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THE UNUSUAL RELATIVISTIC SOLAR PROTON EVENTS OF 1979 AUGUST 21 AND 1981 MAY 10

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ABSTRACT

Sixty-nine ground level events (GLEs) caused by relativistic solar protons have been observed from 1942 to 2005. GLEs are characteristically associated with intense solar flares [having peak ~9 GHz flux densities S_P(9 GHz) > 10^3 sfu] and fast (>1000 km s^{-1}) coronal mass ejections (CMEs). The small GLEs on 1979 August 21 and 1981 May 10 provide an exception to these rules of thumb. In comparison with other GLEs, they were associated with significantly weaker flares [S_P(9 GHz) < 30 sfu vs. a median value of ~8000 sfu for all GLEs] and slower CMEs (plane-of-sky speeds ~800 km s^{-1} vs. a median of ~1600 km s^{-1}). The sunspot groups in which these two events originated ranked near the bottom of GLE-parent regions in terms of sunspot area (~100 millionths of a solar hemisphere [msh] vs. a median of ~850 msh). What enabled these two otherwise commonplace solar eruptions to accelerate protons to GeV energies? In both cases, intense, long-duration, metric type II bursts were observed. In addition, both of these GLEs occurred when the background ~10 MeV proton intensity at 1 AU was >1000 times the normal background because of preceding SEP events originating in active regions that were located in each case ~100° east of the active region responsible for the GLE. We suggest that the relativistic solar protons observed in these two events resulted from CME-driven shock acceleration of an elevated coronal seed population, reflecting the enhanced background proton intensity at 1 AU. For this scenario, the timing onset of the relativistic protons in the two events indicates that the shocks had access to the energetic seed particles within ~2–5 $R_\odot$ of the solar surface. While an elevated ~10 MeV proton background at Earth is a favorable/common condition for GLE occurrence, it is not a requirement.

Subject headings: Sun: flares — Sun: particle emission

Online material: color figures

1. INTRODUCTION

A central question in the physics of solar energetic proton (SEP) events concerns the acceleration mechanism of the highest energy (~GeV and above) particles. Protons at these energies give rise to ground level events (GLEs) at Earth, as recorded by neutron monitors. Do these high-energy SEPs arise in flares or shocks? As recently as 1999, it was generally accepted that the bulk of the protons in large SEP events (by definition including all GLEs) were accelerated at coronal/interplanetary shocks. In the two-class, or more appropriately, two-mechanism paradigm (Reames 1999), flare particle events were identified by their low (or negligible) proton fluxes, high ^{3}He/^{4}He ratios (>0.1), high Fe charge states (~20), and high Fe/O ratios (~10 times that of normal coronal abundances), while the largest SEP events, characterized by low ^{3}He/^{4}He ratios (<0.1), low charge states (<14), and low Fe/O ratios (coronal abundances), were attributed to shock waves driven by coronal mass ejections (CMEs). Lee (2005) recently traced the development of evidence for the shock scenario for large SEP events.

The shock picture was challenged by *Advanced Composition Explorer* (*ACE*; Stone et al. 1998) observations of large SEP events with high charge states and Fe/O ratios (Cohen et al. 1999a, 1999b; Mewaldt et al. 2006), suggesting that the flare acceleration mechanism was playing an important role in large SEP events. Cliver (2000) summarized the various lines of evidence, including gamma-ray observations, that were consistent with this viewpoint. Subsequently, Cane et al. (2002) presented radio evidence for a direct flare component, and Cane et al. (2003) used particle composition measurements to argue that the flare component usually dominates SEP events at energies greater than 25 MeV. Alternatively, Tylka et al. (2005; see Mason et al. 1999) emphasized the role of flare-accelerated particles as a seed population for further acceleration by quasi-perpendicular shocks.

GLEs are characteristically associated with both big flares and fast CMEs, making it difficult to isolate the key signatures of SEP acceleration at the Sun. In this study, in an attempt to gain insight to the acceleration mechanism(s) for the high-energy solar particles observed in space, we focus on two GLEs (1979 August 21 and 1981 May 10) that were associated with weak flares and relatively slow CMEs and ask what solar/interplanetary circumstances led to high-energy proton acceleration in these unusual events. Our results are presented in § 2 and discussed in § 3.

2. ANALYSIS

2.1. *Data Table and Sources*

A listing of the dates, times, solar sources, and peak percentage increases of GLEs 1–32 (1942–1978) can be found in Cliver et al. (1982). Coronagraph observations are unavailable for these early events, although it is almost certain (see Kahler et al. 1984) that all had associated CMEs. Data for GLEs 33–69 (1979–2005) are given in Table 1, where in addition to solar source timing (cols. [2] and [3]) and location (col. [5]) data, we list the *Geostationary Operational Environmental Satellite* (*GOES*) peak 1–8 Å flux (col. [4]), the area of the associated sunspot group (col. [6]), the peak radio flux density near 9 GHz [S_P(9 GHz); col. (7)], CME speed and width (cols. [8] and [9]), the pre-event SEP background level at ~10 MeV (col. [10]), and the GLE percentage increase (col. [11]). Flare, active region, and radio burst data were taken from Solar-Geophysical Data (1979–2005). *GOES* >10 MeV proton data and soft X-ray data were obtained

TABLE 1

Solar Eruptions Associated with GLEs, 1979–2005

GLE No. (1)	Date (2)	1–8 Å: Peak Time (UT) (3)	1–8 Å: Peak Flux[a] (4)	Hα Location (5)	Sunspot Area[b] (msh) (6)	S_P(9 GHz)[c] (sfu) (7)	CME: Speed[d] (km s^{-1}) (8)	CME: Width (deg) (9)	Pre-Event 15–25 MeV Intensity[e] (10)	GLE Increase[f] (%) (11)
33	1979 Aug 21	0620	C6	N17W40	30	25	690F	110	20	6
34	1981 Apr 10	1655	X2	N07W36	260	1654	N.O.	N.O.	0.006	2
35	1981 May 10	0732	M1	N03W75	160	24	830G	80	4	3
36	1981 Oct 12	0636	X3	S18E31	1260	19400	R	360	3	11
37	1982 Nov 26	0253	X4	S12W87	1660	8500	R	60	0.04	6
38	1982 Dec 7	2354	X2	S19W86	750	24700	1250E	100	0.08?	56
39	1984 Feb 16	(∼0900)	(C1)	∼W130	...	(16)	1200E	60	0.001?	72
40	1989 Jul 25	0843	X2	N26W85	140	814	N.O.	N.O.	0.001?	4
41	1989 Aug 16	0107	X12	S15W85	870	22500	N.M.	55	40	15
42	1989 Sep 29	(1132)	X9	∼W100	...	(13255)	1828	77	0.009	270
43	1989 Oct 19	1256	X12	S25E09	1070	34139	N.O.	N.O.	0.01	53
44	1989 Oct 22	1805	X2	S27W32	890	30500	...	...	20	20
45	1989 Oct 24	1831	X5	S29W57	850	48500	1453	108	30	95
46	1989 Nov 15	0659	X3	N11W28	510	3623	N.M.	50?	0.008	5
47	1990 May 21	2217	X5	N34W37	740	6400	N.O.	N.O.	0.04	14
48	1990 May 24	2051	X9	N36W76	730	44000	N.O.	N.O.	0.2	10
49	1990 May 26	2058	X1	∼W100	...	(1200)	N.O.	N.O.	2	8
50	1990 May 28	(0433)	(C1)	∼W120	...	(347)	N.O.	N.O.	0.7	6
51	1991 Jun 11	0209	X12	N32W15	1910	17000	N.O.	N.O.	∼1?	14
52	1991 Jun 15	0817	X12	N36W70	2330	15883	N.O.	N.O.	1	28
53	1992 Jun 25	2014	X3	N10W68	1200	20000	N.O.	N.O.	0.008?	5
54	1992 Nov 2	0308	X9	∼W100	...	(17500)	N.O.	N.O.	0.008	7
55	1997 Nov 6	1155	X9	S18W63	814	9200	1556	360	0.1	11
56	1998 May 2	1342	X1	S15W15	430	1700	938	360	0.01	7
57	1998 May 6	0809	X2	S15W64	610	1430?	1099	190	0.04	4
58	1998 Aug 24	2212	X1	N35E09	490?	2000	N.O.	N.O.	0.07	3
59	2000 Jul 14	1024	X5	N22W07	530	8800	1674	360	0.04	29
60	2001 Apr 15	1350	X14	S20W84	360	1626	1199	167	0.7	57
61	2001 Apr 18	(0214)	(C2)	∼W115	...	(100)	2465	360	5	14

TABLE 1—*Continued*

GLE No. (1)	Date (2)	1–8 Å: Peak Time (UT) (3)	1–8 Å: Peak Flux[a] (4)	Hα Location (5)	Sunspot Area[b] (msh) (6)	S_P(9 GHz)[c] (sfu) (7)	CME: Speed[d] (km s $^{-1}$) (8)	CME: Width (deg) (9)	Pre-Event 15–25 MeV Intensity[e] (10)	GLE Increase[f] (%) (11)
62....................	2001 Nov 4	1620	X1	N07W19	550	2800	1810	360	0.1	3
63....................	2001 Dec 26	0540	M7	N08W54	750	3800	1446	>212	0.1	7
64....................	2002 Aug 24	0112	X3	S02W81	1570	11350	1913	360	1	5
65....................	2003 Oct 28	1110	X17	S16E08	2130	70000	2459	360	2	12
66....................	2003 Oct 29	2049	X10	S15W02	2580	11000	2029	360	700	8
67....................	2003 Nov 2	1725	X8	S14W56	2090	18500	2598	360	10	7
68....................	2005 Jan 17	0952	X3	N13W23	1460	16500	2094	360	100	N/A
69....................	2005 Jan 20	0701	X7	N12W58	1220	53000	3242	360	30	277

[a] Soft X-ray peak flux classification: $Cn, Mn, Xn = n \times (10^{-3}, 10^{-2}, 10^{-1})$ ergs cm $^{-2}$ s $^{-1}$. Classifications in parentheses indicate behind-the-limb events. Detector saturated for GLEs 41, 43, and 52; the listed time marks the onset of saturation.

[b] For events near the limb, area values for 1–2 days preceding were used, when the position of the sunspot was listed as $\sim$W60°. For GLEs from 1970 to 1978, sunspot areas are as follows: 1971 January 24 (410); 1971 September 1 (N/A, behind limb), 1972 August 4 (1140), 1972 August 7 (910), 1973 April 29 (480), 1976 April 30 (250), 1977 September 19 (920), 1977 September 24 (N/A), 1977 November 22 (150), 1978 May 7 (990), and 1978 September 23 (840).

[c] 1 sfu $= 1 \times 10^{-22}$ W m $^{-2}$ Hz $^{-1}$. Average values for all stations reporting in the 8–12 GHz range, after discarding any widely divergent values. Values in parentheses from limb-occulted flares were not used in the histogram of Fig. 2.

[d] N.O. indicates no observations; N.M. indicates CME observed, speed not measured; speed qualifiers are E for estimate, F for fair, and G for good; R indicates remnants of CME observed. Speed for GLE 69 taken from Gopalswamy et al. (2006).

[e] *IMP 8* 15–25 MeV intensities (protons cm $^{-2}$ s $^{-1}$ sr $^{-1}$ MeV $^{-1}$) are given for 1979–2000. For 2001–2005, the listed intensities are for the *GOES* >10 MeV channel (protons cm $^{-2}$ s $^{-1}$ sr $^{-1}$). The 15–25 MeV background intensities for GLEs occurring from 1974 to 1978 are as follows: 1976 April 30 (0.001), 1977 September 19 (0.08?), 1977 September 24 (0.01), 1977 November 22 (0.001), 1978 May 7 (0.1), and 1978 September 23 (0.001).

[f] Worldwide data from the Australian Antarctic Division Web site through GLE 54; single station data from Oulu for subsequent events (Gopalswamy et al. 2006). N/A indicates observations not yet available. Occurrence of GLE 68 from M. A. Shea (2005, private communication).

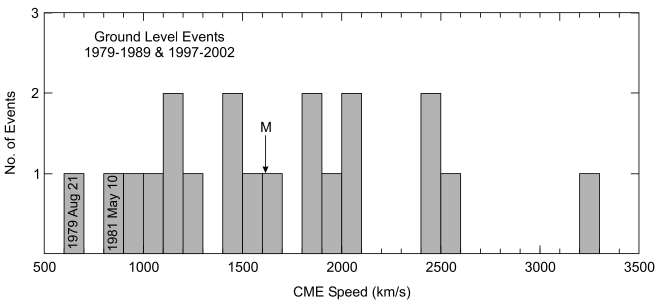

FIG. 1.—Histogram of the plane-of-sky speeds of CMEs associated with GLEs from 1979–1989 and 1997–2005. The median speed value is indicated by "M."

from the SPIDR Web site[1] maintained by the National Geophysical Data Center. For column (10), we used 15–25 MeV proton data from the Charged Particle Measurement Experiment on *Interplanetary Monitoring Platform 8* (*IMP 8*)[2] for 1979–2000 and *GOES* >10 MeV data thereafter. GLE peak percentage increases were obtained from the worldwide GLE Web site[3] maintained by the Australian Antarctic Division for events through 1992. For GLEs after 1992, we list the peak percentage value from the Oulu neutron monitor[4] (Gopalswamy et al. 2006) as a representative value of the size of each event. CME parameters were obtained from the Solwind experiment on *P78-1* for 1979–1985 (Michels et al. 1982),[5] the Coronagraph/Polarimeter (MacQueen et al. 1980; Burkepile & St. Cyr 1993) on *Solar Maximum Mission* (*SMM*) for 1980 and 1984–1989, and the Large Angle Spectroscopic Coronagraph (LASCO, Brueckner et al. 1995; Yashiro et al. 2004)[6] on *Solar and Heliospheric Observatory* (*SOHO*) for 1996 to the present.

2.2. *GLEs and CMEs*

Coronagraph observations were available for 25 of the GLEs in Table 1. Of these 25 GLEs, only one event (1989 October 22; GLE 44 in Table 1) with complete coronagraph coverage lacked a reported CME. This GLE was associated with a flare occurring relatively close to disk center (S27° W32°). Because coronagraphs are most sensitive to emission originating in the plane of the sky and are thus best suited to observe limb events (Webb & Howard 1994), the absence of an observed CME does not necessarily mean that none occurred. In fact, both the peak soft X-ray intensity and duration of the associated flare (X2, $\sim$7 hr) imply CME occurrence for the 1989 October 22 event. Yashiro et al. (2005) report that essentially all X-class flares have associated CMEs, while Sheeley et al. (1983) found that all soft X-ray flares with durations >6 hr were associated with CMEs.

A histogram of CME plane-of-sky speeds for the GLEs listed in Table 1 is given in Figure 1. For this sample, the median speed was $\sim$1600 km s^{-1}. (Gopalswamy et al. [2006] obtained a deprojected median speed of $\sim$1850 km s^{-1} for GLE-associated CMEs during the *SOHO* epoch.) The median CME angular span at the limb for the listed events was $\sim$80° for pre-LASCO GLEs and 360° for events during the *SOHO* epoch. For comparison, only $\sim$1% of LASCO CMEs have speeds >1500 km s^{-1}, and only $\sim$3% are full halos (Gopalswamy et al. 2005). Only three CMEs in Figure 1 had plane-of-sky speeds <1000 km s^{-1}. One

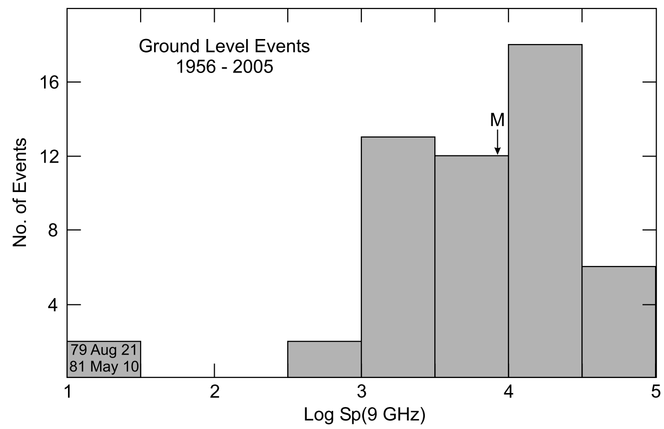

FIG. 2.—Peak flux density at $\sim$9 GHz of radio bursts associated with GLEs, 1956–2005. The median peak flux density value is indicated by "M."

of these three—the CME associated with the 1998 May 2 GLE—had a speed of 938 km s^{-1}, but the associated flare was located near disk center (S15° W15°), indicating a large projection effect and a reduced plane-of-sky speed. The GLEs on 1979 August 21 (CME speed of 690 km s^{-1}) and 1981 May 10 (830 km s^{-1}), however, originated closer to the limb (at W40° and W75°, respectively), consistent with a relatively low radial speed (for this sample of events). As seen in § 2.3, the flares associated with these two GLEs were also weaker than the norm for such events.

2.3. *A Big Flare is Not a Requirement for a GLE*

Cliver et al. (1983a) showed that the GLE on 1979 August 21 originated in a relatively small soft X-ray flare (C6; 2B optical) with peak 9 GHz radio flux density $S_P(9\ \mathrm{GHz}) = 27$ sfu ($1\ \mathrm{sfu} = 1 \times 10^{-22}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$). S_P(9 GHz) is well correlated with flare >25 keV peak hard X-ray intensity (e.g., Kane 1974) and is therefore a measure of the strength of the flare impulsive phase. The histogram of Cliver et al. (1983a) giving S_P(9 GHz) values for GLEs from 1956 to 1979 is updated to the present in Figure 2. GLEs associated with behind-the-limb flares, for which the microwave burst source might be partially occulted, are not included in the histogram. In the figure it can be seen that the $\sim$9 GHz bursts associated with the GLEs of 1979 August 21 and 1981 May 10 were anomalously small, <30 sfu in each

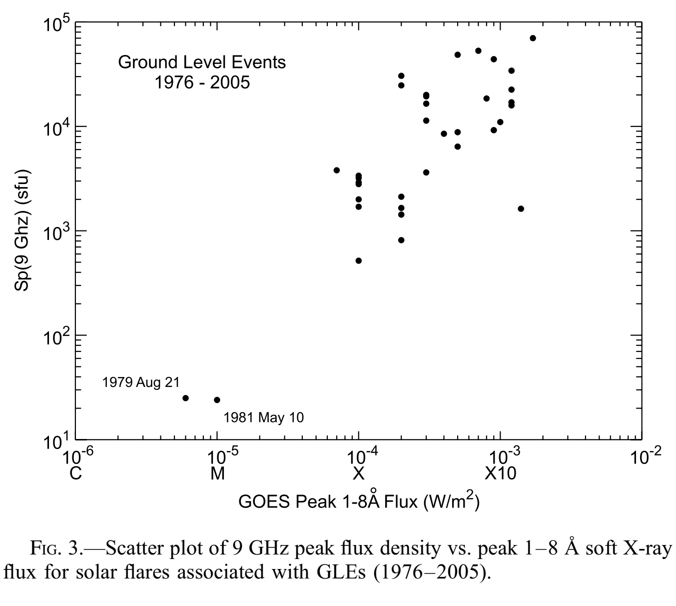

FIG. 3.—Scatter plot of 9 GHz peak flux density vs. peak 1–8 Å soft X-ray flux for solar flares associated with GLEs (1976–2005).

[1] See http://spidr.ngdc.noaa.gov/spidr.
[2] See http://sd-www.jhuapl.edu/IMP/imp_index.html.
[3] See http://aadc-maps.aad.gov.au/aadc/gle.
[4] See http://cosmicrays.oulu.fi.
[5] See http://lasco-www.nrl.navy.mil/solwind.html.
[6] See http://cdaw.gsfc.nasa.gov/CME_list.

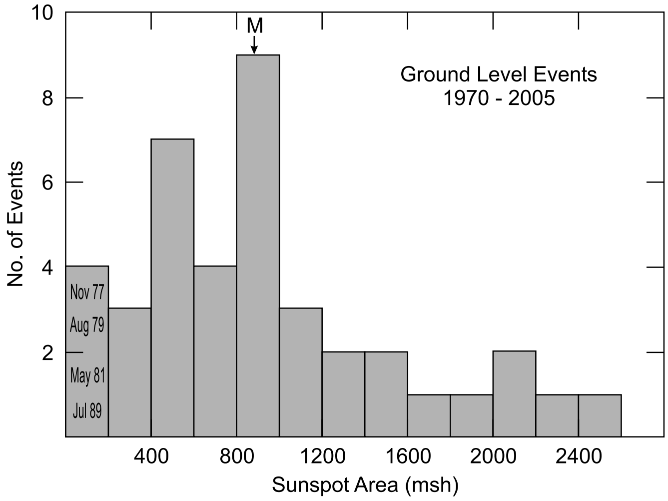

Fig. 4.—Sunspot areas of solar active regions associated with GLEs, 1970–2005. The median sunspot area is indicated by "M."

case. None of the other 50 GLEs in Figure 2 had S_P(9 GHz) values <500 sfu. For all events in the histogram, the median S_P(9 GHz) value is ~8000 sfu. The peak soft X-ray fluxes of the 1979 August (C6) and 1981 May (M1) GLE-associated flares are at least 1 order of magnitude smaller than those of all of the other disk flares listed in Table 1, except for the 2001 December 26 flare, which had an M7 classification. The anomalously weak peak soft X-ray and 9 GHz emissions of the flares associated with the 1979 August and 1981 May GLEs are highlighted in the scatter plot of these parameters for all GLEs from 1976 to 2005 (Fig. 3).

The histogram in Figure 4 gives the distribution of sunspot areas of GLE-associated active regions (1970–present), where the area was measured on the day of the GLE (or 1–2 days earlier for regions near the limb; see Dodson & Hedeman 1969). As can be seen in the figure, the active regions in which the GLEs of 1979 August 21 (McMath region 16218; sunspot area is 30 millionths of a solar hemisphere [msh]) and 1981 May 10 (McMath 17624; 160 msh) arose are on the low side of the distribution of all such regions. The median sunspot area of GLE source regions during this period was 850 msh, although the distribution is broad and continuous from <100 to >2500 msh.

We do not believe that the anomalous positions of the 1979 August and 1981 May events in Figures 2 and 3 (nor their locations at the low edge of the distributions in Figs. 1 and 4) are due to misassociations. In particular, we do not think that these GLEs originated in back-side eruptions for which the flare impulsive phase may have been occulted. Cliver et al. (1983a) considered back-side SEP observations as well as radio burst trajectories based on data obtained by the *International Sun-Earth Explorer 3* (*ISEE 3*) low-frequency radio experiment

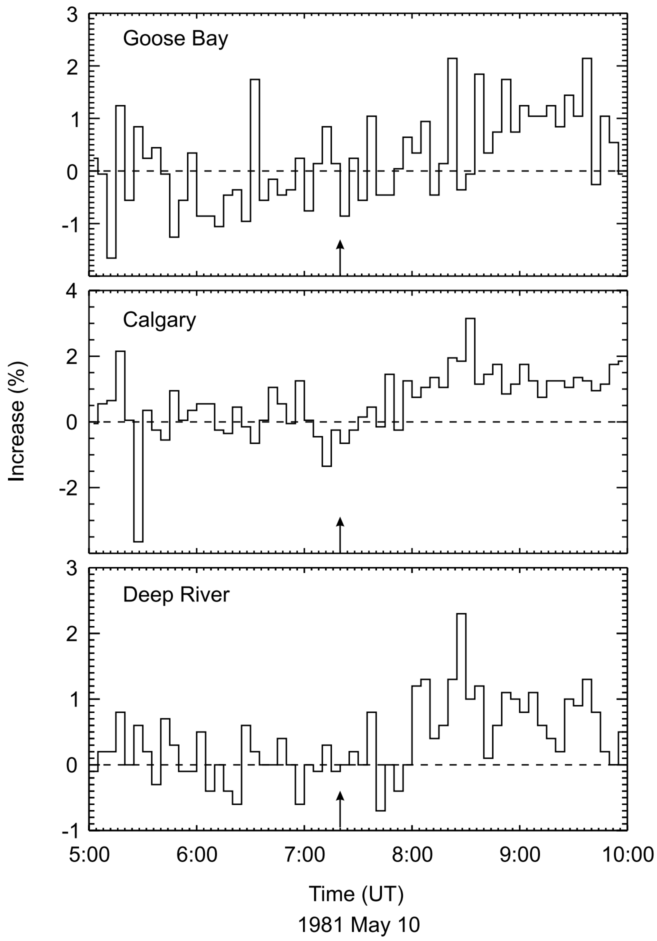

Fig. 5.—Neutron monitor observations of the 1981 May 10 GLE from three Canadian stations (Goose Bay, cutoff rigidity is 0.52 GeV, altitude is 46 m; Calgary, 1.1 GeV, 1128 m; and Deep River, 1.15 GeV, 145 m). Arrows in each panel indicate the timing of the GLE-associated flare.

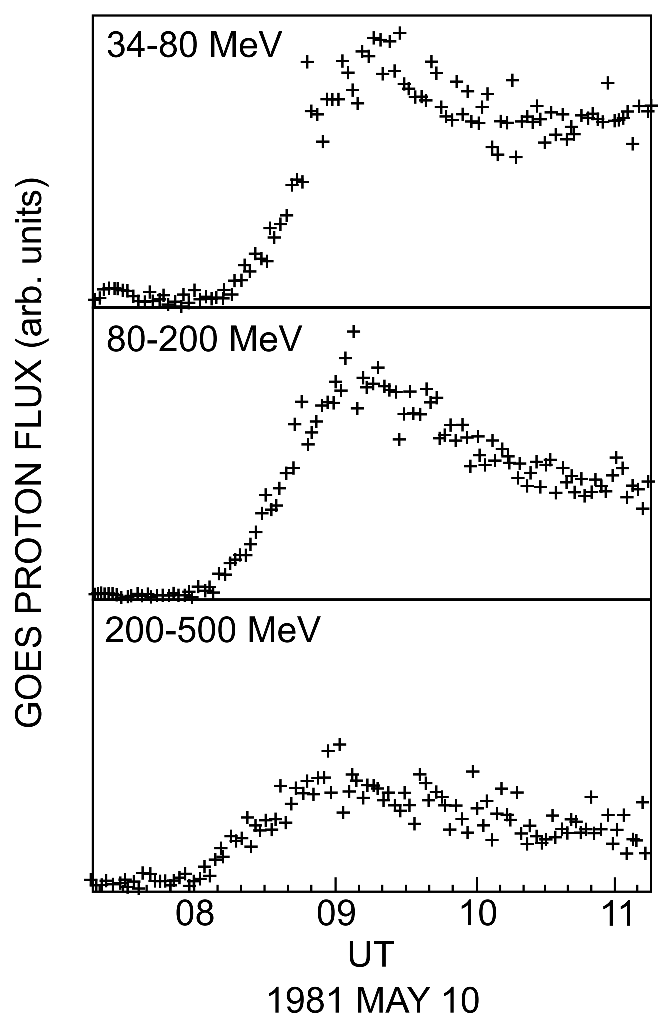

Fig. 6.—SEP time profiles observed by *GOES* for the 1981 May 10 event.

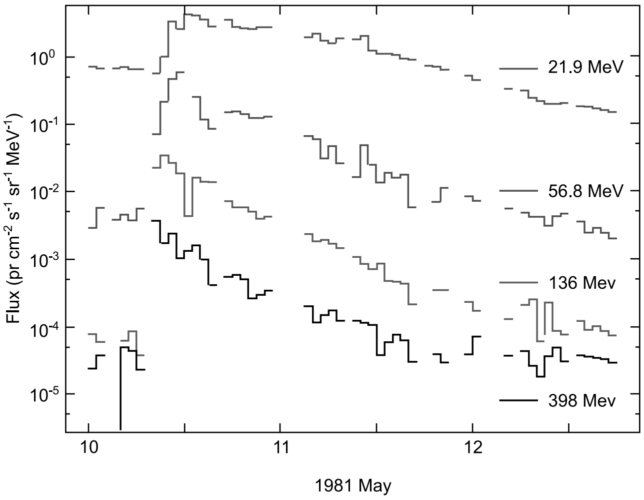

FIG. 7.—Time intensity traces of the 10 May 1981 SEP event observed at several energies by the NASA/GSFC instrument on *IMP 8*. [*See the electronic edition of the Journal for a color version of this figure.*]

(Knoll et al. 1978) to conclude that the GLE on 1979 August 21 was linked to the 2B flare at N17° W40°. In § 2.4 we present evidence supporting the association of the GLE on 1981 May 10 with the flare listed in Table 1.

2.4. *The Solar Source of the 1981 May 10 GLE*

Neutron monitor records of the 1981 May 10 GLE from three Canadian stations are shown in Figure 5. The event was a marginal GLE with a generally noisy profile and peak increases at the various stations of only a few percent. High time resolution *GOES* proton data in Figure 6 indicate event onset at ~0805 UT in the highest energy channel. Velocity dispersion can be seen in the peaks at the various energies in the *GOES* data and also in the NASA/GSFC *IMP 8* SEP time profiles (Fig. 7).[7]

A 1N flare beginning at 0715 UT with a maximum at ~0720 UT was observed at N03° W75°. In the series of Hα images from Kanzelhoehe Solar Observatory in Figure 8 (W. Otruba 2005, private communication), the flare appears to be located within the solar limb on the visible disk. The four stations reporting the event listed its center at W73°, W74°, W77°, and W84°, respectively. We note that several other events in Table 1 with flare locations closer to the limb, and even up to 10° beyond the limb, had 9 GHz peak intensities that were orders of magnitude larger than the value of 24 sfu (based on observations from Toyakawa [25 sfu] and Gorky [23 sfu]) for the 1981 May 10 GLE.

The most promising region to have produced a back-side western hemisphere flare on May 10 was Hale region 17609, which produced nine C-class and two M-class flares before rotating behind the limb on May 6–7 (Boulder Preliminary Report). This region produced no C-class flares after May 2 and by May 4 (W60°) had a simple CSO sunspot classification (bipolar, symmetric, open; 140 msh). (The region persisted through the back-side passage, however, and returned on May 21 as Hale 17663, which produced nine C-class flares and one M-class flare during its disk passage and had a peak sunspot area of 400 msh on May 28.) Had region 17609 or any other back-side region been the source of the GLE on May 10, the occurrence of the 1N/M1 flare at W75° would have been coincidental, perhaps triggered by a back-side event. For reasons given below, we do not believe this to be the case.

The Solwind CME data (Figs. 9 and 10) show a bright curved front CME off the west limb, roughly centered on the flare site,

[7] See http://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys.

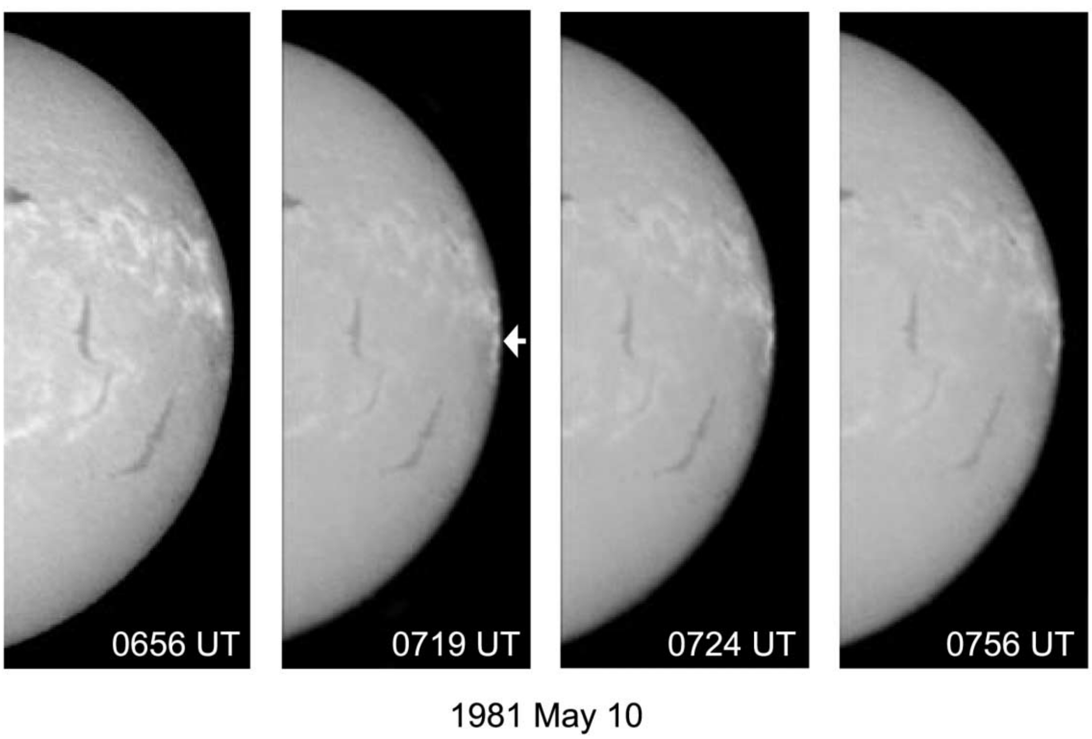

FIG. 8.—Hα filtergrams of the 1N flare (N03° W75°) associated with the GLE on 1981 May 10. A preflare image is given in the panel on the left. The arrow in the image in the second panel, taken near flare maximum, points to the flare. Solar north is at the top, and west is to the right. Filtergrams courtesy of Kanzelhoehe Solar Observatory.

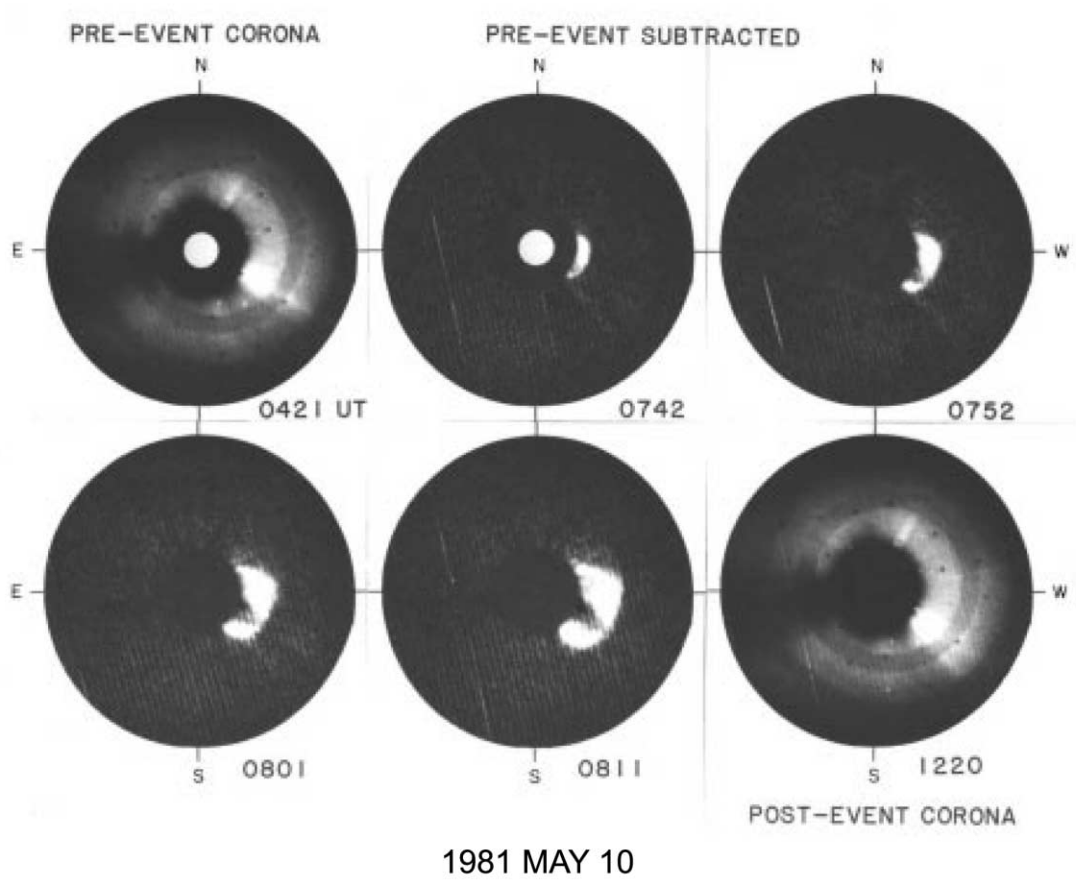

FIG. 9.—Solwind coronagraph observations of the CME associated with the 1981 May 10 GLE.

with a linearly extrapolated limb time of ∼0710 UT. The Hα flare onset and rise of the soft X-ray burst both occur at ∼0715 UT. These spatial and temporal agreements are consistent with the front side flare being the source of the CME and the SEP event. Additional evidence for the GLE origin in association with the listed W75° flare is provided by the *ISEE 3* low-frequency radio burst trajectory in Figure 11 from Cliver et al. (1989), which

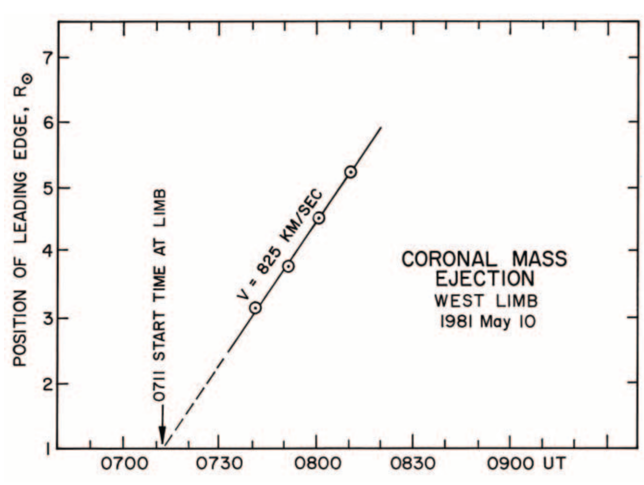

FIG. 10.—Height-time plot of the CME associated with the 1981 May 10 GLE.

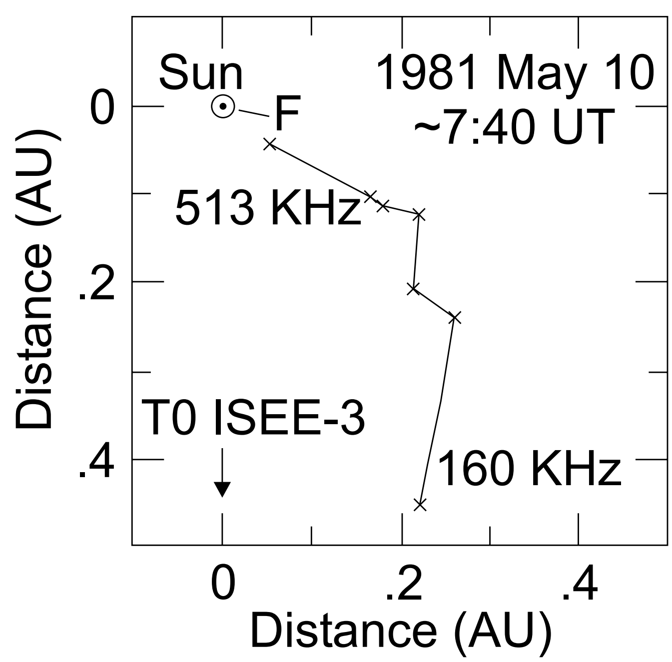

FIG. 11.—Trajectory, as viewed from above the ecliptic plane, of the *ISEE 3* low-frequency type III burst associated with the 1981 May 10 GLE (taken from Cliver et al. 1989). "F" marks the position of the flare.

indicates that the particles observed at Earth originated from near the western limb on the front side.

The *Helios* spacecraft was located off the east limb of the Sun on 1981 May 10, with a nominal magnetic connection at ~E65°. An increased flux of low-energy protons is observed at *Helios* at ~0800 UT, but this enhancement is isotropic, or even sunward directed, and lacks velocity dispersion (M.-B. Kallenrode 2005, private communication). The SEP increase at *Helios* follows a shock observed early on May 10; we do not believe that these SEPs are associated with the flare at W75°.

2.5. *Seed Particles in the 1979 August and 1981 May GLEs*

What enabled the relatively unimpressive solar eruptions associated with the GLEs of 1979 August 21 and 1981 May 10 to accelerate protons to GeV energies? Figure 12 shows that the 1979 event arose out of a ~10 MeV SEP background more than 4 orders of magnitude above its normal quiet-Sun level of $\sim10^{-3}$ protons $cm^{-2}\ s^{-1}\ sr^{-1}\ MeV^{-1}$. This enhanced pre-event SEP background is associated with intense X-class flares from the east limb of the Sun on August 18 (X6, E90°) and (possibly) 20 (X5, E77°) from McMath active region 16239 (sunspot area of 1230 msh on August 21). The Johns Hopkins University Applied Physics Laboratory (JHU/APL) *IMP 8* SEP record at the time of the 1981 May 10 GLE is shown in Figure 13, where it can be seen that the 10 MeV background preceding the GLE on the 10th was enhanced by a factor of $>10^3$ above its quiet-time level due to an eruption in McMath region 17638 at N09° E37° late on 1981 May 8. Thus, for both the 1979 August 21 and 1981 May 10 GLEs, the elevated pre-event background is attributed to an active region located ~100° east of the GLE source region at the time of the GLE. Like active region 16239 in 1979 August, McMath 17638 (620 msh on May 10) was a large complex region and a moderate flare producer. Together these two regions gave rise to 12 M-class or larger flares during their disk passages (five from 16239, seven from 17638). In comparison, the two active regions associated with the GLEs (McMath 16218 and 17624) produced a total of two M-class flares (including the M1 flare on May 10), both from 17624.

The enhanced pre-event ~10 MeV background levels at Earth (Figs. 12 and 13) observed for these two GLEs represent a relatively rare condition that may have facilitated the acceleration of high-energy SEPs. From 1977 to 1982, corresponding to the maximum of solar cycle 20, a 15–25 MeV enhancement of 10^3 or more above the background occurred ~5% of the time for which observations were available. Both the 1979 August 21 and 1981 May 10 solar eruptions had strong associated coronal shocks, as indicated by intense, long-lasting (August 21, ~30 minutes; May 10, ~25 minutes) metric type II bursts. The metric radio spectrogram for the August 21 event is given in Cliver et al. (1983a). The spectrogram for the May 10 event can be seen in Figure 14 along with the trace of the 1 MHz emission from the low-frequency experiment on *ISEE 3*. The prominent type II bursts and high SEP backgrounds in these two events prompt us to suggest that shock acceleration of an elevated energetic seed population was responsible for the two unusual GLEs that originated in modest solar events.

Under this scenario, at least part of the SEP population observed at 1 AU must extend back to the Sun, where it can be accelerated by the coronal/interplanetary shocks. We can use the onset time of the earliest arriving GLE particles to infer the SEP injection onset at the Sun and the height of the shock above the

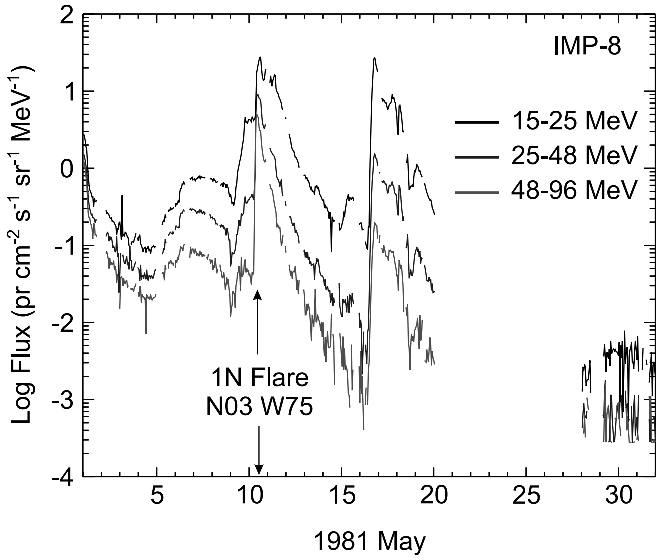

Fig. 13.—*IMP 8* (JHU/APL) observations of SEP activity during 1981 May. The timing of the GLE-associated flare on May 10 is shown by the arrow. [*See the electronic edition of the Journal for a color version of this figure.*]

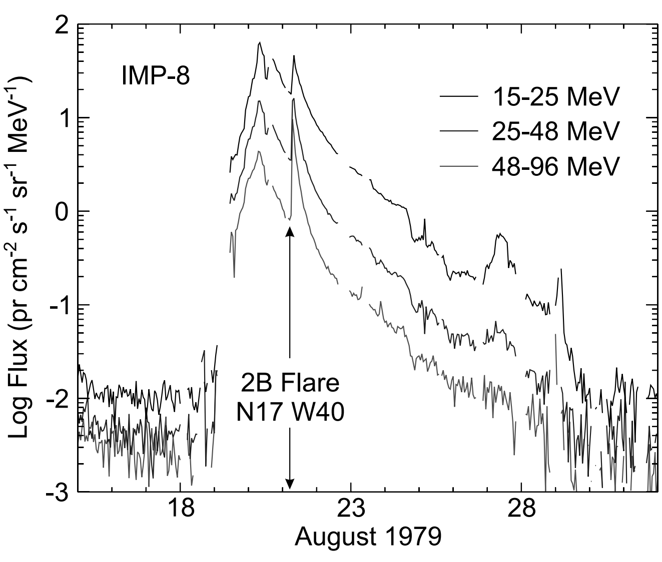

Fig. 12.—*IMP 8* (JHU/APL) observations of SEP activity during the second half of 1979 August. The timing of the GLE-associated flare on August 21 is shown by the arrow. [*See the electronic edition of the Journal for a color version of this figure.*]

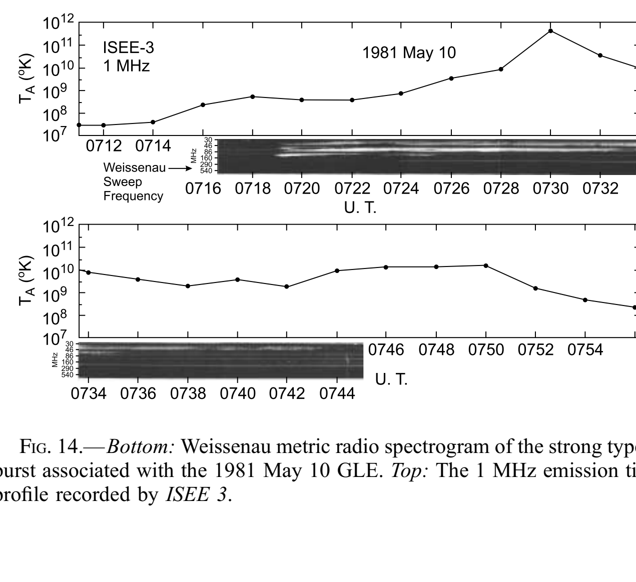

Fig. 14.—*Bottom:* Weissenau metric radio spectrogram of the strong type II burst associated with the 1981 May 10 GLE. *Top:* The 1 MHz emission time profile recorded by *ISEE 3*.

solar surface at this time. Cliver et al. (1983a) obtained a GLE onset time of 0633 ± 3 UT for the 1979 August event. For the 1981 May 10 event, the onset time in the *GOES* 200–500 MeV channel (Fig. 6) is ~0805 UT. This is a relatively long delay from the Hα (1–8 Å) maximum of ~0720 UT (0732 UT), but delays of this order have been observed for other small GLEs (Cliver et al. 1982). If we assume a nominal 11 minute propagation time for the first arriving GLE particles, we use the formulae in Leblanc et al. (2001) to obtain a radial (vs. projected) CME leading edge height at injection onset of ~2–3 $R_\odot$ for the 1979 August event (see Fig. 5 in Cliver et al. 1983a) and 4–5 $R_\odot$ for the 1981 May event (Fig. 9). From the GLE (or high-energy SEP) profiles for these events (see Shea & Smart 1984 for the 1979 August GLE), we deduce that the bulk of the relativistic protons were injected when the CME leading edge was located at ~3–4 $R_\odot$ for the 1979 August event and ~9 $R_\odot$ for the 1981 May event. These inferred heights for the peaks of the injection profiles are consistent with those of Kahler (1994), who found that the peaks of >500 MeV proton injection profiles occurred when CMEs reached heights of 5–15 $R_\odot$ or greater. In the above analysis, the height ranges for both the onset and peak of the injection profiles are based on the assumptions of zero scattering for the first arriving particles and radial CME propagation. Including scattering will reduce the inferred heights.

2.6. *Seed Particles and GLEs, 1973–2005*

We checked the level of ~10 MeV pre-event enhancement at 1 AU for each of the 15 GLEs occurring from 1973 November through 1989 August (Table 1).[8] For this interval the undisturbed background level of the 15–25 MeV channel on *IMP 8* was $\leq 2 \times 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}. For five GLEs (1976 April 30, 1977 November 22, 1978 September 23, 1984 February 16, and 1989 July 25), the pre-event level was ~10^{-3} protons. A check of ~1 MeV fluxes for these five events also revealed essentially quiet pre-event levels. Thus, an enhanced SEP background at 1 AU is not a necessary condition for a GLE.

While an elevated ~10 MeV level is not a necessary condition for a GLE, it is a relatively common circumstance for such high-energy SEP events. One-fourth (11) of the 43 GLEs from late 1973 to the present had 15–25 MeV pre-event levels at 1 AU of ~10^0 protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} or greater (a ~1000-fold enhancement above quiet-time levels), and another seven events had pre-event levels $\geq 10^{-1}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}.[9] For 15 of the 18 GLEs arising from elevated ($\geq 10^{-1}$) SEP backgrounds at 1 AU during this period the pre-GLE background was due to an eruption from the same region that produced the GLE. The only exception, in addition to the 1979 August and 1981 May events, was 1978 May 7.

Because GLEs, including the 1979 August and 1981 May events, are typically associated with strong shocks and because some GLEs arise from undisturbed ~10 MeV backgrounds at 1 AU, we checked to see whether strong shocks occurring when the ~10 MeV intensity at 1 AU was <1 proton cm^{-2} s^{-1} sr^{-1} MeV^{-1} were as likely to produce GLEs as those occurring when the background intensity was ≥1 proton. We considered the period from 1977 to 1982 at the peak of cycle 21. We defined strong shocks as type II bursts with a duration ≥24 minutes reported by any of the three standard metric sweep frequency patrols for this interval (Culgoora, Harvard, and Weissenau) and required a burst intensity level of "2" or "3" for some part of the burst duration. This definition admits the type II burst associated with the 1981 May GLE (burst duration is 24.9 minutes). From 1977 to 1982, 43 such bursts were associated with western hemisphere (W00°–W90°) flares. Three of the 11 GLEs during this interval (including the 1979 August and 1981 May events) occurred on an enhanced (≥10^0 protons) ~10 MeV background at 1 AU; one of these three GLEs (1981 October 12) originated on the eastern solar hemisphere. One GLE during this period (1977 September 24) arose in an eruption behind the west limb. Three of the nine W00°–W90° GLEs lacked ≥24 minute type II bursts. The comparison of long/intense type II bursts and GLEs is shown in the contingency matrix in Table 2, where it can be seen that strong shocks occurring on a ~10 MeV background of ≥1 proton at 1 AU are 5 times more likely (50% vs. 10%) to produce a GLE than comparable shocks on a lower background.

TABLE 2
Contingency Matrix Showing the Effect of a High SEP Background at 1 AU on GLE Occurrence for Long-Duration, Intense Metric Type II Bursts Associated with Western Hemisphere Flares

Long, Intense Type II	GLE Yes	GLE No
With high SEP background	2	2
Without high SEP background	4	35

The two events in Table 2 for which strong shocks on a high background did not result in a GLE occurred on 1978 May 7 (1N/M4 flare at W68°) and 1982 February 3 (2B/X1 at W30°). Factors that might contribute to the absence of GLEs in the null events include shock geometry (Tylka et al. 2005) or unfavorable shock propagation (away from the field lines connected to Earth). We note that while there is no evidence for a fresh SEP injection at any energy in either of these two events, the high pre-event backgrounds could have masked a relatively large ~10 MeV event (with peak intensity on the order of the NOAA Space Environment Center forecast threshold of 10 protons cm^{-2} s^{-1} sr^{-1}).

3. DISCUSSION

3.1. *Summary*

High-energy (~GeV) SEP events on 1979 August 21 and 1981 May 10 were associated with flares with weak impulsive phases [S_P(9 GHz) < 30 sfu] and relatively slow (~800 km s^{-1}) CMEs. In contrast, the median peak ~9 GHz flux density of GLE-associated flares is ~8000 sfu, and the median speed of GLE-associated CMEs is 1600 km s^{-1}. We hypothesize that the solar events in these two cases "overachieved" because of an elevated coronal seed population (associated with a >1000-fold enhancement of the quiet-time 10 MeV intensity at 1 AU) from an earlier SEP event that was further accelerated by a CME-driven shock associated with the weak impulsive phase flares under consideration. In both of these cases, the earlier SEP event originated ~100° east of the GLE-parent flare. In our proposed scenario, depicted in Figure 15, SEP and CME timing data indicate that the shocks would have had initial access to the elevated seed population within ~2–5 $R_\odot$.

[8] During the last months of 1989, the background level of the 15–25 MeV detector on *IMP 8* underwent a permanent increase to ~10^{-2} protons. *IMP 8* data were not available for the 2001–2005 GLEs in Table 1. For these years, *GOES* >10 MeV data are listed in col. (10) in Table 1.

[9] Assuming a SEP event power-law spectrum in energy $E^{-\gamma}$, where $\gamma = 3$ (e.g., van Hollebeke et al. 1975), a *GOES* >10 MeV intensity >4 protons cm^{-2} s^{-1} sr^{-1} corresponds to a 15–25 MeV intensity >10^{-1} protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}, and a *GOES* >10 MeV intensity of >40 protons cm^{-2} s^{-1} sr^{-1} corresponds to a 15–25 MeV intensity >10^0 protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}.

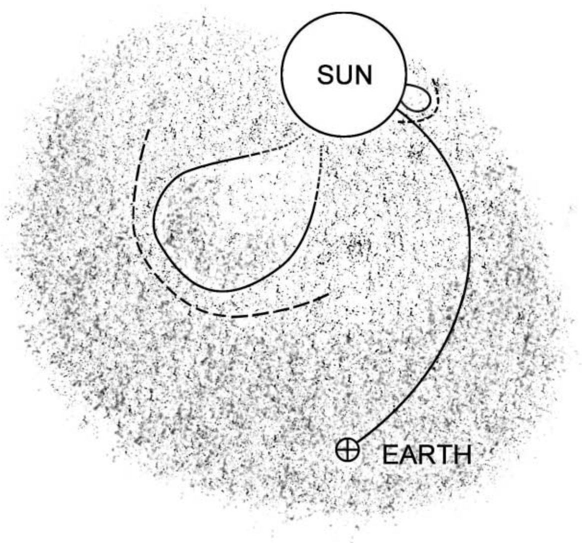

FIG. 15.—Schematic showing the relative positions of the CMEs responsible for the preceding SEP events in 1979 August and 1981 May (which were responsible for the high backgrounds) and the GLE-associated eruptions. The curved dashed lines indicate the CME-driven shocks. In this picture, shocks driven by the large eastern hemisphere eruptions, which occurred in each case about two days prior to GLEs, provided seed particles (indicated by the clumpy gray shading) for the favorably located CME-driven shocks linked to the GLEs. The Parker spiral field line connecting the Sun to Earth is drawn. The scale size for the eastern CME is given by the Sun-Earth distance, while the western hemisphere eruption (scaled by the solar radius) is shown at an early stage, when the CME and its shock are low in the atmosphere.

Kahler (2001) previously reported that elevated levels of ambient ~10 MeV protons at 1 AU were correlated with peak intensities of SEP events. While an enhanced ~10 MeV proton background at Earth appears to be a favorable condition for GLE occurrence, it is not a necessary condition. Five of 15 GLEs occurring from 1973 November through 1989 August arose from quiet SEP backgrounds (down to ~1 MeV) at 1 AU. Kahler (2001) also reported several cases of large SEP events arising out of a quiet ~10 MeV *GOES* background at 1 AU.

3.2. *Controversy: Flares and Shocks in Large SEP Events*

The 1979 August 21 event stands at the center of the current controversy involving the relative importance of flares and CME-driven shocks for the acceleration of high-energy SEPs at the Sun. Cane et al. (1981) featured this event in their discovery paper on shock-accelerated (SA) low-frequency type III bursts, so called because they are highly associated with metric type II bursts. Cane et al. argued that such low-frequency type III bursts provided evidence of acceleration of electrons by coronal shocks. An example of an SA type III burst can be seen in Figure 14 for the 1981 May 10 event. The most intense 1 MHz emission in this event ($T_A \geq 10^{10}$ K) occurred from ~0728 to 0734 UT and from ~0744 to 0750 UT. No metric (300–30 MHz) type III emission was reported for this flare.

Cliver et al. (1983a) presented 1979 August 21 as a notable example of a SEP event associated with a flare with a weak impulsive phase (Cliver et al. 1983b). For such SEP events, Cliver et al. (1983b) noted that while the associated flares lacked strong impulsive phases, they characteristically exhibited direct and/or indirect evidence for mass ejection and shock wave formation. They concluded that the shock and not the flare was essential for SEP acceleration.

Recently, Cane et al. (2002) have reinterpreted SA events (which they renamed type III-*l* bursts) in terms of acceleration of electrons via reconnection at the flare site in the aftermath of a CME. This picture is similar to that proposed by Švestka et al. (1980) for the prolonged low-energy "tails" of SEP events (now generally attributed to shocks) and that proposed by Cliver et al. (1986) to account for the electrons responsible for the metric type IV bursts (storm continuum) associated with large flares. In the revised scenario of Cane et al. (2002), the metric shocks and low-frequency type III bursts may overlap in time, but there is no causal relationship. In their picture, the high pre-event SEP backgrounds observed in the 1979 August 21 and 1981 May 10 GLEs would be incidental rather than essential (because the reconnection takes place within closed field regions on the Sun), as would the observed intense, long-lasting metric type II bursts and inferred coronal shocks. If the previously accelerated SEPs (energetic seed population) were to play a role in the type III-*l* scenario, they would have to penetrate the erupting CME to gain access to the reconnection region and then upon acceleration would have to escape through the overlying field. Kahler et al. (2000) have previously conducted an unsuccessful search for SEP events associated with the soft X-ray arcades (long-duration flares) that lacked coronal/interplanetary shocks and concluded that such events were not likely contributors to SEP events at Earth.

Cane et al. (2002) left unanswered the question of why slow CMEs (that do not drive coronal/interplanetary shocks) such as those considered by Kahler et al. (2000) do not give rise to type III-*l* bursts and stressed the high degree of association between the type III-*l* bursts and SEP events (MacDowall et al. 2003). Alternatively, Cliver et al. (2004) reported a strong association between SEP events and type II bursts, particularly when lower frequency events (in the decametric/hectometric range) were taken into account (see also Gopalswamy et al. 2002). These various associations between solar activity and SEP events are a manifestation of the "big flare syndrome" (Kahler 1982), which states in effect that "big flares have more of everything," making it problematic to draw definitive conclusions based on investigations of large events. Focusing on flares like 1979 August 21 and 1981 May 10 that lack some of the trappings of the classic big flares gives the opportunity for insight on the physical mechanism(s) for high-energy SEP acceleration. These events reiterate the general importance of CME-driven shocks for large high-energy particle events.

In this context, it is useful to consider the other basic category of SEP events, those that lack evidence for shocks and that exhibit the marked abundance anomalies (Reames et al. 1985; Mason et al. 1986; Reames 2000) that characterize SEP acceleration in flares. Recently, a list of large impulsive (i.e., flare or flare-dominated) SEP events observed during solar cycle 23 has been compiled by Reames & Ng (2004). Type II bursts were reported for ~25% of the listed events. The two largest proton events on the list that lacked associated type II emission had >10 MeV peak proton intensities of ~1 proton cm^{-2} s^{-1} sr^{-1}. The associated flares, occurring on 2002 August 19 and 20, had M2.0 and M3.4 soft X-ray classifications, respectively. In contrast, the 1979 August and 1981 May GLEs, which were associated with somewhat smaller soft X-ray flares, had peak >10 MeV intensities on the order of ~100 protons cm^{-2} s^{-1} sr^{-1}, consistent with the view that the high-energy SEPs in these events do not represent a direct flare component. The absence of large "pure flare" proton events poses a challenge to the direct flare hypothesis of Cane et al. (2003). Indeed, the shock scenario for large SEP events had its origins (e.g., Lin 1970) in the observation that large SEP events were characteristically associated with metric type II bursts. Additional difficulties with the direct flare hypothesis include the lack of SEP spectral hardening at high energies[10] and the observed delays of GLE injection profiles with respect to flare electromagnetic emissions (Tylka et al. 2005).

3.3. *Speculations on Other GLE Anomalies*

GLEs and high-energy gamma-ray events involve additional anomalies, besides that presented by the 1979 August and 1981 May events (Figs. 2 and 3), that either have been or could be described in terms of SEP acceleration by shocks rather than by a direct flare mechanism. These include (1) GLEs whose onset is delayed by hours from the associated flare, as observed for the 1959 July 15 and 1972 August 4 GLEs (Pomerantz & Duggal 1974); (2) GLEs associated with poorly connected flares, located $\sim 100°$ (1967 January 28) from the footpoint of the nominal magnetic spiral to Earth (Dodson & Hedeman 1969; see also Cliver et al. 2006); and (3) various aspects of solar gamma-ray flares including long-duration (hours) events (Kanbach et al. 1993; Ryan 2000), events with a delayed pion-rich component (Chupp et al. 1987; Dunphy & Chupp 1994), and events with spatially extended sources (Vestrand & Forrest 1993).

The long-duration gamma-ray flares (LDGRFs; Ryan 2000) are of particular interest. The hard-spectrum late-phase emission in these events runs counter to the intuitive notion that flare emissions become softer in time (Cliver 1996; Ryan 2000). The characteristic pion-dominated spectrum of the extended emission requires >300 MeV protons (with an effective threshold close to $\sim$500 MeV). Four of the five long-duration gamma-ray events from western hemisphere sources listed by Ryan (2000) were associated with GLEs in Table 1 (GLEs 42, 48, 51, and 52), suggesting an explanation in terms of particles precipitating from a coronal shock, as has been proposed for certain of the LDGRFs (1982 June 3, Ramaty et al. 1987; 1989 September 29 [GLE 42], Cliver et al. 1993). Alternatively, the time-extended emissions may arise from a combination of prolonged acceleration at the flare site and trapping (e.g., Ryan & Lee 1991; Hudson & Ryan 1995; Akimov et al. 1996).

For the LDGRFs and other gamma-ray anomalies, a shock-based explanation seems at least as plausible as the flare alternative, and for the delayed GLEs and poorly connected GLEs, the shock scenario is preferred. For example, observations of poorly connected GLEs are naturally explained in terms of acceleration at a widespread shock, and in one case (1971 September 1; Cliver 1982), there is prima facie evidence for shock acceleration of GeV protons in that the first arriving high-energy SEPs at 1 AU appear to be injected near the time that the shock front (manifested by a type II burst) sweeps past the solar footpoint of the nominal interplanetary magnetic field line connected to Earth.

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[10] Such a flattening is observed in high-energy electron events associated with intense impulsive flares (Moses et al. 1989). Such flares are characteristically associated with CMEs and type II shocks (Cliver 1996).

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