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- Axial length of cylindrical flux ropes is within 1 and 2 AU

Correspondence to:

Q. Hu,
qh0001@uah.edu

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Magnetic field line lengths inside interplanetary magnetic flux ropes

Qiang Hu¹, Jiong Qiu², and Säm Krucker³
¹Department of Space Science and CSPAR, The University of Alabama in Huntsville, Huntsville, Alabama, USA,

²Department of Physics, Montana State University, Bozeman, Montana, USA, ³Space Science Laboratory, University of California, Berkeley, California, USA

Abstract We report on the detailed and systematic study of field line twist and length distributions within magnetic flux ropes embedded in interplanetary coronal mass ejections (ICMEs). The Grad-Shafranov reconstruction method is utilized together with a constant-twist nonlinear force-free (Gold-Hoyle) flux rope model to reveal the close relation between the field line twist and length in cylindrical flux ropes, based on in situ Wind spacecraft measurements. We show that the field line twist distributions within interplanetary flux ropes are inconsistent with the Lundquist model. In particular, we utilize the unique measurements of magnetic field line lengths within selected ICME events as provided by Kahler et al. (2011a) based on energetic electron burst observations at 1 AU and the associated type III radio emissions detected by the Wind spacecraft. These direct measurements are compared with our model calculations to help assess the flux rope interpretation of the embedded magnetic structures. By using the different flux rope models, we show that the in situ direct measurements of field line lengths are consistent with a flux rope structure with spiral field lines of constant and low twist, largely different from that of the Lundquist model, especially for relatively large-scale flux ropes.

1. Introduction

Magnetic flux ropes are a type of well organized magnetic field structures embedded in space plasmas. The existence of such structures is best confirmed by in situ spacecraft observations and the associated modeling when the structure is traversed by the spacecraft [e.g., Burlaga, 1995; Lepping et al., 1990, 1997]. In addition, many studies on the origination of such structures also provide mostly indirect evidence to support such interpretation of these structures as magnetic flux ropes [e.g., Webb et al., 2000; Longcope et al., 2007; Qiu et al., 2007; Démoulin, 2008; Qiu, 2009; Vourlidas, 2014]. They are found in interplanetary coronal mass ejections (ICMEs), the interplanetary counterparts of CMEs originating from the Sun.

Some ICMEs are traditionally categorized as magnetic clouds (MCs) that possess a specific set of signatures based on in situ spacecraft measurements of both magnetic field and bulk plasma properties. A more modern view of all ICMEs containing flux ropes is also emerging [Gopalswamy et al., 2013a, 2013b; Xie et al., 2013; Hu et al., 2014]. This seems reasonable especially considering that most origination mechanisms for CMEs involve magnetic flux ropes no matter whether they are considered to be preexisting prior to eruption or generated during the process. Moreover, the subsequent argument is that such structures originating from the Sun and propagating into the interplanetary space may not be properly detected by the in situ spacecraft. Each spacecraft only provides a very localized, single-point measurements of the structure traversed. Therefore, depending on the relative spacecraft path across the structure, the variability and limitation in the in situ signatures of magnetic flux ropes are significant, resulting in the incidences when the flux rope structure is present, but the in situ signatures are lacking [e.g., Jian et al., 2006]. However, if one adheres to the traditional definitions of MCs, which satisfies these criteria: (1) relatively strong magnetic field magnitude, (2) smooth rotation in magnetic field direction, and (3) relatively low proton β , the ratio between the plasma pressure and the magnetic pressure, one can likely derive a magnetic flux rope structure from the in situ data.

Effort has been put on in situ modeling of magnetic flux rope structures in order to extend the current capability thus to better reveal and characterize these structures in a quantitative manner. Various flux rope models utilize in situ spacecraft measurements of magnetic field and plasma parameters along the spacecraft path and are based on either a cylindrical or toroidal geometry and magnetohydrostatic theory. They range from

the well-known one-dimensional (1-D) linear force-free cylindrical model [Lundquist, 1950] to the corresponding toroidal model [Marubashi and Lepping, 2007; Romashets and Vandas, 2003] and to the fully two and a half-dimensional (2.5-D) Grad-Shafranov (GS) reconstruction model [Hu and Sonnerup, 2002]. One particular model that has not been widely recognized is the so-called Gold-Hoyle (GH) model that was originally developed by Gold and Hoyle [1960] and was only applied in a limited number of studies [Farrugia et al., 1999; Dasso et al., 2006; Hu et al., 2014]. The distinct features of this model, remaining 1-D, are that the field line twist is constant across the radius and the corresponding equilibrium state is nonlinear force free.

In our latest study of Hu et al. [2014], we showed that the flux rope structures as derived from the generally nonforce-free GS method are more consistent with the GH model than with the Lundquist model, especially in that the field line twist distributions within ICME flux ropes remain fairly constant for large-size, low-twist flux ropes. In the present study, we intend to elaborate more on this finding and present additional consistency check by utilizing the unique measurements of field line lengths inside MCs.

A unique set of in situ spacecraft observations besides the magnetic field and plasma parameters in interplanetary space is the energetic electron burst onset. They appear as sudden increase in electron flux of energies up to a few hundred keV [Krucker et al., 1999; Kahler and Ragot, 2006; Wang et al., 2011] as the electron beams propagate away from the source on the Sun to the location of the spacecraft along individual field lines connecting both ends. Under certain assumptions such as scatter-free propagation and coincidental release at the time of associated Type III radio burst, the path lengths of magnetic field lines can be derived especially inside MCs. There are two ways to obtain the length estimate based on electron burst onset observations: one is to directly calculate the length traveled by the product of the speed of electrons (of known energy) and the travel time (taken as the difference between the onset time at 1 AU and the release time as given by the corresponding Type III onset time); the other is to linearly fit the onset times of electrons of different energies versus their inverse speeds (so-called inverse-beta method) [Kahler and Ragot, 2006] and the slope yields the path length. The first study of comparing field line path lengths inside an MC utilizing the electron burst measurements was carried out by Larson et al. [1997]. They combined multiple in situ measurements from the Wind spacecraft during an MC interval to derive field line lengths as measured by the energetic electrons travel time multiplied by the speed which were then compared with the lengths estimated based on certain flux rope models of MCs. They found for one particular MC event that the path lengths at several locations inside the MC ranging from about 1.2 AU near the center to about 3 AU near the boundary, consistent with flux rope model estimates. Such type of study, rare but important, provided unique and direct supporting evidence for the interpretation of MC structures as magnetic flux ropes. Not until recently did Kahler et al. [2011a, 2011b] extended that unique study by applying the same analysis to a set of Wind MC events and additional electron burst onsets from the ACE spacecraft. They derived the field line lengths based on in situ electron burst onset and associated Type III radio burst following the approach of Larson et al. [1997] and compared with two flux rope models: one being the Lundquist model and the other flux conservation model given in Larson et al. [1997]. Their comparison indicated poor correlation between the measured and the model field line lengths with the latter being exceedingly larger, ≥ 4 AU with maxima reaching about 10 AU, especially for the Lundquist model. Their results cast doubt on the model fit to MC flux ropes by the Lundquist model which intrinsically possesses the property of increasing field line twist thus length from the center toward the boundary of the flux rope at a rapid rate, approaching infinity at the boundary defined as a circular cylindrical surface of vanishing axial magnetic field. In addition, our own analysis [Hu et al., 2014] also showed that the field line twist estimates from the GS method are not consistent with the Lundquist model but more aligned with the GH model of constant twist. In the present study, we will focus our analysis on the field line length estimates based on the GS reconstruction results, supplemented by the corresponding estimates based on the GH model as well. It is worth noting that we focus on large-scale coherent magnetic structures of MCs as related to in situ energetic electron burst measurements. Relevant studies utilizing the same electron measurements from the perspective of solar wind turbulence effect were also attempted [Tan et al., 2014; Ragot, 2006].

Estimates of magnetic field line lengths, by taking advantage of the unique and comprehensive in situ spacecraft measurements, not only provide constraint and validation of flux rope models but also provide possible measurement of one key parameter, the axial length of a cylindrical flux rope. This parameter determines the quantitative measurements of the poloidal magnetic flux and the relative magnetic helicity contents [Qiu et al., 2007; Webb et al., 2010]. Since all existing flux rope models based on in situ measurements are 2-D at best in geometry, significant uncertainty exists for the axial dimension. An effective axial length, L_{eff} , has to be used

Table 1. GS Reconstruction Results of Selected Wind MC Events From *Kahler et al.* [2011a]

MC Event # : GS Interval MM/DD/YYYY hh:mm:ss	$\langle \tau \rangle \pm \Delta \tau$ (Turns/AU)	B_{z0} (nT)	$\Phi_{t,max}$ (10^{21} Mx)	$\Phi_{p,max}$ (10^{21} Mx)	$K_{r,max}$ (10^{42} Mx ²)	$\bar{\tau}_H$	$\bar{\tau}_F$	τ_0
1: 10/18/1995 18:59:30 to (+1) 19:16:30	1.57 ± 0.26	20	1.2	2.8	2.9	1.9	2.2	1.6
2: 9/18/1997 03:55:30 to (+2) 16:45:30	4.55 ± 1.71	12	0.36	2.1	0.64	5.0	5.9	3.6
3: 11/6/2000 23:08:30 to (+1) 18:46:30	2.16 ± 0.31	25	0.90	2.0	1.9	2.3	2.2	2.2
4: 7/10/2001 18:31:30 to (+2) 07:47:30	6.66 ± 2.13	7.8	0.039	0.35	0.012	8.3	9.0	6.0
5: 10/1/2002 00:49:30 to 19:31:30	4.20 ± 0.54	26	0.22	0.99	0.23	4.7	4.4	5.0
6: 7/24/2004 11:56:30 to (+1) 07:01:30	2.11 ± 0.83	22	1.6	2.9	3.5	1.4	1.8	1.6
7: 8/30/2004 01:4:30 to 21:42:30	1.24 ± 0.41	12	0.38	0.55	0.24	1.7	1.4	1.2

in order to determine the quantities of poloidal magnetic flux and relative magnetic helicity within a cylinder of finite length L_{eff} that are equivalent to the corresponding content contained within the actual flux rope structure. Based on geometrical considerations, one would expect that the derived field line lengths based on cylindrical models might yield greater values than those of alternative (preferably three-dimensional) flux rope models with tapered legs. In our effort to connect the ICME flux ropes with their solar source region properties, particularly by comparing the magnetic flux contents at both ends, a somewhat arbitrary range of $L_{\text{eff}} \in [0.5, 2.0]$ AU was used [Qiu *et al.*, 2007; Hu *et al.*, 2014]. We strive to gain more insight and to obtain a refined range of effective axial length from the current analysis of magnetic field line length estimates inside MCs.

The article is organized as follows. We present the detailed description of magnetic field line length estimates inside the MCs in the next section, for the Wind spacecraft MC events given by *Kahler et al.* [2011a] for which the length measurements based on electron burst onset were published. We will reconstruct the structures of these MC events and derive the relevant characteristic parameters by using the GS method and the GH model will be primarily utilized to provide extrapolated estimates on field line lengths. The approach of obtaining various length estimates is described in section 2. These estimates are compared one by one with the corresponding electron burst measurements from the Wind spacecraft. Three cases are selected to be presented in detail in section 3. A summary of our results and comparison for all events is given in section 4. We finally conclude and discuss the implications of our results in the last section.

2. Magnetic Field Line Length Estimates

We reexamine the MC events listed in Table 1 of *Kahler et al.* [2011a], total of eight Wind spacecraft MC events with given electron burst measurements. We are able to successfully reconstruct seven MC events by the GS method, except for the one on 2 May 1998 for which a valid solution was not obtained as judged by a set of merit criteria [Hu and Sonnerup, 2002; Hu *et al.*, 2004]. Therefore, this event is excluded from our analysis. In addition, only the measurements of electron burst onsets occurring in the identified GS intervals (see Table 1) are utilized in our analysis. Others falling out of the GS intervals are excluded as well.

2.1. GS Reconstruction Results

The GS reconstruction is to solve the plane Grad-Shafranov (GS) equation of the magnetic flux function $A(x, y)$ (equivalent to the z component of the magnetic vector potential; in direct analogy to a stream function in two-dimensional incompressible flow) on the cross section of a cylindrical flux rope. Therefore, the transverse magnetic field (B_x, B_y) is fully determined by the flux function A and the magnetic field lines are lying on cylindrical isosurfaces of A , called A shells. The nonvanishing axial magnetic field component B_z becomes a function of A only, yielding a cylindrical but nonaxisymmetric flux rope configuration. Detailed descriptions of the method and the latest updates as applied to flux rope reconstructions were reported in Hu and Sonnerup [2002] and Hu *et al.* [2013, 2014].

Various physical quantities characterizing such a flux rope structure can be derived including the axial magnetic field B_z , the axial electric current density and current, the toroidal (axial) and poloidal magnetic flux $\Phi_{t,p}$, the relative magnetic helicity K_r , and the magnetic field line twist. They are all functions of A alone and vary across distinct A shells. Figure 1 shows the summary plots of these quantities as they vary along the A shells

Figure 1. Summary plot of various physical quantities (unsigned) versus the shifted flux function for the Wind MC events: (counterclockwise from the top left panel) the poloidal (red pluses) and toroidal magnetic flux $\Phi_{p,t}$, the relative magnetic helicity, the field line twist estimates τ_H (red dots) and τ_F (blue dots) [Hu et al., 2014], the axial current, the axial current density, and the axial magnetic field.

for all the Wind MC events we examined. They generally exhibit a similar pattern to the other flux rope events as we first reported in Hu et al. [2014] in this congregated manner. The magnetic fluxes increase monotonically from the center toward the outer boundary while the poloidal flux is generally larger than the toroidal flux. The relative magnetic helicity also increases monotonically and smoothly. So does the electric current since they are all accumulative integral quantities. The axial field, on the other hand, shows a monotonically declining profile from the center outward, typical of a flux rope structure. The maximum value (B_{z0}) ranges between a few and a few tens of nanotesla. The most irregular variation exists in the current density which represents the first-order derivative of a transverse pressure with respect to A . The field line twist estimates displayed here, i.e., $\tau_H = |K_r|/\Phi_t^2$ and $\tau_F = \Phi_p/\Phi_t$, are only for qualitative visual inspection since they are less reliable as we discussed in Hu et al. [2014]. Several scalar quantities representing the total magnetic flux and magnetic helicity contents within certain boundary $A = A_b$ are given in Table 1 together with the approximate average twist estimates $\bar{\tau}_H$, $\bar{\tau}_F$. The other estimates for average twist ($\langle\tau\rangle$ and τ_0) are based on more quantitatively reliable calculations to be described below.

In our latest study of Hu et al. [2014], we performed systematic study of field line twist distribution within ICME flux ropes based on the GS reconstruction method. The field line twist, $\tau(A)$, also as a single-variable function of A , is obtained by the graphic method described in the appendix of Hu et al. [2014]. That is for each individual field line lying on a distinct surface of one particular A value, usually an open-ended cylindrical surface of closed side, denote the axial length in z direction along which the field line completes one full turn, L_z in AU (see Figure 5 for an illustration of the determination of L_z), then the field line twist is simply

$$\tau(A) = \frac{1}{L_z(A)}, \quad (1)$$

in unit of turns/AU. Separately, the actual field line length L_s is easily obtained by the line integral tracing along each individual spiral field line, i.e., by summing up the distances between the pair of end points of each line

Figure 2. Summary plot of field line (top) twist τ and (bottom) length L_s distributions (both for $L_{\text{eff}} = 1$ AU) versus the shifted flux function for the Wind MC events. Different colors represent different MC events as indicated by the legend in the top panel. The square symbol and associated error bar at the end of each curve where $|A'| \equiv A_c$ indicate the mean and the standard deviation of each curve. The dashed horizontal line denotes a nominal twist value of 1.5 turns/AU.

no longer complete one full turn within the computational box. For example, this refers to the cuboid outlined in Figure 5 for MC event 1. Field lines winding along the axis, completing multiple turns never go out of the box and are confined within certain cylindrical surface. The outermost one is where the deep blue line is lying. If one takes a closer look from a different viewpoint, then in Figure 4c, contours represent the projected flux rope field lines when viewed along the axial (z) direction. Therefore, spiral field lines completing multiple turns inside the rectangular (x, y) domain appear as *closed* contours (or loops) enclosed by the thick white dashed contour line of $|A'| = A_c$ inside of which the field line twist τ and length L_s estimates can be derived as discussed above based on the GS reconstruction result by the graphic method following *Hu et al. [2014]*. For regions outside of the dashed white loop where $|A'| > A_c$, the field lines reach out of the box, and no corresponding field line twist τ and length L_s estimates by the graphic method of *Hu et al. [2014]* based on the GS reconstruction result are available.

Figure 3. The mean and standard deviation of field line twist $\tau(A)$ of 25 magnetic flux rope events. Each data point with associated error bar is plotted at the corresponding value of A_c . The dashed horizontal line denotes a nominal twist value of 1.5 turns/AU.

segment. The results for the seven MC events by this approach are shown in Figure 2. In Figure 2 (top), the mean value of each curve (each MC event) $\langle \tau(A) \rangle$ and the corresponding standard deviation $\Delta \tau$ as given in Table 1 are shown as the square symbol and the associated error bar, respectively. They generally indicate that for most MC events, the twist remains fairly constant, excluding the region close to the center. The shifted flux function defined by subtracting the flux function value A_0 at the flux rope center from the GS reconstruction result

$$A' = A - A_0 \quad (2)$$

is therefore always 0 at the flux rope center. Correspondingly, the length distribution shows a variable rate of increase with increasing $|A'|$. Note that each curve ends at certain value of A or $|A'| = A_c$ corresponding to the outermost closed loops on the flux rope cross section, represented by the equi-value contours of A . Beyond this boundary, the field lines can

To circumvent this limitation and after observing that the twist distributions exhibit a trend of remaining fairly constant throughout the outer region of a flux rope, as first reported in *Hu et al. [2014]* and further demonstrated here, we employ a theoretical, constant-twist flux rope model to assist in the analysis. To reinforce and justify this additional approach, we put the results for all the MC events we have examined in *Hu et al. [2014]* and the present study together in Figure 3, showing the average twist and associated standard deviations as they vary with A_c . The mean and median values of all points are 4.0 and 3.6 turns/AU, respectively. If the point of the largest

standard deviation is excluded, they become 3.8 and 3.3 turns/AU, respectively. For half of the MC events of average twist less than the median value, the standard deviations are small, indicating a flat profile of $\tau(A)$. Another general trend is that the larger size the flux rope is as indicated by larger value of A_c , the smaller and less variable the twist becomes. Both Figures 2 and 3 also indicate that the majority of twist is larger than or equal to a nominal value 1.5 turns/AU (dashed horizontal line) which falls within the range of critical values corresponding to kink instability (about 1 to 3 turns) according to a number of theoretical and numerical studies [e.g., Hood and Priest, 1979; Török et al., 2004; Fan and Gibson, 2007].

2.2. Constant-Twist Gold-Hoyle (GH) Flux Rope Model

The constant-twist or so-called Gold-Hoyle (GH) flux rope model was originally developed by Gold and Hoyle [1960]. It possesses rather simple and elegant forms for the magnetic field components in axisymmetric cylindrical coordinate (r, ϕ, z) [Farrugia and other, 2013]

$$B_z = \frac{B_0}{1 + T_0^2 r^2} \quad (3)$$

$$B_\phi = \frac{B_0 T_0 r}{1 + T_0^2 r^2}. \quad (4)$$

Here the field line twist by definition, $\frac{1}{r} \frac{B_\phi}{B_z} = T_0 = \pm 2\pi\tau_0$, is strictly constant and is in the unit of radians/AU, which is also a signed quantity indicating the chirality of the flux rope. The parameter B_0 corresponds to the axial magnetic field strength at the center of the flux rope ($r = 0$) which is set to be B_{z0} from the GS results as given in Table 1. They usually correspond to the maximum axial field during the interval (see Figure 1). The center of the flux rope is determined from the GS result as well and since we are only interested in deriving an approximation of field line length as function of A' , we don't need to explicitly calculate r . Thus, no explicit fitting to the magnetic field data as usually done for an analytic flux rope model is performed in the present study. The length can be expressed explicitly as a function of A' thus can be directly estimated for each A' value obtained from the GS reconstruction. The other parameter, τ_0 , also given in Table 1 for each MC event, is obtained by taking the mean value of τ for the outer loops where the twist variation is minimal, excluding the central core of each flux rope as we discussed earlier in section 2.1. Largely based on the GS reconstruction results, the GH model provides an alternative and additional means of estimating, especially extrapolating field line lengths some of which are not available through the direct GS model estimates.

From the GH model, because of the simple forms of the magnetic field components and the axisymmetric geometry, the shifted flux function can be derived analytically, $A' = -\frac{B_0}{2T_0} \ln(1 + T_0^2 r^2)$. This shifted flux function always has value zero at flux rope center ($r = 0$) and the twist (T_0) carries a sign, positive for right-handed chirality and negative otherwise. Subsequently, the field line length per AU (i.e., for a section of the cylinder with an axial length $L_{\text{eff}} = 1$ AU) can be written as a function of A' ($T_0 \equiv \pm 2\pi\tau_0$)

$$L_{\text{GH}} = e^{-T_0 A' / B_0}, \quad (5)$$

which also equals $\sqrt{1 + T_0^2 r^2}$ and tends to increase linearly with radial distance r from the center of the flux rope when $|T_0| r \gg 1$. It is also worth noting that the GH model corresponds to a nonlinear force-free configuration with the nonconstant force-free parameter $\alpha = \frac{2T_0}{1 + T_0^2 r^2}$, varying with radial distance, i.e., along A shells as well, as originally derived by Gold and Hoyle [1960].

Table 2 summarizes the analysis results of measured and derived magnetic field line lengths inside the selected MCs examined by Kahler et al. [2011a]. The entries of date (first column), Type III radio emission times (second column), measured field line path lengths L_e and D (third and fourth columns) are taken from Table 1 of Kahler et al. [2011a]. The path lengths D were obtained via the inverse-beta approach and were deemed inferior to the measurements L_e by the direct travel time dispersion analysis. There are a few unacceptable values of $D < 1$ AU. The uncertainty in L_e presented here is owing to the uncertainty in the exact timing of the arrival of the energetic electrons. The last two columns list the corresponding estimates of field line lengths based on the direct GS reconstruction output, L_s , and the GH model approximation, L_{GH} , respectively. The latter is obtained by applying the equation (5) for the corresponding A' and additional parameters supplied by the GS reconstruction results, i.e., the parameters τ_0 and $B_0 = B_{0z}$ from Table 1. The corresponding electron

Table 2. Measured and Derived Magnetic Field Line Lengths Inside Magnetic Flux Ropes^a

Date	Type III (UT)	L_e (AU)	D (AU)	L_s (AU)	L_{GH} (AU)
18 Oct 1995	19:56 (22:20:35)	3.3–4.0	3.30	...	2.08 ± 0.60
19 Oct 1995	05:18 (05:53:17)	1.5–1.7	1.06	1.51–1.51	1.50 ± 0.003
19 Oct 1995	08:46 (09:30:58)	1.2–1.6	1.33	1.40–1.47	1.40 ± 0.002
19 Oct 1995	10:28 (11:15:20)	1.1–2.3	1.65	1.48–1.51	1.48 ± 0.02
19 Oct 1995	16:57 (17:25:50)	1.7–2.2	1.45	...	2.16 ± 0.06
18 Sep 1997	16:06 (16:52:37)	2.6–3.2	1.69	...	2.63 ± 0.05
18 Sep 1997	17:09 (17:56:00)	2.7–3.1	2.05	...	2.38 ± 0.04
18 Sep 1997	19:51 (20:19:57)	1.8–2.1	1.33	1.89–1.94	1.90 ± 0.02
20 Sep 1997	03:16 (03:53:15)	2.1–2.8	1.33	...	3.85 ± 0.12
07 Nov 2000	00:08 (00:56:14)	1.1–1.6	1.08	...	2.13 ± 0.54
07 Nov 2000	15:40 (16:33:22)	1.2–2.1	0.98	1.45–1.55	1.41 ± 0.04
10 Jul 2001	22:53 (+1 00:44:47)	1.5–2.5	1.41	...	1.85 ± 0.26
12 Jul 2001	01:11 (02:28:27)	2.7–3.6	2.05	...	1.53 ± 0.02
01 Oct 2002	09:12 (11:55:21)	1.7–2.7	1.57	1.11–1.35	1.22 ± 0.04
24 Jul 2004	18:43 (19:16:51)	1.3–1.5	1.14	1.07–1.09	1.15 ± 0.01
30 Aug 2004	03:09 (03:44:47)	1.9–3.0	0.54	...	3.49 ± 0.10
30 Aug 2004	16:13 (17:47:05)	3.0–3.4	3.01	3.13–3.26	3.10 ± 0.13
30 Aug 2004	18:09 (18:57:40)	2.7–3.4	3.31	3.29–3.41	3.17 ± 0.12

^aThe date, Type III times, L_e , and D are taken from Table 1 in Kahler *et al.* [2011a].

burst onset times at 1 AU are also given in the second column inside the parentheses. Note that only the onset dates and times within the GS reconstruction intervals as indicated in Table 1 are listed for which our analysis can yield at least one estimate of L_s and L_{GH} . The others are considered outside of MC interval; hence, no analysis results are available. For the times listed which correspond to locations inside the MC but outside the loop boundary $|A'| = A_c$, the estimates of L_s are not available while the estimates based on the GH model approximation can still be obtained. We defer detailed comparisons among these length estimates and discussion of their implications to section 4.

3. Case Studies

In what follows three MC events are chosen to be presented as detailed case studies. The MC event 1 and 2 are selected because they possess the maximum number of electron burst onsets inside the MCs among all the events. The MC event 7 also contains a modest number of electron onset times and represents an extreme case of relatively and persistently long measured path lengths L_e throughout the MC interval. Thus, these MC events facilitate a direct and broad comparison between measured L_e and estimated path lengths based on the GS reconstruction results and the GH model approximations.

3.1. MC Event 1: 18 October 1995

This event was also presented in Larson *et al.* [1997] and Kahler *et al.* [2011a], which possesses the maximum number of electron burst occurrences throughout the MC interval. The in situ signatures of an MC structure are also strong, as seen from Figure 4a. The magnetic field magnitude is elevated and remains around 20 nT, the rotation in the GSE-Z component is the largest and clearly seen, and the plasma β is fairly low ~ 0.1 , even after taking into account the electron temperature contribution ($T_e/T_p \sim 5$). This is a relatively strong and long-duration MC event with a constant speed profile and dominant magnetic field, indicating a typical flux rope type magnetic structure embedded. This MC event was also examined by Hu and Sonnerup [2002] as a typical MC event to showcase the first application of the GS reconstruction method to the large-scale quasi-static MC flux rope structures observed in situ at 1 AU. The general presentation of the GS results is shown in Figures 4b and 4c. The data and a functional fitting to the transverse pressure $P_t = p + B_z^2/2\mu_0$, the sum of the plasma pressure and the axial magnetic pressure, versus the flux function A as obtained along the spacecraft path at $y = 0$ are given in Figure 4b, together with a fitting residual R_f indicating the goodness of fit of $P_t(A)$ [Hu *et al.*, 2004]. Figure 4c shows the typical presentation of the cross-sectional map of the flux rope

Figure 4. The GS reconstruction result for MC event 1 in Table 1. (a) Time series of Wind spacecraft measurements: (from top to bottom panels) the in situ magnetic field magnitude (black) and GSE-X (red), Y (green), and Z (blue) components; the plasma bulk flow speed, the proton density (left axis; blue) and proton (black), and electron (green; if available) temperature (right axis); the plasma β (black) and the electron over proton temperature ratio (red; if available); and the plasma and axial magnetic field (red) pressure. The vertical lines mark the GS reconstruction interval as given beneath the last panel. (b) The measurements of $P_t(x, 0)$ versus $A(x, 0)$ and the fitted $P_t(A)$ curve (thick black line). The flux rope boundary is marked at $A = A_b$ and a fitting residue R_f is denoted. The vertical dashed line marks $|A'| = A_c$. (c) The cross-sectional map of the solution $A(x, y)$ (black contour lines) and the axial field $B_z(A)$ (filled contours in color). The yellow arrows are the measured transverse magnetic field along the spacecraft path ($y = 0$). The white contour lines highlight the boundary $A = A_b$ (outer solid) and $|A'| = A_c$ (inner dashed) while the white dot denotes the center where the axial field is the maximum and $A \equiv A_0$ ($A' \equiv 0$). The crosses along $y = 0$ denote the locations where the electron burst onsets were observed. The ones inside the white dashed loop are in black.

Figure 5. Three-dimensional view of the flux rope structure toward Sun for MC event 1 with selected field lines. The view angle is such that north is upward and the ecliptic plane is horizontal. Black lines are the field lines rooted at the foot points where the electron onsets were observed. Circles mark the locations where the field lines complete one full turn around the z axis. The orientation of z axis is given on top in GSE coordinate. The color curves on the plane at $z = 0$ where all the field lines are rooted are the contours of $A(x, y)$ within the boundary $A = A_b$. An illustrative example of the determination of $L_z(A)$ (thus in turn $\tau(A)$ by equation (1)) for the magenta field line is also shown.

Figure 6. Field line (top) twist and (bottom) length distributions along the A shells for MC event 1. The twist values obtained by the graphic method are shown in thick black curve. The results from the other three approximate methods are given by the thin blue, green, and red curves, respectively, as indicated by the legend, which end at $A = A_b$. The horizontal dashed line denotes τ_0 as given in Figure 6(top) in turns/AU. In Figure 6(bottom), the magenta lines represent the length estimate L_s , the dotted lines L_{GH} , and the black thick vertical lines L_e with uncertainties. The crosses mark the locations along the A shells where the measurements of L_e were obtained, and the corresponding estimates of L_{GH} . The set of thinner magenta and dotted curves originating from 1 at $A' = 0$ corresponds to the default value $L_{eff} = 1$ AU. The other set corresponds to $L_{eff} = 1.3$ AU in this case.

structure as a contour plot of $A(x, y)$ with the axial component B_z superposed in color. It can also be viewed as a projection of the winding magnetic field lines lying on different isosurfaces of A (A shells) onto the (x, y) plane. Figure 5 shows a rendering of the 3-D view with a few selected field lines including the ones rooted on the locations of electron burst onset observations inside the surface $|A'| = A_c$. Therefore, the projected field lines that complete multiple turns around the z axis will appear as the closed loops on the cross-sectional map of Figure 4c enclosed by the thick dashed loop highlighted in white where $|A'| \equiv A_c$. There are five incidences of electron burst onsets along $y = 0$ as marked by cross signs with three occurring inside (in black) and the other two outside (in white) of the white dashed loop.

Figure 6 shows the distributions of field line twist estimates (top panel) and the corresponding lengths (bottom panel) versus the shifted flux function $A - A_0$, i.e., A' , including the available measurements of L_e with uncertainties, scattered at different A shells within the flux rope. Note that the shifted flux function is signed in this plot with the flux rope center always located at $A = A_0$, i.e., $A' \equiv 0$. Therefore, the sign of the shifted flux function simply indicates the chirality of the flux rope: negative (positive) means right (left) handed. The black thick curve and the three colored thin curves (see the legend in the top right-hand corner) represent the field line twist estimates based on the graphic method and the other three approximate methods utilizing the magnetic flux and relative magnetic helicity content estimates, as described in details by Hu et al. [2014]. The graphic method yields the most accurate estimate but is limited to the inner region of loops satisfying $|A'| < A_c$. The results for the other three methods are only for reference purposes to visually inspect whether they follow the graphic method and the general trend of the twist distribution beyond the boundary where the graphic method ceases to provide an estimate [Hu et al., 2014]. As discussed earlier in Hu et al. [2014], the estimate by $-d\Phi_p/d\Phi_t$ (green

Figure 7. The GS reconstruction result for MC event 2 in Table 1. Format is the same as Figure 4.

curve) would exhibit erroneous behavior of rapid rise toward the boundary of the flux rope (large A' values), as seen here, due to the rapid decrease in the estimate of $d\Phi_r$, but not in $d\Phi_p$. Overall, the twist distribution remains fairly low and constant with larger variations near the flux rope center, yielding $\tau_0 = 1.6$ turns/AU for this case as indicated by the horizontal dashed line.

The corresponding length estimates (magenta curves and dotted curves) and measurement of L_e (thick black horizontal and vertical lines) are overplotted versus the shifted flux function in the bottom panel. There are two sets of estimates in this case. The thinner ones rise from 1 AU at $A = A_0$ and increase toward the outer loops and they correspond to the estimates by using the default value $L_{\text{eff}} = 1$ AU. They do not intersect the measured L_e at the locations along the A shells marked by the cross signs. For this particular case, there were five incidences of electron burst onset occurring within the GS interval with one occurring very close to the

Figure 8. Field line (top) twist and (bottom) length distributions along the A shells for MC event 2. Format is the same as Figure 6. Legend in Figure 8(top) is omitted. Here the effective axial length takes the default value $L_{\text{eff}} = 1$ AU only.

flux rope center. There is a short vertical thick black line and a cross at $A - A_0 \approx 0$, indicating the range and average of L_e measured at that location. This measurement at this location enables us to determine L_{eff} for this flux rope event since the field line at the location near the center of the flux rope is mostly straight. Therefore, a direct measurement of L_{eff} is obtained in this case by taking the midpoint of the range of L_e measured, $L_{\text{eff}} \approx 1.3$ AU. Then the actual field line length estimates of both L_s and L_{GH} are raised from their default values by simply multiplying the L_{eff} determined, resulting in the set of thick magenta and dotted curves. These corrected values will be used in the summary comparison with measurements. They now intercept a majority of vertical thick black lines except the one of the largest L_e at a location near the boundary. This adjustment by an $L_{\text{eff}} > 1$ AU only applies when such a direct measurement of L_e is available near the center of a flux rope. We choose the criterion for such locations along the A shells satisfying $|A - A_0| < 10$ T m.

3.2. MC Event 2: 18 September 1997

This MC event has a very long duration, about 2.5 days as seen in Figure 7a. The speed is fairly low, around 300–350 km/s during the GS interval. There are significant variations in the proton temperature T_p (the black trace in the third panel of Figure 7a) which does not show clear decrease inside the GS interval compared with the T_p values immediately outside, indicating the possible presence of significant plasma pressure. This results in a fairly modest plasma $\beta \sim 0.5$ within the GS interval, which is still depressed due to the relatively strong magnetic field magnitude. The plasma pressure becomes comparable to the axial magnetic pressure near the middle of the interval as shown in the fifth panel of Figure 7a, albeit there is less variation (smaller gradient) in the plasma pressure. The corresponding $P_t(A)$ plot and the corresponding cross-sectional map are given in Figures 7b and 7c, respectively. Again this is a right-handed flux rope with a cross-sectional size of about 0.25 AU across. The inner loops enclosed by the thick white dashed loop in Figure 7c occupies an area of a diameter about 0.1 AU. In this case, all the electron onset locations are outside of the closed loops bounded by the thick white dashed loop where $|A'| \equiv A_c$ except for one point barely touching this boundary. Therefore, most of the length estimates have to be obtained by the GH model-based extrapolation.

The corresponding results including the field line twist distribution and the actual measurements L_e are shown in Figure 8, in the same format as Figure 6. The twist distribution remains fairly constant, especially in regions farther away from the flux rope center, yielding $\tau_0 \approx 3.6$ turns/AU. The field line length estimates L_s rises from 1 AU at $A' = 0$ and increases to about 1.9 AU at $|A'| = A_c$, matching the measured L_e at that location. Beyond that point, no estimates of L_s are available, but the estimates by L_{GH} are able to continue as illustrated by the dotted curve as $|A'|$ increases toward the outer boundary of the flux rope. These estimates seem to match the additional measurements of L_e except for the last point (leftmost vertical bar) which is significantly lower than the estimated value $L_{\text{GH}} \approx 3.8$ AU, denoted by the cross sign at top. In this case, since there is no electron burst onset measurements close to the flux rope center, the axial length of the flux rope is unknown and the default value $L_{\text{eff}} = 1$ AU is used to obtain the corresponding field line length estimates from the flux rope models. The agreement with the measurements L_e is reasonable. For most MC events examined in this study, we have to adopt this approach assuming $L_{\text{eff}} = 1$ AU. MC event 1 presented earlier and MC event 7, to be presented in the following subsection, are the only two exceptions.

Figure 9. The GS reconstruction result for MC event 7 in Table 1. Format is the same as Figure 4.

3.3. MC Event 7: 30 August 2004

Event 7 is also a relatively large-scale MC event with a duration a little less than 24 h, resulting in a relatively large-scale MC flux rope structure. The in situ data given in Figure 9a indicate a typical MC event: clear enhancement of the magnetic field magnitude and rotation in direction, low proton temperature and low proton β within the GS interval. Although the magnetic pressure still dominates, because the ratio T_e/T_p reaches 10 in the GS interval, the plasma β is modest and in the range 0.1–1.0, owing largely to the contribution by the electron temperature to the total plasma pressure. The GS reconstruction results including the contributions

Figure 10. Three-dimensional view of the flux rope structure toward Sun for MC event 7. Black lines are the field lines rooted at the foot points where the electron onsets were observed. Format is the same as Figure 5.

Figure 11. Field line (top) twist and (bottom) length distributions along the A shells for MC event 7. Format is the same as Figure 6. Legend in Figure 11(top) is omitted. Here the set of thicker magenta and dotted curves corresponds to $L_{\text{eff}} \approx 3.0$ AU.

of both T_e and T_p are shown in Figures 9b and 9c, in the same format as before. The $P_t(A)$ curve shows a slight bend over near the end to the right, which corresponds to the center of the flux rope as represented by the maximum A value. This behavior indicates a slight decrease in axial current density thus a weaker transverse field in the center. The corresponding cross-sectional map in Figures 9c reflects this behavior with the transverse field nearly vanishing near the center, whereas the axial field B_z maintains a strong and flat distribution inside a large area enclosed by the inner white dashed loop. Such a configuration indicates that the field lines near the center are nearly straight with low twist. The 3-D view of field lines is shown in Figure 10 where the inner field line, for example, the one of magenta color, is winding along the axis to large distance, ~ 1 AU, before completing one full turn. The two black lines rooted on two electron onset locations (two crosses inside the inner white dashed loop on Figure 9c) near the center show similar behavior to the magenta line. Both the field line length estimates L_s and L_{GH} for these two locations are available while only the estimate L_{GH} for the other location outside of the loop $|A'| = A_c$ is available. Figure 11 shows the twist distribution and various length estimates along the A shells, similar to Figure 6. Here the adjusted length estimates are also given for an $L_{\text{eff}} \approx 3.0$ AU, based on one measurement of L_e close to the flux rope center where $|A'| < 10$ T m. The average twist is fairly low, yielding $\tau_0 \approx 1.2$ turns/AU for the outer loops, the lowest among all the MC events. The one electron burst onset measurement near the center yields a unusually large axial length of the flux rope, but the accordingly adjusted length estimates (thick magenta and dotted curves) show better agreement with measurements, matching two out of three values of L_e . The one mismatch at the far left is almost outside of the flux rope boundary defined by $A = A_b$ beyond which the flux rope interpretation based on the GS solution is less

Figure 12. Summary and comparison of field line length estimates with L_e : (a) the ensemble of measurements L_e versus $|A'|$ for all MC events; the dashed and dotted lines mark the variations of field line lengths of GH model with certain constant twist, and the vertical dashed line denotes $|A'| = 10 \text{ T·m}$ (see text for details); (b) the one-to-one plot of L_s (in magenta) versus L_e ; and (c) the one-to-one plot of both L_s and L_{GH} versus L_e where the latter (L_{GH}) is marked by black crosses and vertical lines. In Figures 12b and 12c, the dashed line denotes the one-to-one diagonal line while the dotted lines mark a 10% uncertainty bound.

reliable. In other words, the location of this point could be outside of the MC flux rope and shall be excluded from the field line length comparison.

4. Summary and Interpretation of Results

In this section, we summarize our analysis results presented in Table 2 and make direct comparison between the measured path lengths L_e (and D) and the derived ones from the direct GS model output L_s and the constant-twist GH model estimates L_{GH} . For these handful of MC events, the path lengths obtained from the energetic electron burst onset measurements are in the range of 1 to 4 AU. A few exceptions exist for results corresponding to D which are less than 1 AU, thus deemed unacceptable. The apparent limitations and pitfalls of obtaining D based on energetic electron beams dispersion were discussed in several works [e.g., Kahler and Ragot, 2006; Wang et al., 2011] but will not be repeated here. We adopt the results published by Kahler et al. [2011a] and their approach of weighing more the measurements of L_e as better approximations of field line path lengths.

The derived path lengths from the GS together with the GH flux rope models are within the same range as L_e but are subject to an uncertainty in the effective length, L_{eff} , the length of a section of the infinite long cylinder

Figure 13. Summary and comparison of field line length estimates with D which were given by Kahler *et al.* [2011a] without associated uncertainties. Here a uniform 10% uncertainty in D is assumed. Format is the same as Figure 12. Length estimates (D) less than 1 AU are omitted.

that would correspond well to the flux rope structure and the intrinsic characteristic quantities. Therefore, the actual field line length estimates are obtained by multiplying the lengths given for a section of unit axial length (usually 1 AU) by L_{eff} in AU, whenever such a determination is available, as described in the case studies of MC events 1 and 7 presented in sections 3.1 to 3.3. The uncertainty estimates in L_s and L_{GH} are based on errors propagated from the uncertainties associated with the measured electron onset times within the GS intervals.

Figure 12 shows the ensemble distribution of measured field line path length L_e along the A shells and the one-to-one comparison between L_s (and L_{GH}) and L_e for all MC events, each of one or multiple-electron onsets. Figure 12a shows collectively all the measured L_e along the A shells within GS intervals and their associated uncertainties. They exhibit a general trend of increasing path lengths with increasing $|A'| = |A - A_0|$, i.e., with increasing radial distance away from the flux rope center where $A' \equiv 0$. For the onsets located near the center (to the left of the vertical dashed line of $|A'| = 10$ T·m) the path length L_e would represent a direct measurement of L_{eff} . For example, the one closest to $A' = 0$ at $L_e \approx 1.3$ AU corresponds to the onset in MC event 1 presented in section 3.1. The ones clustered around $L_e \approx 3.0$ AU correspond to those in MC event 7 discussed in section 3.3. Their locations on the cross-sectional maps of GS reconstruction results are close to the center of the flux ropes where the field line twist values are small. A few guide lines are also drawn to further elucidate the trend and the coverage of the constant-twist GH model estimates. From the

GS reconstruction results, an ensemble of field line twist is obtained and presented in Table 1 and Figure 3, for example, from which a mean value of twist, as well as the minimum and maximum values are obtained. They are utilized to provide an estimate of coverage by the area bounded by the curves based on equation (5) varying along A shells for a given constant twist. In Figure 12a, the set of blue (red) curves corresponds to the length distribution along A shells based on the GH model for a constant twist of the minimum, mean, and maximum value from all field line twist estimates, respectively, for $L_{\text{eff}} = 1$ AU (2 AU). In particular, the length variations for the mean twist values are drawn by dashed lines. Therefore, it can be seen that the majority of the measurements falls within the region with the lower and upper bound provided by the GH model of the minimum and the maximum twist and for $L_{\text{eff}} \in [1, 2]$ AU. One exception is the measurements from MC event 7 as we discussed earlier which might be an indication that the effective length could reach 3 AU in extreme cases.

Figure 12b shows the direct comparison of L_s versus L_e with associated uncertainties. Due to the limitation of the direct field line length estimate from the GS reconstruction results, only nine pairs of data points are available (the fifth column in Table 2). It shows good one-to-one correlation, especially considering that the correlation may be further improved because the low points of low L_s values beneath the dashed diagonal line could be raised by a possible correction of being multiplied by an $L_{\text{eff}} > 1$ AU. The same comparison with expanded length estimates including additional GH model estimates is shown in Figure 12c where the additional pairs of L_{GH} and L_e are marked by a cross and in black (the last column of Table 2). The correlation deteriorates compared with Figure 12b. However, the number of outliers from the one-to-one line is few, especially counting only the ones above the dashed line, about 3, out of a total of 18, for the reason discussed above regarding Figure 12b. For completeness, we also show the same set of results and comparisons with L_e replaced by D (fourth column in Table 2) in Figure 13. The alternative length estimates D were provided by Kahler *et al.* [2011a] without error estimates and were not used in their comparison. The agreement of various model length estimates with the measurements seem to degrade compared with the previous figure. For instance, the number of points above the dashed line increases in both Figures 12b and 12c.

5. Conclusions and Discussion

In conclusion, we have examined the flux rope structures embedded within seven MC events, in particular the field line length and twist distributions, based on the GS reconstruction method and the constant-twist GH flux rope model. We carry out direct comparison of field line length estimates with the unique measurements of field line path lengths obtained from timing observations of energetic electrons traveling along individual field lines from Sun to Earth. We limit our analysis to the same set of MC events reported by Kahler *et al.* [2011a] and employ their published measurements of L_e to facilitate a highly comparative study but with flux rope models different from the two models employed by Kahler *et al.* Our conclusion, somewhat in contrary to that of Kahler *et al.*, is that the flux rope interpretation of the magnetic structures embedded within MCs is largely consistent with the analysis of direct comparison between the modeled field line length estimates and the direct measurements L_e . The correlations between L_e and L_s (and L_{GH}) are well established as seen in Figure 12 and the field line length does exhibit a general trend of increasing from the flux rope center. Such a trend as displayed in Figure 12a as a function of the shifted flux function has general implication for a flux rope structure independent of specific models. On the other hand, we agree with Kahler *et al.* [2011a] and others on that such a comparison provides additional evidence for the inconsistency of Lundquist model in characterizing the flux rope structures observed in situ at 1 AU. As we indicated in Hu *et al.* [2014], the magnetic field line twist distribution within MC flux ropes often exhibits inconsistency with the Lundquist model, but better supports the GH model of a constant twist (see Figure 3 and associated descriptions). The present study further supports the findings of such inconsistency and provides additional support for the GH model by the direct comparison of field line length estimates with the corresponding measurements. It is also important to show that some electron burst onset observations are able to provide a direct measurement of the axial length of the section of a cylindrical flux rope, a critical parameter for the existing flux rope models. Based on our analysis of a limited number of MC events, we argue that under most circumstances, such a constraint on the effective axial length of a cylindrical flux rope is $L_{\text{eff}} \in [1, 2]$ AU, which has significant applications for the relevant studies of deriving and relating various physical quantities to their solar sources.

It might not be hard to perceive why the comparison with the Lundquist model failed. Based on the Lundquist model, the field line length would increase to infinity at the boundary at which the axial field vanishes by definition. Therefore, the Lundquist model would yield large path lengths toward the outer loops of a flux

rope. On the other hand, the GH model length would possess a more modest rate of increase from the center to the outer boundary of the flux rope, approximately linearly with r as indicated by equation (5), remaining finite. Therefore, the correlation between L_e and L_{GH} is more favorable. As we discussed in Hu *et al.* [2014], the underlying theoretical consideration for advocating the GH model is that it describes space plasmas in nonlinear force-free state which is well preserved from its origination from the Sun, propagation through the interplanetary space to reaching Earth. The ideal magnetohydrodynamic (MHD) conditions are probably well satisfied during the processes in the space plasma on the Sun and in the interplanetary space. The flux surfaces embedded within these structures remain distinct and well preserved upon their generation and are not destroyed by finite and highly localized resistivity, resulting in a nonlinear force-free state as observed in situ at 1 AU.

As an ongoing effort, we are extending the analysis to more events and utilizing more comprehensive sets of available observations. Some issues not addressed in the present work will be pursued in the forthcoming studies. For example, generally, we would expect difficulty when the measured path lengths are exceedingly long and near the flux rope center as we explained in the case study of MC event 7. Our interpretation of a flux rope structure with an unusually long axial length of ~ 3 AU needs to be further validated by additional event studies. Another related issue is what effect there is regarding the finite plasma pressure gradient. A slight change in the model output of the configuration of the flux rope would affect the spatial locations of the electron onsets where the measurements of L_e were taken. Such a change in location would yield change in the length estimates by specific models. The amount of change may depend on whether or not the plasma pressure gradient is taken into account. Therefore, a detailed assessment of the differences as resulted from the GS reconstruction results (nonforce free in general) and the GH model (nonlinear force-free) estimates is planned for future work.

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