Evidence in magnetic clouds for systematic open flux transport on the Sun

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[1] Most magnetic clouds encountered by spacecraft at 1 AU display a mix of unidirectional suprathermal electrons signaling open field lines and counterstreaming electrons signaling loops connected to the Sun at both ends. Assuming the open fields were originally loops that underwent interchange reconnection with open fields at the Sun, we determine the sense of connectedness of the open fields found in 72 of 97 magnetic clouds identified by the Wind spacecraft in order to obtain information on the location and sense of the reconnection and resulting flux transport at the Sun. The true polarity of the open fields in each magnetic cloud was determined from the direction of the suprathermal electron flow relative to the magnetic field direction. Results indicate that the polarity of all open fields within a given magnetic cloud is the same 89% of the time, implying that interchange reconnection at the Sun most often occurs in only one leg of a flux rope loop, thus transporting open flux in a single direction, from a coronal hole near that leg to the foot point of the opposite leg. This pattern is consistent with the view that interchange reconnection in coronal mass ejections systematically transports an amount of open flux sufficient to reverse the polarity of the heliospheric field through the course of the solar cycle. Using the same electron data, we also find that the fields encountered in magnetic clouds are only a third as likely to be locally inverted as not. While one might expect inversions to be equally as common as not in flux rope coils, consideration of the geometry of spacecraft trajectories relative to the modeled magnetic cloud axes leads us to conclude that the result is reasonable.

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1. Introduction

[2] Magnetic clouds are the well-studied subset of interplanetary coronal mass ejections (ICMEs) that have relatively smooth magnetic signatures and relatively clear boundaries. *Shodhan et al.* [2000] used those boundaries to document topological properties of magnetic field lines within clouds. Using suprathermal electrons as sensors of magnetic connection to the Sun, they found that most magnetic clouds at 1 AU contain a mix of open and closed field lines, that is, field lines connected to the Sun at only one end mixed with doubly connected loops. Because the magnetic signature of a cloud is a continuous rotation of the field signaling passage of a coherent structure with flux rope properties, the open and closed field lines most likely form a set of nested coils [e.g., *Gosling et al.*, 1995]. These coils presumably leave the Sun in a coronal mass ejection (CME) and constitute a flux rope shaped into a loop with legs extending back to the Sun, where some of the field lines in the legs have lost their connection. Figure 1 illustrates loss of connection of one end of a single field line threading a magnetic cloud (in this case, a field line that lies along the axis of the cloud).

[3] The means by which the foot of a field loop loses its connection to the Sun is presumably interchange reconnection with nearby open field lines, as illustrated in Figure 2. *Crooker et al.* [2002] and *Owens and Crooker* [2006] propose that interchange reconnection may eventually open all field lines in CMEs, long after they have left the Sun, thus balancing the heliospheric flux budget without calling upon an additional process of disconnection through reconnection of open field lines elsewhere. Roughly half of the interchange reconnection that opens fields in CMEs, however, must occur before the ICMEs reach 1 AU. The reason is that, on average, magnetic clouds observed at 5 AU are only negligibly more open (45%) than those observed at 1 AU (41%) [*Crooker et al.*, 2004], implying that the rate of interchange reconnection between those two distances must be considerably less than the rate that occurred as the CME left the Sun. Figure 2 illustrates interchange reconnection during liftoff. Evidence for the process in EUV and X ray data for the CME on 12 May 1997 has been presented

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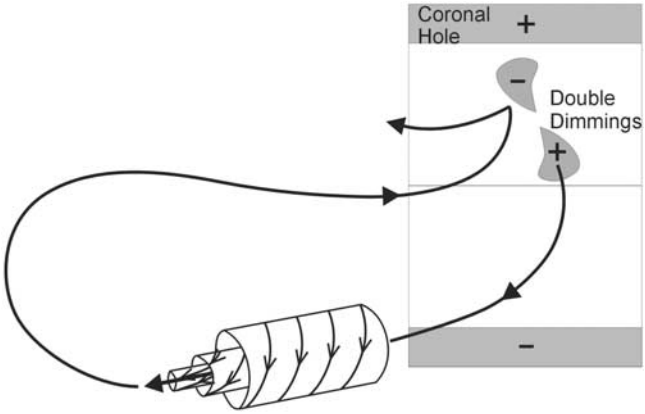

Figure 1. Schematic drawing of the 15 May 1997 magnetic cloud at 1 AU and its connection to the solar surface, represented by a 90°-wide longitudinal slice from a rectangular synoptic map for Carrington Rotation 1922. The gray foot points of the legs of the cloud represent double dimmings observed in EUV. The positive leg is connected while the negative leg has been released by interchange reconnection with positive fields from the northern coronal hole [adapted from *Crooker and Webb*, 2006].

independently by *Attrill et al.* [2006] and *Crooker and Webb* [2006]. The magnetic cloud generated by that CME was completely open by the time it reached 1 AU, implying that in this case all of the interchange reconnection that opened the cloud occurred as part of the CME release process.

[4] The aspect of interchange reconnection in CMEs most relevant to this paper is that the process transports open flux. The foot of the positive open field line that interchange reconnects with the negative leg of the coiled loop in Figure 2 moves from point 1 to point 2, a distance larger than the span between the CME legs. If all of the interchange reconnection takes place with only one leg of the CME, in the sense drawn, then open flux will be transported in only one direction, and the open field lines in the resulting magnetic cloud at 1 AU would all have the same polarity, in this case positive, as shown in Figure 1. In contrast, if some interchange reconnection also takes place in the positive leg with a nearby reservoir of negative open field lines, then some open flux would be transported in the opposite direction, and the open field lines in the resulting magnetic cloud at 1 AU would have mixed polarity. Thus the polarity of open field lines in magnetic clouds at 1 AU gives information about the location and sense of interchange reconnection and flux transport back at the Sun.

[5] This paper presents the results of an analysis of the polarity of open field lines in 72 magnetic clouds and discusses the implications for global flux transport. *Owens et al.* [2007] have proposed that the kind of transport described here can reverse the polarity of the solar field in the course of the solar cycle. For example, in the 12 May 1997 CME, for which Figure 1 illustrates the foot point geometry in the schematic synoptic magnetogram, *Attrill et al.* [2006] and *Crooker and Webb* [2006] conclude that interchange reconnection transported the foot points of the positive open flux observed in the corresponding magnetic cloud at 1 AU from the northern coronal hole to the equatorward dimming region. This southward transport of $\sim 10^{13}$ Wb of flux over $\sim 50°$ of latitude for a single event during the rising phase of the solar cycle represents a giant step in the right direction toward reversing the field, according to the estimates of *Owens et al.* [2007]. More will be said about this kind of transport in section 3 of the paper, following the analysis in section 2.

[6] The data described in section 2.1, which were used to analyze field polarity reported in section 2.2, were also used to determine the local geometry of the magnetic field in a cloud. Specifically, the field polarity determined from the electron data was compared with the local magnetic field direction to determine whether or not the field was inverted, that is, locally turned back on itself, as it is in some segments of the coil in Figure 2. Section 2.3 reports on the results of this analysis.

2. Analysis

2.1. Data

[7] One hundred magnetic clouds have been identified in data from the Magnetic Field Investigation [*Lepping et al.*, 1995] on the Wind spacecraft during the years 1995–2006. These are listed at http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_S1.html along with parameters derived from fits to a force-free flux rope model, as discussed by *Lepping et al.* [2006]. We use the boundaries of these fitted magnetic clouds to search for open fields within them. Although the location of magnetic cloud boundaries is subject to uncertainty, we treat this uncertainty as having minimal impact on our goal of finding representative open fields within cloud intervals, especially in view of the large number of events analyzed.

[8] To identify open and closed fields within the magnetic clouds, we use color-coded suprathermal electron pitch angle distributions (PADs) derived from the 3-D plasma and energetic particle instrument [*Lin et al.*, 1995]

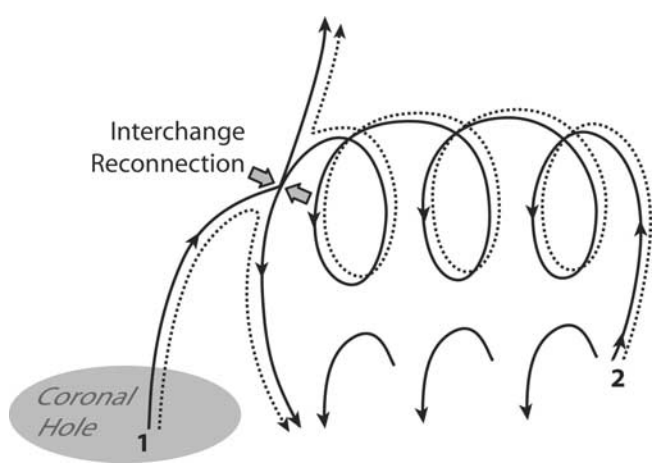

Figure 2. Interchange reconnection between an open field line from a coronal hole and a coiled field loop in a rising coronal mass ejection. The reconnection creates a small loop and an open coil, indicated by dashed lines, and transports the foot point of the open field line from point 1 to point 2 (modified from *Harra et al.* [2007], with kind permission from Springer Science and Business Media).

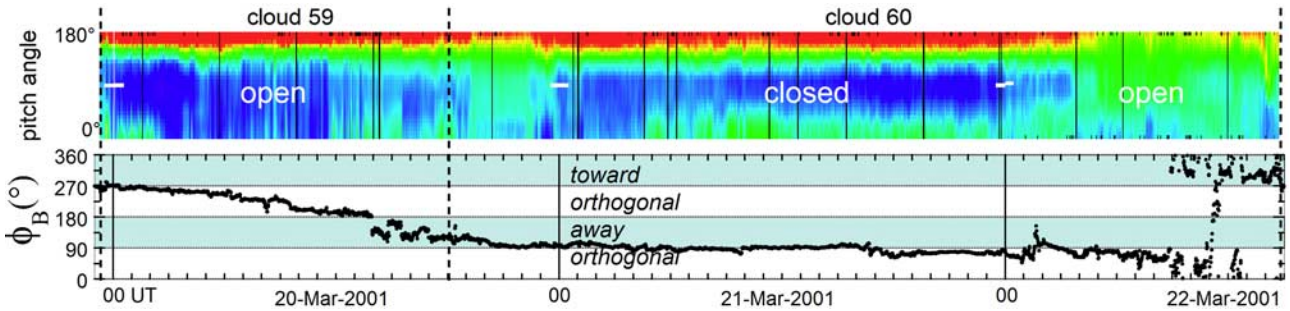

Figure 3. Time variations of 165-eV electron pitch angle distributions (PADs) and magnetic longitude ϕ in Geocentric Solar Ecliptic coordinates, where $\phi = 0°$ points radially toward the Sun, from Wind spacecraft measurements during passage of two magnetic clouds, numbered according to Table 1. Dashed vertical lines mark the cloud boundaries. PADs are normalized by mean flux intensity and are color coded, with highest intensities in red. The direction of the heat flux, or strahl, indicated by the band at 180° pitch angle, is antiparallel to the magnetic field signaling negative (toward) solar polarity in intervals labeled "open." An additional band at 0° indicates counterstreaming in both directions in the interval labeled "closed." The local polarity, however, indicated by ϕ, lies near or in the away quadrant much of the time, signaling an inverted configuration.

on the Wind spacecraft. For a selected energy band within the range ~160–260 eV, these PADs are normalized by the mean flux intensity in each distribution and plotted as a function of time on daily and monthly scales at http://plasma2.ssl.berkeley.edu/wind3dp/sumplots/directory.html. For cases that had ambiguous signatures and occurred after the 25 August 1997 launch of the Advanced Composition Explorer (ACE) spacecraft, stacked, color-coded PADs as a function of time for a range of suprathermal energies from the Los Alamos Solar Wind Electron Proton Alpha Monitor (SWEPAM) [*McComas et al.*, 1998] were consulted to help resolve those ambiguities.

[9] Figure 3 (top) shows an example of time variations of color-coded 165 eV PADs from the Wind spacecraft within the boundaries of two successive magnetic clouds (numbered as listed in Table 1) which passed on 20–22 March 2001. The red band at 180° pitch angle indicates a strong beam of electrons, or strahl, flowing antiparallel to the magnetic field. Since strahl electrons have their origin on the Sun, a single beam antiparallel to the field indicates open fields that are rooted in the Sun with negative (toward the Sun) polarity, as in the interval on 20 March labeled "open." Open fields with negative polarity also occurred on 22 March, as labeled, but there the red band has been replaced with a broad green band signifying a much broader, weaker strahl. In other segments of the plot, the continuous band at 180° pitch angle is occasionally joined by a green band at 0°, parallel to the field, signaling weak counterstreaming beams. Together these most likely indicate closed fields, that is, fields connected to the Sun at both ends [*Gosling et al.*, 1987], as in the interval on 21 March labeled "closed." There the much stronger beam at 180° is interpreted as passage through the leg rather than the apex of the magnetic cloud, where fields in that leg point toward the Sun [e.g., *Kahler et al.*, 1999]. Overall Figure 3 indicates that the open fields interspersed between closed fields in the successive magnetic clouds were all of a single polarity, negative in this case. This pattern is common, as will be documented in section 2.2.

[10] The greatest source of uncertainty in using electron PADs to identify open and closed fields, as in Figure 3, comes from the ambiguity between the signature of closed fields and the signature of plasma depletion at 90° pitch angle [*Gosling et al.*, 2001, 2002]. Depletion arises from focusing and mirroring effects on field lines connected to downstream regions with elevated magnetic field strength. In the region marked "closed" in Figure 3, for example, did these effects produce a hole at 90° pitch angle in a green-colored background (halo) population, or did electrons streaming from the far foot points of loops connected to the Sun create green bands at 0° pitch angle? In questionable cases, searching the higher-energy PADs from ACE for counterstreaming was helpful in resolving some of the ambiguity. We assume this uncertainty does not have any substantial negative impact on the outcome of the present study, which focuses on open fields, since signatures of open fields without 90° pitch angle depletions are commonly found in magnetic clouds for at least some fraction of their duration.

[11] The cases in Figure 3 also exemplify the impact of uncertainty in boundary location. On the basis of plasma characteristics (not shown), one might argue that only one magnetic cloud passed, with a leading boundary at ~1700 UT on 19 March and a trailing boundary at ~2300 UT on 21 March. This would reduce the number of events analyzed by one, but the case would still be categorized as one with open fields of a single polarity.

[12] Figure 3 (bottom) shows the time variation of the direction of the local magnetic field longitude angle ϕ. The background is marked with quadrants centered on the Parker spiral pointing toward and away from the Sun and the intervening quadrants orthogonal to the Parker spiral. The local field drifts from the edge of the toward quadrant to the edge of the away quadrant during 20 March and remains there until it jumps back to the toward quadrant ~0900 UT on 22 March. Because the true polarity, that is, the polarity of the field line as it leaves the Sun, as indicated by the electrons, is solidly negative, the drift of ϕ to the away quadrant indicates that much of the structure has fields

Table 1. Boundaries and Field Properties of 100 Magnetic Clouds

			Start Date[a]				End Date[a]						
Cloud Number	Web Number	Year	Month	Day	DOY	Time (UT)	Month	Day	DOY	Time (UT)	Open Fields?	Solar Polarity	Local Field Polarity
1	1	1995	2	8	39	5.8	2	9	40	0.8	yes	toward	away
2	2	1995	3	4	63	10.8	3	5	64	3.8	yes	away	away
3	2.2	1995	4	3	93	7.8	4	4	94	10.8	yes	away	away
4	3	1995	4	6	96	7.3	4	6	96	17.8	yes	toward	ortho, toward
5	4	1995	5	13	133	10.9	5	13	133	16.4	yes	away	toward
6	5	1995	8	22	234	21.3	8	23	235	19.3	yes	away	toward, ortho
7	6	1995	10	18	291	19.8	10	20	293	1.3	yes	toward	toward
8	7	1995	12	16	350	5.3	12	16	350	22.3	yes	toward	ortho
9	8	1996	5	27	148	15.3	5	29	150	7.3	yes	away	away, toward
10	9	1996	7	1	183	17.3	7	2	184	10.3	yes	away	away
11	10	1996	8	7	220	12.3	8	8	221	10.8	yes	toward	toward
12	11	1996	12	24	359	2.8	12	25	360	11.3	yes	toward	ortho, away
13	12	1997	1	10	10	5.3	1	11	11	2.3	yes	away, toward	ortho
14	13	1997	2	10	41	3.4	2	10	41	18.4	yes	away	toward
15	14.1	1997	4	11	101	5.6	4	11	101	19.1	no	–	–
16	14.2	1997	4	21	111	14.5	4	23	113	6.5	yes	toward	toward
17	15	1997	5	15	135	9.1	5	16	136	1.1	yes	away	away
18	16	1997	5	16	136	6.1	5	16	136	13.9	yes	away	toward
19	17	1997	6	9	160	2.3	6	9	160	23.3	yes	toward	toward
20	18	1997	6	19	170	5.1	6	19	170	15.9	no?	–	–
21	19	1997	7	15	196	8.8	7	15	196	23.8	yes	away	toward, ortho, away
22	20	1997	8	3	215	14.1	8	4	216	1.9	yes	away	away
23	21	1997	9	18	261	0.5	9	20	263	12.5	yes	away	away
24	22	1997	9	22	265	0.8	9	22	265	17.3	yes	away	away, ortho
25	23	1997	10	1	274	16.3	10	2	275	22.8	no	–	–
26	24	1997	10	10	283	23.8	10	12	285	0.8	no	–	–
27	25	1997	11	7	311	15.8	11	8	312	4.3	yes	toward	ortho
28	26	1997	11	8	312	4.9	11	8	312	14.9	yes	toward	ortho, away
29	27	1997	11	22	326	15.8	11	23	327	12.3	yes	away	away, ortho
30	28	1998	1	7	7	3.3	1	8	8	8.3	yes	away	ortho, toward
31	29	1998	1	8	8	14.9	1	8	8	21.6	yes	toward	ortho
32	30	1998	2	4	35	4.5	2	5	36	22.5	yes	away	toward
33	31	1998	3	4	63	14.3	3	6	65	6.3	yes	away	away, toward
34	32	1998	5	2	122	12.3	5	3	123	17.3	yes	toward	toward
35	33	1998	6	2	153	10.6	6	2	153	15.9	yes	away	away
36	34	1998	6	24	175	16.8	6	25	176	21.8	yes	away	away, ortho
37	35	1998	8	20	232	10.3	8	21	233	19.3	yes	toward	toward, ortho
38	36	1998	9	25	268	10.3	9	26	269	13.3	no	–	–
39	37	1998	10	19	292	5.1	10	19	292	14.6	no	–	–
40	38	1998	11	8	312	23.8	11	10	314	1.3	yes	away	ortho, toward
41	39	1999	2	18	49	14.3	2	19	50	12.3	no	–	–
42	40	1999	4	16	106	20.3	4	17	107	21.3	no	–	–
43	41	1999	8	9	221	10.8	8	10	222	15.8	no	–	–
44	42	1999	9	21	264	21.1	9	22	265	5.1	no?	–	–
45	43	2000	2	12	43	17.1	2	13	44	0.6	yes	away	toward
46	44.1	2000	2	21	52	9.8	2	22	53	13.3	yes	toward	ortho
47	44.2	2000	6	24	176	8.3	6	25	177	20.3	yes	toward	toward
48	44.3	2000	7	1	183	8.8	7	2	184	3.3	yes	toward	away, ortho, toward
49	45	2000	7	15	197	6.8	7	15	197	14.3	–	–	–
50	46	2000	7	15	197	21.1	7	16	198	9.9	–	–	–
51	47	2000	7	28	210	21.1	7	29	211	10.1	yes	toward	toward
52	48	2000	8	1	214	0.1	8	1	214	15.9	yes	away	away
53	49	2000	8	12	225	6.1	8	13	226	5.1	yes	away	away
54	50	2000	9	18	262	1.9	9	18	262	15.1	no	–	–
55	51	2000	10	3	277	17.1	10	4	278	14.1	yes	away	toward, ortho, away
56	52	2000	10	13	287	18.4	10	14	288	16.9	no	–	–
57	53	2000	10	28	302	23.3	10	30	304	0.3	no	–	–
58	54	2000	11	6	311	23.1	11	7	312	18.1	no	–	–
59	55.1	2001	3	19	78	23.3	3	20	79	18.3	yes	toward	ortho, away
60	55.2	2001	3	20	79	17.8	3	22	81	14.8	yes	toward	away, ortho, toward
61	56	2001	4	4	94	20.9	4	5	95	8.4	no?	–	–
62	57	2001	4	12	102	7.9	4	12	102	17.9	no	–	–
63	58	2001	4	22	112	0.9	4	23	113	1.4	yes	toward	ortho, toward, away
64	59	2001	4	29	119	1.9	4	29	119	12.9	yes	away	away
65	60	2001	5	28	148	11.9	5	29	149	10.4	yes	away	away, ortho

Table 1. (continued)

Cloud Number	Web Number	Year	Start Date[a] Month	Start Date[a] Day	Start Date[a] DOY	Start Date[a] Time (UT)	End Date[a] Month	End Date[a] Day	End Date[a] DOY	End Date[a] Time (UT)	Open Fields?	Solar Polarity	Local Field Polarity
66	61	2001	7	10	191	17.3	7	12	193	8.8	yes	toward, away	away
67	62	2001	10	31	304	21.3	11	2	306	10.3	yes	toward, away	ortho
68	63	2001	11	24	328	15.8	11	25	329	13.3	no	–	–
69	64	2002	3	19	78	22.9	3	20	79	15.4	yes	toward	ortho
70	65	2002	3	24	83	3.8	3	25	84	22.8	yes	toward	toward, ortho, away
71	66	2002	4	18	108	4.3	4	19	109	2.3	no	–	–
72	67	2002	4	20	110	11.8	4	21	111	16.8	yes	away	away
73	68	2002	5	19	139	3.9	5	19	139	23.4	yes	away	away
74	69	2002	5	23	143	23.4	5	24	144	16.9	no	–	–
75	70	2002	8	1	213	11.9	8	1	213	22.6	yes	toward	away, ortho
76	71	2002	8	2	214	7.4	8	2	214	21.1	yes	toward	ortho
77	72.1	2002	9	3	246	0.3	9	3	246	18.8	yes	toward, away	toward, away
78	72.2	2002	9	30	273	22.6	10	1	274	11.9	yes	away	toward, away
79	73	2003	3	20	79	11.9	3	20	79	22.4	yes	away	ortho, away
80	74	2003	6	17	168	17.8	6	18	169	8.3	yes	toward	ortho, toward
81	75	2003	7	10	191	19.9	7	11	192	8.9	no?	–	–
82	76	2003	8	18	230	11.6	8	19	231	4.4	no?	–	–
83	77	2003	11	20	324	10.8	11	21	325	2.3	–	–	–
84	78	2004	4	4	095	2.8	4	5	096	14.8	yes	toward, away	ortho, ortho
85	79	2004	7	22	204	15.4	7	22	204	23.1	yes	away	away
86	80	2004	7	24	206	12.8	7	25	207	13.3	no	–	–
87	81	2004	8	29	242	18.7	8	30	243	20.8	yes	toward	ortho
88	82	2004	11	8	313	3.4	11	8	313	16.6	yes	away	away, ortho
89	83	2004	11	9	314	20.9	11	10	315	3.4	yes	away	ortho
90	84	2004	11	10	315	3.6	11	10	315	11.1	yes?	away	ortho, away
91	85	2005	5	15	135	5.7	5	15	135	22.3	no	–	–
92	86	2005	5	20	140	7.3	5	21	141	5.3	yes	away	ortho, toward, ortho
93	87	2005	6	12	163	15.6	6	13	164	7.1	yes	away	toward, away
94	88	2005	6	15	166	5.8	6	16	167	7.8	yes	away	away, ortho
95	89	2005	7	17	198	15.3	7	18	199	3.8	yes	toward, away	ortho
96	90	2005	10	31	304	2.9	10	31	304	20.4	yes	away	away, ortho, toward
97	91	2005	12	31	365	14.8	1	1	001	10.8	no	–	–
98	92	2006	2	5	036	19.1	2	6	037	13.1	yes	away, toward	away
99	93	2006	4	13	103	14.8	4	13	103	20.8	no	–	–
100	94	2006	4	13	103	20.6	4	14	104	9.9	yes	away, toward	toward

[a]Dates are numerical, and times are in decimal format; read 2 8 39 5.8 as 8 February, DOY 39, 0548 UT.

turned back on themselves. Inverted fields like these are not as common as might be expected in flux ropes, however, as will be documented in section 2.3.

[13] In contrast to Figure 3, Figure 4 shows a magnetic cloud with what look to be open fields of both polarities. In the same format as Figure 3, Figure 4 shows time variations of color-coded 165 eV PADs within the boundaries of a magnetic cloud which passed the spacecraft on 5–6 February 2006. From ~2100 UT on 5 February to ~0130 UT on 6 February, the red band at 0° pitch angle indicates mostly open fields that are rooted in the Sun with positive (away) polarity, whereas, in the interval ~0800–1000 UT on 6 February, the red band at 180° pitch angle appears to indicate at least some open fields with negative (toward) polarity. The local field longitude ϕ drifts from an orthogonal orientation into the away quadrant in the first open interval and remains there until the end of the second open interval. This pattern is consistent with the positive solar polarity in the first interval but opposite to the negative solar polarity in the second, thus indicating a local inversion there. Before, between, and after the two intervals marked "open," the PADs show broad counterstreaming beams. These most likely indicate closed fields, although depletion of 90° pitch angle electrons cannot be ruled out, as discussed above. We classify the 5–6 February 2006 event as a magnetic cloud with open fields of mixed polarity, even though it is possible that those of negative polarity are actually closed. As will be seen in section 2.2, magnetic clouds with open fields of mixed polarity are not nearly as common as those with open fields of a single polarity.

2.2. Polarities of Open Fields

[14] Table 1 lists the start and end times of the 100 magnetic clouds used for this analysis. The first column numbers them sequentially, and, for reference the second column lists the numbering posted on the Web site. The last three columns list whether or not the magnetic cloud had any open fields (yes or no), the solar polarity of those fields (away and/or toward), and the direction of the local field relative to the Sun along the Parker spiral angle (away, toward, and/or orthogonal). All three of these columns are

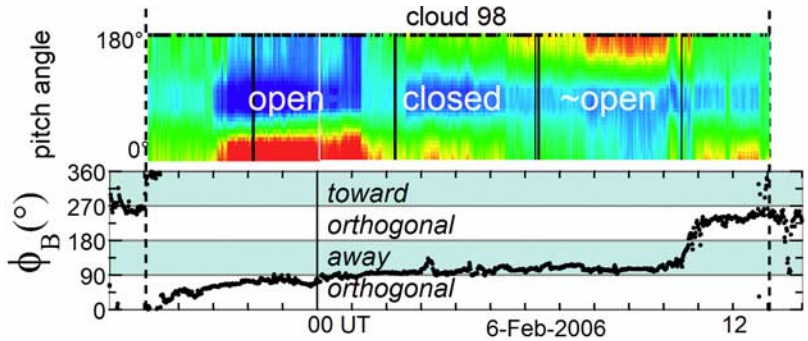

Figure 4. Same as Figure 3 for a magnetic cloud with open fields first parallel (0°) and then antiparallel (180°) to the magnetic field signaling positive (away) and negative (toward) solar polarities. The negative fields locally lie in the away quadrant, signaling an inverted configuration.

blank for three of the cases owing to contamination of the electron signatures by energetic particle events.

[15] The remaining 97 magnetic clouds were analyzed for topological properties. Fine structure on scales of <1 h was ignored. Of the 97 cases, 25 (26%) were categorized as having no open fields and were dropped from further consideration; hence, the last two columns in Table 1 for these cases are also blank. The number of cases with no open fields is proportionally higher than the 14% found by *Shodhan et al.* [2000] and *Crooker et al.* [2004]. Owing to difficulties in distinguishing 90° pitch angle depletions from counterstreaming on closed loops, as discussed in section 2.1, some of the cases in Table 1 are more questionable than others, as indicated with a question mark.

[16] Of the 72 magnetic clouds that are listed as having open fields, the solar polarity of those fields is of only one sign in 64 (89%) cases, as indicated in the pie chart in Figure 5a. This finding comprises the primary result of this paper. It implies that interchange reconnection during CME liftoff occurs predominantly in only one leg of the CME. Further implications are discussed in section 3. Table 1 also reveals that the ratio of negative (toward) to positive (away) polarity in the 64 cases of single sign is 26/38. The reason for this imbalance between polarities is not understood. Table 2 summarizes the magnetic cloud properties discussed in this section and, also, in section 2.3.

2.3. Local Field Inversions

[17] By comparing the solar polarity determined from the electron data with the in situ orientation of the magnetic field, one can test to what degree the fields in magnetic clouds are locally inverted, as expected for coils in a flux rope. In Figure 2, for example, after reconnection, the field line forming the open coil has portions directed toward the Sun, even though it is rooted in the Sun with away polarity. A comparison between the solar and local polarity in the last two columns of Table 1 gives the relevant information. If the polarities are opposite, as for cloud 1, then the open fields are inverted, whereas if they are the same, as for cloud 2, the fields are not inverted. (In cases where the polarities are mixed, the order in which they are listed reflects the order in which they occur in order to reveal whether or not the fields are inverted. For example, in cloud 77, both the solar and local polarities are listed as "toward, away," indicating no inversion.) Only 27 of the 72 magnetic clouds

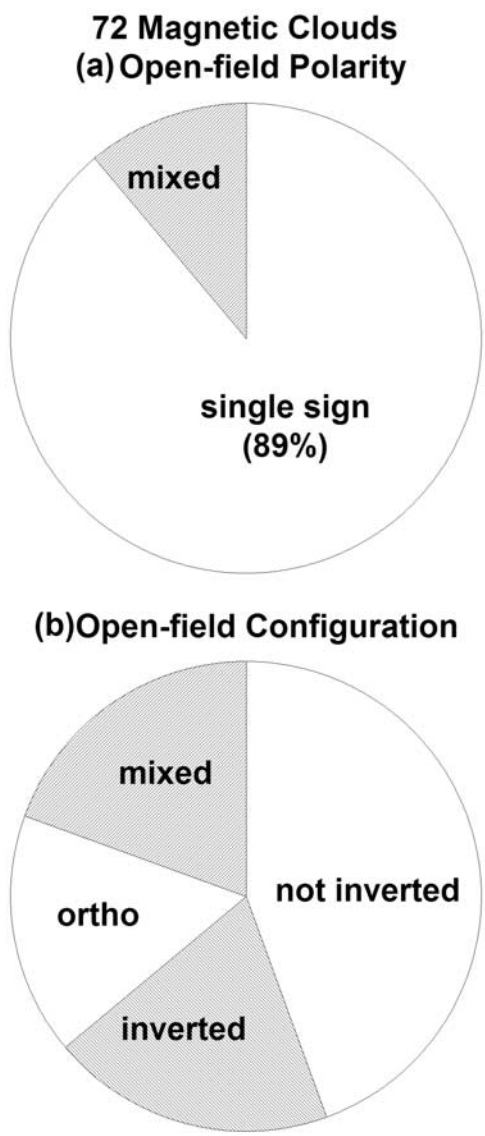

Figure 5. Properties of open fields in 72 magnetic clouds: (a) Polarities are mostly of a single sign, implying that cloud fields preferentially open by interchange reconnection in only one leg of their closed loops, and (b) contrary to expectations, fewer field lines in clouds are inverted than not inverted.

Table 2. Summary of Field Properties of 100 Magnetic Clouds

Properties	Number of Cases
Cloud Classification	
Contaminated data	3
Completely closed	25
Some open fields	72
Polarities of Open Fields	
Single	64
Toward	26
Away	38
Mixed	8
Configuration of Open Fields	
Inverted	6
Inverted + ortho	8
Not inverted	21
Not inverted + ortho	11
Ortho	12
Mixed	14

with open fields, however, meet these simple criteria: six are inverted and 21 are not inverted. If we add to these categories cases that exhibit inverted or noninverted fields mixed with fields orthogonal to the Parker spiral, as might be expected, for example, along the leading edge of the open coil in Figure 2, then the numbers expand to 14 inverted and 32 not inverted. Of the remaining 26 magnetic clouds with open fields, 12 have only orthogonal fields and 14 have a mix of inverted and noninverted fields, some with orthogonal fields, as well. These statistics are listed in Table 2 and are illustrated in the pie chart in Figure 5b. Overall, although inversions are common, they are not equally as common as noninverted fields, as might be expected from Figure 2. Possible reasons for these unmet expectations are discussed in section 3.

3. Discussion

[18] Whereas earlier papers have shown that most magnetic clouds in the heliosphere contain open field lines [*Shodhan et al.*, 2000; *Crooker et al.*, 2004], the present paper goes on to show that those open field lines are predominantly of a single polarity at 1 AU. We thus conclude that the interchange reconnection that opens magnetic clouds before they reach 1 AU occurs primarily at a single site with open fields of a single polarity. As closed coiled loops rise through the corona, field lines in one leg of those loops reconnect with a bundle of open field lines of the opposite polarity, thus systematically transporting those open fields from their original location, presumably a coronal hole, to the foot point of the opposite leg of the rising loops (Figures 1 and 2).

[19] We note that the proposed mode of flux transport is not inconsistent with the disappearance of dimmings, which presumably mark the foot points of the flux rope loop. For the 12 May 1997 event illustrated in Figure 1, one might expect that dimming in the equatorward region was long lived, since the equatorward foot point remained connected to the Sun. Although the equatorward dimming region did disappear, *Attrill et al.* [2006] found that it did so at a rate slower than in the poleward region. They suggest that the slower disappearance might reflect a random diffusion process of open-field foot points out of the region through interchange reconnection low in the solar atmosphere with small loops in the magnetic carpet.

[20] The implied systematic transport of open flux may be a key component in the reversal of the solar-heliospheric magnetic field, as proposed by *Owens et al.* [2007]. Because the pattern of magnetic cloud foot points tends to reflect the Hale Law for sunspot polarity [e.g., *Bothmer and Schwenn*, 1997], with the leading foot point at lower latitude having the same polarity as the polar coronal hole in that hemisphere at the start of the solar cycle (Figure 1), the interchange reconnection acts first to transport open fields from the polar coronal holes toward the equator. As the cycle progresses, *Owens et al.* [2007] illustrate how interchange reconnection in CMEs combined with the Hale pattern of their foot points will continue to transport the open flux across the equator and then toward the poles to complete the reversal. On the basis of observed CME rates and estimates of ICME flux content, and assuming that all fields in ICMEs eventually open by interchange reconnection, following *Owens and Crooker* [2006], *Owens et al.* [2007] calculate that, on average, the flux in each CME would have to be transported by $\sim 5°$ of latitude to complete the reversal in 11 years. Since 5° is an order of magnitude smaller than the 50° over which flux was transported in the May 1997 event, as discussed in section 1, the proposition that interchange reconnection in CMEs is the means by which the heliospheric field reverses seems to be a highly reasonable one.

[21] To that argument we add that even if open flux is transported in opposite directions in a given event, as implied for the 9 magnetic clouds with mixed polarities in Table 1 and as may be more common for interchange reconnection that occurs long after CMEs leave the Sun, the net transport of signed flux will still be about the same as if all of the flux of a single polarity were transported in one direction. For example, if in Figure 1 some of the field lines in the positive, equatorward leg of the magnetic cloud interchange reconnected with nearby negative open fields, those negative open fields would be transported poleward to the negative foot point of the cloud. This poleward transport of negative flux, like the equatorward transport of positive flux depicted there, acts in the direction that will change the polarity of the solar field in the course of the solar cycle. The only caveat is that if a given loop interchange reconnects in both of its legs, the resulting field line will disconnect from the Sun, as illustrated by *Gosling et al.* [1995]. While evidence of disconnected fields has been found in some magnetic clouds [e.g., *Larson et al.*, 1997, 2000], it is an uncommon property [*Shodhan et al.*, 2000] and would thus have little impact on the net transport of flux by interchange reconnection in CMEs.

[22] Although the findings of this study are consistent with the systematic flux transport required by the *Owens et al.* [2007] model, we add that they only go so far as to demonstrate that transport is predominantly in a single direction in each ICME. Determining whether that is the expected direction and estimating whether sufficient flux was transported would require a follow-up study of the solar configuration of the magnetic field surrounding each associated CME.

[23] A secondary finding of our study is that local field inversions in magnetic clouds are not as common as one might expect from passage through coiled configurations. That is, in passing through flux ropes, one might expect to encounter as many fields turned back on themselves as not, whereas the results show less than half as many. These results can be understood, however, with further consideration of flux rope geometry. Histograms (not shown) of the axis elevation and azimuthal angles derived from the force-free flux rope fits to all 100 magnetic clouds indicate that most axes lay close to the ecliptic plane and close to perpendicular to the Sun-Earth line. For this head-on orientation, a spacecraft passing close to the axis, through the heart of the flux rope, would encounter no inverted fields. Inverted fields would be encountered only with passage considerably above or below the axis, and then only half the time, depending upon the field polarity. Furthermore, the 32 cases without inverted fields have a disproportionate number of axes closer to alignment with the Sun-Earth line, indicating passage through the legs of those flux ropes. Fewer inverted fields would be expected in the legs because the field coils there presumably are less tightly wound and have circular projections in planes more perpendicular than parallel to the Sun-Earth line. In view of these considerations, the finding that inverted fields are not as common as noninverted fields in magnetic clouds seems reasonable.

4. Conclusions

[24] Suprathermal electrons in magnetic clouds at 1 AU serve as remote sensors of reconnection processes at the Sun. From an analysis of these electrons in this study and earlier studies, we conclude that in at least 74% of magnetic clouds some closed fields undergo interchange reconnection with open fields during or shortly after CME release. Moreover, in an overwhelming majority of these cases, the site of the interchange reconnection is confined to one leg of the flux rope loop that composes the magnetic cloud. This systematic pattern of interchange reconnection in CMEs transports large amounts of open flux on the Sun across large distances, of the scale of the angular widths of CMEs, consistent with the hypothesis that CMEs play a major role in the solar cycle reversal of the Sun's magnetic field [e.g., *Owens et al.*, 2007].

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