Small-scale Magnetic Flux Ropes and Their Properties Based on In Situ Measurements from the Parker Solar Probe

Yu Chen1 © and Qiang Hu12 ©

1 Center for Space Plasma and Aeronomic Research (CSPAR), The University of Alabama in Huntsville, Huntsville, AL 35805, USA; qh0001@uah.edu
2 Department of Space Science, The University of Alabama in Huntsville, Huntsville, AL 35805, USA

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Abstract

We report small-scale magnetic flux ropes via the in situ measurements from the Parker Solar Probe during the first six encounters, and present additional analyses to supplement our prior work in Chen et al. These flux ropes are detected by the Grad–Shafranov-based algorithm, with their durations and scale sizes ranging from 10 s to 1 hr and from a few hundred kilometers to 10 au, respectively. They include both static structures and those with significant field-aligned plasma flows. Most structures tend to possess large cross helicity, while the residual energy is distributed over wide ranges. We find that these dynamic flux ropes mostly propagate in the antisunward direction relative to the background solar wind, with no preferential signs of magnetic helicity. The magnetic flux function follows a power law and is proportional to scale size. We also present case studies showing reconstructed two-dimensional (2D) configurations, which confirm that both the static and dynamic flux ropes have a common configuration of spiral magnetic field lines (also streamlines). Moreover, the existence of such events hints at interchange reconnection as a possible mechanism for generating flux rope-like structures near the Sun. Lastly, we summarize the major findings, and discuss the possible correlation between these flux rope-like structures and turbulence due to the process of local Alfvénic alignment.

Unified Astronomy Thesaurus concepts: Astronomy data analysis (1858); Interplanetary turbulence (830); Solar magnetic reconnection (1504); Solar magnetic fields (1503); Solar wind (1534)

Supporting material: machine-readable table

1. Introduction

From the solar corona to interplanetary space, magnetic field lines—which can stretch, twist, and reconnect—are ubiquitous. As a result of such processes, many structures are present in the solar wind. Magnetic flux ropes are one of them, with their configurations consisting of helical field lines. The traditional concept of the magnetic flux rope refers to a quasi-static structure, i.e., a structure with almost no remaining plasma flow, as viewed from a frame moving with the structure. The identification of magnetic flux ropes has been carried out at a wide range of scales—e.g., for durations ranging from several minutes to days—at different heliocentric distances (Cartwright & Moldwin 2010; Chen & Hu 2020). In the study of Chen & Hu (2020), we reported thousands of small-scale magnetic flux ropes (SFRs) with monthly occurrence rates of over two hundred at both 1 au and 3.5 au, via ACE and Ulysses spacecraft measurements (see also Chen et al. 2019). The most distant observations of SFRs have been obtained via the in situ measurements from the two Voyager spacecraft. The spacecraft traversed a dozen small structures with durations of fewer than 9 hr at 9.57 au. Questions arise after finding these flux ropes at such distances: what kinds of variation or evolution will they display? Do these flux ropes originate from the Sun?

The large-scale counterparts of SFRs, which are usually classified as magnetic clouds, are a subset of interplanetary coronal mass ejections. With the help of the corona graph instrument, one can definitely observe the fact that, near the Sun, coronal mass ejections (CMEs) usually have clear expansions after being ejected from the Sun, and propagate into interplanetary space, before being intercepted by one or more spacecraft. However, many basic questions concerning SFRs remain. For instance, it is uncertain whether SFRs expand similarly to CMEs. On one hand, the flux rope merging process causes SFRs to increase in scale size. The observational results have confirmed this finding that two flux ropes merge into a larger structure (Zheng et al. 2017). Consequently, such a merging process, due to magnetic reconnection, leads to an increase in the toroidal flux, while the poloidal flux remains unchanged (Fermo et al. 2011). However, one should notice that what we rely upon are mostly one-point observations, which deliver information about SFRs via time series data. Uncertainty exists in any analysis, due to such a limitation on untangling the spatial-temporal ambiguities. Therefore, we adopt an approach combining statistical analyses with individual case studies, safeguarded by a set of quantitative metrics. It is also imperative to expand the analysis to additional spacecraft data sets, in order to further examine the properties of SFRs and to address the questions regarding their origin and evolution.

From our prior studies, the statistical properties of SFRs identified via several data sets from 0.3 to 8 au hinted that they may have multiple origins. First, the Sun, as the source of the whole solar system, is generally believed to be responsible for generating these structures, likely near its surface. The observational analyses provide certain evidence for this view. For example, the occurrence of SFRs at 1 au generally follows the variation of the sunspot number with a short delay (Hu et al. 2018). Furthermore, the macroscopic properties at different distances and latitudes are usually in accordance with the solar...
wind characteristics (Chen et al. 2019). On the other hand, the widely identified current sheet structure exists at flux rope boundaries, and this coexistence complies with the scenario of turbulence-generated structures at magnetohydrodynamics (MHD) scales (Greco et al. 2008; Servidio et al. 2009; Pecora et al. 2021). In addition, the non-Gaussian distribution of the probability density function of the axial current density in these observational analyses is also consistent with that of turbulence-generated quasi-2D structures (Zheng & Hu 2018). Thus, turbulent reconnection could also act as a possible mechanism for producing SFRs, especially at the local site. In retrospect, the theoretical mechanism relating to magnetic reconnection was proposed when the notion of SFRs was first put forward (Moldwin et al. 2000). This process is possibly associated with instabilities, which are able to produce the magnetic island configuration in the simulations (Nykyri & Otto 2004; Drake et al. 2006), although it can be regarded as a fundamental mechanism applicable to different plasma regimes.

With the launch of the Parker Solar Probe (PSP) mission, our focus turns to the inner heliosphere, given PSP’s close approach to the Sun. One of the major discoveries has been the “omnipresent” existence of magnetic switchbacks (Bale et al. 2019; Kasper et al. 2019; Dudok de Wit et al. 2020; Horbury et al. 2020). The possible generation mechanisms of these spikes in both magnetic and plasma in situ measurements include interchange reconnection between open and closed magnetic field lines (Yamauchi et al. 2004; Sterling & Moore 2020; Zank et al. 2020; Liang et al. 2021). In particular, such reconnection has been proposed as a mechanism for producing magnetic flux ropes in the low slow corona (Drake et al. 2021). They suggested that a flux rope structure with field-aligned plasma flows could be generated in a unidirectional background field, and survive over long distances. Such a type of flux rope, if crossed by a spacecraft, could also result in magnetic field reversals, indicative of switchbacks. Our recent study in Chen et al. (2021) has confirmed this overlapping of identified flux rope and switchback intervals. They share two circumstances: (1) the spike fully encloses the flux rope or vice versa; and (2) the two intervals have a partial overlap. Since both structures have been identified from single spacecraft measurements simultaneously or sometimes successively, it is very likely that they form via the same mechanism(s) or represent manifestations of the same structure. Moreover, similar power-law distributions of the waiting times also hint at this suggestion.

We have implemented an automated detection algorithm based on the Grad–Shafranov (GS) reconstruction method (Hu 2017; Hu et al. 2018) used in the previous studies (Chen et al. 2020, 2021), in which relatively low sample rate data from PSP were employed. The duration range was 5.6 minutes to ∼6 hr. In this study, we perform the extended GS-based detection algorithm for shorter durations, i.e., starting at a few seconds (∼1000 km in cross-sectional size at a distance of a few tens of solar radii) to time periods around the first six perihelia. This additional analysis significantly extends the spatial scales examined at close distances from Sun that better represent the inertia range turbulence, and alternatively the corresponding granular or supergranular structures on the solar surface. The current analysis also yields improved statistics in terms of a significantly enlarged event sample size. Another major finding in our recent works is the prevailing dynamic flux rope structures identified by the PSP data set. By “dynamic”, we mean those flux ropes with magnetic field lines that still take twisted shapes, but also contain significant remaining plasma flows that are aligned with the local magnetic field. Preliminary statistical analyses reveal that such structures show no significant deviation from static flux ropes in terms of their magnetic field configurations and other properties, for a limited sample of events (Chen et al. 2021). In this study, we thus adopt a broad definition of flux ropes, and combine the previous separately defined structures of flux ropes and flux ropes with field-aligned flows into one unified entity, i.e., SFRs, or sometimes flux rope-like structures, because they are all governed by one generalized GS-type equation, to be described in Section 2.

This paper is organized as follows. In Section 2, we briefly recap the process of the GS-based detection algorithm, and list the searching criteria. In Section 3, we present an overview of SFR structures in six encounters (E1–E6), and show the statistical analyses of some basic parameters—including the Walén test slope, normalized cross helicity and residual energy, duration, and scale size—for the identified SFR intervals. We also examine the correlation between selected parameters and the poloidal magnetic flux per unit length. In Section 4, we present selected case studies, and confirm the findings in Drake et al. (2021) that some magnetic switchback and flux rope-like structures can coincide. Finally, in Section 5, we summarize our major findings, and discuss the similarities and differences of flux rope-like structures with turbulence and their relation to dynamic Alfvénic alignments.

### 2. The Method Based on the GS-type Equation

In this study, we use the extended approach of the automated flux rope detection algorithm based on the original GS equation (Sonnerup & Guo 1996; Hau & Sonnerup 1999; Sonnerup et al. 2006), which describes the force balance between the Lorentz force and the gradient of the thermal pressure $p$ in 2D geometry ($\partial / \partial z = 0$ but $B_z = 0$), i.e., $\nabla^2 A = -\mu_0 dP/dA = -\mu_0 (p + B_z^2/2\mu_0) dA$. As introduced in Hu & Sonnerup (2001, 2002), Zheng & Hu (2018), and Hu et al. (2018), an SFR interval can possess a double-folding pattern between the inbound and outbound paths along the spacecraft’s trajectory. Such a pattern is represented by two $P_t$ versus $A$ branches, where $P_t$ is the transverse pressure and $A$ is the magnetic flux function, both obtained from the time series data. The original GS-based algorithm automatically scans all of the data arrays to look for good-quality patterns, i.e., candidates for SFRs. Notice that all of the calculations are processed in the comoving frame, i.e., the de Hoffmann–Teller (HT) frame (Khrabrov & Sonnerup 1998), with a constant frame velocity. In such a frame, the $z$-axis, i.e., the axis of a flux rope, is obtained via a trial-and-error process in the program loop. In the plane perpendicular to the $z$-axis, the $x$-axis is determined by the projection of the spacecraft’s path, and the $y$-axis completes the right-handed coordinate system (Hu & Sonnerup 2002). The detailed flowchart illustrating the logic flow of the algorithm can be found online.\(^8\) A full description of the implementation is given in Hu et al. (2018).

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\(^8\) [http://fluxrope.info/flowchart.html](http://fluxrope.info/flowchart.html)
The extended GS-based algorithm takes modified forms of $P_t$ and $A$, denoted by $P_t'$ and $A'$, respectively, as implemented in Chen et al. (2021), taking into account the nonvanishing remaining flow. The single-valued relationship of $P_t'$ versus $A'$ enables it to be applicable to those structures with remaining plasma flows that are aligned with and proportional to the local magnetic field in a proper frame of reference. A new type of GS equation is developed (Teh 2018):

$$\nabla^2 A' = -\mu_0 \frac{d}{dA'} \left[ (1 - \alpha)^2 \frac{B_r^2}{2\mu_0} + (1 - \alpha) \rho \right]$$

$$+ \alpha (1 - \alpha) \frac{B^2}{2\mu_0},$$  \hspace{1cm} (1)

where $\alpha = \langle M_A^2 \rangle \approx \text{Const}$ and $\langle M_A \rangle$ is the average Alfvén Mach number, the ratio between the remaining flow and the local Alfvén velocity. This formulation is consistent with an alternative and more general formulation presented by Sonnerup et al. (2006), with $P_t'$ corresponding to the terms enclosed in the square brackets to the right-hand side of Equation (1).

We use this extended formulation to search for the new double-folding pattern of $P_t'$ versus $A'$, where

$$A'(x, 0) = -\int_0^1 (1 - \alpha) B_r(x', 0) dx',$$  \hspace{1cm} (2)

a line integral of the measured magnetic field component $B_r$ along the spacecraft path at $y = 0$. Similar to Hu et al. (2018), Table 1 lists the criteria for this algorithm. It is implemented via a set of sliding windows ranging from 10 to 344 s in size (the range of duration of the identified SFR intervals). We use the Walén test slope to evaluate the Alfvénicity of a structure. This is calculated via the linear regression between the three components of $V_{rel} - V_{HT}$ and $V_A$, where $V_{rel}$ is the relative proton bulk velocity that takes spacecraft velocity into account.

| Table 2 |
|-------------------------------|
| Detection Results during the First Six PSP Encounters |
| PSP Encounters | E1 | E2 | E3 | E4 | E5 | E6 |
| Time Period (days) | 12 | 12 | 8 | 14 | 16 | <8 |
| SFR Duration (s) | 10–2605 | 10–1205 | 10–3697 | 10–343 | 10–2633 | 10–1793 |
| Event Counts | 1003 | 1466 | 850 | 1459 | 820 | 243 |

Figure 1. Summary plots for the first three perihelia: (a)–(c) E1, 2018 October 31 to November 12; (d)–(f) E2, 2019 March 30 to April 11; and (g)–(i) E3, 2019 August 23 to 31. For each encounter, the panels show the time series plot of the radial magnetic field $B_R$, the corresponding heliocentric distance of each event (the colored symbol), with the color representing the Walén test slope as indicated by the colorbar (the second panel), and the distribution of normalized cross helicity $\sigma_c$ as well as normalized residual energy $\sigma_r$ (the right panel). The radial magnetic field measurements with 1 s cadence and a 1250 s running average are shown by the gray and black curves, respectively.
(both given in an inertia frame), $V_{HT}$ is the velocity of the HT frame, and $V_A$ is the local Alfvén velocity. Since we do not distinguish static flux ropes from Alfvénic ones in this study, the threshold of the Walén test slope is relaxed to 1.0. Moreover, in order to eliminate small fluctuations, we set a limit on the field magnitude, i.e., 25 nT. Considering the
applicability of the new GS Equation (1) to avoid the singularity of \( \alpha = 1 \), we also set \( \langle M_A \rangle \) to less than 0.9. Last but not least, the absolute value of the correlation coefficient \( R \) between \( V_{\text{rel}} - V_{\text{HT}} \) and \( V_A \), is required to be \( \geq 0.8 \), to indicate that the remaining plasma flow is well aligned with the local magnetic field, such that \( \alpha \approx \text{Const} \) can be satisfied.

In addition, two auxiliary parameters are employed to evaluate the Alfvénicity, i.e., the normalized cross helicity density \( \sigma_c \) and the normalized residual energy density \( \sigma_r \) (Matthaeus & Goldstein 1982; Roberts et al. 1987; Bavassano et al. 1998). These two quantities are approximated in the time domain, and are calculated by the following equations:

\[
\sigma_c = 2 \langle v \cdot b \rangle / (\langle v^2 \rangle + \langle b^2 \rangle) \tag{3}
\]

\[
\sigma_r = (\langle v^2 \rangle - \langle b^2 \rangle) / (\langle v^2 \rangle + \langle b^2 \rangle), \tag{4}
\]

where \( v \) represents the remaining flow velocity in the HT frame, \( b \) is the magnetic field in the Alfvén unit, and \( \langle \cdot \rangle \) means the average within the event interval. In addition to the Walén test slope, these two quantities can also specify the degree of the Alfvénicity. Generally, high Alfvénicity is pronounced when \( \sigma_c \) and \( \sigma_r \) approach \( \pm 1 \) and 0, respectively (Bruno & Carbone 2013). Moreover, depending on the polarity of the background magnetic field, the cross helicity with large magnitudes usually indicates outward-/inward-propagating Alfvén waves. Meanwhile, we also obtain the extreme value of the poloidal magnetic flux function, \( A_m \), residing in the array \( A(x, 0) = A'/(1 - \alpha) \) from Equation (2). As previously mentioned, \( A \) represents the magnetic flux function. Therefore, the quantity \( A_m \) here refers to the difference in \( A \) between the boundary and the center of the structure, thus the absolute value
Am yields the amount of poloidal magnetic flux per unit length. The sign Am indicates the sign of the magnetic helicity or the chirality of the SFR.

The data of the magnetic field and proton bulk properties are recorded by the FIELDS Experiment (Bale et al. 2016) and the Solar Wind Electrons Alphas and Protons (SWEAP; Kasper et al. 2016; Case et al. 2020) instrument suite, respectively. The magnetic field and plasma bulk parameters (for protons only; no electron data is available), including velocity, number density, and temperature, are public data with the tag “Only Good Quality,” and are available on the NASA CDAWeb. This study mainly focuses on periods in which the high-cadence encounter mode is on. During these time periods, the data resolution for plasma is usually about 0.873 s, while the cadence of the magnetic field is always less than 0.437 s. In this study, we downsample all data to a cadence of 1 s.

3. Macroscopic Properties

As listed in Table 2, the extended GS-based algorithm is applied to time periods around the first six PSP perihelia, when high-cadence data are available. The time periods for detection range from 2018 October 31 to November 12, 2019 March 30 to April 11, 2019 August 23 to 31, 2020 January 23 to February 8, 2020 May 29 to June 14, and 2020 September 18 to October 1, for encounters E1–E6, respectively. The new detection is implemented for a total detection period of over two months. As previously mentioned, the duration limit in the detection is set to $10 \sim 344$ s. In order to acquire event characteristics on a wider range of scales, we also combine the current detection results with the SFR candidates that have durations from 337 s to $\sim 6$ hr in the prior study (Chen et al. 2021). During the 70 days of the detection periods, we identify a total of 5841 events, including both static and dynamic flux ropes, at heliocentric distances between 0.13 and 0.35 au. The durations and scale sizes of these events range from 10 to 3697 s and from $3.99 \times 10^{-6}$ to $5.96 \times 10^{-3}$ au, respectively. On average, the daily occurrence rate is about 103 events per day for E1–E4, which is fairly persistent. For E5–E6, the occurrence rate drops, and this is ascribed to the lack of solar wind velocity data near the perihelia.

Figures 1 and 2 present time series plots in encounters E1–E6 for the radial magnetic field $B_R$, the radial distance $r$ of PSP, the distributions of the Walén test slope, and normalized cross helicity $\sigma_c$ as well as residual energy $\sigma_r$. In both figures, panels (a), (d), and (g) show the radial magnetic field $B_R$ and its 1250 s
running average. Obvious enhancements of the magnetic field intensity can be seen when PSP approaches the perihelia with decreasing radial distance. Such a process is sometimes followed by a change of magnetic polarity, accompanied by a corresponding change in the electron pitch angle distribution (not shown), indicative of the heliospheric current sheet (HCS) crossing (Whittlesey et al. 2020). Complete crossings of HCS are pronounced in encounters E4 and E5 (Phan et al. 2021), and possibly E6 as well. In the first three encounters, one polarity, mostly negative, dominates during the time periods in Figure 1. Panels (b), (e), and (h) present the values of the Walén test slopes for identified SFRs as a function of time and the corresponding heliocentric distances. Although the values of the Walén test slopes range from −1 to 1, as indicated by each colorbar, 99% of the events in E1–E3 possess positive slopes (995/1003 in E1; 1452/1466 in E2; and 841/850 in E3). On the other hand, such a ratio changes in E4–E6, since the radial magnetic field turns to become positive in the outbound paths. According to Phan et al. (2021), the three HCS crossings in E4 and E5 start from 2020 February 1, 04:03:46 UT, 2020 June 8, 11:05:56 UT, and 22 June 8, 15:40:45 UT, respectively. Before the HCS crossings, 98% of the events (1281/1288 in E4 and 705/737 in E5) have positive Walén test slopes under the circumstance of the negative radial magnetic field. After a complete crossing, when $B_R$ changes the sign, 84% of the events (134/171 in E4 and 79/83 in E5) possess negative slopes with simultaneously positive $B_R$. It seems that the PSP also completed an HCS crossing in E6, although this was not covered in Phan et al. (2021). In Figures 2(g)–(h), there are negative (positive) Walén test slopes mainly associated with the positive (negative) $B_R$, although the event counts decrease significantly due to data gaps. In Figures 1(c), (f), and (i), the distributions of normalized cross helicity $\sigma_c$ and normalized residual energy $\sigma_r$ are displayed in black and blue lines, respectively. The distributions of $\sigma_r$ cluster within the negative value range, from −1 to 0. This corresponds to one of our detection criteria, e.g., $\langle M_4 \rangle < 0.9$, and demonstrates that the kinetic energy within these flux rope-like structures is modestly smaller than the magnetic energy. The results in encounters E2, E3, and E4 seem to have random $\sigma_r$ values, while the results in E1 and E5 tend to have skewed values, toward $\sim 0$, and $\sim -1$, respectively. Although the distributions in E5 and E6 may be limited by event counts, these values suggest that there seems to be significant variability in Alfvénicity, mostly ranging from modest to high levels, as judged by the values of $\sigma_c$. The distributions of $\sigma_c$ in all of the encounters are asymmetric. The positive signs of $\sigma_c$ are dominant in the first three encounters, while minority events have negative signs. Again, this indicates that the positive values appear to take place in the background field of mostly negative polarity. When the background field polarity changes from being negative to positive, more negative values arise. Such a change is seen in E4–E6. Clearly, these changes are due to the HCS crossings during E4–E6, which coincide with the change in sign of $\sigma_c$. The overall tendency indicates that the cross helicity $\sigma_c$ is largely positive in a background field of negative polarity (the $B_R$ component), and vice versa. Such a correspondence implies that most structures, if they can, propagate outward (away from the Sun) (Tu & Marsch 1995; Bruno & Carbone 2013; Zhao et al. 2021), which is consistent with the finding in Parashar et al. (2020).

We also compare the Walén test slope with the normalized cross helicity $\sigma_c$ as well as the distribution of the poloidal magnetic flux of each SFR, i.e., $|A_m|$, in Figure 3. For each circle in Figure 3(a), the blue and red colors denote the positive and negative signs of $A_m$, while the size of the circle represents its magnitude. The symbols are largely aligned with the diagonal line, indicating that the Walén test slope and $\sigma_c$ have the same sign and are also comparable in magnitude. It seems that these two quantities are connected intrinsically, which is expected, since they both reflect the relation between the remaining flow and Alfvén velocities. However, the physical connection between these two quantities is unknown. Additionally, in combination with the distributions of $\sigma_r$, those events that possess positive (negative) Walén test slopes in the background of negative (positive) $B_R$ also correspond to outward-propagating SFRs (if they can). The ratio is 98.02% in E1–E5. Only 1.98% of the events have the same signs for both the Walén test slopes and $B_R$, which indicates possibly inward-propagating structures. Events with positive/negative signs of $A_m$ are marked in blue and red, respectively. Notice that the chirality or the sign of magnetic helicity is equivalent to the sign of $A_m$. In total, there are 3279 and 2562 events possessing negative and positive magnetic helicity, respectively. For a flux rope configuration, the positive or negative sign of helicity corresponds to right-handed or left-handed chirality, respectively. Although the numbers of events are different, no significant preferential distribution of the poloidal flux for events with positive and negative magnetic helicity is revealed, as seen in Figure 3(b). The overall distribution (for either $A_m > 0$ or $A_m < 0$) behaves like a power-law function.

Figure 4 presents the distributions of event duration and cross-sectional scale size. The duration measures the length of an event interval, while the scale size in this study is calculated by multiplying the $x$ component of $V_{PT}$ and the event duration. Although the event duration has been replenished to 6 hr, events with smaller durations and scale sizes still prevail. In the previous report (Chen & Hu 2020), we found that distributions...
of these two parameters follow power laws at different heliocentric distances, i.e., 0.3 \sim 9 \text{ au}. Such tendencies now extend to smaller scales and to smaller heliocentric distances. Each distribution approximately follows a single power-law function. The power-law indices are around \sim 1.8. We notice that Dudok de Wit et al. (2020) reported the power-law distribution of the duration of the magnetic switchback with indices falling within \sim 1.4 and \sim 1.6. Actually, their work includes lots of events that are shorter than ours, i.e., with durations down to 10^{-2} \text{ s}, because they based their analysis solely on magnetic field data. Those events dominate, and thus have significant effects on the power-law indices. In Dudok de Wit et al. (2020), at the lower end of the distribution of the duration, events under different thresholds of normalized deflection parameters follow a unified power law, then start to deviate at the tails. The scales of our events correspond to these deviating parts. Therefore, a direct comparison is hard to achieve at the present time, although a certain degree of similarity in terms of a power-law distribution in duration is seen.

Figure 5 shows distributions of the orientation of the flux rope central axis, i.e., the z-axis. The angles \theta and \phi are the polar and azimuthal angles in the radial–tangential–normal (RTN) coordinates, where R represents the radial direction from the Sun to PSP, T is the cross product of the solar rotation axis and the R axis, and N follows the right-handed orthogonal rule. These two angles describe the angles of the z-axis with respect to N, and its projection onto the RT plane with respect to R, respectively. The polar angle of the z-axis covers almost all angles from 0° to 90°, and has gradually more events lying close to the RT plane. The projection of the flux rope z-axis onto the RT plane has a broad distribution of angles with respect to the R-direction, peaking approximately between \sim 120° and 220°. Such a preferred orientation was also found in Dudok de Wit et al. (2020) (Figure 2 therein), where the peak distribution of the azimuthal angle was found to center at around 170°.

We also examine the correlation between the flux rope parameters and \|A_m\|. Figure 6 presents 2D distributions of various parameters, such as the averaged solar wind speed \langle V_{SW} \rangle, the proton \beta, the scale size, the products of \langle |B_z| \rangle and the radial distance r as well as one half of the scale size, together with the corresponding poloidal magnetic flux \|A_m\|. The bins with the most events cluster near \|A_m\| \approx 10^{-2} \text{ T \cdot m}, but each distribution has a different tendency for each pair of individual parameters. Figure 6(a) presents the solar wind speed averaged within each event interval versus \|A_m\|. Events occur in the solar wind ranging from a rather slow speed, i.e., \sim 187 \text{ km s}^{-1}, to a fast one, around 668 km s^{-1}. Most events cluster between 300 and 400 km s^{-1} in these first six
encompassings. Figure 6(b) displays the relation between the $|A_m|$ and the proton $\beta$, where $\beta = n k_B T / (B^2/2\mu_0)$, involving the proton density $n$ and temperature $T$ only. Most events tend to have $\beta$ values $\leq 1$. Only a few events have $\beta$ values larger than 1. Notice that this is the distribution for the proton $\beta$ only. One may estimate that the plasma $\beta$ values will increase when additional contributions to the plasma pressure from electrons and alpha particles are included. Such tendencies indicate that the magnetic pressure inside most events may dominate over the thermal pressure. The overall tendency is that the averaged solar wind speed and the proton $\beta$ have slight variations with increasing $|A_m|$. Figure 6(c) presents the distribution of the scale size versus $|A_m|$. Generally, the scale size of most events is located from $10^{-5}$ to $10^{-3}$ au, while $|A_m|$ is mainly distributed from $10^{-3}$ to 1 T·m. Such ranges demonstrate that these events are rather small in terms of their spatial scale sizes and amounts of flux. The overall trend presents a positive correlation, i.e., larger events tend to have larger poloidal magnetic flux. Figure 6(d) shows the two products involving the average magnetic field component $\langle |B| \rangle$, one as a proxy to the poloidal magnetic flux per unit length, versus $|A_m|$, which are well separated in this plot. The top fraction is the product of $\langle |B| \rangle$ and the radial distance $r$ where an event is detected. The other fraction is obtained by multiplying $\langle |B| \rangle$ and one half of the scale size. This correlates well with $|A_m|$ because they are intimately related through Equation (2). In other words, they are expected to fall along the diagonal line that is shown. By contrast, the average values in the top fraction do not seem to follow a line parallel to the diagonal line, which implies that a radial change of scale size proportional with $r$ is not likely.

Table 3 presents a brief description of the event list attached to this paper. It includes the start and end times of each event interval in UT, the event duration, the average magnetic field strength, the average proton beta, the average solar wind speed, the polar angle and azimuthal angle of the flux rope $z$-axis and its three components in RTN coordinates, the flux rope scale size, the Walén test slope, the average Alfvén Mach number, the heliocentric distance at which an event is identified, the densities of normalized cross helicity and residual energy, and the extreme value of the magnetic flux function $A_m$.

4. Case Studies: Configurations of SFRs

Interchange reconnection happens between the closed and open magnetic field lines. Such a process may produce magnetic switchbacks (Bale et al. 2019; Kasper et al. 2019). Furthermore, this reconnection process was shown by Drake et al. (2021) to be able to generate magnetic flux ropes, which exhibit signatures of magnetic field reversals when crossed by a spacecraft. They identified the observational signatures of possible SFRs within a magnetic switchback interval on 2018 November 5, from 05:45:54 to 05:47:38 UT, which lasted for less than 2 minutes. Notice that our previous study (Chen et al. 2021) has a lower duration limit of 5.6 minutes. We can only deduce that the coexistence of switchback and SFR intervals may also be applicable to smaller structures, i.e., with durations down to a few seconds. The new detection reported in the
The present study now enables us to have a direct comparison for shorter duration events.

We first reconstruct the whole switchback interval denoted above by assuming that possible multiple flux ropes have one similar z-axis. Figure 7(a) shows the 2D cross-sectional map of the magnetic field configuration. Multiple closed transverse magnetic field line regions and the gradient of the unipolar axial field $B_z$ confirm the existence of multiple flux ropes. The transverse magnetic field and the remaining flow vectors along the spacecraft’s path are denoted by the white and green arrows, respectively. At the beginning and end of this interval, two sets of vectors are completely reversed, and the axial field $B_z$ remains positive, which accords with the signatures of switchback (or spike) boundaries. Moreover, these two sets of vectors seem to be aligned with each other along the spacecraft’s entire path at $y = 0$. The magnitude of the remaining flow, however, tends to be different within each flux rope interval. For example, the green vectors across the first flux rope are rather small when compared with the average Alfvén speed for the whole interval, 83 km s$^{-1}$. Such a magnitude indicates a small Walén test slope, i.e., corresponding to a quasi-static flux rope. In the second or third flux rope interval, these vectors become large, as indications of Alfvénic structures. Figure 7(b) presents the two sets of data points corresponding to the two branches and the fitted $P_1'(A')$ curves from which the cross-sectional map is reconstructed.

Figure 7(c) presents the Walén relation between the two velocities. Although the Walén test slope may become large in some segments, the Alfvénicity remains modest for the whole interval, with a Walén slope of 0.381. Moreover, the correlation coefficient is 0.99, which indicates a good alignment between the remaining plasma flow and the local magnetic field.

As previously mentioned, in order to present the overall structure for the whole switchback interval, Figure 7 is obtained by assuming that the flux ropes have the same z-axis. Now, we perform the new GS-type reconstruction for two individual subintervals. Figure 8 shows the results for two intervals close to the first and third flux rope intervals identified by Drake et al. (2021). The cross-sectional maps in panels (a) and (d) and the double-folding patterns in panels (b) and (e) demonstrate the flux rope configurations. In panels (c) and (f), the Walén relation again indicates that these two flux ropes have different levels of Alfvénicity, as indicated by the magnitudes of the corresponding Walén slopes.

Figure 9 displays the corresponding field line configurations in a 3D view toward the Sun. Such a configuration is derived from the GS reconstruction results (Hu & Sonnerup 2001). Since all three field components are known (in the comoving frame and due to invariance in the z-dimension), one can generate the corresponding values $B_x$, $B_y$, and $B_z$ in a 3D cuboid and thus obtain magnetic field lines in a 3D view. In this view, the spacecraft’s path is directly pointing into the plane of sky along the dot. The N-direction points vertically upward. The magnetic field lines twist along the z-axis, lying on distinct cylindrical surfaces, and thus form the projection of closed field line regions, as presented in the 2D cross-sectional plots in the plane perpendicular to the z-axis. The flux rope z-axes are not the same, but largely along the N-direction. The strong axial fields yield the largest components in the N-direction for the two events. Notice that the event interval for Figure 9(b) possesses a modest Alfvénicity and high correlation coefficient between the remaining flow and the magnetic field (see Figure 8). Therefore, the twisted magnetic field lines in Figure 9(b) also represent the streamlines as viewed in the HT frame. The same applies to Figure 9(a), although the remaining flow is small in magnitude.

In addition to those events reported in Drake et al. (2021), we select one further case from our event list to show the variability in field line configurations. Figures 10 and 11 present the corresponding reconstruction results, the Walén relation, and the 3D field line view for the event from 2020 June 2, from 18:53:56 to 18:54:35 UT. The duration is 40 s, and the scale size is $2.93 \times 10^{-5}$ au (about 4383 km). Again, the closed transverse field lines and unipolar axial field verify the configuration of a flux rope, which does not differ from any static SFR structure. Such a flux rope has a rather small scale and contains field-aligned plasma flows with relatively high Alfvénicity ($\langle \mathcal{M}_A \rangle = 0.68$ and the Walén test slope is 0.66). The remaining flow vectors along the spacecraft’s path are comparable to the average Alfvén speed. The 3D view of this event also exhibits an evident knottedness in magnetic fields (and streamlines).

5. Summary and Discussion

By applying the extended GS-based algorithm to the PSP in situ measurements over the first six encounters, we have detected nearly six thousand small-scale magnetic flux ropes, including both static structures and those carrying significant
field-aligned plasma flows. The durations of these events range from 10 to 3697 s, and the scale size is as small as $10^{-6}$ au. We examine the Alfvénicity of these structures with respect to the background radial magnetic field, and show distributions of the normalized cross helicity, the normalized residual energy, and the sign of magnetic helicity. The results indicate that most dynamic SFRs have modest to high Alfvénicity and propagate antisunward. The identified SFRs do not exhibit a preferential sign of magnetic helicity. We also present the macroscopic properties of these structures, such as the distributions of duration, scale size, and $z$-axis orientation angles. The correlations of selected parameters with the poloidal magnetic flux per unit length are displayed via 2D histograms. Moreover, we also carry out GS-type reconstruction to show 2D magnetic field configurations for selected cases. These are composed of spiral field lines, which also represent streamlines in the comoving frame of reference. The results indicate the correspondence between small-scale flux ropes and magnetic switchbacks. The major findings are summarized as follows.

1. Most SFR structures possess positive signs of normalized cross helicity (a peak at $\sim 1$) in the first three encounters, while the background radial field $B_R$ is largely negative. For E4–E6, such a dominance changes with the change in polarity of the magnetic field after HCS crossings. The distributions of the normalized residual energy density have different preferences that vary from $-1$ to 0.

2. The Walén test slopes and cross helicity of most events have the same signs, although the relationship between the two quantities is not linear. The results indicate that the remaining plasma flows inside these structures possess either positive or negative correlation with the local magnetic field.

3. The magnetic helicity of the identified flux rope structures does not have a preferential sign, which implies that the magnetic field lines twist equally in either a right-handed or left-handed manner, corresponding to right-handed or left-handed chirality.

4. The flux rope $z$-axis orientation shows an increasing tendency for a small inclination angle with respect to the RT plane. A broad peak is centered around the $R$-direction between $\sim 120^\circ$ and $220^\circ$ in the distribution of the azimuthal angle.

5. The distributions of the poloidal magnetic flux per unit length $|A_m|$, duration, and scale size generally follow power-law functions. The scale size and a proxy of poloidal magnetic flux distributions seem to scale with $|A_m|$.

6. The overlapping of switchback and SFR intervals for durations as small as a few seconds is confirmed via the new GS-type reconstruction. Such overlapping includes both quasi-static and Alfvénic SFRs. The latter structures still possess a configuration of twisted field lines (equivalent to streamlines), characteristic of a magnetic flux rope.

In this paper, we further reveal the variability in the configurations of flux ropes, broadly defined, at close distances from the Sun. They reach temporal scales down to a few seconds. Our results reveal the prevalence of modest to high Alfvénicity in these broadly defined SFR structures. Our extended GS-type reconstruction is able to characterize their configurations under a unified theoretical framework. We find that flux rope-like structures arise very frequently in the inner heliosphere ($r < 0.3$ au), with a daily occurrence rate of over one hundred in some encounters. Considering the close heliocentric distances at which they were detected, and the overlapping with magnetic switchbacks, it is very likely that these flux rope-like structures are formed via similar mechanisms, such as interchange reconnection in the low slow corona, as proposed by Drake et al. (2021).
Another interesting fact is that while static SFRs have been conjectured to be generated via MHD turbulence at larger heliocentric distances (Zheng & Hu 2018), the broadly defined flux ropes (i.e., allowing for modest to high levels of Alfvénicity) in this study may also be tied to turbulence. As demonstrated here, the magnetic field and remaining plasma flows constitute the Alfvénic alignment inside these twisted structures. Such an alignment, as a result of the rapid relaxation processes intrinsic to ideal MHD, occurs locally and is associated with kinetic energy and pressure gradients (Matthaeus et al. 2008; Osman et al. 2011). Moreover, it appears to be random, contains broad changes, and complies with the MHD turbulence description involving the ideal MHD invariants, such as magnetic helicity and cross helicity, parameters commonly derived from in situ measurements. Notice that such a correlation does not necessarily require a high correlation coefficient between the magnetic field and the velocity. In other words, the Walén test slopes can range from small, modest, to high values, as we present here.

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ORCID iDs

Yu Chen © https://orcid.org/0000-0002-0065-7622
Qiang Hu © https://orcid.org/0000-0002-7570-2301

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