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Associations Between Coronal Mass Ejections and Solar Energetic Proton Events

S. W. KAHLER

American Science and Engineering, Inc., Fort Washington, Cambridge, Massachusetts
Emmanuel College, Boston, Massachusetts

N. R. SHEELEY, JR., R. A. HOWARD, M. J. KOOMEN,[1] AND D. J. MICHELS

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D. C.

R. E. MCGUIRE,[2] T. T. VON ROSENVINGE, AND D. V. REAMES

Laboratory for High Energy Astrophysics, Goddard Space Flight Center, Greenbelt, Maryland

We have used data from the Naval Research Laboratory (NRL) white light coronagraph on the P78-1 spacecraft and energetic ($E > 4$ MeV) proton data from the Goddard Space Flight Center (GSFC) detectors on the IMP 8 and ISEE 3 spacecraft to investigate the association between proton events originating in flares and coronal mass ejections (CME's). The primary data were 50 prompt proton events observed between April 1979 and February 1982 for which reduced coronagraph data were available. H alpha flares could be confidently associated with 27 of these events, and in 26 of these 27 cases an associated CME was found, indicating a high but not perfect association of prompt proton events with CME's. Peak proton fluxes correlate with both the speeds and the angular sizes of the associated CME's. We show that the CME speeds do not significantly correlate with CME angular sizes, so that the peak proton fluxes are correlated with two independent CME parameters. With larger angular sizes, CME's are more likely to be loops and fans rather than jets and spikes and are more likely to intersect the ecliptic. Which of these factors is important to the peak proton flux correlation cannot be determined from the data. We find weak evidence that steeper proton spectra are associated with faster and wider CME's. Two of the 50 proton events of the study and two additional events, all with no associated CME's, share common characteristics: relatively short duration (~ 1 day) proton events with low fluxes, parent flares with short (~ 10 min) soft X ray duration, close magnetic connection to the earth, and gamma ray and metric type II emission.

INTRODUCTION

A considerable amount of evidence now exists to suggest that solar flares which result in the production of interplanetary energetic protons of energies $E \geq 10$ MeV are characterized by large ejections of mass from the corona. *Pallavicini et al.* [1977] used X ray flare images from Skylab to show that there are two kinds of solar coronal flares. The first are characterized by small volumes, large energy densities, and short time scales, probably due to energy release occurring in one or several low-lying coronal magnetic arches. The second are characterized by large volumes, low energy densities, and long time scales. Prior to this time, *Sheeley et al.* [1975] found that this second kind of event was associated with a coronal mass ejection (CME), and by using EUV and X ray images they found that during their decay phases these events consisted of arcades of magnetic arches, with the highest temperature X ray arches overlying those formed at lower temperatures. Similar arcades had earlier been observed in the H alpha line as "post-flare loops" by *Bruzek* [1964*a*, *b*], who reported a good correlation between flares with postflare loops and polar cap absorption (PCA) events observed at the earth.

[1] Permanently at Sachs/Freeman Associates, Inc., Bowie, Maryland.
[2] Also at Department of Physics and Astronomy, University of Maryland, College Park.

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A second line of evidence associating interplanetary proton events with CME's involves metric type II bursts. *Lin* [1970] and subsequent investigators have found that energetic proton events are well associated with type II bursts. The association between type II bursts and coronal H alpha ejecta was first studied by *Giovanelli and Roberts* [1958] and *Warwick* [1965]. Later, *Munro et al.* [1979] showed that type II bursts observed during Skylab were well associated with CME's seen in the Skylab white light coronagraph. This led to a model of the type II burst due to plasma turbulence in a detached shock wave moving ahead of the CME [*Maxwell and Dryer*, 1981]. The association between type II bursts and proton events, presumed due to acceleration of the protons by the shock [*Lee and Fisk*, 1982; *Achterberg and Norman*, 1980], then requires that the proton event be associated with the CME which drives the shock. This view has been challenged by *Wagner and MacQueen* [1983], who propose that the type II shock is generated after the CME begins and then moves through the preexisiting CME with a speed exceeding that of the CME front. In addition, the recent finding by *Sheeley et al.* [1984] of a class of type II bursts without associated CME's casts further doubt on the driven shock model.

Previously, the most direct evidence relating proton events and CME's came from the comparison of the two phenomena by *Kahler et al.* [1978] (hereinafter KHV) using proton events observed by the IMP 7 spacecraft and CME's observed by the Skylab coronagraph. On the basis of 18 proton events they found evidence that CME's are required for the occurrence of proton events. They suggested that protons gain access to the interplanetary medium after being accelerated in shock fronts

TABLE 1. Flare and CME Associations of Proton Events

Flare Association[b]	CME Association[a]			
	− −	−	+	+ +
Y	0	1	5	21
P	3	3	4	3
N	2	2	6	0

[a]CME associations are − −, very improbable; −, improbable; +, probable; and + +, very probable.
[b]Flare associations are *Y*, likely; *P*, possible; and *N*, no candidate.

ahead of the CME's and that the angular sizes of the CME's could explain the fast propagation region defined by *Reinhard and Wibberenz* [1974].

The purpose of this paper is to discuss a comparison between proton events and CME's more comprehensive than that carried out in the KHV study. The present study is based on nearly 3 years of observations around the recent maximum of solar activity with the Naval Research Laboratory (NRL) Solwind coronagraph on the P78 1 satellite and Goddard Space Flight Center (GSFC) experiments on IMP 8 and ISEE 3. We first test the earlier result found by KHV, that all prompt proton events appear to be associated with CME's. We then look for correlations between proton and CME parameters and examine the morphologies of CME's associated with proton events. An inverse correlation is done in which CME's associated with proton events are compared with those with no proton events. Finally, we discuss the implications of our findings.

DATA ANALYSIS

The Proton Data and Flare Associations

We examined the particle data from the GSFC experiments on the ISEE 3 and IMP 8 spacecraft. The ISEE program has been described by *Ogilvie et al.* [1977], and details of the GSFC medium-energy cosmic ray experiment on the ISEE 3 are presented by *von Rosenvinge et al.* [1978]. The experiment consists of two telescopes, the very low energy telescope (VLET) and the high-energy telescope (HET). We used primarily counting rates and fluxes of particles of 4–70 MeV from the HET. The 4–18-MeV data were not available from August 14, 1979 to January 25, 1980.

The IMP 8 spacecraft was launched in October 1973. The instruments are designed to measure fluxes as a function of energy and to make elemental identifications of protons, alpha particles, and heavier ions from $E < 1$ MeV/nucleon to $E > 400$ MeV/nucleon, as well as to measure the flux of relativistic electrons between 3 and 18 MeV. The separation and identification of individual elements is accomplished by measurement of differential energy loss dE/dx and total energy E by using multiple detector elements. The instrument package consists of three particle telescopes covering different ranges of energy. For our analysis we used data from the Low Energy Detector (LED), which covers a proton energy range of <1 to 22 MeV, and the Medium Energy Detector (MED), which covers a proton energy range of 20 to more than 400 MeV.

In selecting particle events, each well-defined increase in the 4–22-MeV proton flux was classified either as an *F* event, indicating that in our judgement the event was prompt and probably originated in a solar flare; a *U* event, for uncertainty about its origin; or an *NF* event, for a nonflare origin. To classify an event as *F*, we used both IMP and ISEE data to look for velocity dispersion, a relatively hard energy spectrum, and the absence of a magnetic sudden commencement near the event onset or maximum. The smallest 4–22-MeV peak flux detectable above the lowest background level was about 3×10^{-3} protons cm^{-2} sr^{-1} s^{-1} MeV^{-1}. No solar data were considered at this stage of the analysis, even though four *U* events appeared to be well associated with large solar flares, and only *F* events were used in the analysis. A list of all *F* events from March 1979 through February 1982 was compiled for the comparison with the coronagraph data.

We then attempted to associate each *F* event with an H alpha flare to set temporal and spatial limits on candidates for associated CME's. In general, most, but not all, such energetic proton events can be associated with reported H alpha flares [e.g., *van Hollebeke et al.*, 1975]. Lack of a reported flare candidate is usually presumed due to a lack of H alpha data coverage or to a flare from behind the solar limb. We know of no case in which a proton event has been associated with a frontside solar disturbance lacking an accompanying H alpha flare. *Sanahuja et al.* [1983] associated an erupting filament with a large ~10-MeV proton event and pointed out that it was not associated with a major solar flare. Even in that case two weak 1*F* H alpha flares with long durations were reported which accompanied the filament eruption. The point here is not that the chromospheric H alpha flare is energetically important for either proton acceleration or CME's but that it serves as a convenient tracer of the important coronal processes giving rise to these phenomena.

The comprehensive H alpha flare listings of Solar Geophysical Data bulletins were used in making the associations. Since these listings extended only through July 1980 at the time of this study, prepublication listings supplied by J. McKinnon of NOAA were used to extend the list through February 1982. Besides an appropriate timing of 1 to a few hours prior to the proton event onset and a disk position consistent with the rise time and duration of the proton event (short time scales requiring relatively well-connected H alpha flares), we looked for large size and long duration in candidate-associated H alpha flares. An associated GOES soft *X* ray long decay event (LDE) (KHV) and an associated reported metric type II burst [*Kahler*, 1982] were also considered desirable, but not necessary, in making the flare association. For each proton event the flare association was classified as *Y*, for a very likely association; *P*, for one or more possible candidates but no convincing association; and *N*, for no H alpha flare candidate found. Following the discussion of *Kane et al.* [1984], we classified the August 19, 1979 proton event, characterized by a rapid rise phase atypical of east limb events, as a *Y* event due to a large flare partially occulted behind the east limb.

The Coronagraph Data

The NRL Solwind coronagraph on the P78 1 satellite has been described by *Michels et al.* [1982] and *Sheeley et al.* [1980*a*, *b*]. Briefly, since March 1979 the Solwind instrument has imaged the white light solar corona from 2.5 to 10 R_0 with an angular resolution of 1.25 arc min per pixel. Full field of view images are obtained every 10 min of the 1-hour daylit portion of the 97-min orbit. To survey the data, a differenced image for each orbit is routinely obtained by subtracting a base image taken at the beginning or middle of each day from those of each orbit during the subsequent 12-hour period. Transient events identified in these images can then be studied

TABLE 2. List of Proton Events with Likely (*Y*) H Alpha Flare Associations

Proton Event			H Alpha Flare[a]			Associated CME[b]				
Date	Onset Time, UT	F(4–22)[c]	Size	Onset, UT	Position	Speed	Onset, UT	Position Angle	Angular Size	Morphology
					1979					
Aug. 19	0200	7 (1)	SB	(1421)	08°N 90°E	···		120°	120°	filled loop[d]
Aug. 21	0730	8 (0)	2B	0550	17°N 40°W	690	0600	300°	110°	spikey fan
Nov. 15	2230	3 (1)	2B	2122	29°N 35°W	1190	2140	312°	110°	unfilled loop
					1980					
March 25	0730	5 (−3)	2F	0400	26°S 25°W	···		···		faint enhancement[d]
April 4	1730	9 (−1)	1N	1454	27°N 35°W	···		···	360°	halo
May 21	2330	1.7 (−2)	2N	2049	14°S 15°W	420	2045	190°	20°	filled loop
June 7[e]	0130	8 (−2)	1B	0116	13°N 72°W				none	
Nov. 10	1230	1.3 (−1)	2B	1140	11°S 54°W	>660	1113	295°	30°	fan[d]
Nov. 11	1930	5 (−1)	2B	1729	11°S 69°W	···		230°	40°	fan
					1981					
Feb. 6	0130	1.1 (−2)	1B	(2222)	15°S 60°W	560	2252	285°	90°	filled loop
March 7	0830	3 (−1)	SN	0613	22°S 79°W	1125	0631	270°	50°	filled loop
March 25	2130	7 (−2)	2B	2039	09°N 87°W	825	2050	300°	80°	multiple spike
March 30	0130	1.3 (1)	1N	0017	15°N 72°W	>1300	0049	275°	150°	quadrant filler
April 1	0330	3 (0)	3B	0102	43°S 52°W	1310	0135	220°	100°	filled loop
April 3	1230	3 (0)	1B	0908	43°S 81°W	1680	0949	215°	70°	partly filled loop
April 4	0700	···	2N	0502	44°S 87°W	900	0444	230°	40°	filled fan
April 10	1630	1.2 (1)	2B	1632	08°N 36°W	···		300°	–	unknown[d]
April 28	2130	2 (1)	1B	<2205	16°N 90°W	1044	2100	275°	30°	loop
May 9	0600	1.2 (1)	1B	(2201)	09°N 38°E	500	2225	70°	140°	filled loop
May 10	0830	9 (1)	1B	0715	05°N 74°W	830	0712	260°	95°	filled loop
May 16	1230	7 (1)	3B	0754	11°N 15°E	···		···	360°	halo
Oct. 8	0000	1.5 (0)	1N	(2259)	17°S 83°E	···		75°	150°	quadrant filler
Oct. 12	0730	9 (0)	2B	0615	18°S 32°E	···		···	360°	halo
Nov. 9	1500	3 (−1)	2B	1225	17°S 17°E	···		···	–	possible head on[d]
Nov. 14	2300	3 (−1)	2B	2209	16°N 47°W	585	2131	280°	120°	filled loop
Dec. 9	2200	4 (1)	2B	1817	12°N 16°W	···		270°	80°	quadrant filler
					1982					
Feb. 8	1700	3 (−1)	1B	1250	13°S 88°W	1305	1248	270°	40°	filled loop

[a]Listed are size and brightness, onset time (parentheses indicate previous day), and location.
[b]Speeds in km s^{-1} and position angle in degrees measured eastward in the plane of the sky from the north pole.
[c]Peak flux in protons cm^{-2} sr^{-1} s^{-1} MeV^{-1}. Numbers in parentheses indicate powers of 10.
[d]The CME association is +, as given in Table 1.
[e]First of two flares on June 7 for which there were proton events but no CME's. The CME association is −.

in greater detail by performing the subtractions for all the images during the relevant orbit. Properties of CME's, such as spatial structure, angular size, position angle, and speed, have been measured and cataloged. In some cases the data coverage is limited due to calibration, bad data, or lack of observations, and the speeds cannot be determined. In other cases the first image after a data gap of several hours is used as the base image, and the resulting differenced images show a depletion at the position of the remains of a CME in the base image. In such cases the timing of the CME, as well as the speed, is in doubt. During the period examined in this study, CME's occurred at the rate of about two per day. *Sheeley et al.* [1982] have recently presented a sample of the observed events from the same time period.

Proton Event and CME Associations

All *F* proton events, regardless of flare association, were compared with the coronagraph data to look for associated CME's. We required that coronagraph data be available for a 4-hour period following either the time of maximum of the associated H alpha flare or the estimated time interval of proton injection in the case of no associated flare. For each of the 50 proton events satisfying this criterion we classified the association with a CME as − −, very improbable, no CME was observed; −, improbable, a CME was observed but it was probably not associated with the event; +, probable, an observed CME could not be associated with certainty; or + +, very probable, a clear association. For proton events with a *Y* or *P* flare association the timing and position angle of the CME had to be consistent with an origin in that flare to rate a + or + + association. In cases with an *N* flare association the CME association was determined primarily by the CME timing and whether the proton counting rate profile was consistent with a flare event on the same limb as the observed CME.

The results of the CME associations with proton events are shown in Table 1. The important result is that 26 of the 27 proton events for which good flare associations were found (the *Y* events) were probably or very probably associated with CME's. We give the basic proton, flare, and CME data for the *Y* events in Table 2. The proton onset times are generally accurate to within ±1 hour. The peak 4–22-MeV fluxes from the IMP 8 experiment were corrected for background and are generally accurate to within ±30%. We tried to avoid any energetic storm particle fluxes in making this estimate. The proton events of April 1, 1981 and November 14, 1981 and

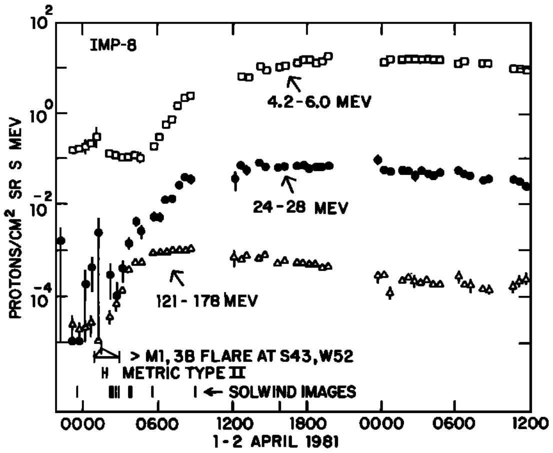

Fig. 1. IMP 8 proton fluxes in three energy bands during the event beginning ~0300 UT April 1, 1981.

their associated CME's are shown in Figures 1 to 4. In addition, the proton event and associated CME of August 21, 1979 was shown by *Kahler et al.* [1983*a*].

There were several reasons for classifying the CME associations of five of the Table 2 *Y* events as + rather than + +. The associated CME's of the flares of August 19, 1979 [*Kane et al.*, 1984] and November 10, 1980 both occurred at appropriate times and on the appropriate limbs, i.e., east or west, but were not centered in the appropriate quadrants. It is not yet obvious that CME's necessarily project radially above their associated flares, but we have preferred to rate those two associations as only probable, +. In the three events of March 25, 1980, April 10, 1981, and November 9, 1981, only the late stage of each CME could be observed due to a data gap of several hours following the associated flare.

We should expect to find a number of proton events due to flares beyond the west limb. Each of the six *N*, + events of Table 1 was attributed to a west limb transient with no observed flare, a result probably due to flares beyond the limb. One of these CME events, on September 1, 1980, is shown by *Sheeley et al.* [1982]. Several of the *P* events may also be due to such flares in cases where the tentative flare identification is in error.

The proton event of June 7, 1980 is the only *Y*, − event of Table 1. It has been attributed to the 1*B* H alpha flare beginning 0311 UT in Hale region 16886 [*von Rosenvinge et al.*, 1981]. This flare is briefly described by *Rust et al.* [1981] and is well known as a gamma ray line event [*Forrest et al.*, 1981]. A closer examination of the particle data, however, shows that energetic electrons were produced in both this flare and the earlier 1*B* flare, another gamma ray line event (D. J. Forrest, private communication, 1983) beginning at 0116 UT in the same region. Energetic protons were produced in the first flare and possibly in the second, since the proton fluxes continued to rise after the second flare. The GOES 1–8 Å *X* ray profiles of both flares are very impulsive, making them unlikely candidates for CME associations [*Sheeley et al.*, 1983*a*]. A narrow CME at 260° was first observed at 0304 UT extending to 5 R_0. The most likely injection time for that CME is ~2312 UT on June 6, but a time of 0116 UT, the onset of the first of the two proton flares, cannot be completely ruled out due to a poor determination of the CME velocity. We find no evidence of any additional mass ejection associated with the later 0311 UT flare. Taken as a single proton event, the association is therefore considered improbable, −, in Table 1. This differs from our earlier preliminary classification of the event as probable, + [*Kahler et al.*, 1983*a*].

Let us consider the best cases for further counterexamples to the general rule that all proton events from flares are associated with CME's. Since each of the six proton events in the "minus" column of Table 1 has a candidate CME with a possible association, we search for possible counterexamples from among the five events of Table 1 with − − CME associations. The two proton events with no (*N*) associated flares are those beginning 1330 UT, February 7, 1981 and 2300 UT, February 9, 1982. In the first case there are no obvious H alpha flare or type II metric burst candidates to associate with this event, and the possibility of a nonflare origin or a backside event cannot be ruled out. The second event, of February 9, 1982, is complex, with a previous event in progress. Electron data indicate an onset at ~2300 UT, but there are no candidate flares at that time. A type II burst is reported at 2005 UT but also without any H alpha or *X* ray flares. A more rapid increase in the proton fluxes occurs after 0500 UT on February 10, and this increase, which shows velocity dispersion, may be due to a 2*B* flare at ~0100 UT at 16°N, 54°E. This flare is probably associated with the remains of a fan transient observed at 0457 UT in the solar northeast quadrant. Thus the February 9, 1982 event is really too complex to serve as a good counterexample.

Of the three *P* events in the "minus-minus" column of Table 1, the proton event of 2000 UT, May 4, 1981, is tentatively associated with a 1*B* flare at ~0839 UT at 14°N, 16°E. If a flare occurred later (there are no obvious candidates), an associated CME could have been missed in the coronagraph data gap from 1250 to 2051 UT. The 2130 UT, March 28, 1980 proton event is tentatively associated with a 1*B* flare at 2004 UT at 14°N 00°E. Unless it was large, a CME from this central meridian location may not have been observable [cf. *Howard et al.*, 1982]. The third proton event, beginning 1900 UT, December 12, 1979, constitutes the best case for a counterexample to the rule of CME associations. It is tentatively

TABLE 3. Proton Events With No CME Associations

Proton Event			H Alpha Flare					
Date	Onset Time	$F(4-22)^a$	Size	Onset, UT	Longitude	Type II	Gamma Ray Line	1–8-Å *X* ray
Dec. 12, 1979	1930	4 (−3)	1N	1714	79°W	possible	···	M4
June 7, 1980	0130	8 (−2)	1B	0116	72°W	yes	yes	M2
			1B	0311	74°W	yes	yes	M8
Aug. 13, 1982	2330	~2 (−2)	SN	2301	59°W	possible	no	C8
Aug. 14, 1982	0530	1.1 (0)	1B	0507	62°W	yes	possible	M4

[a]Peak flux in protons cm^{-2} sr^{-1} s^{-1} MeV^{-1}. Numbers in parentheses indicate powers of 10.

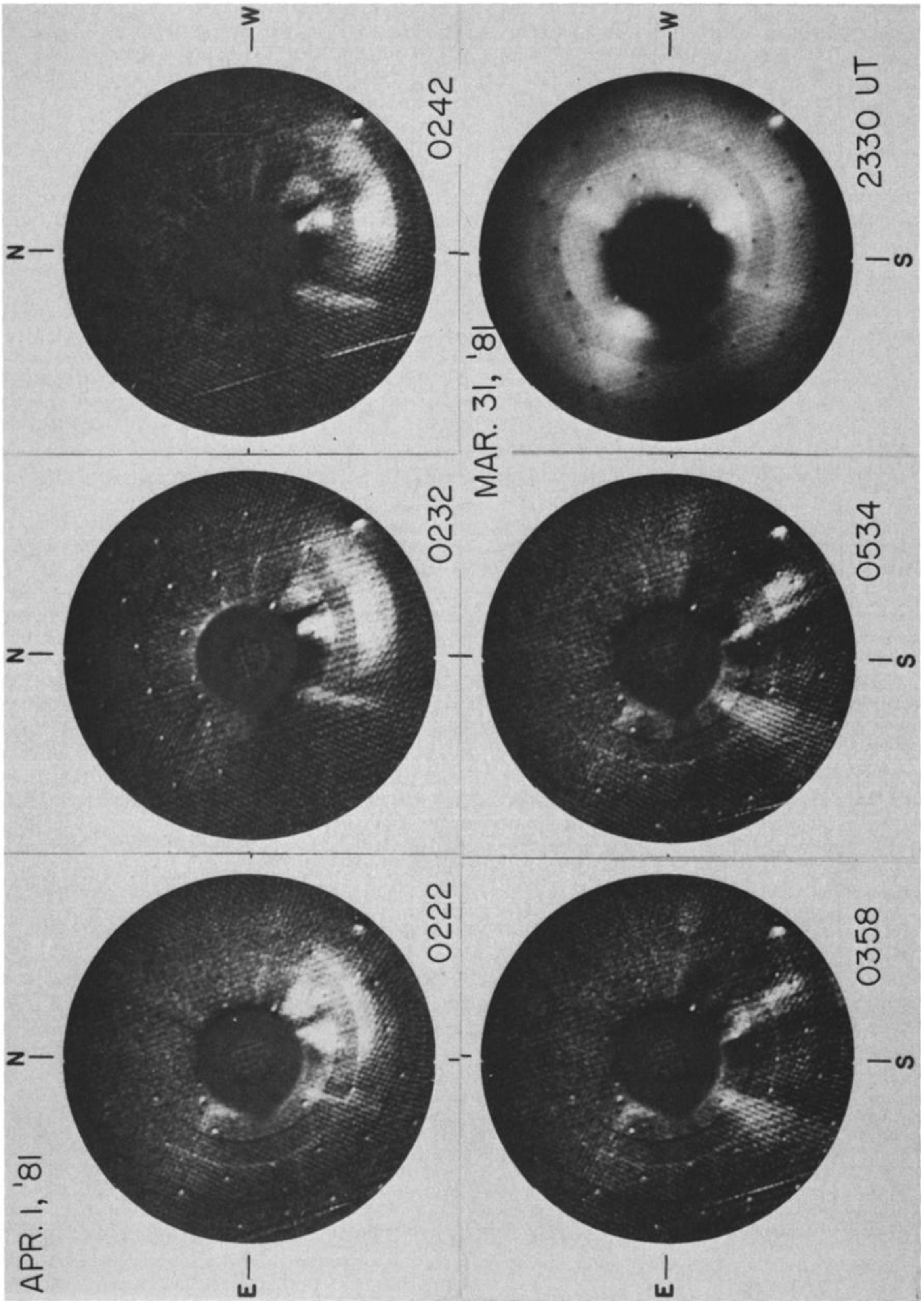

Fig. 2. Solwind subtracted images showing the CME of April 1, 1981 associated with the proton event of Figure 1. The unsubtracted image of 2330 UT March 31, shows coronal structure before the CME.

associated with a 1*N* flare at 11°N, 79°W with a 1714 UT onset. Two other H alpha flares were reported within 15 minutes of this event, but the strongest *X* ray and microwave emissions are temporally associated with the 1714 UT event.

Of the 40 *Y* and *P* events of Table 1 we have found only two cases, those of December 12, 1979 and June 7, 1980, for which an associated CME can be considered unlikely. With no further such examples the existence of a class of proton flares with no associated CME's would be doubtful. However, we have found two additional such proton events which are not part of our study period. These events, both in August 1982, and their associated H alpha flares are listed in Table 3 along with the two events from our study. All the proton events are relatively short, lasting only ~1 day. In addition, all the associated flares show remarkable similarities. They are magnetically well connected to the earth with longitudes ranging from 59°W to 79°W. The 1–8-Å *X* ray events are quite impulsive, being about 10–15 minutes in duration, which indicates a low probability for CME association [*Sheeley et al.*, 1983*a*]. In two of the three cases for which the Solar Maximum Mission spacecraft (SMM) observations exist, gamma ray line events were observed (D. Forrest, private communication, 1983). In addition, the flare of August 14, 1982 was observed as a gamma ray event at energies above 2 MeV (P. Evenson, private communication, 1984). Finally, three flares definitely had metric type II bursts, one (August 13, 1982) was associated with a possible type II burst reported by Culgoora, Australia, and one (December 12, 1979) had a short metric burst with possible type II characteristics observed at Ft. Davis (A. Maxwell, private communication, 1984). The events of Table 3 establish a class of flares energetic enough to result in coronal shocks, impulsive phase ion production, and interplanetary protons, but without CME's bright enough to be observable with the Solwind coronagraph.

Correlations Between Proton Event and CME Characteristics

We have used a number of different terms to describe the observed CME morphologies, such as loops, fans, blobs, spikes, jets, halos, and quadrant fillers. Many events appear as combinations of such structures. To some extent, the description we use depends on the brightness and timing of the observed event. A quadrant filler or fan may be the late stage of

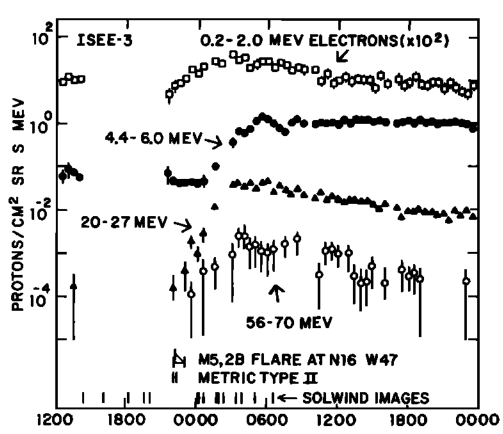

Fig. 3. ISEE 3 proton fluxes in three energy bands during the event beginning ~2300 UT November 14, 1981. The proton event was accompanied by a relativistic electron event shown in the top plot.

an earlier unobserved loop, for example. The halo event is a newly discovered three-dimensional structure directed toward or away from the earth [*Howard et al.*, 1982]. One question we can ask is whether the CME's associated with proton events show any distinct morphologies. Examining the best associated CME's of Table 1, the 21 *Y*, + + events, we find that 20 of those events are classified as loops, halos, fans, or quadrant fillers. We estimate that about half of all the ~900 transients cataloged so far fit these descriptions, so there is a clear bias of the proton event association for loop and fan CME's and against spikes, jets, blobs, or irregular structures.

In most cases of associated CME's the speeds could be deduced and the angular sizes measured. Sometimes these parameters appear to vary during an event, generally increasing with time, in which case the maximum values were assumed. To search for parametric correlations between CME's and proton events, we have compared the CME angular sizes and speeds with the associated proton event fluxes and spectral indices. The background-corrected 4–22-MeV peak fluxes of events with probable flare associations are given in Table 2. The plot of 4–22-MeV peak fluxes against CME speeds for all the associated west limb + and + + CME's of Table 1 is shown in Figure 5. The east limb events were not used due to the expected large modulation of those peak proton fluxes. Events with no (*N*) flare associations are indicated on the plot, as are those due to flares within 45° of solar central meridian. In the latter cases the speeds are probably underestimated by perhaps a factor of 2, since we are using speeds measured in the plane of the sky, and in these events the speeds should have larger components along the line of sight. Variations among events in proton flux modulations as well as uncertainties in measuring the CME parameters suggest that considerable statistical noise will be present in any correlation between proton and CME parameters. Nevertheless, we find a significant correlation between the peak 4–22-MeV proton fluxes *F* and CME speeds *V* of Figure 5. The correlation coefficient is 0.56 for 21 events, indicating a correlation at better than the 99% confidence level [*Bevington*, 1969], and the least squares best fit to the data, treating the two parameters as equivalent, is

$$\log F(p\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}\ MeV^{-1}}) = 3.7 \times 10^{-3}\ V(\mathrm{km\ s^{-1}}) - 3.5$$

The angular extents of nearly all the CME's of Table 2 lie on or close to the ecliptic at $\phi = 90°$ or 270°, but one event, on May 21, 1980, is clearly confined to a small angle out of the ecliptic. Angular sizes range from about 20° for the May 21, 1980 event to a full 360° for the head on, or halo, events. A plot of peak flux *F* against angular size θ for all the west limb + and + + events of Table 1 for which angular sizes are well determined yields a significant correlation, as shown in Figure 6. The correlation coefficient of $r = 0.48$ for 25 events is significant at the 98% confidence level. The least squares best fit, again treating the two parameters as equivalent [*Bevington*, 1969], yields

$$\log F(p\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ MeV^{-1}}) = 3.5 \times 10^{-2}\ \theta(\mathrm{degrees}) - 2.9$$

We also looked for correlations between spectral indices of proton energy and CME speeds and angular sizes. Using the ratios of IMP 8 4–22- to 20–80-MeV fluxes as spectral indices for the + and + + west limb events, we found correlation coefficients of $r = 0.31$ (20 events) for *V* and $r = 0.36$ (24 events) for θ, marginally significant at the 80% and 90% con-

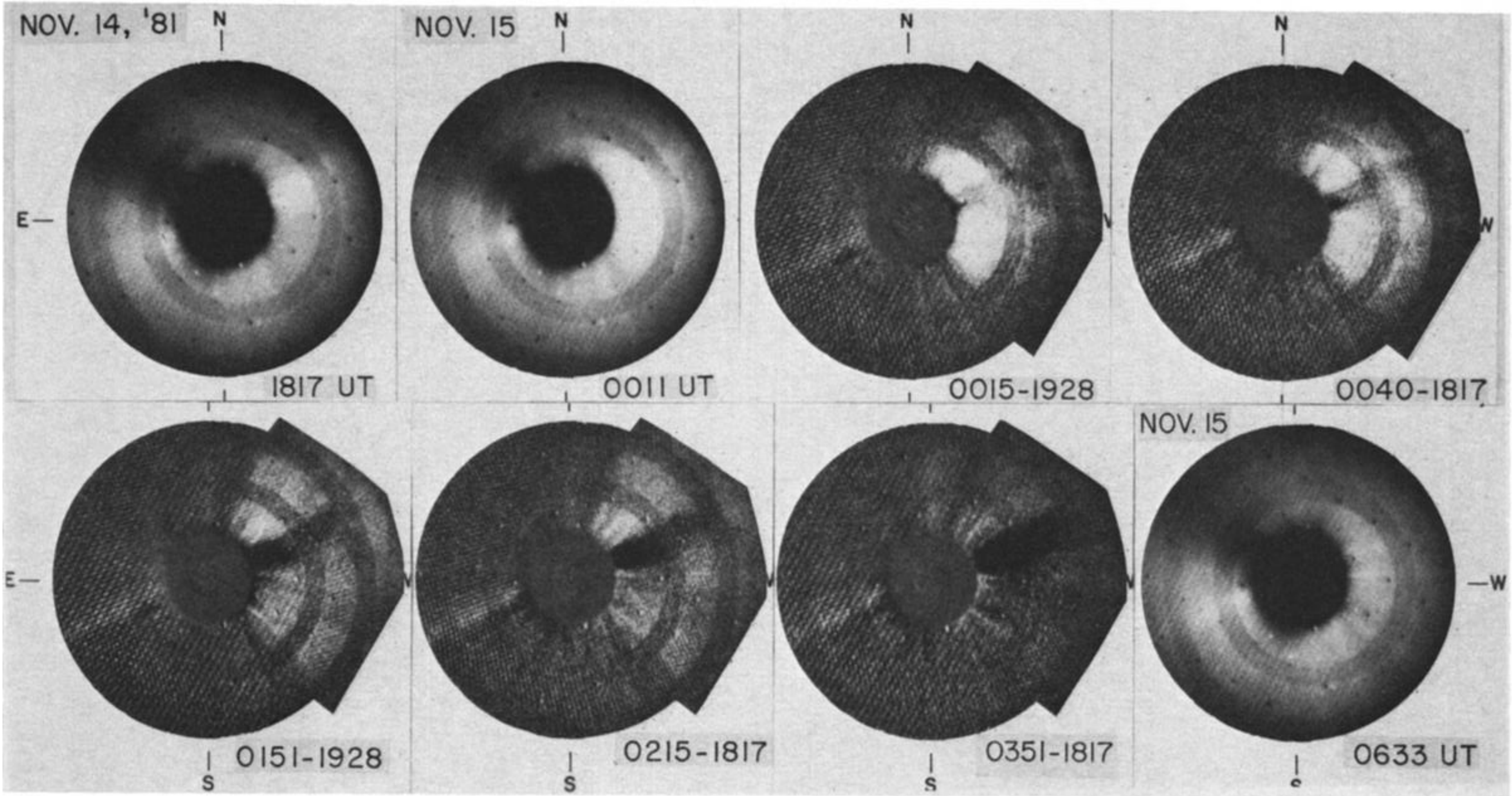

Fig. 4. Solwind images showing the CME of November 15, 1981 associated with the proton event of Figure 3. Both subtracted and unsubtracted images are shown. The preexisting coronal streamer at 290° disappears during the CME event.

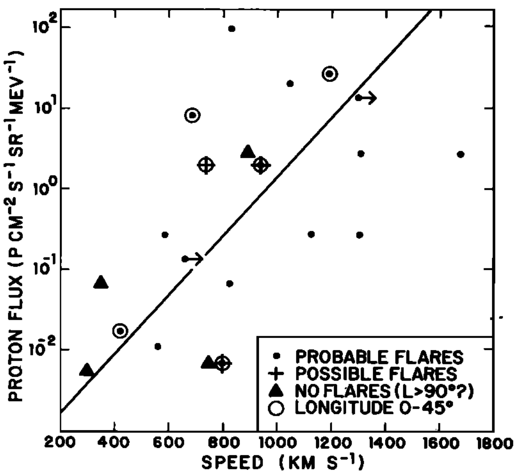

Fig. 5. Plot of the IMP 8 peak 4–22-MeV proton fluxes and the associated CME speeds. All the events of Table 1 with probable (+) and very probable (++) west limb CME associations for which speeds could be determined were used in the plot. Circled events are those for which the parent flare was within 45° of central meridian and for which the speeds are probably underestimated by a factor of less than or equal to 2. Events with no (*N*) flare associations, indicated by triangles, are probably due to flares behind the west limb. The two points with arrows are lower limits. The solid line indicates the least squares best fit to the data. Uncertainties in the data values vary from event to event, but typically both parameters are accurate to within ±20%.

fidence levels, respectively. The sense of the correlation was that larger CME speeds and angular sizes correlated with steeper energy spectra.

Inverse Correlations

We have seen in the preceding discussion that the data are consistent with the conclusion that, except for a small class of events, every flare proton event is associated with a CME and that the faster the associated CME speed, the greater the peak 4–22-MeV proton flux. We now consider the inverse correlation: given the presence of a CME, what can we say about the association of a proton event with that CME? As in the previous section, we attempt to minimize the effects of interplanetary modulation of particle fluxes by considering only west limb CME's, i.e., those with position angles 180° to 360°, and particle events. In view of the speed correlation shown in Figure 5, we began with a list of all observed west limb CME's with speeds of $V \geq 500$ km s^{-1}, a total of 80 events. These events were compared to the particle flux plots to look for associated proton events. If the background 4–22-MeV fluxes exceeded 1.3×10^{-1} particles cm^{-2} sr^{-1} s^{-1} MeV^{-1} and no event was observed, or if an event was observed but the timing of the onset was earlier than about 1 hour or later than about 4 hours after the estimated CME onset, the CME association was considered indeterminate. Twenty events were in this category. Of the remaining CME events, 22 were associated with proton events and 38 were not, with only two of the 22 proton events originally classified uncertain (*U*) as to whether they had flare origins. The distribution of these events by CME speeds is given in Figure 7, which shows that as the speed increases, so does the probability of an associated proton event, a result logically consistent with that of Figure 5. The median speed of the CME's with no proton events was 660 km s^{-1}; that of CME's with proton events was 890 km s^{-1}.

The angular size distributions of high-speed CME's with and without associated proton events are shown in Figure 8.

TABLE 4. Ecliptic Intersections of West Limb Transients with Speeds $V \geq 500$ km s^{-1}

	Proton Events			Nonproton Events		
	Yes	No	Total	Yes	No	Total
$\theta \geq 60°$	11	4	15	9	5	14
$\theta < 60°$	3	4	7	7	17	24
All θ	14	8	22	16	22	38

Here again there is a significant difference between the two, with the CME's associated with proton events having statistically larger angular sizes. The median values of the two groups are 42° and 80°, a factor of ~2 in difference. Directly related to this is the difference in the morphologies of the two groups. Eighteen of the 22 CME's with proton events were associated with loops, fans, or quadrant fillers, structures tending to have large angular sizes, while only 16 of the 38 CME's without proton events were associated with those structures.

The statistically larger angular sizes of CME's with proton events could be due to any of several different effects. We consider here three possibilities:

1. There is a correlation between speeds and angular sizes of CME's such that the results of Figures 7 and 8 are not independent.

2. The physically important factor is whether the CME intersects the ecliptic, and CME's with larger angular sizes are more likely to do so.

3. The angular size, independent of speed and intersection of the ecliptic, is a physically important factor.

To investigate possibility 1 we looked for a correlation between CME angular sizes and speeds for the 80 events of $V \geq 500$ km s^{-1} and found a correlation coefficient of $r = 0.07$, indicating a correlation significant at less than the 50% confidence level [*Bevington*, 1969]. Examining only those 22 CME's associated with proton events, we find $r = 0.05$, significant at well under the 50% confidence level. Since the median angular sizes of the two groups of Figure 8 differed by a factor of 2, we rule out possibility 1 and conclude that the occurrence of a proton event depends on two independent CME parameters, speed and angular size.

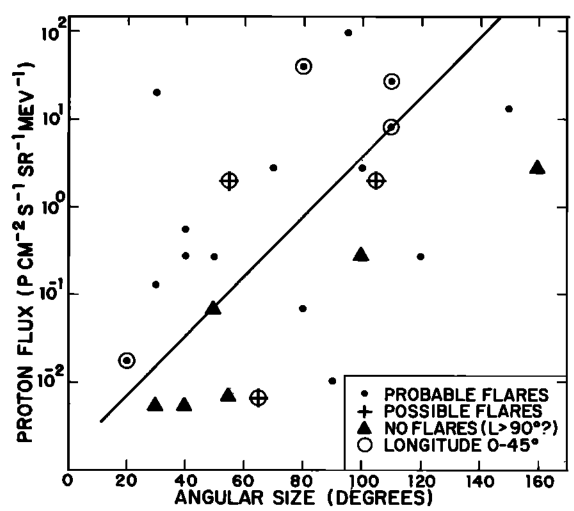

Fig. 6. Plot of the IMP 8 peak 4–22-MeV proton fluxes against the angular widths of the associated CME's. All west limb events of Table 1 for which the proton fluxes and CME angular sizes could be determined were used. Solid line represents the least squares best fit. Symbols are same as in Figure 5.

To distinguish between possibilities 2 and 3, we have divided the 80 west limb CME's into two groups, those with angular sizes $\theta \geq 60$ and those with $\theta < 60°$. These groups were then further subdivided into those CME's with proton events and those without; indeterminate events were excluded. Counting CME's with position angle boundaries exactly at $\phi = 270°$ as not intersecting the ecliptic, we find from Table 4 that of the 22 CME's with proton events, 14 intersected the ecliptic, and 15 were at least 60° in size. Of the 38 CME's without proton events, 16 intersected the ecliptic, and 14 were at least 60° in size. Since these sets of numbers are nearly identical, they do not allow us to determine which of the two coupled factors, CME angular size or CME intersection of the ecliptic, is the physically significant one in deciding, independently of CME speed, whether an associated proton event will occur.

The coronagraph enables us to observe CME's from solar sources well behind the limb as well as from sources on the visible disk. Some of the nonproton events of Table 4 should therefore be due to proton flares sufficiently far behind the limb that no protons could be observed at the Earth. Figures 7 and 8 suggest that the CME's of these unobserved proton events should be faster and wider than average, so that a correction for these events would result in even larger differences of speed and width between the proton and the nonproton events.

DISCUSSION

The 50 events of Table 1 yield two exceptions to the main conclusion of KHV and our preliminary finding [*Kahler et al.*, 1983*a*] that a CME may be a necessary requirement for the occurrence of a flare proton event. These exceptions appear to be members of a rather small, well-defined class of events discussed below. The CME association does hold, however, for the great majority of proton events we have studied. Although the observed frequency of occurrence of CME's is about two per day, the probability of a chance association between the proton event and a CME is small. This is because once the proton H alpha flare is identified, any candidate CME had to be associated spatially as well as temporally with that flare.

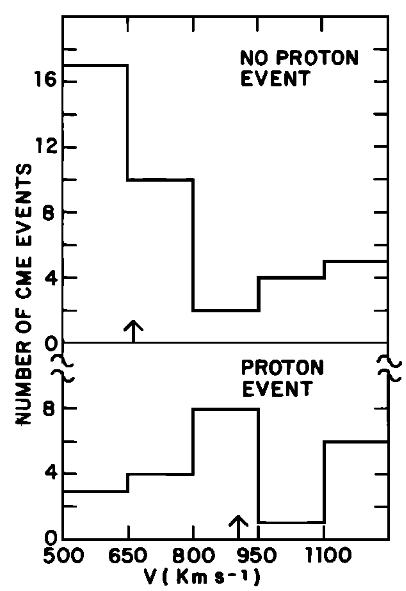

Fig. 7. Number of west limb CME events with (below) and without (above) associated proton events as a function of CME speed. Arrows indicate the median speeds for each distribution. The last speed bin includes all speeds of at least 1100 km s^{-1}.

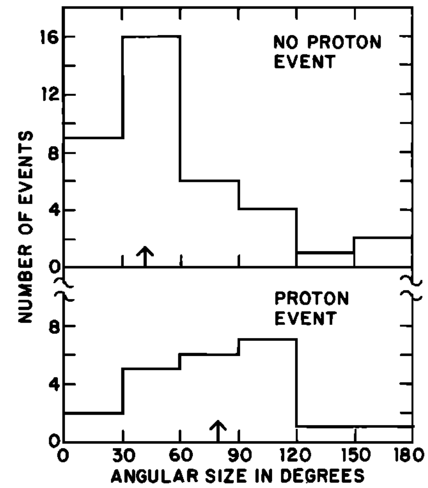

Fig. 8. Number of west limb CME events with (below) and without (above) associated proton events as a function of CME angular size. Arrows mark the median values of each distribution.

The significance of the association between proton events and CME's is confirmed by the correlations we have found between 4–22-MeV peak proton fluxes and CME speeds and angular sizes shown in Figures 5 and 6. The Skylab CME data of KHV were found to be consistent with a correlation between 4–23-MeV proton fluxes and CME speeds, but their result was not conclusive. A comparison of our Figure 5 with their Figure 5 indicates that the fit derived for our data is not inconsistent with their data points, although most of them would lie to the right of our best fit line, indicating lower fluxes for similar speeds.

KHV considered the question of whether the association between proton events and CME's is due to the big flare syndrome, in which we select for analysis very energetic events which have a high probability of producing both energetic protons and CME's independently of any direct causal relationship. They argued against this possibility by showing that peak 1–8-Å *X* ray fluxes as a measure of flare energy served as a poor guide to the proton events of their sample. Recently, *Sheeley et al.* [1983*a*] have compared *X* ray events and CME's and found that for a given *X* ray event the probability of an associated CME is a strongly increasing function of *X* ray event duration but only a weakly increasing function of *X* ray peak intensity. They concluded that their results supported the concept of two classes of *X* ray events, one with statistically long durations and associated CME's and the other with short durations and non associated CME's. In another recent study, *Cliver et al.* [1983*b*] found that proton flares show a wide range of peak 3-cm microwave fluxes. The preceding studies all indicate that proton events generally arise from a particular kind of flare characterized by mass ejections rather than by large *X* ray or microwave fluxes. However, it is still possible that particle acceleration occurs in a process which is not directly dependent on the CME. The correlation of more energetic CME's, characterized by larger angular sizes and speeds, with larger particle fluxes remains consistent with the concept.

Although other interpretations may be possible, such as the *Schatten and Mullan* [1977] model in which the CME acts as a temporary trap for previously accelerated particles, we feel, as did KHV, that the basic reason for the correlation between

CME's and flare protons is that the CME acts as a driver to set up a coronal shock in which protons are accelerated. Accordingly, we would expect that the faster the CME, the greater the probability of setting up a shock, as found by *Gosling et al.* [1976], or the higher the Mach number of the resulting shock. This, in turn, would imply a greater probability for the occurrence of a proton event, just as we found in Figure 7.

If it is not due to the big flare syndrome, the reason for the correlation between the 4–22-MeV peak proton fluxes and the angular sizes of the associated CME's is not obvious. We have determined that the correlation between CME speed and angular size, if it exists, is small, so that the correlation between peak proton fluxes and CME speeds does not imply a similar correlation between peak proton fluxes and CME angular sizes. The latter correlation is independent of the former.

We have considered two reasons for the angular size correlation, both of which are equally supported by the data. One is that the important factor is the proximity of the CME to the ecliptic. In this case we presume that all CME's of sufficient speed are associated with shock-produced energetic protons, but those protons may not reach the earth if they are confined to magnetic field lines out of the ecliptic. In this connection we note that *Sheeley et al.* [1983*b*] found that nearly all the CME's well-associated with interplanetary shocks observed at the Helios spacecraft lay in or tangential to the ecliptic. However, the May 21, 1980 proton flare, described by *Hoyng et al.* [1981], resulted in a CME only 20° wide which lay close to the south ecliptic pole. There is also evidence that high-latitude open magnetic field lines converge toward the solar equator [*Suess et al.*, 1977; *Levine*, 1978]. In addition, *Hildner* [1977] reported that, on average, the midlatitudes of Skylab CME's were approximately 2.5° closer to the equator at 4 R_0 than at 2 R_0. This suggests that protons accelerated in association with high-latitude CME's in the low corona at altitudes of 2–3 R_0 may escape along ecliptic field lines. Thus there is no observational or theoretical requirement that a CME must lie in the ecliptic for the associated protons to reach the earth.

The other possible reason for the angular size correlation is that it is the size itself that is important. In this case it could indicate a larger area over which proton acceleration takes place. If there is substantial proton diffusion in the region of the shock, then the larger CME area implies a larger and more intense source for energetic protons observed at the earth. Another interpretation is that the size itself is not so important as the structure of the CME. The larger angular sizes are generally a reflection of the fact that the CME's are loops and fans rather than the narrower jets, spikes, and blobs. The broader structures may somehow give rise to more favorable conditions for proton acceleration than the narrow ones. Unfortunately, it does not appear that the present data allow us to discriminate among the several possibilities explaining the dependence of peak proton fluxes on the CME angular sizes.

We might expect that the more energetic CME's, those with greater speeds and angular sizes, would result in proton events with flatter energy spectra. We found, however, that if any spectral dependence is present, it is such that steeper spectra in the 4–80-MeV range are associated with greater CME speeds and angular sizes. However, these correlations were present at only the 80% and 90% confidence levels, respectively.

These observations have been limited in several respects. CME speeds are determined only in the plane of the sky and only for the fastest moving feature of a given event. The angular sizes are generally functions of time or radial position and cannot always be measured precisely. Furthermore, the proton fluxes and spectra are subject to interplanetary propagation effects. However, the use of the 3-year data base of the NRL coronagraph observations has allowed us to deduce the basic properties of CME's important to the production of energetic protons. More detailed observations will be required to provide further understanding of these results.

The proton events of Table 3, which constitute the only observed exceptions to the general rule of CME associations for proton events, are of considerable interest for the clues they offer to energetic proton propagation. One striking feature of these events is their relatively short durations for both the proton events (~ 1 day) and the associated soft X ray flares (~ 10 minutes). The short X ray time scales and lack of associated CME's suggest that these flares could be members of the class of compact, low-lying flares distinguished by *Pallavicini et al.* [1977]. A similar argument has been advanced by *Kahler et al.* [1983*b*] for flares producing type II bursts but no CME's. It therefore appears that both compact and large mass ejection flares are capable of producing interplanetary proton events, although only a small minority of all observed proton events are due to the compact flares.

The mechanisms of acceleration and release of interplanetary protons in the flares of Table 3 are not clear. The good type II burst association allows the possibility of coronal shock acceleration, which we favor for the events associated with CME's. On the other hand, the observation of gamma ray line emission in two or three of the four observed flares indicates the presence of energetic protons in the flare impulsive phases [*Chupp*, 1982]. Protons resulting from the decay of neutrons escaping gamma ray flares have been seen in two cases by *Evenson et al.* [1983], but the correlation between near-earth proton fluxes and gamma ray line fluences is poor [*von Rosenvinge et al.*, 1981; *Cliver et al.*, 1983*a*].

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R. A. Howard, M. J. Koomen, D. J. Michels, and N. R. Sheeley, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375.

S. W. Kahler, AFGL/PHP, Hanscom AFB, MA 01731.

R. E. McGuire, T. T. von Rosenvinge, and D. V. Reames, Laboratory for High Energy Astrophysics, Goddard Space Flight Center, Greenbelt, MD 20771.

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