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SOLAR FLARE NUCLEAR GAMMA-RAYS AND INTERPLANETARY PROTON EVENTS

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ABSTRACT

We have compared separately compiled lists of solar flare nuclear γ-ray line (GRL) events and solar energetic proton (SEP) events for the period from 1980 February to 1985 January. The GRL data are from the gamma-ray spectrometer on the *Solar Maximum Mission* (*SMM*) satellite. For SEP parent flares not observed by *SMM*, we inferred GRL fluences, or upper limits, from correlations between the 4–8 MeV GRL fluence and other (>300 keV X-ray, 9 GHz microwave) flare emissions. As our principal result, we find a lack of correlation between flare 4–8 MeV GRL fluences and the peak fluxes of ~10 MeV protons in interplanetary space. This poor correlation is primarily due to several large SEP events that originated in flares without detected (or inferred) GRL emission. The converse case of GRL flares unassociated with SEP events is rare. The ratio (R) of the number of ~10 MeV protons that produce GRL emission at the flare site to the number of ~10 MeV protons detected in space can vary from event to event by 4 orders of magnitude. There is a clear tendency for impulsive flares to have larger values of R than long-duration flares, where the flare time scale is given by the e-folding decay time of the associated soft X-ray emission. We discuss these findings in terms of other recent work on particle acceleration in solar flares.

Subject headings: gamma-rays: general — particle acceleration — Sun: flares

I. INTRODUCTION

The acceleration of protons to high energies during solar flares has been of interest since the first report, over four decades ago, of a solar "cosmic-ray" event at Earth (Forbush 1946). Much of what we know about proton acceleration (see Ramaty *et al.* 1980; Vlahos *et al.* 1986; Lin 1987; and Ramaty and Murphy 1987 for recent reviews) has come from the study of solar energetic particles in space. Until the launch of the *Solar Maximum Mission* (*SMM*) satellite in 1980, any additional information on the acceleration of nuclei had to be inferred, with few exceptions (Chupp, Forrest, and Suri 1975; Hudson *et al.* 1980; Chambon *et al.* 1981; and Prince *et al.* 1982), from the electromagnetic emissions of flare-energized electrons. To date, the gamma-ray spectrometer (GRS) on *SMM* has observed the γ-ray line emission due to protons interacting in the solar atmosphere from ~50 flares. This makes it possible to compare statistically the properties of solar energetic protons observed in space with those of the proton population at the flare site.

The earliest such comparisons using these new data yielded a surprising lack of correspondence between flare nuclear γ-ray line fluences and the sizes of interplanetary proton events. However, these early reports were based for the most part on a relatively small sample of events observed mainly in 1980–1981 (von Rosenvinge, Ramaty, and Reames 1981 [two events]; Pesses *et al.* 1981 [<10 events]; and Cliver *et al.* 1983*a* [16 events]) (see also Chambon *et al.* 1981; Yoshimori and Watanabe 1985). More recently, preliminary reports have been given for two studies on extended data sets (Cliver *et al.* 1987*a* [48 events] and Kallenrode *et al.* 1987 [24 events]). This paper is an expanded version of our preliminary (Cliver *et al.* 1987*a*) report. In it, we compare γ-ray line (GRL) and solar energetic proton (SEP) events observed from 1980 February through 1985 January in order to substantiate and better characterize the lack of correlation between GRL fluences and SEP event peak fluxes. For example, we will show that while even large SEP events can originate in flares lacking detectable GRL emission, the converse case of flares with a significant GRL line fluence but lacking protons in space is rare.

A second focus of this paper is the finding by Cane, McGuire, and von Rosenvinge (1986) and Bai (1986) (see Kocharov, Kovaltsov, and Kocharov 1983) that the characteristic time scale of the flare X-ray emission (hard or soft) is an important parameter that can "order" the γ-ray/proton observations. In particular, for a sample of 10 GRL/SEP flares, Bai (1986) showed that the ratio of the number of γ-ray producing protons to the number of interplanetary protons varies greatly from event to event but that, on average, this ratio is higher for impulsive flares than for gradual flares. In the present study, we examine how this ratio varies with flare scale time for the 1980–1985 GRL/SEP data set.

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The paper is organized as follows: In § II we discuss the instrumentation and our event selection criteria and present the data tables. In § III we present the scatter plot of SEP event peak flux versus GRL fluence, and in § IV we examine the relationship between the flare soft X-ray decay time and the ratio of "solar" to "interplanetary" ~10 MeV protons. The observational results are summarized in § V. In § VI we discuss our findings in the context of other recent work on particle acceleration in flares.

II. DATA CONSIDERATIONS

a) Proton Data

Near-Earth proton fluxes were measured by the Goddard Space Flight Center (GSFC) experiments on *IMP 8* (Kahler *et al.* 1984) and *ISEE 3* (von Rosenvinge *et al.* 1978). We used the following selection criteria to obtain a sample of proton events: (1) a peak 20–40 MeV flux ($J[>20$ MeV$]) \geq 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} and (2) evidence of velocity dispersion in the time-intensity profile, either during the event rise or at maximum. Demanding >20 MeV ions and velocity dispersion discriminates against corotating (Fichtel and McDonald 1967) and energetic storm particle (ESP) (Bryant *et al.* 1962; Datlowe 1972; Wenzel *et al.* 1985) events. Secondary considerations that influenced our identification of SEP events included the presence of $\gtrsim 200$ keV electrons (the lowest energy channel on *IMP 8* or *ISEE 3*) and a proton time-intensity profile with a fast rise followed by an exponential decay. Particle events often exhibit fluctuations during their decay phase, and it can be difficult to determine if flux enhancements at these times, particularly small ones, represent a new injection or are merely due to modulation of previously accelerated particles. To simplify the search procedure, we required that such events show an increase of at least 5 times the enhanced ($>10^{-3}$) preevent background.

Using these criteria, we identified 64 SEP events occurring during the period from 1980 February to 1985 January that had confident/probable visible hemisphere flare associations. Although we did our proton event search using >20 MeV data, we recorded the peak 9–23 MeV fluxes ($J[>9$ MeV$]$), with background subtracted, for eventual comparison with the 4–8 MeV γ-ray emission. We used the peak flux because, in diffusion theory, the peak flux observed at Earth is proportional to the total number of protons released at the flare site (e.g., Van Hollebeke, Ma Sung, and McDonald 1975). The parent flare association for each of the 64 SEP events was based on Hα, soft X-ray, and discrete and sweep frequency radio burst data published in *Solar Geophysical Data* (SGD). Approximately 70% (47/64) of the identified flares had their 1–8 Å maximum within 2 hr of the particle event onset time (determined from hourly averaged data); for only five events (four from eastern hemisphere flares) was the delay to SEP onset >4 hr. Forty-nine of the 64 proton flares occurred in the western solar hemisphere.

In our determination of the timing and value of the 9–23 MeV peak proton flux for the 64 events, we did not attempt to distinguish between "prompt" and "delayed" components, but selected the largest peak following event onset that could reasonably be attributed to a given flare. Of course, the longer the delay between the flare and the $J(>9$ MeV$)$ proton event maximum, the greater the chance of additional particle injections. For 41 of the 64 events, the delay to the $J(>9$ MeV$)$ maximum was ≤ 15 hr. Fourteen of the 23 events with delays greater than 15 hr originated in eastern hemisphere flares. The median delay to maximum for these 14 events was 44 hr (range from 18–80 hr) versus a median delay of 19 hr (range from 16–56 hr) for the nine western hemisphere events with long delays. The long delay proton events are strongly associated with interplanetary shocks (see Cane and Stone 1984; Cane, Reames, and von Rosenvinge 1988). For the 21 such SEP events occurring before 1983 March, 11 of 13 eastern hemisphere events and four of eight western events have interplanetary type II associations (Cane 1985).

We used GSFC *Helios* particle observations to include the well-studied GRL/neutron flare of 1982 June 3 (Chupp *et al.* 1987) in our data set. The near-Earth (*IMP 8*) 20–40 MeV peak flux from this flare was less than 10^{-3}, and thus this event was not admitted by our selection criteria. However, the *Helios* satellite was well connected to the E71 flare site, and a large SEP event was observed there (McDonald and Van Hollebeke 1985). Our final data set then contained a total of 65 SEP events. We used *Helios* particle data for one other SEP event on our list. For the 1980 June 21 event, we used the 11–22 MeV proton data published by McDonald and Van Hollebeke (1985) because *Helios* was better connected than Earth to the W90 flare site and observed a ~10 MeV proton flux more than 10^2 times larger than that observed by *IMP 8* or *ISEE 3*. (The delay to maximum as measured by near-Earth satellites was 56 hr for this event.) For the 1980 June 21 and 1982 June 3 events, *Helios* was located at ~0.5 AU (0.54–0.57), and the lower limits of the peak fluxes were taken to be one-fourth of the observed values, assuming scatter free transport, in order to normalize these flux values to 1 AU. For diffusive transport, these lower limits would be approximately one-sixth of the values observed at *Helios*.

b) Gamma-Ray Data

The GRL data were obtained by the *SMM* gamma-ray spectrometer (GRS). The GRS is a multicrystal Na I (Tl) scintillator spectrometer that provides a 476-channel pulse-height spectrum over the energy range 300 keV–9 MeV. This instrument also has a thick Cs I (Na) crystal that is used in conjunction with the seven Na I crystals to form a high-energy (10–100 MeV) detector (see Forrest *et al.* 1980 for a detailed description of this instrument).

Prompt nuclear de-excitation lines in the range from 4 to 8 MeV result when accelerated protons and α-particles interact with ambient helium and heavier nuclei (carbon, nitrogen, and oxygen). Underlying emission in this energy range is due to accelerated carbon and heavier nuclei interacting with ambient hydrogen and helium and also to bremsstrahlung from energetic electrons (see Ramaty and Murphy 1987). The contribution from electrons is removed by (1) fitting a power-law spectrum to the photon emission over the range from 300 keV to 1 MeV, (2) extrapolating this spectrum to the 4–8 MeV range, and (3) subtracting it from the observed spectrum, leaving the 4–8 MeV nuclear excess. The time-integrated excess (fluence) is proportional to the total number of ~10 MeV ions interacting at the flare site.

Using this technique, 45 GRL flares with significant ($\geq 2\ \sigma$) nuclear emission at 4–8 MeV were identified in the GRS data for the 5 yr period of the study. We shall refer to these events as "GRL flares" but it should be kept in mind that this distinction is dependent on the threshold sensitivity of the GRS. Protons may be accelerated in smaller flares, only their line emission is too weak to be detected by the GRS. We were able to unambiguously associate 43 of these 45 2 σ events with solar flares: 25 from the western hemisphere and 18 from the east. For the purposes of this study, we note that the 4–8 MeV line emission has the advantage of being isotropic (Ramaty 1986) and is caused by ions with energy $\gtrsim 10$ MeV, comparable to that of the SEPs considered.

c) *Comparison of the SEP and GRL Event Lists*

There were 18 common events in the sample of 65 SEP flares and 45 *SMM* GRL flares observed from 1980 February to 1985 January. For nine of the other 47 SEP events, the *SMM* GRS observed the impulsive phase of the parent flare, but no GRL emission was detected (for six of these nine events, no >300 keV emission was observed). GRS observations were not available for the remaining 38 SEP flares. To obtain an estimate of the 4–8 MeV emission in these events, we used correlations between the 4–8 MeV fluence and other flare emissions. For eight of the 38 events for which (1) the parent flare was observed by the University of California, Berkeley, experiment on *ISEE 3* (Anderson *et al.* 1978) and (2) photons greater than 300 keV were detected, we used the relationship that Forrest (1983) (see Vlahos *et al.* 1986, p. 2–33) has found between the >300 keV electron bremsstrahlung continuum fluence and the 4–8 MeV nuclear γ-ray line fluence to infer a "proxy" GRL fluence. This correlation holds over approximately three orders of magnitude of the >300 keV fluence (F). For $2.5 < \log F < 4$, the full width of the scatter in the 4–8 MeV fluence is about a factor of 5; for $\log F < 2.5$, the scatter increases to a factor of ~ 25. From a comparison of hard X-ray data for a sample of six events observed by both *SMM* and *ISEE 3*, we found generally good agreement ($\pm 30\%$ in five cases) between fluence measurements at greater than 300 keV.

ISEE 3 also observed the parent flares for 23 other flares for which *SMM* GRS data were unavailable. In these 23 cases, however, >300 keV photons were not detected, and we could not use the correlation from Forrest (1983). (The collecting area of the University of California, Berkeley, hard X-ray experiment on *ISEE 3* is less than one-tenth that of the GRS.) Instead, we used the correlation shown in Figure 1 between the 4–8 MeV GRL fluence for all GRL flares in our sample and the flare-associated 9 GHz peak flux density (S_p[9 GHz]) to infer an upper limit to the GRL fluence for these 23 events and also for seven other SEP parent flares observed by neither *SMM* nor *ISEE 3*. It has recently been shown (Kai, Kosugi, and Nitta 1985; Cliver *et al.* 1986; Bai 1986) that the basic flare time scale is an important parameter to consider in correlations of this type. Thus in Figure 1 we have differentiated between impulsive (*filled circles*) and gradual (*open circles*) events. We define impulsive events as those with a soft X-ray e-folding decay time (τ), measured from the peak of the event, of ≤ 10 minutes; for gradual events, $\tau > 10$ minutes. (The rationale for making the separation at $\tau = 10$ minutes is given in § IV.) As can be seen from the figure, the gradual events tend to be "microwave-rich" (see Bai 1986). The dashed line is the least-squares fit to all of the data points. It has the equation

$$\log (4\text{–}8 \text{ MeV GRL fluence}) = 1.47 \log (S_p[9 \text{ GHz}]) - 4.08 ,$$

with a correlation coefficient $r = 0.67$. The dot-dashed line is drawn at the upper edge of the scatter for the gradual events; the solid line represents the upper edge of the scatter for impulsive flares. We used the appropriate "upper edge" line to obtain upper limits for the 4–8 MeV GRL fluence for the 30

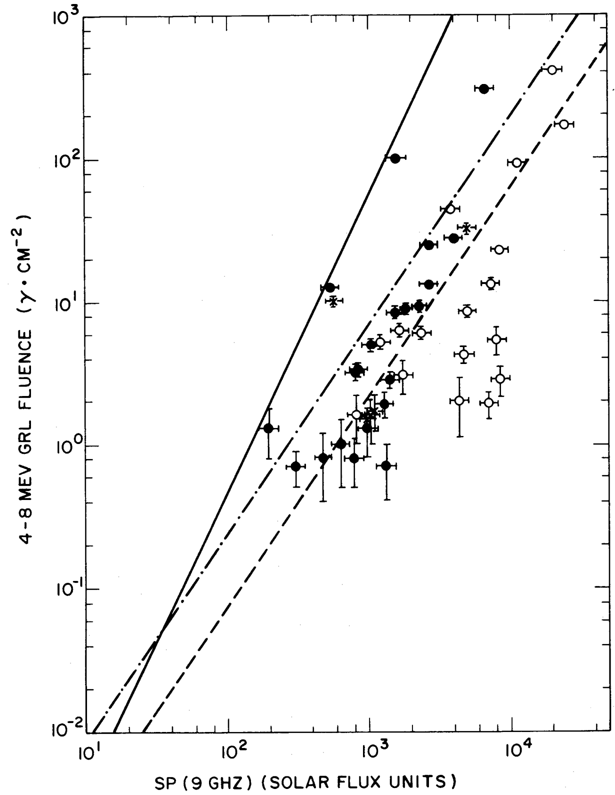

FIG. 1.—Scatter plot of 4–8 MeV GRL fluence vs. 9 GHz peak flux density (S_p[9 GHz]) for GRL flares observed from 1980 February to 1985 January. Filled circles indicate impulsive flares; open circles denote gradual flares. For data points indicated by a cross, the time scale of the flare was indeterminate. The dashed line is the least-squares fit to all the data points. The dot-dashed line is drawn at the upper edge of the scatter for gradual flares, and the solid line indicates the upper edge of the scatter for impulsive flares.

remaining SEP parent flares. Most (25) of these SEP flares were gradual events. Inferred upper limits with values less than 0.1 photons cm^{-2} were set equal to 0.1 photons cm^{-2}.

d) *Data Table*

The 65 proton events with confident flare associations are listed in Table 1. Columns (1)–(4) give the event number and the date, location, and Hα classification of the parent flare. The time of maximum, the peak flux classification (Cn, Mn, X$n = n \times 10^{-3}$, 10^{-2}, and 10^{-1} ergs cm^{-2} s^{-1}), and the e-folding decay time (τ, in minutes, measured from the event maximum) of the flare-associated 1–8 Å soft X-ray burst are given in columns (5), (6), and (7). Columns (8) and (9) give the time of the 9 GHz microwave burst maximum and the peak flux density (S_p[9 GHz]) in solar flux units (1 sfu $= 10^{-22}$ W m^{-2} Hz^{-1}). The S_p(9 GHz) values are average values for all stations reporting in the 8–12 GHz range, after discarding any widely divergent values. We estimate the uncertainties in these peak flux density values to be $\pm 15\%$ (Kahler 1982). Column (10) gives the earliest reported start time and latest reported end time of associated metric type II emission. Column (11) indicates the sensor (S = *SMM*; I = *ISEE 3*; μ = microwave) used to measure or infer the γ-ray data in columns (12)–(14). For the 19 events with an "S" in column (11), columns (12)–(14) give the onset time of the >300 keV event, its duration, and the 4–8 MeV GRL fluence or a 1 σ upper limit (three cases). For these 19 events, the 4–8 MeV emission was deter-

TABLE 1

SOLAR PROTON EVENTS, 1980–1985

Event Number (1)	Date (2)	Hα Flare Location (3)	Hα Flare Class (4)	1–8 Å Peak Time (UT) (5)	1–8 Å CMX Intensity Class (6)	1–8 Å Decay Time (τ) (Minutes) (7)	9 GHz Peak Time (UT) (8)	9 GHz Peak Intensity (sfu) (9)	Type II Starting and Ending Times (UT) (10)	Data Source (11)
1..........	1980 Feb 15	S10W71	−F	2119	C6	36	2114	56	2120–2127	μ(I)
2..........	1980 Mar 25	S26W25	2F	0429	C8	10	0429	$\lesssim 18$	0424–0439	S*
3..........	1980 Apr 4	N27W35	1N	1523	M5	66	1508	115	1503–1528	μ(I)
4..........	1980 May 21	S14W15	2N	2107	X1	13	2056	1248	2057–2127	S
5..........	1980 Jun 7	N12W74	1B	0314	M7	2	0313	535	0313–0332	S
6..........	1980 Jun 21	N19W90	1B	0120	X3	5	0119	1585	0120–0138	S
7..........	1980 Jun 27	S25W67	−B	1619	M7	7	1616	1318	1620–1643	I
8..........	1980 Jul 5	N28W28	1B	2246	M9	22	2240	235	2244–2255	S*
9..........	1980 Jul 23	S19E17	3B	0103	M9	33	0057	1107	0100–0123	I
10..........	1980 Aug 21	N19W11	1B	1904	M8	8	1908	65	1901–1908	μ(I)
11..........	1980 Oct 15	N21E55	3N	0543	M2	117	0550	47	0520–0549	μ(NO)
12..........	1980 Nov 6	S13E70	2N	0352	X9	24	0346	5000	0346–0435	S
13..........	1980 Nov 11	S11W69	2B	1746	M5	25	~1745	?	1744–1749	S
14..........	1980 Nov 23	N11W20	1B	1905	M2	45	1856	32	1845–1919	μ(I)
15..........	1981 Mar 7	S22W79	−N	0635	M2	~45?	0633	~45	0622–0647	μ(NO)
16..........	1981 Mar 25	N09W87	2B	2045	X1	14	2044u	1564	2042–2107	I
17..........	1981 Mar 30	N13W72	1N	0054	M3	144	0050	128	...	μ(I)
18..........	1981 Apr 1	S43W52	3B	0153	X2	DG	0146	5000	0138–0158	S
19..........	1981 Apr 3	S41W83	1N	1015	M8	36	1020	606	0948–1019	μ(NO)
20..........	1981 Apr 10	N07W36	2B	1655	X2	14	1648	1654	1649–1716	S
21..........	1981 Apr 24	N18W50	2B	1400	X6	22	1402	6163	1355–1429	I
22..........	1981 May 8	N09E37	2B	2252	M8	114	2234	980	2233–2254	S*
23..........	1981 May 10	N03W75	1N	0732	M1	50	0740	25	0719–0744	μ(I)
24..........	1981 May 16	N11E14	3B	0859	X1	52	0839	1626	0825–0841	μ(NO)
25..........	1981 Jun 18	S25W35	1N	0959	M1	78	1009	20	...	μ(I*)
26..........	1981 Jul 20	S25W75	1B	1329	M5	67	1318	615	1322–1332	S*
27..........	1981 Oct 7	S17E83	1N	2308	X4	23	2305	8480	2259–2349	S
28..........	1981 Oct 12	S18E31	2B	0636	X3	46	0633	19400	0627–0715	I
29..........	1981 Nov 7	S07W39	1B	0357	M7	DG	0356	474	0400–0421	μ(I)
30..........	1981 Nov 9	S17E17	2B	1312	M4	63	1313	530	1242–1319	μ(I)
31..........	1981 Nov 14	N15W47	2B	2220	M5	32	2208	942	2204–2220	μ(I)
32..........	1981 Dec 5	N22W40	...	1440	C3	?	~1400	<20	...	μ(I*)
33..........	1981 Dec 9	N10W16	2B	1918	M5	35	1924	320	...	S*
34..........	1981 Dec 27	S13E16	1B	0343	C7	225	0340	18	0250–0300	μ(I*)
35..........	1982 Jan 2	N19W88	1B	0617	M8	16	0611	822	0614–0651	S
36..........	1982 Jan 30	S14E13	2B	2358	X1	20	2352	1636	...	μ(I)
37..........	1982 Feb 1	S16W09	3B	1409	X3	17	1404	~1750	...	μ(I)
38..........	1982 Feb 8	S13W88	1B	1253	X1	7	1249	1550	1250–1315	I/S
39..........	1982 Mar 7	N19W53	2B	0315	X3	16	0308	4602	0306–0331	μ(I)
40..........	1982 Mar 30	N12W12	2B	0543	X3	19	0538	1746	0538–0558	S
41..........	1982 Jun 3	S09E71	2B	1147	X8	6	1143	6830	1144–1210	S
42..........	1982 Jun 25	N17W56	2B	1946	M2	3	1945	25	...	μ(I)
43..........	1982 Jul 9	N18E76	3B	0742	X10	12	0737	3855	0744–0817	S
		N11E80	1B	0904	X1	59	0837	174	...	
44..........	1982 Jul 19	N21W45	2B	0104	X1	10	0101	1326	0106–0124	S
45..........	1982 Aug 8	S09W65	1N	0205	M7	5	0205	630	0205–0220	S
46..........	1982 Aug 14	N11W63	1B	0509	M4	3	0508	1823	0512–0536	I
47..........	1982 Sep 4	N12E38	2B	0053	M6	22	0048	43	0056–0116	
		N12E33	2N	0314	M4	202	0442	77	0236–0248	μ(NO)
48..........	1982 Sep 19	S14E06	2B	1547	C9	140	1507	19	1459–1521	μ(I*)
49..........	1982 Nov 22	S11W36	1N	1829	M7	97	1815	1301	...	μ(NO)
50..........	1982 Nov 26	S12W87	1N	0253	X4	57	0234	8500	0234–0250	S
51..........	1982 Dec 7	S19W86	1B	2354	X3	31	2359	24700	2344–0024	S
52..........	1982 Dec 17	S07W20	3B	1857	X10	8	1855	3436	1854–1917	I/S
53..........	1982 Dec 19	N10W75	1B	1650	M9	92	1635	92	1625–1633	μ(I)
54..........	1982 Dec 25	S17E45	3B	0754	X1	18	0747	2146	...	I
55..........	1983 Feb 3	S17W07	2B	0611	X4	14	0605	7398	0602–0628	S
56..........	1983 Mar 10	S24W55	1N	0923	M1	DG	0930	28	0850–0910	μ(I*)
57..........	1983 Apr 15	S12W90	1B	0215	C4	15	...	...	0207–0246	S*
58..........	1983 May 12	S10W40	1B	0257	M6	7	0255	1146	0255–0333	I
		S30E15	2B							
59..........	1983 May 15	S12W82	1B	0853	X2	16	0919	1933	...	μ(I)
60..........	1983 Oct 14	N14W56	2B	1606	C8	28	1615	19	...	μ(I*)
61..........	1984 Jan 31	N18W54	1B	0733	M2	30	0728	305		
		N17W55	−B	1226	C8	214	1052	38	...	μ(I*)
62..........	1984 Mar 14	S11W43	2B	0334	M2	50	0327	287	0328–0339	μ(NO)
63..........	1984 Apr 25	S11E45	3B	0005	X13	16	0001	20500	...	S
64..........	1984 Jun 5	S14W58	1N	0216	C3	~40?	0223	7	0204–0230	μ(I)
65..........	1985 Jan 22	S10W40	1N	0004	X5	11	0000	2370	...	S

TABLE 1—*Continued*

γ-Rays			9–23 MeV Protons				
300 keV Onset (UT) (12)	300 keV Duration (s) (13)	4–8 MeV Fluence (γ cm^{-2}) (14)	Peak Time (UT) (15)	Peak Flux (protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) (16)		Confidence of Association (17)	Notes (18)
...	...	<0.1	16/04 ± 2	2.5 ± 0.5	−2	2	1
042620	160	<0.7	14 ± 1	4 ± 1	−3	2	2
...	...	<0.3	≤23 ± 1	≳3.8 ± 0.8	−1	1	3
205442	98	<0.5	22/16 ± 4	2 ± 1	−2	1	
031157	66	12.3 ± 0.7	08 ± 1	2.7 ± 0.3	−2	1	4
011820	66	98.3 ± 1.9	03 ± 1	1(+0.2, −0.75)	+1	1	5
161400	240	6.2 ± 5.5	28/03 ± 1	2.2 ± 0.4	−2	1	
223724	900	<1.5	06/10 ± 1	7 ± 1	−2	2	6
005524	280	3.6 ± 3.1	25/10 ± 1	3.2 ± 0.5	−1*	1	3
...	...	<0.2	23 ± 1	1.6 ± 0.3	−2	2	7
...	...	<0.1	6/05 ± 1	7 ± 1	−1	1	3
034440	115	8.4 ± 0.7	07/03 ± 3	1 ± 0.2	−2	1	
174354	82	<0.5	12/05 ± 3	1 ± 0.5	−1	1	3
...	...	<0.1	24/04 ± 2	6 ± 1	−1	1	3, 8
...	...	<0.1	19 ± 2	1 ± 0.2	−1	2	9
203900	660	3.5 ± 3.0	26/11 ± 1	4 ± 1	−2	1	
...	...	<0.4	20 ± 2	2 ± 0.4	0	1	
013321	1524	32.1 ± 2.2	18 ± 2	5 ± 1	−1	1	3
...	...	<3.3	18 ± 1	1.1 ± 0.3	−1	2	10
164630	115	6.2 ± 0.6	11/00 ± 2	3 ± 0.5	0	1	
134422	1860	34 ± 24	21 ± 1	1.8 ± 0.3	+1	1	3
221700	1800	<2.2	11/10 ± 1	2.2 ± 0.4	+1*	1	3, 11
...	...	<0.1	15 ± 1	1.4 ± 0.4	+1	1	
...	...	<14	20 ± 1	3 ± 0.5	+1	1	3
...	...	<0.1	16 ± 1	3 ± 0.5	−2	1	
131100	900	<1.5	20 ± 1	1 ± 0.2	+1	1	
225615	98	2.8 ± 0.7	11/07 ± 3	5 ± 2	0*	1	3
062200	2160	148 ± 97	14/03 ± 1	1 ± 0.2	+2*	1	3
...	...	<12	08 ± 1	2 ± 0.4	−2	1	
...	...	<2.7	11/09 ± 5	2 ± 0.5	−1*	1	3
...	...	<6.3	15/06 ± 1	1.2 ± 0.2	−1	1	
...	...	<0.1	06/09 ± 1	4 ± 0.5	−1	1	3, 12
185730	2100	<2.4	10/≥09	≳1 ± 0.2	+1	1	3
...	...	<0.1	28/15 ± 2	4 ± 0.5	−1*	2	3, 13
061012	131	1.6 ± 0.6	08 ± 1	8.1 ± 1.1	−2	1	
...	...	<15	31/18 ± 1	9 ± 1	+1	1	3, 14
...	...	<16	02/12 ± 12	2 ± 1	+1	1	3, 15
124828	300	37.2 ± 26.5	16 ± 1	3 ± 0.5	−1	1	16
...	...	<62	18 ± 1	2 ± 0.4	0	1	
053625	246	3.0 ± 0.8	31/0 ± 12	1.5 ± 08	−1	1	
114244	66	300 ± 3.2	15 ± 1	4 (+1, −3)	+1	1	17
...	...	<0.1	21 ± 1	1.6 ± 0.4	−2	2	18
073526	148	43.3 ± 1.2	12/03 ± 3	4 ± 1	0*	1	3, 19
010021	82	<0.5	05 ± 1	8 ± 2	−2	1	
020355	66	1.0 ± 0.5	09 ± 3	1 ± 02	−2	1	
050600	180	4.8 ± 4.2	07 ± 1	4 ± 2	−1	1	20
			06/02 ± 1	3 ± 0.5	0*	1	3, 21
...	...	<0.2					
...	...	<0.1	20/17 ± 3	4 ± 1	−2*	1	3
...	...	<10	23 ± 1	2.5 ± 0.5	0	1	
022904	≥410	≥22.7 ± 1.1	15 ± 2	1 ± 0.2	+1	1	22
233813	2720	167 ± 3.3	08/09 ± 2	~9 ± 2	+1	1	
185157	480	30 ± 21.5	18/02 ± 1	4 ± 1	0	1	23
...	...	<0.3	20/05 ± 1	4.8 ± 0.4	0	1	
074430	240	18.1 ± 12.9	26/12 ± 3	2 ± 0.5	−1*	1	24
060319	328	13.1 ± 1.0	04/12 ± 6	1 ± 0.2	+1*	1	3
...	...	<0.1	13 ± 1	1.2 ± 0.2	−1	1	
020700	600	<1.3	16/03 ± 2	1 ± 0.2	−1*	2	25
025258	420	5.9 ± 5.1	~7?	~4 ± 1	−2	2	26
...	...	<18	≥13	~6 ± 1	−2	1	
...	...	<0.1	19 ± 1	2.5 ± 0.4	−2	1	27
			18 ± 3	1.2 ± 0.2	−1	1	28
...	...	<0.1					
...	...	<1.2	06 ± 2	2.5 ± 0.5	0	1	29
24/235942	705	~400	26/19 ± 2	9 ± 1.5	+1*	1	
...	...	<0.1	04 ± 1	3.7 ± 0.4	−2	1	29, 30
21/235819	148	5.9 ± 0.6	07 ± 1	4.5 ± 1.5	−1	1	

mined by integrating over the listed time interval. For the six events with "S*" in column (11), no >300 keV emission was observed, and the times indicated in columns (12) and (13) are for the principal, most impulsive, phase of the >25 keV X-ray emission. For these six events, the 1 σ upper limit of the 4–8 MeV emission in column (14) is given by $0.4 \times (\Delta t/60)^{1/2}$, where Δt is the integration time in column (13). For the two events with "I/S" in column (11), the GRS observed significant (2 σ) line emission, but the event was partially eclipsed and the γ-ray data were inferred from *ISEE 3* >300 keV observations. For these two events and the 8 events with "I" in column (11), the times given in columns (12) and (13) are for the principal component of hard X-ray emission observed by *ISEE 3*, and the 4–8 MeV fluence was inferred from the relationship between the >300 keV continuum emission and the 4–8 Mev GRL fluence (Forrest 1983). For the 30 remaining events, an upper limit to the 4–8 MeV fluence (col. [14]) was inferred from the microwave–GRL correlation in Figure 1. These events are indicated by a "μ" in column (11). For events with "μ(I)" in this column, the parent flare was observed by *ISEE 3* but no >300 keV emission was observed; in seven cases, "μ(I*)" denotes that no >30 keV emission was detected by the University of California, Berkeley, instrument. For the seven events for which neither *SMM* nor *ISEE 3* data were available, the entry "μ(N.O.)" (no observations) is made in column (11).

Columns (15) and (16) give the time of maximum and the peak flux in the 9–23 MeV proton channel. In column (16), the peak flux values of all SEP events with rise times greater than 24 hr are marked with an asterisk to indicate the possibility of shock-particle "contamination" in such events (see Cane, Reames, and von Rosenvinge 1988). Eleven of these 13 SEP events originated in eastern hemisphere flares; two (numbers 55 and 57) were from the west. Column (17) gives our subjective degree of confidence in the flare/proton event association (1 = high confidence; 2 = probable, but for some reason open to question). We rated 55 of the associations as "1." The reasons for the 10 less confident associations are detailed in the notes to Table 1 (col. [18]) along with other comments bearing on the associations and listed data.

We examined the *IMP 8* and *ISEE 3* proton data for the 27 *SMM* GRL events that were not associated with any of the 65 SEP events listed in Table 1 to see if these flares might have associated proton emission that failed to meet our selection criteria (either lower flux $[J(>20 \text{ MeV}) < 10^{-3}]$ or lacking velocity dispersion). These 27 events and their proton circumstances are listed in Table 2. The most common occurrence at the time of these events was an enhanced ($>10^{-3}$) particle background on which no sign of a fresh proton injection was observed following the listed flare (19 cases). In two cases, a small event can be associated with GRL emission; in five cases

Notes to Table 1

(1) Culgoora reports intensity 2 type IV from 2121–2300 UT. The sharp rise in the 20–40 MeV profile indicates a magnetically well-connected source region. The unimpressive Hα and soft X-ray emissions are the reasons for the lower confidence of the association. (2) A simultaneous 1N flare at S24W75 is an alternative candidate source of the type II burst and proton event. (3) This flare was associated with an interplanetary type II burst (Cane 1985). (4) From observations at *Helios* (Neustock, Wibberenz, and Iwers, 1985), three separate flares from the same active region may have contributed to the particle event at Earth. In addition to the listed flare, these include a γ-ray (>300 keV) flare at 0117 UT and a non–γ-ray flare at 0725 UT. It is not possible to separate the contributions of the three flares in the composite particle time profile observed by near-Earth satellites. The assignment of the listed flare is based on the relative amplitudes of the 4–13 MeV events at Helios from the first two flares and the fact that the 9–23 MeV flux near Earth had reached a value close to its peak before the onset of the third flare. (5) A 2N flare at S12E14 at ~0100 UT may contribute to the long duration of the particle event observed at Earth. The association with the listed flare is based primarily on the electron-rich property of the particle event (Evenson *et al.* 1984; Cane, McGuire, and von Rosenvinge 1986). A 9–23 MeV peak flux of $4 \pm 1 \times 10^{-2}$ was observed near Earth at 09 ± 04 UT on June 23. *Helios* was located 0.54 AU from the Sun and was 35° in heliolongitude from the nominal interplanetary spiral connecting to the flare site (McDonald and Van Hollebeke 1985). (6) This is a lower confidence association because the first arriving protons are not observed at Earth until $\gtrsim$04 UT on the 6th. A 2F flare (N30W30) at ~0430 UT on July 6 may be a contributor. *SMM* γ-ray observations begin at 2237.4 UT, after the 2233.6 UT onset time of the 17 GHz burst, but before the microwave burst maximum. (7) A simultaneous 1B flare at N12E62 may contribute, but the relatively prompt increase in the particle event profile is more consistent with a western hemisphere origin. (8) The type II is associated with a −F secondary Hα maximum at 1845 UT. The 1B maximum occurred at 1755 UT, in association with a C3 1–8 Å event. (9) A −N flare (N09E08) had its maximum at 0627 UT, but the abrupt rise of the particle event favors the western hemisphere source. (10) A −N flare (N09E08) had its maximum at 0943 UT. The listed flare is preferred as the source of the type II and the particle event, at least in part, because it originated in the active region that gave rise to the April 1 proton flare (event 18). (11) A 2N flare (N04W56) with maximum at 0248 UT on the 9th may be a contributor, but the slow rise of the particle event indicates an eastern hemisphere source. It is difficult to unambiguously determine the time of maximum of the proton event because of the event on May 10 (event 23). (12) The association of this proton event with a disappearing solar filament is discussed in detail by Kahler *et al.* (1986). Cane, Kahler, and Sheeley (1986) have recently presented additional examples of such events. (13) A 1N flare from the same region with maximum at ~0250 UT is an alternate candidate. (14) A nearby (S12E06) possibly related flare with a 1B maximum at ~0010 on the 31st may have contributed. (15) Yoshimori and Watanabe (1985) report an upper limit of 13 photons cm^2 for the 4.0–6.7 MeV GRL fluence. (16) *SMM* was in eclipse for the γ-ray event onset. GRS observed >300 keV photons beginning at 124917 UT for 131 s and measured a 4–8 MeV fluence of 16.9 ± 1.1 photons cm^{-2}. This event has been discussed by Kane *et al.* (1986). (17) Helios was located 0.57 AU from the Sun and the solar footpoint of the nominal interplanetary magnetic field line through *Helios* was ~3° from the flare site (McDonald and Van Hollebeke 1985). (18) The 20–40 MeV event was extremely impulsive and consisted of only a single (1 hr average) data point above the preevent background. (19) This appears to be a "double flare" (Dodson and Hedeman 1976). The SEP event onset time of 0730 ± 0030 UT favors the earlier flare as the source. (20) The relativistic electron event from this flare has been discussed by Kane, Evenson, and Meyer (1985). (21) This may be a "double-flare" (Dodson and Hedeman 1976). Cane, McGuire, and von Rosenvinge (1986) list the later flare as the source of the proton event (see Cane, Sheeley, and Howard 1987). The SEP event onset at 0630 ± 0030 UT favors this association. Culgoora classified the listed type II from 0236–0248 UT as a "possible type II." (22) The *SMM* satellite went into eclipse at 0235.9 UT, shortly after the 9 GHz peak. (23) A 2B/M4 (S08W14) flare with maximum at 2106 UT and a 1B/M5 (S15W66) flare with maximum at 2250 UT may contribute. In addition, a type II burst is reported in association with a −N flare (S10W12) with maximum at 2030 UT, and another type II was observed beginning at 2148 UT in association with an M5 1–8 Å event, during a period with no Hα coverage. *SMM* was in eclipse at the onset of the listed event. GRS observed >300 keV photons beginning at 185644 UT for 115 s and measured a 4–8 MeV fluence of 6.5 ± 0.8 γ-rays cm^{-2}. (24) The 9–23 MeV time-intensity profile of this event is probably "contaminated" by a large proton event originating in a behind-the-limb flare on December 26 at ~1100 UT. The combined event has a maximum of $1.6 \pm 0.2 \times 10^1$ protons on December 27 at 13 ± 1 UT. (25) The flare may have been partially occulted by the limb. Extrapolation from the positions of previous flares from this region indicates a probable flare longitude of W93. This association is of lower confidence because of the long delay to onset of the particle event. The first arriving electrons were observed at ~06 UT (Cane, McGuire, and von Rosenvinge 1986). An unassociated C6 1–8 Å event had its maximum at 0655 UT. (26) The listed flares had maxima at 0254–0256 UT (W40 flare) and 0256 UT (E15). The abruptly rising particle event profile favors the western hemisphere source. (27) Although no type II/IV events are reported in SGD, weak II/IV activity beginning at 1554 UT and lasting less than 30 minutes was reported in the *Boulder Preliminary Report*. (28) In the 1–8 Å profile, this event has the appearance of a double flare (Dodson and Hedeman 1976). The two flares originated in adjacent active regions. The SEP event onset time of 1400 ± 0200 UT favors the later flare as the particle source. (29) The 9–23 MeV flux measurements are from *ISEE 3* which began to move away from the Earth-Sun line on 1983 December 22 enroute to encounters with Comets Giacobini-Zinner and Halley. On March 14, *ISEE 3* was ~6° west of the Earth-Sun line at ~0.92 AU. (30) On June 5, *ISEE* was ~17° west of the Earth-Sun line at ~0.94 AU.

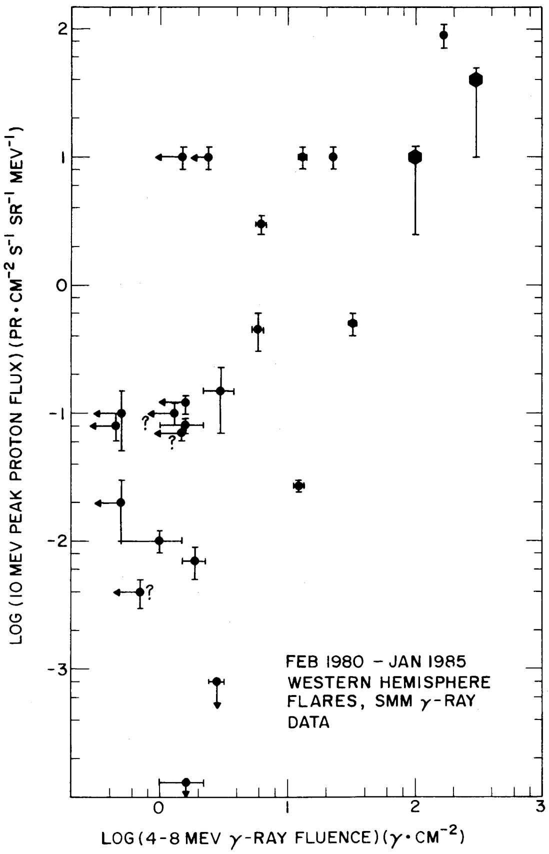

FIG. 2.—Scatter plot of peak interplanetary proton flux near 10 MeV vs. the associated-flare 4–8 MeV GRL fluence for well-connected (W00–90) SEP flares and GRL flares (with "clean" proton circumstances) occurring from 1980 February to 1985 January. The parent flare of each of the SEP events was observed by *SMM*. The hexagonal data points indicate SEP observations from *Helios*; all other SEP data are from the near-Earth *IMP 8* and *ISEE 3* spacecraft. The question marks denote SEP events with less confident flare associations.

the background 9–23 MeV flux was less than 10^{-3} and no event was detected; and for one event proton data were not available.

The data columns for Table 2 are the same as for Table 1 with the following exceptions: Proton events possibly "masked" by enhanced background fluxes are indicated by an "M" in column (14) and the background 9–23 MeV flux at the time of the GRL event is given in parentheses in column (15). The "data source" column and the column giving the level of confidence of the flare association have been omitted.

III. THE 9–23 MeV PEAK PROTON FLUX VERSUS 4–8 MeV GRL FLUENCE

a) Scatter Plot, Only SMM Events

Figure 2 is a scatter plot of $J(>9\text{ MeV})$ versus the 4–8 MeV GRL fluence for only (1) well-connected (western hemisphere) SEP flares in Table 1 that were observed by *SMM* and (2) western hemisphere GRL flares in Table 2 with "clean" proton circumstances (i.e., not masked). Twenty-four events are plotted. The event "accounting" is as follows: 20 (Table 1, western hemisphere SEP flares with GRS data) plus one (event that was poorly connected to Earth [E71] but magnetically well-connected to *Helios*; event 41) plus one (low-flux SEP event [$J(>20\text{ MeV}) < 10^{-3}$] from a western hemisphere flare in Table 2; event 2) plus two (western hemisphere flares from Table 2 that were not accompanied by detectable proton emission on a quiet flux background; events 3 and 5). The two hexagonal data points indicate that the peak $J(>9\text{ MeV})$ flux was measured at *Helios*. The question marks identify SEP events with less confident ("2" in col. [17]) flare associations. From Figure 2 we can see that GRL flares are generally associated with SEP production. Also, *if one begins with a sample of GRL flares*, there is evidence for a relationship between SEP event peak fluxes and GRL emission. We will discuss each of these points in turn.

Favorably located (W00–90) GRL flares (2 σ at 4–8 MeV) tend to produce protons that are observed at 1 AU (13 of 15 events in Fig. 2). The 27 GRL events that lacked SEP association (Table 2) are both significantly smaller and more poorly connected than the 18 *SMM* GRL flares in Table 1. The Table 2 flares have a median 4–8 MeV fluence of 3.2 photons cm^{-2} and a median longitude of E15 compared with 12.7 photons cm^{-2} and W46 for the Table 1 GRL events.

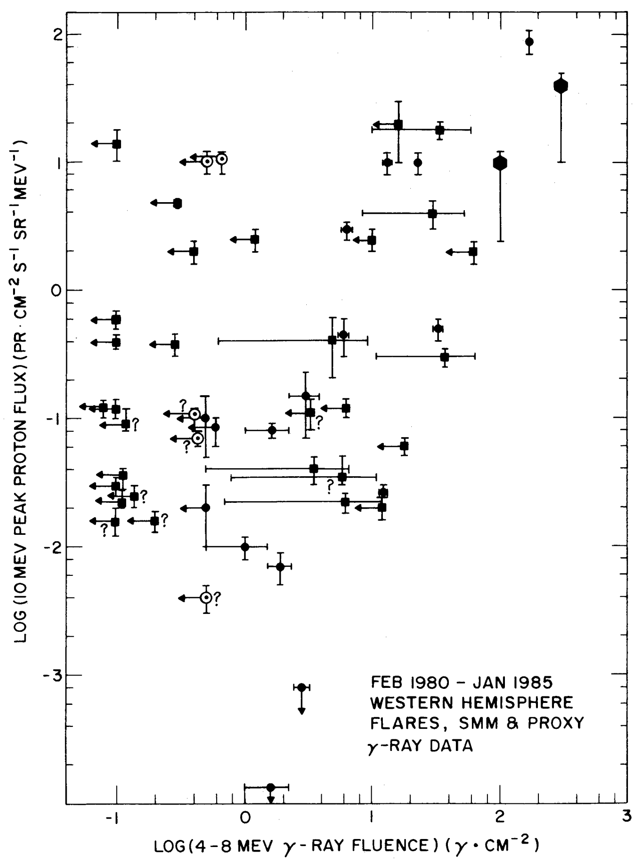

FIG. 3.—Scatter plot of peak interplanetary proton flux near 10 MeV vs. the associated flare 4–8 MeV GRL fluence for well-connected (W00–W90) SEP flares and GRL flares (with "clean" proton circumstances) occurring from 1980 February to 1985 January. Filled circles indicate that the γ-ray data are from the *SMM* GRS. For events represented by hexagonal data points, γ-ray observations are from *SMM* and particle data are from *Helios*. All other SEP data on this plot are from the near-Earth *IMP 8* and *ISEE 3* spacecraft. Circled dots indicate that the SEP event parent flare was observed by *SMM* but no >300 keV emission was detected. Filled squares indicate data points where the GRL fluence or an upper limit was inferred from *ISEE 3* >300 keV X-ray data or ground-based microwave observations. The question marks indicate SEP events with less confident flare associations.

TABLE 2

GAMMA-RAY LINE FLARES NOT IN TABLE 1

Event Number (1)	Date (2)	Hα Flare: Location (3)	Hα Flare: Class (4)	1–8 Å: Peak Time (UT) (5)	1–8 Å: CMX Intensity Class (6)	1–8 Å: Decay Time (τ) (Minutes) (7)	.9 GHz: Peak Time (UT) (8)	.9 GHz: Peak Intensity (sfu) (9)	Type II Starting and Ending Times (UT) (10)	γ-Rays: 300 keV Onset (UT) (11)	γ-Rays: 300 keV Duration (s) (12)	γ-Rays: 4–8 MeV Fluence (γ cm^{-2}) (13)	9–23 MeV Protons: Peak Time (UT) (14)	9–23 MeV Protons: Peak Flux (protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) (15)	Notes (16)
1..........	1980 Jun 4	S14E59	1B	0655	M7	8	0655	855	...	065419	49	3.3 ± 0.4	...	<4 −4	
2..........	1980 Jun 29	S27W90	1F	1043	M4	8	1042	1300	1048–1100	104141	66	1.9 ± 0.4	15 ± 1	7 ± 2 −3	
3..........	1980 Jul 1	S12W38	1B	1628	X2	5	1627	1432	1628–1651	162652	66	2.8 ± 0.4	...	<8 −4	
4..........	1980 Nov 7	N09W08	2B	0208	X3	24	0205	7100	...	020412	66	1.9 ± 0.4	M	(1 ± 0.2 −2)	
5..........	1981 Feb 17	N20W20	1B	2152	X1	DG	2147	1030	2151–2209	214611	82	1.6 ± 0.6	...	<1 −4	
6..........	1981 Feb 26	S13E53	−B	1426	X2	1	1425	809	...	142439	98	3.2 ± 0.5	...	<7 −4	
7..........	1981 Apr 26	N15W74	2N	1235	X1	62	1153	8050	...	114405	344	5.3 ± 1.2	M	(6 ± 1 0)	
8..........	1981 Apr 27	N17W90	1N	0820	X5	38	0814	11483	0813–0836	080328	967	92.0 ± 1.8	M	(6 ± 1 0)	
9..........	1981 May 4	N15E18	1B	0840	M9	8	0840	985	...	083808	180	1.3 ± 0.5	M	(3.5 ± 0.5 −1)	1
10..........	1981 13 May	N10E55	3B	0425	X1	86	0419	4362	...	041341	295	2.0 ± 0.9	M	(6 ± 1 −1)	2
11..........	1981 Jul 19	S09E68 S28W56	2B 2B	0537	X3	26	0559	4740	0558–0600	055844	131	4.2 ± 0.6	...	<1 −4	3
12..........	1981 Jul 26	S15E29	1B?	1353	X3	2	1354	470	...	135318	33	0.8 ± 0.4	M	(2 ± 0.4 −2)	
13..........	1981 Sep 7	N11E29	−B	2226	M4	DG	2223	1100	2227–2249	222251	98	1.7 ± 0.5	M	(8 ± 1 −1)	
14..........	1981 Oct 14	S06E86	−B	1710	X3	7	1707	2719	1711–1719	170517	82	24.5 ± 1.1	M	(3 ± 0.5 +1)	
15..........	1981 Nov 12	?	?	1606	X1	10	1602	1334	...	160123	49	0.7 ± 0.3	...	DG	
16..........	1982 Jan 28	N08E42	2B	0717	M9	30	0722	1225	0703–0734	072124	131	5.1 ± 0.6	30/15 ± 9	3.5 ± 0.5 −2	4
17..........	1982 Feb 5	S15W43	1B	0910	M5	DG	0907	990	0907–0922	090510	164	1.5 ± 0.5	M	(5 ± 1 −1)	
18..........	1982 Apr 2	N08W63	2B	0909	M7	9	0908	195	0911–0921	090701	98	1.3 ± 0.5	M	(6 ± 1 −3)	
19..........	1982 Jun 15	S11W89	1N	0032	M5	5	0031	1040	...	003015	82	4.9 ± 0.5	M	(2 ± 0.4 −1)	
20..........	1982 Jun 15	S21E66	1B	1514	X1	9	1512	2300	1512–1543	151134	148	9.1 ± 0.7	M	(1.2 ± 0.2 −1)	
21..........	1982 Jul 9	N18E74	2B	2108	M8	DG	2107	567	2110–2115	210610	164	9.9 ± 0.8	M	(2 ± 0.4 −2)	5
22..........	1982 Nov 22	S08W34	−N	1225	M2	2	1223	302	...	122312	16	0.7 ± 0.2	M	(3 ± 0.5 −2)	
23..........	1982 Dec 15	S10E15	1B	1634	X5	6	1632	2706	1632–1656	163044	229	13.0 ± 0.8	M	(4 ± 0.5 −1)	
24..........	1982 Dec 18	S10W20	1B	0825	X1	7	0822	791	0833–0835	082144	49	0.8 ± 0.3	M	(3.5 ± 0.5 0)	6
25..........	1982 Dec 29	S13W12	2B	0646	X2	4	0645	1839	0646–0711	064410	131	8.8 ± 0.7	M	(8 ± 2 −1)	
26..........	1983 May 7	S29E66	2B	2221	X3	4	2218	4067	2222–2257	221636	131	27.2 ± 1.3	M	(3 ± 0.5 −3)	
27..........	1983 May 9	S29E41	2B	2309	X2	9	2306	1567	2307–2330	230417	328	8.2 ± 0.9	M	(5 ± 1 −3)	

NOTES.—(1) In the *IMP 8* 20–40 MeV profile, a long slow rise from an elevated background (10^{-2} protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) begins late on the 4th. This event has a broad maximum ($\sim[6–8] \times 10^{-2}$) from ~12 UT on May 6 to ~18 UT on May 8. Although we do not have an alternate candidate parent flare, we do not believe that the listed impulsive flare, which lacked any associated metric emission, could have given rise to such an extended proton event. (2). In the *IMP 8* 20–40 MeV profile, an enhancement on the decay of an earlier event begins at ~12 UT. This enhancement peaks at ~16 UT at a level of 3.2×10^{-2} protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}. The preevent level was 2.5×10^{-2}. Because fluctuations of this order are common, we do not associate this increase with the listed flare and consider any possible event from the listed flare to be "masked." Yoshimori and Watanabe (1985) report a 4–6.7 MeV GRL fluence of 50 ± 9 photons cm^{-2} for this event. (3) Reported Hα maxima range from 0523 to 0538 UT for the flare at E68 and from 0534 to 0538 UT for the flare at W56. The reported end times of both flares encompass the ~0559–0601 UT interval during which the 4–8 MeV event is observed. Thus the flare association for this γ-ray event is east-west ambiguous. (4) In the *IMP 8* 20–40 MeV profile, the gradual increase that we associate with this flare began after ~1800 UT on the 28th. Sudden commencements were reported at 1745 UT on January 29 and 1100 UT on February 1. The second of these shocks may have originated with the listed flare. (5) The 20–40 MeV trace is rising at the time of this flare because of particles from the event at ~0740 UT listed in Table 1 (event 43). (6) Beginning at ~10 UT, the 20–40 MeV profile rises from a (decaying) enhanced background of 4×10^{-1} protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} to a peak of 5.5×10^{-1} at ~13 UT. This relatively small increase does not show velocity dispersion and appears to be a modulation of the flux from the event on 1982 December 17 (event 52 in Table 1).

The two western hemisphere flares with "clean" proton circumstances that lacked SEP association (1980 July 1 [event 2 in Table 2], W38, 2.8 photons cm^{-2}; 1981 February 17 [event 5], W20, 1.6 photons cm^{-2}) were both relatively small GRL events, ranking in the lowest third and quarter, respectively, of the 45 2 σ events observed by *SMM*. The magnetic connection of the flare site to the Earth may also be a factor in the failure to detect SEPs from these flares. This connection is especially important for impulsive flares, since the particle "cone of emission" in such events may be relatively narrow (half-angle $\sim 30°$) (Cane, McGuire, and von Rosenvinge 1986). The 1980 July 1 flare (Rust 1983) had an impulsive flare soft X-ray profile; the 1–8 Å time-intensity trace was not available for the 1981 February 17 flare.

We checked the events from Table 2 that are not plotted in Figure 2 to see if there were any cases of western hemisphere flares with large GRL fluences and relatively low SEP event "masking" levels. The four largest western hemisphere events in Table 2 (events 7, 8, 19, and 25) all occurred during times when the background 9–23 MeV flux was relatively high ($\geq 2 \times 10^{-1}$).

For the events in Figure 2 that had detectable GRL fluences (not upper limits) and detectable (greater than 10^{-3}) $J(>9$ MeV) values, there is a good correlation between the 4–8 MeV fluence (G) and $J(>9$ MeV). The least-squares relationship for the 13 such events is given by

$$\log (J[>9 \text{ MeV}]) = 1.74 \log (G[4\text{–}8 \text{ MeV}]) - 2.02$$

and the correlation coefficient $r = 0.84$.

b) *Scatter Plot, Including Proxy GRL Data*

There are two large ($J[>9$ MeV$] = 10$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) proton events in Figure 2 from flares that lacked detectable 4–8 MeV emission. For both of these flares (events 26 and 33 in Table 1), no >300 keV photons were detected by the GRS. From the correlation between the >300 keV and the 4–8 MeV fluences (Forrest 1983), one can infer that the 4–8 MeV fluences in these flares are less than 0.5 photons cm^{-2}, a factor of 3 or 4 below the measured 1 σ upper limits plotted in Figure 2. The resultant further separation of these two data points from the trend line through the data suggests that the correlation of SEP peak fluxes and GRL emission may, in fact, not be as good as it appears to be in Figure 2, where only SEP flares observed by *SMM* are considered. To expand the data set it is necessary to use proxy GRL data based on *ISEE 3* >300 keV X-ray observations or on ground-based microwave data. We can thus add 29 western hemisphere events to Figure 2. The expanded plot is shown in Figure 3, where the data points are interpreted as follows: *filled circle—SMM* γ-ray measurement; *circled dot*—upper limit of 0.5 photons cm^{-2} based on the absence of >300 keV photons in the GRS data and the >300 keV vs. 4–8 MeV GRL fluence correlation; *filled square*—the actual data points are based on *ISEE 3* >300 keV data and the upper limits are from the microwave–GRL correlation in Figure 1.

The data points in Figure 3 that, as a group, lie furthest from the least-squares line derived for the GRL events of Figure 2 are the seven points in the upper left-hand corner that correspond to relatively large SEP events ($J[>9$ MeV$] \geq 4 \times 10^{-1}$) from flares without detectable/inferred GRL emission (less than 1 photons cm^{-2}). The seven events are 1980 November 23 (event 14 in Table 1), 1981 March 30 (event 17), 1981 May 10 (event 23), 1981 July 20 (event 26), 1981 December 5 (event 32), 1981 December 9 (event 33), and 1982 December 19 (event 53). Photons greater than 300 keV were not detected in any of these flares (*SMM*, two cases; *ISEE 3*, five cases). One of the flares (flare 32) lacked >30 keV X-rays. The five flares observed by *ISEE 3* all had $S_p(9 \text{ GHz}) \lesssim 100$ sfu. The existence of SEP flares that lack GRL emission has been reported by Pesses *et al.* (1981), Cliver *et al.* (1983*a*), Yoshimori and Watanabe (1985), and Kallenrode *et al.* (1987). Because of the potential significance of these events for our understanding of particle acceleration processes in flares, it is useful to reexamine the basis for the SEP event/flare association in these cases. Otherwise, one might argue that such events are the result of misidentifications and that in each case the actual parent flare occurred behind the limb and the γ-ray emission was occulted.

We address this conjecture in detail in the Appendix by (1) a more detailed discussion of the basis for the flare association in each of these seven events and (2) a statistical approach that considers the fraction of large events that might be expected, from previous studies, to arise in flares on the invisible hemisphere. The result of both of these approaches is to validate our "non–GRL" flare associations for these large SEP events. The fact that only two of these seven SEP parent flares were observed by *SMM*, compared with six of seven by *ISEE 3* (all except event 33), is roughly consistent, given the small numbers, with the differences between the observing duty cycles of the two spacecraft, $\lesssim 50\%$ for *SMM* versus $\gtrsim 80\%$ for *ISEE 3*.

For each of the seven SEP events, particle onset times, obtained from hourly averaged data, occurred within 2 hr of the 1–8 Å maximum of the identified flare. The delays from the 1–8 Å maximum to the 9–23 MeV event peak range from 7 hr (1981 May 10 and 1981 July 20) to 19 hr (1981 March 30), with a median delay of 12 hr (median logitude = W75), compared with a median delay of 8 hr for the eight large ($\geq 4 \times 10^{-1}$) western hemisphere flares in Table 1 with measurable *SMM* GRL fluences (median longitude = W46). For the three events with relatively long rise times (1981 March 30, 1981 December 5 [18 hr], and 1981 December 9 [$\gtrsim 14$ hr]), the 9–23 MeV maxima occurred well before (≥ 35 hr) any associated geomagnetic storm sudden commencement (SC). Thus these particle flux increases cannot be energetic storm particle (ESP) events. For two of these events (1981 March 30 and 1981 December 9), the >20 MeV profile did not rise monotonically to maximum but exhibited structure during the rise phase.

We determined the differential power-law spectrum in energy ($E^{-\gamma}$) over the range 20–80 MeV for the seven events and obtained the following values of γ: 1980 November 23, 2.5 ± 0.1; 1981 March 30, 4.2 ± 0.8; 1981 May 10, 2.4 ± 0.2; 1981 July 20, 1.9 ± 0.1; 1981 December 5, 4.6 ± 0.4; 1981 December 9, 4.4 ± 0.2; and 1982 December 19, 2.1 ± 0.1. The median value of $\gamma = 2.5$ is comparable to the $\gamma \sim 2.6$ value found by Van Hollebeke, Ma Sung, and McDonald (1975) for a sample of 32 well-connected events. It is interesting to note that the three events with soft spectra all lacked metric type II bursts (see Kahler *et al.* 1986) and also had longer delays to maximum.

In addition to the seven events discussed above, four large ($J[>9$ MeV$] \geq 4 \times 10^{-1}$) SEP events associated with eastern hemisphere flares also lacked detectable inferred GRL emission. These events (1980 October 15 [event 11], 1981 May 8 [event 22], 1981 December 27 [event 34], and 1982 September 4 [event 47]) were all associated with strong interplanetary shocks (Cane 1985); the SEP peaks are delayed by 23, 59, 35, and 49 hr, respectively.

IV. THE SCALE TIME OF FLARE SOFT X-RAY EMISSION AND THE RATIO OF SOLAR TO INTERPLANETARY PROTONS FOR GRL/SEP FLARES

a) An Index of Flare Impulsiveness

Following Cane, McGuire, and von Rosenvinge (1986; hereafter CMR), we have made a determination of the characteristic scale time (τ) of the flare soft X-ray emission, taken to be the *e*-folding decay time measured from the peak of the 1–8 Å event, for all of the flares in Tables 1 and 2. This "index of flare impulsiveness" differs from that of CMR, who divided events into two classes: "long duration" if the 1–8 Å emission lasted for more than 1 hr at greater than 10% of the peak intensity, and "impulsive" events with durations less than 1 hr at this level. We have determined τ for the flares in the CMR study and find that, in general, their impulsive events have $\tau \leq 10$ minutes and their gradual events have $\tau > 10$ minutes. Of 26 impulsive events from CMR, 23 had $\tau \leq 10$ minutes; 37 of 38 gradual events had $\tau > 10$ minutes. Thus, for the 64 (of 71) cases from CMR that we were able to classify, the "$\tau \leq 10$ minutes" and the "less than 1 hr at 10% of peak" techniques agreed 94% (60/64) of the time. By using the $\tau \leq 10$ minute divider, we also find good agreement with the impulsive (10/12 cases with available 1–8 Å data) and gradual (20/20) flares classified by Bai (1986) on the basis of the durations (total and "spike") of flare hard X-ray emission.

For the parameter τ, we arbitrarily define three groupings of events: impulsive ($\tau \leq 10$ minutes), intermediate (10 minutes $< \tau \leq 30$ minutes), and gradual ($\tau > 30$ minutes). Figure 4 contains a histogram of τ for (*a*) the 40 of 45 2 σ GRL events with available 1–8 Å profiles and (*b*) the 61 of 65 SEP flares for which τ could be determined. The two distributions are not mutually exclusive; there are 18 common events. As a group, the GRL events are clearly more impulsive, with a median τ value of 9 minutes, compared with 23 minutes for the SEP flares. Detectable (2 σ) GRL events with τ values greater than 30 minutes are rare.

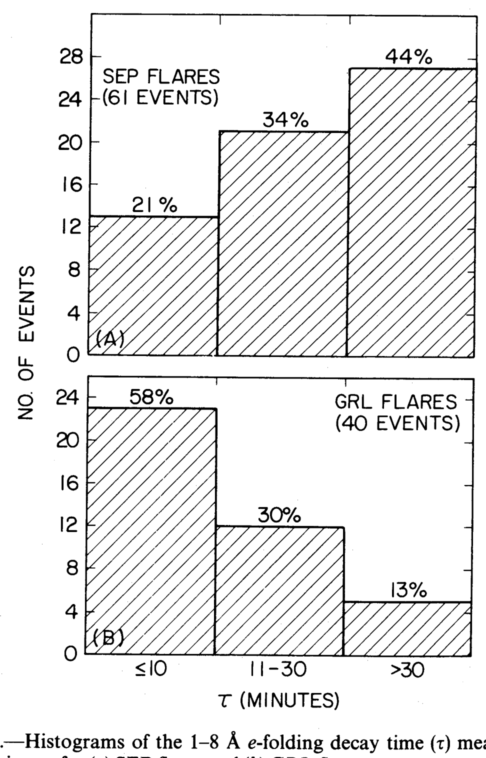

FIG. 4.—Histograms of the 1–8 Å *e*-folding decay time (τ) measured from event maximum for (*a*) SEP flares and (*b*) GRL flares.

b) The Ratio of Solar to Interplanetary Protons at ~10 MeV

Figure 5 is the same as Figure 3 except that the impulsiveness of the flares is now indicated. The symbols for each data point are defined as follows: *filled circles*—impulsive flares ($\tau \leq 10$); *half-filled circles*—intermediate flares ($10 < \tau \leq 30$); and *open circles*—gradual flares ($\tau > 30$). From this figure we note that (1) the "main sequence" of 20 GRL events (with finite GRL fluences and SEP event peak fluxes, not upper limits) for which the 4–8 MeV GRL emission and ~10 MeV SEP peak flux are correlated consists primarily of impulsive (10 cases) and intermediate (7 cases) flares, rather than gradual events (2 cases) (τ unavailable for one case), and (2) the seven large ($J[>9 \text{ MeV}] \geq 4 \times 10^{-1}$) events in the upper left-hand corner are gradual ($\tau > 30$ minute) flares.

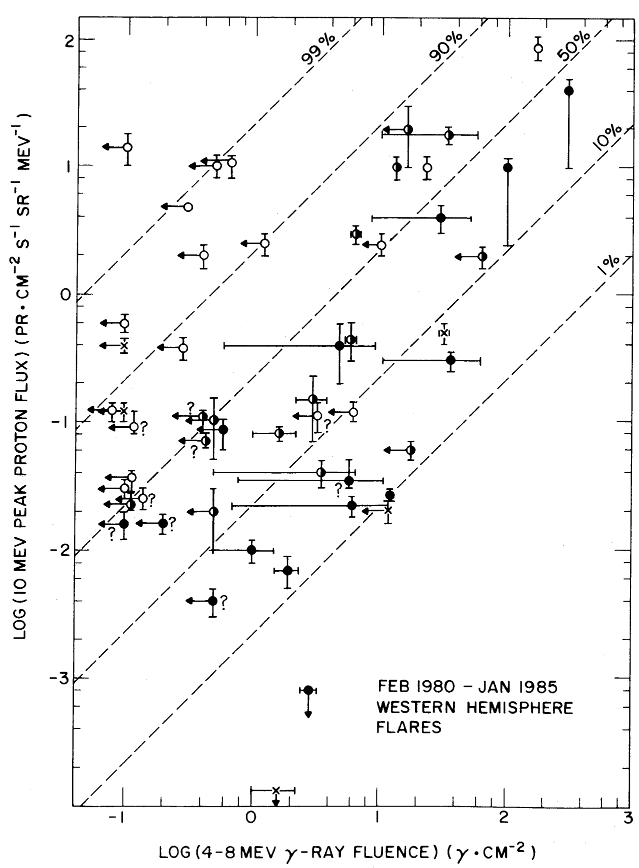

FIG. 5.—Scatter plot of $J(>9$ MeV) vs. the 4–8 MeV GRL fluence for well-connected (W00–90) SEP and GRL flares. The plotted data points are the same as in Fig. 3, but the symbols used for the data points now indicate the time scale, τ, of the flare soft X-ray emission: *filled circles*: $\tau \leq 10$ minutes; *half-filled circles*: 10 minutes $< \tau \leq 30$ minutes; *open circles*: $\tau > 30$ minutes. For the data points marked with crosses, soft X-ray data were unavailable. The dashed lines give the inferred fractional escape probability of ~10 MeV protons for events occupying different regions of the scatter plot. The question marks denote SEP events with less confident flare associations.

The dashed lines drawn on Figure 5 indicate the fraction of ~10 MeV protons that "escape" into interplanetary space (F_{esc}) for events lying in different regions of the scatter plot. The F_{esc} calculation is based on the assumption that the population of protons observed in space and the population generating γ-ray emission in the solar atmosphere both originally belonged to a single distribution of particles accelerated at the flare site. The percentages indicated on the dashed lines were scaled from the fractional escape probability of ~1% calculated by von Rosenvinge, Ramaty, and Reames (1981) for the impulsive 1981 June 7 flare, since the spectra of the GRL-producing protons and the SEPs accelerated in this event are representative of GRL and SEP event spectra in general (see Murphy and Ramaty 1984; Van Hollebeke, Ma Sung, and McDonald 1975). Thus, for any given event in Figure 5,

$$F_{esc} = N_{esc}/(N_{tr} + N_{esc}) ,$$

where

$$N_{tr} \propto \text{number of trapped} \sim 10 \text{ MeV protons} = (1/12.3) \times G(4\text{–}8 \text{ MeV}) ,$$

and

$$N_{esc} \propto \text{number of escaping} \sim 10 \text{ MeV protons} = (1/0.027) \times J(9\text{–}23 \text{ MeV}) \times 10^{-2} .$$

Von Rosenvinge, Ramaty, and Reames (1981) obtained the ~1% F_{esc} value for the June 7 flare by assuming that the escaping protons diffused isotropically in space. They suggested that this figure could be reduced to ~0.1% because the isotropic diffusion assumption is not realistic (see Cane, McGuire, and von Rosenvinge 1986).

From Figure 5 it can be seen that the most impulsive events tend to have the smallest escape probabilities (~1%–50%), while in gradual events, ~10 MeV protons have a greater likelihood (~50%–100%) of escape. This is consistent with Bai's (1986) result, based on a small sample of events, that the ratio of γ-ray–producing ("trapped") to interplanetary ("escaping") protons is higher in impulsive flares than in long-duration events. Since the points for events with intermediate values of τ tend to fall between those of the impulsive and gradual events, there is evidence in this figure for a progression of F_{esc} to larger values as τ increases.

The term "fractional escape probability" implies that all of the protons observed in space are accelerated at the flare site. There is growing evidence that such a picture may not apply. For example, for certain flares, SEP acceleration may be prolonged well out into the corona (Beeck *et al.* 1987) and beyond into interplanetary space (Cane, Reames, and von Rosenvinge 1988). The ratio (R) of "solar" (those interacting at the Sun to produce GRL emission) to "interplanetary" (those observed in space, i.e., SEPs) protons is an alternative parameter that is freer of connotations about where the particles were actually accelerated. A plot of this parameter versus τ is given in Figure 6. Despite the scatter and the large fraction (29/48) of events with only upper or lower limits for R, the data in Figure 6 display an apparent trend. If we take the limiting values of R to be the actual values for events with upper (lower) limits, then the median value of R for the 15 impulsive ($\tau \leq 10$) events is 100, compared with $R = 7.1$ for the 15 intermediate events ($10 < \tau \leq 30$), and $R = 0.9$ for the 18 gradual ($\tau > 30$) events.

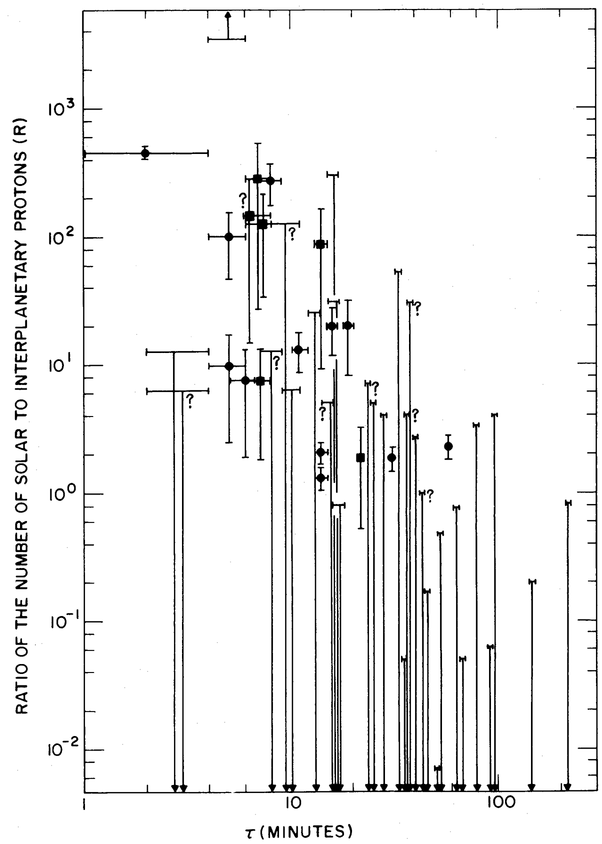

FIG. 6.—Scatter plot of the ratio of solar to interplanetary ~10 MeV protons vs. τ, the decay constant of the flare soft X-ray emission. Filled circles indicate that the γ-ray data are from *SMM*; filled squares denote *ISEE 3* observations. The question marks indicate SEP events with less confident flare associations.

V. OBSERVATIONAL RESULTS

From this study of solar energetic proton (SEP) events observed at 1 AU and γ-ray line (GRL) flares covering the first five years of the *Solar Maximum Mission* (*SMM*), we obtained the following results:

1. The numbers of flare-accelerated ~10 MeV protons as deduced from GRL emission are not well correlated with the ~10 MeV proton population observed in interplanetary space.
2. This lack of correlation results primarily from a group of large SEP events from flares that lacked detectable GRL emission. Conversely, almost all favorably located GRL flares were associated with interplanetary proton events.
3. The ratio (R) of the number of ~10 MeV protons that interact at the Sun to produce GRL emission to the number of ~10 MeV protons observed in interplanetary space varies from event to event by 4 orders of magnitude, from 0.01–100, and is inversely proportional, with much scatter, to the e-folding decay time of the flare-associated soft X-ray emission.

It is important to note that these results are based in large part upon the use of proxy GRL data for SEP flares not observed by the *SMM* satellite.

VI. DISCUSSION

a) Proton Flares With Weak Impulsive Phases

A key result of this study is our identification of a number (greater than 10) of relatively large ($J[>9 \text{ MeV}] \geq 4 \times 10^{-1}$ protons $\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{MeV}^{-1}$) proton events that originated in solar flares that lacked detectable ($2\ \sigma$) 4–8 MeV γ-ray line emission. We have supported these flare–SEP event associations (see Appendix) by a detailed consideration of the flare and proton event characteristics and also from a statistical approach based on the fraction of large SEP events that one might expect to arise in backside flares during a given interval.

The identification of large SEP/non–GRL flares was anticipated by work on a sample of SEP flares observed prior to 1980 when *SMM* was launched. Cliver, Kahler, and McIntosh (1983) found that $\sim 15\%$ of all large ($J[>10 \text{ MeV}] \geq 10$ protons $\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$) SEP events observed from 1965 to 1979, including one relativistic proton event (Cliver *et al.* 1983*b*), originated in flares with "weak impulsive phases" as measured by the peak microwave emission; specifically, for these flares, the microwave peak flux density $S_p(9 \text{ GHz}) \leq 100$ sfu. (For the 5 yr period considered in this study, the corresponding figure is 14% [3/21 events].) The characteristics that Cliver, Kahler, and McIntosh found in the weak impulsive phase flares (long-duration soft X-ray emission, shock association, and weak microwave emission) are generally shared by the seven flares in the upper left-hand corner of Figure 3. These seven events had a median τ value of 58 minutes (ranging from 35 to 144 minutes), had metric and/or interplanetary type II associations in all but one case, and had a median $S_p(9 \text{ GHz})$ value of 92 sfu (ranging from less than 20 to 615 sfu). In contrast, the 45 GRL events in our data sample characteristically originated in impulsive flares ($\tau_{\text{med}} = 9$ min; ranging from 1 to 86 minutes) with strong impulsive phase emission (median $S_p[9 \text{ GHz}] = 1654$ sfu; ranging from 195 to 24700 sfu).

b) Paradigms for Proton Acceleration in Solar Flares

The weak impulsive phase flares are of interest since, as a group, they are largely responsible for the poor correlation between ~ 10 MeV SEP event peak flux and 4–8 MeV GRL emission (Fig. 3). How do these events fit into our picture of proton acceleration in flares? We consider two basic possibilities: (1) a single process or mechanism accelerates both GRL-producing protons and SEPs but only a small fraction ($\lesssim 10\%$) are trapped in the weak impulsive flares, and (2) different acceleration processes apply for the GRL–producing protons, and for the SEPs observed in space following weak impulsive phase flares. We will consider each of these alternatives in turn.

i) Single Acceleration Process, Variable Escape

This hypothesis is attractive because of its simplicity. Support for this point of view comes from the similarity of energy spectra deduced both for GRL–producing protons and for those observed in space (SEPs). In general, a Bessel function with $\alpha T = 0.025 \pm 0.010$ provides a reasonable fit to both types of data (Murphy and Ramaty 1984; McGuire, von Rosenvinge, and McDonald 1981). The simultaneity (within ~ 1 s) of electron and proton acceleration over a broad range of energies (Forrest and Chupp 1983) is also consistent with a single acceleration mechanism. In addition, the good correlation that Forrest (1983) has found between the >300 keV electron bremsstrahlung continuum fluence from γ-ray flares and the 4–8 MeV line fluence implies that (1) for the GRS flares, protons and electrons are accelerated to high energies by a single common process, and, more profoundly, (2) since the correlation extends down to the GRS threshold, this process may account for particle acceleration in less energetic, and perhaps all, flares. The relationship of R versus τ in Figure 6 is also suggestive of a single acceleration process, the characteristics of which are somehow dependent on τ. In this plot, although one must be cautious because of the large number of events with only an upper limit for R, the impulsive GRL events appear to connect smoothly to the gradual flares with weak impulsive phases that produced large SEP events.

Pallavicini, Serio, and Vaiana (1977) have associated impulsive soft X-ray flares with low-lying ($<10^4$ km) sources and gradual events with extended ($\sim 5 \times 10^4$ km) structures. This suggests that the variation of R with τ may be explained in terms of ease of proton escape from the acceleration region (see Hudson 1985) since, no matter which acceleration mechanism applies, protons accelerated or trapped higher in the corona should have greater access to open field lines. This picture implies a rather static magnetic field geometry for GRL/SEP flares. In a more realistic scenario, still in the context of the single acceleration hypothesis, the apparent relationship in Figure 6 might result because long-duration SEP flares are more likely to involve coronal mass ejections (Kahler *et al.* 1984; Sheeley *et al.* 1983) that open up field lines and allow protons to escape.

There are arguments that weaken the above case for a single acceleration process in solar flares. First, Forrest *et al.* (1985) have identified an extended or delayed stage of γ-ray emission in the 1982 June 3 flare with properties (pion enrichment and spectral hardening) different from that of the impulsive phase. Murphy, Dermer, and Ramaty (1987) (see Hua and Lingenfelter 1987; Ramaty, Murphy, and Dermer 1987) have interpreted the GRS and interplanetary particle data for this event in terms of stochastic acceleration in a turbulent magnetic field followed by shock acceleration for the SEPs and delayed pions. However, the relative importance of the roles played by trapping versus acceleration in this and another energetic GRL/SEP flare (Rieger *et al.* 1987) is uncertain. The observed spectral variations may result from energy-dependent trapping/precipitation and escape (see Ryan 1986).

A second mitigating factor for the case for a single acceleration process concerns the >300 keV versus 4–8 MeV fluence correlation (Forrest 1983). The traditional "break" in energy between the first and second phase acceleration processes corresponds to nonrelativistic electron energies $\lesssim 100$ keV. The 100 keV separator is based largely on the spectra of "scatter-free" electron events observed at 1 AU (Lin 1974). A second phase was thought to be necessary to accelerate particles to higher energies. Thus Bai and Dennis (1985) and Bai (1986) have argued that the >300 keV versus 4–8 MeV fluence correlation exists because relativistic electrons, required to produce the >300 keV continuum, are accelerated by the same "second step" process that accelerates the protons responsible for the γ-ray lines. Those authors maintain that because GRL flares are strongly associated with metric type II/IV bursts and have flat hard X-ray spectra that continue to harden after the peaks of the events (see Cliver *et al.*, 1986), they involve a different acceleration process than that operating in lower energy (non–GRL) flares. The key test to address this point is to see if the 4–8 MeV fluence (or >300 keV fluence) is correlated with the fluence of lower energy ($\gtrsim 50$ keV) X-rays or if the scatter increases significantly in such a plot indicating the presence of a separate "first-step" process.

ii) *Two (or More) Acceleration Processes*

The classic two-phase particle acceleration paradigm for solar flares proposed by Wild, Smerd, and Weiss (1963) and de Jager (1969) consisted of an impulsive phase process associated with type III (fast-drift) metric radio emission, followed by a prolonged, and delayed (by minutes), shock-related process associated with a type II (slow-drift) radio burst. The first phase was thought to accelerate primarily low-energy (< 100 keV) electrons ("pure electron events") and the second phase accounted for relativistic electrons and SEPs ("mixed events") (Lin 1974). Recently, *SMM* observations (Forrest and Chupp 1983; Kane *et al.* 1986) showing that ions can be accelerated to ~ 10 MeV energies with virtually no delay (~ 1 s) with respect to low-energy 50 keV electrons have prompted various proposed modifications of the classic two-phase paradigm. Cane, McGuire, and von Rosenvinge (1986) retain the basic two-phase picture but require that in certain intense (i.e., GRL) events the traditional impulsive phase process now be capable of accelerating electrons to relativistic energies and protons to moderate (< 40 MeV) energies. Other approaches invoke a "second step" (Bai 1986) or "intermediate" process (de Jager 1987) to bridge the gap between the traditional (< 100 keV) impulsive phase and the shock-associated second phase. Both Bai's "second step" and de Jager's "intermediate" process occur within the flare impulsive phase.

An important extension of the classic two-phase picture was brought about by the work of Reames, von Rosenvinge, and Lin (1985), who reported an association between ^{3}He-rich events and nonrelativistic ($\lesssim 100$ keV) electron events. The ^{3}He-rich events (see Ramaty *et al.* 1980 and Kocharov and Kocharov 1984 for reviews) are characterized by reduced ^{1}H/^{4}He ratios and enhanced abundances of Fe and other heavy elements. Energetic (≥ 1 MeV) protons are observed in a relatively small fraction ($\lesssim 25\%$) of these events (Kahler *et al.* 1985). Kahler *et al.* (1985) also find that the ^{3}He-rich events, unlike the energetic proton events, are generally unaccompanied by either type II shocks or coronal mass ejections (see Lin 1974; Kahler *et al.* 1984). Thus it is clear that the ^{3}He-rich events are produced in the traditional flare impulsive phase. significant Reames *et al.* (1988) have shown that statistically anticorrelations exist between the ^{3}He/^{4}He ratios and the intensity of the flare event as measured at kilometric wavelengths and in hard and soft X-rays. One explanation they suggest for this result is that, in more intense events, mixing occurs between an ^{3}He-enriched particle population accelerated in a compact flare by the impulsive phase process and a "normal" population accelerated from ambient coronal abundances by a shock propagating away from the flare site.

The case for two distinct acceleration processes for energetic (~ 10 MeV) protons is based, in part, on differences between impulsive and gradual GRL/SEP flares in terms of the e/p ratios (Evenson *et al.* 1984; Cane, McGuire, and von Rosenvinge 1986; Bai 1986) of associated interplanetary particles, the ratio of interplanetary to γ-ray–producing protons (i.e., R^{-1}; Bai 1986), the peak fluxes and "cones of emission" of SEP events (Cane, McGuire, and von Rosenvinge 1986), and the flare-associated metric radio continua and kilometric wavelength emissions (Cane, McGuire, and von Rosenvinge 1986). Neither the distribution of soft X-ray durations for the events considered by Cane, McGuire, and von Rosenvinge (1986) nor the distribution of hard X-ray durations (total or "spike") considered by Bai (1986) show evidence of bimodality (nor do the τ values for the GRL/SEP flares in this study [see Fig. 3 in Cliver *et al.* 1987*a*]). Some of the above parameters, in particular the e/p and R ratios, appear to vary rather smoothly with τ.

There are two additional observations that provide more compelling evidence for two distinct classes of SEP events, and thus, presumably, for two separate acceleration processes in solar flares. First, Evenson *et al.* (1985) have divided the electron events observed in space into two classes on the basis of their spectra. Their class I events in most (16/19) cases had a power-law spectrum in kinetic energy, while each of their 31 class II events could be fitted with a power-law spectrum in momentum (rigidity). All of their class I events were associated with impulsive flares as classified by Cane, McGuire, and von Rosenvinge (1986), and all of their class II events originated in long-duration flares. Their class II spectra are consistent with acceleration by a single shock, but the class I events require more complicated models. The results of the Evenson *et al.* (1985) paper have recently been confirmed in a detailed study by Moses *et al.* (1988). Second, Reames (1988) has found a bimodal distribution of Fe/O ratios in daily averages of particles observed in space over an 8.5 yr period. The population with enhanced Fe/O ratio showed correlated enhancements in ^{3}He/^{4}He, e/p, and ^{4}He/^{1}H. Reames identifies this population with the flare impulsive phase and suggests that the population with more "normal" abundances is accelerated by coronal and interplanetary shocks.

How do the weak impulsive phase SEP flares fit into the two-phase acceleration paradigm? Since it is largely the seven large SEP events that lacked GRL emission that are responsible for the poor overall correlation between 10 MeV SEP event peak flux and 4–8 MeV GRL emission in Figure 3, it is natural to ask if these flares might somehow constitute a special class of events that are distinct from flares lying on the "main sequence" of the scatter plot. The histograms of τ in Figure 4 for GRL and SEP flares suggest the following picture. GRL emission is basically an impulsive flare (phase) phenomenon, while SEP flares in general, and the weak impulsive phase events in particular, are characterized by the long-duration X-ray emissions indicative of second phase acceleration. In the weak impulsive phase flares, the impulsive (first) phase acceleration process is muted or absent, and shock acceleration on open field lines predominates to produce the protons observed in space. The "main-sequence" events consist of both impulsive and long-duration flares (see Fig. 5), as identified by Cane, McGuire, and von Rosenvinge (1986) and Bai (1986). The long-duration flares on the main sequence are "hybrids" in which both types of acceleration occur, and the particles observed at 1 AU represent a mixture of impulsive phase and shock accelerated protons (see Bai 1986). Even for the impulsive flares, for which GRL fluences and SEP peak fluxes are correlated, there is evidence in certain cases (Forrest *et al.* 1985; Cane, McGuire, and von Rosenvinge 1986) for more than one acceleration process.

In this picture, both the poor correlation between flare GRL fluence and SEP event peak flux in Figure 3 and the apparent continuum relationship between R and τ in Figure 6 result from the presence or overlap of two different types of flares or acceleration processes. In impulsive flares most of the accelerated protons are trapped (von Rosenvinge, Ramaty, and

Reames 1981) and R is large. For the weak impulsive phase flares, which are an extreme or more "pure" class of gradual flares, nearly all of the protons escape and R is small.

Evidence for prolonged acceleration of SEPs following solar flares has recently been presented by Beeck *et al.* (1987) and Cane, Reames, and von Rosenvinge (1988) (see Mason, Gloeckler, and Hovestadt 1984; Reames and Stone 1986). Beeck *et al.* examined two SEP events using multispacecraft observations and deduced extended (~4–8 hr) particle injection profiles and suggested shock acceleration out to distances of 10–20 $R_{\odot}$ as the most plausible explanation. Cane, Reames, and von Rosenvinge (1988) have interpreted the time profiles of extended SEP events as evidence for prolonged acceleration by interplanetary shocks. The shock effects are most prominent at lower (≤ 20 MeV) proton energies but in certain cases can extend to energies as high as 100 MeV. The SEP events with long rise times in our sample were strongly associated with interplanetary type II bursts indicative of strong shocks (Cane 1985).

iii) *Synopsis*

Whereas the observational results of this paper alone are not inconsistent with a single acceleration process for solar flares, the preponderance of all of the available evidence favors two (or more) phases or modes of particle acceleration over the simpler single-process picture. In the flare impulsive phase, low-energy ($\lesssim 100$ keV) electrons and ^{3}He particles are preferentially accelerated. Signatures of this acceleration phase include impulsive hard and soft X-ray bursts and type III/V radio bursts. Coronal mass ejections and type II shocks characteristically do not accompany the first phase process, but this distinction becomes blurred for the more energetic impulsive flares associated with GRL emission and relativistic electrons in space. For example, most (72%) of the impulsive flares studied by Cane, McGuire, and von Rosenvinge (1986) were associated with metric type II bursts. At present it is not clear whether the impulsive GRL events represent simply a more intense form of the first phase process (Cane, McGuire, and von Rosenvinge 1986) or require an additional second step (Bai 1986) acceleration process operating within the impulsive phase. The bulk of the ~10 MeV protons accelerated during impulsive flares remain trapped at the Sun, presumably on the low-lying loops that typify these events. There is no consensus on the mechanism(s) responsible for impulsive (first) phase acceleration in solar flares (see Forman, Ramaty, and Zweibel 1986 for a review of acceleration processes). Candidates include acceleration in DC electric fields (e.g., Colgate 1978; Spicer 1982; Haerendel 1987; Martens 1988), stochastic acceleration in turbulent plasma (e.g., Barbosa 1979; Ramaty 1979; Mullan 1980; Matthaeus, Ambrosiano, and Goldstein 1984; Dröge and Schlickeiser 1986; Steinacker, Dröge, and Schlickeiser 1988), and even shock acceleration (Bai *et al.* 1983; Ellison and Ramaty 1985; Cane, McGuire, and von Rosenvinge 1986). The second phase or mode of flare particle acceleration is generally taken to involve a coronal shock (e.g., Achterberg and Norman 1980; Lee and Fisk 1982; Ellison and Ramaty 1985; Lee and Ryan 1986; Decker and Vlahos 1986) that is responsible for the SEP events observed at 1 AU, particularly the larger events with normal ^{3}He/^{4}He and e/p ratios. Since the particles are accelerated high in the corona, and likely beyond in the interplanetary medium, they have ready access to open field lines. Flare phenomena associated with second phase acceleration include coronal mass ejections, type II/IV radio bursts, and long-duration soft and hard X-ray bursts.

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APPENDIX

JUSTIFICATION FOR FLARE ASSOCIATIONS FOR LARGE SEP EVENTS FROM NON–GRL FLARES

I. EVENT BY EVENT BASIS

The seven flares under consideration are 1980 November 23 (event 14 in Table 1), 1981 March 30 (event 17), 1981 May 10 (event 23), 1981 July 20 (event 26), 1981 December 5 (event 32), 1981 December 9 (event 33), and 1982 December 19 (event 53). Our subjective level of confidence in the association of each of these events, based on the particle event onset time and time-intensity profile and on the flare timing, characteristics, and location, was rated as "1" (col. [17] in Table 1). The association for the 1981 May 10 event has been discussed by Cliver *et al.* (1984). The identified flare for this SEP is closely associated in time and space with a coronal mass ejection and was accompanied by a long-duration metric type II burst. The 1982 December 19 event, although relatively weak in microwave emission (S_p[9 GHz] ~ 100 sfu), was associated with a major 1–8 Å burst (Cane 1985) and is thus a good candidate to have produced a proton event (Nonnast, Armstrong, and Kohl 1982). The solar association for the 1981 December 5 event has been discussed in detail by Kahler *et al.* (1986). This event and the flares on 1980 November 23 and 1981 December 9 have been associated by Cane (1985) with interplanetary (kilometric) type II bursts which often accompany large SEP events (Cane and Stone 1984).

For six of the seven flares (all except 1981 December 9) observations were available from the radio astronomy experiment on *ISEE 3* (Knoll *et al.* 1978). This experiment observes the radio emission produced by flare-accelerated $\lesssim 100$ keV electrons as they stream outward along the interplanetary magnetic field. The intensity and the mean arrival direction (azimuth relative to the Earth-Sun line) of the radio emission are observed at 23 frequencies (1980–30 kHz). Source directions can be used to construct trajectories for the radio bursts associated with the six flares and thus give information on the validity of our flare/SEP event associations, since SEP events are always accompanied by low-energy electrons. Trajectories projected in the ecliptic plane, as shown in Figure 7, are constructed from the intersections of the observed azimuths and an assumed relation between the emission frequency (f) and the radial distance (r) from the Sun. In this figure, positions for emission frequencies from 1980 kHz to about 160 kHz are plotted for four of the events. The emission frequency-distance scale used was the " RAE model,"

$$f(\text{kHz}) \simeq 58 r\text{AU}^{-1.315}$$

(Fainberg and Stone 1971). (It was necessary to increase the coefficient to 100 to obtain intersections for the event of 1982 December 19.) The other two events observed by *ISEE 3* have trajectories which are further to the east.

These trajectories indicate front-side sources for the six observed events. It should be noted that the second intersections of the azimuths and the frequency-distance scale would place the trajectories in the far quadrant, appropriate for a source behind the limb. Although such trajectories might be conceivable for the most westerly events based on the observed azimuths alone, the large peak radio intensities observed for these events (range in log from 5.2 to 6.7 [sfu]) support locating their trajectories in the front-side hemisphere, thereby directing their emission toward the spacecraft.

For five of the seven events (1980 November 23, 1981 July 20, 1981 December 5, 1981 December 9, and 1982 December 19), the *Helios* satellite (H1) was magnetically rooted to a point behind the west limb of the Sun (range from W110 to W150) and was thus in good position to view particles from hypothetical occulted flares. If the source of any of these five events was, in fact, located behind the west limb, then we might expect a larger, more prompt, SEP event at *Helios* than at Earth. In three of these five events (1980 November 23, 1981 December 5, and 1981 December 9), the *Helios* SEP data from the GSFC detectors (Table 3) are consistent with the visible hemisphere flare we have identified and argue against a behind-the-limb source. In these three cases the identified flare was east of the nominal W57 field line connecting to Earth, and the SEP event at *Helios* was smaller (by factors of 6, ~30, and 250, respectively) than the event at *IMP 8*. The maxima of the *Helios* 11–22 MeV profiles for the November 23 and December 9 events are delayed with respect to the *IMP 8* profiles. The delay for the November 23 event is so great as to call into question our identification of the *Helios* event beginning on November 25 with the *IMP 8* event beginning late on November 23. If these *Helios* and *IMP 8* events are not related, then the Table 1 event was small at *Helios* and the ratio of *IMP 8* to *Helios* peak fluxes near 10 MeV for this event is ~100. For two events in Table 3 (1981 July 20 and 1982 December 19), the identified flare was located at W75,

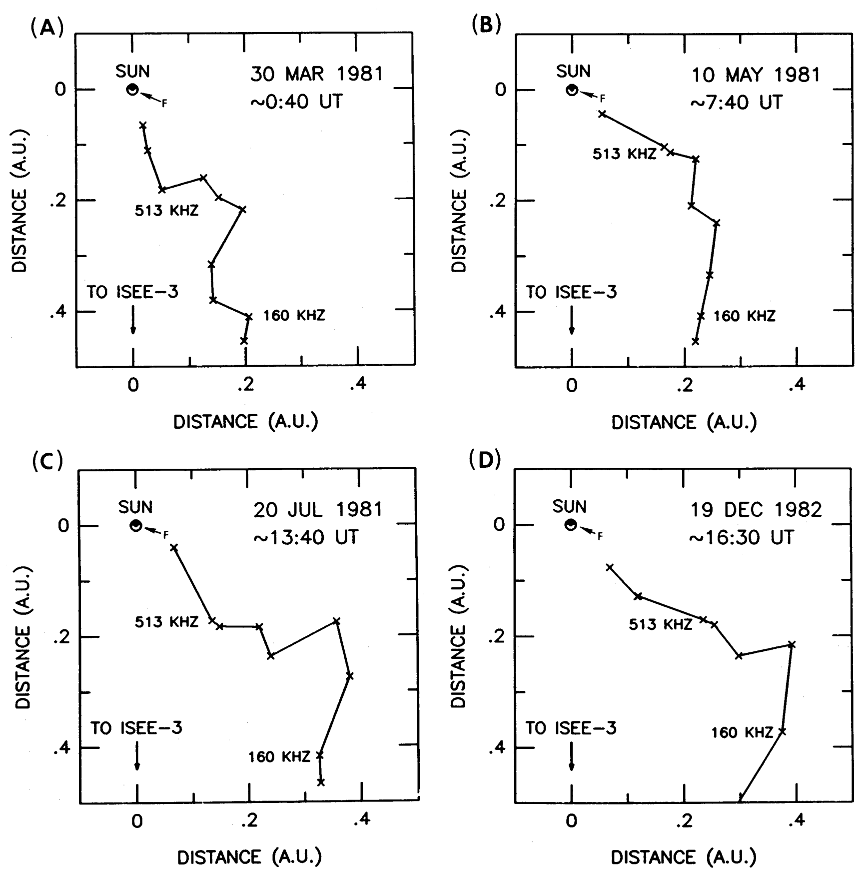

FIG. 7.—View from the north ecliptic pole of the positions of the low-frequency radio emission associated with the non–GRL proton flares of (*a*) 1981 March 30, (*b*) 1981 May 10, (*c*) 1981 July 20, and (*d*) 1982 December 19. The flare site is indicated in each case by an arrow.

TABLE 3

COMPARISON OF NEAR-EARTH AND *Helios* OBSERVATIONS OF LARGE SEP EVENTS FROM FLARES THAT LACKED DETECTABLE GRLs

TABLE 1 EVENT NUMBER	FLARE			NEAR-EARTH PROTONS			*Helios* PROTONS			
	Date	Time	Location	Solar Footpoint[a]	Delay to Peak (hr)	$J(>9$ MeV) (protons cm^{-2} s^{-1} sr^{-1} MeV^{-1})	Solar Footpoint[a]	Distance (AU)	Delay to Peak (hr)	$J(>11$ MeV)[b] (protons cm^{-2} s^{-1} sr^{-1} MeV^{-1})
14.......	1980 Nov 23	1905	W20	W57(± 10)	9 ± 2	$6 \pm 1 \times 10^{-1}$	W150	0.4	51 ± 1	$9 \pm 1 \times 10^{-2}$
26.......	1981 Jul 20	1329	W75	W57	7 ± 1	$1 \pm 0.2 \times 10^{1}$	W125	0.7	26 ± 9?[c]	$2(+1, -0.5) \times 10^{1}$?
32.......	1981 Dec 5	1440	W40	W57	19 ± 1	$4 \pm 0.5 \times 10^{-1}$	W125	0.45	15 ± 1[d]	$1.2 \pm 0.2 \times 10^{-2}$[d]
33.......	1981 Dec 9	1918	W16	W57	$\gtrsim 14$	$\gtrsim 1 \pm 0.2 \times 10^{1}$	W135	0.4	41 ± 12	$4(+1, -2) \times 10^{-2}$
54.......	1982 Dec 19	1650	W75	W57	12 ± 1	$4.8 \pm 0.4 \times 10^{0}$	W110	0.45	18 ± 1	$6 \pm 1 \times 10^{1}$

[a] Based on a nominal solar wind speed of 400 km s^{-1} (see Nolte and Roelof 1973).

[b] Peak flux at 11–22 MeV measured by the GSFC detector on *Helios*.

[c] Lower energy ($\sim$6 MeV) protons observed at *Helios* have a sharp maximum near the time of shock passage at 2344 UT on July 21) (R. Schwenn, private communication, 1987).

[d] There is a gap in GSFC data from 12 UT on December 5 until 7 UT on December 6. The listed data are from the 13–27 MeV channel on the University of Kiel particle detector on *Helios* (G. Wibberenz, private communication, 1987). See Kahler *et al.* (1986) for the *IMP 8* particle profiles.

between the solar footpoints of the field lines connecting to *IMP 8* and *Helios*. The data for the 1981 July 20 event are inconclusive. Similar rise profiles were seen at *IMP 8* and *Helios*; the effect of a shock can be seen later in the event in the *Helios* data (see footnote 3 to Table 3). For the 1982 December 19 event, the 11–22 MeV event at *Helios* was a factor of 12 larger than the corresponding 9–23 MeV event at *IMP 8*, suggesting that the source identified in Table 1 is wrong and favoring a behind-the-limb flare. We note in this case, however, that the SEP event at *Helios* was bounded by two strong shocks occurring on December 19 at 0400 UT ($\Delta v = 124$ km s^{-1}; $n_2/n_1 = 1.8$; $v_s = 603$ km s^{-1}) and December 20 at 1108 UT ($\Delta v = 458$ km s^{-1}; $n_2/n_1 = 3.4$; $v_s = 1006$ km s^{-1}) (R. Schwenn, private communication, 1987), and the SEP event profile drops abruptly after the passage of the second shock.

II. FRACTION OF LARGE SEP EVENTS FROM BEHIND-THE-LIMB FLARES

In this section, we present an additional, statistical argument, for the validity of the flare associations for the 11 large SEPs that originated in flares without detectable GRL emission (seven western and four eastern hemisphere flares from Table 1). Specifically, we provide evidence that these events, as a group, cannot be attributed to flares from behind the limb. If we have done our SEP event/flare associations correctly, then we might expect that the percentage of SEP events we infer to have arisen in back-side flares should be comparable to that found in previous studies. Of particular relevance to the 11 large SEP events under consideration are the studies of Fritzova-Svestkova and Svestka (1971) and Smart *et al.* (1976), who conclude that 25%–30% and $\sim$20%, respectively, of all polar cap absorption (PCA) events arise in back-side flares. After Smart and Shea (1971), the detection threshold for a PCA event corresponds to a SEP event with an integral flux $J(>10$ MeV$) \geq 10^1$ protons cm^{-2} s^{-1} sr^{-1}. This is equivalent to a differential flux $J(9\text{–}23$ MeV$) \geq 7.4 \times 10^{-1}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} (assuming an E^{-3} spectrum; van Hollebeke, Ma Sung, and McDonald 1975), which is comparable to the lower flux limit (4×10^{-1}) for the 11 large SEP events being considered. We were able to make confident front-side flare associations for 27 of 34 events occurring from 1980 February through 1983 February that satisfied our selection criteria and also had (near-Earth) $J(>9$ MeV$) \geq 4 \times 10^{-1}$. This $\sim$80% association rate is consistent with the $\sim$20% fraction of large events inferred to have arisen in back-side flares by Smart *et al.* (1976) (see Van Hollebeke, Ma Sung, and McDonald 1975), but lower than the 25%–30% figure of Fritzova-Svestkova and Svestka (1971). While this suggests that some additional SEP events in our sample may have arisen in back-side flares, even using the 30% figure still leaves at least seven of the 11 events with front-side associations ($11 - [27 - (0.7 \times 34)] = 7.8$), if one makes the questionable assumption that all four of the "misassociated events" come from the 11 large SEP events that lacked detectable GRL emission.

Our velocity dispersion requirement for SEP event selection was not used by either Fritzova-Svestkova and Svestka (1971) or Smart *et al.* (1976). We surmised that removing this criterion might admit more SEP events that originate in flares well-removed from the observation site, i.e., potential back-side events, thus reducing our SEP event/flare association percentage. To test this hypothesis, we dropped the velocity dispersion requirement for SEP events observed between 1980 February and 1983 February. This allowed five additional events with $J(>9$ MeV$) \geq 4 \times 10^{-1}$ to enter the sample. These five events and the seven large SEP events for which we were unable to confidently identify a visible disk parent flare are listed in Table 4. Contrary to our expectations, we were able to identify plausible disk flare candidates for all five of the SEP events in Table 4 that lacked velocity dispersion (flares 1, 2, 6, 9, and11). In each case, the $J(>9$ MeV) maximum followed the associated flare by greater than 30 hr. Three of the identified flares (flares 1, 6, and 9) were associated with interplanetary type II bursts (Cane 1985). In three cases (events 1, 9, and 11) the 9–23 MeV event maximum was coincident (± 1 hr) with a geomagnetic storm sudden commencement. Event 11 appears to be a "delayed" component of event 49 in Table 1 (see footnote 10 to Table 4). The inclusion of the four "new" events (all except event 11) in our sample of large SEP events increases our association rate slightly to 82% (31/38). More significantly, two of the newly admitted SEP flares in Table 4 (events 1 and 2) lacked detectable (2 σ) 4–8 MeV GRL emission. Event 2 was observed by the GRS on *SMM*. For the 1980 July 17 flare (event 1), $S_p(9$ GHz$) = 75$ sfu and, from Figure 1, we infer a GRL fluence of less than 0.2 γ-rays cm^{-2}.

TABLE 4

LARGE SEP EVENTS FROM 1980 FEBRUARY TO 1983 FEBRUARY NOT IN TABLE 1

	>20 MeV ONSET		9–23 MeV PROTONS						
EVENT NUMBER	Date	Time (UT)	Date of Maximum	Peak Time (UT)	Peak Flux (protons cm^{-2} s^{-1} sr^{-1} MeV^{-1})	REASON EVENT IS NOT IN TABLE 1, LACKED	IDENTIFIED FLARE	NOTES	REFERENCE
1........	1980 Jul 17	~11	Jul 18	19 ± 1	1×10^1	Velocity dispersion	Jul 17, 0612, 2N, S11E06	1, 2	1, 2
2........	1981 Apr 15	~17	Apr 16	15 ± 8	4×10^{-1}	Velocity dispersion	Apr 14, 2353, 1N, N13E73, II		1
3........	1981 Apr 28	~23	Apr 29	06 ± 1	8×10^0	Front-side candidate	Region 17590, ≳W105, II	3	1, 2
4........	1981 Apr 30	~06	Apr 30	16 ± 2	5×10^0	Front-side candidate	Region 17590, ≳W120, II		1, 2
5........	1981 Jul 24	<17	Jul 25	09 ± 2	1×10^0	Frontside candidate	Jul 22, 2246, −N, N15W14; Jul 23, 1045, 1N, N14W18	4	
6........	1981 Aug 7	~19	Aug 10	≤07	$\gtrsim 3 \times 10^0$	Velocity dispersion	Aug 7, 1916, 1B, S09E25	1, 5	1
7........	1981 Sep 6	~18	Sep 7	14 ± 2	9×10^{-1}	Frontside candidate	?	6	
8........	1982 Jun 4	<18	Jun 9	09 ± 5	1×10^0	Frontside candidate	Region 18382/83, ≳W150, II	7	1, 3, 4, 5
9........	1982 Jul 12	<22	Jul 13	17 ± 1	1×10^2	Velocity dispersion	Jul 12, 0955, 3B, N11E36	1, 8	2, 3
10........	1982 Jul 22	~18	Jul 22	21 ± 1	$\gtrsim 3 \times 10^0$	Frontside candidate	Region 18474, ≳W100, II	1, 9	1, 3
11........	1982 Nov 23	~20	Nov 24	10 ± 1	8×10^0	Velocity dispersion	Nov 22, 1829, 1N, S11W36	1, 10	1, 2
12........	1982 Dec 26	~16	Dec 27	~06 ± 2	$\gtrsim 1 \times 10^0$	Frontside candidate	Region 4025, ≳W135; Region 4026, ≳W125	11	

NOTES.—(1) An interplanetary type II burst was reported in association with this flare (Cane 1985). (2) A sudden commencement (SC) occurred on July 18 at 1925 UT. (3) Boulder reports a 1B flare at N16W90 beginning before 2205 UT on April 28. (4) SCs occurred on July 25 at 0515 UT and 1322 UT. The listed flares are the most likely visible disk candidates to have been the source of an SC. Two flares on July 24 (0752 UT, 1N, S16E56; ~1100 UT, 1N?, N17W33) are candidate sources of the SEP event, but not an SC. None of these sources are convincing associations. (5) An SC occurred on August 10 at 0433 UT. (6) There are no good candidate front-side or back-side sources for this event. (7) We favor the back-side flare(s) associated with the type II bursts on June 3 from 0234 to 0302 UT and from 0402 to 0450 UT (Cliver *et al.* 1987*b*) over the 1982 June 3 flare in Table 1 (event 41) because the 1–2 MeV electron profile at *Helios* continues to rise after the decay of the impulsive event (McDonald and Van Hollebeke 1985). A 2B flare at S09E25 with maximum at 1633 UT on June 6 may contribute to the long-duration SEP event. SCs were observed on June 6 at 0243 UT and on June 9 at 0039 UT. (8) An SC occurred on July 13 at 1617 UT. (9) A 1N flare with maximum at 1707 UT is reported in region 18474 at N16W89 in conjunction with an M5 (at 1734 UT) 1–8 Å event and a type II burst from 1720 to 1730 UT. Extrapolating from the positions of earlier major flares from this active region indicates a probable flare location at ~W100–W105. A −F flare (N29W86) with maximum at 1727 UT from region 18473 is a less likely source. The particle detector on *IMP 8* is saturated. (10) This is the delayed component of event 49 in Table 1. An SC occurred on November 24 at 0921 UT. A significant dip between the peaks at >20 MeV caused us to "decouple" these events in our initial survey. (11) This event is superposed on event 54 in Table 1. The events are cleanly separated in the *Helios* data; *Helios* was connected to a point behind the west limb of the Sun (~W120) and does not observe prompt particles from the flare on December 25 (E45). It is not clear which flare the eventual 9–23 MeV maximum at ~13 UT on December 27 should be attributed to, but the front-side flare is the more likely source of the SC (see note [24] to Table 1).

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