Kinetic-scale Current Sheets in Near-Sun Solar Wind: Properties, Scale-dependent Features and Reconnection Onset

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Abstract

We present statistical analysis of 11,200 proton kinetic-scale current sheets (CS) observed by the Parker Solar Probe during 10 days around the first perihelion. The CS thickness $\lambda$ is in the range from a few to 200 km with the typical value around 30 km, while current densities are in the range from 0.1 to 10 $\mu$A m$^{-2}$ with the typical value around 0.7 $\mu$A m$^{-2}$. These CSs are resolved thanks to magnetic field measurements at 73–290 samples s$^{-1}$ resolution. In terms of proton inertial length $\lambda_p$, the CS thickness $\lambda$ is in the range from about 0.1 to 10$\lambda_p$ with the typical value around 2$\lambda_p$. The magnetic field magnitude does not substantially vary across the CSs, and accordingly the current density is dominated by the magnetic-field-aligned component. The CSs are typically asymmetric with statistically different magnetic field magnitudes at the CS boundaries. The current density is larger for smaller-scale CSs, $J_0 \sim 0.15 \times (\lambda/100 \text{ km})^{-0.76} \mu$A m$^{-2}$, but does not statistically exceed the Alfvén current density $J_A$ corresponding to the ion-electron drift of the local Alfvén speed. The CSs exhibit remarkable scale-dependent current density and magnetic shear angles, $J_0/J_A \sim 0.17 \times (\lambda/\lambda_p)^{0.67}$ and $\Delta \theta \sim 21^\circ \times (\lambda/\lambda_p)^{0.32}$. Based on these observations and comparison to recent studies at 1 au, we conclude that proton kinetic-scale CSs in the near-Sun solar wind are produced by turbulence cascade, and they are automatically in the parameter range, where reconnection is not suppressed by the diamagnetic mechanism, due to their geometry dictated by turbulence cascade.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Interplanetary turbulence (830)

1. Introduction

Spacecraft measurements in the solar wind allow in-situ analysis of the turbulence in a magnetized weakly collisional plasma that is typical of numerous astrophysical systems (e.g., Mac Low 1999; Matthaeus & Velli 2011; Zhuravleva et al. 2014; Li et al. 2020). Remote and in-situ measurements at radial distances larger than 0.3 au showed that solar wind heating should continuously occur within a few tens of solar radii of the Sun as well as further out in the heliosphere (e.g., Kohl et al. 1996; Cranmer et al. 2009; Hellinger et al. 2013). The dissipation of turbulent magnetic field fluctuations is expected to be the most important solar wind heating mechanism (e.g., Vasquez et al. 2007b; Cranmer et al. 2009; Hellinger et al. 2013). Numerical simulations showed that turbulence dissipation should be spatially intermittent with substantial plasma heating localized around coherent structures, such as current sheets, which occupy a relatively small volume (Karimabadi et al. 2013; Zhdkankin et al. 2013, 2014; Wan et al. 2014, 2016). Spacecraft measurements at 1 au confirmed that plasma heating indeed occurs around current sheets (Osman et al. 2011, 2012; Wu et al. 2013), but contributions of various plasma heating mechanisms are still not entirely understood (e.g., Goldstein et al. 2015; Kiyani et al. 2015). One of the mechanisms initiating particle heating and turbulence dissipation is magnetic reconnection, which can also substantially affect development of the turbulence cascade at proton and subproton scales (e.g., Matthaeus & Lamkin 1986; Servidio et al. 2011, 2015; Cerri & Califano 2017; Franci et al. 2017, 2018; Papini et al. 2019). Because magnetic reconnection is sufficiently fast only in current sheets with thickness around proton kinetic scales (e.g., Cassak et al. 2006), the understanding of turbulence dissipation in astrophysical plasma can be advanced by analysis of proton kinetic-scale current sheets observed in the solar wind. In this paper we present a statistical analysis of proton kinetic-scale current sheets (CS) observed by the Parker Solar Probe (PSP) spacecraft in the previously unexplored near-Sun solar wind, within a few tens of solar radii from the Sun (Fox et al. 2016).

The presence of CSs, originally termed directional discontinuities, on a wide range of temporal scales was established by previous spacecraft measurements at 1 au (e.g., Burlaga et al. 1977; Tsurutani & Smith 1979; Lepping & Behannon 1986; Söding et al. 2001; Artemyev et al. 2018, 2019). In most of these studies CSs were selected using magnetic field measurements with resolutions of a few seconds at best. The typical CS thickness was around 1000 kilometers or 10 proton inertial lengths; the occurrence rate was a few tens per day. However, magnetic field measurements at higher resolution (1/3 and 1/11 s) allowed resolving CSs with thickness around one proton inertial length and showed they are much more abundant, a few hundred CSs per day (Vasquez et al. 2007a; Podesta 2017;
Vasko et al. 2021, 2022). The magnetic field variation across the proton kinetic-scale CSs is predominantly a rotation through some shear angle, rather than magnitude variation (Vasquez et al. 2007a; Vasko et al. 2021, 2022), that is also typical of larger-scale CSs (e.g., Burlaga 1969; Lepping & Behannon 1986; Artemyev et al. 2019). Based on the distribution of waiting times, it was hypothesized that kinetic-scale CSs in the solar wind are produced by turbulence cascade (Vasquez et al. 2007a; Greco et al. 2008, 2009; Perri et al. 2012). Vasko et al. (2022) further supported this hypothesis by demonstrating that the current density and shear angle across the CSs depend on CS thickness in a scale-invariant fashion expected for turbulent fluctuations.

The observations of reconnecting CSs at 1 au were reported fairly recently (Phan et al. 2006; Gosling 2007; Gosling et al. 2007). The reconnection was identified by a plasma jet within a CS and found to be often, though not always, associated with a bifurcated magnetic field profile (Gosling & Szabo 2008; Phan et al. 2010; Mistry et al. 2015). The spacecraft measurements also showed that magnetic reconnection in the solar wind does result in plasma heating (Phan et al. 2006; Enzil et al. 2014; Pulupa et al. 2014; Mistry et al. 2017). The plasma measurements at 3 s resolution or, equivalently, ≈1000 km spatial resolution showed that magnetic reconnection at 1 au is relatively rare, about one reconnecting CS per day (Phan et al. 2010; Gosling 2012; Osman et al. 2014). The fundamental questions are what is the occurrence of reconnection at proton kinetic scales and why it is so rare at spatial scales of ≈1000 km. Although the occurrence of reconnection at proton kinetic scales has not been established yet, the recent analysis by Vasko et al. (2021) has shown that the presence or absence of reconnection in such CSs is not determined by the diamagnetic suppression condition. Note that previously Phan et al. (2010) showed that reconnecting CSs are in the parameter range, where reconnection cannot be suppressed by the diamagnetic mechanism (Swisdak et al. 2003, 2010), while the analysis by Vasko et al. (2021) showed that all proton kinetic-scale CSs are automatically in that parameter range due to their geometry dictated by turbulence cascade.

The high-resolution magnetic field measurements aboard the recently launched PSP spacecraft allow resolving proton and subproton kinetic-scale CSs in the near-Sun solar wind. The previous measurements of near-Sun solar wind, at radial distances as close as 60 solar radii, were done aboard the Helios spacecraft (Rosenbauer et al. 1977). However, the highest magnetometer resolution aboard Helios was 0.25 s, and only CSs with thickness larger than about 10 proton inertial lengths were resolved (Söding et al. 2001). Phan et al. (2020) have recently used PSP measurements to address the occurrence of magnetic reconnection in the near-Sun solar wind. Using plasma measurements at 0.2–0.9 s cadence and magnetic field measurements downsampled to 0.2 s, they resolved CSs with thickness larger than about 10 proton inertial lengths and found a negligible amount of reconnecting CSs among them.

In this paper we present the analysis of 11,200 proton kinetic-scale CSs observed by the PSP around the first perihelion. The properties of these CSs will be compared to those recently reported at 1 au (Vasko et al. 2021, 2022). The paper is organized as follows. Section 2 describes the data set and methodology. Section 3 overviews the considered interval and presents several case studies. Section 4 presents the epoch analysis and CS properties. Section 5 presents the test of the diamagnetic suppression condition of magnetic reconnection. Section 6 presents the scale dependence of various CS properties. Sections 7 and 8 present the discussion and summary of the results.

2. Data and Methodology

We consider PSP measurements over 10 days around the first perihelion, from 2018 November 1 to November 10. We use the magnetic field measurements provided by the FIELDS instrument suite (Bale et al. 2016). In particular, we use the merged fluxgate and search-coil magnetometer measurements (Bowen et al. 2020), with a sampling rate of about 290 S s⁻¹ (samples per second) from November 5 to November 7 and gradually reduced to 73 S s⁻¹ as the spacecraft moved away from the perihelion. We use the ion and electron moments provided the Solar Wind Electrons Alphas and Protons (SWEAP) instrument suite (Kasper et al. 2016), including the Solar Probe Cup (SPC; Case et al. 2020) and the Solar Probe Analyzers Electrons (SPAN-E; Whittlesey et al. 2020). Estimates of the proton density, bulk velocity, and radial proton temperature were all available at 0.2–0.9 s cadence. The electron velocity distribution functions available at 28 s cadence have been previously analyzed and fitted to a combination of core, halo, and strahl populations (Halekas et al. 2020). We use the total electron density of the three components and the core electron temperature as a proxy of the total electron temperature, because the thermal and dynamic pressures of the halo and strahl populations were lower than a few percent of the core electron pressure (Halekas et al. 2020). We will also present plasma density estimates delivered by the quasi-thermal noise spectroscopy available at about 7 s cadence (Moncuquet et al. 2020). The procedure of CS selection and methodology, briefly described below, is equivalent to those used at 1 au (Vasko et al. 2021, 2022).

The selection of CSs is based on the partial variance increments (PVI) method (e.g., Greco et al. 2008, 2018). We compute the PVI index, PVI(t, τ) = (Σα α B α(t + τ) − Bα(t))² / (σα²)², where Bα(t, τ) = Bα(t + τ) − Bα(t) are magnetic field increments of various magnetic field components (α = X, Y, Z) and σα are the standard deviations of ΔBα(t, τ) computed over 1 h intervals, that is, over several outer correlation scales of the turbulence in the near-Sun solar wind (Chen et al. 2020). Coherent structures at various temporal scales correspond to non-Gaussian fluctuations with, for example, PVI > 5. We used only the PVI index computed at the minimum time increment τ determined by the sampling rate of magnetic field measurements, so that τ is in the range from 1/73 to 1/290 s. This allows analysis of the thinnest coherent structures still resolvable by PSP magnetic field measurements. Because the PVI index is proportional to the local current density (Chasapis et al. 2017; Yordanova et al. 2020), our focus on fluctuations with PVI > 5 translates into selection of the most intense coherent structures. Note that it is not our purpose to select all CSs present in the solar wind at various spatial scales, but rather to collect a sufficiently representative data set of proton kinetic-scale CSs to address their properties and origin.

In addition to current sheets, there are other types of coherent structures among the non-Gaussian fluctuations (PVI > 5) such as Alfvén vortexes (Perrone et al. 2020) and ion-cyclotron waves (Bowen et al. 2020a, 2020b). We considered each continuous cluster of points with PVI > 5 over several nested 0.1–2 s intervals around its center and used maximum variance
analysis (e.g., Sonnerup & Scheible 1998) to compute the unit vector $\mathbf{x}'$ along the magnetic field component with the largest variation. We visually inspected all $\mathbf{B} \times \mathbf{x}'$ profiles and selected clusters of points with $\mathbf{B} \times \mathbf{x}'$ reversing the sign within at least one of the intervals. We then manually adjusted the boundaries, so that each boundary has at least one point of magnetic field measurements, and excluded events with substantial relative variations in the magnetic field at the boundaries. The selected CSs were visually classified into nonbifurcated and bifurcated, the latter type often seen in reconnecting CSs (e.g., Phan et al. 2010, 2020; Mistry et al. 2017). A short temporal duration of the CSs did not allow establishing the presence or absence of reconnection jets using proton flow velocity measurements and, thus, we could not determine the fraction of reconnecting CSs in our data set. The final data set includes 11,200 CSs with 1,277 of them classified as bifurcated.

For each CS we use the local coordinate system $xyz$ most suitable for describing a local CS structure (e.g., Knetter et al. 2004; Gosling & Phan 2013; Phan et al. 2020): unit vector $\mathbf{z}$ is along the CS normal determined by the cross product of the magnetic fields at the CS boundaries; unit vector $\mathbf{x}$ is along $\mathbf{x}'$; unit vector $\mathbf{y}$ completes the right-handed coordinate system, $\mathbf{y} = \mathbf{z} \times \mathbf{x}$. Because the Taylor hypothesis was valid during the first perihelion (Chen et al. 2020; Chhiber et al. 2021), the temporal profiles of the CSs are translated into spatial profiles by computing the spatial distance, $z = -V_0(t - t_0)$, where $t_0$ is an arbitrary moment of time and $V_0$ is the normal component of the local proton flow velocity at the moment closest to a CS. We estimate the current density components as follows

$$J_x = \frac{1}{\mu_0 V_n} \frac{dB_y}{dt}, \quad J_y = -\frac{1}{\mu_0 V_n} \frac{dB_x}{dt}, \quad J_z = \frac{1}{\mu_0 V_n} \frac{dB_z}{dt},$$

where $\mu_0$ is the vacuum permeability. We also present the current densities parallel and perpendicular to local magnetic field, $J_{||} = (J_B x + J_y B_x)/B$ and $J_{\perp} = (J_y B_x - J_x B_y)/B$. By noting that the magnetic field of a locally planar CS can be described as

$$B = B(z) \sin \theta(z) \mathbf{x} + B(z) \cos \theta(z) \mathbf{y} + B_z \mathbf{z},$$

we find that

$$J_{||} = \frac{B}{\mu_0} \frac{d\theta}{dz}, \quad J_{\perp} = \frac{1}{\mu_0} \frac{dB}{dz},$$

where $\theta(z)$ and $B(z)$ describe, respectively, the magnetic field rotation and magnitude variation within the CS, and $B_z$ is negligibly small compared to $B(z)$. Note that Equation (2) is the most general expression for the magnetic field of a CS with nonzero $B_z$, while specific models widely used in theoretical studies (e.g., Landi et al. 2015; Boldyrev & Loureiro 2018; Neukirch et al. 2020) correspond to specific profiles of $B(z)$ and $\theta(z)$. Equation (3) shows that the parallel current density determines the magnetic field rotation, while the perpendicular current density determines the variation in the magnetic field magnitude within the CS. The ratio between the perpendicular and parallel current densities can be approximately estimated as follows

$$J_{\perp}/J_{||} \approx \Delta B/\langle B \rangle \Delta \theta,$$

where $\langle B \rangle$ is the typical/averaged magnetic field magnitude, and $\Delta B$ and $\Delta \theta$ are, respectively, the magnetic shear angle and variation in the magnetic field magnitude across CS.

The collected proton kinetic-scale CSs have relatively short temporal duration, more than 85% of the CSs have temporal duration of less than 0.5 s. The cadence of plasma measurements, especially 28 s cadence for electrons, does not allow reliable estimates of plasma $\beta$ at the CS boundaries, because magnetic fields at the CS boundaries generally vary on a timescale of 0.9–28 s. We determine the variation in plasma $\beta$ across each CS as proposed by Vasko et al. (2021). We assume there is a pressure balance, $8\pi P + B^2 = 8\pi \Pi = \text{const}$ or $8\pi P/B^2 + 1 = 8\pi \Pi/B^2$, where $P$ is the thermal plasma pressure. There are several proton measurements and one point of electron measurements around each CS, and the constant parameter $\Pi$ can be determined by averaging the pressure balance across the CS, $\Pi = \langle B^2 \rangle/8\pi + \langle P \rangle$ and $8\pi \Pi/(B^2) = (8\pi P/B^2) + 1$, where we assume that the spatial averaging of the thermal plasma pressure is equivalent to time-averaging done by PSP plasma instruments. The variation in plasma beta can be estimated as follows

$$\Delta \beta \approx (1 + \beta) \left( \frac{\langle B^2 \rangle}{\langle B^2 \rangle} \right),$$

where $\beta = (8\pi P/B^2) = (8\pi P + \langle B^2 \rangle)/\langle B^2 \rangle - 1$ is the averaged plasma beta.

3. Overview and Case Studies

Figure 1 presents an overview of the considered 10 day interval. Over this interval, the spacecraft was at radial distances from 0.17 to 0.24 au, that is, from 35 to 50 solar radii, and remained within the inward magnetic field sector without crossing the heliospheric current sheet (Phan et al. 2020; Szabo et al. 2020). No coronal mass ejections were observed in the considered interval (Phan et al. 2020; Szabo et al. 2020). The spacecraft was approximately corotating with the Sun and connected to the same coronal hole (Bale et al. 2019; Badman et al. 2020). Panels (a)–(d) present 1 minute averages of the magnetic field magnitude, proton flow velocity, densities, and temperatures of protons and electrons as well as plasma density estimates provided by the quasi-thermal noise spectroscopy. The magnetic field magnitude was about 100 nT at the perihelion on November 6, and around 50 nT as the spacecraft moved to a radial distance of 50 solar radii from the Sun on November 1 and 10. The solar wind was typically slow with a proton flow velocity below 400 km s$^{-1}$, except for the $\approx 20$ hr period of fast solar wind between November 9 and 10. The three plasma density estimates in panel (c) are consistent with each other within a few tens of percent over the entire interval, except for the fast solar wind interval, where the proton densities were about 4 times smaller than the plasma density estimates provided by the quasi-thermal noise spectroscopy. We will use the electron density estimates, calibrated to best match proton densities and the results of quasi-thermal noise spectroscopy, as plasma density estimates. The proton temperature during the considered interval varied between about 10 and 100 eV, while the electron temperature remained around 30 eV. Panel (e) presents 1 minute averages of proton and electron betas and shows that both quantities varied in the range from 0.1 to 5.

Panel (f) presents the percentage of magnetic field increments with PVI > 5 computed for 1 h intervals. The averaged percentage of 1.3% is 4 orders of magnitude larger.
than one would observe if the magnetic field increments had Gaussian probability distributions. The non-Gaussian distributions of magnetic field increments are consistent with previous observations in the solar wind (e.g., Sorriso-Valvo et al. 1999; Greco et al. 2009; Chhiber et al. 2021). Panel (g) shows that the number of bifurcated CSs per day varied from 500 to 1500, while the averaged occurrence rate is 1120 CSs per day. The percentage of bifurcated CSs per day varies from 5% to 15% with the averaged value around 10%. Panel (h) shows that the number of CSs per hour varies from 0 to 200 with an averaged value of around 50 CSs per hour.

Figure 2 presents several CSs from our data set. The left panels present a nonbifurcated CS. Panel (a) shows the magnetic field magnitude and three magnetic field components in the spacecraft coordinate system XYZ. The magnetic field rotates across the CS through a shear angle $\Delta \theta \approx 77^\circ$. The magnetic field magnitude changes across the CS by $\Delta B \approx 8$ nT, while the mean of the magnetic field magnitudes at the CS boundaries is $\langle B \rangle \approx 45.6$ nT. The magnetic field variation within CS is relatively large, and the difference between maximum and minimum values of the magnetic field magnitude is $\Delta B_{\text{max}} \approx 25$ nT. Panel (b) presents the magnetic field in the local CS coordinate system xyz. The magnetic field $B_x$ varies across the CS by $\Delta B_x \approx 57.3$ nT. The CS is not perfectly symmetric; the mean of $B_x$ values at the CS boundaries is $\langle B_x \rangle \approx 6.8$ nT. The values of $B_z$ at the CS boundaries are similar, and their mean value is $B_z \approx 30$ nT. The normal component $B_n$ is around zero at the CS boundaries and remains small within the CS. The CS is observed in a plasma with plasma density of 209 cm$^{-3}$, electron temperature of 25 eV, and proton temperature of 70 eV, so that electron and proton betas are $\beta_e \approx 1$ and $\beta_p \approx 2.8$. Using Equation (5) we found that plasma beta varies across the CS by $\Delta \beta \approx 1.4$.

Panels (c) and (d) present the current densities $J_y$ and $J_z$ as well as the components parallel and perpendicular to the local magnetic field. The CS central region, where $|B_x - \langle B_x \rangle| < 0.2 \Delta B_x$, is highlighted in panels (b)-(d). We characterize the CS intensity by $I_{\text{peak}}$, that is, the absolute peak value of the parallel current density $J ||$, and by $J_0$, that is, the absolute value of the parallel current density $J ||$ averaged over the CS central region. For the considered CS we have $J_0 \approx 1.5 \mu A/m^2$ and $I_{\text{peak}} \approx 2.35 \mu A/m^2$ or $J_0 \approx 0.63 J_x$ and $I_{\text{peak}} \approx 1.05 J_x$ in units of the local Alfvén current density $J_A = e N_0 V_A$, where $N_0$ is the plasma density, $V_A = (B^2 / (\mu_0 m_p e))^1/2$ is the local Alfvén speed, and $m_p$ and $e$ are the proton mass and charge, respectively. The CS thickness is determined as follows

$$\lambda = \frac{\Delta B_x}{2 \mu_0 J_0}.$$  

(6)

The CS thickness is $\lambda \approx 14$ km, while in units of the local proton inertial length $\lambda_p$ and thermal proton gyroradius $\rho_p$ we have $\lambda \approx 0.93 \lambda_p$ and $\lambda \approx 0.6 \rho_p$. Note that strictly speaking $\lambda$ is a half thickness, because according to Equation (6) the magnetic field can be approximated as $B_x \approx (B_x + 0.5 \Delta B) \tanh(z/\lambda)$, but we keep to the terminology often used in theoretical studies and refer to this parameter as thickness.

The right panels in Figure 2 present a bifurcated CS observed in a plasma with a density of 343 cm$^{-3}$, electron temperature of 36 eV, and proton temperature of 15 eV, so that $\beta_e \approx 1.1$ and $\beta_p \approx 0.5$. The current densities $J_y$ and $J_\parallel$ have bifurcated profiles, and accordingly magnetic field rotation occurs in two steps, in contrast to the relatively smooth rotation in nonbifurcated CSs. As the $J_\parallel$ profile is bifurcated, the current density averaged over the CS central region does not reflect the actual CS intensity and cannot be used to estimate the CS thickness. We have determined the temporal duration of each bifurcated CS manually as the half of the temporal distance between the two steps of magnetic field rotation. The spatial scale corresponding to this temporal duration will be referred to as the thickness of a bifurcated CS. For the considered CS we have $\lambda \approx 36$ km; that is around $3 \lambda_p$ or $4.4 \rho_p$.

4. Statistical Properties

Figure 3 presents the averaged magnetic field profiles of nonbifurcated and bifurcated CSs. Before computing the averaged profiles, individual CS profiles were appropriately
normalized and aligned. The individual profiles of $B_x$ and $B_t$ were, respectively, normalized to $B_0 = 0.5 \Delta B_x$ and $\langle |B| \rangle$, where a signed quantity of $B_0$ was used so that $B_x/B_0$ was always negative/positive at the left/right boundary. The individual profiles of $B_x$ and $B_t$ were both normalized to $B_x$. The individual profiles were aligned by normalizing the spatial distance $z$ to CS thickness $\lambda$ and setting $z = 0$ at the CS center. The center of a nonbifurcated CS corresponds to $B_x = \langle B_x \rangle$, while for a bifurcated CS it is in the middle between the two steps of magnetic field rotation. Each $B_x/B_0$ profile with smaller absolute value at the right boundary was reflected with respect to $z = 0$ and multiplied by $-1$. The other magnetic field profiles corresponding to that $B_x/B_0$ profile were reflected too. The reflection procedure allows us to keep the smaller of the $B_x/B_0$ absolute values at the left boundary, so that the averaged CS asymmetry can be revealed.

The averaged profiles of bifurcated and nonbifurcated CSs along with individual CS profiles are shown in panels (a) and (b) of Figure 3. The averaged $B_x/B_0$ profiles demonstrate that both bifurcated and nonbifurcated CSs are typically asymmetric with left and right boundary values around $-0.75$ and 1.25, respectively. In addition, the averaged $B_t/B_0$ profiles show that magnetic field rotation occurs relatively smoothly in nonbifurcated CSs and, in contrast, in two steps in bifurcated CSs. The averaged $B_y/B_0$ profiles demonstrate that statistically this magnetic field component has similar values at the CS boundaries and a few percent larger value around the CS central region. The averaged $B_x/B_t$ profiles show that the normal component is around zero at the CS boundaries and remains small within the CS. Note that each individual $B_x/B_t$ profile was multiplied by its sign around the CS central region to reveal the absolute value of $B_x/B_t$ in the averaged profile. The averaged profiles of $B/\langle B \rangle$ show that the magnetic field magnitude varies within both CS types by only a few percent. The magnetic field magnitude is larger at the right boundary; that is consistent with the asymmetry in the $B_x$ profiles. In other words, the averaged profiles indicate that $\Delta(B^2) \approx \Delta(B_x^2 + B_t^2) \approx \Delta(B_y^2)$, which can be rewritten as follows

$$\langle B \rangle \Delta B \approx \langle B_x \rangle \Delta B_x,$$

where we took into account that $\Delta(B^2) = 2\langle B \rangle \Delta B$ and $\Delta(B_x^2) = \langle B_x \rangle \Delta B_x$.

The statistical distributions in panels (c)–(f) of Figure 3 show that bifurcated and nonbifurcated CSs have similar distributions of the major CS parameters. The thickness of both CS types is in the range from a few to 200 km with the typical value around 30 km. Both CS types are typically asymmetric, $\langle B_x \rangle / \Delta B_x \geq 0.1$ for about 40% of the CSs, with relatively small variation in the magnetic field magnitude within the CS and between CS boundaries, $\Delta B_{\text{max}} / \langle B \rangle \lesssim 0.1$ and $\Delta B / \langle B \rangle \lesssim 0.1$. The region highlighted in panels (b)–(d) and (f)–(h) is the CS central region, where $|B_x - \langle B_x \rangle| < 0.2 \Delta B_x$ (see Section 3 for details).
for about 95% of the CSs. The only substantial difference
between the two CS types is that magnetic
field rotation occurs
smoothly within nonbifurcated CSs and in two steps within
bifurcated CSs. This difference can be also demonstrated
quantitatively. For each CS we compute a correlation
coefficient between the $J_||$ profile and a model nonbifurcated
profile $J_|| \cdot \text{sech}^2(V_s t / \lambda)$, where $V_s$ is the normal component of
the local proton flow velocity, $t = 0$ corresponds to $B_s = \langle B_s \rangle$, and
$\lambda$ was determined by Equation (6) for all CSs. The
probability distributions in Figure 4 demonstrate that the
correlation coefficient is below (above) 0.5 for more than 90%
(80%) of the bifurcated (nonbifurcated) CSs, which proves the
adequacy of our visual CS classification.

Figure 5 compares the thickness of the CSs to the local proton inertial length $\lambda_p$ and thermal proton gyroradius $\rho_p = \lambda_p \beta_p^{1/2}$, where $\beta_p$ is the proton beta. Panel (a) shows that although the local proton inertial length for the CSs varied only between 10 and 25 km, there is a trend that the CSs observed at larger $\lambda_p$ tend to have larger thicknesses. Panel (b) presents the probability distribution of $\lambda/\lambda_p$ and shows that the CS thicknesses are in the range from about 0.1–10$\lambda_p$ with the typical value around 2$\lambda_p$. Thus, the collected CSs are structures

![Figure 3. Panels (a) and (b) present the epoch analysis of the nonbifurcated and bifurcated CSs (see Section 4 for details). The individual CS profiles (gray) shown in panels (a) and (b) were appropriately normalized and aligned; the averaged profiles (black) are shown along with error bars indicating the standard deviations. The individual $B_x$ profiles were normalized to $B_0$, that is, the half difference of $B_x$ values at the right and left CS boundaries; the individual $B_y$ and $B_z$ profiles were normalized to $B_s$, that is, the half sum of $B$ values at the CS boundaries; and the spatial coordinate $z$ across each CS was normalized to the CS thickness $\lambda$. Panels (c)-(f) present the statistical distributions of various parameters of bifurcated and nonbifurcated CSs including the thickness $\lambda$, asymmetry $<B_x>/\Delta B_x$, relative variation $\Delta B/\langle B \rangle$ of the magnetic field magnitude across the CS, and maximum relative variation $\Delta B_{\text{max}}/\langle B \rangle$ in the magnetic field magnitude within the CS.](image-url)
at proton kinetic scales, with about 10% of the CSs at subproton scales, \( \lambda \lesssim \lambda_p \). Panel (b) shows that the probability distribution of \( \lambda/\lambda_p \) is identical with the one of \( \lambda/\lambda_p \), because according to panel (c) proton beta \( \beta_p \) is between 0.4 and 2 for more than 80% of the CSs. The total plasma beta was between 0.5 and 3 for about 90% of the CSs with the typical value around 1.5.

5. Tests of the Diamagnetic Suppression Condition

Swisdak et al. (2010) showed that magnetic reconnection in a planar CS with magnetic shear angle \( \Delta \theta \) and plasma beta variation \( \Delta \beta \) between the CS boundaries is allowed/suppressed if the following condition is satisfied/violated (see also Swisdak et al. 2003)

\[
\Delta \beta \lesssim 2(L/\lambda_p)\tan(\Delta \theta/2),
\]

where \( L \) is the scale of plasma pressure gradient across the X line, which should be of the order of 1 proton inertial length for magnetic reconnection to be sufficiently fast (e.g., Cassak et al. 2006). The violation of this criterion results in suppression of magnetic reconnection, because the diamagnetic drift of the X line becomes comparable with the characteristic Alfvén speed (Swisdak et al. 2010). Note that Equation (8) is necessary, but not sufficient for magnetic reconnection. Although the magnetic field magnitude does not substantially vary across the CSs (Figure 3(e)), it does result in plasma beta variation \( \Delta \beta \), which might be of importance for the reconnection development.

Before testing the diamagnetic suppression Equation (8), we address the origin of the magnetic field magnitude variation across the CSs.

Figure 6 presents a further experimental test of Equation (7) and clarifies the dependence of \( \Delta B/(B) \) on local plasma parameters. Panel (a) shows that there is a correlation between \( \Delta B/(B) \) and \( \langle \beta \rangle \Delta B_s/(B)\kappa_2 \), especially at \( \Delta B/(B) \gtrsim 0.01 \). This confirms that the magnetic field variation across the CSs is predominantly due to the \( \beta_s \) asymmetry. Panel (b) shows that there is a positive correlation between \( \Delta B/(B) \) and \( \Delta \theta \) and reveals the upper threshold, \( \Delta B/(B) \lesssim \Delta \theta/2 \). This threshold follows from Equation (7) once we take into account that \( \langle \beta_s \rangle \lesssim 0.5 \Delta B_s \) and \( \Delta B_s \approx \langle B \rangle \Delta \theta \). Panel (c) presents the probability distribution functions of \( \Delta B/(B) \) for the CSs observed at \( \beta < 1.5 \) and \( \beta > 2.5 \). These distributions show that larger values of \( \Delta B/(B) \) are observed at higher plasma betas. Panel (d) shows the probability distribution of \( \Delta B/(B) \Delta \theta \), which is a proxy of the ratio between the perpendicular and parallel current densities (see Equation (4)). For more than 95% of the CSs we have \( \Delta B/(B) \Delta \theta \lesssim 0.1 \), so that the current density in the CSs is dominated by the parallel component. Similarly we have found that statistically \( \Delta B_{\text{max}}/(B) \lesssim \Delta \theta \) (not shown here). Note that similarly to \( \Delta B/(B) \) we observe larger values of \( \Delta B/(B) \Delta \theta \) at larger plasma betas (not shown here).

Figure 7 presents a test of the diamagnetic suppression condition (Equation (8)). Panels (a) and (b) show that all bifurcated as well as nonbifurcated CSs satisfy Equation (8) with \( L = 2 \lambda_p \) and only about 1% of the CSs of both types violate this condition with \( L = \lambda_p \). In the Swisdak et al. (2010) theory, parameter \( L \) is the scale of the plasma pressure gradient across the X line, while for each CS we could estimate only the local CS thickness \( \lambda \). It is reasonable to test Equation (8) for \( L = \lambda \), because \( \lambda \) characterizes the local scale of the plasma pressure gradient across a CS before reconnection potentially occurs. Panel (c) shows that about 99% of the CSs satisfy Equation (8) with \( L = \lambda \). As the previous observations at 3 s temporal or, equivalently, \( \approx 1000 \) km spatial resolution showed that only a relatively small fraction of the CSs in the solar wind are reconnecting (e.g., Gosling 2012; Osman et al. 2014), the fact that Equation (8) is satisfied by almost all the CSs implies that the diamagnetic suppression condition does not control reconnection onset and occurrence in the solar wind.

6. Scale-dependent CS Properties and Critical Current Density

Figure 8 presents the analysis of averaged and absolute peak values, \( J_0 \) and \( J_{\text{peak}} \), of the parallel current density within the CSs. In this section we do not consider bifurcated CSs (about 10% of all CSs), because \( J_0 \) does not reflect their actual current density. Panel (a) shows that the current density \( J_0 \) is inversely correlated with the CS thickness \( \lambda \), so that smaller-scale CSs tend to be more intense. We reveal the trend, shown in panel (a), by sorting the CSs into bins corresponding to different values of \( \lambda \), and computing the median value of \( J_0 \) within each bin. The error bars in panel (a) correspond to the 15th and 85th percentiles of \( J_0 \) within each bin. The number of CSs within each bin is shown at the bottom of panel (a). We also fitted the scattered data in panel (a) by a power-law function and found
the following best fit

\[ J_0 = 150 \text{ nA m}^{-2} \times \left( \frac{\lambda}{100 \text{ km}} \right)^{-0.76}, \]

which well describes the median profile revealed by binning the data. The median profiles in panels (b) and (c) show that the current density \( J_{\text{peak}} \) and corresponding ion-electron drift velocity \( J_{\text{peak}}/eN_0 \) are positively correlated with the local Alfvén current density \( J_A = eN_0V_A \) and Alfvén speed \( V_A \), respectively. The CSs tend to be more intense at larger Alfvén speeds. In addition, panels (b) and (c) show that the current densities \( J_{\text{peak}} \) are statistically below some threshold, \( J_{\text{peak}} \lesssim J_A \) for more than 99% of the CSs and \( J_{\text{peak}} \lesssim J_A/2 \) for about 98% of the CSs.

Figure 9 reveals the scale dependence of various CS properties in normalized units. The scale-dependent trends of the various quantities in panels (a)–(c) are demonstrated by the median profiles revealed by sorting the CSs into bins. The number of CSs within each bin is shown in panel (d). Panel (a) shows that the normalized current density, \( J_0/J_A \), is inversely correlated with the normalized CS thickness, \( \lambda/\lambda_p \). The least-squares fitting of the scattered data by a power-law function reveals the following best fit

\[ J_0/J_A = 0.17 (\lambda/\lambda_p)^{-0.67}, \]

which also well describes the median profile in panel (a). Panel (b) shows that the CS amplitude \( \Delta B/(B) \) is positively correlated with \( \lambda/\lambda_p \). The best fit by a power-law function

\[ \Delta B/(B) = 0.35 (\lambda/\lambda_p)^{0.31} \]

again well describes the median profile in panel (b). Finally, as in a CS with relatively constant magnetic field magnitude, the CS amplitude \( \Delta B/(B) \) is proportional to the shear angle \( \Delta \theta \), the latter is expected to be scale-dependent. Panel (c) confirms the scale dependency of the magnetic field shear angle. The best fit by a power-law function

\[ \Delta \theta = 0.36 (\lambda/\lambda_p)^{0.32} \approx 21^\circ (\lambda/\lambda_p)^{0.32} \]

well describes the median profile in panel (c).
In this paper we presented a statistical analysis of 11,200 CSs in the near-Sun solar wind observed aboard the PSP around 0.2 au, at radial distances of 35–50 solar radii from the Sun. These CSs are proton kinetic-scale structures with thickness in the range from about 0.1 to 10\(\lambda_p\) with the typical value around 2\(\lambda_p\), where \(\lambda_p\) is the local proton inertial length. The CSs have similar scales in units of the local thermal proton gyroradius, because the beta was around one (Section 2). The resolution of these thin CSs became possible thanks to high resolution (73–290 S s\(^{-1}\)) magnetic field measurements provided by the FIELDS instrument suite (Bale et al. 2016; Bowen et al. 2020). The previous studies of CSs in the near-Sun solar wind were limited to magnetic field measurements at 0.2 s resolution aboard Helios (Söding et al. 2001) and the PSP (Phan et al. 2020) spacecraft, so that only CSs with thickness larger than 10\(\lambda_p\) were resolved. Note that our CS data set is biased toward the thinnest resolvable CSs, because we focused on proton kinetic-scale CSs, which are expected to be crucial for turbulence dissipation and development of turbulence cascade (e.g., Servidio et al. 2015; Cerri & Califano 2017; Franci et al. 2017, 2018; Papini et al. 2019). This data set is sufficiently representative though to address the properties and origin of proton kinetic-scale CSs in the near-Sun solar wind. In this section we summarize the results of this study and compare the properties of kinetic-scale CSs in the near-Sun solar wind to those reported at 1 au (Vasquez et al. 2007a; Vasko et al. 2021, 2022).

We have found the occurrence rate of proton kinetic-scale CSs around 0.2 au to be on average 1120 CS per day, while at 1 au it is about 150 CS per day (Vasquez et al. 2007a; Vasko et al. 2021). The radial trend of the occurrence rate consistent with observations at 0.2 and 1 au would be \(\approx 1/R^{1.3}\), where \(R\) is the radial distance from the Sun. The larger occurrence rate closer to the Sun is consistent with the previous studies of larger-scale CSs at the radial distances of 0.3–19 au (Tsurutani & Smith 1979; Söding et al. 2001). We stress however that the actual trend can be affected by the selection procedure of the CSs. For example, in this study as well as at 1 au only the PVI index computed at the minimum time increment was used to...
collect the CSs. The time increment was 1/73–1/290 s in this study and 1/3–1/11 s at 1 au (Vasquez et al. 2007a; Vasko et al. 2021, 2022).

We have found that the CSs in the near-Sun solar wind are typically asymmetric with small relative variations in the magnetic field magnitude between the CS boundaries as well as within the CS (Section 4). We observe that these variations, \( \Delta B / \langle B \rangle \) and \( \Delta B_{\text{max}} / \langle B \rangle \), are statistically much smaller than shear angle \( \Delta \theta \), so that the magnetic field variation within the CSs is predominantly rotation, rather than variation in the magnetic field magnitude. Accordingly, the current density in the CSs is dominated by the magnetic-field-aligned component (Section 5). We have found that about 10% of the CSs are bifurcated, that is, magnetic field rotation within CS occurs in two steps, which is often seen in reconnecting CSs (e.g., Gosling & Szabo 2008; Phan et al. 2010; Mistry et al. 2017). Note though that the fraction of reconnecting CSs in our data set could not be determined, because the cadence of proton measurements of 0.2–0.9 s is insufficient to establish the presence or absence of plasma jets at proton kinetic scales, while a bifurcated magnetic field profile does not necessarily imply reconnection (Gosling & Szabo 2008; Schindler & Hesse 2008). All the CS properties (asymmetry, small variations in the magnetic field magnitude, dominance of parallel current, \( \approx 10\% \) of bifurcated CSs) in the near-Sun solar wind are identical with those at 1 au (Vasquez et al. 2007a; Vasko et al. 2021, 2022). Moreover, the averaged magnetic field profiles of the CSs in the near-Sun solar wind (Figure 3) are identical with those at 1 au (Vasko et al. 2021).

We have found that the relative variation \( \Delta B / \langle B \rangle \) in the magnetic field magnitude across the CSs is statistically small, but tends to be larger at larger plasma betas (Section 5). The same dependence of \( \Delta B / \langle B \rangle \) on \( \beta \) has been observed at 1 au (Vasko et al. 2021). The magnetic field magnitude variation translates into a plasma beta variation \( \Delta \beta \), which could, in principle, control magnetic reconnection via the diamagnetic suppression mechanism (Swisdak et al. 2003, 2010). We have shown that Equation (8), a necessary condition for reconnection to occur, is satisfied by almost all of the CSs. As only a small fraction of the CSs in the solar wind are expected to be reconnecting (e.g., Gosling 2012; Osman et al. 2014), this implies that the presence or absence of reconnection within proton kinetic-scale CSs are not controlled by the diamagnetic mechanism. Studies at 1 au showed that Equation (8) is satisfied not only by reconnecting CSs (Phan et al. 2010; Gosling & Phan 2013), but by almost all proton kinetic-scale CSs too (Vasko et al. 2021). Moreover, Vasko et al. (2021) have shown that this condition is satisfied automatically due to the geometry of solar wind CSs dictated by their source, which is turbulence cascade according to previous studies at 1 au (Vasquez et al. 2007a; Greco et al. 2008, 2009; Perri et al. 2012; Zhdankin et al. 2012; Vasko et al. 2022). Thus, similarly to CSs at 1 au, the proton kinetic-scale CSs in the near-Sun solar wind automatically satisfy the necessary condition for reconnection, and as reconnection likely occurs only in a small fraction of the CSs (Gosling 2012; Phan et al. 2020), we conclude that the diamagnetic suppression condition does not control magnetic reconnection in the solar wind.

We have found that the CSs with smaller thickness tend to have a larger averaged current density, \( J_0 \approx 150 \mu A m^{-2} \times (\lambda / 100 \text{ km})^{-0.76} \). The peak current density values \( J_{\text{peak}} \) are in the range from 100 nA m\(^{-2}\) to 10 \( \mu \) A m\(^{-2}\) (Figure 8), with the typical value around 700 nA m\(^{-2}\). The current densities and corresponding ion-electron drift velocities tend to be larger at larger local Alfvén speeds \( V_A \) and Alfvén current densities \( J_A \) (Figure 8). The trends observed in Figure 8 for the CSs in the near-Sun solar wind are equivalent to those observed at 1 au, where it was found that \( J_0 \approx 0 \text{ nA m}^{-2} \times (\lambda / 100 \text{ km})^{-0.53} \), and \( J_{\text{peak}} \) and \( J_{\text{peak}}/eN_0 \) are positively correlated with \( J_A \) and \( V_A \).
The comparison of these trends to Equations (9, 12) – interpreted by Vasko et al. 2022 – shows that the magnetic field components $B_x$ reversing sign across the CS has different absolute values at the CS boundaries, and accordingly the magnetic field magnitudes at the CS boundaries are statistically different. This asymmetry results in plasma beta variation across the CSs.

3. The analysis of plasma beta variations and magnetic shear angles across the CSs showed that magnetic reconnection within proton kinetic-scale current sheets is not controlled by the diamagnetic suppression mechanism.

4. The CSs with smaller thickness tend to have larger current densities, and the best power-law fit of the trend is given by Equation (9). The current densities and corresponding ion-electron drift velocities are larger at larger local Alfvén current densities $J_A$ and Alfvén speeds $V_A$.

5. Normalized quantities such as the amplitude $\Delta B_x/B$, current density $J_0/J_A$, and shear angle $\theta$ are scale-dependent on the normalized CS thickness $\lambda/\lambda_p$. The best power-law fits of the scale dependence of these quantities are given by Equations (10–12).

The normalized properties of the proton kinetic-scale CSs at 0.2 au are very similar to those at 1 au. The CS properties are different in physical units due to the different background plasma density and magnetic field, but in normalized units the CSs have similar and similarly scale-dependent current densities, amplitudes, and shear angles. Based on observations and theoretical analysis at 1 au (Vasko et al. 2021, 2022), we conclude that proton kinetic-scale CSs in the near-Sun solar wind are produced by turbulence cascade and are automatically in the parameter range, where reconnection cannot be suppressed by the diamagnetic suppression mechanism.

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8. Conclusions

We have analyzed 11,200 proton kinetic-scale CSs observed by the PSP in the near-Sun solar wind during 10 days around the first perihelion. The results of this study can be summarized as follows:

1. The CSs have thicknesses from a few to about 200 km with the typical value around 30 km. In terms of proton kinetic scales, the thickness of the CSs is in the range of 0.1–10 proton inertial lengths or thermal proton gyroradii. The current densities of the CSs are in the range from 100 nA m$^{-2}$ to 10 μA m$^{-2}$ with the typical value around 700 nA m$^{-2}$. About 10% of the CSs are bifurcated with magnetic field rotation within the CS occurring in two steps, in contrast to the relatively smooth rotation in nonbifurcated CSs. The properties of bifurcated and nonbifurcated CSs are essentially identical.

2. The magnetic field magnitude does not substantially vary within the CSs, and accordingly the current density is dominated by the magnetic-field-aligned component. Nevertheless, the CSs are typically asymmetric; that is, the magnetic field component $B_x$ reversing sign across the CS has different absolute values at the CS boundaries, and accordingly the magnetic field magnitudes at the CS boundaries are statistically different. This asymmetry results in plasma beta variation across the CSs.

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