ASSOCIATIONS BETWEEN CORONAL MASS EJECTIONS AND INTERPLANETARY SHOCKS

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ABSTRACT

We are in the process of comparing nearly continuous complementary coronal observations and interplanetary plasma measurements for the years 1979-1982. Our preliminary results show that almost all low-latitude high-speed coronal mass ejections (CME's) were associated with shocks at HELIOS 1. Some suitably directed low-speed CME's were clearly associated with shocks while others may have been associated with disturbed plasma (such as NCDE's) without shocks. A few opposite-hemisphere CME's associated with great flares also seemed to have been associated with shocks at HELIOS.

Introduction

Since March 1979 the NRL white-light coronagraph (SOLWIND) has been monitoring the solar corona routinely from the Earth-orbiting satellite P78-1 while the MPAe plasma detector has been monitoring interplanetary conditions from the Sun-orbiting spacecraft HELIOS 1. During this time, the orbital phase and 0.5-year period of HELIOS 1 caused it to dwell for 6-month intervals alternately off the east and west limbs of the Sun as seen from Earth (Figure 1). In this configuration, HELIOS has been ideally situated to detect the interplanetary signatures of coronal mass ejections (CME's) in or near the plane of the sky where they are most visible from Earth. In the limited space available here, we shall summarize our progress in comparing these complementary observations during 1979-1981 and the beginning of 1982. Other discussion and illustrations are contained in the earlier paper by Schwenn (1982).

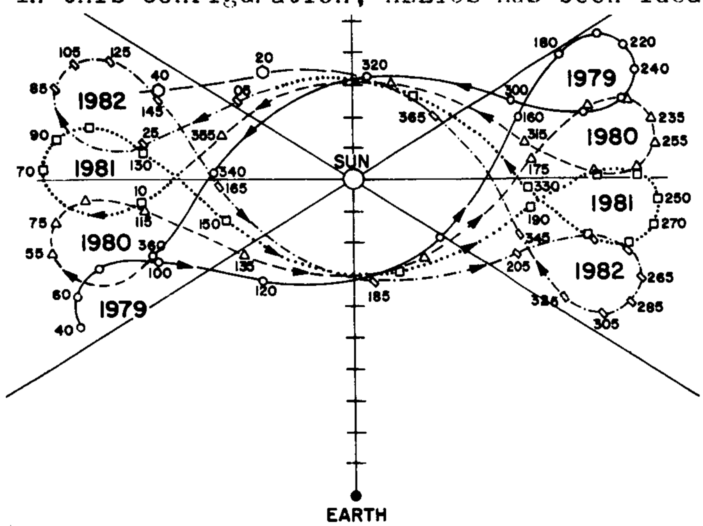

Figure 1 The HELIOS 1 orbit in a fixed Sun-Earth system during 1979-1982. Annually coded tick marks are placed at 20-day intervals, and reference lines are drawn at $\pm 32^{\circ}$ to the east-west direction.

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Although our initial objective was to identify and characterize the interplanetary signatures of coronal mass ejections, we thought that it would be more efficient to begin with the reverse association. We supposed that most outward-moving interplanetary disturbances would have detectable sources at the Sun, whereas many solar-generated disturbances would either miss HELIOS 1 or not reach it at all. In principle, after we had identified all of the HELIOS-effective CME's, we could then look to see if any of the remaining ones had interplanetary signatures that we might have overlooked initially.

Considering the vast number of irregular plasma fluctuations that might be expected at HELIOS since 1979, we began by identifying only the most prominent structures. To our surprise, nearly all of them were shocks and relatively few were non-compressive density enhancements (NCDE's) or other large density fluctuations. This meant that, at least as a starting point, we could limit our selection of prominent interplanetary disturbances to shocks without losing an appreciable number of events. This restriction had the advantage that forward shocks could be identified easily and objectively by a simultaneous sudden increase in proton speed, density, and temperature (as well as magnetic field strength for fast-mode shocks). Moreover, it would be relatively effortless to generalize our selection to include all shocks, not just the prominent ones. Although we would eventually identify and search for the origin of non-shock disturbances such as NCDE's and magnetic clouds, for the moment we should hope to obtain those relations from a consideration of the inverse (forward) associations. We have already found several examples of magnetic clouds in the driver gas following CME-associated shocks (cf. Schwenn, 1982), one of which has been described in detail by Burlaga et al. (1982).

Preliminary Results

A. From Shocks to CME's

To date (March 17, 1983), we have identified 80 shocks while HELIOS was within $\pm$ 30° of the Sun's east or west limbs and during which there were complementary SOLWIND observations. In an exploratory and partially subjective process, we have looked to see whether these shocks were associated with CME's that originated at the Sun a few days earlier, the exact time interval depending on HELIOS's distance from the Sun and an assumed average transit speed in the range 500-1500 km/sec. The breakdown of associated CME's was:

Table 1

YES	40	(50%)
POSSIBLE	19	(24%)
INDETERMINATE	20	(25%)
DOUBTFUL	1	(1%)
TOTAL	80	(100%)

In general, YES meant that we found a big, bright, suitably-timed CME whose projected direction was (with two exceptions) toward HELIOS. The fact that the two exceptional CME's were especially large (rare) and occurred in the absence of other candidates gave us some confidence that these two ill-directed associations were not coincidences. POSSIBLE meant that we found a suitably-timed CME whose association seemed possible, but less obvious, due to a variety of factors such as the CME's faintness, small size, and unfavorable direction together with some coronal data gaps that could have hidden a more likely candidate.

INDETERMINATE meant that substantial data gaps made it impossible to determine whether or not a respectable and suitably-timed CME might have occurred. Within each search interval of 1-3 days (depending on HELIOS's distance from the Sun) such data gaps sometimes ranged from 8 hours to 24 hours of each day. For one relatively weak shock (1/23/81), the coronal observations were reasonably complete, but showed no candidate CME. There was a single 8-hour data gap, but the lack of obvious changes across the gap made the occurrence of a CME seem unlikely. We called this association DOUBTFUL. Further study of the POSSIBLE and INDETERMINATE cases may help to clarify whether or not some shocks (other than co-rotating shocks or bow-shocks) are undetectable as they transit the coronagraph's field of view.

Table 2 summarizes the 40 confident associations. The bottom line shows the average values of CME speed v(CME), shock transit speed v(AVE), and *in situ* shock speed v(SH) for those associations for which all three values were known. (v(SH) was computed from the mass flux conservation equation assuming the flow to be normal to the shock surface.) The three speeds v(CME), v(AVE), and v(SH) had the average values 755, 750, and 672 km/sec, respectively. The near equality of v(CME) and v(AVE) reflects the averaging effect of the high-speed but decelerating events for which v(CME) > v(AVE) and the low-speed accelerating events for which v(CME) < v(AVE). Approximately half of these CME's were associated with obvious SMS-GOES 1-8 A X-ray events, and for the associated ones the average X-ray duration was 5.5 hours. 45% of the shocks were followed by disturbed conditions that marked the presence of possible driver gas.

In those cases for which we have examined interplanetary magnetic field measurements (courtesy Dr. F. Neubauer), we have tabulated the Alfvenic Mach number, M, defined as the shock speed relative to the ambient flow divided by the Alfven speed in the ambient plasma. To the extent that the Alfven speed greatly exceeds the local sound speed, M approximates the fast-mode Mach number and should exceed 1 for fast-mode shocks. (The shocks in this list of confident associations were all fast-mode shocks in the sense that the field strength increased behind each shock. However, we did find some slow-mode shocks whose associations with CME's are classed as POSSIBLE.) Table 2 shows that, on the average, these shocks were relatively strong with M=3.4, and that virtually all of them had $M \geq 1$. We have tabulated the density ratio, n_2/n_1, across the shock because it was currently available for all but the most poorly observed shocks. As one can see, this value was in the range 1-4 (as required by the Rankine-Hugoniot relations) and had a respectable average value of 2.4.

Note that the CME's in Table 2 tended to be centered at low latitudes (23° on the average), and were relatively broad (averaging $\pm 43^\circ$ on either side of center). As mentioned above, only two of these CME's (4/1/81 and 4/10b/81) originated on the west limb when HELIOS 1 was off the east limb. The fact that these two associations were so convincing suggests that on rare occasions a major CME may generate a shock wave that extends through a very wide longitude range, and that one or two similar opposite-limb associations now classed as POSSIBLE, INDETERMINATE or DOUBTFUL may be valid associations.

TABLE 2 INTERPLANETARY SHOCKS AND THEIR ASSOCIATED CME's

CME DATE	CME LOCATION	SHOCK DATE	SHOCK LOCATION	V_{CME} (km/sec)	V_{AVE} (km/sec)	V_{SH} (km/sec)	X-RAY DURATION (HRS)	DENSITY RATIO N2/N1	ALFVENIC MACH NO. M	PISTON?
5/27/79	N15(±25)-W	5/28/79	0.43AU, W90	270	560	605	—	3.0	4.2	YES
6/9/79	S40(±40)-W	6/11/79	0.60, W112	600 A	480	325	—	1.8	1.5	NO
7/3/79	N30(±40)-W	7/5/79	0.83, W120	590	610	~655	—	~3.2	~5 ?	?
7/19/79	N45(±45)-W	7/21/79	0.93, W120	≥550	740	460	?	2.7	—	NO
10/10/79	S08(±18)-W	10/13/79	0.72, W106	~170 ?	~475	440	—	2.4	1.3	YES ?
2/27/80	S40(±30)-E	2/29/80	0.98, E78	≥600	690	580	3	1.4	2.2	NO
3/2/80	S70(±90)-E	3/5/80	0.98, E79	—	750 ?	525	—	2.5	3.0	YES
3/19/80	S30(±30)-E	3/22/80	0.92, E84	550 A	490	435	—	1.5	4.7	NO
3/27/80	S20(?)-E B	3/29/80	0.89, E85	—	770	640	5	2.7	—	YES
6/18/80	N00(±50)-W	6/19/80	0.53, W91	—	620	530	—	3.9	6.2	YES
6/20/80	N35(±50)-W	6/22/80	0.57, W95	~250	430	415	—	2.8	—	?
7/9/80	N25(±25)-W	7/10/80	0.76, W106	—	~680	550	—	3.7	1.7	YES ?
7/18/80	S20(±70)-W	7/20+/80	0.84, W106	~400 ?	545	~465 ?	—	~1.9 ?	~4.9 ?	?
7/29/80	S20(±40)-W	8/1/80	0.91, W106	~700 ?	550	495	3	2.0	1.6	NO
9/1/80	N10(±50)-W	9/3/80	0.98, W99	960	770	590	—	2.2	4.8	YES
11/14/80	N25(±50)-W	11/14b/80	0.51, W107	~1100 ?	~1510	1305	8	?	5.7	YES
11/17/80	N10(±30)-W	11/18/80	0.46, W115	225	665	~565 ?	—	~1.6 ?	≥ 1 ?	NO
1/25/81	S25(±65)-E	1/27a/81	0.84, E83	—	890	705	—	2.1	2.2	YES
1/26/81	N00(±30)-E	1/27b/81	0.84, E83	~1200	875	~700	—	~1.9 ?	~0.8 ?	NO
2/26/81	S05(±45)-E	3/1/81	0.98, E88	660	760	655	5	3.9	—	YES
3/6/81	N00(±50)-E	3/9/81	0.98, E91	—	550	445	—	3.6	—	NO
3/19/81	N40(±35)-E	3/21/81	0.97, E95	—	~745	660	—	1.7	—	NO
4/1/81	S50(±50)-W	4/3/81	0.94, E99	1200	740	510	5	1.8	—	NO
4/6/81	N30(±35)-E	4/8/81	0.92, E100	~950	905	730	2	1.7	1.1	?
4/10a/81	N20(±45)-E	4/13a/81	0.89, E100	810	520	435	2	1.7	2.2	—
4/10b/81	N25(±50)-W	4/13b/81	0.89, E100	—	570	770	3	2.1	5.2	YES
4/18/81	[S45(±25)-E] [& 360°]	4/20/81	0.85, E101	[1130] [& 750]	740	~530 ?	—	?	~2.2 ?	YES
5/8/81	N25(±60)-E	5/10/81	0.67, E95	1000	970	650	12	2.7	2.7	NO
5/10/81	N05(±40)-E	5/11/81	0.66, E95	1460	1440	~1330	7	2.5	4.6	YES
5/13/81	N15(±50)-E	5/13/81	0.63, E94	1500	1470	1310	9	2.0	5.1	YES
5/16/81	360°	5/16/81	0.59, E93	—	1790	≥605	13	—	≥ 1	?
7/20/81	S10(±55)-W	7/21/81	0.72, W90	—	870	735	4	2.9	—	YES
7/22/81	S30(±40)-W	7/24/81	0.74, W91	800	710	635	10 ?	2.2	—	NO
10/18/81	N40(±40)-W	10/20b/81	0.89, W76	~850 ?	620	555	—	2.9	—	NO
11/15/81	N05(±55)-W	11/16/81	0.67, W79	≥550 ?	680	545	3	2.6	—	?
11/18/81	N00(±60)-W	11/20a/81	0.63, W82	900 A	910	~1170 ?	5	2.0	—	YES
11/19/81	N25(±25)-W	11/20b/81	0.63, W82	800	790	985	4	1.5	—	YES
1/10/82	N25(±25)-E	1/12/82	0.54, E110	570	455	405	EPL	1.7	—	?
2/10/82	N35(±20)-E	2/11/82	0.84, E98	>500 ?	1020	765	1	1.9	—	NO
2/23/82	S20(±40)-E	2/27/82	0.93, E100	365	500	435	—	2.4	—	YES
AVE.:	LAT 23°(±43°)			755	750	672	YES 19 (48%) NO 21 (52%) AVE. 5.5 HRS	2.4	3.4	YES 18 (45%) NO 14 (35%) IND. 8 (20%)

A. These three events accelerated to the indicated speeds before leaving the field of view.

B. The 3/27/80 CME occurred in a SOLWIND data gap, but was observed by the HAO/SMM coronagraph (Illing and Sawyer, 1983).

This conclusion is consistent with past studies of interplanetary shocks associated with certain great solar flares (cf. Intrilligator 1980). However, as we shall see in section B, most major CME's do not show such a broad heliospheric influence, especially in latitude.

Finally, note that five of these confidently associated CME's had speeds less than 400 km/sec. The transit and in situ speeds were self-consistent, but were substantially higher than the observed CME speeds. We believe that this reflects the fact that some initially slow CME's produce higher-speed interplanetary shocks. It does not seem to be the result of an incorrect association or a low-speed projection of a high-speed CME well out of the sky plane. We suppose that either a much faster shock preceded the front of the coronal material or that the ejected material accelerated outside of our 10 $R_\odot$ field of view. (Accelerations of coronal material sometimes occurred in our field of view; in Table 2 we indicated such cases by the letter "A".)

Figure 2 shows a 270 km/sec mass ejection on May 27, 1979 and its associated shock at HELIOS on May 28. SOLWIND and HELIOS data were virtually continuous and revealed no other coronal or interplanetary events. Nor were there any major X-ray events in the 1-8 Å flux. The transit speed of 560 km/sec was comparable to the in situ speeds of 605 km/sec at HELIOS (0.43 AU, W 90°) and of 570 km/sec at PIONEER-VENUS (0.73 AU, W 122°) on May 29 (Russell and Mihalov, 1982).

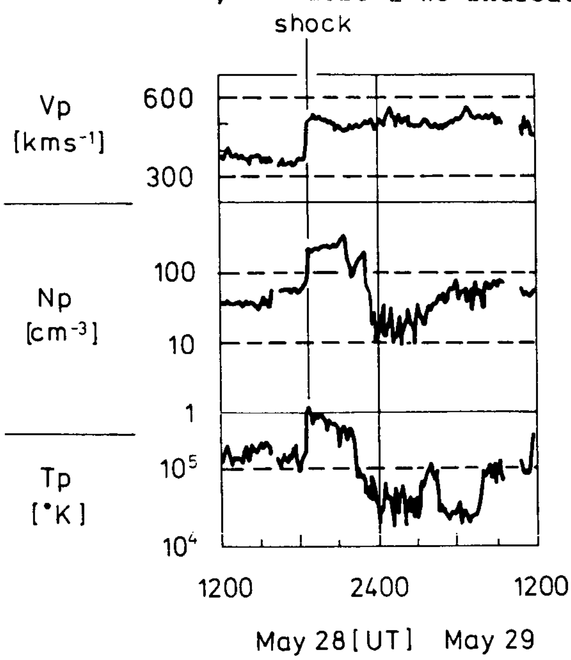
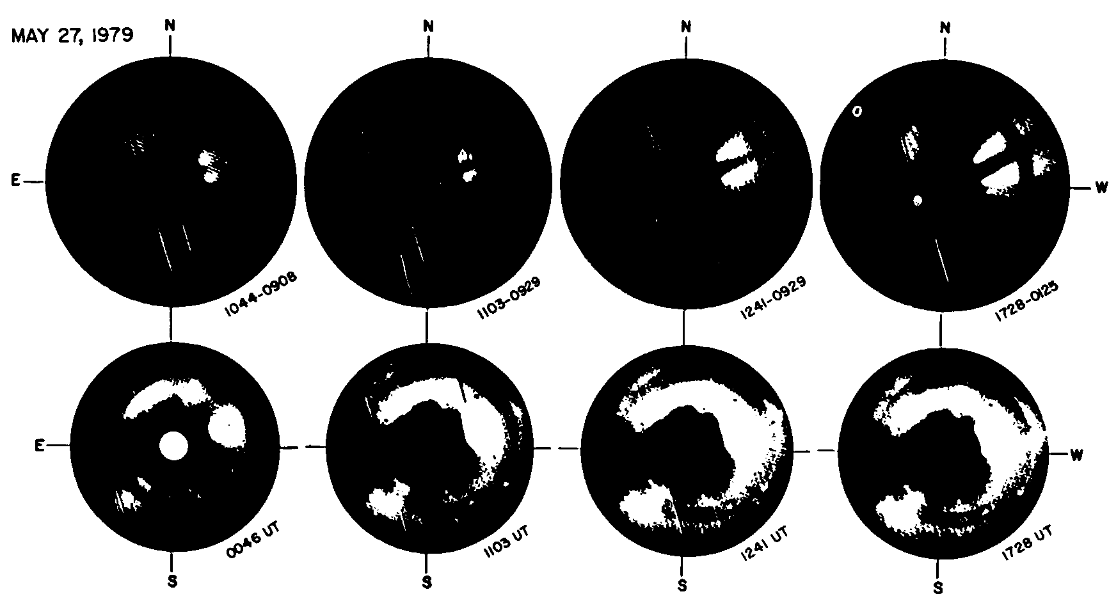


Figure 2 May 27, 1979 mass ejection (below) with its shock and piston signatures at HELIOS 1 (left).



As Figure 2 shows and as we have noted elsewhere (Sheeley et al. 1982), the May 27, 1979 CME involved the eruption or splitting of a helmet streamer. Such streamer eruptions are ubiquitous and constitute a general class of CME characterized by low speed (usually 100-300 km/sec), by a narrow shape with little latitudinal expansion, and by the lack of an obvious signature in the spatially integrated X-ray flux. Several of them belong to our class of POSSIBLE shock associations.

Figure 3 shows high-speed CME's on May 10, 1981 (1460 km/sec) and May 13, 1981 (1500 km/sec), and the associated shocks at HELIOS 1 on May 11 and May 13, respectively. (The shock on May 10 was associated with a 1000 km/sec CME on May 8.) Note that the 600 km/sec speed behind the May 10 shock constituted the ambient speed for the May 11 and May 13 shocks whose post-shock flows exceeded the 1000 km/sec limit of the plotter. The two CME's in Figure 3 are not especially massive (perhaps $5x10^{15}$ gm) compared to other events, but are probably especially energetic due to their high speeds and correspondingly large kinetic energies. They were associated with long-duration X-ray events and H-alpha flares in the same active region. The similar whip-like structures of their northern edges suggest that this pair of CME's may be the coronal analogue of homologous flares. (It is probably impossible to tell whether or not the flares were homologous because the May 10 flare was greatly foreshortened at the east limb.)

B. From CME's to Interplanetary Disturbances

In this phase of our study we began with the major CME's that we had not already found to be associated with shocks. A priori, we suspected that there would be many such mass ejections whose projected directions were toward HELIOS 1. This was a false impression. Of the 27 major CME's in HELIOS's hemisphere, 17 failed to come within 15^{o} of the solar equator. On the average, they were centered at 68^{o} and had latitudinal spans of 34^{o} each side of center. Only one of these events had a possible association with a non-compressive density enhancement (NCDE), and we suppose that that association was a coincidence.

The remaining 10 major CME's spanned or at least grazed the solar equator (taken to coincide with the ecliptic within our measurement accuracy). On the average these CME's were centered at 24^{o} and had spans of 32^{o} on each side of center. Table 3 summarizes the associations of these CME's with interplanetary events:

Table 3

CME's with initially overlooked shocks	2
CME with a possible weak shock	1
CME's associated with disturbed flows, including NCDE's	5
CME with no interplanetary signature	1
CME preceding sub-Alfvenic conditions	1
Total	10

On detailed examination of the interplanetary magnetic field measurements, we found that two of these CME's were associated with weak shocks that we had overlooked initially (but which we have included now in part A of this section). Another CME may have been associated with a small shock in a plasma

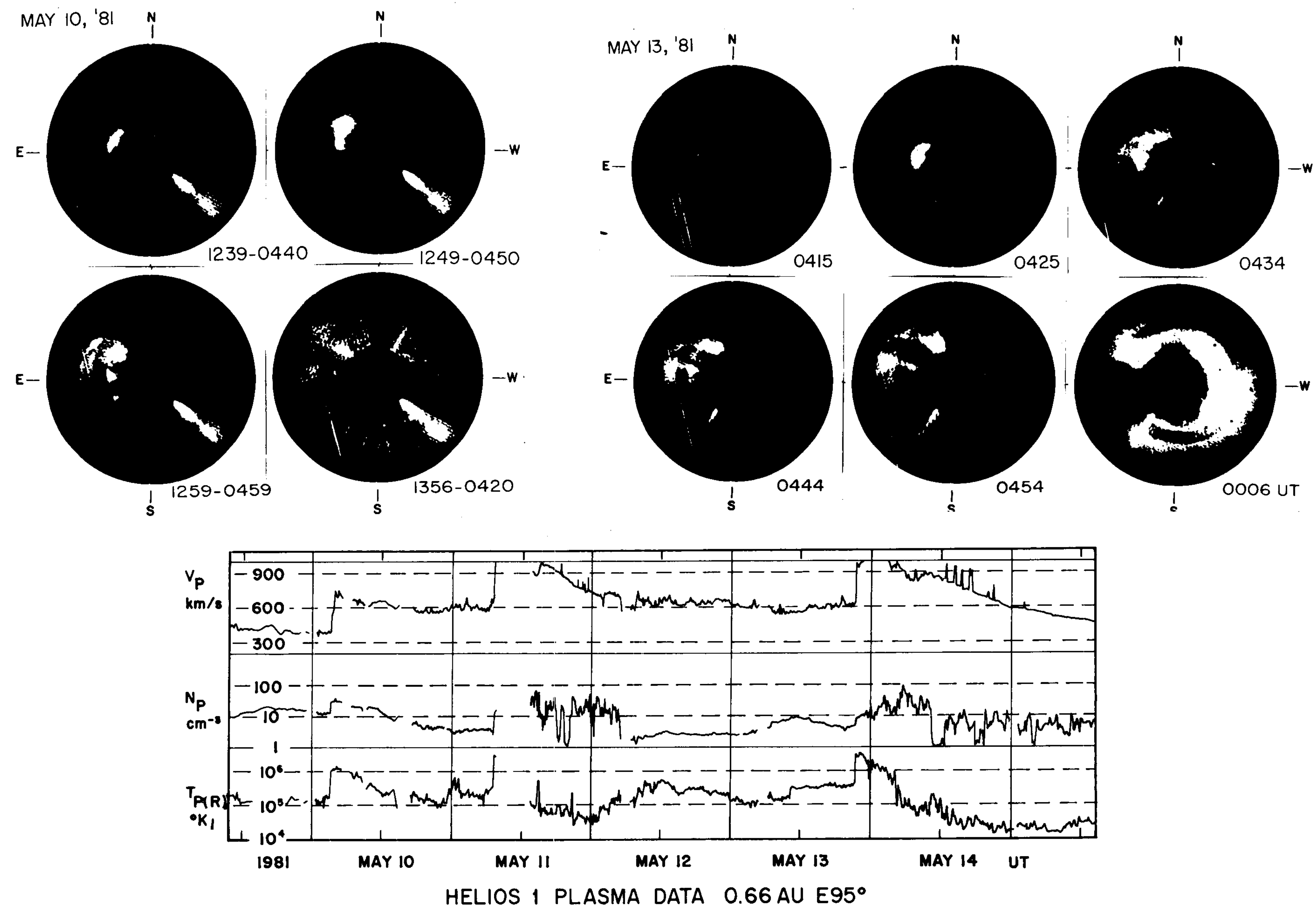


Figure 3 Homologous, 1500 km/sec mass ejections on May 10 and May 13, 1981, and their associated shocks at HELIOS 1 on May 11 and 13. (The May 10 shock was associated with an earlier CME on May 8.)

data gap. Five CME's were associated with disturbed plasma flows, three of which were NCDE's. One of these CME's had the moderately high speed of 560 km/sec, but the other four had speeds less than 450 km/sec. Two of these CME's were very slow streamer eruptions.

The CME without an obvious interplanetary signature was a wide ($\pm 45^{\circ}$), high-latitude (S45°), fast (680 km/sec) event that just grazed the solar equator. This grazing condition, together with the 53° longitude difference between HELIOS's location at (.43 AU, E105°) and the associated H-alpha flare's location at S22, E52 on December 3, 1979, may have been sufficient to cause the shock to have missed HELIOS.

Finally, in Table 2 a lone classic streamer eruption on June 6, 1980 preceded the anomalous sub-Alfvenic conditions that Schwenn has described elsewhere in these Solar Wind Five Proceedings. This CME occurred too late to have been the source of the anomalous interplanetary conditions. Moreover, if this CME had an interplanetary signature it was probably lost in the variety of unusual plasma fluctuations accompanying the sub-Alfvenic flow.

DISCUSSION

Our associations between high-speed CME's and interplanetary shocks are consistent with Gosling et al.'s (1976) associations between high-speed CME's and metric type II and IV radio bursts. Also, our associations are consistent with the results of Chao and Lepping (1974) who associated solar flares and shocks at Earth during the 4-year interval 1968-1971 near the peak of the previous sunspot cycle. Using metric radio burst data to make their associations "85% credible", they obtained typical transit speeds, v(AVE), of 600-700 km/sec and typical *in situ* shock speeds, v(SH), of 400-500 km/sec, and concluded that flare-associated shocks decelerate *en route* from the Sun.

In their direct comparison between the Sept. 7, 1973 flare-associated CME and its subsolar interplanetary shock, Gosling et al. (1975) obtained v(AVE) = 950 km/sec and v(SH) = 722 km/sec from which they also deduced a deceleration. Although the CME's leading edge had left the field of view prior to their first observation, their estimate, v(CME) = 960-1300 km/sec, is consistent with our results. As one can see in Table 2, for high-speed CME's, we obtained v(CME) > v(AVE) > v(SH). Not only does this general result provide strong support for the deceleration of high-speed shocks, but also it suggests that v(CME), the speed of the CME's leading edge, is closely related to the coronal shock speed. However, we do not yet know whether v(CME) represents the speed of the shock itself or whether it more properly represents the speed of the shock's driver material.

An underlying theme of post-Skylab reviews (Gosling 1975, 1976; MacQueen 1980) is that the interplanetary response to large flare events is well known. Furthermore, our future challenge is to understand the connection, if any, between typical low-speed CME's and non-shock solar wind variations such as non-compressive density enhancements (NCDE's) (Gosling et al. 1977, 1981) and, more recently, magnetic clouds (Burlaga et al. 1981; Klein and Burlaga 1982). Our preliminary results indicate that whereas some slow CME's may be associated with NCDE's, others seem to be clearly associated with interplanetary shocks. While these latter cases may not be consistent with our Skylab experience, they are consistent with a number of shock-associated filament disappearances observed thereafter (Joselyn and Bryson 1980; Gosling et al. 1980; Schwenn et al. 1980; Sanahuja et al. 1982).

We should like to emphasize that these results are preliminary, and that our study is far from complete. We do not yet know whether some large, travelling interplanetary shocks may originate in solar events without CME's, but we have seen that a significant fraction of them do originate with CME's. (We have identified a few co-rotating shocks associated with coronal holes but not with CME's.) We have not yet studied the non-shock interplanetary disturbances in detail, but we have seen that after the shock-associated CME's were selected, there were few CME candidates left for non-shock associations. In contrast, during the Skylab mission in 1973-1974 the IMP 7 and 8 spacecraft observed approximately 2.7 NCDE's per month, but no shocks at all (Gosling et al. 1977). Finally, we should like to emphasize that this paper concerns the associations between CME's and events at HELIOS 1, but not at other spacecraft. We have also found obvious associations with shocks at HELIOS 2 (May 9, 1979), ISEE 3 (Nov. 29, 1979 and Sept. 5, 1982), and PIONEER-VENUS (May 10 and May 29, 1979). Many others will follow when we start to examine these data systematically.

Acknowledgements. We are indebted to F. Neubauer whose magnetometer data made posible the confirmation of weak shocks and the calculations of Alfvenic Mach Numbers. We are grateful to L. Burlaga, H. Cane, E. Hildner, A. Hundhausen, and J. Gosling for useful discussions, and to D. Roberts, F. Harlow, W. Funk, R. Chaimson, and R. Seal for technical support. We acknowledge the DOD Space Test Program and the NASA Office of Heliospheric Physics for a variety of support including DPR W-14,429.

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