

Kinetic-scale current sheets in the solar wind at 5 AU

I.Y. Vasko^{1,2}, K. Alimov³, T.D. Phan³, F.S. Mozer³, and A.V. Artemyev^{2,4}

¹William B. Hanson Center for Space Sciences, University of Texas at Dallas, Richardson, TX, USA

²Space Research Institute of Russian Academy of Sciences, Moscow, Russia

³Space Science Laboratory, University of California, Berkeley, California, USA

⁴Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

Key Points:

- Current sheets are predominantly rotations of the magnetic field on proton kinetic scales
- Scale-invariant properties strongly indicate that current sheets are produced by turbulence
- The asymmetry of current sheets is typically insufficient to suppress magnetic reconnection

Corresponding author: Ivan Y. Vasko, Ivan.Vasko@UTDallas.edu

Abstract

We present statistical analysis of 16,903 current sheets (CS) observed over 641 days aboard Ulysses spacecraft at 5 AU. We show that the magnetic field rotates across CSs through some shear angle, while only weakly varies in magnitude. The CSs are typically asymmetric with statistically different, though only by a few percent, magnetic field magnitudes at the CS boundaries. The dataset is classified into about 90.6% non-bifurcated and 9.4% bifurcated CSs. Most of the CSs are proton kinetic-scale structures with the half-thickness of non-bifurcated and bifurcated CSs within respectively 200–2,000 km and 500–5,000 km or $0.5\text{--}5\lambda_p$ and $0.7\text{--}15\lambda_p$ in units of local proton inertial length. The amplitude of the current density, mostly parallel to magnetic field, is typically within $0.05\text{--}0.5\text{ nA/m}^2$ or $0.04\text{--}0.4J_A$ in units of local Alfvén current density. The CSs demonstrate approximate scale-invariance with the shear angle and current density amplitude scaling with the half-thickness, $\Delta\theta \approx 16.6^\circ (\lambda/\lambda_p)^{0.34}$ and $J_0/J_A \approx 0.14 (\lambda/\lambda_p)^{-0.66}$. The matching of the magnetic field rotation and compressibility observed within the CSs against those in ambient solar wind indicate that the CSs are produced by turbulence, inheriting thereby its scale-invariance and compressibility. The estimated asymmetry in plasma beta between the CS boundaries is shown to be insufficient to suppress magnetic reconnection through the diamagnetic drift of X-line, but magnetic reconnection is probably suppressed by other processes. The presented results will be of value for future comparative analysis of CSs observed at different distances from the Sun.

Plain Language Summary

Current sheets are coherent structures potentially contributing into solar wind heating. These structures are highly-likely produced by turbulence, but the alternative hypothesis of coronal origin has not been ruled out. The analysis of current sheets at different distances from the Sun may potentially shed light onto the origin and contribution of these structures into solar wind heating. While there are comprehensive analyses of solar wind current sheets at 1 AU and near the Sun, there is still no equivalent analysis of these structures well beyond 1 AU. In this study we present an extensive statistical study of current sheets observed aboard Ulysses around 5 AU. We demonstrate that the current sheets are predominantly rotations of the magnetic field, typically occurring on proton kinetic scales and exhibiting approximate scale-invariance. We provide strong evidence that the current sheets are produced by turbulence and inherit the scale-invariance and magnetic field compressibility typical of turbulence. The presented results will be of value for future comparative analysis of solar wind current sheets observed at different distances from the Sun.

1 Introduction

Solar wind current sheets were observed aboard early spacecraft missions at 0.3–1 AU (Burlaga, 1969; Mariani et al., 1973; Burlaga et al., 1977; Lepping & Behannon, 1986; Söding et al., 2001), 1–8 AU (Tsurutani & Smith, 1979; Tsurutani et al., 1996) and 20 AU (Söding et al., 2001). It was demonstrated that the current sheets are predominantly magnetic field rotations that is the magnetic field rotates across a current sheet through some shear angle, while remains almost constant in magnitude. The early studies used current sheet selection procedures based on magnetic field measurements with the temporal resolution exceeding ten seconds. The current sheets revealed at 1 AU had spatial thickness, computed by assuming the structures are frozen into local plasma flow, larger than about one thousand kilometers or ten proton inertial lengths (Burlaga et al., 1977; Lepping & Behannon, 1986). The typical occurrence rate of current sheets at 1 AU was about one per hour (Mariani et al., 1973; Burlaga et al., 1977) and decreased with increasing radial distance from the Sun (Lepping & Behannon, 1986; Tsurutani & Smith, 1979; Tsurutani et al., 1996). The early studies were heavily focused on classifying current sheets in terms of tangential and rotational discontinuities based on the magnetic field component along the normal computed by Min-

imum Variance Analysis (MVA). Multi-spacecraft observations showed however that MVA is typically not reliable in estimating the normal to solar wind current sheets and showed that the normal magnetic field component is often within the methodology uncertainty and much smaller than local magnetic field magnitude (Horbury et al., 2001; Knetter et al., 2004; Wang et al., 2024). The latter implies the normal is often almost perpendicular to local background magnetic field in accordance with early theoretical reasoning (Matthaeus et al., 1990; Bieber et al., 1996; Leamon et al., 1998, 2000). The relative occurrence of tangential and rotational discontinuities is still not known (Neugebauer, 2006; Artemyev, Angelopoulos, Vasko, Runov, et al., 2019; Artemyev, Angelopoulos, & Vasko, 2019; Wang et al., 2024). The spacecraft observations and numerical simulations have shown that most of current sheets in the solar wind are produced by turbulence and substantially contribute into development of turbulence cascade as well as solar wind heating (see, e.g., reviews by Matthaeus et al. (2015) and Greco et al. (2018)). Note that a fraction of current sheets, especially large-scale structures, may originate in solar corona (e.g., Borovsky (2008)). The need for understanding plasma turbulence and solar wind heating have recently stimulated comprehensive analyses of solar wind current sheets using high-resolution magnetic field measurements.

Substantial progress has been achieved by the analysis of current sheets at 1 AU using magnetic field measurements with the temporal resolution of $1/3$ – $1/22$ s (Vasquez et al., 2007; Perri et al., 2012; Borovsky & Podesta, 2015; Podesta, 2017; Perrone et al., 2017; Borovsky & Burkholder, 2020; Vasko et al., 2021, 2022; Wang et al., 2024). It has been shown that solar wind current sheets are much more abundant than reported in the early studies, their average occurrence rate is about ten per hour, while the half-thickness is typically about 100 km or one proton inertial length (Vasquez et al., 2007; Vasko et al., 2021, 2022; Wang et al., 2024). The early studies missed a substantial fraction of current sheets present at 1 AU, because the selection procedures were based on magnetic field measurements of low temporal resolution and biased to current sheets with larger thickness. The recent analyses have also revealed scale-dependent properties of solar wind current sheets (Vasko et al., 2022; Wang et al., 2024), which along with other arguments (Greco et al., 2008, 2009; Zhdankin et al., 2012) indicate that most of these structures are produced by turbulence. Solar wind current sheets can provide substantial contribution into magnetic field turbulence spectra and affect the break scale between inertial and sub-ion turbulence ranges (Borovsky & Podesta, 2015; Borovsky & Burkholder, 2020). Parker Solar Probe measurements have recently allowed analysis of current sheets around 0.2 AU (Phan et al., 2020; Lotekar et al., 2022). The critical finding of the statistical analysis by Lotekar et al. (2022) is that the properties of current sheets at 0.2 and 1 AU while different in physical units, become essentially identical once normalized to local plasma parameters. Similar extensive analysis of current sheets well beyond 1 AU would be highly valuable for clarifying to what extent current sheet properties at different radial distances are controlled by local plasma parameters.

Several previous studies yielded valuable information about current sheets beyond 1 AU (Tsurutani & Smith, 1979; Tsurutani et al., 1996; Söding et al., 2001; Erdős & Balogh, 2008; Miao et al., 2011; Artemyev et al., 2018). In particular, the previous analyses of current sheets observed aboard Ulysses spacecraft at 5 AU revealed the average occurrence rate of 15–25 current sheets per day (Tsurutani et al., 1996; Erdős & Balogh, 2008; Miao et al., 2011), temporal width from a few to a few tens of seconds (Miao et al., 2011; Tsurutani et al., 1996), spatial half-thickness from about 1,000 to 10,000 km (Erdős & Balogh, 2008), and a positive correlation between the shear angle and temporal width (Miao et al., 2011). A comprehensive study of current sheets at large radial distances is however still necessary for future comparative analyses of current sheets observed at different radial distances. In this paper we present the analysis of current sheets observed aboard Ulysses around 5 AU based on the methodology previously used at 0.2 and 1 AU (Lotekar et al., 2022; Vasko et al., 2021, 2022). Similarly to the latter studies we consider Ulysses observations around solar minimum and almost within the ecliptic plane. The revealed distributions of current

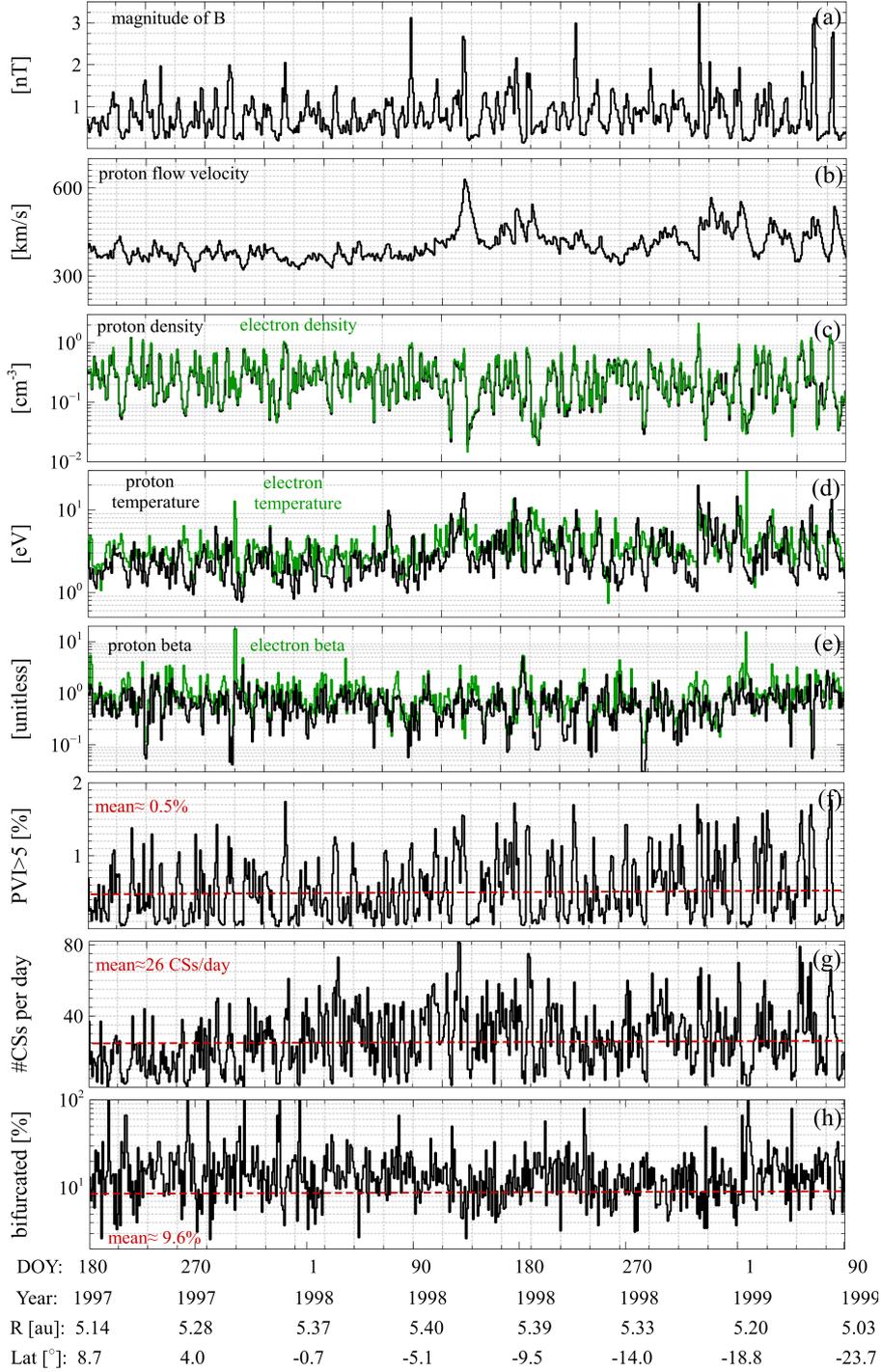


Figure 1. Overview of Ulysses observations over 641 days, from 1997 June 6 to 1999 March 31: (a)–(e) daily averages of the magnetic field magnitude, ion flow velocity, proton and electron densities, temperatures and betas; (f) daily averages of the percentage of data points with the PVI index above the threshold of PVI= 5; (g) the daily occurrence of current sheets and (h) the percentage of current sheets classified as bifurcated. The red lines in panels (f)–(h) represent the averaged values of the corresponding quantities over the 641 days. The labels at the bottom indicate year, DOY (Day Of Year), radial distance and heliographic latitude.

119 sheet properties will be of value for future comparative analyses of current sheets observed
 120 at different radial distances from the Sun.

121 2 Data and methodology

122 We consider Ulysses observations over 641 days, from 06/29/1997 to 03/31/1999 that
 123 is around solar minimum, when the spacecraft was at about 5 AU and close to the ecliptic
 124 plane, at heliographic latitudes within 25° . We use magnetic field measurements provided at
 125 the temporal resolution of 1 or 2s by the VHM (Vector Helium Magnetometer) instrument
 126 (Balogh et al., 1992), and electron and ion moments (density, flow velocity and temperature)
 127 provided at about 6 minute cadence by the SWOOPS (Solar Wind Observations Over the
 128 Poles of the Sun) experiment (Bame et al., 1992). While the original magnetic field data
 129 had the temporal resolution of 1s for about 70% of data points, we used magnetic field
 130 data at 1s resolution obtained by interpolation. The magnetic field is provided in the **RTN**
 131 coordinate system, where **R** is along the Sun-spacecraft axis, **T** is the cross product of the
 132 solar rotation axis and **R**, and **N** is the cross product of **R** and **T**. Only electron and proton
 133 moments are used in this study, while the density of alphas was less than 5% of the ion
 134 density for more than 95% of data points and never exceeded 20%. We use the mean of
 135 upper and lower estimates of the proton temperature provided by Ulysses, but the presented
 136 results would not change if we used the upper or lower estimates instead.

137 Figure 1 overviews Ulysses observations over the 641 days. Panels (a)–(d) present daily
 138 average values of the magnetic field magnitude, ion flow speed, density and temperature of
 139 protons and electrons. The magnetic field magnitude was about 0.2–2 nT, the solar wind
 140 speed was typically within 450 km/s, electron and proton densities varied between about
 141 0.01 and 1 cm^{-3} , while electron and ion temperatures were mostly within 1–10 eV. Panel (e)
 142 shows that electron and proton betas were similar and typically around one. We collected
 143 current sheets using the Partial Variance Increments (PVI) methodology (Greco et al., 2008,
 144 2018) previously implemented at 0.2 and 1 AU (Vasko et al., 2021, 2022; Lotekar et al., 2022).
 145 In this methodology we compute magnetic field increments $\Delta B_i(t, \tau) = B_i(t + \tau) - B_i(t)$,
 146 where the subscript numerates three magnetic field components, while the time lag τ is
 147 dictated by data resolution of 1s. Standard deviations σ_i of magnetic field increments are
 148 computed every 4 hours, since that is around the correlation scale of turbulence at 5 AU
 149 (Smith et al., 2001; Cuesta et al., 2022). We eventually compute the PVI index, $\text{PVI}_\tau(t) =$
 150 $[\sum_i \Delta B_i^2 / \sigma_i^2]^{1/2}$, and identify data points with $\text{PVI}_\tau > 5$. Panel (f) shows that the daily
 151 average percentage of such data points substantially varies, while its mean value of 0.5% is
 152 four orders of magnitude larger than would be observed if the magnetic field increments had
 153 Gaussian probability distributions. The non-Gaussian probability distributions strongly
 154 indicate the presence of current sheets and other coherent structures (e.g., Greco et al.
 155 (2009, 2018); Matthaeus et al. (2015); Perrone et al. (2017)). We collect current sheets by
 156 encompassing each continuous cluster of points with $\text{PVI}_\tau > 5$ by nested intervals up to one
 157 minute in duration. If the maximum variance component computed by MVA (Sonnerup &
 158 Scheible, 1998) reversed sign within any of the nested intervals, we attempted to manually
 159 adjust boundaries to the left and right of the magnetic field reversal. If we could select
 160 sufficiently wide boundaries, not shorter than the temporal half-thickness of the reversal,
 161 with relatively stable magnetic field, the event was considered a current sheet (CS). Panel
 162 (g) shows that the daily average occurrence rate of CSs substantially varies, while the mean
 163 value of about 26 CSs/day is similar to the previously reported occurrence rates at 5 AU
 164 (Tsurutani et al., 1996; Erdős & Balogh, 2008; Miao et al., 2011). About 9.4% of the CSs
 165 were categorized as bifurcated (see below), their daily average occurrence is presented in
 166 panel (h). The final dataset includes 16,903 CSs and the corresponding list can be found at
 167 Vasko et al. (2024).

168 Multi-spacecraft observations at 1 AU showed that CSs in the solar wind can be consid-
 169 ered locally planar structures frozen into local plasma flow (Burlaga & Ness, 1969; Horbury
 170 et al., 2001; Knetter et al., 2004; Wang et al., 2024). These analyses demonstrated that

171 the magnetic field component along the normal to a CS is typically much smaller than lo-
 172 cal magnetic field magnitude, hardly measurable even using multiple spacecraft. The most
 173 accurate single-spacecraft estimate of the normal is therefore delivered by the cross-product
 174 of magnetic fields at the CS boundaries (Knetter et al., 2004; Wang et al., 2024). The
 175 single-spacecraft methodology based on the cross-product normal and frozen-in assumption
 176 used previously for the analysis of magnetic reconnection and CSs at 0.2 and 1 AU (Phan
 177 et al., 2010, 2020; Mistry et al., 2017; Vasko et al., 2021; Lotekar et al., 2022; Eriksson et
 178 al., 2022) has been recently shown to actually deliver accurate estimates of the CS thickness
 179 and current density (Wang et al., 2024). We use this methodology for the CSs observed
 180 aboard *Ulysses* at 5 AU.

181 Figure 2 demonstrates the application of this methodology for several CSs from our
 182 dataset. Panels (a) and (e) present three magnetic field components in the **RTN** coordinate
 183 system along with the magnetic field magnitude. Panels (b) and (f) show the same magnetic
 184 field in the CS coordinate system \mathbf{xyz} , where unit vector \mathbf{z} is along the cross-product
 185 normal, unit vector \mathbf{x} is along $\mathbf{x}' - \mathbf{z} \cdot (\mathbf{x}' \cdot \mathbf{z})$ with \mathbf{x}' being the maximum variance vector
 186 determined by MVA, while unit vector \mathbf{y} completes the right-handed coordinate system.
 187 The maximum variance vector \mathbf{x}' is typically almost perpendicular to the cross-product
 188 normal and, therefore, vectors \mathbf{x} and \mathbf{x}' are basically identical (not shown). The normal
 189 magnetic field component B_z is by definition zero at the boundaries, but also remains
 190 small within the CSs. The CS central region highlighted in the panels corresponds to
 191 $|B_x - \langle B_x \rangle| < 0.2\Delta B_x$, where $\langle B_x \rangle$ is the mean of B_x values at the CS boundaries, while
 192 ΔB_x is the variation of that component between the boundaries. The assumption that
 193 CSs are frozen into local plasma flow allows translating time into space and estimating the
 194 current density corresponding to temporal magnetic field gradients: $J_x = (\mu_0 V_n)^{-1} dB_y/dt$
 195 and $J_y = -(\mu_0 V_n)^{-1} dB_x/dt$, where V_n is the normal component of local ion flow velocity
 196 that is positive due to appropriate choice of the normal, while $dt = 1s$ is dictated by
 197 data resolution. Panels (c) and (g) present current density components J_x and J_y , while
 198 panels (d) and (h) demonstrate current density components parallel and perpendicular to
 199 local magnetic field, $J_{\parallel} = (J_x B_x + J_y B_y)/B$ and $J_{\perp} = (J_y B_x - J_x B_y)/B$, where B is
 200 the magnetic field magnitude. The magnetic field rotation is relatively smooth across the
 201 CS in panels (a)–(d), while occurs in two steps for the CS in panels (e)–(h). These CSs
 202 exemplify non-bifurcated and bifurcated CSs in our dataset, whose classification was carried
 203 out visually.

204 The adequacy of the visual classification was substantiated *a posteriori* by computing
 205 for each CS the cross-correlation coefficient between the observed profile of $J_y(t)$ and a
 206 model non-bifurcated profile, $J_{\text{mod}}(t) = \langle J_y \rangle \text{sech}^2(t/\tau_{\text{CS}})$, where the brackets denote aver-
 207 aging over the CS central region, $t = 0$ corresponds to the middle of the CS central region,
 208 and τ_{CS} is the temporal half-thickness determined by $\Delta B_x/2\tau_{\text{CS}} = \langle dB_x/dt \rangle$. The results of
 209 these computations (SM; Supporting Materials) showed that the cross-correlation coefficient
 210 is below (above) 0.5 for more than 95% (90%) of the bifurcated (non-bifurcated) CSs, sub-
 211 stantiating thereby the adequacy of the visual classification. The temporal scale determined
 212 by $\Delta B_x/2\tau_{\text{CS}} = \langle dB_x/dt \rangle$ does not necessarily reflect the temporal half-thickness of a bifur-
 213 cated CS. We determined the temporal half-thickness τ_{CS} of bifurcated CSs manually as a
 214 half of the duration between the middles of the two steps of magnetic field rotation (Figure
 215 2). The spatial half-thickness for both bifurcated and non-bifurcated CSs was computed
 216 using the frozen-in assumption, $\lambda = V_n \tau_{\text{CS}}$.

217 The non-bifurcated CS shown in Figure 2 is observed at local plasma density of 0.3
 218 cm^{-3} , proton and electron temperatures of 3 eV, and proton and electron betas of $\beta_e \approx$
 219 $\beta_p \approx 1.5$. The local magnetic field magnitude is described by the mean value of magnetic
 220 field magnitudes at the CS boundaries, $\langle B \rangle \approx 0.55$ nT. This CS is a proton kinetic-scale
 221 structure, since the spatial half-thickness of $\lambda \approx 220$ km is around $0.5\lambda_p$, where λ_p is
 222 local proton inertial length. The magnetic field rotates across the CS through shear angle
 223 $\Delta\theta \approx 65^\circ$. Since the current density is dominated by the parallel component (Figure

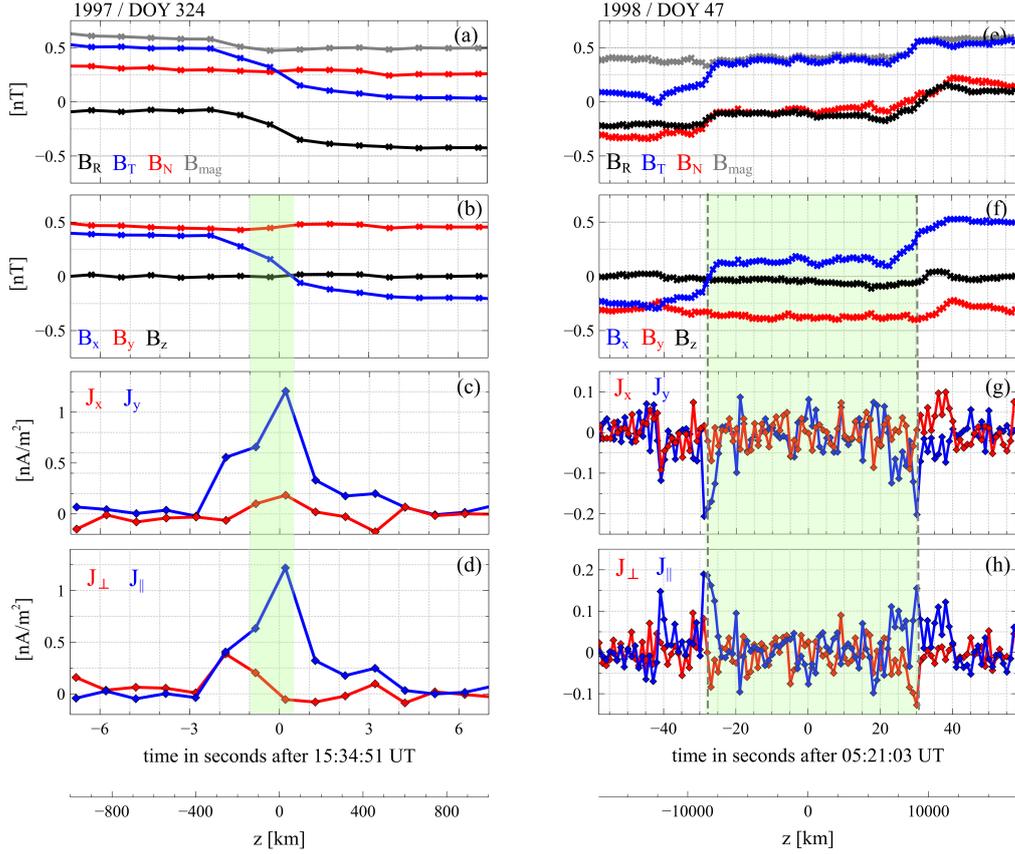


Figure 2. Examples of non-bifurcated (left) and bifurcated (right) current sheets. Panels (a) and (e) show magnetic field magnitude and three magnetic field components in the **RTN** coordinate system. Panels (b) and (f) present three magnetic field components in local coordinate system **xyz** defined in Section 2. Panels (c) and (g) show current densities J_x and J_y estimated by assuming that current sheets are frozen into local plasma flow: $J_x = (\mu_0 V_n)^{-1} dB_y/dt$ and $J_y = -(\mu_0 V_n)^{-1} dB_x/dt$, where V_n is the normal component of local proton flow velocity, while $dt = 1s$ is dictated by data resolution. Panels (d) and (h) present current densities parallel and perpendicular to local magnetic field, $J_{\parallel} = (J_x B_x + J_y B_y)/B$ and $J_{\perp} = (J_y B_x - J_x B_y)/B$, where B is the magnetic field magnitude. The bottom axes demonstrate the spatial coordinate across each CS, $z = V_n t$ with $t = 0$ corresponding to the middle of the CS central region. The latter are highlighted in the panels and correspond to $|B_x - \langle B_x \rangle| < 0.2 \Delta B_x$, where $\langle B_x \rangle$ is the mean of B_x values at the CS boundaries, while ΔB_x is their difference. The dashed gray lines in the left panels indicate the manually determined middles of the two steps of magnetic field rotation for the bifurcated CS.

224 2), the current density amplitude can be represented by averaged value $J_0 = \langle J_{\parallel} \rangle$ of the
 225 parallel current density, and peak value J_{peak} of its magnitude. The observed current density
 226 amplitudes of $J_0 \approx 1.1 \text{ nA/m}^2$ and $J_{\text{peak}} \approx 1.2 \text{ nA/m}^2$ are both close to local Alfvén current
 227 density $J_A \approx 1.1 \text{ nA/m}^2$. Note that $J_A = en_e V_A$ is the current density corresponding to
 228 the drift between electrons and ions of local Alfvén speed, where n_e is local plasma density,
 229 $V_A = \langle B \rangle (\mu_0 n_e m_p)^{-1/2}$ is local Alfvén speed, e and m_p are the proton charge and mass.

230 The bifurcated CSs shown in Figure 2 is observed at local plasma density of about 0.5
 231 cm^{-3} , proton and electron temperatures of respectively 0.6 and 1.6 eV, proton and electron
 232 betas of $\beta_e \approx 0.8$ and $\beta_p \approx 2$, and local magnetic field magnitude of $\langle B \rangle \approx 0.5$ nT. The
 233 spatial half-thickness of the bifurcated CS is $\lambda \approx 8,400$ km that is around $30\lambda_p$ and the
 234 magnetic field rotates across the CS through shear angle $\Delta\theta \approx 94^\circ$. For bifurcated CSs we
 235 characterize the current density by the peak magnitude J_{peak} of the parallel current density.
 236 The observed peak value of $J_{\text{peak}} \approx 0.2$ nA/m² is around $0.15 J_A$. Note that although we
 237 presented the spatial scales of both CSs in units of local proton inertial length, similar scales
 238 would be observed in units of thermal proton gyroradius $\rho_p = \lambda_p \beta_p^{1/2}$, because proton beta
 239 β_p was close to one.

240 The relative variation of the magnetic field magnitude within both CSs is among the
 241 largest in our dataset. The variation of the magnetic field magnitude between the CS
 242 boundaries is $\Delta B \approx 0.2\langle B \rangle$ for the non-bifurcated CS and $\Delta B \approx 0.4\langle B \rangle$ for the bifurcated
 243 CS. The corresponding maximum variation of the magnetic field magnitude, that is the
 244 difference between its maximum and minimum values within CS, is respectively $\Delta B_{\text{max}} \approx$
 245 $0.3\langle B \rangle$ and $0.54\langle B \rangle$. Since the magnitudes of B_y values at the CS boundaries are basically
 246 identical (Figure 2), the magnitude variation ΔB is due to different magnitudes of the
 247 corresponding B_x values, $\Delta(B^2) \approx \Delta(B_x^2)$ that is equivalent to $\langle B \rangle \Delta B \approx \langle B_x \rangle \Delta B_x$. The
 248 relative variation $\Delta B / \langle B \rangle$ critically depends on parameter $\langle B_x \rangle / \Delta B_x$ representing the CS
 249 asymmetry. For both CSs presented in Figure 2 the asymmetry parameter was $\langle B_x \rangle / \Delta B_x \approx$
 250 0.15.

251 Even though challenging to demonstrate experimentally, it is reasonable to assume that
 252 solar wind CSs are pressure-balanced structures that is the total of plasma thermal pressure
 253 P and magnetic field pressure $B^2/2\mu_0$ remains constant, $2\mu_0 P + B^2 = 2\mu_0 P_0 = \text{const}$ or
 254 $2\mu_0 P/B^2 + 1 = 2\mu_0 P_0/B^2$. The latter relation allows estimating the variation of plasma
 255 beta between the CS boundaries, $\Delta\beta = 2\mu_0 P_0 \Delta(B^{-2})$, which will be of value for testing
 256 one of the conditions necessary for magnetic reconnection to occur (Swisdak et al., 2003;
 257 Swisdak et al., 2010; Phan et al., 2010). The mean of the pressure balance relation at the
 258 CS boundaries allows excluding P_0 and revealing that

$$\Delta\beta = (1 + \beta)\Delta(B^{-2})/\langle B^{-2} \rangle, \quad (1)$$

259 where $\beta \equiv \langle 2\mu_0 P/B^2 \rangle = (2\mu_0 \langle P \rangle + \langle B^2 \rangle) \langle B^{-2} \rangle - 1$ is the mean of plasma beta values at
 260 the boundaries (Vasko et al., 2021). We estimated β by assuming that the plasma pressure
 261 observed aboard Ulysses at the temporal resolution of about 6 minutes adequately reflects
 262 the mean $\langle P \rangle$ of plasma pressure values at the boundaries. For the CSs shown in Figure 2
 263 we found $\beta \approx 3.2$ and $\Delta\beta \approx 1.8$ for the non-bifurcated CS, and $\beta \approx 3.3$ and $\Delta\beta \approx 3.4$ for
 264 the bifurcated CS.

The presented analysis was carried out for all the 16,903 collected CSs, including 15,309
 non-bifurcated and 1,594 bifurcated CSs. Note that bifurcated magnetic field profile does
 not necessarily imply magnetic reconnection (Gosling & Szabo, 2008; Phan et al., 2020) and
 we are not able to determine the fraction of reconnecting CSs in our dataset because of the
 low temporal resolution of plasma measurements. For each CS in our dataset we determined
 shear angle, half-thickness, current density amplitudes, and quantities characterizing the CS
 asymmetry and magnetic field magnitude variation within CS. The statistical distributions
 of these parameters are presented in the next section. The half-thickness and current density
 amplitudes are compared to local proton inertial length and Alfvén current density, that
 is the Alfvén units typically used in turbulence simulations (e.g., Zhdankin et al. (2013);
 Franci et al. (2017); Papini et al. (2019); Jain et al. (2021)). We complete this section by
 pointing out that local magnetic field of solar wind CSs can be described by a universal
 one-dimensional model

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

265 where $B(z)$ and $\theta(z)$ determine spatial profiles of magnetic field magnitude and rotation,
 266 while B_z is equal or close to zero, $B_z \ll B$. The current density components parallel and

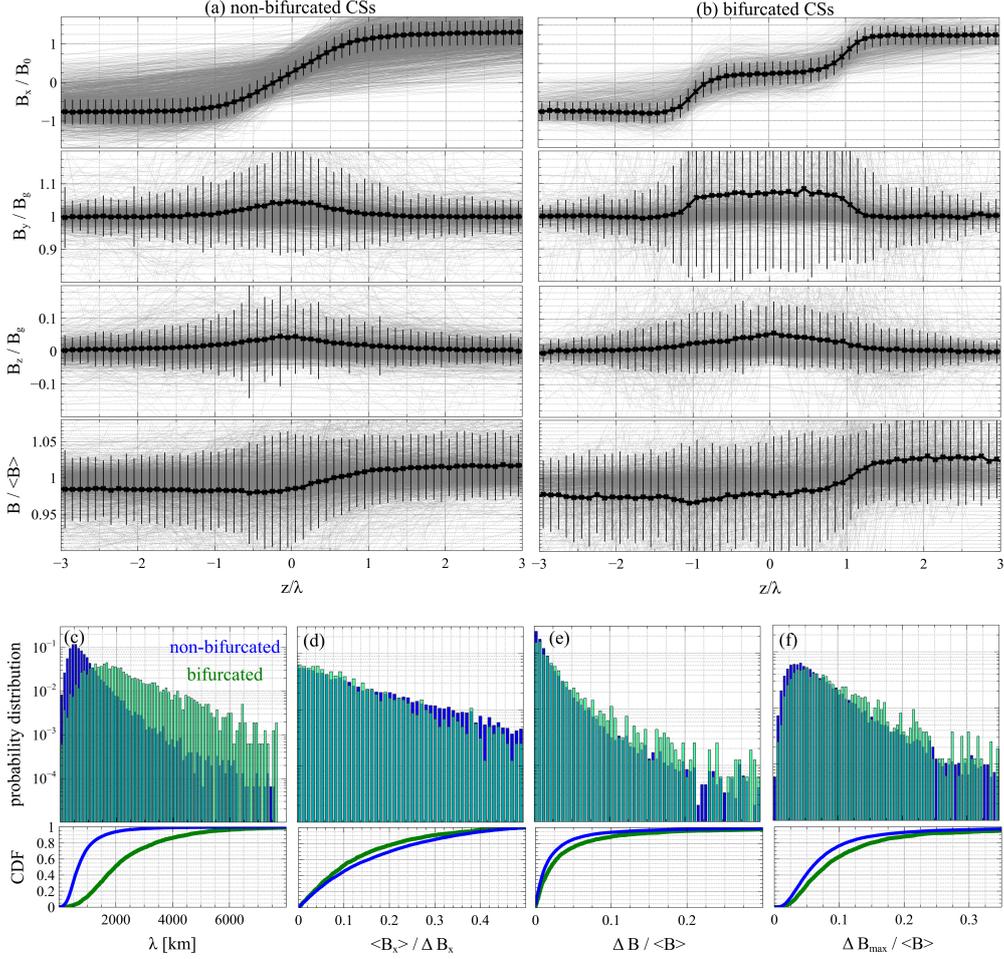


Figure 3. Averaged (black) and individual (gray) magnetic field profiles of (a) non-bifurcated and (b) bifurcated CSs. Before averaging, individual profiles were first aligned by setting $z = 0$ in the middle of the CS central region and normalizing the spatial coordinate to the CS half-thickness, $z \rightarrow z/\lambda$. Individual profiles of B_x were then normalized to $B_0 = 0.5\Delta B_x$ that is a half of the difference between B_x values at the CS boundaries. Individual profiles of B_y and B_z were normalized to guide field B_g that is the mean of B_y values at the CS boundaries. Individual profiles of magnetic field magnitude B were normalized to $\langle B \rangle$ that is the mean of magnetic field magnitudes at the CS boundaries. The error bars in panels (a) and (b) indicate standard deviations. Panels (c)–(f) present probability and corresponding cumulative distributions of the CS half-thickness λ , parameter $\langle B_x \rangle / \Delta B_x$ quantifying the CS asymmetry, and parameters $\Delta B / \langle B \rangle$ and $\Delta B_{\max} / \langle B \rangle$ quantifying the relative variation of the magnetic field magnitude between the CS boundaries and within CS.

267 perpendicular to local magnetic field are solely determined by magnetic field rotation and
 268 magnitude variation

$$J_{\parallel} = (B/\mu_0) d\theta/dz, \quad J_{\perp} = (1/\mu_0) dB/dz \quad (2)$$

269 By the order of magnitude we have

$$J_{\perp}/J_{\parallel} \approx \Delta B / \langle B \rangle \Delta\theta \quad (3)$$

270 and use this parameter in the next section to quantify the ratio between average values of
 271 the perpendicular and parallel current densities.

272 3 Statistical results

273 3.1 Current sheet properties and scale-invariance

274 We determine typical magnetic field profiles of bifurcated and non-bifurcated CSs by
 275 averaging appropriately aligned and normalized magnetic field profiles of the collected CSs.
 276 The individual magnetic field profiles were aligned by setting the CS center, where $B_x =$
 277 $\langle B_x \rangle$, at $z = 0$ and normalizing the spatial coordinate to the CS half-thickness, $z \rightarrow z/\lambda$.
 278 For bifurcated CSs the center was set in the middle between the two steps of magnetic
 279 field rotation, since we typically had $B_x \approx \langle B_x \rangle$ over the entire plateau in between the
 280 steps. Each individual profile of magnetic field magnitude B and guide field component
 281 B_y was normalized to the mean of their values at the CS boundaries. The mean guide
 282 field B_g was also used to normalize the corresponding B_z profile. Each profile of B_z/B_g
 283 was also multiplied by its sign at the CS center, so that the averaged profile could reveal
 284 the magnitude of B_z/B_g around the CS central region. The individual B_x profiles were
 285 normalized to $B_0 = \Delta B_x/2$ that is a signed quantity representing the variation of B_x
 286 between the CS boundaries. Note that B_x/B_0 always varies from a negative value at the
 287 left boundary to a positive value at the right boundary. Each profile of B_x/B_0 with a smaller
 288 magnitude at the right boundary was reflected with respect the CS center and multiplied
 289 by -1 to always have the smaller magnitude of B_x/B_0 at the left boundary. If the reflection
 290 was required for a B_x/B_0 profile, it was also performed for other corresponding magnetic
 291 field profiles. The reflection procedure was necessary to reveal the asymmetry typical of the
 292 CSs in the averaged profiles.

293 Figure 3 presents the averaged magnetic field profiles along with the profiles of individ-
 294 ual CSs. The averaged profiles in panels (a) and (b) clearly demonstrate that magnetic field
 295 rotation occurs smoothly across non-bifurcated CSs, while in two steps across bifurcated
 296 CSs. The averaged B_x/B_0 profiles show that both types of CSs are typically asymmetric
 297 with the left and right boundary values of about -0.75 and 1.25 , respectively. In contrast,
 298 the guide field typically has identical boundary values according to the averaged B_y/B_g pro-
 299 files and increases by about 10% toward the CS central region. The normal component is by
 300 definition close to zero at the boundaries, while also remains small, less than about $0.1B_g$,
 301 within CS. The averaged profiles of $B/\langle B \rangle$ show that the boundary values of the magnetic
 302 field magnitude differ by a few percent, which is due to statistically different magnitudes
 303 of B_x values at the boundaries, $\Delta B^2 = \Delta(B_x^2) + \Delta(B_y^2) \approx \Delta(B_x^2)$ that is equivalent to
 304 $\langle B \rangle \Delta B \approx \langle B_x \rangle \Delta B_x$. The probability and corresponding cumulative distributions in panel
 305 (c) demonstrate that bifurcated CSs are statistically wider than non-bifurcated CSs. The
 306 corresponding median values of the CS half-thickness are around 700 and 2,000 km, while
 307 the scales of both types of CSs range from a few tens to 10,000 km. The statistical distri-
 308 butions in panels (d)–(f) demonstrate that bifurcated and non-bifurcated CSs have more
 309 or less similar asymmetry and variations of the magnetic field magnitude. Both types of
 310 CSs are typically asymmetric with $\langle B_x \rangle / \Delta B_x \gtrsim 0.1$ for more than 50% of the CSs. The
 311 magnetic field magnitude does not substantially vary within the CSs, since for more than
 312 90% of the CSs we have $\Delta B / \langle B \rangle \lesssim 0.1$ for the variation of the magnetic field magnitude
 313 between the CS boundaries and $\Delta B_{\max} / \langle B \rangle \lesssim 0.2$ for the maximum variation.

314 Figure 4 demonstrates that some of the CS parameters depend on local plasma beta
 315 β . Panels (a) and (b) present probability and cumulative distributions of $\Delta B / \langle B \rangle$ and
 316 $\Delta B_{\max} / \langle B \rangle$ for 5,197 CSs observed at $\beta < 1$ and 4,238 CSs observed at $\beta > 3$. The
 317 distributions demonstrate that larger variations of the magnetic field magnitude are typi-
 318 cal at larger betas. Panel (c) presents corresponding statistical distributions of parameter
 319 $\Delta B / \langle B \rangle \Delta \theta$ quantifying the ratio between average values of the parallel and perpendicular
 320 current density according to Eq. (3). The distributions demonstrate that the current den-

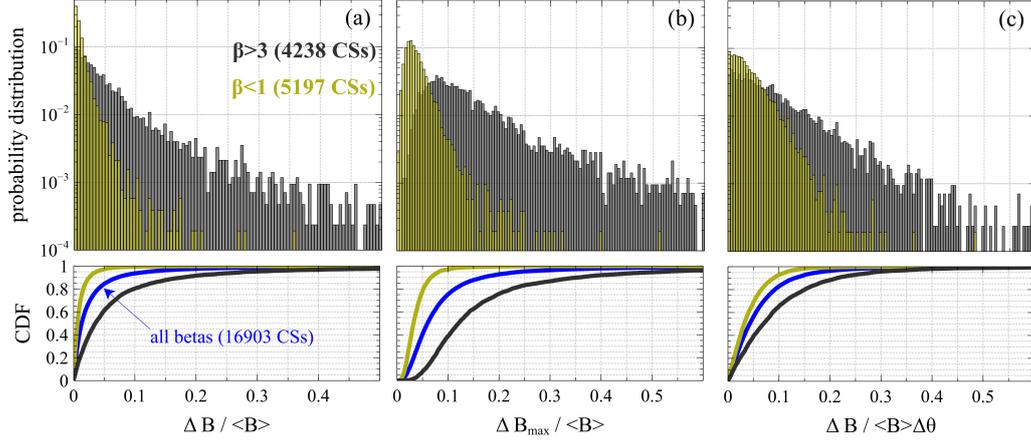


Figure 4. Probability and cumulative distributions of parameters $\Delta B / \langle B \rangle$, $\Delta B_{\max} / \langle B \rangle$ and $\Delta B / \langle B \rangle \Delta \theta$ for subsets of the CSs observed at different plasma betas, $\beta < 1$ and $\beta > 3$. The bottom panels also present the cumulative distributions corresponding to all the CSs in our dataset. Note that according to Eq.(3) parameter $\Delta B / \langle B \rangle \Delta \theta$ quantifies the ratio between average perpendicular and parallel current densities within CS.

321 city in the CSs is typically dominated by the parallel component, $\Delta B / \langle B \rangle \Delta \theta \lesssim 0.1$ for more
 322 than about 90% of the CSs, but the relative magnitude of the perpendicular current density
 323 tends to be larger at larger betas. The scatter plots between local beta and the considered
 324 CS parameters also demonstrate positive correlation (SM).

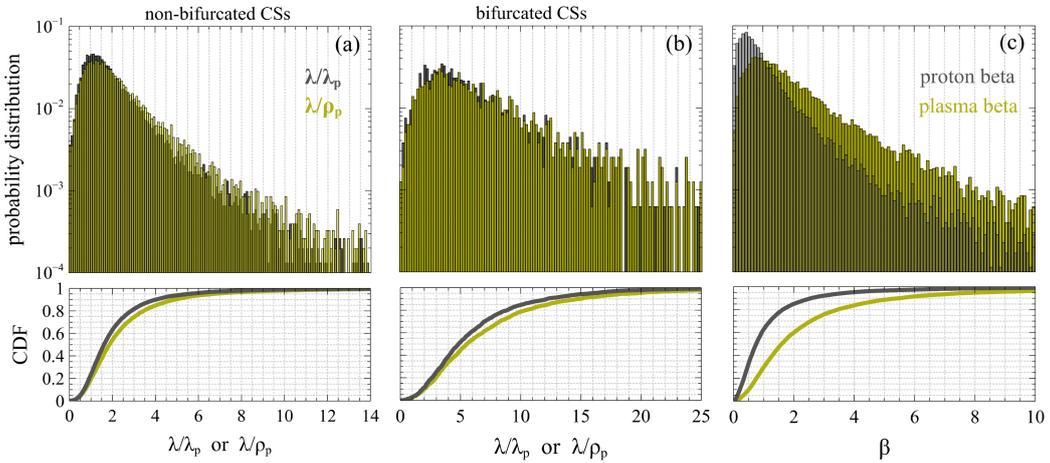


Figure 5. Panels (a) and (b) present probability and cumulative distributions of the half-thickness of non-bifurcated and bifurcated CSs in units of local proton inertial length λ_p and thermal proton gyroradius ρ_p . Panel (c) presents probability and cumulative distributions of proton beta and total plasma beta corresponding to the CSs in our dataset.

325 Figure 5 presents the half-thickness of the CSs in units of proton inertial length λ_p and
 326 thermal proton gyroradius $\rho_p = \lambda_p \beta_p^{1/2}$. The probability and cumulative distributions in

327 panels (a) and (b) show that both types of CSs are typically proton kinetic-scale structures.
 328 For non-bifurcated CSs the median value of the half-thickness is about $1.5\lambda_p$, the corre-
 329 sponding 5th and 95th percentiles are respectively around 0.5 and $5\lambda_p$. For bifurcated CSs
 330 the median value is around $5\lambda_p$, while the 5th and 95th percentiles are about 0.7 and $15\lambda_p$.
 331 We observe similar spatial scales in units of thermal proton gyroradius, because proton beta
 332 β_p was typically around one. Panel (c) shows that the median value of proton beta is about
 333 0.7, while the 5th and 95th percentiles are respectively about 0.15 and 3. Note that electron
 334 and proton betas had almost identical probability distributions (SM), while in panel (c) we
 335 show the statistical distribution of total plasma beta, $\beta = \beta_p + \beta_e$.

336 Figure 6 demonstrates statistical distributions of amplitudes of the parallel current
 337 density observed within the CSs. Panel (a) shows that the averaged and peak amplitudes,
 338 J_0 and J_{peak} , have basically identical statistical distributions. The median value of both
 339 current density amplitudes is around 0.15 nA/m^2 , while the 5th and 95th percentiles are
 340 about 0.05 and 0.5 nA/m^2 . The statistical distributions in panel (b) demonstrate that
 341 in units of local Alfvén current density the observed current density amplitudes have the
 342 median value of about $0.1J_A$, while the 5th and 95th percentiles are about 0.04 and $0.4J_A$.
 343 Panel (c) shows that independent of the type of CSs, the peak current density J_{peak} is
 344 strongly correlated with local Alfvén current density J_A , which varies in our dataset from
 345 0.1 to 10 nA/m^2 . Similar strong correlation is observed between J_0 and J_A (not shown).

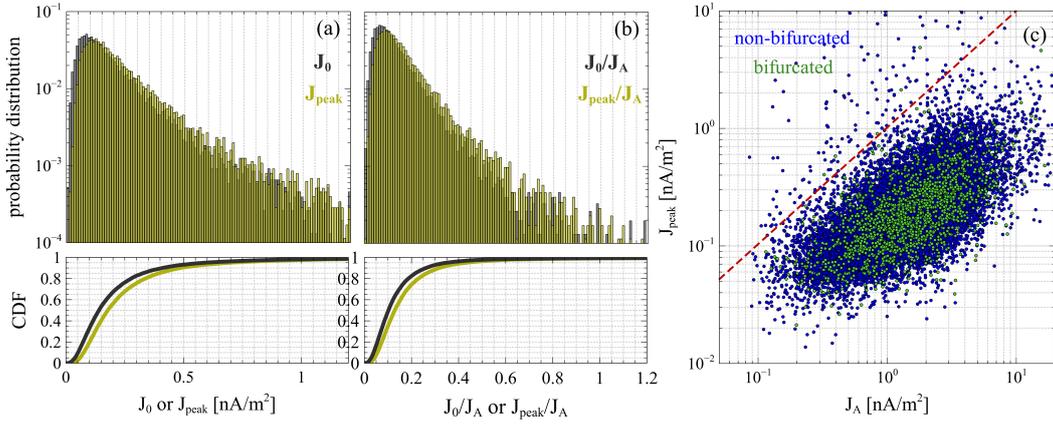


Figure 6. Panel (a) presents probability and cumulative distributions of the peak value J_{peak} of the parallel current density within CS and the current density amplitude J_0 averaged over the CS central region. Note that the averaged amplitude J_0 was computed only for non-bifurcated CSs, while J_{peak} was computed for both types of CSs. Panel (b) shows probability and cumulative distributions of the current density amplitudes normalized to local Alfvén current density J_A . Panel (c) demonstrates a scatter plot between current density amplitude J_{peak} and local Alfvén current density J_A for bifurcated (green) and non-bifurcated (blue) CSs. The red line in panel (c) corresponds to equality of the two quantities.

346 Figure 7 shows that to some extent the CSs exhibit scale-invariance that is several of
 347 the CS parameters depend on their spatial scale in a power law fashion. The scatter plots in
 348 panels (a)–(c) demonstrate that the shear angle as well as the normalized magnetic field and
 349 current density amplitudes are correlated with the CS half-thickness normalized to proton
 350 inertial length. The correlation can be quantified by fitting scattered data to a power law
 351 as well as binning the data as shown in panel (d) and computing the median value of a
 352 considered CS parameter within each bin. We also computed the 15th and 85th percentiles
 353 within each bin to demonstrate, where 70% of the CSs resides. The median profiles in panels

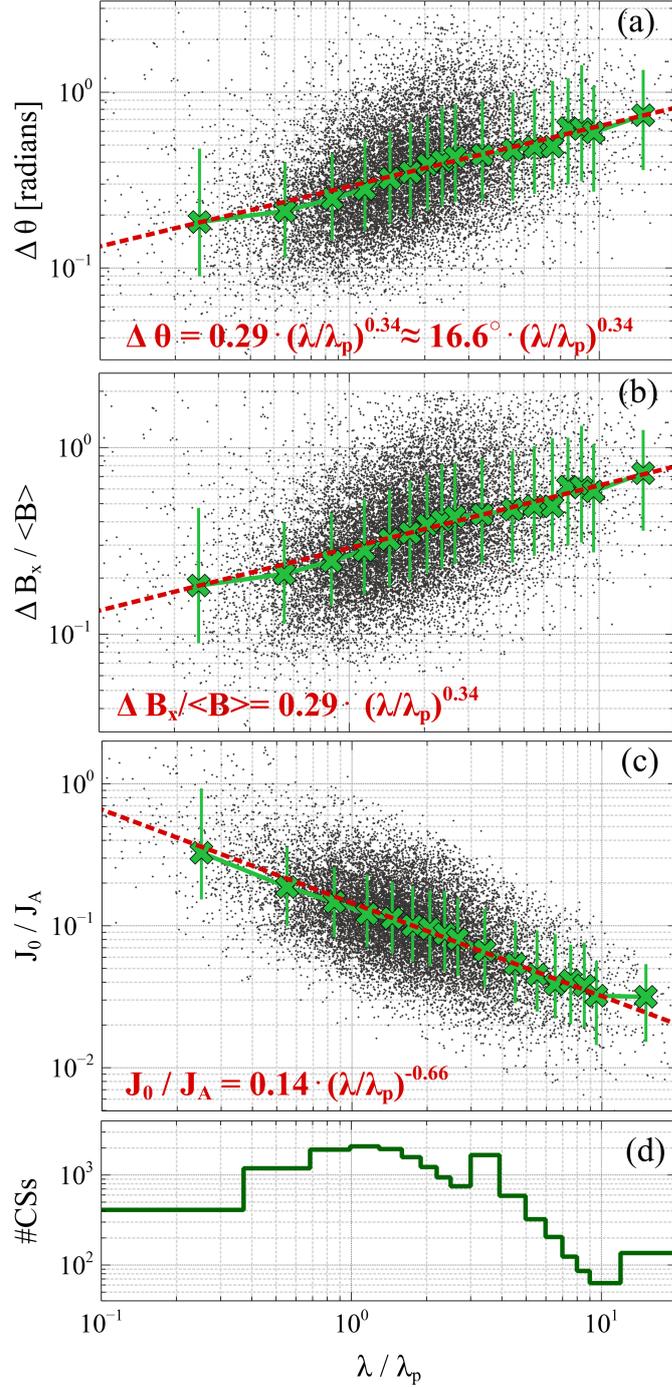


Figure 7. Scatter plots of normalized half-thickness λ / λ_p versus (a) magnetic shear angle $\Delta \theta$, (b) normalized magnetic field amplitude $\Delta B_x / \langle B \rangle$ and (c) normalized current density J_0 / J_A . These scatter plots were produced for non-bifurcated CSs, since the averaged value J_0 only reflects the current density amplitude of non-bifurcated CSs. The non-bifurcated CSs were sorted into bins corresponding to different values of the normalized half-thickness and median values of the quantities shown in panels (a)–(c) were computed within each bin. The number of CSs within each bin is shown in panel (d). Panels (a)–(c) present the median profiles (green curves) along with error bars indicating the 15th and 85th percentiles within each bin. The panels also present the best power law fits of the scattered data (red curves) along with the best fit parameters.

354 (a)–(c) demonstrate that shear angle $\Delta\theta$ and magnetic field amplitude $\Delta B_x/\langle B \rangle$ tend to
 355 increase with increasing spatial scale, while, in contrast, current density amplitude J_0/J_A
 356 increases with decreasing spatial scale. The same trends are revealed by the best power law
 357 fits

$$\Delta\theta \approx 16.6^\circ (\lambda/\lambda_p)^{0.34}, \quad \Delta B_x/\langle B \rangle \approx 0.29 (\lambda/\lambda_p)^{0.34}, \quad J_0/J_A \approx 0.14 (\lambda/\lambda_p)^{-0.66}. \quad (4)$$

358 Note that the scale-dependencies of $\Delta\theta$ and $\Delta B_x/\langle B \rangle$ are basically equivalent, because in
 359 the case of CSs with moderate asymmetry and relatively constant magnetic field magnitude
 360 (Figure 3) we have $\Delta B_x \approx 2\langle B \rangle \sin(\Delta\theta/2)$ that is approximately equivalent to $\Delta B_x/\langle B \rangle \approx$
 361 $\Delta\theta$. The scale-dependence of the current density amplitude could be also deduced from the
 362 scale-dependence of the shear angle, because according to Eq. (2) we have $J_0 \approx \langle B \rangle \Delta\theta/2\mu_0\lambda$
 363 that is equivalent to $J_0/J_A \approx \Delta\theta (2\lambda/\lambda_p)^{-1}$. In the next section we match the scale-
 364 dependence of the shear angle against the scale-dependence of all magnetic field rotations
 365 in ambient solar wind.

366 3.2 Current sheets versus turbulence properties

367 We quantify the properties of all magnetic field fluctuations in ambient solar wind by
 368 computing at each moment of time the angle α_τ between magnetic field vectors separated
 369 by time lag τ

$$\alpha_\tau(t) = \cos^{-1} \left[\frac{\mathbf{B}(t+\tau) \cdot \mathbf{B}(t)}{B(t+\tau)B(t)} \right] \quad (5)$$

370 At each moment of time we also compute parameter χ_τ characterizing the compressibility
 371 of magnetic field fluctuations

$$\chi_\tau(t) = \frac{\delta b_\tau - 2 \sin(\alpha_\tau/2)}{\delta b_\tau}, \quad \delta b_\tau = \frac{|\mathbf{B}(t+\tau) - \mathbf{B}(t)|}{\langle B \rangle_\tau}, \quad (6)$$

372 where $\langle B \rangle_\tau \equiv (B(t+\tau) + B(t))/2$. Note that $\chi_\tau \in [0, 1]$ with $\chi_\tau = 0$ corresponding to purely
 373 incompressible fluctuations (magnetic field rotations), and $\chi_\tau = 1$ corresponding to purely
 374 compressible fluctuations (magnitude variations of a unidirectional magnetic field). The
 375 statistical properties of parameters α_τ and χ_τ were previously addressed for magnetic field
 376 fluctuations at 1 AU (Zhdankin et al., 2012; Chen et al., 2015). In this section not only do
 377 we present similar analysis of magnetic field fluctuations observed aboard Ulysses over the
 378 641 days, but also match statistical properties of parameters α_τ and χ_τ against equivalent
 379 CS parameters. The latter include shear angle $\Delta\theta$ and parameter χ_{CS}^b computed using Eq.
 380 (6) for magnetic fields at the CS boundaries. Parameter χ_{CS}^b characterizes the magnetic field
 381 compressibility between CS boundaries and can be expressed through previously introduced
 382 quantities

$$\chi_{CS}^b = \frac{(1 + \xi^2)^{1/2} - 1}{(1 + \xi^2)^{1/2}}, \quad \xi \equiv \frac{\Delta B \cos(\Delta\theta/2)}{2\langle B \rangle \sin(\Delta\theta/2)}. \quad (7)$$

383 Since typically $\xi \approx \Delta B/\langle B \rangle \Delta\theta$ and $\xi \ll 1$ (Figure 4), we have $\chi_{CS}^b \approx 0.5(\Delta B/\langle B \rangle \Delta\theta)^2$
 384 that is also equivalent to $\chi_{CS}^b \approx 0.5(J_\perp/J_\parallel)^2$ according to Eq. (3). We also apply Eq.
 385 (6) to compute parameter χ_{CS}^{\max} for magnetic fields \mathbf{B}_{\min} and \mathbf{B}_{\max} corresponding to the
 386 minimum and maximum magnetic field magnitudes within CS. This parameter is a measure
 387 of the maximum compressibility within CS and can be expressed through Eq. (7) with
 388 appropriate replacements, $\Delta B \rightarrow \Delta B_{\max}$, $\langle B \rangle \rightarrow (B_{\min} + B_{\max})/2$ and $\Delta\theta \rightarrow \cos^{-1}(\mathbf{B}_{\min} \cdot$
 389 $\mathbf{B}_{\max}/B_{\min}B_{\max})$.

390 Figure 8 presents statistical properties of magnetic field rotation angles α_τ for a broad
 391 range of time lags, $\tau = 1\text{--}300$ s. Probability density functions (PDFs) of α_τ shown in panel
 392 (a) demonstrate that smaller rotation angles are typical at smaller time lags. For each time
 393 lag τ we computed the mean rotation angle $\langle \alpha_\tau \rangle$ and PDFs of $\alpha_\tau/\langle \alpha_\tau \rangle$ shown in panel (b).

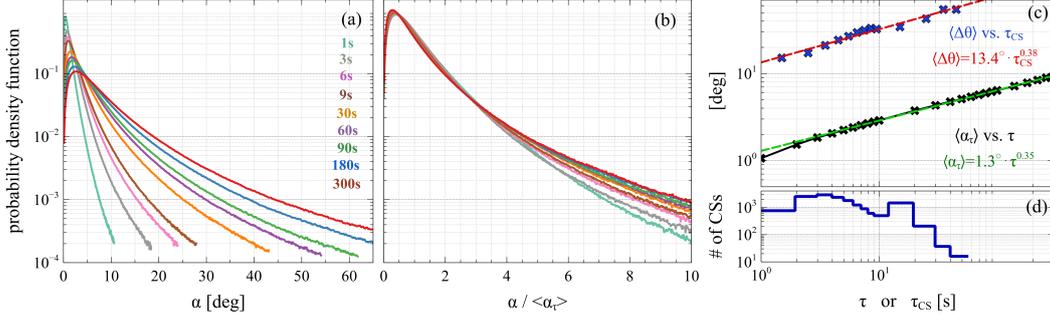


Figure 8. The analysis of magnetic field rotation angles across all magnetic field fluctuations observed over the considered 641 days: (a) probability density functions of magnetic field rotation angles α_τ at temporal scale τ that was varied between 1 and 300s (Eq. (5)); (b) probability density functions of α_τ normalized to mean rotation angle $\langle\alpha_\tau\rangle$ at scale τ ; (c) the mean rotation angle $\langle\alpha_\tau\rangle$ versus τ along with the best power law fit (green). Panel (c) also presents the mean shear angle $\langle\Delta\theta\rangle$ versus CS temporal scale, obtained by binning the CSs by temporal half-thickness τ_{CS} as shown in panel (d). The red line shows the best power law fit to the observed trend of larger $\langle\Delta\theta\rangle$ for larger τ_{CS} .

394 The latter PDFs practically collapsed to a universal distribution, indicating thereby that
 395 magnetic field fluctuations of different temporal scales observed aboard Ulysses are to some
 396 extent self-similar. Similar self-similarity was previously reported for magnetic field rotations
 397 at 1 AU (Zhdankin et al., 2012; Chen et al., 2015). In panel (c) we match the properties of
 398 rotation angles across the CSs and all the magnetic field fluctuations. Panel (c) demonstrates
 399 that the mean rotation angle $\langle\alpha_\tau\rangle$ scales with the time lag, $\langle\alpha_\tau\rangle \approx 1.3^\circ \tau^{0.35}$, though a slight
 400 deviation off that scaling is observed at $\tau \approx 1$ s. We computed the mean shear angle $\langle\Delta\theta\rangle$
 401 for CSs of different temporal scales by binning the CSs according to their temporal half-
 402 thickness τ_{CS} , which varies from about 1 to 60s according to panel (d). The best power
 403 law fit to the trend revealed by the bin-averaging, $\langle\Delta\theta\rangle \approx 13.4^\circ \tau_{CS}^{0.38} \approx 10.3^\circ (2\tau_{CS})^{0.38}$, is
 404 practically identical to the scaling followed by all the magnetic field rotations in the solar
 405 wind, except that the mean shear angle is much larger, because CSs are the largest magnetic
 406 field rotations at any given scale. Note that the scaling relation involving $2\tau_{CS}$ reflects that
 407 $\Delta\theta$ is the angle between magnetic fields at the CS boundaries separated by roughly $2\tau_{CS}$.

408 Figure 9 matches the magnetic field compressibility within the CSs against all magnetic
 409 field fluctuations in ambient solar wind. Panel (a) presents PDFs of χ_τ computed for $\tau = 1$ –
 410 300s, while corresponding cumulative distributions are shown in panel (b). The magnetic
 411 field fluctuations at smaller temporal scales tend to have higher compressibility that is larger
 412 relative variations of the magnetic field magnitude. The higher compressibility at smaller
 413 scales was previously reported for magnetic field fluctuations at 1 AU (Hamilton et al.,
 414 2008; Podesta, 2009; Chen et al., 2015). Panels (c) and (d) present PDFs and cumulative
 415 distributions of parameters χ_{CS}^b and χ_{CS}^{\max} . Since the CSs have temporal half-thickness τ_{CS}
 416 from about 1 to 60s, we also duplicate in panels (c) and (d) the statistical distributions of χ_τ
 417 for $\tau = 1$ and 60s. The compressibility between the CS boundaries quantified by parameter
 418 χ_{CS}^b is much smaller than typical compressibility of ambient magnetic field fluctuations at
 419 comparable temporal scales. In quite a contrast, the maximum compressibility within CS
 420 quantified by parameter χ_{CS}^{\max} is practically identical to that of the ambient fluctuations.
 421 Panel (e) presents mean value $\langle\chi_\tau\rangle$ versus τ as well as mean values of χ_{CS}^b and χ_{CS}^{\max} computed
 422 by binning the CSs by their temporal half-thickness τ_{CS} as shown in panel (f). All the mean
 423 values of compressibility increase toward smaller scales and we also observe $\langle\chi_{CS}^b\rangle \ll \langle\chi_\tau\rangle$

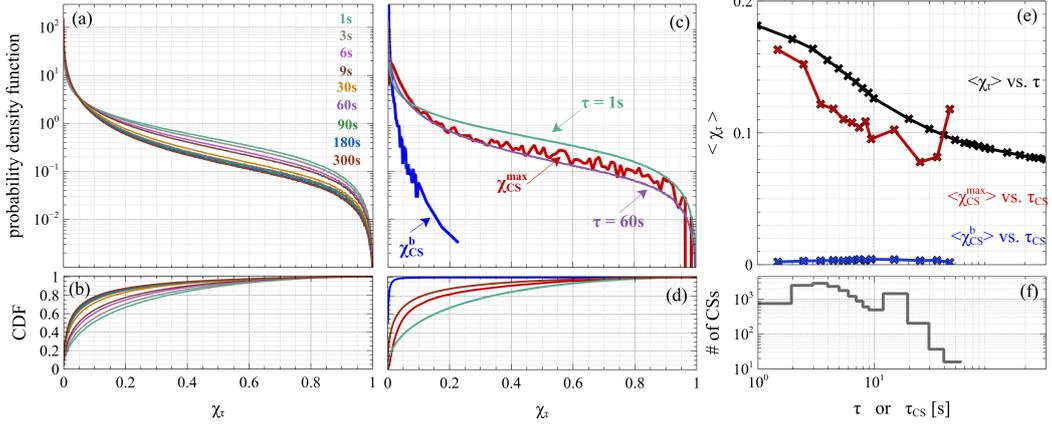


Figure 9. The analysis of compressibility of all magnetic field fluctuations observed over the considered 641 days. The compressibility of fluctuations at temporal scale τ is quantified by parameter $\chi_\tau \in [0, 1]$ defined by Eq. (6) with $\chi_\tau = 0$ and $\chi_\tau = 1$ corresponding respectively to purely incompressible (magnetic field rotations) and compressible (magnitude variations of a unidirectional magnetic field) fluctuations. Panels (a) and (b) present probability density functions and corresponding cumulative distributions of parameter χ_τ at temporal scales τ between 1 and 300s. Panels (c) and (d) duplicate the latter distributions for $\tau = 1$ and 60s along with distributions of parameters χ_{CS}^b and χ_{CS}^{\max} quantifying magnetic field compressibility within the CSs (Eq. (7)). Panel (e) presents mean compressibility $\langle \chi_\tau \rangle$ versus τ along with mean values $\langle \chi_{CS}^b \rangle$ and $\langle \chi_{CS}^{\max} \rangle$ of magnetic field compressibility observed within CSs of different scales, obtained by binning the CSs by their temporal half-thickness τ_{CS} as shown in panel (f).

424 and $\langle \chi_{CS}^b \rangle \ll \langle \chi_{CS}^{\max} \rangle$. Note that $\langle \chi_{CS}^b \rangle$ is around 10^{-3} , which is consistent with the fact
 425 that $\chi_{CS}^b \approx 0.5(\Delta B / \langle B \rangle \Delta \theta)^2$ and typical values of $\Delta B / \langle B \rangle \Delta \theta$ (Figure 4). Thus, the
 426 maximum compressibility within the CSs is basically identical to that of ambient magnetic
 427 field fluctuations at comparable temporal scales, while the compressibility computed between
 428 the CS boundaries is about two orders of magnitudes lower.

3.3 Current sheets and magnetic reconnection

429
 430 The collected CSs have the typical temporal scale from about 1 to 60s. In turn, the tem-
 431 poral resolution of plasma measurements aboard Ulysses is only around 6 minutes, which im-
 432 plies magnetic reconnecting cannot be identified by resolving plasma jets potentially present
 433 within the CSs. We can however test one of the theoretical conditions necessary for mag-
 434 netic reconnection to occur. Swisdak et al. (2010) showed that magnetic reconnection is
 435 suppressed in the case of a sufficiently high CS asymmetry, $\Delta\beta \gtrsim 2(L/\lambda_p) \tan(\Delta\theta/2)$, where
 436 $\Delta\beta$ is the plasma beta variation between the CS boundaries, $\Delta\theta$ is the shear angle, while
 437 parameter L/λ_p is of the order of one and represents the typical scale of plasma pressure
 438 gradient across X-line.

439 Figure 10 presents the test of this condition for both bifurcated and non-bifurcated CSs
 440 with the plasma beta variation $\Delta\beta$ estimated by Eq. (1). Panels (a) and (b) show that
 441 independent of the type, most of the CSs are in the parameter range, where reconnection
 442 cannot be suppressed due to the asymmetry. For both types of CSs we have only about 11%
 443 and 5% of the CSs with $\Delta\beta \gtrsim 2(L/\lambda_p) \tan(\Delta\theta/2)$ for $L/\lambda_p = 1$ and $L/\lambda_p = 2$, respectively.
 444 Panel (c) matches $\Delta\beta$ against $2(\lambda/\lambda_p) \tan(\Delta\theta/2)$, testing thereby the same condition with
 445 parameter L equal to the observed CS half-thickness λ . We have only about 7% of the

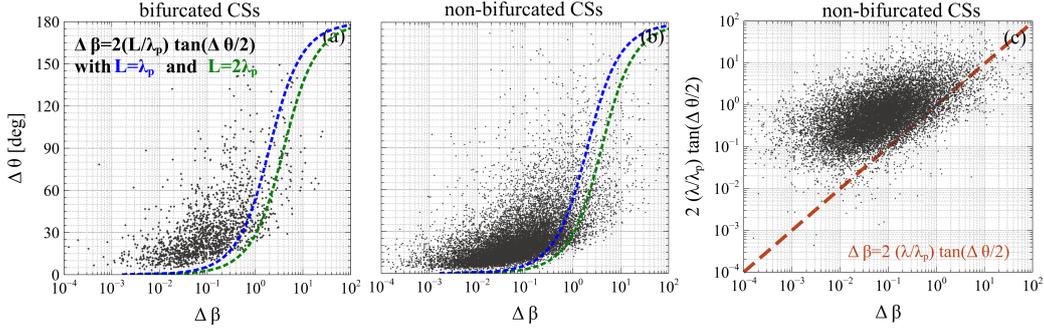


Figure 10. Testing of the suppression condition of magnetic reconnection through the diamagnetic drift of X-line (Section 3.3). Magnetic reconnection is suppressed, when the difference $\Delta\beta$ of plasma betas at the CS boundaries is sufficiently large, $\Delta\beta \gtrsim 2(L/\lambda_p)\tan(\Delta\theta/2)$, where L/λ_p is of the order of one. Panels (a) and (b) present the test of the suppression condition with $L/\lambda_p = 1$ and 2 for bifurcated and non-bifurcated CSs, while panel (c) presents the test of this condition with $L = \lambda$.

446 CSs with $\Delta\beta \gtrsim 2(\lambda/\lambda_p)\tan(\Delta\theta/2)$. This analysis demonstrates that for most of the CSs
 447 magnetic reconnection cannot be suppressed by the asymmetry and is, in principle, allowed
 448 if not suppressed by other processes.

449 4 Discussion

450 Solar wind CSs were observed at 0.3–8 AU and 20 AU aboard early spacecraft missions
 451 (Burlaga, 1969; Mariani et al., 1973; Burlaga et al., 1977; Tsurutani & Smith, 1979; Lepping
 452 & Behannon, 1986; Söding et al., 2001). The selection procedures implemented in the early
 453 studies were based on magnetic field data of relatively low temporal resolution and were
 454 naturally biased toward large scale CSs. The high-resolution magnetic field measurements
 455 aboard modern spacecraft missions demonstrated that CSs are much more abundant and
 456 statistically thinner than reported early on (Vasquez et al., 2007; Perri et al., 2012; Podesta,
 457 2017; Artemyev, Angelopoulos, & Vasko, 2019; Vasko et al., 2021, 2022; Lotekar et al., 2022;
 458 Wang et al., 2023). The CSs were also shown to substantially contribute into magnetic field
 459 spectra of solar wind turbulence (Borovsky & Podesta, 2015; Borovsky & Burkholder, 2020)
 460 and potentially cause plasma heating (Osman et al., 2012; Wu et al., 2013; Qudsi et al.,
 461 2020; Sioulas et al., 2022). There are several comprehensive analyses of solar wind CSs at
 462 0.2 and 1 AU, but only few analyses of similar structures at the distances well beyond 1 AU.
 463 The results of previous studies of CSs at 5 AU are highly valuable (Tsurutani et al., 1996;
 464 Erdős & Balogh, 2008; Miao et al., 2011), but insufficient for matching against the recent
 465 results reported at 0.2 and 1 AU (Vasko et al., 2021, 2022; Lotekar et al., 2022).

466 We presented the analysis of 16,903 CSs collected over 641 days of Ulysses observations
 467 at 5 AU near the ecliptic plane and close to solar minimum. The revealed occurrence rate
 468 of 26 CSs/day is close to occurrence rates of 15–25 CSs/day observed previously aboard
 469 Ulysses at 5 AU (Tsurutani et al., 1996; Erdős & Balogh, 2008; Miao et al., 2011). The CSs
 470 in our dataset have temporal half-thickness τ_{CS} between about 1 and 60s, which is similar
 471 to temporal scales reported by Miao et al. (2011) and Tsurutani et al. (1996). Note that our
 472 dataset contains small scale CSs not captured by Erdős and Balogh (2008), whose dataset
 473 included CSs with scales larger than 1,000 km, probably because CSs were selected using
 474 magnetic field data downsampled to 10s. The averaged profiles in Figure 3 demonstrate
 475 that the magnetic field rotates across CS, while remains almost constant in magnitude in
 476 accordance with previous observations (Tsurutani & Smith, 1979; Tsurutani et al., 1996).

477 The averaged profiles reveal that the CSs are statistically asymmetric with a few percent dif-
 478 ference in the magnetic field magnitude at the CS boundaries, mostly due to the asymmetry
 479 of the maximum variance component. About 9.4% of the CSs were classified as bifurcated:
 480 magnetic field rotation is relatively smooth across non-bifurcated CSs, while occurs in two
 481 steps across bifurcated CSs. Both types of CSs have almost identical statistical distributions
 482 of the CS asymmetry and relative variations of the magnetic field magnitude, but bifurcated
 483 CSs tend to have larger scales. The 5th and 95th percentiles of the CS half-thickness are
 484 about 200 and 2,000 km for non-bifurcated CSs, while the corresponding quantifies for bi-
 485 furcated CSs are about 500 and 5,000 km (Figure 3). The current density in the CSs is
 486 typically 0.05–0.5 nA/m² and dominated by the component parallel to local magnetic field
 487 (Figures 4 and 6). The average perpendicular current density is typically less than 10% of
 488 the total current density, but along with magnetic field magnitude variations tends to be
 489 larger for CSs observed at larger plasma beta (Figure 4).

490 The CSs are predominantly proton kinetic-scale structures with spatial scales of the
 491 order of local proton inertial length. The 5th and 95th percentiles of the CS half-thickness
 492 are about 0.5 and $5\lambda_p$ for non-bifurcated CSs and about 0.7 and $15\lambda_p$ for bifurcated CSs.
 493 Note that the CSs have similar scales in units of thermal proton gyroradius $\rho_p = \lambda_p\beta_p^{1/2}$,
 494 because proton beta β_p was around one (Figure 5). The parallel current density amplitude
 495 in the CSs is strongly correlated with local Alfvén current density $J_A = en_eV_A$ and typically
 496 resides between about 0.04 and $0.4J_A$ with the median value of about $0.1J_A$. The electron-
 497 ion drift velocity corresponding to the observed current density amplitudes is then typically
 498 between 0.04 and 0.4 of local Alfvén speed V_A or local ion-acoustic speed c_{IA} , because
 499 electron beta β_e is around one (Figure 1) and we have $c_{IA} = V_A(\beta_e/2)^{1/2} \approx V_A$. Since
 500 electron to ion temperature ratio is also around one (Figure 1), the estimated electron-ion
 501 drift velocities are well below the threshold of the ion-acoustic instability (e.g., Boldyrev et
 502 al. (2015)). We expect therefore the CSs observed at 5 AU to be stable to the ion-acoustic
 503 instability.

504 The CSs exhibit a sort of scale-invariance in that several properties are correlated with
 505 the half-thickness in approximately a power law fashion (Figure 7 and Eq. (4)). We discuss
 506 only the scale-invariance of the shear angle $\Delta\theta \approx 16.6^\circ(\lambda/\lambda_p)^{0.34}$, since the observed scale-
 507 invariance of normalized magnetic field and current density amplitudes can be deduced
 508 by noticing that $\Delta B_x/\langle B \rangle \approx 2\sin(\Delta\theta/2) \approx \Delta\theta$ and $J_0/J_A \approx \Delta\theta(2\lambda/\lambda_p)^{-1}$. The scale-
 509 invariance of the shear angle is practically consistent with the scaling of the mean shear
 510 angle with the temporal half-thickness, $\langle \Delta\theta \rangle \approx 13.4^\circ\tau_{CS}^{0.38} \approx 10.3^\circ(2\tau_{CS})^{0.38}$ (Figure 8c)
 511 that is certainly not surprising, since according to the Taylor hypothesis we have $\lambda =$
 512 $V_n\tau_{CS}$. Note that a positive correlation between $\Delta\theta$ and τ_{CS} was previously pointed out,
 513 but not quantified, by Miao et al. (2011). The revealed scale-invariance indicates that the
 514 CSs are highly-likely produced by turbulence cascade (Boldyrev, 2005; Vasko et al., 2022).
 515 This hypothesis was further supported by matching the magnetic field rotation angle and
 516 compressibility in the CSs against equivalent properties of all the magnetic field fluctuations
 517 observed over the considered 641 days. The magnetic field rotation angles α_τ on different
 518 temporal scales τ were shown to be approximately self-similar, because the PDFs of α_τ
 519 practically collapsed to a universal distribution once at every scale τ we normalized angles
 520 α_τ to corresponding mean value $\langle \alpha_\tau \rangle$ (Figure 8a,b). Similar self-similarity was reported for
 521 magnetic field rotations (Zhdankin et al., 2012; Chen et al., 2015) and increments (Kiyani
 522 et al., 2009; Alberti et al., 2020; Chhiber et al., 2021) at 1 AU and near the Sun, and is
 523 considered a strong evidence for turbulence cascade development (e.g., Bruno and Carbone
 524 (2013)). The fact that the scaling of the mean rotation angle with temporal scale, $\langle \alpha_\tau \rangle \approx$
 525 $1.3^\circ\tau^{0.35}$, is similar to the scaling revealed for the CSs strongly indicates that the CSs
 526 are produced by turbulence. We also demonstrated that magnetic field compressibility
 527 within the CSs is practically identical with that of ambient magnetic field fluctuations at
 528 comparable temporal scales (Figure 9). Note that the magnetic field compressibility tends
 529 to be larger for smaller scale CSs (Figure 9e) and at larger betas (Figure 4). The CSs are
 530 therefore following the trends well established for solar wind turbulence at 1 AU in that

531 the compressibility increases toward smaller scales and at larger plasma betas (Smith et
 532 al., 2006; Hamilton et al., 2008; Podesta, 2009; Chen, 2016). We may speculate therefore
 533 that the compressibility observed *within* the CSs is inherited from ambient turbulence. In
 534 quite a contrast, the compressibility computed *between* the CS boundaries and quantified
 535 by $\chi_{\text{CS}}^b \approx 0.5(\Delta B/\langle B \rangle \Delta \theta)^2$ is statistically much lower than observed in ambient solar wind
 536 (Figure 9). In other words, the ratio between average perpendicular and parallel current
 537 densities $J_{\perp}/J_{\parallel} \approx \Delta B/\langle B \rangle \Delta \theta$ is typically much smaller within the CSs than in ambient
 538 solar wind at comparable temporal scales.

539 The relatively low temporal resolution of plasma measurements aboard Ulysses did
 540 not allow us to estimate the fraction of reconnecting CSs in our dataset. Note that a
 541 bifurcated magnetic field profile does not necessarily imply magnetic reconnection and vice
 542 versa magnetic reconnection does not always imply a bifurcated profile (Gosling & Szabo,
 543 2008; Phan et al., 2020). The previous observations at 1 AU and near the Sun showed that
 544 the occurrence of magnetic reconnection is about a few percent (Gosling, 2012; Osman et al.,
 545 2014; Eriksson et al., 2022; Fargette et al., 2023). If similar occurrence is typical at 5 AU,
 546 there should be a few hundred reconnecting CSs in our dataset. While the factors controlling
 547 magnetic reconnection in the solar wind are still not entirely established, here we considered
 548 whether magnetic reconnection can be suppressed through the diamagnetic drift of X-line
 549 resulting from different values of plasma beta at the CS boundaries (Swisdak et al., 2003;
 550 Swisdak et al., 2010). Note that this mechanism was previously shown to control magnetic
 551 reconnection at the Earth’s magnetopause (Phan et al., 2013) and highly likely at the
 552 Saturn’s magnetopause (Masters et al., 2012). We showed that the difference $\Delta\beta$ between
 553 plasma betas at the CS boundaries is typically too low to suppresses magnetic reconnection.
 554 Only 5–11% of the CSs have $\Delta\beta$ sufficiently high to suppress magnetic reconnection, while
 555 for most of the CSs magnetic reconnection is, in principle, allowed (Figure 10). This *does*
 556 *not* imply however that magnetic reconnection will always occur, since most likely it will
 557 be suppressed by other processes like the shear of plasma flow velocity (Doss et al., 2015;
 558 Phan et al., 2020) or relatively slow reconnection rate compared to turbulence nonlinear
 559 time (e.g., Zhdankin et al. (2013); Boldyrev and Loureiro (2020)).

560 We collected CSs using the PVI methodology (Greco et al., 2008, 2018), but used only
 561 the PVI index corresponding to the smallest time increment dictated by data resolution
 562 and applied the PVI threshold of 5. This methodology is identical to that used previously
 563 at 0.2 and 1 AU (Vasko et al., 2021, 2022; Lotekar et al., 2022). The use of PVI indexes
 564 corresponding to larger time increments would not substantially expand our dataset, because
 565 high PVI events of different temporal scales are typically nested into each other (Greco et
 566 al., 2016) and the 1 min window around points with $\text{PVI} > 5$ in our selection procedure
 567 allows identifying coherent structures with up to ≈ 1 min scales. Our dataset could be
 568 expanded however by lowering the PVI threshold and identifying CSs with smaller current
 569 density and, hence, larger scales, since $J_0 \propto \lambda^{-0.66}$ (Figure 7). Even though our dataset is
 570 biased toward smaller scale CSs, we believe most of CSs present at 5 AU has been captured,
 571 because the revealed occurrence rate is consistent with previous reports at 5 AU, where
 572 different selection procedures were implemented (Tsurutani et al., 1996; Erdős & Balogh,
 573 2008; Miao et al., 2011). Before conclusion we point out that our analysis was solely devoted
 574 to CSs, while other coherent structures, not least important for solar wind dynamics, such
 575 as flux ropes and Alfvén vortexes (Roberts et al., 2016; Perrone et al., 2017; Zhao et al.,
 576 2021) were excluded by requiring magnetic field profiles typical of CSs.

577 5 Conclusion

578 We presented a statistical analysis of 16,903 CSs observed over 641 days aboard Ulysses
 579 spacecraft at 5 AU, close to the ecliptic plane and around solar minimum. The results of
 580 this study can be summarized as follows.

- 581 1. The CSs are essentially magnetic field rotations, with relatively small variations of
582 the magnetic field magnitude and predominantly parallel (magnetic field-aligned) cur-
583 rent density. For more than 90% of the CSs we have $\Delta B/\langle B \rangle \lesssim 0.1$ for the relative
584 magnetic field magnitude variation between the CS boundaries, $\Delta B_{\max}/\langle B \rangle \lesssim 0.2$
585 for the maximum relative variation within CS, and $\Delta B/\langle B \rangle \Delta \theta \lesssim 0.1$ for the ratio
586 between average perpendicular and parallel current densities (Eq. (3)). The relative
587 magnetic field magnitude variations and perpendicular current density tend to be
588 larger at higher plasma beta.
589
- 590 2. The CSs are typically asymmetric with statistically different magnitudes of the max-
591 imum variance component B_x , which reverses sign across CS, at the CS boundaries.
592 For more than 50% of the CSs we have $\langle B_x \rangle / \Delta B_x \gtrsim 0.1$, where $\langle B_x \rangle$ is the mean of
593 B_x values at the CS boundaries, while ΔB_x is their difference.
594
- 595 3. About 9.4% of the CSs were classified as bifurcated. Both types of CSs have basically
596 identical statistical distributions of the CS asymmetry and relative variations of the
597 magnetic field magnitude.
598
- 599 4. The CSs are proton kinetic-scale structures. For non-bifurcated CSs the 5th and 95th
600 percentiles of the half-thickness are respectively about 200 and 2,000 km or 0.5 and
601 $5\lambda_p$ in units of local proton inertial length. Similar quantities for bifurcated CSs are
602 about 500 and 5,000 km or 0.7 and $15\lambda_p$.
603
- 604 5. The current density observed in the CSs is strongly correlated with local Alfvén cur-
605 rent density. The 5th and 95th percentiles of the current density amplitude are about
606 0.05 and 0.5 nA/m² or 0.04 and $0.4J_A$ in units of local Alfvén current density. The
607 electron-ion drift velocity within the CSs is well below the ion-acoustic instability
608 threshold.
609
- 610 6. The CSs exhibit a sort of scale-invariance (Figures 7 and 8). The shear angle
611 scales with spatial and temporal half-thickness: $\Delta \theta \approx 16.6^\circ (\lambda/\lambda_p)^{0.34}$ and $\langle \Delta \theta \rangle \approx$
612 $13.4^\circ \tau_{\text{CS}}^{0.38} \approx 10.3^\circ (2\tau_{\text{CS}})^{0.38}$, where in our dataset τ_{CS} is predominantly between 1
613 and 60s.
614
- 615 7. The magnetic field rotation and compressibility within the CSs are quite similar
616 to those typical of ambient magnetic field fluctuations (Figures 8 and 9). The
617 scaling $\langle \alpha_\tau \rangle \approx 1.3^\circ \tau^{0.35}$ of the mean rotation angle $\langle \alpha_\tau \rangle$ at temporal scale τ ob-
618 served for all magnetic field rotations in the solar wind is quite similar to the scaling
619 $\langle \Delta \theta \rangle \approx 10.3^\circ (2\tau_{\text{CS}})^{0.38}$ revealed for the CSs.
620
- 621 8. For most of the CSs the asymmetry of plasma beta between the CS boundaries is
622 insufficient to suppress magnetic reconnection through the diamagnetic drift of X-
623 line. Even though typically allowed by this condition, magnetic reconnection can be
624 suppressed or controlled by other mechanisms not considered in this study.

625 In conclusion, the CSs observed at 5 AU are typically magnetic field rotations on proton
626 kinetic scales. There are strong indications that these structures are produced by turbulence,
627 inheriting scale-invariance and compressibility. The observed asymmetry in plasma beta is
628 insufficient to suppress magnetic reconnection in the CSs, but other processes not considered
629 here may suppress or control it. The presented results will be of value of future comparative
630 analyses of current sheets observed at different radial distances from the Sun.

Data Availability Statement

The list of all current sheets considered in this paper is available at Vasko et al. (2024). The Ulysses data used in this paper are publically available at <https://www.cosmos.esa.int/web/ulysses>.

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