Statistical Relationship between Interplanetary Magnetic Field conditions and the Helicity of Flux Transfer Event Flux Ropes

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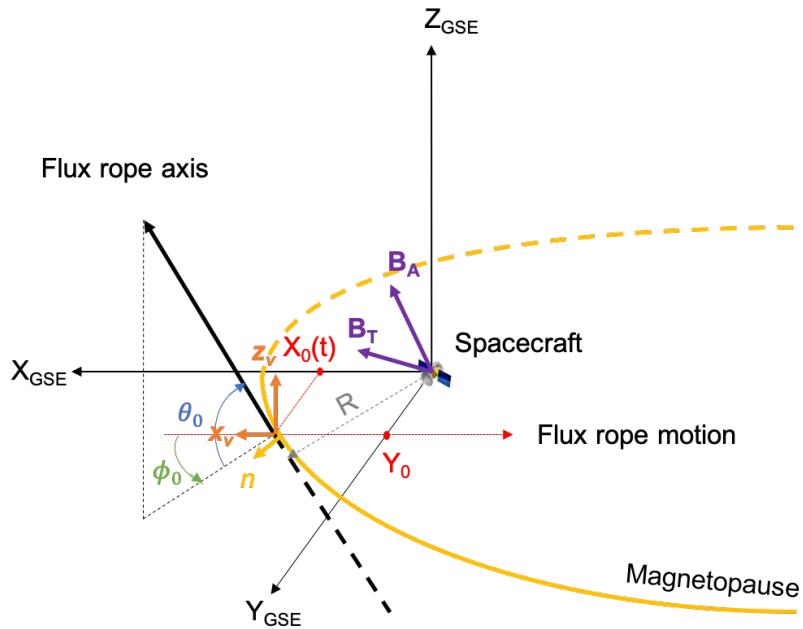
Introduction

This supplementary information includes details of the FTE flux rope fit parameters and detailed analyses of the solar wind conditions preceding the events. The FTEs are listed in Table S1 with their beginning and end time. Table S1 includes the flux rope model fit parameters as introduced in Section 2.2 in the main text. The fit parameters are obtained from the cylindrically symmetric force-free flux rope model with a constant α as in Burlaga (1988). The model fit parameters consist of two angles (θ_0, ϕ_0) for characterizing the orientation of the flux rope axis, the impact parameter y_0, and the helicity sign $H = \pm 1$, where H=1 is right-handed (RH) and H=-1 is a left-handed (LH) flux ropes. We illustrate the geometry of magnetic flux rope for the purpose of fitting into the model in Fig S1, adapted from Burlaga (1988). The quality of the model fit to the data is indicated by the deviation of the observed data from the model and

defined as $\chi^2 = \sum_i (|\boldsymbol{B}_{data,i} - \boldsymbol{B}_{model,i}|)^2 / N$ where N is the number of vectors of magnetic field measurements.
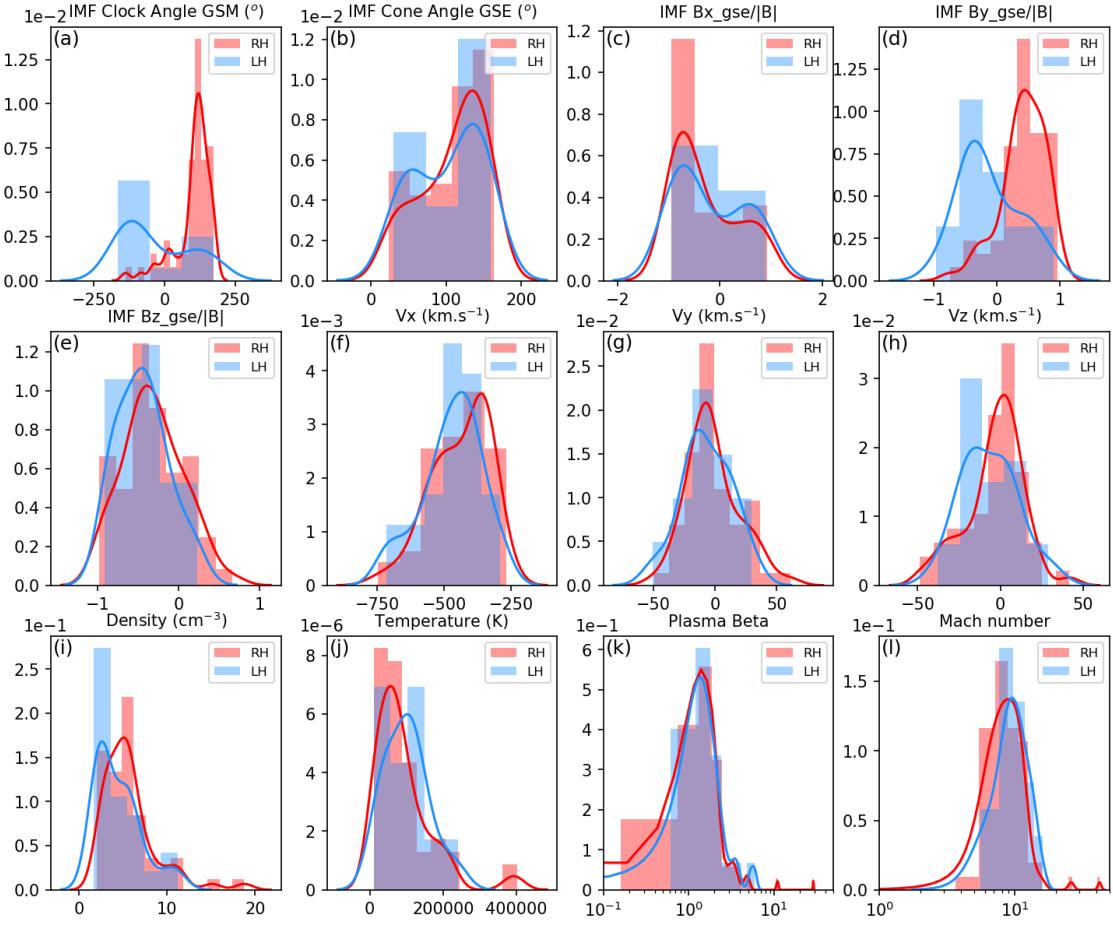
The analyses of the solar wind conditions preceding all of the FTEs are shown in Fig S2. Using the model fitting, the FTEs are categorized into RH and LH flux ropes. There are 59 RH and 25 LH flux ropes. Fig S2 shows the normalized distributions of the averaged solar wind conditions 15 minutes before the FTEs. It is clearly seen that the IMF clock angle is negative (e.g., IMF $B_Y < 0$) for LH flux ropes while the IMF clock angle is positive (e.g., IMF $B_Y > 0$) for RH flux ropes. The distributions of other solar wind parameters do not show significant difference between the two.

For the LH flux ropes, we found that there are 9 out of 25 events that are preceded by duskward IMF. As per the scenario, described in the paper, wherein the sign of helicity is controlled by the IMF B_Y sign which fixes the topology of the magnetic field in-between the sequential X-lines forming FTEs, such cases constitute outliers. In search for a controlling factor, we analyze the solar wind conditions preceding the events specifically for LH flux ropes only. Fig S3 shows normalized distributions of the average solar wind conditions 15 minutes before the LH flux ropes. The LH flux ropes are divided into the regular group (16 events) that are preceded by IMF $B_Y < 0$ and the outlier group (9 events) that are preceded by IMF $B_Y > 0$. It can be seen that the IMF cone angle (panel (c)) between two groups are different. The ratio of IMF $B_x / |\boldsymbol{B}|$ for the outlier group is mainly negative while the IMF B_x of the normal group is mostly positive. The magnitude of the IMF $B_x / |\boldsymbol{B}|$ for the outlier group is also stronger. The distributions of other solar wind parameters show slight differences between the two groups, which may be enhanced for a larger data set.
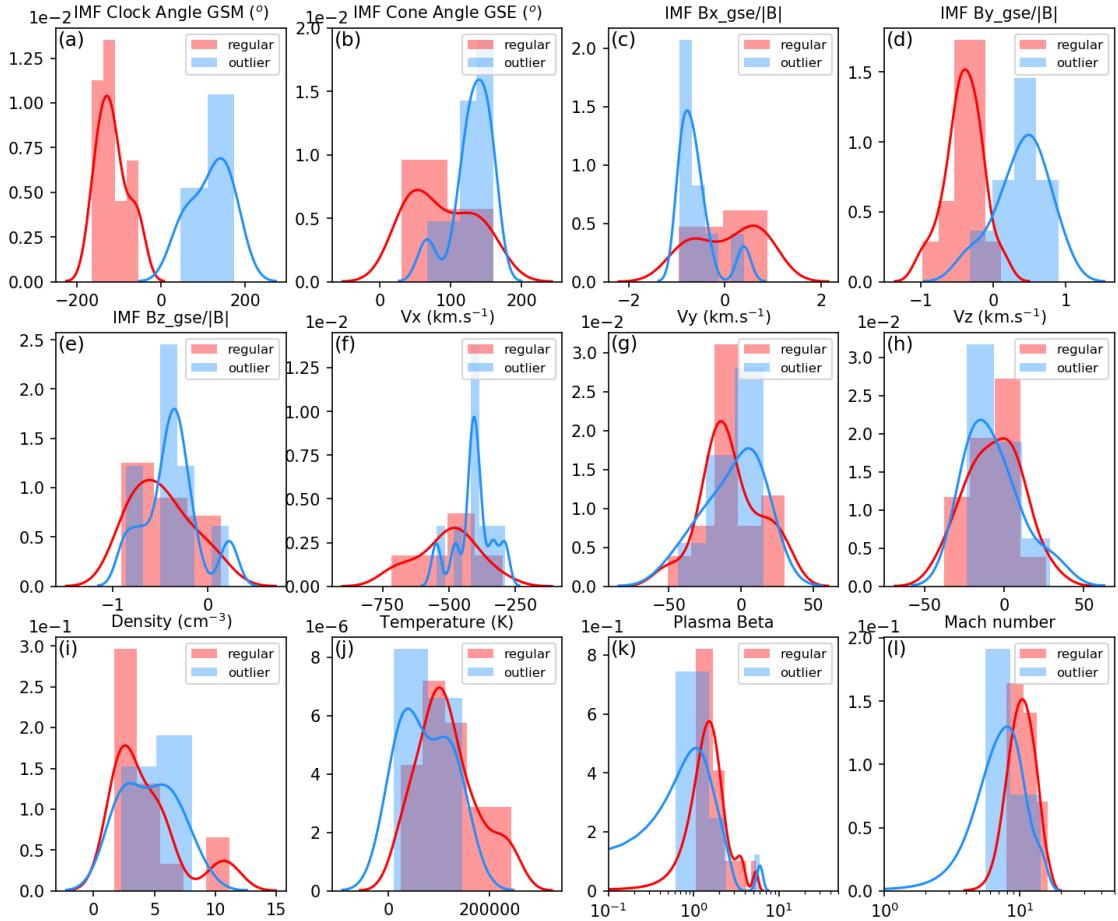

Fig S1. The geometry of magnetic flux rope passing a spacecraft in which we model following Burlaga (1988), adapted from Figure 2 of Burlaga (1988).

Fig S2. Normalized distributions of the average solar wind conditions 15 minutes before the right-handed (RH) and left-handed (LH) flux ropes. The solar wind parameters are shown as the following. (a) IMF clock angle in the GSM coordinate system. (b) IMF cone angle in the GSE coordinate system. (c,d,e) IMF B_X, B_Y, and B_Z in the GSE coordinates normalized by the IMF magnitude. (f,g,h) Ion bulk flow velocity V_X, V_Y, and V_Z components in the GSE system. (i) Ion number density. (j) Ion temperature. (k) Plasma beta. (l) Alfvén Mach Number.

Fig S3. Normalised distributions of the average solar wind conditions 15 minutes for the LH flux ropes that are preceded by IMF $B_Y < 0$ (regular group) and IMF $B_Y > 0$ (outlier group). The panel format is the same as in Figure S1 except for (b,c,d) that are the IMF B_X, B_Y, and B_Z components in the GSE coordinates normalized by the total IMF magnitude. (f,g,h) Ion bulk flow velocity V_X, V_Y, and V_Z components in the GSE system. (i) Ion number density. (j) Ion temperature. (k) Plasma beta. (l) Alfvén Mach Number.

Table S1. List of FTE flux ropes observed by MMS1 with their model fit parameters. The start and end times delineate the FTE intervals based on the bipolar component variation and enhanced core field signatures. The fit parameters (θ_0, ϕ_0, Y_0, H) are obtained from optimization of Burlaga (1988)'s cylindrically symmetric force-free flux rope model with a constant α. The χ^2 is the deviation of the observational data from the most optimized modeled flux rope data, normalized by the number of data points in each event.

Event	Start time	End time	θ_0 (deg)	ϕ_0 (deg)	Y_0 (R_E)	H	χ^2
1	2015-09-14 16:06:51.000	2015-09-14 16:07:33.000	38.0	-175.0	1.0	1	0.0033
2	2015-09-23 08:15:03.000	2015-09-23 08:15:36.000	18.0	171.0	-0.6	1	0.0038
3	2015-09-23 10:56:28.000	2015-09-23 10:56:58.000	-26.0	14.0	-0.1	-1	0.0033
4	2015-09-25 09:24:22.793	2015-09-25 09:24:52.977	41.0	147.0	-0.5	1	0.0053
5	2015-09-25 09:57:43.000	2015-09-25 09:58:28.000	-20.0	-38.0	1.0	-1	0.0037
6	2015-10-03 10:45:51.000	2015-10-03 10:46:34.000	17.0	179.0	1.0	1	0.0037
7	2015-10-03 13:27:12.396	2015-10-03 13:27:42.044	14.0	177.0	0.7	1	0.0034
8	2015-10-06 17:28:07.567	2015-10-06 17:28:17.015	50.0	8.0	-1.0	1	0.0081
9	2015-10-08 07:41:32.693	2015-10-08 07:41:59.549	20.0	174.0	1.0	1	0.0046
10	2015-10-11 11:05:13.000	2015-10-11 11:05:57.000	29.0	173.0	1.0	1	0.0046
11	2015-10-20 06:16:03.000	2015-10-20 06:17:26.000	41.0	180.0	-0.5	1	0.0029
12	2015-10-22 13:40:19.000	2015-10-22 13:40:48.000	-17.0	-6.0	-0.8	-1	0.0034
13	2015-10-31 05:45:52.000	2015-10-31 05:46:27.000	19.0	173.0	0.9	1	0.0037
14	2015-11-05 04:58:41.290	2015-11-05 04:58:51.487	-37.0	-19.0	-1.0	-1	0.0079
15	2015-11-05 14:07:07.131	2015-11-05 14:07:44.639	-45.0	16.0	-1.0	-1	0.0048
16	2015-11-05 14:36:39.263	2015-11-05 14:36:44.695	35.0	-180.0	1.0	1	0.0093
17	2015-11-06 06:57:42.000	2015-11-06 06:58:26.000	-21.0	-4.0	-1.0	-1	0.0033
18	2015-11-06 13:23:48.000	2015-11-06 13:24:29.000	33.0	171.0	-0.3	1	0.0055
19	2015-11-06 13:26:17.915	2015-11-06 13:26:32.647	31.0	6.0	-1.0	1	0.0066
20	2015-11-08 14:02:51.000	2015-11-08 14:03:23.000	20.0	-170.0	1.0	1	0.0034
21	2015-11-09 10:06:54.162	2015-11-09 10:07:02.160	36.0	112.0	0.1	1	0.0128

22	2015-11-10 02:43:43.908	2015-11-10 02:44:10.768	30.0	152.0	-0.8	1	0.0061
23	2015-11-11 03:56:21.000	2015-11-11 03:57:18.000	20.0	-176.0	0.4	1	0.0028
24	2015-11-12 07:06:01.695	2015-11-12 07:06:06.617	-60.0	-180.0	-0.9	-1	0.013
25	2015-11-12 07:20:20.201	2015-11-12 07:20:35.685	-46.0	-21.0	-1.0	-1	0.0055
26	2015-12-02 10:00:42.427	2015-12-02 10:01:26.951	-15.0	-10.0	0.9	-1	0.0036
27	2015-12-02 10:21:35.000	2015-12-02 10:21:59.000	-12.0	-7.0	1.0	-1	0.003
28	2015-12-05 00:40:35.058	2015-12-05 00:40:43.465	54.0	38.0	0.7	1	0.0113
29	2015-12-05 00:40:50.216	2015-12-05 00:41:04.843	24.0	7.0	-1.0	1	0.0078
30	2015-12-08 10:30:06.246	2015-12-08 10:30:17.494	40.0	-154.0	0.1	1	0.0096
31	2015-12-11 12:23:27.054	2015-12-11 12:23:35.626	32.0	-175.0	1.0	1	0.0098
32	2015-12-19 09:27:02.581	2015-12-19 09:27:18.115	45.0	-180.0	0.1	1	0.006
33	2016-01-23 23:26:20.490	2016-01-23 23:26:37.970	-13.0	-75.0	-1.0	-1	0.0068
34	2016-01-23 23:45:12.961	2016-01-23 23:45:25.871	-48.0	62.0	0.1	-1	0.0055
35	2016-01-27 22:17:19.000	2016-01-27 22:18:02.000	-24.0	3.0	0.8	1	0.0023
36	2016-01-27 22:49:42.164	2016-01-27 22:49:48.419	-30.0	-38.0	0.4	1	0.01
37	2016-01-29 22:38:50.825	2016-01-29 22:38:59.880	-37.0	77.0	-1.0	-1	0.0142
38	2016-01-31 05:54:46.000	2016-01-31 05:55:47.000	-30.0	4.0	1.0	1	0.0046
39	2016-02-01 22:26:45.004	2016-02-01 22:26:51.898	54.0	-175.0	0.1	1	0.008
40	2016-02-07 03:06:51.154	2016-02-07 03:07:33.233	-11.0	3.0	1.0	-1	0.0027
41	2016-02-11 01:56:07.266	2016-02-11 01:56:26.135	-34.0	-7.0	1.0	-1	0.0088
42	2016-02-11 01:56:30.049	2016-02-11 01:56:39.605	14.0	-45.0	-0.4	1	0.0076
43	2016-02-11 01:57:06.171	2016-02-11 01:57:16.309	25.0	-96.0	-1.0	1	0.0108
44	2016-02-11 02:00:20.668	2016-02-11 02:00:44.815	-20.0	134.0	-0.7	1	0.0063
45	2016-02-11 02:39:04.000	2016-02-11 02:40:45.000	-30.0	33.0	1.0	1	0.0046
46	2016-02-11 02:46:21.943	2016-02-11 02:46:53.569	-34.0	25.0	-0.7	1	0.004

47	2016-02-14 01:25:36.846	2016-02-14 01:25:50.260	-60.0	70.0	-1.0	-1	0.0092
48	2016-02-15 01:28:58.000	2016-02-15 01:29:49.000	-31.0	-5.0	-0.1	1	0.003
49	2016-02-19 22:55:42.433	2016-02-19 22:55:53.393	27.0	-125.0	1.0	1	0.0115
50	2016-02-19 23:53:43.419	2016-02-19 23:54:06.796	-26.0	-51.0	0.8	1	0.0047
51	2016-02-19 23:54:35.258	2016-02-19 23:54:58.486	-35.0	-48.0	-1.0	1	0.0082
52	2016-02-28 00:58:54.553	2016-02-28 00:59:16.930	24.0	-10.0	-1.0	1	0.0058
53	2016-10-10 15:43:20.000	2016-10-10 15:43:54.000	18.0	172.0	0.0	1	0.003
54	2016-10-27 12:00:43.000	2016-10-27 12:01:09.000	61.0	-172.0	-0.1	1	0.0056
55	2016-11-06 16:52:52.000	2016-11-06 16:53:30.000	32.0	5.0	-1.0	1	0.006
56	2016-11-08 10:49:25.000	2016-11-08 10:50:24.000	70.0	3.0	-1.0	1	0.0045
57	2016-11-08 11:19:54.000	2016-11-08 11:20:42.000	-34.0	-1.0	-1.0	-1	0.004
58	2016-11-08 13:55:34.000	2016-11-08 14:01:03.000	-18.0	-10.0	-0.4	1	0.0012
59	2016-11-12 18:19:44.000	2016-11-12 18:20:11.000	16.0	178.0	-1.0	-1	0.0044
60	2016-11-15 12:20:40.201	2016-11-15 12:20:49.706	31.0	174.0	1.0	1	0.0104
61	2016-11-15 15:49:46.000	2016-11-15 15:50:07.000	19.0	174.0	-1.0	-1	0.0049
62	2016-11-23 09:03:15.000	2016-11-23 09:03:45.000	1.0	164.0	0.6	1	0.0053
63	2016-11-27 08:39:08.000	2016-11-27 08:40:05.000	28.0	-174.0	1.0	1	0.004
64	2016-12-02 09:30:09.603	2016-12-02 09:30:19.524	33.0	-177.0	-0.8	1	0.0082
65	2016-12-14 05:30:40.000	2016-12-14 05:31:07.000	9.0	1.0	0.9	-1	0.0025
66	2016-12-19 07:42:04.000	2016-12-19 07:43:34.000	13.0	-180.0	-0.1	1	0.0026
67	2016-12-19 09:15:40.000	2016-12-19 09:17:46.000	6.0	-180.0	-1.0	1	0.0013
68	2016-12-19 13:54:51.000	2016-12-19 13:56:05.000	36.0	175.0	1.0	1	0.004
69	2016-12-23 03:16:48.000	2016-12-23 03:17:08.000	51.0	-128.0	0.9	-1	0.0093
70	2016-12-26 14:50:36.000	2016-12-26 14:52:36.000	16.0	-171.0	-0.8	1	0.002
71	2016-12-27 08:02:30.190	2016-12-27 08:02:35.208	29.0	-180.0	0.1	-1	0.0135

72	2016-12-28 06:32:50.089	2016-12-28 06:32:57.921	32.0	-180.0	1.0	1	0.0135
73	2016-12-29 11:12:00.000	2016-12-29 11:12:26.000	26.0	1.0	-0.8	1	0.0058
74	2016-12-29 12:18:11.000	2016-12-29 12:19:03.000	-20.0	-1.0	-0.9	-1	0.0036
75	2017-01-01 03:01:02.993	2017-01-01 03:01:13.648	-33.0	-32.0	-0.6	1	0.0061
76	2017-01-01 06:27:39.512	2017-01-01 06:27:41.575	30.0	-162.0	-0.1	1	0.0186
77	2017-01-11 04:22:47.969	2017-01-11 04:22:59.126	20.0	155.0	0.5	1	0.0094
78	2017-01-13 00:58:21.296	2017-01-13 00:58:47.966	22.0	-175.0	-1.0	-1	0.0033
79	2017-01-15 01:11:04.000	2017-01-15 01:11:57.000	-25.0	1.0	1.0	1	0.0032
80	2017-01-29 01:52:19.844	2017-01-29 01:52:32.496	-32.0	3.0	0.3	1	0.0055
81	2017-01-29 01:52:32.578	2017-01-29 01:52:46.879	-31.0	-32.0	-0.1	1	0.0084
82	2017-01-29 01:57:08.049	2017-01-29 01:57:21.139	-29.0	23.0	0.7	1	0.0055
83	2017-02-04 00:14:40.907	2017-02-04 00:14:56.063	-15.0	14.0	0.6	1	0.0071
84	2017-02-04 07:49:16.574	2017-02-04 07:49:21.439	38.0	154.0	1.0	-1	0.0148