THE ASTROPHYSICAL JOURNAL, **260**:362–370, 1982 September 1

INJECTION ONSETS OF ~2 GeV PROTONS, ~1 MeV ELECTRONS, AND ~100 keV ELECTRONS IN SOLAR COSMIC RAY FLARES

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Received 1981 October 26; accepted 1982 March 17

ABSTRACT

We review the data for all 32 ground-level cosmic-ray events (GLEs) observed from 1942 through 1978 and infer injection onset times for the ~2 GeV protons, ~1 MeV electrons, and ~100 keV electrons. Contrary to previous investigations, we find no compelling evidence for a systematic delay in GLE onset times. The most likely time of GeV proton injection onset in these large flares appears to be near the maximum of the first significant microwave peak. We note that GLEs with long delays to onset tend to be small in size. In addition, the data indicate a systematic phase relationship among the injection onsets of the three particle species considered, with the low-energy electron onset times preceding those of the relativistic protons by $\lesssim 5$ min, and the relativistic electrons following the GeV protons by $\gtrsim 5$ min. This phase relationship holds even when the inferred injection times of all three species follow the flare flash phase by >20 min. To account for these observations, we suggest a picture in which the earliest observed particles are injected when an outward moving acceleration region at a shock front intersects the open field lines connecting to Earth.

Subject headings: cosmic rays: general — particle acceleration — Sun: flares

I. INTRODUCTION

A persistent problem of solar cosmic-ray research has been the lack of observations bearing on the timing and conditions in which protons that escape to the interplanetary medium are first accelerated in the corona. In contrast to the electrons, proton bremsstrahlung and gyrosynchrotron emission are negligible, and the observed γ-ray line emission, directly attributable to the presence of energetic ($E \gtrsim 10$ MeV) protons (Ramaty *et al.* 1980), may be unrelated to the solar protons observed in space (Chambon *et al.* 1981; von Rosenvinge, Ramaty, and Reames 1981; Pesses *et al.* 1981). To compound the difficulty, inferences about coronal acceleration processes drawn from observations of solar protons at 1 AU are generally compromised by the effects of proton scattering in the interplanetary medium. We can, however, hope to learn something about the onset of proton acceleration and/or injection into space from observations of the earliest arriving protons for which the scattering effects should be minimized. The short (~11 min) interplanetary travel times of the first relativistic (>500 MeV) solar protons observed in ground-level events (GLEs) make GLEs a unique data source from which to infer the timings of proton injection onsets in large solar flares.

Earlier attempts to infer the initiation of proton injection from solar flares using GLE onsets were made by Carmichael (1962) and Kodama *et al.* (1977). Carmichael (1962) first called attention to what he termed the "transit time anomaly" for solar cosmic-ray events. The transit time anomaly, ΔT_A, is defined as follows:

$$\Delta T_A = \Delta T_{\text{onset}} - 11 \text{ min} ,$$

where ΔT_{onset} is the deduced Sun-Earth transit time for the first arriving relativistic protons and 11 min is the nominal transit time for a ~2 GeV proton traversing a 1.3 AU Archimedes spiral path. By making the assumption that protons are accelerated to GeV energies at the start of the flare-associated microwave burst, Carmichael found ΔT_A values of 7–19 min for a small sample of well-connected (W20–W90) cosmic-ray flares. Using the same assumption, Kodama *et al.* (1977) reported a *systematic* minimum $\Delta T_A \approx 9$ min for all GLEs observed through 1973, independent of the longitude of the parent flare.

Because of their high velocities, energetic electrons also have short interplanetary travel times. Although the injection onsets of both the nonrelativistic (Lin 1974) and relativistic (Simnett 1974) electrons have been discussed at length in the literature, the injections of these species relative to energetic protons have been discussed for only a very few events (Lin and Anderson 1967; Lin 1970; Simnett 1971; Bieber *et al.* 1980).

In an effort to learn something about the onset of particle injection and/or acceleration in large solar flares, we review the relativistic proton onsets for the 32 GLEs observed between 1942 and 1978, and, for the GLEs since 1966, we also examine the observed onsets of the

TABLE 1

GLE Cosmic Ray and Associated Flare Data

Event	Date	Solar Coordinates[a]	T_1 (Hα onset)[a]	T_2 (radio main onset)[b]	T_3 (first μ wave peak)	T_4 (type II onset)[a]	T_5 (9 GHz burst max)[a]	T_6 (Hα max)[a]	GLE Onset[c]	GLE Rise Times (min)[d]	% Increase[e]
1	1942 Feb 28	N07 E04	N.O.[f]	1200[g]	1205 ± 5[h]	N.O.	N.O.	N.O.	1200(−18, +0)[i]	43(−18, +0)	600
2	1942 Mar 7	N07 W90	N.O.	0442[g]	0450 ± 2[h]	N.O.	N.O.	N.O.	0500(−18, +0)[i]	37(−18, +0)	750
3	1946 Jul 25	N22 E15	1615	1624[j]	1627[h]	N.O.	N.O.	1640	1645 ± 15[i, k]	128 ± 15	1100
4	1949 Nov 19	S02 W70	1029	1029[g]	1032[h]	N.O.	N.O.	1033	1044 ± 1[l]	16 ± 1	2000
5	1956 Feb 23	N23 W80	0331	0332	0336	N.O.	0336[m]	0342	0343 ± 1	8 ± 8	4554
6	1956 Aug 31	N15 E15	1226	1236	1240	N.O.	1240[m]	1243	1250 ± 15	7 ± 7	3
7	1959 Jul 16	N16 W31	2114	2118	2122	N.R.	2154[m]	2132	(17)0100 ± 60[n]	960 ± 170[n]	10
8	1960 May 4	N13 W90	1000	1015	1017	N.O.	1033	1016	1030 ± 1	7 ± 2	290
9	1960 Sep 3	N18 E88	0037	0103	0105	N.R.	0108	0108	0200 ± 60	490 ± 67	4
10	1960 Nov 12	N27 W04	1315	1326	1327	N.O.	1332	1330	1335 ± 5	157 ± 8[o]	135
11	1960 Nov 15	N25 W35	0207	0219	0222	0221	0228	0221	0230 ± 5	29 ± 4	88
12	1960 Nov 20	N25 W113	2017	2023	2027	2028	2027[m]	2020	2058 ± 3	120 ± 67	8
13	1961 Jul 18	S07 W59	0920	0944	0947[p]	N.O.	0958[m]	1005	1015 ± 5	59 ± 11	24
14	1961 Jul 20	S06 W90	1553	1552	1553	1554	1554	N.R.	1615 ± 10	15 ± 14	7
15	1966 Jul 7	N35 W48	0025	0026	0028	0038	0037	0040	0055 ± 5	14 ± 14	3
16	1967 Jan 28	N22 W154[q]	N.R.[f]	N.R.	N.R.	N.R.	N.R.	N.R.	0302 ± 3	...	?
17	1967 Jan 28	N22 W154[q]	[q]	[q]	[q]	0754	[q]	[q]	0810 ± 10	145 ± 16	21
18	1968 Sep 29	N17 W51	1618	1617	1620	1619	1620	1623	1710 ± 20	50 ± 36	1
19	1968 Nov 18	N21 W87	1017	1027	1027	1026[r]	1027	1035	1038 ± 3	10 ± 7	14
20	1969 Feb 25	N13 W37	0900	0910	0912	N.R.	0912	0913	0915 ± 5	25 ± 11	16
21	1969 Mar 30	N19 W106	limb activity	0247	0248	0250	0249	loops/surges?	0400 ± 60	705 ± 75	9
22	1971 Jan 24	N19 W49	2309	2315	2313/2322[s]	2316/2325[s]	2322	2316/2330[s]	2328 ± 3	15 ± 4	26
23	1971 Sep 1	S11 W120	limb activity	1934	1936	1934	1941	active prominence	2000 ± 5	165 ± 11	16
24	1972 Aug 4	N14 E08	0621	0621	0625	N.R.	0632	0635	1330 ± 30[n]	160 ± 4[n]	15
25	1972 Aug 7	N14 W37	1505	1515	1516	1519	1522	1520/1528[t]	1528 ± 3	15 ± 4	8
26	1973 Apr 29	N13 W73	2056E	2056	2100	2101	2103	2100/2108[t]	2143 ± 3	15 ± 11	3
27	1976 Apr 30	S08 W46	2048	2103	2104	2106	2109	2103	2123 ± 3	15 ± 4	4
28	1977 Sep 19	N08 W57	0955E	1030	1032	1035	1036	1042	1100 ± 15[u]	15 ± 4	2
29	1977 Sep 24	N10 W120	N.R.	0554	0555	0555	0555	N.R.	0608 ± 3	10 ± 4	6
30	1977 Nov 22	N24 W40	0945	0959	1001	N.R.?	1003	1007	1013 ± 3	25 ± 4	25
31	1978 May 7	N23 W72	0327	0323	0324	0327	0330	0336U	0336 ± 1	5 ± 4	80
32	1978 Sep 23	N35 W50	0944	0957	1002	0958	1002	1010	1028 ± 3	30 ± 4	8

[a] Data sources: *Solar Geophysical Data*, *Quarterly Bulletin of Solar Activity*, *Catalog of Solar Particle Events* (CSPE).

[b] Numbers 5–26 (Kodama *et al.* 1977).

[c] Numbers 5–21 (CSPE).

[d] Numbers 1–4 (D'Arcy 1960).

[e] Numbers 1–4, 24–32 (Duggal 1979); numbers 5–21 (CSPE).

[f] N.O. = no observations; N.R. = not reported.

[g] Hα flash phase onset (Ellison, McKenna, and Reid 1961).

[h] Hα flash phase maximum (Ellison, McKenna, and Reid 1961).

[i] Forbush 1946.

[j] Lovell and Banwell 1946.

[k] Neher and Roesch 1948.

[l] Forbush, Stinchcomb, and Schein 1950.

[m] 10 cm maximum (Kodama *et al.* 1977).

[n] Interplanetary acceleration event (Pomerantz and Duggal 1974).

[o] Based on time of first maximum, a later maximum occurred in association with a sudden commencement (Carmichael 1962).

[p] Švestka 1970.

[q] Dodson and Hedeman 1969.

[r] Decimetric band.

[s] Second time used (Palmer, Smerd, and Riddle 1972).

[t] Second time used.

[u] Preliminary value.

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nonrelativistic and relativistic electrons. In § II we compare the GLE onsets with the timings of the flare electromagnetic emissions to deduce the most probable coronal injection/acceleration onset time. In § III we review the nonrelativistic and relativistic electron onset data for the GLEs of the 20th and 21st solar cycles, and in § IV we summarize the salient observational facts pertaining to particle injection onsets and suggest a simple model to account for these observations.

II. RELATIVISTIC PROTONS

In Table 1 we present data for the 32 GLEs observed from 1942 through 1978. For each event, we list six candidate times (T_i) for the proton injection onset: T_1, Hα onset; T_2, radio main onset; T_3, first significant $\gtrsim 9$ GHz peak; T_4, earliest reported metric Type II onset; T_5, $\gtrsim 9$ GHz maximum; and T_6, Hα maximum. For each available time parameter we determined $\Delta T_{\rm onset}$ (and hence ΔT_A) by the relationship:

$$\Delta T_{\rm onset} = {\rm GLE}_{\rm onset} - (T_i - 8\ {\rm min})\ ,$$

where ${\rm GLE}_{\rm onset}$ is the earliest reported onset time of the GLE and ($T_i - 8$ min) is the time of the particular flare phase under consideration adjusted for the Sun-Earth propagation time of electromagnetic waves. The "radio main onset" time, T_2, used by Kodama *et al.* (1977) and Carmichael (1962) in their determination of ΔT_A, is defined as the onset of the initial dramatic increase in the microwave flux-density profile during the flare. The "first significant peak" time, T_3, refers to the initial ~500 solar flux unit (1 sfu = 10^{-22} W m^{-2} Hz^{-1}) peak or plateau in the microwave temporal flux-density profile, with preference given to the higher ($\gtrsim 9$ GHz) frequencies. For the events in Table 1, T_3 followed T_2 by 2.8 ± 1.8 min. In general, it was necessary to inspect original records (or published copies) to determine T_2 and T_3. In Figure 1, the flare phases, T_i (i = 1–6), are indicated on the microwave burst profile for the flare associated with the GLE of 1972 August 7.

The GLE onset times, which form the crux of this study, were obtained by careful inspection of the neutron monitor records from the world-wide observing network. While it was necessary for our purposes to obtain the earliest observed onset times, we attempted to confirm all onset times reported in Table 1 and, if we were unable to do so, selected a later time for which there was agreement. For this reason, the onset times of some events in Table 1 are slightly later than those reported in Shea and Smart (1973) or in Švestka and Simon (1975). For two of the events, 1956 February 23 and 1971 January 24, the onset time was moved earlier by 2 min upon reexamination of original and published data. Although the neutron monitor reports for several recent events are not complete, we have data from favorably located neutron monitor stations for each of these events and are confident that our listed onset times will not vary significantly from the final accepted values.

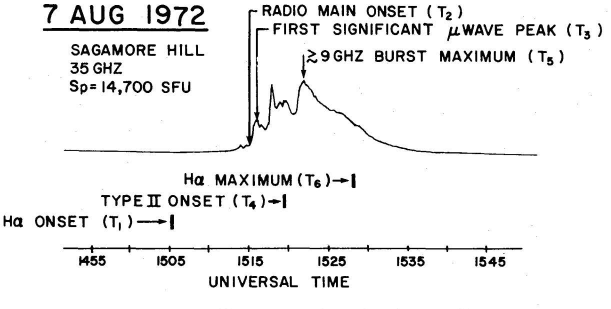

FIG. 1.—Sagamore Hill 35 GHz flux-density profile for the GLE-associated flare of 1972 August 7. The flare phases T_i (i = 1–6) that were considered as possible candidates for proton acceleration/injection onset are indicated.

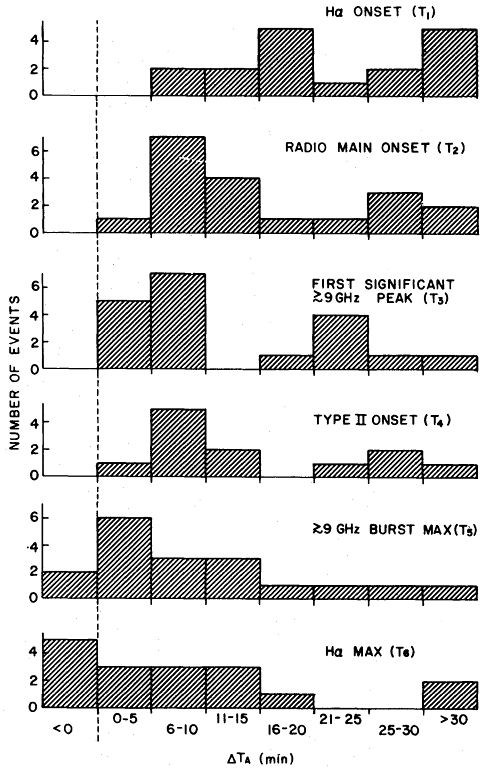

FIG. 2.—Histograms of ΔT_A, the transit-time anomaly, for each of the six flare phases considered as candidates for the injection onset of GeV protons (Table 1). Only those GLE events with uncertainties in $\Delta T_A \leq 5$ min were used.

Figure 2 contains histograms of ΔT_A for the six flare-timing parameters under consideration. Only those events having ΔT_A values with uncertainties ≤ 5 min were included in this figure. The ΔT_A distribution is seen to approach zero without becoming negative if one assumes that the earliest arriving GeV protons are injected at the time of the first significant peak in the microwave flux-density profile (T_3). Injection slightly later, near the onset of the Type II burst (T_4), cannot be ruled out when one considers the smaller sample size for T_4 and the average delay of only 1.4 ± 3.0 min between T_3 and T_4 for Table 1 events. As Figure 2 shows, making the assumption that GeV protons are first injected later in the flare event, near the $\gtrsim 9$ GHz maximum (T_5) or the Hα maximum (T_6) times, results in unrealistic negative values of ΔT_A for two and five events, respectively, demonstrating that, contrary to earlier claims (Mathews and Lanzerotti 1973), the injection of GLE protons prior to Hα maximum is not a rare occurrence. The assumption that GeV particles are initially produced earlier in the flare, near the Hα (T_1) or radio main (T_2) onset times, gives the appearance of a systematic minimum delay as reported by Kodama *et al.* (1977).

If we extrapolate from Figure 2 and make the assumption that protons in GLE-associated flares are *typically* accelerated to GeV energies near the time of the first microwave peak, then we are left with significant values of ΔT_A in many events. As Figure 3 shows, the observed delays do not exhibit a strong longitudinal dependence. For relativistic solar protons, there appears to be no preferred longitude range in the western hemisphere, consistent with the broad "fast propagation region" found by Reinhard and Wibberenz (1974) and Ma Sung, van Hollebeke, and McDonald (1975) for lower energy particles. It would appear that GeV protons can be injected onto field lines connecting to Earth from anywhere in the western hemisphere within ~10 min of the flare flash phase. However, we note that several events within ~10° of the nominal W55 solar footpoint of the Sun-Earth Archimedean spiral have ΔT_A values >20 min (see Ma Sung, van Hollebeke, and McDonald 1975).

We also find that GLEs (originating in favorably located flares) with large values of ΔT_A tend to be small events (Fig. 4). Since the observed rise times of GLEs (Table 1) do not vary greatly, a similar relationship can be shown to exist between the GLE linear rise rate (% increase min^{-1}) and ΔT_A. This implies that the plot of Figure 4 could be interpreted in terms of an observational threshold effect, with the smaller events requiring a longer time to be detected above the background galactic cosmic-ray counting rate. However, for reasons discussed in § IV, we no longer favor this explanation, which we suggested earlier (Cliver *et al.* 1981), as the principal cause of the GLE size versus ΔT_A relationship.

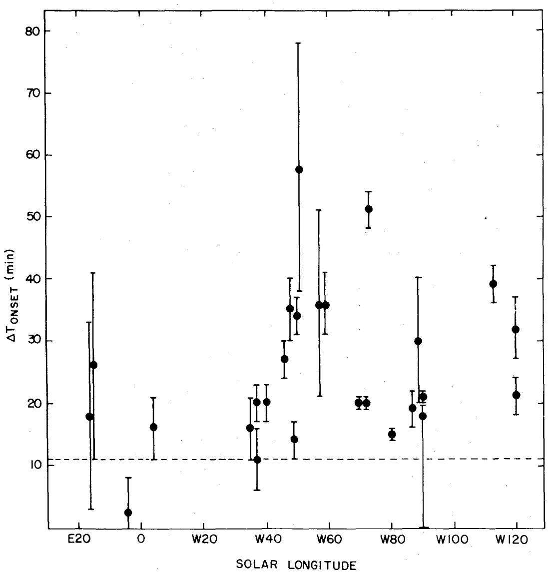

FIG. 3.—Delay to onset of GLE events as a function of solar longitude. Distance of each point above dashed line drawn at 11 min (nominal Sun-Earth transit time for a 2 GeV proton traversing a 1.3 AU spiral path) represents the transit time anomaly, ΔT_A, for that event. Injection onset time was assumed to be T_3, the first significant microwave peak. Only events with uncertainties in $\Delta T_{\mathrm{onsets}} \leq 20$ min were included.

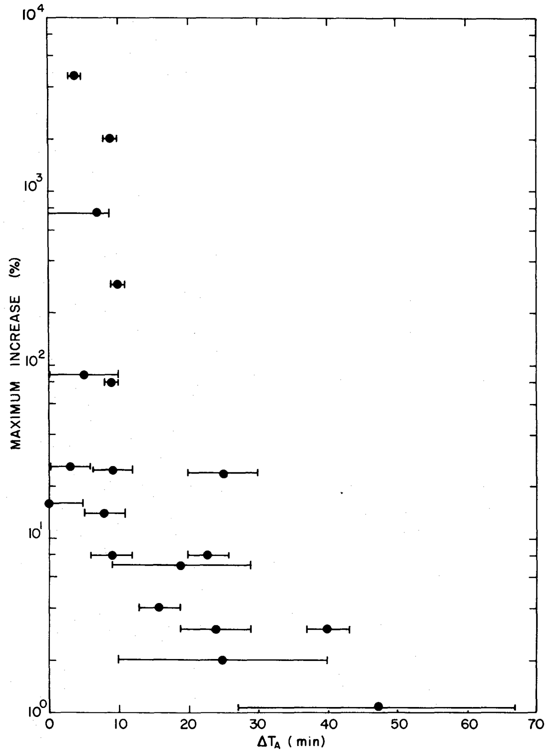

FIG. 4.—GLE size as a function of ΔT_A ($T_i = T_3$), the transit-time anomaly. Only well-connected (W20–W90) events were considered.

III. ELECTRONS

The electron onset times for GLEs with well determined onsets and from favorably located (W20–W90) flares are listed in Table 2. High time resolution measurements of solar electrons were not available for the GLEs prior to the 20th solar cycle. The nonrelativistic electrons are the >40 keV electrons reported on by Lin and his co-workers (Lin 1970; Lin 1974). The response of their detector is such that if one assumes that the incident flux of electrons has a power-law spectrum with a slope of ~ −3, the first electrons detected should have energy ~100 keV (van Hollebeke, Wang, and McDonald 1972) and interplanetary propagation times ≈20 min, assuming a nominal 1.3 AU Archimedes spiral path. Most of the relativistic electron onsets were measured by the GSFC experiment (van Hollebeke, Wang, and McDonald 1974) aboard *IMP* satellites IV and V (effective energy ≈0.7 MeV, transit time ≈ 12 min) or the Cal Tech experiment (Mewaldt

TABLE 2

ONSET AND INJECTION TIMES FOR GLE PARTICLES

		ONSET TIMES			INFERRED INJECTION TIMES		
EVENT	DATE	~100 keV[a] Electrons	~2 GeV Protons	~1 MeV[b] Electrons	~100 keV[c] Electrons	~2 GeV[d] Protons	~1 MeV[e] Electrons
1	1966 Jul 7	0105 ± 5	0055 ± 5	0105 ± 6	0045 ± 5	0044 ± 5	0054 ± 6
2	1968 Nov 18	1042[f]	1038 ± 3	1030 ± 30	1022	1027 ± 3	...
3	1969 Feb 25	0915 ± 45	0915 ± 5	0926 ± 6	...[g]	0904 ± 5	0915 ± 6
4	1971 Jan 24	2333 ± 2	2328 ± 3	2340 ± 5	2313 ± 2	2317 ± 3	2328 ± 5
5	1972 Aug 7	~1600[h]	1528 ± 3	1540 ± 5	...	1517 ± 3	1528 ± 5
6	1973 Apr 29	2150 ± 3	2143 ± 3	2146 ± 7	2130 ± 3	2132 ± 3	2135 ± 7
7	1976 Apr 30	N/A	2123 ± 3	2119 ± 1	N/A	2112 ± 3	2108 ± 1
8	1977 Nov 22	1022 ± 2	1013 ± 3	1020 ± 2	1002 ± 2	1002 ± 3	1009 ± 2
9	1978 May 7	0340 ± 2	0336 ± 1	0341 ± 1	0320 ± 2	0325 ± 1	0330 ± 1
10	1978 Sep 23	1032 ± 2	1028 ± 3	1032 ± 1	1012 ± 2	1017 ± 3	1021 ± 1

[a] Data sources: event 1, Lin and Anderson 1967; events 2 and 3, Axisa 1972 (private communication); event 4, van Hollebeke, Wang, and McDonald 1974; events 5, 6, 8–10, Lin 1981 (private communication).

[b] Data sources: event 1, >3 MeV, Cline and McDonald 1968; event 2, >1 MeV, Lanzerotti 1970; event 3, >7.5 MeV, Dilworth *et al.* 1972; events 4 and 5, >0.5 MeV, van Hollebeke, Ma Sung, and McDonald 1975; events 6–10, >1 MeV, onsets determined from data supplied by J. W. Bieber.

[c] Onset time minus 20 min.

[d] Onset time minus 11 min.

[e] Events 1, 3, 6–10, onset time minus 11 min; events 4, 5, onset time minus 12 min.

[f] No uncertainty listed for this measurement. An uncertainty of 1 min was used in Fig. 5.

[g] Injection times not calculated for events with large uncertainties.

[h] Onset masked by upstream particles, Lin 1981 (private communication).

et al. 1976) aboard *IMP* satellites VII and VIII (energy ≥ 1 MeV, transit time ≈ 11 min). Our procedure for obtaining the electron onset times for those events for which we had data was to identify the time of the first indication of a rise above the background level.

While we do not have electron data for enough GLEs to construct meaningful ΔT_A histograms as we did for the GeV protons, it is possible to investigate the injection onset times of the three species under consideration relative to each other (Fig. 5). Several features are apparent in this diagram. First, the inferred injections of the low energy electrons characteristically precede those of the GeV protons by times $\lesssim 5$ min. Lin (1974) has reported that this effect is consistently observed in "mixed" events in which energetic protons and nonrelativistic and relativistic electrons are all observed (see Sullivan 1970). Second, we note that the inferred injections of the ~1 MeV electrons characteristically seem to follow those of the GeV protons by $\gtrsim 5$ min. This was not anticipated since the relativistic electrons and energetic protons observed at Earth are assumed to be accelerated together in a second stage (i.e., shock-related) process (Ramaty *et al.* 1980). Perhaps the most surprising and interesting result from Figure 5, however, is that the phase relationship and time differences of the onsets of the three species are maintained *independently of* ΔT_A. In Figure 6 we have plotted ΔT_s versus ΔT_A for Table 2 events, where ΔT_s is the maximum separation between the inferred injection times of any two of the three species considered. ΔT_s is a lower limit when observations for only two of the species were available. From Figure 6, ΔT_s is seen to be independent of ΔT_A, with a typical value ~10 min. For the extreme case of the 1973 April 29 event, the ~100 keV and ~1 MeV electrons and the >500 MeV protons appear to have been injected within ~5 min of each other, ~40 min after the flare flash phase as identified by an impulsive ~10,000 sfu burst at 35,000 MHz and a large group of Type III bursts (*Solar-Geophysical Data*).

IV. DISCUSSION

Any model of particle acceleration/injection in solar cosmic-ray events must account for the following observational facts regarding injection onset:

1. GeV protons are present and can be injected onto interplanetary magnetic field lines relatively early in the flare process, specifically near the first significant microwave maximum.
2. For certain events, the first arriving GeV protons are able to reach the open field lines connecting to Earth from anywhere in the solar western hemisphere within ~10 min of the flare flash phase.
3. Some apparently well-connected events may experience delays of >20 min.
4. GLEs (originating in favorably located flares) with significant ΔT_A values tend to be small events.
5. The inferred injection onset times of the ~100 keV electrons systematically precede those of the GeV protons by $\lesssim 5$ min, and those of the ~1 MeV electrons by ~10 min, independently of ΔT_A.

The traditional approach to proton acceleration and injection in flares is to treat them as separate processes. Thus, for example, in the "birdcage" model of Newkirk and Wentzel (1978), the particles are accelerated at the flare site and then propagate along adjacent closed loops until they reach open field lines and escape. In contrast

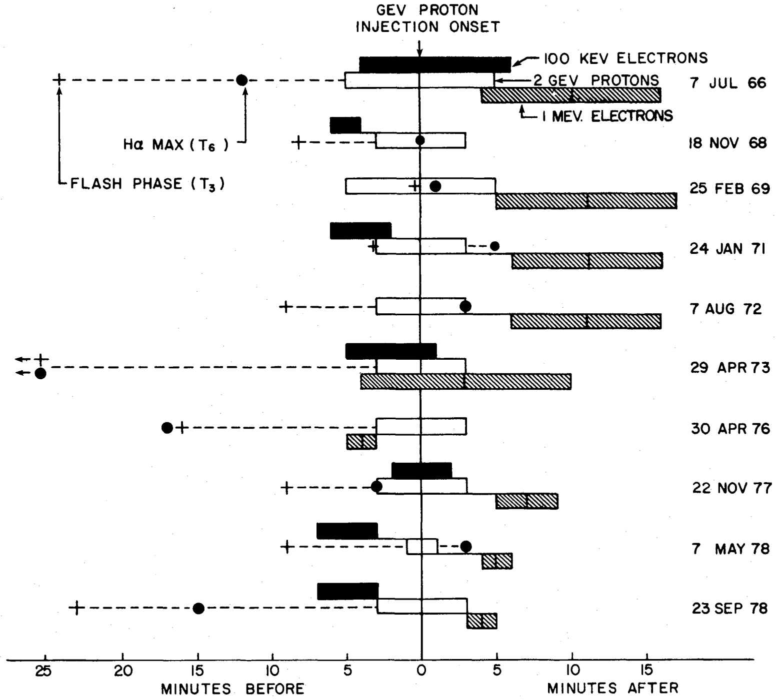

FIG. 5.—Inferred injection onsets of the nonrelativistic and relativistic electrons in GLE events relative to the inferred injection onsets of GeV protons (Table 2). Only well-connected (W20–W90) GLE events with small onset time uncertainties (≤ 5 min) were considered.

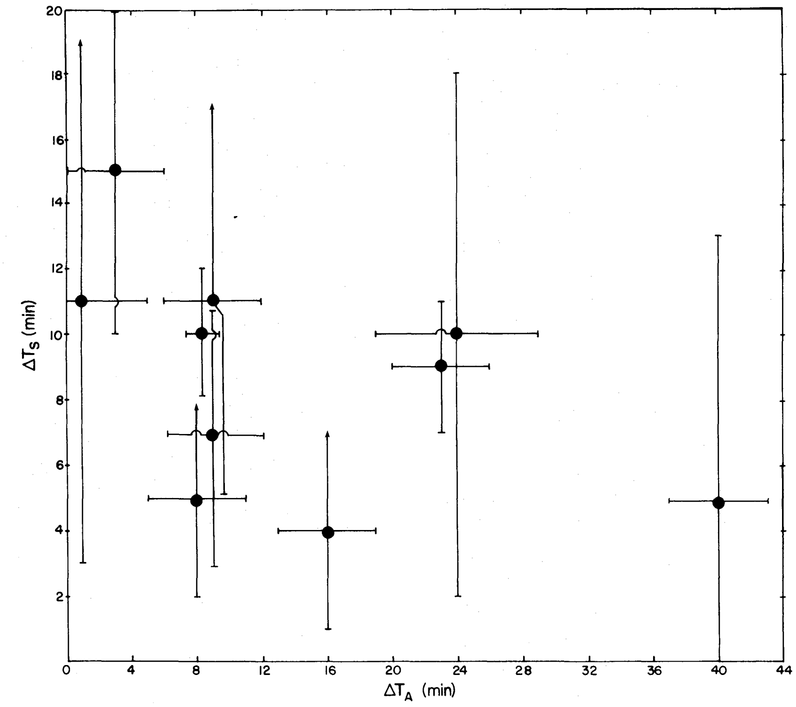

FIG. 6.—Maximum separation between the inferred injection onsets of the ~2 GeV protons, ~1 MeV electrons, and ~100 keV electrons as a function of ΔT_A for recent well-connected (W20–W90) GLE events. A lower limit is indicated when data for only two of the three species were available.

to this view, we favor a picture in which the particles observed at Earth are accelerated over a wide area for an extended time by means of an outward propagating shock wave and injection closely follows acceleration (Kahler, Hildner, and van Hollebeke 1978; Hudson, Lin, and Stewart 1982; Cliver 1982). The essentials of this picture are as follows. Acceleration begins immediately as the shock begins to propagate outward from the flare site. While we propose no specific mechanism for particle acceleration at the shock front, several theories as to how this might occur have been advanced recently in the literature (Gubchenko and Zaitsev 1978; Lee and Fisk 1981; Decker, Pesses, and Armstrong 1981). Basically each of these proposals involves the gradual acceleration of particles to higher energies, either by means of $\boldsymbol{V} \times \boldsymbol{B}$ acceleration at the shock front (e.g., Pesses 1979) or a Fermi acceleration between upstream (from the shock) and downstream magnetic scattering centers (e.g., Lee and Fisk 1981). As the shock wave propagates outward, an increasing fraction of the accelerated particles should be injected into the interplanetary medium because of the more ready access to open field lines. Injection of particles that are detected at Earth will begin when the acceleration region of the shock front intersects the open field lines that connect to Earth. For those cases in which the acceleration region does not intersect the interplanetary magnetic field lines connecting the Earth with the Sun, injection onto these field lines could still occur for initially trapped particles that reach the injection region via a slower "diffusive-type" process (see Mullan and Schatten 1979).

In Figure 2, we have demonstrated that, at least in some cases, the relativistic protons injected into interplanetary space can be produced very near the flare flash phase (when the shock should begin to develop). Because GLE protons can be produced so near the flash phase, it is impossible to tell from these data (Fig. 2) whether acceleration takes place in a first stage or a second stage shock-related process. In either case, the observation of several events with $\Delta T_A \leq 5$ min argues against proton acceleration models such as that of Schatten and Mullan (1977) and Mullan (1980) which require prolonged acceleration times of ~ 15 min.

An advantage of the shock front acceleration/injection model is that it provides a simple explanation for the observed fast propagation of protons. From Figure 3 we note that GLE-associated flares located as far east as E15 and as far west as W120 had ΔT_A values ≈ 20 min, implying azimuthal propagation rates in the corona $\gtrsim 200° \text{ hr}^{-1}$. A spherically expanding shock front with a characteristic leading edge velocity of 1000 km s^{-1} will sweep through a radius of 90° of solar azimuth in ~ 20 min, or $270° \text{ hr}^{-1}$. Particle acceleration and injection at such a shock could thus easily account for the broad "fast propagation region" discussed by several authors and evident in Figure 3 for GeV protons. To our knowledge, no mechanism (other than direct propagation and those involving a shock front) has yet been proposed that can reproduce these "propagation" rates (see Mullan and Schatten 1979). In addition, Hudson, Lin, and Stewart (1982) and Cliver (1982) have recently presented observations of events in which particle injection onset coincided with the passage of a shock front (associated with an observed Type II burst) across the nominal footpoint of the Archimedean spiral field line connecting to Earth.

In the context of the model we have proposed, the long delays observed for some well-connected events in Figure 3 (and, equivalently, the well-documented cases of anomalous propagation observed by the *Pioneer* satellites; e.g., Keath *et al.* 1971; Palmer and Smerd 1972) could be explained by a nonuniform or directional shock front expansion. Uchida, Altschuler, and Newkirk (1973) have presented theoretical arguments for such a nonuniform expansion, and this phenomenon has been well observed, via the shock wave associated Type II burst, with radio interferometers (e.g., Smerd 1970; Gergely and Kundu 1976). Thus, proximity of a flare to the solar footpoint of the field line that connects to Earth does not ensure prompt injection of particles (small ΔT_A) unless the shock initially develops in that direction.

As mentioned above, we previously (Cliver *et al.* 1981) suggested a threshold effect explanation for the GLE size versus ΔT_A relationship in Figure 4. However, since there is no reason to expect the onsets of the associated electron events (which typically rise several orders of magnitude above background) to be similarly delayed, the consistent phases of the injection onsets of the three particle species in Figure 5 argue that any threshold effect on GLE onset delays is probably only of second-order importance.

The average GLE rise time (T_R) for well-connected (W20–W90) events (excluding event No. 7) in Table 1, defined to be the time from event onset to maximum as measured by the neutron monitor station showing the largest increase and whose asymptotic cone of acceptance (McCracken *et al.* 1968) includes the nominal direction of the Archimedean spiral path, is 21.3 min. For 12 cases, T_R was $\lesssim 15$ min. These short rise times indicate that GeV proton production peaks fairly quickly and suggest an alternative explanation for the GLE size versus ΔT_A relationship in Figure 4 that, while not unique, is consistent with the acceleration/injection picture we have proposed. In terms of our model, a rapidly decaying GeV proton production profile implies that those GLEs with larger values of ΔT_A and, hence, longer delays to "turn on" (as seen from Earth) should appear to be weaker. This is in agreement with Figure 4.

In regard to Figure 5, the arrival of the ~ 100 keV electrons prior to that of the MeV electrons and protons was noted earlier and attributed to the acceleration of the low energy electrons during the flash phase, with the MeV electrons and protons being accelerated later in a second stage process (Lin 1974). However, if this were the case, it is difficult to see how the ~ 100 keV electrons would have been so systematically delayed for events with large values of ΔT_A; we believe they must also have been accelerated in a shock-related process.

We are not aware of previous observations establishing a systematically later onset time for MeV electrons relative to energetic protons. Other observations, specifically the observed nearly constant ratio of ~1 MeV electron to ~10 MeV proton peak fluxes (Ramaty *et al.* 1980, p. 144), suggest that relativistic electrons and energetic protons are accelerated in a common process. Moreover, Ramaty *et al.* demonstrated that the very small electron to proton ratio observed at high (>10 MeV) energies (Datlowe 1971) is qualitatively consistent with the acceleration of these species in a shock-related Fermi process. However, the fact that the inferred order of the injection onsets of the three particle species considered in this study resists any easy arrangement in terms of energy, rigidity, or velocity, suggests that the picture of a single simple acceleration mechanism for all three species may not apply. The detailed specification of the applicable coronal acceleration and energy loss mechanisms represents a significant challenge for our understanding of the acceleration/injection process in flares. While the effects of interplanetary scattering may be nonnegligible even for the earliest arriving particles, it is difficult to see how such scattering alone could produce the qualitative result of Figure 5. We submit that the apparent systematic phase relationship among the injection onsets of the three particle species, which is maintained independently of ΔT_A, results from the control of the operant acceleration process(es) by a single agent—a shock wave.

V. CONCLUSION

From an analysis of the 32 GLEs observed between 1942 and 1978 we have determined the following:

1. There is no compelling evidence for a systematic delay in the onsets of GLEs as had been previously reported (Kodama *et al.* 1977); the most likely time for injection onset of GeV protons in cosmic-ray flares appears to be near the time of the first significant microwave peak.

2. For certain GLE-associated flares located at various longitudes across the solar western hemisphere (W04–W90), the earliest arriving GeV protons were able to reach the open field lines connecting to Earth within ~10 min of the flare flash phase. Conversely, some apparently well-connected (i.e., near W55) events exhibited delays of ~20 min.

3. GLE events with long delays to onset tend to be small in size.

4. There is a systematic phase relationship between the inferred injection onset times of the ~2 GeV protons, ~1 MeV electrons, and ~100 keV electrons in cosmic-ray flares, with the low energy electrons preceding the GeV protons by $\lesssim 5$ min and the relativistic electrons following the GeV protons by $\gtrsim 5$ min. This phase relationship holds even when the onsets of all three species are substantially delayed.

To account for these observations we favor a model in which all three particle species are accelerated in an expanding shock front. Injection, as viewed from Earth, begins when the outward moving acceleration region first intersects the open field lines connecting to Earth. The detailed nature of the acceleration process(es) operating at the shock front remains to be specified.

Over the years many people have sent two of us (D. F. S. and M. A. S.) GLE data, and we gratefully acknowledge their contributions to this study. In particular, we wish to thank Dr. M. Bercovitch for the Canadian data for the most recent GLEs. We also wish to thank Drs. J. W. Bieber and R. P. Lin for providing electron onset data and Drs. M. A. Bell and H. J. Wiehl and Maj. J. Gayvert for kindly providing microwave data. We are grateful to Dr. R. P. Lin for his helpful critique of the original manuscript. Finally, we thank S. Horning for assistance with the data reduction. One of us (S. W. K.) was supported by a Research Associateship from the National Research Council.

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