspond to current sheets inside the HCS, but MVA techniques do not elucidate whether they are flux-rope-like plasmoids or simply embedded current sheets.

During the period from 06:36 to 06:57, PSP appears to pass through a plasmoid entrained within the HCS reconnection exhaust. This is indicated by a smooth reversal in which B_N changes sign. Within this region, there is a further reduction in $|\mathbf{B}|$, a reversal in B_M , a further enhancement in n_p , a slower v_L jet than in the first part of the crossing, and a reduction of proton temperature, particularly in the parallel direction. The profiles of these plasma parameters are also smoother inside the plasmoid. From 06:36, the strahl switches to 180° in the PAD, but an omnidirectional enhancement in pitch angle flux indicates significant scattering of the suprathermal electrons. The scattering coincides with a region of higher plasma beta, as commonly observed in the solar wind (e.g., J. S. Halekas et al. 2021).

From around 06:40 to 06:51, the PAD exhibits counterstreaming (bidirectional) strahl signatures, indicating that this part of the HCS magnetic field is connected to the Sun at both ends (e.g., D. J. McComas et al. 1989; J. T. Gosling et al. 2006, although other explanations have been proposed—see O. Khabarova et al. 2021). The presence of counterstreaming strahl antisunward of an HCS reconnection site is unexpected and will be explored in Section 3.3. It should be briefly noted that some PAD pixels may be erroneous due to binning errors or spacecraft contamination (e.g., D. McGinnis et al. 2019). While this is unlikely to affect the results of this study, care should be taken when interpreting PAD time steps exhibiting a maximum pitch angle flux not at 0° or 180° . In any case, the suprathermal electron components are clearly scattered within the HCS, and particularly between around 06:40 and 06:51, corroborating our interpretation of the electron PAD.

Beyond 06:51, the 0° strahl population drops out, except for a brief return at 06:55, after which PSP exits the plasmoid at

⁹ Viewed on <https://connect-tool.irap.omp.eu/> using the ADAPT coronal field model.

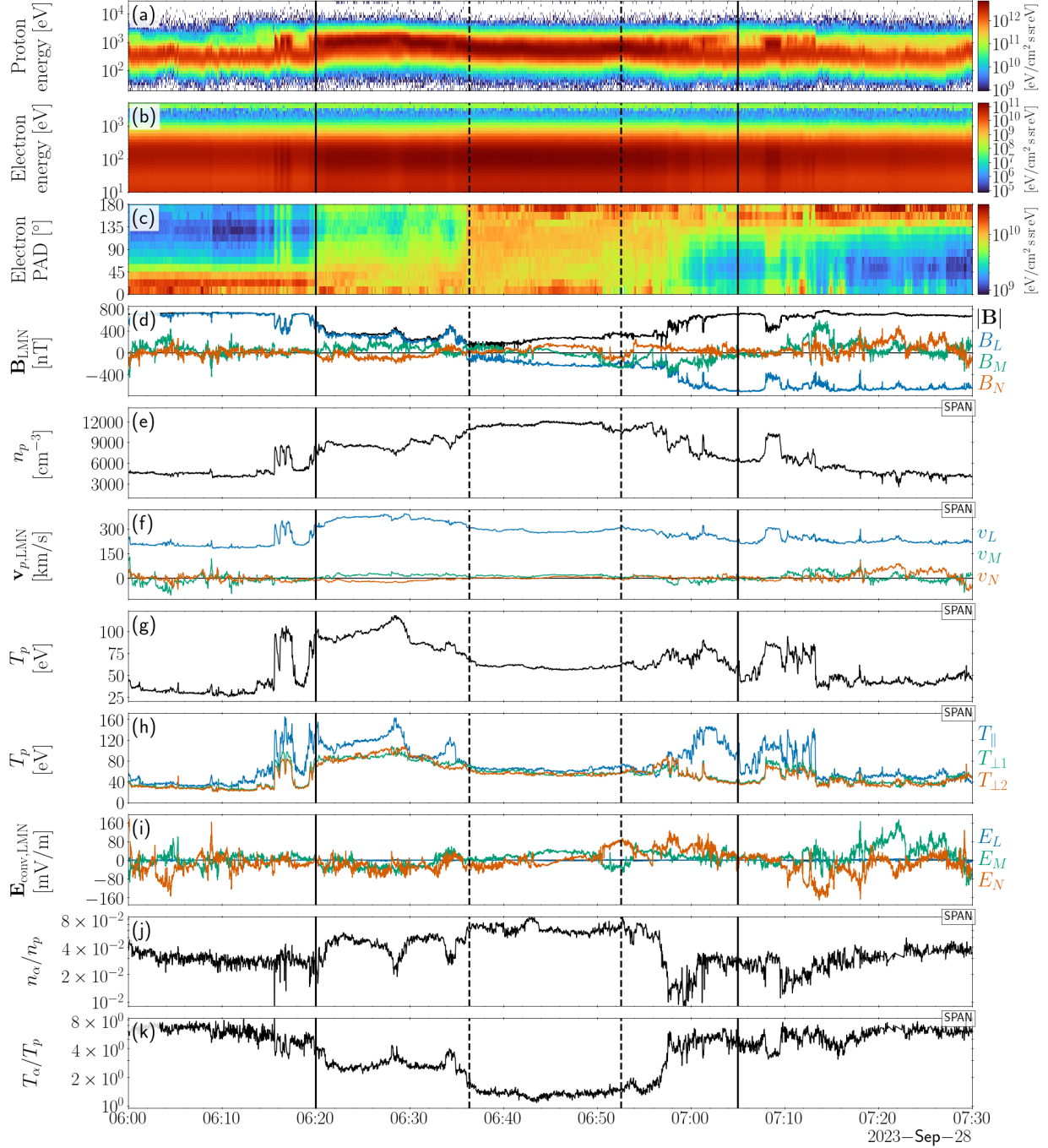


Figure 2. Detailed view of the E17 HCS crossing. (a) and (b) SPAN-Ion and SPAN-Electron omnidirectional energy spectra. (c) SPAN-Electron PAD averaged over energy channels 300–800 eV. (d) FIELDs magnitude and vector $\mathbf{B}$ rotated into LMN . (e)–(h) SPAN-Ion plasma moments, with $\mathbf{v}_p$ rotated into LMN . (i) Convective electric field $\mathbf{E}_{\text{conv}} = -\mathbf{v}_p \times \mathbf{B}$ in LMN coordinates. (j) Alpha-to-proton density ratio from moments. (k) Alpha-to-proton temperature ratio from moments. Solid vertical bars denote the boundaries of the HCS, and dashed vertical bars represent the edges of the flux rope discussed in the text.

approximately 06:57. By 06:59, the electron heat flux no longer exhibits an omnidirectional component, but the 180° strahl is still more diffuse than outside the HCS. From this point, the HCS properties are similar to those of the first part of the crossing. At around 07:05, PSP reenters the IMF, having crossed through the HCS entirely. The solar wind conditions in this IMF sector are similar to those prior to the HCS crossing. There is a short partial crossing back into the HCS at around 07:10, after which PSP remains in the solar wind away from the IMF boundary.

3.2. Flux Rope Embedded in Reconnection Exhaust

A key advantage of in situ measurements is the ability to directly probe the structure of an event. We use this capability to explore the properties of the plasmoid observed by PSP from around 06:36 to 06:57. Here, using regular MVA on $\mathbf{B}_{\text{rtm}}$ in the interval 06:36:19–06:52:30, it is determined that the plasmoid’s maximum, intermediate, and minimum variance axes are $\hat{L}' = [-0.21, -0.36, 0.91]_{\text{rtm}}$, $\hat{M}' = [-0.62, 0.77, 0.17]_{\text{rtm}}$, and $\hat{N}' = [0.76, 0.52, 0.39]_{\text{rtm}}$, respectively, with eigenvalues $\lambda_{L'} = 12$, $\lambda_{M'} = 5299$, and $\lambda_{N'} = 584$.

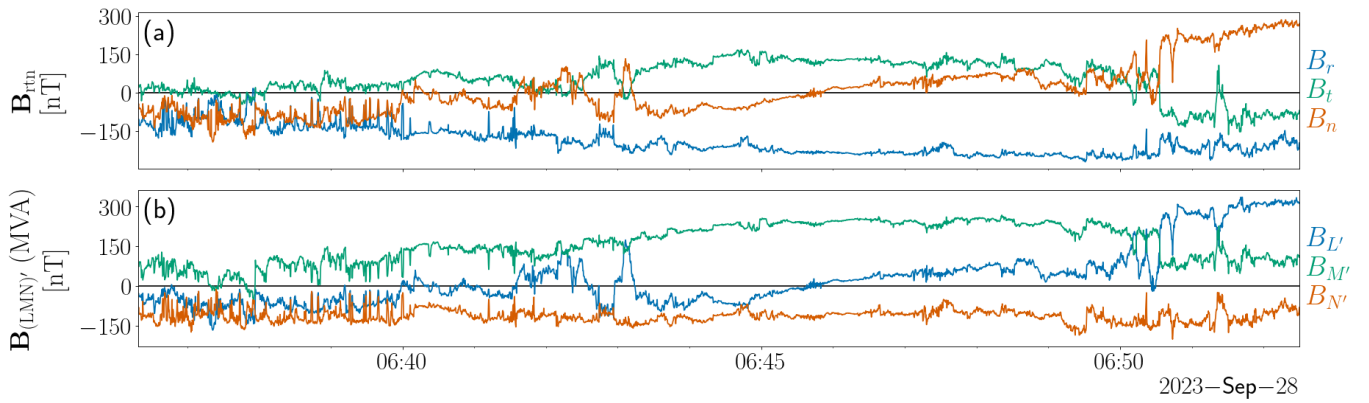


Figure 3. Traditional MVA as applied to B_{rtn} in the window 2023 September 28/06:36:19–06:52:30. Panel (a) shows the unrotated magnetic field. Panel (b) shows $B_{(LMN)'}$ for the flux rope.

Figure 3(b) shows B_{rtn} rotated into the MVA coordinate system, $B_{(LMN)'}$. The typical signatures of a magnetic flux rope can be seen: (i) a bipolar modulation in $B_{L'}$ corresponding to the component of the azimuthal field that changes sign across the flux rope, (ii) a unipolar peak in $B_{M'}$ corresponding to the guide field component, and (iii) no large-scale variation in the other azimuthal component, $B_{N'}$, where $B_{N'}$ is nonzero because PSP does not pass directly through the core (see, e.g., J. Briggs et al. 2011; M. Hesse & M. G. Kivelson 2013; G. A. DiBraccio et al. 2015). These results suggest that the structure of this plasmoid is that of a magnetic flux rope, as opposed to a magnetic island or loop-type structure (which would not have a core field). The flux rope field components do not vary smoothly, suggesting a non-force-free field configuration.

The flux rope properties are as follows. From the maximum of $B_{M'}$, the guide field is $\gtrsim 267$ nT. The acute angle between the M' -axis (along the “barrel” of the flux rope) and the N -axis (the normal to the HCS) is 39° , demonstrating that the flux rope is oriented obliquely within the HCS rather than having its core axis entrained largely in the HCS ($\hat{L}$ – $\hat{M}$) plane. The askew orientation of the flux rope may suggest that it did not originate in the HCS, instead being generated at lower altitudes within the corona and propagating out in the vicinity of the HCS. This possibility is supported by comparison between the plasma properties inside the flux rope and the rest of the HCS crossing, which reveals some significant differences. These can be viewed in Figure 2 by comparing the conditions between the dashed vertical lines to those between the solid vertical lines.

The flux rope features a reduction and isotropization of the proton temperature, accompanied by an enhancement in number density and a reduction in proton bulk speed. Figure 2(j) shows an increase in alpha abundance relative to the protons, indicative of a different source region possibly related to fast solar wind (e.g., J. Huang et al. 2023 and references therein). There is a simultaneous reduction in the ratio of alpha-to-proton temperature caused by a drop in the alpha temperature, as shown in Figure 2(k). Based on its strahl electron signatures, the flux rope also appears to be connected to the Sun at both ends, which is unexpected in a region of otherwise disconnected outflow and will be discussed in the next section. The evidence discussed here suggests that, despite being embedded within HCS reconnection exhausts, the flux rope was not generated by magnetic reconnection in

the HCS and instead may have coronal origins closer to the Sun.

To constrain the spatial extent of the flux rope, we use the distance traversed in the $\hat{L}'$ – $\hat{N}'$ plane as a lower bound for the diameter, $d_{\text{FR}} \gtrsim \Delta t \sqrt{(\mathbf{v}_{\text{rel}} \cdot \hat{L}')^2 + (\mathbf{v}_{\text{rel}} \cdot \hat{N}')^2}$, where $\mathbf{v}_{\text{rel}} = (\langle \mathbf{v}_p - \mathbf{v}_{\text{sc}} \rangle)_{(LMN)'}$ is the average plasma velocity in the spacecraft frame (in flux rope MVA coordinates) and $\Delta t = 971$ s is the duration of the flux rope traversal. This estimation gives $d_{\text{FR}} \gtrsim 9.1 \times 10^4$ km ($0.13 R_S$), which is around 20% of the HCS thickness. We expect the true diameter to be greater than our estimate from d_{FR} , although less than the HCS thickness ($0.66 R_S$), for two reasons: first, PSP does not pass directly through the center of the flux rope core (the impact parameter is nonzero), so its trajectory in the $\hat{L}$ – $\hat{N}$ plane is a chord rather than a diameter; second, the flux rope is non-force-free, so it is unlikely to be cylindrically symmetric. Furthermore, the MVA window may not entirely encompass the flux rope bounds, especially if the edges feature complex or distorted topology, leading to an underestimation of the flux rope extent.

3.3. Counterstreaming Strahl Electrons

During an IMF sector boundary crossing, dominant electron strahl pitch angle fluxes switch from 0° to 180° (or vice versa; N. U. Crooker et al. 2004). The strahl undergoes this change across the E17 HCS crossing, but as noted in Section 3.1, there is an unexpected measurement of bidirectional strahl within the embedded flux rope plasmoid, indicating closed IMF lines connected at both ends to the solar corona. This observation is in direct contrast with positive plasma jetting in v_L —an indication that the X-line is upstream of the HCS crossing—which should lead to magnetic disconnection from the Sun (J. T. Gosling et al. 2005a; T. D. Phan et al. 2021). A cursory assessment of other encounters to date (e.g., N. Fargette et al. 2026) reveals that most antisunward exhausts exhibit strahl dropout, and vice versa, but E17 is one of a minority of events that violate this convention. In this section, we explore some possible explanations for the observations in E17.

It has been pointed out that not all suprathermal electrons originate in the solar corona, with some features being generated locally (O. Khabarova et al. 2020). However, electron populations generated by local dynamics are expected to be hot, yet we observe a slight reduction in T_e during the HCS crossing (based on calculated moments; J. S. Halekas

et al. 2020). Thus, we believe the counterstreaming strahl observed in this event has solar origins. A different possibility, which we do not support due to its excessive complexity and difficulty to verify, is that the observed flux rope is subject to out-of-plane torsion (e.g., a kink instability) at adjacent locations in the HCS. To exhibit bidirectional strahl, the flux rope would have to twist such that it undergoes reconnection with the surrounding IMF on both sides of the site of PSP's HCS crossing. Another explanation attributes counterstreaming strahl observations to trapped electrons circulating around detached magnetic-island-like plasmoid configurations (J. T. Gosling et al. 1987; D. J. McComas et al. 1989). We discount this interpretation for the present event because it requires magnetic geometry that differs from our observations of a flux rope plasmoid.

Figure 2(c) shows bidirectional pitch angle flux concentrated in the core of the flux rope, suggesting a loop of Sun-connected field lines penetrating the magnetically disconnected reconnection exhaust by passing along the flux rope. The origin of this flux rope is unknown, but we believe it is likely to be different from the origin of the reconnection exhaust within which it is embedded. It is possible that the flux rope is a streamer blob originating at the tip of the helmet streamer, produced by interchange or pinch-off reconnection. In that case, the blob has become entrained in the exhaust of a later HCS reconnection event. This potential scenario warrants further exploration in a simulation study to establish how a magnetically connected streamer blob can propagate within disconnected flux caused by HCS reconnection.

Diagrams of this interpretation are given in Figure 4. Figure 4(a) demonstrates the magnetic connectivity suggested by the in situ observations, with Sun-connected flux (in the form of a flux rope) propagating within the disconnected region antisunward of HCS reconnection. Strahl electrons emanate from the Sun along the flux rope in both directions, giving rise to bidirectional strahl measured by PSP during its glancing traversal of the structure. The remainder of the exhaust crossing features strahl dropout, as expected for antisunward HCS reconnection.

Figure 4(b) expands on this interpretation, representing the HCS as two layers of a box passed through by PSP. Figure 4(b) is best read following the trajectory of Parker while referring to Figure 4(c), which shows the electron PAD in the strahl energy range (numbered corresponding to different strahl signatures in conjunction with the diagram in the cartoon). The enumeration in the cartoon corresponds to the following features.

1. PSP begins this interval in the $+B_r$ solar wind, with collimated 0° electron strahl.
2. PSP encounters diffuse electron strahl (partial heat flux dropout) in the $+B_r$ sector of the HCS.
3. The $-B_r$ sector exhibits more complete heat flux dropout.
4. PSP encounters a flux rope in the $-B_r$ sector, containing counterstreaming electron strahl.
5. PSP returns to the $-B_r$ HCS sector.
6. PSP reenters the IMF, where 180° collimated electron strahl is observed.

This interpretation suggests a complex magnetic topology with large-scale Sun-connected flux propagating within plasma jetting caused by reconnection in the HCS. The precise origin

of the flux rope and how it came to be entrained within the HCS reconnection exhaust is unknown, but the differences in density, speed, and temperature suggest formation under different circumstances from the remainder of the exhaust, likely at lower latitudes, for example, at the tip of the helmet streamer. These observations imply that future investigations are needed to explain other instances of unexpected strahl signatures in HCS reconnection outflows (e.g., E. Berriot et al. 2025). Furthermore, this example highlights the need for careful investigation of magnetic field and strahl signatures when determining the properties of reconnection exhausts in the near-Sun HCS.

4. Comparison with Remote Observations

Processing of WISPR images by the LW technique (Appendix of R. A. Howard et al. 2022) has revealed a near-continuous flow of streamer blobs in regions associated with the HCS (e.g., P. C. Liewer et al. 2024). The examples analyzed by P. C. Liewer et al. (2024) present strong evidence for magnetic-reconnection-driven dynamics influencing slow solar wind, producing quasiperiodic blobs with a flux-rope-like appearance in close proximity to the HCS. The flux rope central to the present study is an intriguing candidate for comparison to the streamer blobs, as its properties suggest it did not originate from the same HCS reconnection event as the exhaust within which it is embedded. While it would be unlikely to image the in situ structure directly because of its size compared to PSP, as well as its orientation relative to WISPR's line of sight (LOS), the LW images of E17 contain several features that complement our discussion of the in situ observations.

Four frames from the LW movie are shown in Figure 5, annotated to highlight features of interest. Figure 5(a) shows an example of a blob as observed around 7 hr before the HCS crossing. The blob is imaged here before passing out of view as PSP continues along its trajectory (approximately aligned with 0° helioprojective latitude, HPLT). Figure 5(b) features a string of smaller blobs emitted at a similar HPLT; these structures are more consistent with the size of the in situ flux rope ($\gtrsim 0.13 R_S$), but it should be noted that they will not be intercepted by PSP as they are above its orbital path. In the L3 FITS images (which represent true brightness rather than emphasizing differences; not shown), these blobs are obscured by a coronal ray, which corresponds to a fold in the heliospheric plasma sheet (HPS) tangent to WISPR's LOS (e.g., N. Poirier et al. 2020). As such, these blobs are likely to be traveling within the HCS at a significant distance from PSP, as explained by the minimal change in their apparent size from Figures 5(b)–(d) compared to other features. It would be interesting for a future study to analyze the trajectory of these blobs, in order to investigate how typical the blob intercepted by PSP is in terms of size and speed with respect to the HCS. For example, P. C. Liewer et al. (2023) found velocities of ~ 190 and $\sim 270 \text{ km s}^{-1}$ for two HCS blobs observed by WISPR when the blobs were at $\sim 9 R_S$, whereas M. L. Ascione et al. (2024) inferred a velocity of $\sim 330 \text{ km s}^{-1}$ for a blob traveling between 17 and $23 R_S$. For comparison, in situ particle velocity measurements indicate that the blob intercepted by PSP in this study was traveling at around 300 km s^{-1} at $12.3 R_S$.

The train of blobs is still visible 2 hr before the HCS crossing, as shown in Figure 5(c). Two other features have

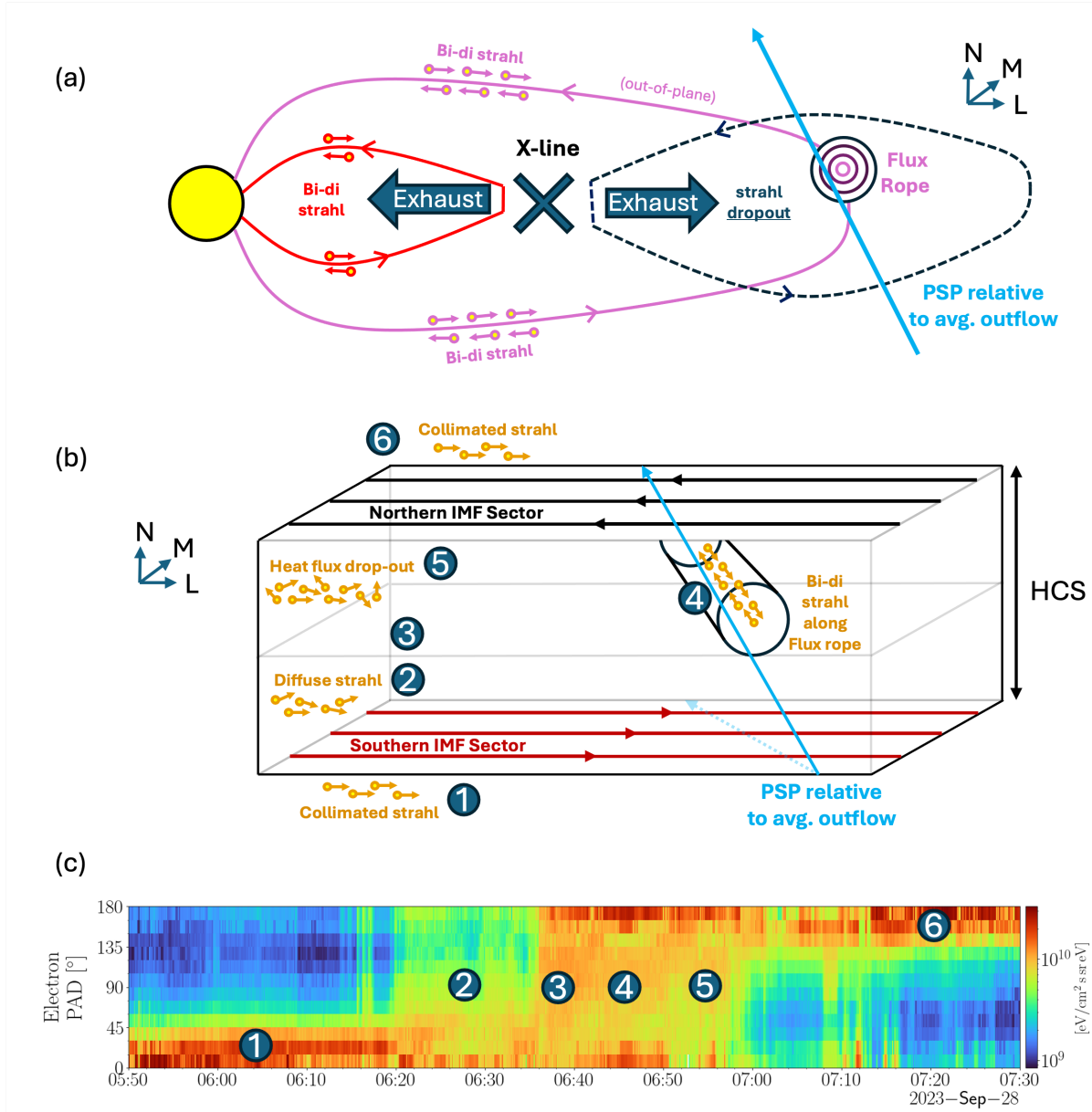


Figure 4. Illustrations representing an interpretation of the in situ measurements. (a) A simplified 2D view of the system, with upstream reconnection leading to disconnected exhausts. The flux rope is embedded in the outward exhaust but still connected to the corona at both ends. For this to be possible, the flux rope axis (purple) is out of plane. Approximate reference LMN axes are given, but it should be noted that this diagram is not intended to represent the physical orientation with respect to the Sun. (b) Depiction of the 3D HCS crossing, highlighting differences in strahl observations (numbered in order depicted). In panels (a) and (b), PSP’s velocity is relative to the outflow speed, and the motion of strahl electrons is represented by yellow circles with directional arrows. (c) Electron PAD as in Figure 2(c), annotated to match panel (b).

come into view in this frame: at around -10° HPLT, the HPS is now visible, and at -30° HPLT, an elongated density enhancement is just about to exit the WIS-O FOV. We interpret the former to be WISPR imaging the local HPS because the feature is moving from frame to frame in a negative HPLT direction, unlike distant coronal rays, which are obscured by the LW processing technique due to their relative lack of motion. Figure 5(d) shows the frame preceding the start of the in situ HCS crossing, where the HPS is imaged at -30° HPLT, about to exit the bottom of the WIS-O FOV. To clarify, the features that appear in WISPR do not necessarily correspond to the structures intercepted in situ. Figure 5(e) plots latitude against time (coplotted with PSP’s heliocentric distance and Carrington longitude; see

P. C. Liewer et al. 2023 for the method to create these maps and discussion of their interpretation) across a fixed range of solar elongation from 54° to 56° , confirming that the moving streak from around -10° HPLT in Figure 5(c) to $<-30^\circ$ after Figure 5(d) is the HPS. The measurement of the HPS contemporaneously with the in situ signatures corroborates our interpretation of this event as an HCS crossing.

The presence of the HPS in Figures 5(c)–(e) implies that WISPR’s LOS along the plasma sheet is maximized at around -30° HPLT, suggesting a prograde current sheet inclination of $\sim 60^\circ$ (between PSP’s orbital trajectory $\hat{i}$ and the current sheet normal $\hat{N}$). This appears to contradict the MVA-derived HCS orientation ($\hat{N} \sim \hat{i}$). However, in the MVA case, the plasma sheet would be perpendicular to WISPR’s FOV, making

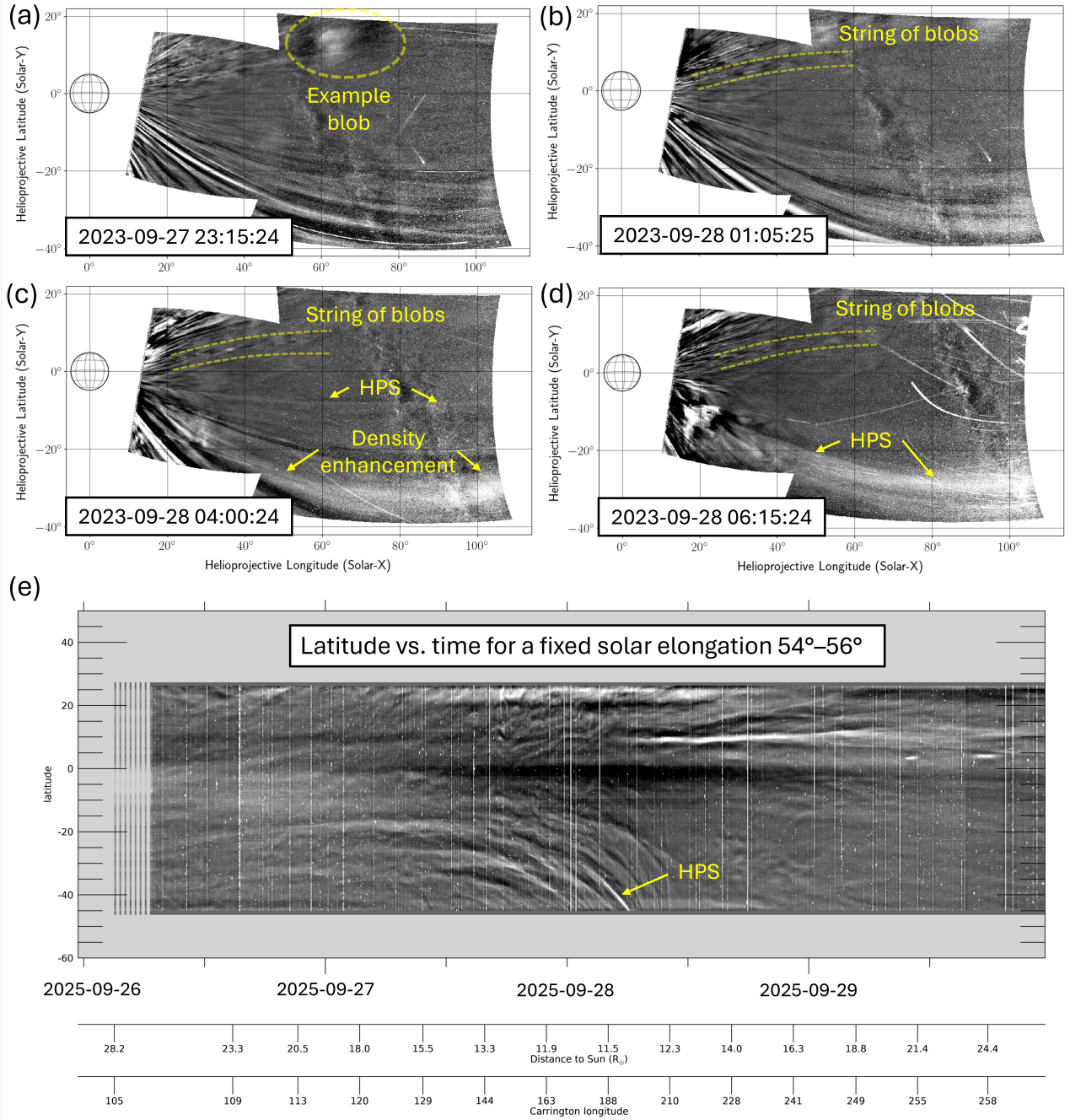


Figure 5. Selected LW-processed WISPR images for comparison to in situ measurements. (a)–(d) Frames consisting of composite maps where WIS-I and WIS-O images have been projected onto a common helioprojective coordinate system, annotated to enhance the description in the text. The images are recreated from LW FITS files. (e) Latitude versus time map for 54°–56° demonstrating the HPS observation at around 03:00–06:15, adapted from <https://wispr.nrl.navy.mil/encounter17-summary>. Credit: NASA/JPL. Data processed by Paulo Penteado (JPL/Caltech).

observation by WISPR unlikely. On the other hand, if the HCS normal was inclined by 90° relative to $\hat{t}$, we would expect WISPR to see two HPS streaks exiting the top and bottom of the FOV, but only the bottom one is visible. A possible HCS configuration that is consistent with Figures 5(c)–(e) and Section 2.2 is that the local HCS normal is approximately parallel to PSP’s trajectory, but there is a fold at a location in the $-\hat{n}$ direction below which the HCS normal is inclined by $\sim 60^\circ$ from PSP’s orbital path. A folded HCS could also explain the short partial crossings before and after the main

event present in Figure 2(b), where PSP briefly dips into the ripples without passing all the way through.

Overall, this section demonstrates WISPR observations of structures that may be similar to the flux rope measured inside the HCS, giving context to the in situ observations. Since flux ropes originating from magnetic reconnection at the helmet streamer are prevalent in and around the near-Sun HCS (e.g., B. Lavraud et al. 2020; V. Réville et al. 2022; N. Poirier et al. 2023; P. C. Liewer et al. 2024) and streamer blobs are hypothesized to consist of flux-rope-like topology (e.g.,

E. Sanchez-Diaz et al. 2019), the possibility that the present flux rope is a streamer blob could reconcile its apparently contradictory plasma properties compared to the HCS reconnection exhaust within which it is embedded. Future studies may wish to investigate other HCS crossings for similar events, comparing the properties of intercepted blobs to their surrounding HCS conditions and incorporating modeling to characterize the implications of these features on the variability of the slow solar wind.

5. Summary

PSP's close encounters with the Sun have revealed unexpectedly abundant magnetic reconnection events in the near-Sun HCS (e.g., T. D. Phan et al. 2021). In the present paper, we evaluate the HCS crossing on 2023 September 28, during which PSP is traveling outbound from the perihelion of E17. PSP detects a reconnection exhaust originating from an upstream X-line, based on the presence of antisunward jetting and proton temperature enhancement. Embedded within the exhaust is a non-force-free flux rope oriented obliquely to the current sheet, with the unusual feature of counterstreaming strahl electrons—indicative of Sun-connected field lines at both ends—despite being contained within an antisunward reconnection exhaust.

Differences in plasma properties between the flux rope and the HCS exhaust suggest that the former was not produced by the same reconnection event as the latter. In addition to hosting bidirectional strahl electrons, plasma within the flux rope is cooler and more isotropic and has modified alpha particle properties, implying a lower-altitude source region. However, the plasma properties within the flux rope are distinct from the slow solar wind measured outside the HCS, with the flux rope plasma being denser, hotter, and faster. These observations highlight the possibility that the flux rope is a streamer blob (e.g., N. R. Sheeley et al. 2009), potentially originating from interchange or pinch-off reconnection at the helmet streamer. Remote observations by WISPR reveal similarities between the flux rope and distant streamer blobs entrained within a higher-latitude coronal ray, compounding evidence that PSP has intercepted a streamer blob within the HCS.

The combination of remote and in situ measurements demonstrates the role of reconnection in the formation and evolution of the slow solar wind, generating quasiperiodic structures by means of processes such as pinch-off and interchange reconnection. The HCS constitutes a useful natural laboratory to explore the properties of large-scale magnetic reconnection and its interaction with the low-altitude solar environment. The E17 HCS example provides evidence that Sun-connected flux can propagate within disconnection regions, highlighting the complex topologies to which this region can be host as a result of magnetic reconnection. This encounter is one of a minority of events that contradict the expected strahl behavior in HCS reconnection exhausts, demonstrating the need for further investigation to characterize the impacts of magnetic reconnection on the origin and variability of the slow solar wind.

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Author Contributions

H.C.L. was responsible for writing and submitting the manuscript. H.C.L. and J.P.E. conceived of the study and performed formal analysis. All other authors contributed to the research, gave suggestions, and/or reviewed the manuscript.

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References

- Ascione, M. L., Gutarra-Leon, A. J., Shaik, S. B., et al. 2024, *ApJ*, **973**, 12
- Bale, S. D., Goetz, K., Harvey, P. R., et al. 2016, *SSRv*, **204**, 49
- Berriot, E., Démoulin, P., Alexandrova, O., et al. 2025, *ApJ*, **981**, 140
- Briggs, J., Brain, D., Cartwright, M., Eastwood, J., & Halekas, J. 2011, *P&SS*, **59**, 1498
- Burch, J. L., & Nakamura, R. 2025, *SSRv*, **221**, 19
- Crooker, N. U., Kahler, S. W., Larson, D. E., & Lin, R. P. 2004, *JGRA*, **109**, A03108
- DeForest, C. E., Howard, R. A., Velli, M., Viall, N., & Vourlidas, A. 2018, *ApJ*, **862**, 18
- Desai, M. I., Drake, J. F., Phan, T., et al. 2025, *ApJL*, **985**, L38
- DiBraccio, G. A., Slavin, J. A., Imber, S. M., et al. 2015, *P&SS*, **115**, 77
- Du, S., Li, H., Skoug, R., Steinberg, J., & Guo, F. 2025, *FrASS*, **12**, 1664531
- Eastwood, J. P., Phan, T. D., Drake, J. F., et al. 2026, *ApJ*, **996**, 140
- Fargette, N., Eastwood, J. P., Phan, T. D., Matteini, L., & Franci, L. 2026, *ApJ*, **997**, 174

- Fox, N. J., Velli, M. C., Bale, S. D., et al. 2016, *SSRv*, **204**, 7
- Gosling, J. T. 2012, *SSRv*, **172**, 187
- Gosling, J. T., Baker, D. N., Bame, S. J., et al. 1987, *JGRA*, **92**, 8519
- Gosling, J. T., Borrini, G., Asbridge, J. R., et al. 1981, *JGRA*, **86**, 5438
- Gosling, J. T., McComas, D., Skoug, R., & Smith, C. 2006, *GeoRL*, **33**, L17102
- Gosling, J. T., & Phan, T. D. 2013, *ApJL*, **763**, L39
- Gosling, J. T., Skoug, R. M., McComas, D. J., & Smith, C. W. 2005a, *GeoRL*, **32**, L05105
- Gosling, J. T., Skoug, R. M., McComas, D. J., & Smith, C. W. 2005b, *JGRA*, **110**, A01107
- Génot, V., Budnik, E., Jacquety, C., et al. 2021, *P&SS*, **201**, 105214
- Halekas, J. S., Whittlesey, P., Larson, D. E., et al. 2020, *ApJS*, **246**, 22
- Halekas, J. S., Whittlesey, P. L., Larson, D. E., et al. 2021, *A&A*, **650**, A15
- Hesse, M., & Cassak, P. A. 2020, *JGRA*, **125**, e2018JA025935
- Hesse, M., & Kivelson, M. G. 2013, *GMS*, **105**, 139
- Higginson, A. K., Antiochos, S. K., DeVore, C. R., Wyper, P. F., & Zurbuchen, T. H. 2017, *ApJL*, **840**, L10
- Horaites, K., Boldyrev, S., & Medvedev, M. V. 2019, *MNRAS*, **484**, 2474
- Howard, R. A., Stenborg, G., Vourlidas, A., et al. 2022, *ApJ*, **936**, 43
- Huang, J., Kasper, J. C., Larson, D. E., et al. 2023, *ApJS*, **265**, 47
- Kahler, S. W., Crocker, N. U., & Gosling, J. T. 1996, *JGRA*, **101**, 24373
- Khabarova, O., Malandraki, O., Malova, H., et al. 2021, *SSRv*, **217**, 38
- Khabarova, O., Zharkova, V., Xia, Q., & Malandraki, O. E. 2020, *ApJL*, **894**, L12
- Lavraud, B., Fargette, N., Réville, V., et al. 2020, *ApJL*, **894**, L19
- Lavraud, B., Gosling, J. T., Rouillard, A. P., et al. 2009, *SoPh*, **256**, 379
- Liewer, P. C., Badman, S. T., Linton, M., et al. 2025, *ApJ*, **990**, 24
- Liewer, P. C., Gallagher, B. M., Stenborg, G., et al. 2024, *ApJ*, **970**, 79
- Liewer, P. C., Vourlidas, A., Stenborg, G., et al. 2023, *ApJ*, **948**, 24
- Liou, K., & Wu, C.-C. 2021, *ApJ*, **920**, 39
- Livi, R., Larson, D. E., Kasper, J. C., et al. 2022, *ApJ*, **938**, 138
- McComas, D. J., Gosling, J. T., Phillips, J. L., et al. 1989, *JGRA*, **94**, 6907
- McGinnis, D., Halekas, J., Whittlesey, P., Larson, D., & Kasper, J. 2019, *JGRA*, **124**, 7369
- Moncuquet, M., Meyer-Vernet, N., Issautier, K., et al. 2020, *ApJS*, **246**, 44
- Patel, R., Niembro, T., Xie, X., et al. 2025, *NatAs*, **9**, 1444
- Phan, T. D., Bale, S. D., Eastwood, J. P., et al. 2020, *ApJS*, **246**, 34
- Phan, T. D., Drake, J. F., Larson, D., et al. 2024, *ApJL*, **971**, L42
- Phan, T. D., Lavraud, B., Halekas, J. S., et al. 2021, *A&A*, **650**, A13
- Phan, T. D., Romeo, O. M., Drake, J. F., et al. 2025, *ApJ*, **986**, 209
- Phan, T. D., Verniero, J. L., Larson, D., et al. 2022, *GeoRL*, **49**, e2021GL096986
- Poirier, N., Kouloumvakos, A., Rouillard, A. P., et al. 2020, *ApJS*, **246**, 60
- Poirier, N., Réville, V., Rouillard, A. P., Kouloumvakos, A., & Valette, E. 2023, *A&A*, **677**, A108
- Réville, V., Fargette, N., Rouillard, A. P., et al. 2022, *A&A*, **659**, A110
- Romeo, O. M., Braga, C. R., Badman, S. T., et al. 2023, *ApJ*, **954**, 168
- Runov, A., Baumjohann, W., Nakamura, R., et al. 2008, *JGRA*, **113**, A07S27
- Sanchez-Diaz, E., Rouillard, A. P., Lavraud, B., Kilpua, E., & Davies, J. A. 2019, *ApJ*, **882**, 51
- Sanny, J., McPherron, R. L., Russell, C. T., et al. 1994, *JGRA*, **99**, 5805
- Sheeley, N. R., Lee, D. D.-H., Casto, K. P., Wang, Y.-M., & Rich, N. B. 2009, *ApJ*, **694**, 1471
- Sheeley, N. R., Jr., Wang, Y., Hawley, S. H., et al. 1997, *ApJ*, **484**, 472
- Smith, E. J., Tsurutani, B. T., & Rosenberg, R. L. 1978, *JGRA*, **83**, 717
- Sonnerup, B. U., & Cahill, L. J. 1967, *JGR*, **72**, 171
- Szabo, A., Larson, D., Whittlesey, P., et al. 2020, *ApJS*, **246**, 47
- Vourlidas, A., & Howard, R. A. 2006, *ApJ*, **642**, 1216
- Vourlidas, A., Howard, R. A., Plunkett, S. P., et al. 2016, *SSRv*, **204**, 83
- Wang, Y., Sheeley, N. R., Socker, D. G., Howard, R. A., & Rich, N. B. 2000, *JGRA*, **105**, 25133
- Whittlesey, P. L., Larson, D. E., Kasper, J. C., et al. 2020, *ApJS*, **246**, 74