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Solar wind signatures associated with magnetic clouds

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Abstract. Magnetic clouds are commonly observed in association with bidirectional fluxes of electrons and ions, and in some cases also with shocks and helium enrichments [*Gosling*, 1990; *Richardson*, 1997]. In this work we use satellite data in the solar wind near Earth to study 71 magnetic clouds observed between 1967 and 1984 in order to find possible differences in the characteristics of clouds when they are or they are not associated with shocks and with helium enhancements. In our sample we find that 51% of the clouds were preceded by an interplanetary transient shock and that 65% were associated with a helium enhancement observed before, inside, or after the cloud. To investigate the characteristics of magnetic clouds we consider the spatial profiles of magnetic field and plasma parameters (bulk speed, density, temperature, β, and pressure) inside them, observed as temporal variations as clouds pass plasma and magnetic field detectors on board satellites in near-Earth orbit. The mean magnitudes of these parameters inside the cloud were also considered. We find that the profiles of the magnetic field strength and plasma parameters are different depending on whether the cloud is associated or not with a shock and/or a helium enrichment. The mean values of magnetic field strength, bulk speed, temperature, and pressure are higher for shock-associated clouds than for clouds without a shock. Mean values of bulk speed, density, temperature, and β are different for clouds associated with helium enrichments and for clouds without this signature. Mean values of the magnetic field strength and pressure are very similar for both types of clouds. Some of these results were previously obtained by other authors.

1. Introduction

Magnetic clouds are commonly observed in association with other transient interplanetary signatures such as shocks [*Klein and Burlaga*, 1982], helium enhancements [*Borrini et al.*, 1982a], bidirectional fluxes of suprathermal electrons [*Gosling et al.*, 1987], bidirectional fluxes of ions [*Marsden et al.*, 1987], and decreases in the energetic (> 1 MeV) particle intensity [*Cane et al.*, 1997]. The characteristics of magnetic clouds (MCs) in association with interplanetary shocks has been studied by *Klein and Burlaga* [1982], who found that shock-associated clouds tend to move faster than clouds that are not associated with a shock, and by *Zhang and Burlaga* [1988], who found that in shock-associated clouds the decrease in cosmic ray intensity is larger than in clouds without a shock. In a previous work [*Bravo and Blanco-Cano*, 1998], where we studied a sample of 40 MCs preceded by a shock, we found that 72% were associated with helium enhancements.

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However, possible differences in the general characteristics of clouds associated and not associated with shocks (S) and/or with helium enrichments (A(He), where "A" means abundance) have never been studied. In this work we study 71 MCs observed between 1967 and 1984 at 1 AU, and we investigate such possible differences. Our data set consists of 51 magnetic clouds taken from the literature and 20 from hourly averaged OMNI tape data maintained by the National Space Science Center. To identify magnetic clouds from the OMNI tape data we looked for regions where the magnetic field is higher than in the average solar wind and rotates smoothly through a large angle within a plane. We performed a minimum variance analysis (for a description of this technique, see Appendix A of *Bothmer and Schwenn* [1998] to determine if the field rotation was on a plane, and we consider that this occurs when $\lambda_2/\lambda_3 \geq 2$ (λ_2 and λ_3 are the eigenvalues corresponding to the directions of the intermediate and minimum variance). The choice of 2 is based on the analysis of *Lepping and Behannon* [1980]. The last column in Table 1 gives the value of λ_2/λ_3 for the 20 MCs identified from OMNI tape data. The boundaries of the 51 MCs taken from the literature are considered as reported by the authors who identified the cloud. To determine the boundaries of the 20 MCs identified from OMNI data we consid-

Table 1. IP Magnetic Clouds Used in This Study and Their Association with IP Transients[a].

Cloud					Cloud Morphology						IP Transients			
No.	Date	Ref.[b]	Δt	Δr	B	v	n	T (10^4)	β	P	S	A(He)	Δts	λ_2/λ_3
	1967													
1	Jan. 13	9	33	0.36	C 11	A+ 460	C- 5	E 3.9	E 0.1	C 5	Y		09	
2	Dec. 15	9	27	0.26	B 13	C 390	F 14	F- 3.8	C- 0.2	B 8	N		-	
3	Dec. 30	11, 9	42	0.41	B 13	C- 408	F- 4	B- 6.2	G 0.1	B 8	Y		04	
	1968													
4	Jan. 2	9	36	0.37	B 10	F 425	C 5	B 11.4	E+ 0.2	B 5	N		-	
5	Jan. 27	9	21	0.22	F 6	F 427	C 5	E 7.1	C 0.4	A+ 2	Y		20	
6	Feb. 27	9	18	0.14	D 11	D 324	D 20	G- 5.5	G 0.4	D 7	N		-	
7	Jun. 25	9	17	0.14	F+ 6	D 366	B 12	G- 8.6	G+ 1.8	B 3	N		-	
	1969													
8	Jan. 23	9	27	0.26	D 9	D 374	C 7	E 10.9	C 1.7	D 5	N		-	
9	Feb. 11	9	27	0.29	B 12	C 452	C- 4	A- 2.3	E 0.1	B 6	Y		13	
10	Mar. 4	9	16	0.15	B 10	B 407	C+ 11	D- 5.6	E 0.4	B 6	N		-	
	1971													
11	Apr. 4	O, 1	15	0.16	F+ 11	C 466	F+ 14	G 12.4	C 1.4	F+ 8	Y	Y	04	10.9
12	Apr. 8	9, 1	17	0.14	A 4	A 352	D 13	E 2.4	G 0.8	A 1	N	N	-	
13	Jun. 23	11	27	0.22	C 9	A 339	E 6	C- 2.5	E 0.1	B 3	N		-	
	1972													
14	Jan. 15	9	13	0.11	C 10	A 352	E+ 19	D 8.6	E+ 0.7	B 6	N		-	
15	Feb. 10	9	18	0.16	B 10	A+ 382	E+ 15	D 4.8	E+ 3.2	B 6	N		-	
16	Feb. 17	9, 2	39	0.39	D 8	A 400	C 6	A- 4.8	E+ 0.3	A+ 3	N	Y	-	
17	Mar. 22	9	15	0.12	F 4	C 341	F 15	E 3.7	G+ 1.9	E+ 12	Y		21	
18	Mar. 27	9, 2	25	0.25	D 15	A+ 407	C 7	B- 7.4	E 0.9	D 10	N	Y	-	
	1973													
19	Jan. 20	9, 2	24	0.22	A+ 11	C 400	E 6	E+ 19.8	G 0.5	A 7	N	N	-	
20	Mar. 5	9	24	0.20	B 7	D 358	D 15	E 2.9	G+ 0.7	D 4	N		-	
21	Mar. 31	9	27	0.29	D 17	A 449	E 13	E 4.1	E 0.1	D 14	N		-	
22	Apr. 14	O, 1	19	0.21	F 15	C 465	C..23	G 9.4	C- 0.4	C+13	Y	Y	29	5.7
23	May. 21	1, 9	17	0.27	D 12	B 665	C- 6	C- 9.4	C- 0.6	F+ 7	Y	Y	01	
24	Jun. 28	9	16	0.21	F+ 9	D 547	B 18	D 21.5	F+ 1.4	F+ 8	N		-	
25	Sep. 26	9, 2	30	0.29	B 12	C 415	B 14	A- 2.3	A- 0.1	B 6	N	Y	-	
26	Nov. 21	9	14	0.13	B 12	C 379	B 15	B- 5.9	G 0.5	B 8	N		-	
	1974													
27	Jan. 24	15	30	0.23	D 4	A 316	D 25	A 5.0		B- 4	N		-	
28	Oct. 12	O, 1	35	0.36	B 15	A 421	E 8	G- 4.5	E 0.1	A+ 9	Y	Y	07	21.0
29	Dec. 2	O, 2	19	0.17	D 10	D 350	D 16	E 3.8	E 0.2	D 5	N	Y	-	20.3
	1975													
30	Jan. 7	14	21	0.31	C+ 14	C 725	E 7	G- 12.5			Y	Y	03	
31	Mar. 27	9	15	0.22	B 7	D 608	B 10	B 20.7	G+ 1.3	B 5	N		-	
32	Apr. 20	9	20	0.22	F+ 10	D 474	E+ 17	D 9.1	G+ 1.0	D 7	N		-	
33	May. 25	9	31	0.31	B 9	C 421	D 9	E 3.4	E 0.2	B 4	N		-	
34	Aug. 1	9	21	0.18	B 12	C 370	F+ 11	A- 2.0	E 0.1	D 6	N		-	
35	Nov. 17	9	29	0.25	B 11	C- 369	F 20	E 1.4	E 0.2	B 5	N		-	
	1976													
36	Jan. 10	O, 1	22	0.21	A+ 17		D 20	F 4.1	E 0.1	B 13	Y	N	07	11.7
37	Dec. 8	9	18	0.18	B 10	D 415	A 11	B 9.0	F 0.3	B 5	N		-	
	1977													
38	Jun. 5	9	21	0.18	F+ 5	C 364	F+ 13	A- 2.4	F 0.5	F 1	N		-	
39	Sep. 22	O, 1	32	0.49	B 7	A 640	C 4	F- 15.7	G 0.8		Y	N	06	2.6
40	Sep. 26	9, 2	30	0.28	F+ 10	A 382	C 11	A- 2.7	E 0.4	B 5	N	Y	-	
41	11/25	O, 1	20	0.15	B+ 14	A+ 314	C 16	A 3.8	E+ 0.1	B 9	Y	N	03	25.1
	1978													
42	Jan. 4	9, 2	34	0.46	C+ 15	C 578	F- 5	F- 7.3		A+ 9	Y	Y	16	
43	Jan. 16	9, 16	48	0.30	A+ 11	F+ 320	F- 18	G 1.8	F- 0.1	A+ 5	N		-	
44	Jan. 29	O, 1	18	0.22	B 17	D 538	F 14	F+ 14.1	E+ 0.4	B 14	Y	Y	21	48.8
45	Mar. 2	3	24	0.37	C 20	C 450	F 7	F- 18.1			Y		13	
46	Apr. 3	13	21	0.24	F+ 11	F 464	D- 10	D- 7.2	E+ 0.6	B 6	N		-	
47	Jun. 5	13	20	0.22	F+ 9	C 483	B 10	A- 3.0	A- 0.1	A+ 3	Y		21	
48	Aug. 27	O, 4, 12	24	0.26	B 18	F 445	E+ 17	F+ 9.3	E- 0.5	B+16	Y	N	15	9.3
49	Sep. 29	O, 1	23	0.42	B 16	C 750	C 3	E 15.9	E- 0.2	B 12	Y	Y	08	3.2
50	Oct. 9	O, 4	24	0.22	F+ 8	B 388	F 12	B 6.5	F- 0.4	F+ 4	Y		06	15.1
51	Oct. 17	O, 4	13	0.12	B 10	D 390	C+ 17	D 12.0	E+ 0.8	B 7	Y		20	20.3
52	Oct. 29	O, 4	36	0.34	D 10	C 401	F 8	F 3.0	F- 0.1	D 5	N		-	19.9
53	Nov. 12	O,12	17	0.24	C 12	A+ 569	F 13	C 18.8	C- 0.7	C 10	Y	Y	09	8.9
	1979													

Table 1. (continued)

Cloud					Cloud Morphology						IP Transients			
No.	Date	Ref.[b]	Δt	Δr	B	v	n	T (10^4)	β	P	S	A(He)	Δts	λ_2/λ_3
54	Jan. 7	O, 1	21	0.24	B 12	C 523	B 10	F- 3.9	C- 0.2	B 6	Y	N	31	5.7
55	Feb. 21	O, 4, 12	24	0.30	B 15	B 523	F+ 17	B 9.6	F 0.3	B 12	Y	Y	01	11.5
56	Mar. 22	O, 4, 12	34	0.34	F 13	F 494				:	Y	Y	12	6.9
57	Apr. 03	6, 7	29	0.34	C 15	C 472	B 12	E 9.4			Y	N	04	
58	Apr. 25	6,12	31	0.42	C 12	C 575	C- 7	E 4.7	E 0.1	C 8	Y	Y	09	
59	Sep. 18	13	26	0.23	B 12	B 368	C- 10	E- 2.6	E 0.1	C 6	N		-	
60	Oct. 6	O, 7	13	0.12	B 15	A 406	C 30	C- 6.6	E 0.9	B 12	Y	N	04	6.6
61	Dec. 3	16	28	0.24	B 9	C 353	F 7	A- 1.9	F- 0.1	A+ 3	N		-	
	1980													
62	Feb. 15	13	29	0.25	B 15	C 372	F 6	A- 2.1	E 0.1	B 9	N		-	
63	Mar. 19	16	51	0.39	B 13	C 316	E 10				Y		09	
64	May. 8	8	40	0.36	B 13	A 396	F+ 12	D 5.7	E+ 0.2	B 7	N		-	
65	Jul. 25	O,12	12	0.13	C 11	A+ 462	C 16				Y		07	8.4
66	Dec. 19	16	23	0.27	A+ 30	F 502	F- 8	F 4.9		C 36	Y		08	
	1981													
67	Feb. 6	13	14	0.16	A+ 11	C 495	C 6	A- 1.8			Y		11	
68	Mar. 5	13	33	0.38	C 13	F 495	C 7				Y		09	
69	May 18	12	15	0.25	C 12	C 702	C 6	F 12.2	E 0.1		Y		08	
	1982													
70	Jan. 31	O, 8	15	0.18	B 12	C 512	B 17				Y		11	8.6
71	Feb. 11	8, 16	14	0.18	B 24	C 525	E 9				Y		05	

[a] IP, interplanetary; A, flat profile; B, profile with a maximum; C, descending profile; D, ascending profile; E, profile with a minimum; F, oscillating profile; G, profile with two minima; O, OMNI tape.

[b] 1, Borrini *et al.* [1982a]; 2, Borrini *et al.*, [1982b]; 3, Bothmer and Schwenn [1992]; 4, Bravo and Lanzagorta [1994]; 5, Burlaga *et al.* [1981]; 6, Burlaga *et al.* [1987]; 7, Gosling *et al.* [1987]; 8, Kahler and Reames [1991]; 9, Klein and Burlaga [1982]; 10, Marsden *et al.* [1987]; 11, Marubashi [1986]; 12, Richardson and Cane [1993]; 13, Rust [1994]; 14, Webb *et al.* [1993]; 15, Wilson and Hildner [1986]; 16, Zhang and Burlaga [1988].

ered the duration of the rotation of the magnetic field and of the interval where the magnetic field was higher than average.

We evaluate the average values of plasma and field parameters using the corresponding data found in the OMNI tape, and we analyze their variation inside the various types of clouds. This data set was also used in another paper where we studied the morphology of magnetic clouds in relation to their associated near-surface solar events [see *Bravo et al.*, 1999].

2. General Characteristics of Magnetic Clouds

We consider an interplanetary (IP) signature to be a magnetic cloud when its magnetic field is higher than average and rotates smoothly nearly parallel to a plane during a time interval of the order of a day [*Burlaga et al.*, 1981]. In this study no restriction was imposed on the other parameters of the cloud such as velocity (v), density (n), temperature (T), plasma beta (β), and pressure (P), because we want to study how the variations of these parameters are when the cloud is associated or not associated with transient shocks and with helium enhancements.

Table 1 shows the characteristics of the 71 magnetic clouds studied in this work, indicating if they are associated (Y) or not (N) with shocks and helium enrichments. The first column in Table 1 is the number of the event. The second column gives the date (month and day) of the observation of the cloud at 1 AU. The third column gives the reference in the literature where the cloud was reported, according to the footnote below the table. The fourth and fifth columns show the duration (Δt) and radial extent (Δr) of the MCs in hours and astronomical units (AU), respectively. Δr was obtained as Δt times the mean speed of the cloud. The sixth to eleventh columns give the average values and profiles of the field and plasma parameters of the cloud (which will be explained in section 3). The twelfth and thirteenth columns show the association of the cloud with a shock (S) and with helium enrichments (A(He)). The fourteenth column gives the time delay between the observation of the shock and the starting time of the cloud for the cases where the MC was preceded by a shock. The fifteenth column in Table 1 gives the ratio between the eigenvalues of intermediate and minimum variance directions. In all the columns, blanks mean a lack of information. Following the definition by *Borrini et al.*

[1982a], we considered that the plasma was helium rich when $He^{++}/H^{+} > 0.08$.

3. Values and Profiles of the Magnetic Field and Plasma Parameters Inside MCs

The inspection of the 71 MCs used in this study shows that the plasma and magnetic field parameters are not homogeneous inside a cloud but present different types of profiles. Figure 1 shows two examples, where the variation of the values of B, v, n, T, P, and β inside the clouds observed on November 17, 1975, and on August 1, 1975 (from the list of *Klein and Burlaga* [1982]) can be seen. The average values of the different parameters within each cloud are given in the sixth to eleventh columns in Table 1 in the following order: magnetic field strength (in nT), proton bulk speed (in km s^{-1}), proton density (in cm^{-3}), proton temperature (in K), β parameter, and pressure (in units of 10^{-10} dyn cm^{-2}). The spatial profiles of magnetic field and plasma parameters inside clouds, observed as temporal variations as clouds pass detectors, are of different types: A, flat; B with a maximum; C descending; D ascending; E with a minimum; F oscillating; and G, with two minima. These types are sketched in Figure 2 and indicated in Table 1 beside the average value. When a plus sign is added to the profile letter, it means that the cloud values are mainly above the average value in the solar wind before the cloud (or before the shock, for shock-associated clouds). A minus sign means that the cloud values are mainly below the previous average. The types of profiles shown by the magnetic field strength and plasma parameters inside the clouds in Figure 1 are indicated on the right side of the figure.

We find that certain profiles are absent in some of the MC parameters. The field strength and the bulk speed never show a profile with one (type E) or two minima (type G). The particle density never shows two minima profiles. The parameter β never shows a profile with a maximum (type B) or ascending (type D). The pressure never presents two minima profiles and only in one occasion shows a one-minima profile. The temperature may present any type of profile.

Some of the cloud parameters seem to be related: while for the larger clouds with $\Delta r > 0.3$ AU, we find that $n \leq 12$ and $\beta \leq 1$; for smaller clouds, with $\Delta r \leq 0.3$ AU, the plasma density and β reach greater values, $n \leq 30$ and $\beta \leq 3.2$. That larger clouds have lower densities and lower β can be understood if we consider that these clouds have suffered more expansion while traveling toward the Earth than clouds with smaller Δr. Among the MCs with $\Delta r \leq 0.3$ AU, six had beta values greater than unity, and in five cases, $1 < \beta < 2$. We do not find differences between the properties of these six clouds and MCs with $\beta < 1$.

We also find that for fast clouds ($v > 550$ km s^{-1}) $\beta \leq 1.5$ and $n \leq 13$, but for slower clouds ($v \leq 550$ km s^{-1}) the plasma β and density reach greater values, with $\beta \leq 3.2$ and $n \leq 30$. Although not a real correlation exists, all clouds with $v \geq 550$ km s^{-1} have sizes $\Delta r > 0.22$ AU.

4. Characteristics of Magnetic Clouds Associated and not Associated With Interplanetary Shocks

In our data set, 36 (51%) clouds were preceded by a transient shock. The time delay between the passage of the shock and the appearance of the cloud was between 1 and 31 hours with a mean value $\Delta t_s = 11$ hours. This mean value is consistent with previous results by *Bothmer and Schwenn* [1998]. It is generally believed that interplanetary shocks are generated by solar ejecta propagating at large speeds with respect to the solar wind. However, the large range of values that we find for the time delay between the shock and the MC suggests that clouds may not always be the pistons of interplanetary transient shocks, although it is possible that the shock has outrun the cloud during the transit to 1 AU or that the shock may be associated with a different part of a complex ejecta that includes the magnetic cloud.

4.1. Values and Most Common Profiles of Magnetic Field and Plasma Parameters

Table 2 shows the range of average values (taken over the entire duration of each magnetic cloud), the mean of the average values (taken over the set of studied clouds), and the most common profile for magnetic field and plasma parameters of clouds associated with shocks and of clouds without a shock. We see that the ranges of average values of B, v, n, and P are wider for shock-associated clouds than for clouds without a shock. The mean values of B, v, T, and P in the sample are higher for clouds preceded by a shock than for clouds without a shock. The mean values of the n are similar for both types of clouds.

The most common profiles for B, v, β, and P are the same for MCs preceded by a shock and for MCs without a shock. However, the most common profiles for n and T are different in both samples. For shock-associated MCs the density presents most commonly a descending type of profile, but clouds without a shock present most commonly irregular density profiles. The temperature in shock-associated MCs shows most frequently an irregular profile, but the most common temperature profile in clouds without a shock shows a minimum within the cloud.

4.2. Duration and Radial Extent

Figures 3a and 3b show the distribution of the values of Δt and Δr, respectively, for MCs with and without a shock. The mean values are shown in each panel. No cloud has a duration of less than 12 hours or more than

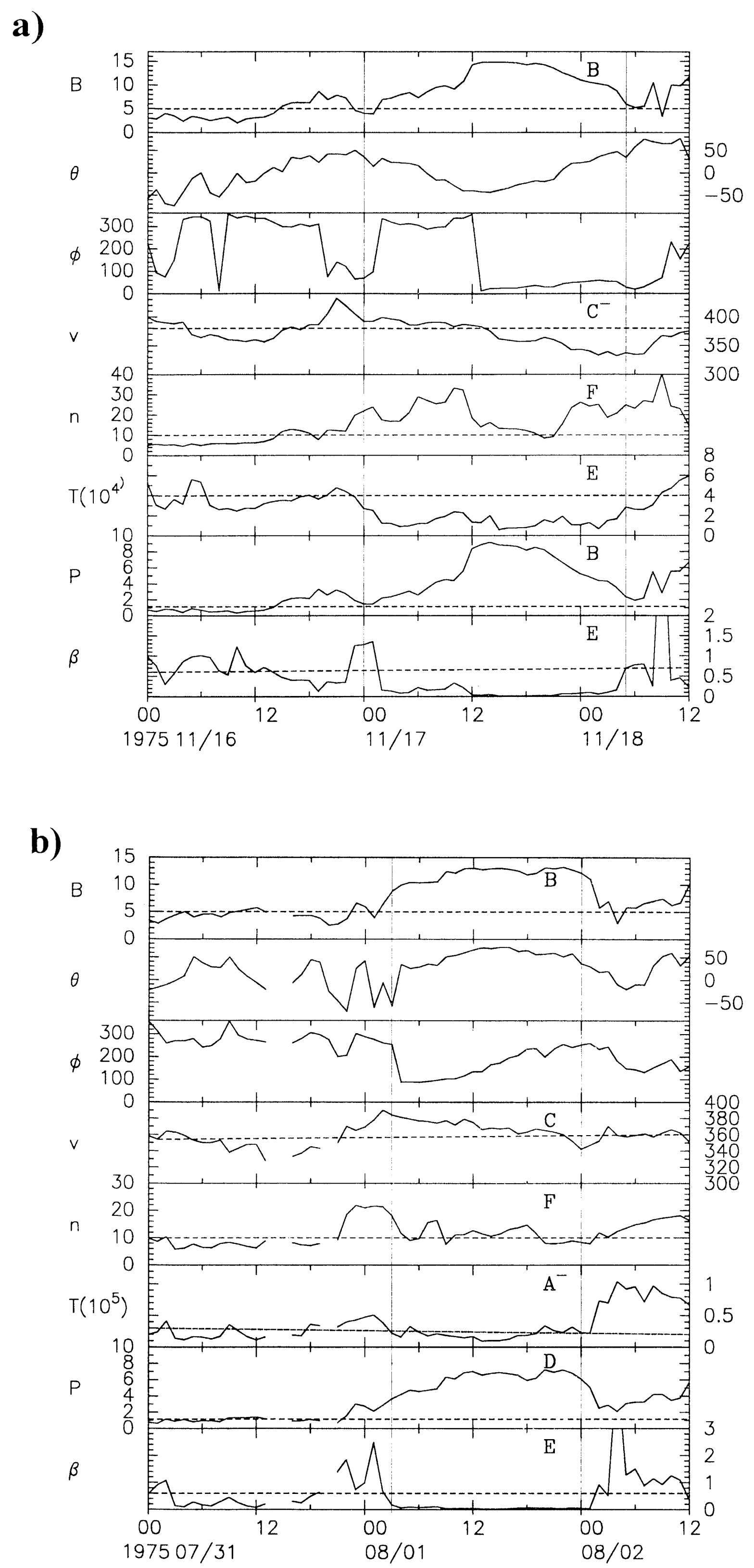

Figure 1. Magnetic clouds observed on (a) November 17, 1975, and (b) August 1, 1975 (OMNI tape data). The duration of the cloud is indicated by vertical lines. The type of each profile is indicated on the right of each panel.

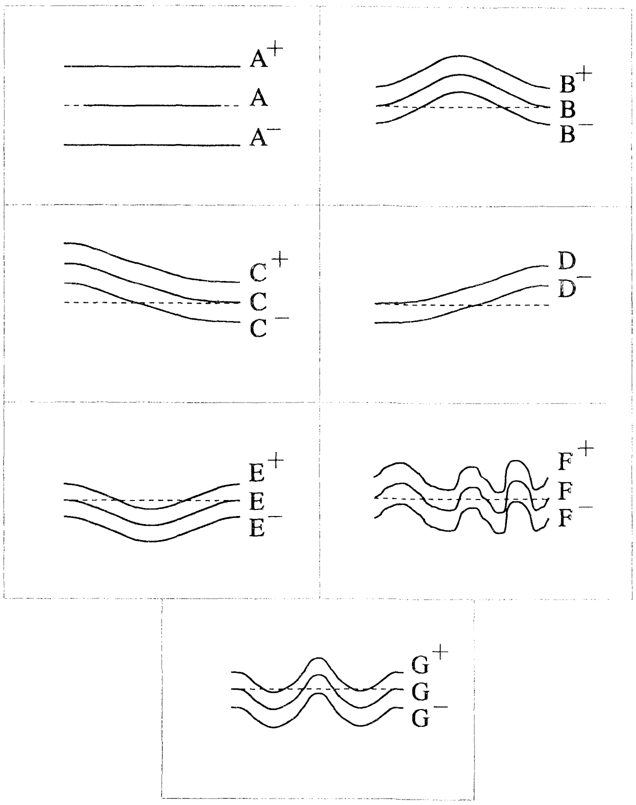

Figure 2. Different types of profiles presented by the magnetic field and plasma parameters inside the interplanetary magnetic clouds in this study. The dashed line represents the value in the solar wind in front of the cloud.

51 hours. The maximum durations were 51 hours for a shock-associated cloud and 48 hours for a cloud without a shock. The most frequent duration was in the interval 20-25 hours for shock-associated clouds and in the interval 25-30 hours for clouds that were not preceded by a shock. The most frequent size was in the interval 0.20-0.25 AU for both types of clouds. The mean duration is similar ($\Delta t \sim 25$ hours) for both types of clouds. However, the mean size of clouds preceded by a shock ($\Delta r = 0.27$ AU) is larger than that of clouds without a shock ($\Delta r = 0.23$ AU). This is a consequence of the fact that the average speeds for the majority of clouds without a shock span a shorter range of values ($v \sim 400$ km s^{-1}) than that for clouds preceded by a shock, as can be seen in Figure 4. Shock-associated clouds have radial extents in the range 0.12 – 0.49 AU, and Δr values for clouds without a shock were in the range 0.11 – 0.39 AU.

5. Characteristics of Magnetic Clouds Associated and not Associated With Helium Enhancements

We looked in the literature and found helium information for 26 of the studied clouds (see references in Table 1). Of these clouds, 65% were associated with a helium enhancement. Table 3 shows the date and durations of 15 of the MCs associated with A(He). The fourth and fifth columns display the date and starting times for the helium events. We do not have the durations of A(He) in many cases, but we know that all helium enrichments lasted at least 2 hours [*Borrini et al.*, 1982b]. The sixth column in Table 3 indicates whether the A(He) was observed before (b), inside (i) or after (a) the magnetic cloud. We find that for clouds without a shock, the A(He) was always observed inside the cloud. In contrast, for shock-associated clouds the helium enrichment can occur before, inside, or after the cloud. This is in agreement with previous findings [*Gosling*, 1990; *Burlaga et al.*, 1998; *Bravo and Blanco-Cano*, 1998] that show that although commonly different signatures appear in a single interplanetary transient event, they are not necessarily simultaneous.

5.1. Values and Most Common Profiles of Magnetic Field and Plasma Parameters

Table 4 shows the range of average values, the mean value, and the most common profile for the magnetic field and plasma parameters of clouds with and without helium enhancements. We can see that for B and v the ranges of average values are larger for A(He) clouds than for clouds without helium. For T, β, and P the ranges of the average values are similar for the two samples. We

Table 2. Values of Parameters and Most Common Profiles for Clouds Associated with Shocks and for Clouds Without a Shock

	Range of Average Values		Mean Values		Most Common Profile	
	Shock	No Shock	Shock	No Shock	Shock	No Shock
B, nT	4-30	4-17	13	10	B	B
v, km s^{-1}	314-750	316-608	497	394	C	C
n, cm^{-3}	3-30	5-20	11	12	C	F
T, 10^4 K	2.3-18.8	1.4- 21.5	8.8	6.2	F	E
β	0.1-1.9	0.1-3.2	0.45	0.57	E	E
P,10^{-10} dynes cm^{-2}	2-36	1-14	10	6	B	B

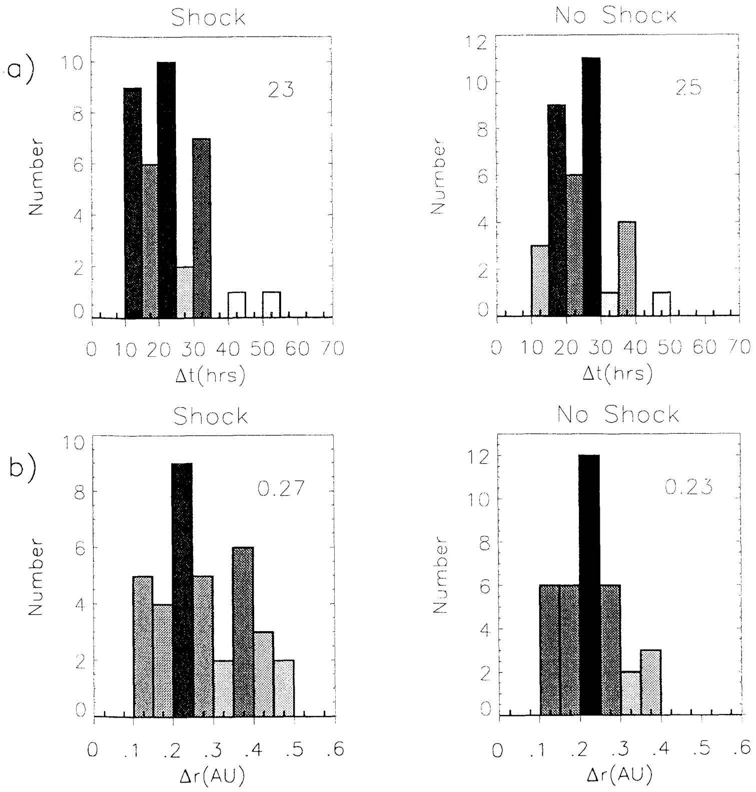

Figure 3. Distribution of the values of (a) δt and (b) δr, of clouds in relation to their association with interplanetary (IP) shocks.

find that the mean speed and temperature of MCs with A(He) are larger than those of MCs without A(He). The mean values of n and β are larger for clouds without A(He), and the mean values of B and P are very similar for both types of MCs.

Figure 5 shows the frequency of occurrence of profiles for parameters inside clouds with and without A(He). The most common profile for B, n, β, and P is the same for clouds with and without A(He). The magnetic field and the pressure have most frequently a maximum (type B) profile. The most common profile for the density was a descending profile (type C), and the most common profile for the β was a minimum (type E) profile. The most common profile for v and T is different for both types of clouds. The speed inside MCs with A(He) most commonly shows a descending profile (type C), while in MCs without A(He) the speed profile is most frequently flat (type A). The temperature of MCs with A(He) shows a similar frequency of occurrence of profiles with a minimum (type E) and with two minima (type G).

5.2. Duration and Radial Extent

Figure 6 shows the distribution of the values of Δt (Figure 6a) and Δr (Figure 6b) for MCs with A(He) and without A(He). The mean values are shown in each panel. No cloud has a duration of less than 15

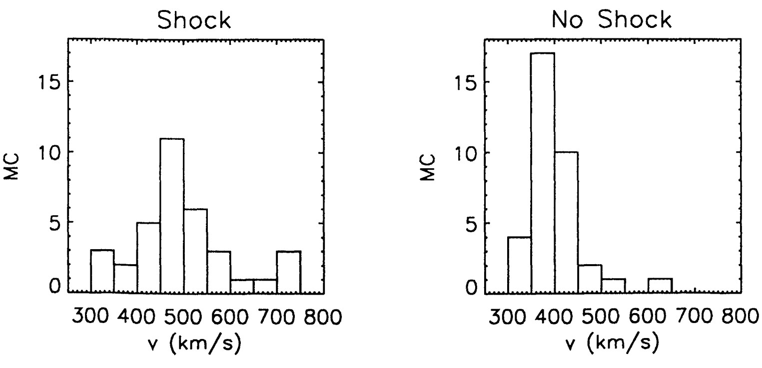

Figure 4. Distribution of velocities for shock-associated clouds and for clouds without a shock.

Table 3. Time of Observation of MCs and Helium Enrichments[a]

	MC		A(He)		
Number	Date	Duration, UT	Date	Time, UT	Occurrence
		Associated With Shock			
22	April 14, 1973	0700-0200[b]	April 13, 1973	1700	b
23	May 21, 1973	0400-2100	April 21, 1973	2100	a
28	Oct. 12, 1974	2000-0800[c]	Oct. 13, 1974	1500	i
42	Jan. 4, 1978	1000-2000[b]	Jan. 5, 1978	1700	i
44	Jan. 29, 1978	1600-1000[b]	Jan. 30, 1978	1300	a
49	Sept. 29, 1978	0500-0400[b]	Sept. 30, 1978	0500	a
53	Nov. 12, 1978	1000-0300[b]	Nov. 12, 1978	1600	i
55	Feb. 21, 1979	0400-0400[b]	Feb. 21, 1979	1600	i
56	March 22, 1979	2030-0630[c]	March 22, 1979	1600	b
			March 23, 1979	0800	i
58	April 25, 1979	0900-1600[b]			i
		Without Shock			
16	Feb. 17, 1972	0600-2100[b]	Feb. 18, 1978	1400	i
18	March 27, 1972	1700-1800[b]	March 27, 1972	2100	i
25	Sept. 26, 1973	0000-0600[b]	Sept. 26, 1973	1600	i
29	Dec. 2, 1974	0000-1900	Dec. 2, 1974	1200	i
41	Sept. 26, 1977	2100-0300[c]	Sept. 27, 1977	0700	i

[a]MCs, magnetic clouds; A(He), helium enrichments; b, before magnetic cloud; a, after magnetic cloud; i, inside magnetic cloud.
[b]Final time corresponds to 1 day after starting time day.
[c]Final time corresponds to 2 days after starting time day.

hours or more than 39 hours. The maximum durations were 39 hours for a cloud with A(He) and 32 hours for a cloud without A(He). The most frequent duration was in the interval 15-20 hours for A(He) clouds and in the interval 20-25 hours for clouds without A(He). The mean duration and radial extent are larger for A(He) clouds ($\Delta t = 0.25$ hour, $\Delta r = 0.30$ AU) than for clouds without a helium enrichment ($\Delta t = 0.22$ hour; $\Delta r = 0.24$ AU). A(He) clouds have sizes in the range $\Delta r = 0.16 - 0.46$ AU, and the sizes for clouds without A(He) were in the range $\Delta r = 0.12 - 0.49$ AU.

6. Discussion and Conclusions

In this paper we perform a statistical analysis of magnetic cloud characteristics and find that magnetic field and plasma parameters (B, v, n, T, β, and P) inside MCs have different spatial profiles. We find that the mean values of the various magnetic field and plasma parameters can be different depending on the association of magnetic clouds with shocks and with helium enhancements. Our study reveals that the mean values of B, v, T, and P are higher for shock-associated

Table 4. Values of Parameters and Most Common Profiles for Clouds Associated With Helium Enhancements and for Clouds Without Helium[a]

	Range of Average Values		Mean Values		Most Common Profile	
	A(He)	No A(He)	A(He)	No A(He)	A(He)	No A(He)
B, nT	8-24	4-18	13	12	B	B
v, km s^{-1}	350-750	314-640	513	444	C	A
n, cm^{-3}	3-23	4-30	11	14	C	C
T, $10^4 K$	2.3-18.8	2.4- 19.8	8.7	8.3	G	F
β	0.1-1.4	0.1-0.9	0.44	0.49	E	E
P, 10^{10} dyn cm^{-2}	3-14	1-16	9	9	B	B

[a]A, flat profile; B, profile with a maximum; C, descending profile; D, ascending profile; E, profile with a minimum; F, oscillating profile; G, profile with two minima.

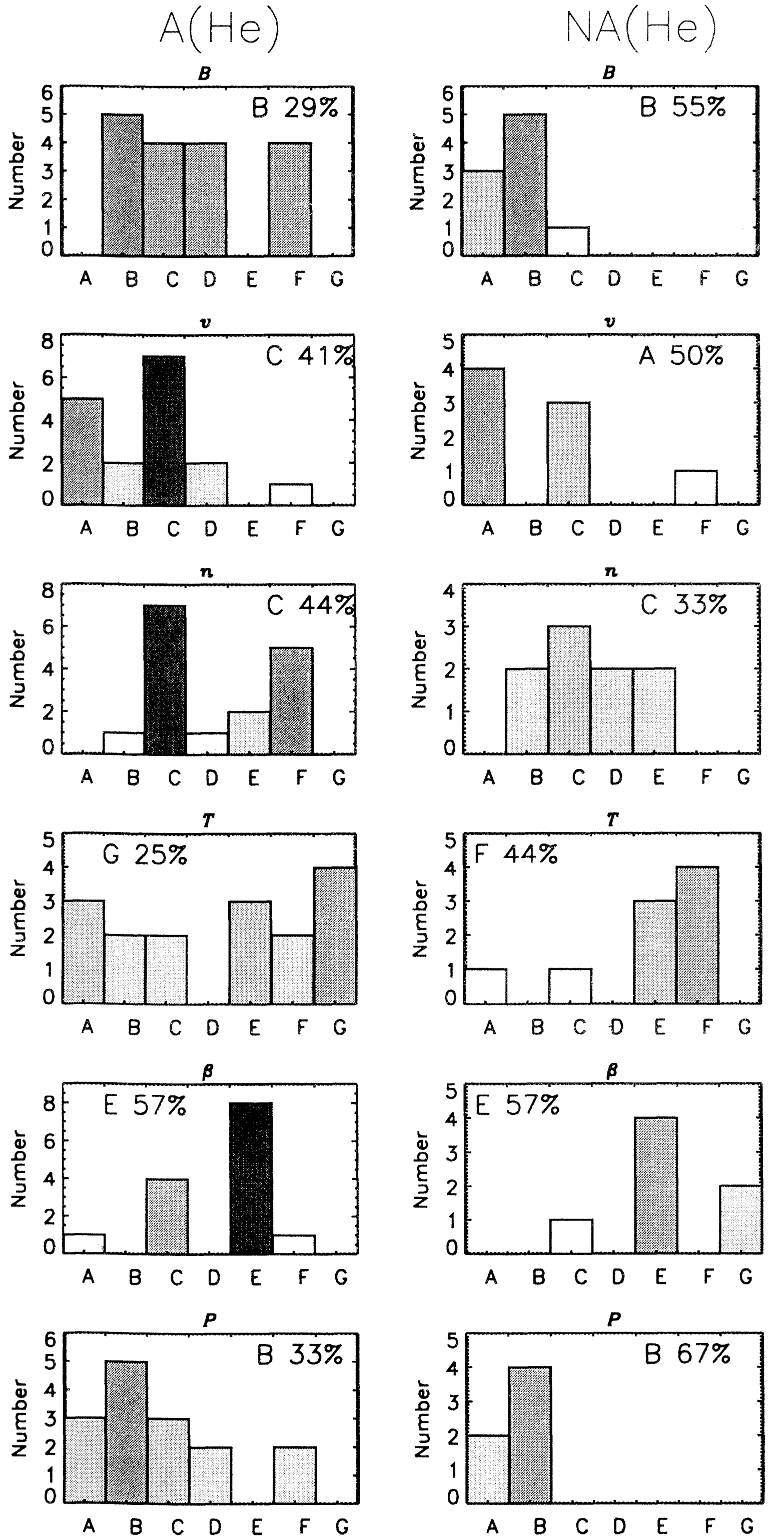

Figure 5. Observed types of profiles for MC parameters for helium enhancement associated clouds (left) and for clouds without helium enhancement (right).

MCs than for clouds without a shock. Tables 2 and 4 show that the magnetic field magnitude and pressure profiles have maxima for all event types (this is MCs with or without shock and MCs with or without helium); the most common profile for the velocity was descending for all types of clouds except for the clouds with no helium. The most common profile of the density was also descending in all cases except for the clouds that are not associated with a shock. All event types most commonly show plasma beta profiles with distinct

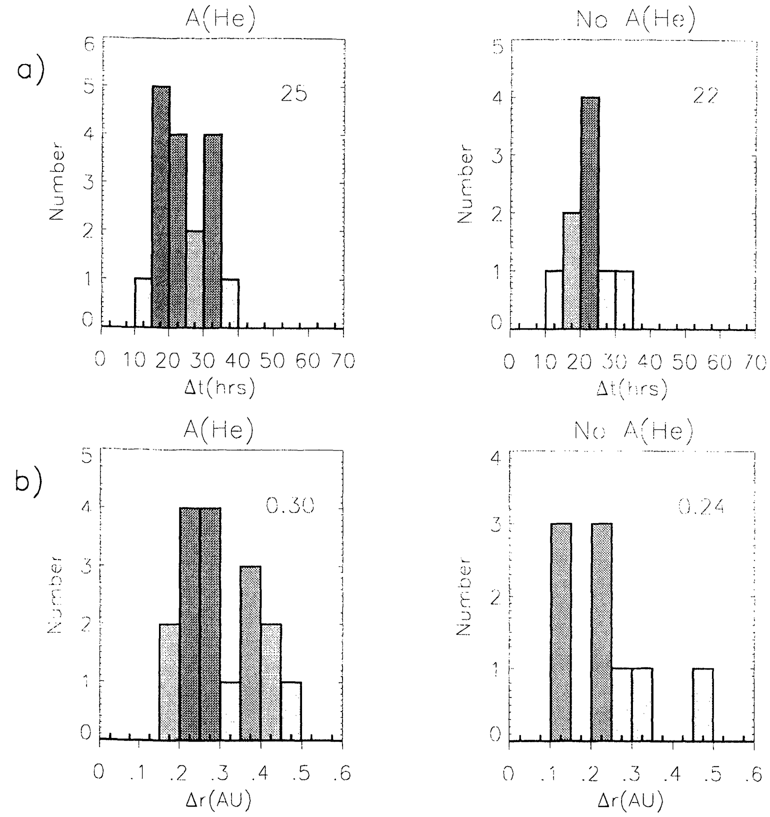

Figure 6. Distribution of the values of (a) Δt and (b) Δr of clouds in relation to their association with helium enrichments.

minima. The most common profiles for the temperature, although assigned to different categories, all show evidence of low-temperature behavior. This is consistent with the fact that the interplanetary counterpart of coronal mass ejections (CMEs), of which magnetic clouds are a subset, is generally assumed to be an expanding structure. This, in turn, results in profiles that typically have low proton and electron temperatures, declining velocity profiles, and high magnetic field magnitude, which when combined with low temperature, results in a low plasma beta.

As noted above, the most common profile for density for shock-associated clouds is descending, which can be interpreted as the result of compression effects taking place at the front of the cloud owing to the shock. In contrast, for MCs without a shock the most common profile for density is of the irregular type.

One particular interesting result of our study is that the average speed of shock-associated clouds can have a wide range of variation (314-750 km s^{-1}), which is not observed for clouds without a shock, whose speeds are constrained to values $\sim$ 400 km s^{-1}. That shock-associated magnetic clouds tend to be faster than clouds without a shock agrees with the findings of *Klein and Burlaga* [1982], but the fact that clouds without a shock have speeds in such a narrow range had never been reported. Near the Sun the outward speeds of CMEs, of which magnetic clouds are a subset, span a wide range of values. The slower events often have speeds $\leq$ 100 km s^{-1}, while the faster can have speeds $\geq$ 1200 km s^{-1}. Moreover, the Solar Maximum Mission (SMM) observations indicate that CME speeds close to the Sun are roughly the same at all heliographic latitutes, and as pointed out by *Gosling et al.* [1994], it seems that the basic acceleration process for many CMEs is essentially the same as that for the normal solar wind. In agreement with our results, at low latitudes, CMEs near 1 AU have speeds greater than 750 km s^{-1}, and they never have speeds less than the minimum solar wind speed of $\sim$ 280 km s^{-1}. Thus the fastest CMEs (magnetic clouds in this case) at low latitudes are decelerated in IP space as they interact with slower plasma ahead, while the slowest CMEs observed in the corona are accelerated further by the time they reach 1 AU [*Gosling*, 1997]. The fact that clouds without a shock have speeds in a very narrow range may be a consequence of slow coronal mass ejections being accelerated by the same forces as the slow solar wind as suggested by *Gosling* [1997]. These clouds seem to be just carried by the solar wind flow.

In our data set, 65% of magnetic clouds are associated with helium enhancements. Because we are using single-spacecraft observations, it is possible that in some cases the magnetic cloud is associated with a helium enrichment which is not detected by the spacecraft, and therefore this percentage of association has to be taken as a lower limit. We find that when clouds without shock are accompanied by helium enhancements, the helium is always inside the cloud. In contrast, when clouds associated with shocks are accompanied by helium enhancements, the helium may appear before, inside, or after the cloud. The fact that helium enhancements are always inside shock-associated clouds suggests that both signatures correspond to the same solar large-scale structure and that the cloud is not totally formed when ejected but that it forms away from the Sun, incorporating the helium-enriched plasma. In fact, we observe that clouds with helium enhancements have larger durations and extents.

The fact that for shock-associated clouds the helium enhancements can appear before, inside, or after the cloud, suggests that helium rich plasma may be released before, at the same time as, or after the plasma that will constitute the cloud. When helium is observed before the cloud, it can not come from low-altitute regions below the coronal cavity but must be released from a nearby place in a previous (most probably related) event. Another finding is that the time delay between the shock and the cloud varies from 1 to 31 hours, which coincides with our previous results in a smaller sample [*Bravo et al.*, 1997; *Bravo and Blanco-Cano*, 1998]. This suggests that clouds cannot always be the pistons of transient interplanetary shocks. Although an alternative explanation could be that the shock may have outrun the ejecta during the transit from the high corona to 1 AU, or that the shock may be associated with a different part of a complex ejecta that includes the magnetic cloud.

Further work considering a larger sample of clouds would be very interesting to evaluate the significance of the results obtained in this study, and a careful analysis of these results must be made in order to obtain their physical implications. Also, Solar and Heliospheric Observatory (SOHO) observations combined with more theoretical efforts would be very valuable to understand the origin of different types of magnetic clouds and their associated signatures.

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