A database of small-scale magnetic flux ropes in the solar wind from Wind spacecraft measurements

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Abstract. We present an extensive study of identifying small-scale magnetic flux ropes with duration between 9 and 361 minutes from Wind spacecraft in-situ measurements. The approach is based on the well-established Grad-Shafranov (GS) reconstruction method applicable to two-dimensional (2D) magnetohydrostatic structures. An automated computer algorithm is developed to sift through the time-series data covering two solar cycles, from 1996 to 2016. A large number of flux rope events is identified and an online database is built to accommodate the outcome from this detection algorithm. We provide detailed descriptions of the key steps of the GS-based detection algorithm and the general features of the online database. Selected preliminary statistical analyses are shown, which yield the following main results. (1) The occurrence of small-scale flux ropes has strong solar cycle dependency. (2) The small-scale magnetic flux ropes in the ecliptic plane tend to align along the Parker spiral direction. (3) Both the duration and scale size distributions of the small-scale magnetic flux ropes obey power laws. We show the similarities and discrepancies in their properties as compared with their large-scale counterparts, the magnetic clouds. We also discuss the implications on their origination mechanisms.

1. Introduction
Magnetic flux ropes are a fundamental type of magnetic field structures occurring in space and laboratory plasmas. In space environment, one prominent type is the relatively large-scale flux ropes, i.e., the so-called magnetic clouds (MCs), which has a clear origin from the Sun. They correspond to the magnetic field structures embedded in coronal mass ejections (CMEs) and possess a winding magnetic field line configuration with a prolonged duration up to days when detected by in-situ spacecraft at a heliocentric distance 1 AU from the Sun. They have been extensively studied in the past decades. On the other hand, the relatively small-scale flux ropes, of duration down to a few minutes or less, just begin to gain renewed interest in the heliospheric community. Although previous attempts had been made, a comprehensive study especially by using the most advanced approaches to the most modern spacecraft observations is still lacking. Whether or not these small-scale flux ropes form a continuum population from their large-scale counterparts, i.e., MCs, has yet to be determined from a more extensive event database that did not exist before. Then the fundamental question regarding their properties and origination can be addressed.

Cartwright and Moldwin [1] carried out an earlier and representative study of identifying and characterizing the small-scale flux ropes in the solar wind with duration $\geq 10$ minutes, similar to...
the range of duration we examine. They surveyed small-scale flux ropes between the heliocentric distances 0.3 and 5.5 AU, from 1974 to 2007. They found that the occurrence rate of small-scale magnetic flux ropes has a negative solar cycle dependency. More events tend to occur during solar minimum rather than solar maximum (see Figure 1; however, be cautioned about the fairly low event counts). We show, however, in Figure 2, based on our database, the event occurrence rate that correlates with the sunspot numbers in solar cycles 23 and 24. Cartwright and Moldwin’s database included small-scale flux ropes from 0.3 to 5 AU. Our database only includes the ones at 1 AU. However due to relatively simplistic approach, their event count is only on the order of \( \sim 1 \) per month, which is a common feature of a handful of such similar studies.

Feng et al. [2, 3] investigated the small to intermediate size magnetic flux ropes that had durations mostly beyond the range we examine. They suggested that the small-scale flux ropes are interplanetary manifestations of small CMEs, originating from weak solar eruptions and forming in the solar corona, just like magnetic clouds. Feng et al. [3] found a positive correlation between the occurrence rate of small- and intermediate-scale magnetic flux ropes and the occurrence rate of magnetic clouds from 1995 to 2005. Therefore, they called these small- and intermediate-scale magnetic flux ropes as small magnetic clouds (SMCs). However, the occurrence trend of SMCs shown by Feng et al. [3] (Figure 4 in their paper) is not consistent with the trend of sunspot numbers. As pointed out by Cartwright and Moldwin [1], Feng et

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**Figure 1.** The upper panel is small-scale flux rope occurrence counts per month of observation for 1974 \( \sim \) 2006. The lower panel is the monthly occurrence counts averaged over solar cycles 21 to 23 (adapted from [1]).
al. [3] did not exclude the Alfvénic waves in their database. Another caveat weakening their conclusion is that the total number of events in their database is also very small.

Gopalswamy et al. [4] investigated the correlation between the annual number of magnetic clouds events and the frontside halo CMEs, and compared both with the sunspot numbers. They found that the main trend of magnetic cloud occurrence counts is consistent with the trend of sunspot numbers. It is because that the magnetic clouds originate from the Sun, as is widely accepted. If both magnetic clouds and small-scale flux ropes originate from solar eruptions, they may share the same dependency with solar activity. However, this fact is still not a sufficient condition such that the small-scale flux ropes originate from the Sun. On one hand, there may be two populations of small-scale flux ropes that have different origins and different solar cycle dependencies, i.e., one population has solar cycle dependency but the other does not. When they are mixed, the solar cycle dependency may still appear. On the other hand, even if all small-scale flux rope events have solar cycle dependency as magnetic clouds do, we still cannot conclude that they originate from the Sun, since magnetic clouds have clear solar eruption correspondences but small-scale flux ropes do not. There may be other local plasma dynamic processes far away from the Sun that could generate the small-scale flux ropes and are also modulated by the solar activity cycle.

In addition, all these previous studies used relatively simple approaches, mostly based on single-point time-series analysis. At times, simple and mostly one-dimensional flux rope models were employed to fit the in-situ data [1]. Hu and Sonnerup [5, 6] developed a new approach to determine the flux rope axial orientation base on the Grad-Shafranov (GS) equation, describing quasi-2D magnetohydrostatic equilibrium suitable for examining cylindrical magnetic flux rope configurations based on in-situ spacecraft data [7]. Specifically, the analysis relies on the theoretical requirement that the transverse pressure $P_t$, the sum of the plasma pressure and the axial magnetic pressure, versus the 2D flux function, $A$, be single-valued and double-folded through a flux rope interval, given a proper determination of a cylindrical geometry ($z$ being the cylindrical axis). An optimal $z$-axis orientation is found via an optimization procedure to minimize a residue representing the degree of satisfaction for $P_t(A)$ being single-valued. We refer readers to Chen et al. [this volume] and [7] for detailed descriptions of the Grad-Shafranov (GS) equation and the corresponding procedures for the GS-based reconstruction technique. In short, a trial-and-error process was devised to search for the optimal $z$ axis orientation in the whole space. An appropriately spaced search grid is constructed on the upper-half hemisphere of a unit sphere in a spherical coordinate, in which each grid point represents one trial $z$-axis orientation (represented by the polar angle $\theta$ and the azimuthal angle $\phi$). All grid points are traversed to find the $z$-axis orientation with the minimum fitting residue of $P_t(A)$, which is taken as the optimal flux rope axial orientation. In our flux rope detecting algorithm, we extend the usage of Hu and Sonnerup’s approach. This approach is not only used for determining the optimal $z$ axis of a flux rope, but also used for checking flux rope candidate. Since in the case of a cylindrical flux rope, an optimal $z$-axis with a reasonable small fitting residue will surely be found. Conversely, small fitting residue of $P_t$ versus $A$ is taken as a main criterion in identifying flux rope candidates, together with additional criteria to be presented in the following sections.

We would like to stress that what distinguishes our analysis from all previous studies is that we have far more number of events, about hundreds per month as opposed to about 1 per month, on average. Therefore, our analysis results will be based on much better statistics with a significantly large number of events.

2. Automated Detection Algorithm Based on the GS Method

In the present study, we detect flux ropes with duration from about 10 minutes to 360 minutes through an automated computer routine based on the GS method. We split this task into multiple iterations. These iterations, corresponding to the ranges of duration of flux ropes to
be identified, are: 10-15 minutes, 15-20 minutes, 20-25 minutes, ..., and 355-360 minutes. Each iteration identifies flux rope candidates with the duration falling in the time range specified. For example, when we run the 10-15 minutes iteration, we set a sliding window width to 15 minutes, and the lower limit of flux rope duration to 10 minutes. With this setting, the program checks the data segment in a sliding 15-minute window, and if the double folded part of $P_t(A)$ is less than 10 minutes, the program will discard it. When this iteration is done, the flux ropes with durations longer than 10 minutes and less than 15 minutes will be discovered and recorded. After all the given data is scanned by the 15-minute window, we go to the next iteration to find flux ropes with other lengths. In practice, we extend the boundary of each iteration by 1 minute to make smooth conjunction between two adjacent iterations. Then the iterations become: 9-16 minutes, 14-21 minutes, 19-26 minutes, ..., and 354-361 minutes.

Our automated detection algorithm is based on the fact that the magnetic flux function $A(x, y)$ is a field line invariant, and the transverse pressure $P_t$ is a single-valued function of $A$, based on the GS equation. As a spacecraft passes through the cross section of a magnetic flux rope with closed transverse field lines, it firstly crosses some transverse magnetic field lines in its first-half path toward the center, then it crosses exactly the same set of transverse field lines, but in reverse order, in its second-half path. Therefore, along the spacecraft path, the measured magnetic flux function $A$ associated with the field lines traversed twice by the spacecraft shows a double-folded pattern, or contains a turn point where an extremum is reached. Since the transverse pressure $P_t$ is a single-valued function of $A$, the two branches of the data points along the first and second halves of the spacecraft path for $P_t$ versus $A$ should coincide as well. Conversely, given a specific time interval of interest, the transverse pressure $P_t$ and the flux function $A$ are calculated from the in-situ spacecraft data. Then we check whether the $P_t$ versus $A$ curve has double-folded feature and how good the overlapping is. Later we will define the selection criteria. If the criteria are satisfied, the structure under checking is considered as a flux rope candidate.

In general, the ground rules we play by are: (1) as many as possible flux rope candidates are to be identified by an exhaustive sifting process through the time-series data, and (2) a single flux rope is to be identified for each interval/event.

A fixed width sliding window is used to select data segment in each iteration. The window width defines the maximum duration of the flux rope to be detected during this iteration. We also define a lower limit of the flux rope duration. The flux ropes only with its length between lower and upper limits will be processed during this iteration. Later we are going to run multiple iterations with different window widths to detect flux ropes with different sizes. Specifying the lower limit will avoid the duplication among the windows with different widths. For the time series magnetic field data within a given window, to make the $P_t$ versus $A$ curve double folded, the $A$ array must have one and only one inflection point (or turn point), defined as the place where the magnetic field component $B_y$ changes sign (see Equation 1). As discussed above, since the transverse pressure $P_t$ is a single-valued function of $A$, the only way to make $P_t$ versus $A$ curve double folded is that the $A$ array has to fold onto itself so that the $P_t$ versus $A$ curve has two branches. If the $A$ array has more than one inflection point, the corresponding $P_t$ versus $A$ curve will be multiple folded, which does not meet the ground rule (2) for a single flux rope configuration. When such a situation occurs, the window may contain more than one flux rope structures. We just need to narrow down the window size to make it contain only one single flux rope structure. On the other hand, a narrow window cannot detect the flux ropes with the lengths longer than it. Therefore, to detect flux ropes with different lengths, we have adopted the strategy of running multiple windows with different widths.

The core procedure for each iteration consists of the following two major steps. A frame of reference co-moving with the structures has to be chosen beforehand, usually as the deHoffmann-Teller (HT) frame or the frame with the constant average solar wind velocity. Both can be used
robustly in this analysis of fairly uniform solar wind flows, at least within each data segment.

- **Step 1.** As the sliding detection window moves forward, we calculate the \( A \) array along the projected spacecraft path (at \( y' = 0 \)) by

\[
A(x', 0) = \int_0^{x'} -B_{y'}(\xi, 0) \, d\xi.
\]  

(1)

Apparenty the inflection point corresponds to the point along the spacecraft path where the field component \( B_{y'} \) changes sign and a point at which the extreme value in \( A \) is reached. If we find the calculated \( A \) array within the window is monotonic or has more than one inflection points, we will do nothing but simply move the window forward by one data point. A monotonic \( A \) array contains no extrema and can never lead to a double-folded \( P_t \) versus \( A \) curve. An \( A \) array with more than one inflection points indicates that the current window may contain multiple flux rope structures. For the former situation, there is no further action needed to be done, and for the latter, a smaller size detection window in another run will take care of it. Once the \( A \) array with only one inflection point is discovered, the \( A \) array will be split into two branches at the inflection point. Then the two branches will be trimmed to have the same \( A \) values at the boundary. Note that the trimming is not according to the number of data points, but is according to the \( A \) value, because a flux rope should have the same \( A \) value at its boundary. After trimming, the two branches may not have the same length, but must have the same or similar boundary \( A \) values. After getting two branches of \( A \) values with the same boundary, we can calculate \( P_t \) values corresponding to each \( A \) value. With both \( P_t \) and \( A \) values obtained along the spacecraft path, we get the two branches of the \( P_t \) versus \( A \) curve.

- **Step 2.** The next step is to examine how well the two branches of the \( P_t \) versus \( A \) curve overlap. Before doing this, another check process can be performed to reduce the further workload. As a physical nature of a flux rope, the total transverse pressure \( P_t \) must reach its maximum in the flux rope center. Reflected in the two branches of the \( P_t \) versus \( A \) curve, the turning point (corresponding to the inflection point in the \( A \) array) must be on the top. We need to remove the cases with turning points not on top. Taking into account the measurement error and small fluctuations, we introduce the tolerance. With tolerance, we require the \( P_t \) value at the turning point be in top 15% of all \( P_t \) values. If the data segment would survive the check after undergoing all the aforementioned procedures, we are ready to obtain two more metrics as defined below to check the double-folding quality.

\[
R_{dif} = \left| \frac{1}{2N} \sum_{i=1}^{N} [(P_t)_i^{1st} - (P_t)_i^{2nd}]^2 \right|^{1/2} / \max(P_t) - \min(P_t),
\]  

(2)

and

\[
R_{fit} = \left| \frac{1}{L} \sum_{i=1}^{L} (P_t(x_i, 0) - P_t(A(x_i, 0)))^2 \right|^{1/2} / \max(P_t) - \min(P_t).
\]  

(3)

We determined that the conditions \( R_{dif} \leq 0.12 \) and \( R_{fit} \leq 0.14 \) could guarantee good flux rope quality while keeping as many candidates as possible.

Equation (2) is modified from Equation (5) in [6], and Equation (3) is taken from [8], subject to adjusted normalization factors. The quantity \( R_{dif} \) represents the point-wise difference between two branches, in which both \( (P_t)_i^{1st} \) and \( (P_t)_i^{2nd} \) are calculated from observational data. Only \( R_{dif} \) alone is not sufficient to decide if a segment of data is a good flux rope candidate or not, because a small \( R_{dif} \) can only guarantee the good double-folding of the two branches of \( P_t \) versus \( A \) curves, no matter what the shape of the folded curve is. A reliable threshold for \( R_{dif} \) is
hard to set for acceptable flux rope candidates. To help with this, we obtain an additional fitting residue by using a 3rd order polynomial to fit the data points of $P_t$ versus $A$. This fitting ignores the time sequence of the data points and merges two branches into one. Its fitting residue is defined in Equation (3) and denoted as $R_{fit}$, where $P_t(x_i, 0)$ is calculated from measured data and $P_t(A(x_i, 0))$ is calculated from the fitting function. In the flux rope searching process, we use only $R_{dif}$ to look for optimal $z$-axis orientation. For a given data segment, the $R_{dif}$ for each trial $z$-axis orientation is calculated, then the $z$-axis orientation with the minimum $R_{dif}$ is taken as the optimal axial orientation. With the determined optimal axial orientation, if both $R_{dif}$ and $R_{fit}$ satisfy our criteria, this data segment will be labeled as a flux rope candidate. The threshold values of $R_{dif}$ and $R_{fit}$ are selected based on examining thousands of data segments with double-folding features in $P_t(A)$, and are given in Table 1.

When a sliding window process is finished for one iteration, we will get a record list of identified flux rope intervals. However, this record list has many overlapped records or intervals. Each group of such overlapping intervals is called a cluster. We clean up such a cluster from the record list in order to obtain uniquely identified flux rope events. We usually pick the interval with the smallest $R_{dif}$ values and discard the others to eliminate overlapping. We have considered possible improvements to avoid the overlapping. One possible method is to move the entire sliding window out of the time range of a flux rope once it is detected. However, we cannot guarantee that the one we picked is the best one in a flux rope cluster. Eventually we decided to slide the detection window continuously to guarantee the detection of the maximum number of flux ropes.

The last check step is the standard Walén test to rule out possible Alfvénic structures or waves [9]. An Alfvén wave or structure may show the similar magnetic field profile in the GSE coordinate system, for instance. The scale size of small flux ropes is comparable with that of Alfvén wave structures. We have to do further test to remove Alfvén waves from our flux rope database. The Walén slope is defined as the slope of the linear regression line between the remaining flow velocity $v'$ in the co-moving reference frame and the local Alfvén velocity, component-wise. We remove the records whose absolute values of Walén test slope are greater than or equal to 0.3 (indicating significant remaining flows in the reference frame). Up to this point, we have finished all major steps to build the flux rope database. At last, we have the option to apply one more criterion. Because the average magnitude of magnetic field in the ambient solar wind is about 5 nT, we remove the flux rope records whose average magnitude of magnetic field is less than 5 nT.

In summary, Table 1 lists the set of metrics and criteria we use in the identification of small-scale flux rope events from the in-situ Wind solar wind observations. The duration $9 \sim 361$ minutes covers the range of most small scale flux ropes, and this range is easily to be extended to intermediate or large size flux ropes, e.g., $6 \sim 12$ hours, to bridge the gap between small-scale flux ropes and MCs. The condition $\bar{B} \geq 5$ nT excludes small fluctuations in solar wind. The metrics $R_{dif}$ and $R_{fit}$ guarantee the good quality of small-scale flux ropes based on the GS method. And the last but a critical condition, Walén test slope $\leq 0.3$, removes the Alfvénic structures or waves.

| Table 1. Small-scale Magnetic Flux Rope Detection Metrics and Criteria |
|---------------------------------------------------------------|
| Duration | $\bar{B}$ | $R_{dif}$ | $R_{fit}$ | Walén test slope |
| 9 $\sim$ 361 (minutes) | $\geq 5$ (nT) | $\leq 0.12$ | $\leq 0.14$ | $\leq 0.3$ |
3. Small-scale Magnetic Flux Rope Database from Wind Spacecraft Measurements

We apply the flux rope detection algorithm based on the GS reconstruction technique to the Wind spacecraft measurements during 1996-2016, covering nearly two solar cycles. We successfully detected a large number of small-scale magnetic flux ropes with more general configurations, including non-force-free and non-axisymmetric configurations. There are a total number of 74,241 small-scale magnetic flux ropes detected, with an average number more than 3,500 per year. This database provides sufficient number of samples for researcher to carry out statistical analysis, correlate with other structures, and examine some special cases in detail.

Figure 2 shows the monthly occurrence counts of small-scale flux ropes from 1996 to 2016, covering solar cycles 23 (from May 1996 to January 2008), and 24 (which began in December 2008, reached its maximum in April 2014, and may have ended in early 2017). The different colors represent different durations of small-scale flux ropes (from 9 minutes to 360 minutes), and the thick black line is the corresponding monthly sunspot number. The events of smaller durations generally have greater rates of occurrence. Clearly the total counts including all events of variable durations follow the monthly sunspot numbers, hinting at solar-cycle dependency of these events. Note that the occurrence counts also vary cycle by cycle. From the sunspot numbers we can see that the solar activity in cycle 23 is more intense than that of cycle 24, and accordingly, the overall small-scale flux rope occurrence counts in cycle 23 is larger than those of cycle 24, approximately proportional to sunspot numbers. The peaks of occurrence counts tend to appear in the declining phase of each solar cycle.
3.1. On-line Database
We have established a website (https://fluxrope.info) to host this database online. We make the database open to public and keep it up to date. More flux rope cases with longer duration and at higher latitude locations will be added in near future. Figure 3 is a screenshot of the home page of the small-scale magnetic flux rope database website. When clicking on any year on the “EVENT LISTS” table, the annual event list page will show up, which is presented in Figure 4 for year 1996. The event list page lists every detected flux rope event in one year in chronological order. For each flux rope record in each row, some basic characteristics are listed such as time range in UT, duration in minutes, fitting residue ($R_{fit}$), average magnetic field strength, maximum magnetic field strength, average plasma $\beta$, average proton $\beta_p$, average solar wind speed, average proton temperature, and flux rope axial orientation. More information on magnetic field and plasma profiles is stored in database and can be put online in new versions of the website. These quantities make it very convenient for us and other researchers to further apply more selection criteria to pick desirable subset of events for different purposes.

The time range for each record is a clickable hyperlink which will navigate to the detailed flux rope information page for each particular event. Figure 5 shows the upper part of an event page and Figure 6 shows the lower part of the event page. In Figure 5, the upper panel in the first column is the plot of $P_t$ versus $A$, from which one can easily judge the “double-folding” quality of $P_t(A)$, a necessary condition for being a flux rope. The lower panel in the first column is the plot of Walén test with the slope and correlation coefficient shown on the plot. From these two quantities one can know the magnitude of the remaining flows for each velocity component in the frame of reference moving with the flux rope structure. Generally speaking, a spread of
The data points horizontally indicates satisfaction of the detection criterion based on the Walén test. In the second and the third columns, the upper panels are the hodograms of the flux rope magnetic field components in the Minimum Variance Analysis (MVA) principal-axes frame and the lower panels are the hodograms of the flux rope magnetic field components in the flux rope reconstruction frame. The movement of the end points of magnetic field vectors is displayed in these hodograms. Generally a smooth rotation in one or two magnetic field components, typical of a flux rope configuration, may be visualized in these plots. The other panels in Figure 5 and Figure 6 are time series data of magnetic field and plasma parameters, including the pitch angle distribution of suprathermal electrons, the temperature of protons and electrons, and plasma $\beta$, when available.

This website provides a large number of small-scale magnetic flux rope events and lots of essential information, which can benefit the relevant studies on small-scale magnetic flux ropes in the solar wind. In the next subsection, we show some selected statistical results obtained from the current small-scale flux rope database based on the Wind spacecraft measurements.

### 3.2. Selected Statistical Properties

In this subsection, we are going to present some statistical properties of the flux ropes in our database. First of all, after analyzing the solar wind speed distribution from our flux rope database, in the following analysis, we split the entire database into two subsets according to the corresponding average solar wind speed either greater or less than 400 km/s. Note that this value is close to the mode and median of the speed distribution (not shown), 402 km/s and 435...
Figure 5. Detailed information for one small-scale magnetic flux rope record: event page part 1.

km/s, respectively.

Figure 7 (a) and (b) show the small-scale flux rope axial orientations in the GSE spherical coordinates based on the last column of the list of even properties. Figure 7 (a) is the polar angle histogram which is binned by 10°, and Figure 7 (b) is the azimuthal angle histogram which is binned by 20°. These two plots indicate that the small-scale flux ropes have preferential axial orientations. From Figure 7 (a), one can see that most small-scale flux ropes have large polar angels, i.e., most of them tend to lie on the ecliptic plane. Figure 7 (b) shows two peaks located at bin 120° ~ 140° and the bin 300° ~ 320°. In fact, these two bins represent two parallel but opposite directions in the GSE XY plane, so they differ by about 180°. Either one of these directions happens to be the tangential direction of the Parker spiral at 1 AU (corresponding to $\phi \approx 135^\circ$ or $315^\circ$). This indicates that the projection of the flux rope axis tends to align with the Parker spiral on the ecliptic plane. The red and blue bars represent the events occurring
under different solar wind speed conditions (blue: $V_{sw} < 400$ km/s; red: $V_{sw} \geq 400$ km/s). Figure 7 (a) and (b) indicate that the small-scale flux ropes have similar orientation preferences in both fast and slow solar wind on the ecliptic at 1 AU.

Figure 8 (a) and (b) show the durations and scale size distribution of small-scale flux ropes in our database. The data points in black in each plot represent the histogram of the entire event set, and the points in blue or red represent the histogram of the the subsets for slow ($V_{sw} < 400$ km/s) and fast ($V_{sw} \geq 400$ km/s) solar wind speed, respectively. In Figure 8 (a), the shapes of these three curves are close to straight lines on the log-log scale except for the high tails to the right. After examining the generation process of our flux rope database, we find that the high tail is due to cutoff effect of a finite range of window widths. In the present database, the longest duration range is $354 \sim 361$ minutes, which means that the flux ropes within this duration range will not be merged into longer flux ropes, since there is no longer durations allowed beyond this
range, thus the cutoff. Actually, the flux ropes in duration ranges shorter than 354~361 minutes may also be enclosed by longer flux ropes with durations beyond 354~361 minutes. This cutoff leads to the enhanced fluctuation and a high tail near the end to the right. To assure this explanation, we manually shifted the cutoff boundary to shorter durations, the high tail also shifted accordingly. In Figure 8 (b), there are low tails at both ends in each curve, which are also caused by the same cutoff effect of finite duration ranges. Due to the boundary cutoff in duration ranges, when convert the duration to scale size, there is a lack of events near the lower and upper scale size boundaries. We exclude these abnormal sections of the data points in the subsequent analyses.

Except for the high tails due to the cutoff effect, Figure 8 (a) shows a linear relation between the flux rope occurrence counts and the duration under logarithmic scales, which indicates a power law distribution of flux rope durations. The color coded straight lines are the corresponding fitted power law functions as denoted. The flux ropes under the slow solar wind condition obey the power law with a power index $\sim -1.74$, while the ones in fast solar wind obey the power law with power index $\sim -2.06$. One can see that the red curve ($V_{sw} > 400$ km/s) has larger absolute slope value than the blue curve ($V_{sw} < 400$ km/s). The intersection of the blue and red curves is located at about 80 minutes. To the left side of the intersection point, there are more flux rope events in fast solar wind, while to the right, there are more flux rope events with low solar wind speed. This indicates that the longer duration flux ropes (duration $> 100$ minutes) tend to occur under the slow solar wind speed.

Figure 8 (b) also exhibits approximately linear relations (in logarithmic scales) between flux rope scale size and occurrence counts, excluding the low ends due to the cutoff effect. This indicates a power law distribution of flux rope scale sizes, properly calculated taking into account the axial orientations. At a glance, the absolute slope of the red curve ($V_{sw} > 400$ km/s) is greater than that of the blue curve ($V_{sw} < 400$ km/s), which is consistent with Figure 8 (a). In other words, the power law slope of the red curve is softer than the blue curve. Comparing with Figure 8 (a), one can see that the flux ropes ranging from 9~361 minutes have the approximately
Figure 8. (a) The histogram of small-scale flux rope duration plotted in logarithmic scales. The time range is from 9 minutes to 361 minutes, with 5 minutes bin size. Note that the high tails to the right ends of the curves are due to duration boundary cutoff effect (see explanations in text). (b) The histogram of small-scale flux rope cross section scale sizes plotted in logarithmic scales, with 0.00025 AU bin size. The flux rope scale size is calculated from the flux rope duration taking into account the axial orientation. Again, the low points to the left and right ends of the curves are due to boundary cutoff effect (see explanations in text). For both (a) and (b), the basic statistical moments and linear regression parameters to each curve are listed, respectively.
corresponding scale-size range of 0.002~0.05 AU (excluding the lower end). When we use power law functions to fit the data, we find that the data points in blue color are fitted very well by a single power-law function with power index $\sim -1.64$, but for the red and black data points, the tails show noticeable deviations from a single fitted lines. Apparently, the deviations in the black data points are due to the deviations in the red ones. We use two power functions with different power indices to fit the red data points, and find that in the scale size range $0.001 \sim 0.01$ AU, the red data points are well fitted by a power law function with a power index $\sim -1.69$, while in the range $0.01 \sim 0.05$ AU, the red data points are well fitted by a power law function with a power index $\sim -2.27$. The breakpoint of the two power laws is at $\sim 0.006$ AU.

It is interesting to note that both Figure 8 (a) and (b) obey the power law distribution. Because the flux ropes can take any axial orientations, it is not guaranteed that a longer duration always corresponds to a larger scale size. However, in Figure 8 (a) and (b), since both of these two quantities obey the power law, they may have a simple linear relationship. The power law distributions are fairly common in nature. these analysis results are relatively new, concerning small-scale flux ropes. We will speculate on these new results in what follows from the perspective of self-organized criticality theory.

The self-organized criticality (SOC) theory was first proposed by Bak et al. [10], and then applied by Lu et al. [11, 12] to solar physics to explain the power law distributions of flare occurrence rate over flare energy, peak flux, and duration. This model is usually referred to as the avalanche model and has been widely used to explain the statistical characteristics of hard X-ray (HXR) flares [12, 13, 14, 15]. The avalanche model predicts a power law distribution for the total energy, the peak luminosity, and the duration of individual events. Li et al. [16] studied the solar flares and CMEs during the solar cycle 23. They found that the solar flare duration distribution obeys a power law with a power index $\sim -2.55$. In Figure 8 (a), we also produce a power law, implying that the occurrence of small-scale flux ropes may be explained by SOC theory. Note that the absolute values of the power indices from our fitted functions are generally smaller than those in Li et al.’s [16] result, since solar flares or CMEs and small-scale flux rope probably involve two different kinds of processes. Although they share the similar statistical characteristics in terms of the power law distributions in certain properties, complying with the SOC theory, the underlying physical mechanism responsible for generating such behavior still cannot be revealed.

Figure 9 (a) is the histogram of average proton temperature within flux ropes plotted in logarithmic scales. We can see that the peaks of blue and red curves are separated, corresponding to different modes. The peak of the red curve ($\langle V_{sw} \rangle >400$ km/s) is near $T_p \approx 0.1$ ($10^6$ K), while the peak of the blue curve ($\langle V_{sw} \rangle <400$ km/s) is near $T_p \approx 0.03$ ($10^6$ K). Therefore, the small-scale flux ropes under low speed solar wind ($\langle V_{sw} \rangle <400$ km/s) tend to have low proton temperature, while the ones under medium and high speed solar wind ($\langle V_{sw} \rangle >400$ km/s) tend to have high proton temperature. Note that the black curve and the red curve are overlapping beyond $T_p = 0.2$ ($10^6$ K), which means that the small-scale flux ropes with proton temperature greater than 0.2 ($10^6$ K) occur dominantly under medium and high speed solar wind conditions. Figure 9 (b) is the histogram of average proton $\beta_p$ (excluding the electron temperature $T_e$) within flux ropes plotted in log-log scales. When the electron temperature $T_e$ measurements are included in calculating plasma pressure, the plasma $\beta$ is further increased with the mean and median values from the distributions slightly above 1.

The low proton temperature $T_p$ as well as low $\beta_p$ is a key characteristic of magnetic clouds. However, for small-scale magnetic flux ropes, the $T_p$ varies case by case and the plasma $\beta$ can become significant. Figure 10 is the 2-D histogram of flux rope $T_p$ versus scale size. The triangle shape distribution stretching down to the right in Figure 10 indicates that the flux ropes with larger scale size (\geq 0.02 AU) usually have lower $T_p$ (\leq 0.1 $10^6$ K). Given that the large-scale magnetic flux ropes (MCs) have low $T_p$, this seems to be a smooth transition from the small-scale
Figure 9. (a) The histogram of average proton temperature within flux ropes in logarithmic scales, with 0.005 (10^6 K) bin size. (b) The histogram of average proton $\beta_p$ within flux ropes in logarithmic scales, with 0.01 bin size. For both (a) and (b), the blue curve represents the flux rope events under solar wind speed $V_{sw} < 400$ km/s, and the red curve with solar wind speed $V_{sw} \geq 400$ km/s. The black curve represents the entire data set.
magnetic flux ropes to their larger counterparts. For the smaller size small-scale flux ropes, the range of $T_p$ spreads widely. Figure 10 shows that the range of $T_p$ of the flux ropes with scale sizes less than 0.05 AU spreads from near 0 to 0.8 ($10^6$ K). When looking into the distribution under different solar wind speed conditions, we find that most of the relatively larger size small-scale flux ropes ($\geq 0.02$ AU) appear in the slow solar wind with low $T_p$. As for the relatively smaller size small-scale flux ropes ($\leq 0.01$ AU), they appear in both fast and slow solar wind.

4. Summary and Discussion

In summary, we have built a small-scale magnetic flux rope database from the Wind in-situ spacecraft measurements in the solar wind, using an automated algorithm based on the GS reconstruction method. We have found, on average, about 3,500 events per year, for the past twenty years. The event duration is between 9 and 361 minutes, and the scale sizes are on the order of $\sim 10^{-3} - 10^{-2}$ AU. Preliminary statistical analysis yields the following results.

(1) The occurrence of small-scale flux ropes has strong solar cycle dependency, which has the same trend as the occurrence of their large-scale counterparts, the magnetic clouds. (2) The small-scale magnetic flux ropes in the ecliptic plane tend to align along the Parker spiral, indicating that they belong to the general population of “flux tubes” [17]. (3) In low speed ($< 400$ km/s) solar wind, the flux ropes tend to have lower proton temperature and higher proton number density, while in high speed ($> 400$ km/s) solar wind, they tend to have higher proton temperature and lower proton number density. (4) Both the duration and scale size distributions of the small-scale magnetic flux ropes obey power laws.

We reported in [18] that the wall-to-wall time distribution obeys double power laws with the break point at 60 minutes (corresponding to the correlation length in solar wind turbulence),

**Figure 10.** The 2-D histogram of flux rope proton temperature *versus* scale size. The bin grids are 200×200. The color bar represents the small-scale flux rope event counts.
which is consistent with the waiting time distributions of magnetohydrodynamic (MHD) turbulence simulations and the related observations. We also performed case studies on the small-scale magnetic flux ropes downstream of interplanetary shocks, and found that the peaks of enhanced ions flux correspond to the merging edges of two adjacent flux ropes, indicating that the merging flux ropes are able to energize particles with appropriate energy bands [19].

Table 2. Observational evidence in support of two competing views on the origin of small-scale flux ropes.

| Solar Origin | Local Origin |
|--------------|--------------|
| Flux rope configuration similar to MCs | — |
| — | Properties similar to 2D MHD turbulence [18] |
| — | Plasma properties different from MCs |

Table 2 lists, tentatively, the observational evidence obtained from our analysis, in support of the two competing views on the origin of small-scale flux ropes. Each column contains the results that have been considered well established and exclusive for the corresponding origination mechanism. This is nowhere near to be complete and we expect the table to be updated when further analyses are to be carried out, especially when the new discoveries are expected to be returned by the upcoming Parker Solar Probe and Solar Orbiter missions. Additionally, based on the present analysis results, the event occurrence rate, the axial orientations, and the power-law distributions in duration and scale sizes seem to be arguably supporting both hypotheses, at least not in direct contradiction to either view. For example, Borovsky [17] analyzed the orientations of 65,860 flux tubes from 1998 to 2004 identified by searching for their boundaries, usually corresponding to discontinuities from the ACE spacecraft in-situ measurements. He found that the axial orientations are mostly aligned with the nominal Parker spiral direction at 1 AU. He therefore advocates the view that these flux tubes are distinct and still rooted on the Sun. They form the “spaghetti-like” structure of the solar wind, connecting back to the source [20]. On the other hand, such axial orientations do not contradict the view that these structures are generated from solar wind turbulence [21, 18] which has a prominent 2D component and the associated (perpendicular) guide field along the Parker spiral direction.

The on-going effort is to extend the range of flux rope duration and scale sizes to larger values including the automated identification of intermediate and large size flux ropes, i.e., interplanetary CMEs. The goal is to find out whether there exists a continuous distribution in the flux rope sizes that can extend into the regime of well-identified ICMEs which have an apparent solar origin. If there were two distinct populations of different origin, then there likely exists an overlapping range for flux rope duration of a few hours. This will need to be examined with additional observations such as elemental compositions and charge states of the plasma.

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