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THE HIGH-ENERGY IMPULSIVE GROUND-LEVEL ENHANCEMENT

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ABSTRACT

We have studied short-lived (21 minute average duration), highly anisotropic pulses of cosmic rays that constitute the first phase of 10 large ground-level enhancements (GLEs), and which extend to rigidities in the range 5–20 GV. We provide a set of constraints that must be met by any putative acceleration mechanism for this type of solar-energetic-particle (SEP) event. The pulses usually have very short rise-times (three to five minutes) at all rigidities, and exhibit the remarkable feature that the intensity drops precipitously by 50% to 70% from the maximum within another three to five minutes. Both the rising and falling phases exhibit velocity dispersion, which indicates that there are particles with rigidities in the range $1 < P$ (GV) < 3 in the beam, and the evidence is that there is little scattering en route from the Sun. We name these events the high-energy impulsive ground-level enhancement (HEI GLE). We argue that the time-dependence observed at Earth at ~5 GV is a close approximation to that of the SEP pulse injected into the open heliospheric magnetic field in the vicinity of the Sun. We conclude that the temporal characteristics of the HEI GLE impose nine constraints on any putative acceleration process. Two of the HEI GLEs are preceded by short-lived, fast-rising neutron and >90 MeV gamma-ray bursts, indicating that freshly accelerated SEPs had impinged on higher-density matter in the chromosphere prior to the departure of the SEP pulse for Earth. This study was based on an updated archive of the 71 GLEs in the historic record, which is now available for public use.

Key words: atmospheric effects – solar–terrestrial relations – Sun: flares – Sun: particle emission – Sun: X-rays, gamma rays

1. INTRODUCTION

Seventy-one ground-level enhancements (GLE) of the cosmic-ray intensity have been recorded, with the first two detected in 1942 by ionization chambers operated in the USA, New Zealand, and Greenland by the Carnegie Institution of Washington. The neutron monitors established for the International Geophysical Year (1957) greatly increased the sensitivity of the worldwide network, and the general properties of the GLE were soon established. They were: a rapid (<1 hr) rise to maximum intensity; a slower decay; strongly anisotropic fluxes early in the event, sometimes persisting throughout the event; and a rigidity spectrum that was much steeper than that of the galactic cosmic radiation, which softened further throughout the event. Further, it was rapidly established that the majority of GLEs were observed following a major solar event on the western portion of the solar disk, later recognized to be a consequence of the spiral nature of the "Parker" heliospheric magnetic field (McCracken 1962c). Hence, GLEs are known to represent the highest-energy portion of the solar-energetic-particle (SEP) spectrum.

The ability to deconvolve the spectral and anisotropic properties of the GLE at Earth was first demonstrated by Shea & Smart (1982) for GLE 31 (1978 May 7). Cramp et al. (1997a, 1997b) extended this work for GLE 38 and 44 (1982 December 7 and 1989 October 22), demonstrating, inter alia, the softening of the spectrum, and the changing direction and diminution of the anisotropy with time. Lovell et al. (1998) studied the large GLE 42 (1989 September 29), using both muon telescope and neutron monitor data and demonstrated the presence of 30 GeV SEPs at early times in the event. To investigate the nature of the acceleration processes, detailed studies were then made of the evolution of the GLE spectra throughout a number of well-observed GLEs. Vashenyuk et al. (2006) extended the concept of Pfotzer (1958) that there were two distinctly different spectral components that they called the prompt and delayed components (PC and DC), with PC being highly anisotropic, and DC mildly so. Vashenyuk et al. (2011) later showed that PC and DC components were present in the majority of 35 GLEs that they studied. They concluded that the spectra of the PC and DC components approximated exponentials and power laws in energy, respectively. From this, they concluded that the PC was accelerated in electric fields associated with magnetic reconnection in the corona (see also Aschwanden 2012) and the DC due to stochastic acceleration in turbulent solar plasma in the outward expanding coronal mass ejection (CME). In a series of three papers, Bombardieri et al. (2006, 2007, 2008) examined the spectra of three large GLEs (59, 60, and 69), concluding that both shock and stochastic acceleration components were present. Struminsky (2006) has proposed that there were multiple acceleration events in GLE 69. Taken together, these and other studies of GLE spectra have provided detailed insight and constraints on the acceleration processes in operation at the Sun (e.g., see Miroshnichenko & Perez-Peraza 2008).

In addition to predicting different spectra, the various putative acceleration mechanisms may be expected to exhibit different characteristic timescales. Thus rapidly developing, spatially limited mechanisms may be expected to have relatively short characteristic timescales (e.g., magnetic reconnection events). Stochastic processes within a large volume may be expected to exhibit longer timescales. In this paper, we accept the view that there are (at least) two separate components of the GLE, named PC and DC by Vashenyuk et al. (2006); and named pulses one and two (P1 and P2) by McCracken et al. (2008). We restrict our studies to the properties of the initial pulse (P1 or PC) in the time domain to determine the temporal constraints that the putative acceleration process must meet. We do not discuss the spectrum in detail, as has been done already to the limits of the available data by the earlier workers cited in the previous paragraph.

Restricting our attention to 10 of the largest GLEs (due to statistical limitations inherent in one-minute data), we show that the average duration of the initial pulse is 21 minutes, with the remarkable feature that the intensity falls precipitously from its peak value as fast as, if not faster than, the rise during the onset phase. Its amplitude is sometimes a factor of 10 greater than that of a subsequent portion of the GLE (P2 or DC) that is observed by many other neutron monitors in the worldwide network. The initial pulse arrives at Earth in an extremely anisotropic manner and consequently is only seen as an isolated pulse by a few detectors (typically three to five) out of the worldwide cosmic-ray detector network of more than 50. Most neutron monitors then see the second, slower-rising, relatively isotropic pulse (P2 or DC). We show that the initial pulse can contain SEPs with energies up to 10 GeV and occasionally up to 30 GeV. To provide a descriptive name for the initial pulse, we name it the high-energy impulsive ground-level enhancement (HEI GLE). About 30% of the world network see the HEI GLE merged with the second, slower pulse, so that they see a faster rising, higher intensity (but single) pulse compared to the rest of the world network (e.g., Vashenyuk et al. 2006, 2011). As proposed by Bieber et al. (2002, 2004, 2007), Ruffolo et al. (2006) and Saiz et al. (2008), the initial pulse may be the source of some of the particles that constitute the subsequent slower-rising GLE.

The ubiquitous nature of the HEI GLE is demonstrated by the fact that every large (>100%) worldwide GLE originating from solar activity at $\geqslant 24°$ West on the solar disk commenced with an HEI GLE.

The presence of >4 GV SEPs in the HEI GLE is particularly informative since they suffer very little velocity dispersion. For simplicity, consider protons, assume that there is no pitch-angle scattering en route to Earth and use a typical value of 1.2 AU for the length of the Parker spiral magnetic field line. Consider a cosmic-ray detector with a geomagnetic cut-off rigidity $P_c =$ 4 GV. The velocity of 4 GV protons is 0.97c, and along a path length of 1.2 AU they take 15 s longer to reach Earth than highly relativistic protons. The highest time resolution of the detectors we work with is one minute (for one event it is 30 s), and hence particles with rigidity $P > 4$ GV will not suffer detectable velocity dispersion. On the other hand, neutron monitors at high latitudes detect cosmic rays with rigidities down to 1 GV (which is determined by the atmospheric cutoff), for which $\beta = v/c \approx 0.7$, and these lower rigidity particles would have a delay time up to four minutes along the 1.2 AU path. Hence a short-lived pulse of cosmic radiation seen by a neutron monitor with $P_c \leqslant 1.0$ GV can be extended by up to four minutes if the asymptotic cone allows all rigidities >1 GV to reach the detector.

Each cosmic-ray detector has its own "asymptotic cone of acceptance" that defines those directions outside the geomagnetic field from which cosmic rays can access the detector (McCracken 1962a, 1962b). We find that the few detectors that see any given HEI GLE view the same portion of the celestial sphere, while those detectors that fail to see it view outside this field. We will show that the nature of the asymptotic cone can have a significant effect on the observed pulse shape for a detector with low cutoff rigidities.

Several examples of the HEI GLE have been discussed in the literature, e.g., by Shea & Smart (1996), Vashenyuk et al. (2006, 2007), McCracken et al. (2008), and Moraal & McCracken (2012); however, these events were so atypical compared to the GLEs observed throughout the world that they have mostly been described as a consequence of short-lived irregularities in the heliospheric field. In this paper, we hypothesize that the characteristics of the initial impulsive events are so similar in 10 separate GLEs that they must represent a consistent, tightly constrained feature of the initial phase of SEP events.

2. The GLE DATABASE

The data selected for use in this paper come from a digital archive of the GLEs that have been observed by neutron monitors (and in a few cases by other detectors) from 1956 until 2006. In its original form the record consists of text files that contain the increases seen by each individual station for each event. Each individual file contains the counting rates from which the increases were calculated as well as housekeeping data such as atmospheric pressure, type of neutron monitor, geographic location, altitude, etc. The digital format was originally designed by Shea et al. (1985), working with the World Data Centers, and later revised by Shea et al. (1987) to accommodate the high-time resolution data necessary for identification of solar neutron events, and this became the default standard that continues to the present day. The original digital format of the records was optimized to minimize the data record size at a time when computer storage was measured in kilobytes. Shea, Smart and colleagues (Gentile 1993) collected and managed this password protected database until 1999, at which time a copy of the database was transferred to M. L. Duldig in Australia. Duldig and colleagues maintained and augmented this database, which was available to the scientific community in a password-protected file (Duldig & Watts 2001). A copy of the database was subsequently transferred to E. Eroshenko at IZMIRAN, Russia, where it has been maintained, updated and is available on the internet. In 2009, H. Moraal and J. P. L. Reinecke converted the GLE database into a single graphical database, and this is currently available at ftp://ftp.puk.ac.za/outgoing/. The early data are mostly five-minute averages, with one-minute averages becoming frequent after 1990. Of the 71 known events from 1942, the archive contains data for 65 of them, from GLE 5 on 1956 February 23 to GLE 70 on 2006 December 13. Other records and the literature provide additional data for these events and for the first four GLEs observed between 1942 and 1949 (e.g., Forbush et al., 1950). The recent GLE 71 of 2012 May 17 is not part of the database.

The database was used by Moraal & McCracken (2012) to analyze the GLEs of solar cycle 23, but this paper is the first in which the entire database has been utilized.

Table 1 shows a compilation of the 44 largest GLEs observed with neutron monitors. By convention they are numbered in chronological sequence, from GLE 1 on 1942 February 28 to GLE 71 on 2012 May 17. We have restricted our study to those GLEs for which the neutron monitor counting-rate increased by 50% for at least one detector in the worldwide network, which gave a total of 19 events. For the events examined, data were typically available from between 30 and 45 stations, totaling more than 600 individual station records for the whole study.

Since the HEI GLE is short-lived, with the highest-intensity peak seldom lasting more than five minutes, it is possible that the rather coarse five-minute temporal resolution widely used for neutron monitors until the 1990s may have obscured the nature of the event in some cases. Paradoxically, some of the highest temporal resolution was available from the continuous

Table 1
Ground-level Enhancements >10% Observed by Neutron Monitors

Sorted by Date (dd/mm/yy)					Sorted by Size					Sorted by Longitude				
GLE#	Incr%	Date	Lat N	Long W	GLE#	Incr%	Date	Lat N	Long W	GLE#	Incr%	Date	Lat N	Long W
5	5000	23/02/56	10	85	∗69	5500	20/01/05	12	58	16	30	28/01/67	∼22	∼150
7	18	17/07/59	16	31	∗5	5000	23/02/56	10	85	39	100	16/02/84	?	∼130
8	270	04/05/60	10	90	∗42	395	29/09/89	∼−24	∼105	23	20	01/09/71	∼−11	∼120
10	150	12/11/60	27	4	∗8	270	04/05/60	10	90	29	12	24/09/77	∼10	∼120
11	110	15/11/60	25	35	∗60	230	15/04/01	−20	85	∗42	395	29/09/89	∼−24	∼105
13	13	18/07/61	−7	59	∗31	210	07/05/78	24	68	22	38	24/01/71	∼19	∼103
16	30	28/01/67	∼22	∼150	∗44	190	22/10/89	−27	32	61	26	18/04/01	−23	117
19	32	18/11/68	21	87	10	150	12/11/60	27	4	∗8	270	04/05/60	10	90
20	35	25/02/69	13	37	∗11	110	15/11/60	25	35	71	23	17/05/12	07	88
22	38	24/01/71	∼19	∼103	∗70	110	13/12/06	6	24	19	32	18/11/68	21	87
22	38	24/01/71	18	49	39	100	16/02/84	?	∼130	38	55	07/12/82	−19	86
23	20	01/09/71	∼−11	∼120	45	95	24/10/89	−29	57	∗5	5000	23/02/56	10	85
24	79	04/08/72	14	−8	43	90	19/10/89	−25	−9	41	24	16/08/89	−15	85
25	17	07/08/72	14	37	59	80	14/07/00	22	7	∗60	230	15/04/01	−20	85
27	12	30/04/76	−8	46	24	79	04/08/72	14	−8	∗48	50	24/05/90	36	76
29	12	24/09/77	∼10	∼120	52	57	15/06/91	36	70	52	57	15/06/91	36	70
30	55	22/11/77	24	40	30	55	22/11/77	24	40	∗31	210	07/05/78	24	68
31	210	07/05/78	24	68	38	55	07/12/82	−19	86	55	18	06/11/97	−18	63
32	12	23/09/78	35	50	∗48	50	24/05/90	36	76	13	13	18/07/61	−7	59
33	11	21/08/79	17	40	65	45	28/10/03	20	−2	67	37	02/11/03	−18	59
36	21	12/10/81	−18	−31	22	38	24/01/71	∼19	∼103	∗69	5500	20/01/05	12	58
38	55	07/12/82	−19	86	22	38	24/01/71	18	49	45	95	24/10/89	−29	57
39	100	16/02/84	?	∼130	67	37	02/11/03	−18	59	63	21	26/12/01	8	54
41	24	16/08/89	−15	85	20	35	25/02/69	13	37	32	12	23/09/78	35	50
42	395	29/09/89	∼−24	∼105	66	35	29/10/03	−19	9	22	38	24/01/71	18	49
43	90	19/10/89	−25	−9	19	32	18/11/68	21	87	27	12	30/04/76	−8	46
44	190	22/10/89	−27	32	16	30	28/01/67	∼22	∼150	∗11	110	15/11/60	25	35
45	95	24/10/89	−29	57	61	26	18/04/01	−23	117	30	55	22/11/77	24	40
46	12	15/11/89	11	28	41	24	16/08/89	−15	85	33	11	21/08/79	17	40
47	24	21/05/90	34	37	47	24	21/05/90	34	37	20	35	25/02/69	13	37
48	50	24/05/90	36	76	71	23	17/05/12	07	88	25	17	07/08/72	14	37
51	12	11/06/91	32	15	36	21	12/10/81	−18	−31	47	24	21/05/90	34	37
52	57	15/06/91	36	70	63	21	26/12/01	8	54	∗44	190	22/10/89	−27	32
55	18	06/11/97	−18	63	23	20	01/09/71	∼−11	∼120	7	18	17/07/59	16	31
59	80	14/07/00	22	7	7	18	17/07/59	16	31	46	12	15/11/89	11	28
60	230	15/04/01	−20	85	55	18	06/11/97	−18	63	∗70	110	13/12/06	6	24
61	26	18/04/01	−23	117	25	17	07/08/72	14	37	51	12	11/06/91	32	15
63	21	26/12/01	8	54	13	13	18/07/61	−7	59	10	150	12/11/60	27	4
65	45	28/10/03	20	−2	27	12	30/04/76	−8	46	66	35	29/10/03	−19	9
66	35	29/10/03	−19	9	29	12	24/09/77	∼10	∼120	59	80	14/07/00	22	7
67	37	02/11/03	−18	59	32	12	23/09/78	35	50	65	45	28/10/03	20	−2
69	5500	20/01/05	12	58	46	12	15/11/89	11	28	24	79	04/08/72	14	−8
70	110	13/12/06	6	24	51	12	11/06/91	32	15	43	90	19/10/89	−25	−9
71	23	17/05/12	7	88	33	11	21/08/79	17	40	36	21	12/10/81	−18	−31

Notes. Asterisks (∗) mark the GLEs that had a high-energy impulsive component, studied in this paper. The ∼ symbol indicates estimates of position, usually behind the limb.

recording traces of the ionization chambers used until the 1960s, and the fast recording systems used by some muon telescopes at that time. (The threshold rigidity for muon detectors is ≈4 GV. This is the minimum rigidity a particle must have to produce secondaries that can be detected by a muon detector at sea level. For neutron monitors this threshold is ≈1 GV.) In some cases, neutron monitors employed "flare alarms" to increase the data-recording rate, typically to once a minute, while others used chart recorders as a subsidiary data recording system that also provided one-minute data resolution.

Based on a partial archive, McCracken et al. (2008) previously identified nine GLEs with impulsive events, and another two were the worldwide differences in onset time suggested that they contained unresolved impulsive events. Moraal & McCracken (2012) then reported a more detailed study of impulsive events in the 13 GLEs during solar cycle 23. To complete these studies, we have used the complete GLE archive, and initially restricted this study to those cases where either (1) the initial impulsive event was seen clearly as an isolated event by at least two detectors, or (2) when a high-resolution, high-cutoff detector saw a well-defined HEI GLE, while no neutron monitor resolved the event (GLE 60 only). We cannot rule out the possibility that an HEI GLE was missed because there was no detector so positioned that the anisotropic beam of radiation was accessible to any detector in the worldwide network.

3. ANALYSIS OF THE ARCHIVAL DATA

Table 2 provides key data for the 10 HEI GLEs we have studied in this paper. Figures 1–4 display four of these 10 events.

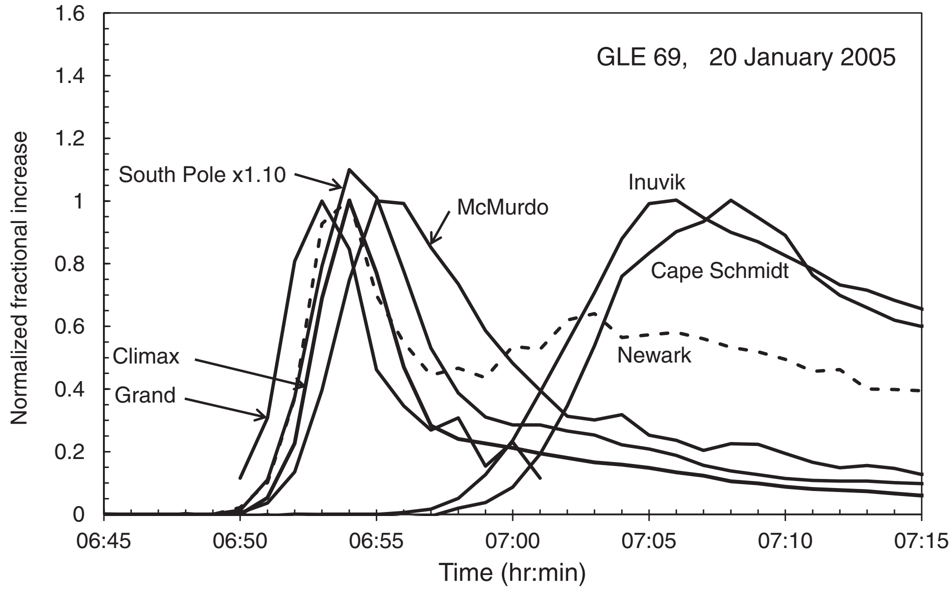

Figure 1. GLE 69 on 2005 January 20 as observed by several neutron monitors. Increases are normalized to their respective peak values. The South Pole increase is multiplied by 1.1 to separate it from the others. The increases at Inuvik and Cape Schmidt are typical of the worldwide GLE. Short-lived pulses were observed by Climax, South Pole, McMurdo and the GRAND muon telescope. Newark saw both the short-lived pulse and the gradual worldwide increase. The short-lived pulses at the polar stations ($P_c < 1$ GV) McMurdo and South Pole are extended relative to those at higher cutoff rigidities due to velocity dispersion.

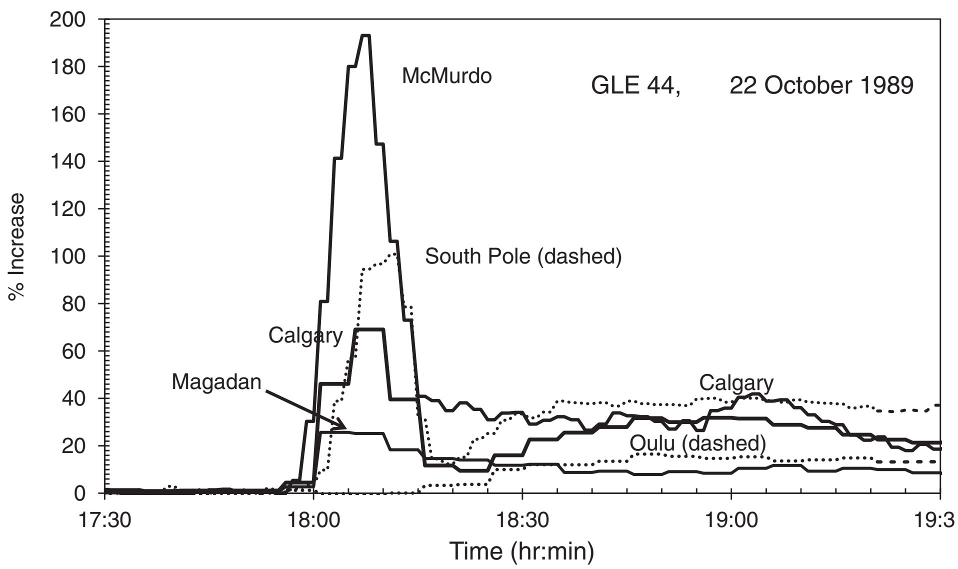

Figure 2. GLE 44 on 1989 October 22. The HEI GLE pulse is seen by McMurdo, South Pole, Calgary and Magadan, but not by Oulu.

Table 1 shows that they were among the most intense ones in the database, and that they all originated from $\geqslant 24°$ west on the solar disk.

To characterize these events, let the SEP injection pulse into the heliomagnetic field near the Sun be given by $f(P, t)$, determined by two main factors; the time dependence and energy characteristics of the acceleration process itself, or, if the particles are trapped in the corona for some time, the characteristics of the release process. If there is little velocity dispersion, as at rigidities $P > 4$ GV, pitch-angle scattering and adiabatic focusing en route from the Sun will be the only processes that will modify $f(P, t)$ before the pulse reaches Earth. We define T_r as the rise time to 90% of the HEI peak; T_p as the duration of the peak; T_f as the fall-time to 50% of the peak; and T_d as the overall duration, $T_d = T_r + T_p + T_f$. When necessary, we interpolate the five-minute data. The statistical fluctuations on such short intervals make the first three estimates for the smaller events somewhat uncertain, however the estimates of T_d are correct to within ±2 minutes for all the events listed. The average duration of the 10 HEI events is $\langle T_d \rangle = 21$ minutes. For comparison, the duration times of the worldwide gradual event of the 10 largest GLEs in Table 1 (up to GLE 39, but excluding GLE 8) were $\langle T_r \rangle = 54$ minutes, $\langle T_f \rangle = 101$ minutes, and $\langle T_d \rangle = 155$ minutes.

In the following, we investigate the properties of $f(P, t)$ and use them to discuss the properties of the acceleration and trapping processes near the Sun.

In Figure 1, for GLE 69 on 2005 January 20, the data for the Inuvik and Cape Schmidt neutron monitors are typical of the GLE observed worldwide. The intensity started to rise at 06:57 UT, reaching a peak ∼10 minutes later. (All times in this paper are in universal time (UT) of observation at Earth).

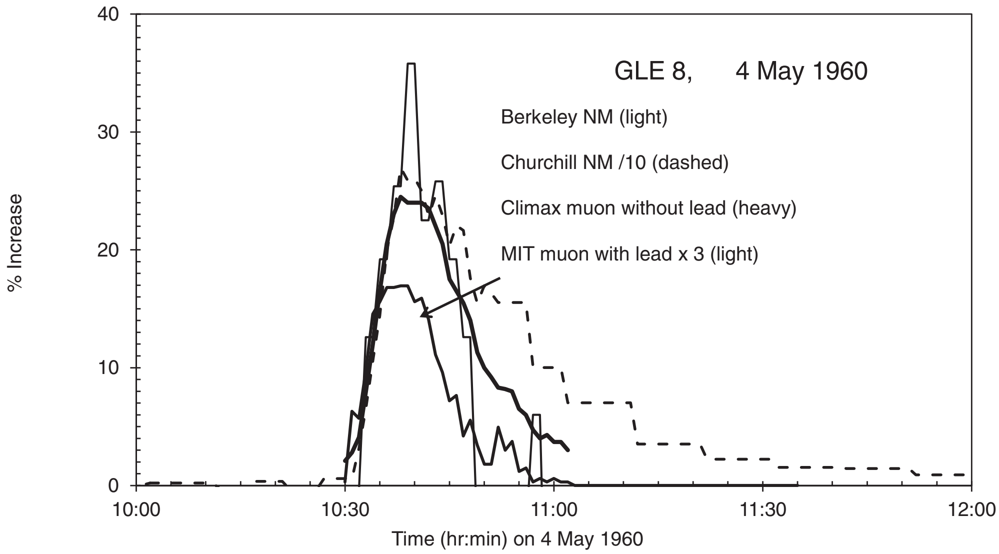

Figure 3. GLE 8 on 1960 May 4. This HEI GLE was not followed by a worldwide gradual GLE.

Table 2
Properties of the 10 HEI GLEs Studied in This Paper

GLE#	Date (dd/mm/yy)	Station	Resolution (minutes)	P_c (GV)	Increase (%)	T_r (minutes)	T_p (minutes)	T_f (minutes)	T_d (minutes)
5	23/02/56	Huancayo IC	5	13.5	22	5	0	7	12
		Huancayo	5	13.5	37	7	0	11	18
		Freibourg IC	5	>4	619	6	0	9	15
8	04/05/60	MIT MT	0.5	>4	...	4	...	4.5	14
(Figure 3)		Climax MT	0.5	>4	...	7	5	6	18
		Berkeley	1	4.5	36	5	...	12	17
		Churchill	...	<1	270	5	3	14	22
11	15/11/60	Deep River	5	1.1	98	∼15	∼15∼2	∼10	∼40
		Mawson	5	<1	160	∼20	0	∼7	∼47
31	07/05/78	Tsumeb	5	9.3	5	7	0	8	15
		Lomnicky Stit	5	4	36	6	0	10	16
		Leeds	1	2.2	84	6	0	10	16
		Kerguelen	5	1.2	215	7	0	9	16
42	29/09/89	New Mex. UG	∼60	>19	2	...	...	...	...
		Darwin	5	11.4	22	8	5	24	37
		Tsumeb	1	9.3	62	12	8	28	48
		Goose Bay	1	<1	175	∼20	?	28	48
44	22/10/89	Moscow	5	2.5	4	...	...	...	...
(Figure 2)		Magadan	5	2.1	26	8	0	11	19
		South Pole	5	<1	101	6	2	4	12
48	24/05/90	Alma Ata	5	6.7	3	10?	0	10?	20
(Figure 4)		Climax	1	3.0	21	7	0	13	20
		Mt. Wellington	1	1.9	52	6	4	10	20
60	15/04/01	GRAND MT	6	>4	...	12	0	15	30
69	20/01/05	GRAND MT	6	>4	...	3	...	2	5
(Figure 1)		Climax	1	3.0	543	3	...	3	6
		Newark	1	...?	143	3.5	...	3.5	7
		South Pole	1	<1	5500	4	...	3	7
		McMurdo	1	<1	2870	5.5	...	4.5	10
70	13/12/06	Jungfraujoch	1	4.4	10	5	3	6	14
		LARC	1	3.4	24	8	3	7	18
		Moscow	1	2.5	25	7	6	6	19
		Kiel	1	3.2	34	7	5	9	19

Notes. MT, muon telescope; UG, underground muon telescope; IC, ionization chamber. All other entries are based on neutron monitor data and there is no qualification after the name of the detector.

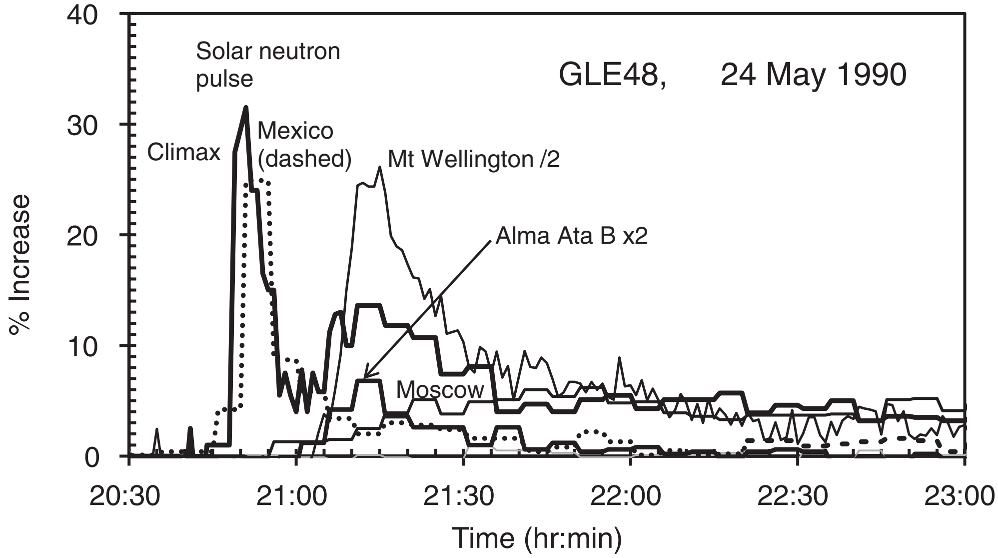

Figure 4. GLE 48 on 1990 May 24. The pulses seen by Climax and Mexico City were due to solar neutrons. The second group of pulses seen by Mt. Wellington, Climax, and Alma Ata are the HEI GLE. Moscow did not see the HEI GLE.

Note, however, the short-lived pulses observed by Climax, South Pole, and McMurdo, and also with the GRAND muon telescope (D' Andrea & Poirier 2005) had risen to their peaks, and decayed rapidly by >50%, before the worldwide GLE commenced at 06:57. Figure 1 shows that within the time resolution of the data, the GRAND muon, and Climax, and South Pole neutron monitor pulses commenced together at $06:50.5 \pm 0.5$, peaked in the interval 06:53–06:55, and thereafter decreased precipitously by 50% during the next three to four minutes. The Newark record in Figure 1 is an example of the manner in which a suitably located detector saw both pulses as separate entities. (The role of velocity dispersion in prolonging the pulses at polar stations such as McMurdo and South Pole at $P_c < 1$ GV will be discussed in Section 4.) The GRAND muon data clearly illustrate the short-lived nature of this event; its "half-width" being only three minutes. Since the initial pulse was seen as a separate entity by only nine detectors worldwide, McCracken et al. (2008) and Moraal & McCracken (2012) argued that the radiation was extremely anisotropic. The initial pulse had an amplitude of ∼3000% at favorably located sea-level detectors compared to ∼300% for the subsequent worldwide pulse. (The geomagnetic field bends cosmic-ray trajectories in such a way that particles arriving vertically (say) at a detector such as a neutron monitor, came from a different direction outside the magnetosphere, called the asymptotic direction. Since these directions differ for each location on Earth, a network of neutron monitors is an efficient anisotropy detector.)

Next, consider GLE 44 on 1989 October 22, as shown in Figure 2, following Shea & Smart (1996). While the data from three detectors have only five-minute resolution, it is still clear that the double-pulse structure was present here as well. The Oulu observations illustrate the smaller "worldwide" GLE, which commenced at about 18:15. A sharply rising and falling pulse was observed to commence 15 minutes earlier at four detectors: South Pole, McMurdo, Calgary, and Magadan. Examination of the asymptotic cones confirms that these four detectors were viewing the same region of the celestial sphere. South Pole, McMurdo, and Calgary also saw the subsequent worldwide pulse, and in all cases the initial pulse was the larger one by a factor >2, and had decayed to <25% of its peak value before the second pulse started. Magadan ($P_c = 2.1$ GV) saw a prominent initial pulse but a very small second pulse. Using all the data recorded worldwide, Cramp et al. (1997a, 1997b) have demonstrated the highly anisotropic nature of the initial phase of this event, and that its spectrum extended to >10 GV.

Figure 3 presents data for GLE 8 on 1960 May 4 from the Berkeley neutron monitor, and also additional data from Palmeira & McCracken (1960), Rose (1960), and Maeda et al. (1961), which is not part of the digital data base. Paradoxically, these 50 year old paper records have the best timing resolution of all the events we analyzed in this paper. The muon telescopes at MIT and Climax (and others at Banff and College Park) and the two neutron monitors saw the same rapid 5.5 ± 1.5 minute rise to maximum, a prolonged peak of 3–5 minutes (depending on statistics), and a fall time (T_f) of 5–7 minutes, except for 14 minutes for the Churchill neutron monitor. While there was 10 cm lead absorber between the scintillators of the MIT telescope, there was no absorber in the Climax or Banff telescopes, and this may account for the marginally greater duration for the latter instruments, since they would respond to somewhat lower primary rigidities than MIT, as explained in the next section. The extended decay phase at Churchill is consistent with velocity dispersion of the 1 GV particles that could access that detector (see Section 4). That is, this event exhibits the same fast rise and fall times evident in Figures 1 and 2, as summarized in Table 2. A worldwide second pulse was not seen for this event; however, Vashenyuk et al. (2011) have recently concluded that there was a DC component merged with the PC.

The rigidity sensitivity of a cosmic-ray detector to an anisotropic flux of SEPs is determined by three factors: (a) the geomagnetic cutoff rigidity, P_c, wherein Earth's magnetic field sets a threshold below which charged particles cannot reach the top of the atmosphere, (b) the specific yield function that quantifies the atmospheric effects as a function of rigidity, and (c) the precise nature of the asymptotic cone with respect to the anisotropic flux. These factors were reviewed in McCracken et al. (2008) and Caballero-Lopez & Moraal (2012). While the cutoff rigidity and atmospheric yield remain essentially the same for a given detector, the anisotropy means that the "effective"

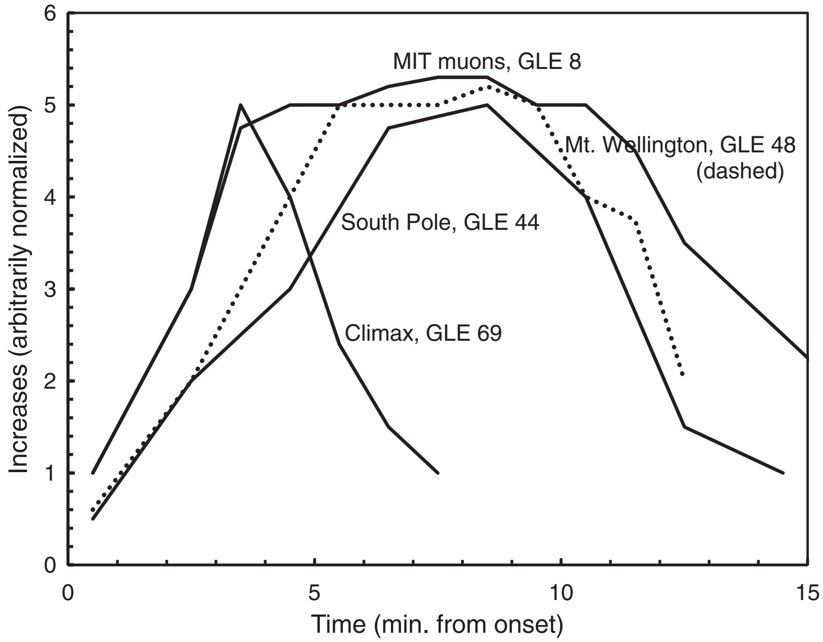

Figure 5. Normalized short-lived HEI GLE pulses from Figures 1, 2, 3, and 4, plotted relative to their onset times. These profiles reflect the injection profiles of the particles at the Sun.

mean detector response will vary from event to event, and can be greatly different from that applicable to the essentially isotropic galactic cosmic radiation.

Referring to Table 2 shows that the short initial HEI pulse usually extends to rigidities $P > 4$ GV. The GRAND muon data indicate the presence of >4 GV SEPs in GLEs 60 and 69. The MIT and Climax muon observations for GLE 8 in Figure 3 indicate the presence of >4 GV SEPs for this event as well. The presence of high-rigidity particles in the initial pulse is unambiguously confirmed by their observation by detectors with high geomagnetic cutoff rigidities. The initial pulse for GLE 8 was observed at Berkeley at $P_c = 4.5$ GV. GLE 48, as shown in Figure 4, was observed at Alma Ata ($P_c = 6.7$ GV). Table 2 shows that Darwin (GLE 42, $P_c = 14.2$ GV), Huancayo (GLE 5, $P_c = 13.5$ GV), Mt. Norikura (GLE 42, $P_c = 11.4$ GV), and Tsumeb (GLE 31, $P_c = 9.29$ GV) provide unequivocal evidence that the spectra of these initial, short-lived HEI events extended to $\geqslant 10$ GV. For GLE 5, the 22% and 37% increases recorded by the Huancayo ionization chamber and neutron monitor, respectively, imply detectable intensities up to 20 GV (see also Vashenyuk et al. 2007, 2008). The initial phase of GLE 42 was observed by a muon telescope situated 28 m water equivalent underground, with a threshold rigidity of 19 GV (Swinson & Shea 1990; see also Lovell et al. 1998; Miroshnichenko et al. 2000). Cramp et al. (1997a) concluded that the spectrum at the onset of GLE 44 extended to >l0 GV. For GLE 70 increases of 25% and 10% were observed at the LARC ($P_c = 3.4$ GV) and Jungfraujoch ($P_c = 4.6$ GV) neutron monitors. We therefore have clear evidence that the spectrum extended to >4 GV for 8 out of the 10 impulsive events that we have considered, and that it attained >20 GV on two occasions.

GLE 11 is one of the smallest GLEs in Table 2, and there is no clear evidence of the first pulse at high energies. Two detectors saw the initial, isolated pulse at the commencement of the GLE, and McCracken (1962b) concluded that the most anisotropic phase at the commencement of the event consisted of two short-lived, magnetic field aligned pulses of radiation that were 25 minutes apart, each with a fall time $T_f < 5$ minutes.

Figure 5 presents the normalized impulsive pulses from Figures 1–4, plotted relative to their onset times. The data used here were either (a) the highest time-resolution available, or (b) the shortest impulsive response seen. The most remarkable feature is that all four show similar rapid decreases from the peak values by ~50% in three to five minutes. The rise times differ by a factor of ~2, and in two cases the fall time is faster than the rise-time, such as for GLEs 44 and 48. Note also that two of the impulsive events, GLE 8 and GLE 48, had flat tops, of duration from three to six minutes. The entries for all 10 events in Table 2 are consistent with these observations, except that the timescales of several events are somewhat longer. Invariably, the SEPs in the impulsive event arrive at Earth 10–20 minutes before those that are seen in the worldwide, slower-rising GLE.

In summary, the observational evidence outlined above leads us to propose that the first relativistic SEPs to reach Earth following a major solar event do so in the form of a rapidly rising, rapidly falling, highly anisotropic pulse that can contain rigidities up to 20 GV, and we refer to it as the HEI GLE. In the following, we study the temporal and other properties of these events in greater detail. We conclude that the HEI GLE is a major contributor to the "prompt component" of the GLE, a model for which was described recently by Miroshnichenko & Perez-Peraza (2008).

4. VELOCITY DISPERSION

Wherever there are one-minute resolution data, some high-latitude neutron monitors with $P_c < 1$ GV see a prolonged pulse, while other seemingly equivalent detectors see a shorter pulse. Thus in Figure 1, McMurdo saw a pulse that persisted for two to three minutes longer than the South Pole, which saw a pulse of duration that approximates that seen at Climax ($P_c = 3.0$ GV). The question is why South Pole saw a short-lived pulse similar to that seen at high rigidities. We have used the observed directional properties of HEI GLE 69 and the detailed asymptotic cones of the detectors in Figure 5 of McCracken et al. (2008) to compute the consequence of velocity dispersion. In this, we assumed that the SEP pulse, $f(P, t)$, injected at the Sun had the same time dependence at all rigidities as that observed by the GRAND muon detector. These computed responses are in excellent agreement with the pulse shapes observed by neutron monitors at Climax, Newark, and South Pole that are delayed by ≈1 minute relative to the GRAND muon measurements. The computed pulse for the McMurdo neutron monitor reaches its 50% down point two to three minutes after the other detectors, also in reasonable agreement with observations. Examination of the asymptotic directions of these detectors shows that for $P > 5$ GV all four detectors sampled the most intense portion of the anisotropic flux. In the case of the South Pole, however, its asymptotic directions for $P < 2$ GV did not sample the highest fluxes. That is, despite its low geomagnetic cutoff, South Pole was essentially a high-rigidity detector for this highly anisotropic event. The asymptotic direction for McMurdo, on the other hand, sampled the anisotropic flux for $1 < P < 10$ GV, and the arrival of the slower, but much higher-intensity low-rigidity particles resulted in the later peak and prolonged decay.

This discussion has not taken into account the effects of pitch-angle scattering and adiabatic focusing on the time profile of the pulses. The former process is due to the magnetic irregularities that will tend to isotropize an originally anisotropic beam. This implies a longer effective total path length of the particles along the magnetic field line, and this will lengthen the resulting pulse. Conversely, adiabatic focusing in the background field reduces pitch angles due to the fact that $\sin^2\theta/B$, where θ is the pitch angle, is a constant of the motion. Since B varies proportional to $1/r^2$ near the Sun, the nearer particles are released from the solar surface, the stronger they will be focused. This focusing will counteract the effects of pitch-angle scattering.

Pitch-angle distributions have been estimated for GLEs 8, 31, and 69, and they approximate Gaussian distributions characterized by a half-angle $\theta_0 = 50^\circ$, as shown in Figure 8 of McCracken et al. (2008). Vashenyuk et al. (2007) estimated $\theta_0 = 25^\circ$ during the initial phase of GLE 5 and Vashenyuk et al. (2011) have shown that the PCs of 35 GLEs exhibited strongly anisotropic pitch angle distributions. McCracken et al. (2008) demonstrated that for GLE 69 the delays introduced by pitch-angle scattering were at most three minutes at $P \approx 1$ GV, for detectors viewing $\sim 30^\circ$ off the axis of the anisotropic flux. The amount of scattering decreases approximately as P^{-1}. Hence, for the GRAND muon detector in Figure 1 and the MIT telescope in Figure 3, we estimate that pitch-angle scattering will have introduced a transit delay of <1 minute. Thus we infer that for the high-resolution, high-rigidity measurements of GLEs 8 and 69, neither velocity nor pitch-angle dispersion has a significant effect on the pulse shape observed at Earth. Consequently, we conclude that the GRAND and MIT muon HEI GLE pulses in Figures 1 and 3, respectively, are close approximations to the time dependence of the 2–5 GV SEP pulse when injected into the heliomagnetic field near the Sun.

The sharply rising and falling intensities in all 10 extremely anisotropic events indicates a limited amount of pitch-angle scattering that suggests that the scattering mean-free-path, λ, in the inner heliosphere for these events may be up to 1 AU. This is not inconsistent with diffusion mean-free paths deduced from the 11 year galactic cosmic-ray cycle by, e.g., Caballero-Lopez et al. (2004). They found that the typical mean-free-path at Earth that fits the magnitude of the modulation at solar minimum conditions, and its radial dependence out to the boundary of the heliosphere, is $\lambda = 0.25P$ (GV) AU.

5. PULSE RISE TIMES

Consider first GLE 69 in Figure 1 and Table 2. The increase commenced at the GRAND muon detector ($P_c > 4$ GV), and the Climax ($P_c = 3.03$ GV), Newark ($P_c = 1.97$ GV), and South Pole ($P_c < 1$ GV) neutron monitors during the same minute. As discussed above, the asymptotic cones of all four detectors are in close proximity for $P > 5$ GV, but they diverge greatly for lower rigidities. Since the pulse commenced at the GRAND muon detector in the interval 06:51–06:52, we conclude that all four detectors saw ∼5 GV particles arriving at that time. Figure 1 shows that the McMurdo neutron monitor, the only detector that was able to detect the lower rigidities of the anisotropic pulse, had delayed rising and falling phases. The velocity dispersion calculations that explain the pulse shapes in Figure 1 are consistent with the lower rigidities leaving the Sun simultaneously with the high rigidities, and experiencing the expected amount of velocity dispersion to prolong the pulse as observed. The observations are therefore consistent with simultaneous injection of SEPs into the heliomagnetic field at all rigidities $P > 1$ GV. The three-minute rise time at the Climax neutron monitor is of particular interest on account of the excellent statistics, and the fact that all particles detected by this instrument traveled at speeds $>0.95c$, with a maximum velocity dispersion <47 s. The Climax data therefore set an upper limit of ≈2.5 minutes for the combination of the pulse rise time itself at injection into the heliomagnetic field and the subsequent <1 minute delays due to pitch-angle scattering en route from the Sun.

Figure 3 and Table 2 show that for GLE 8 the rise time for the MIT data (muon telescope with lead) was ∼4 minutes, and three minutes and one minute longer for the Climax muon telescope and the Churchill neutron monitor, respectively, both being consistent with longer transit times for the lower-rigidity particles seen by the Climax telescope (no lead), and the Churchill neutron monitor.

In summary, Table 2 shows that the pulse rise times were in the range $3 < T_r < 7$ minutes for six events, and in the range 10–15 minutes for the other four events. In every case, inspection showed that invariably the intensity rose rapidly without hesitation for the whole period, the onsets and peaks at lower rigidities being prolonged in a manner consistent with velocity dispersion following a simultaneous injection (for $P > 1$ GV) into the Parker-spiral field near the Sun.

6. PULSE DECAY TIMES AND “FLAT TOPS”

Figure 5 demonstrates the rapidity and similarity of the 50% decrease in intensity that followed the peaks of the HEI pulses in GLEs 8, 44, 48, and 69. Figure 1 shows that the same was evident at the McMurdo, South Pole, Newark and Climax neutron monitors, and the GRAND muon detector. The times to the 50% intensity point from the time of the peak observed at the GRAND muon detector at $P > 4$ GV was 2 minutes for the GRAND muon detector, and 3, 3.5, and 4.5 minutes for the Climax, Newark, and McMurdo neutron monitors, respectively. Allowing for velocity dispersion, together with the fact that the rising phase continued at McMurdo until ≈06:56 UT, this is consistent with a decrease of ∼50% of the injection pulse into the heliomagnetic field at all rigidities $P > 1$ GV within two minutes.

Figures 3 and 5, as well as Table 2, show that for GLE 8 the 50% decay time was 4.5 minutes, as observed at MIT. For the two-minute South Pole neutron monitor data of GLE 44, the 50% decay time was four minutes. Figure 5 and Table 2 confirm that the 50% decay-time T_f was in the range 3–8 minutes on five occasions, ≈10 minutes on three occasions, and twice >15 minutes.

Figure 5 shows that the HEI pulses for GLE 8 and GLE 48 had well-defined "flat tops" where the intensity remained close to the peak value for four to five minutes prior to the precipitous decrease at the end of the pulse. The intensity remained invariant to within the statistical fluctuations during these periods. Table 2 shows that GLEs 11, 42, and 70 also exhibited "flat tops."

Summarizing, a rapid decline in intensity from the peak is a consistent characteristic of all the events under study, with $T_f \approx$ 4–5 minutes on several occasions, and the average for all of these 10 HEI events being ∼10 minutes. Approximately half of all the events had "flat tops" for three to five minutes, during which the intensity remained constant within the statistical precision of the data.

These flat-top profiles suggest either a sustained injection of the pulse, or a gradual release of accelerated particles, or both.

7. RIGIDITY SPECTRUM

As discussed in the introduction, many investigators have concluded that the GLE rigidity spectrum softens with time and that this may be due to two different populations of accelerated particles (e.g., Pfotzer 1958; Cramp et al. 1997a, 1997b; Ruffolo et al. 2006; Vashenyuk et al. 2006, 2007, 2011; Bombardieri et al. 2007, 2008). Consequently, we do not discuss the spectrum in detail here: that has been done already by the above-cited authors to the limits of the available data. We note however that the analysis of GLE 69 by McCracken et al. (2008) showed that the initial impulsive event was the source of the hard spectrum. Thus, the counting ratio of a bare neutron monitor counter to the standard neutron monitor at Sanae showed that the spectrum softened abruptly at the end of the impulsive event (±1 minute), and then changed to a persistently soft spectrum once the worldwide GLE commenced. This correspondence between the HEI GLE and the "prompt component" of Vashenyuk et al. (2006, 2007, 2011) is consistent with the modeling studies of Vashenyuk et al. (2011), and we conclude that the spectrum of the HEI GLE approximates that determined for the prompt component by them.

8. CORRELATIONS WITH NUCLEAR AND OTHER SIGNALS FROM THE SUN

GLEs are invariably associated with short-lived (minutes to hours) radio, optical, and X-ray emissions. These radiations are primarily due to synchrotron and bremstrahlung processes initiated by electrons, which can be accelerated by several solar processes. In addition, on rare occasions there are other signals that are nuclear in nature, which require the presence of a short-lived population of relativistic SEPs impinging on solar matter. The signals we consider here are then conveyed by neutrons and gamma rays, and neither of them is impeded by magnetic fields. Consequently, their time of flight to Earth is relatively well known.

Figure 4 presents data from HEI GLE 48 that occurred on 1990 May 24. The worldwide GLE was small and slow rising, as for example, Moscow, where the increase rose only to ∼5% almost an hour after the start of the event. Mt. Wellington, on the other hand, illustrates the short-lived pulse seen by a small number of detectors as shown in Table 2, up to rigidities 6.75 GV (e.g., Alma Ata B in the figure). The one-minute data from Mt. Wellington show a rise time $T_r = 6$ minutes; peak intensity $T_p =$ 4 minutes, and a fall-time from the peak to 65% of the peak intensity $T_f = 10$ minutes. The five-minute data from Alma Ata are consistent with these times. The impulsive event seen at Mt. Wellington is also included in Figure 5, and this demonstrates its similarity to the other events discussed previously.

As Figure 4 shows, the Climax neutron monitor saw this event. Shea et al. (1991) reported another short-lived pulse about 12 minutes earlier, seen by seven neutron monitors throughout the sunlit hemisphere. Using one-minute data from the Climax neutron monitor, those authors concluded that this earlier pulse was due to solar neutrons that arrived at Earth at about 20:49. Examination of their data, as reproduced in Figure 4, shows that the rising phase was less than one minute, followed by a relatively flat three-minute maximum, followed by a steady six-minute decline to noise level. The characteristics of this pulse are confirmed by the Mexico City neutron monitor, although the time resolution there was only five minutes. The HEI GLE pulse started at Mt. Wellington at 21:01 ± 00:01, yielding a delay of 12 ± 1 minutes between the commencement of the neutron pulse and the charged-particle pulses at Earth. The solar neutron energies must be >0.5 GeV to initiate a nucleonic shower that would be seen at ground level. According to Ramaty (1986) they are understood to be "knock-on" neutrons produced by the impact of >1 GeV particles on ions in the chromosphere. The timing and location are unambiguous—the neutrons are unimpeded by magnetic fields, and matter is required to provide the collisions that produce the neutrons. This implies that the SEPs impinged on the chromosphere. The transit time to Earth for a 1 GeV neutron is ≈9.7 minutes, so the solar neutron pulse indicates that a population of >1 GeV charged particles impinged on the chromosphere starting at 20:39 and extending until 20:49. Solar neutron pulses and the HEI GLEs studied here are very rare events, and this, together with the favorable geometry of the solar activity (76° West) for solar neutrons to reach Earth, leads us to associate the solar neutron pulse with the HEI GLE (see Chupp et al. 1987 for details of neutron detection).

We now consider GLE 69. As discussed in Section 3, and in McCracken et al. (2008), a short-lived, intense HEI GLE was observed to commence at 06:50.5 ± 0.5 by two muon detectors and the Climax and SANAE neutron monitors (all detecting P > 4 GV particles). Some neutron monitors, such as McMurdo observed both the high- and low-rigidity portions of the spectrum, the pulse commencing at the same time as Climax and SANAE, while continuing several minutes longer as a consequence of velocity dispersion. Figure 6, copied from McCracken et al. (2008), compares the pulse profile of the Sanae neutron monitor for GLE 69 with that of the >90 MeV gamma rays observed by the Coronas-F satellite, as described by Grechnev et al. (2008). These gamma rays originate in the decay of π_0 mesons, produced by the collision of >300 MeV particles with solar matter. In this case, the gamma-ray pulse therefore preceded the commencement of the anisotropic neutron monitor pulse that commenced at 06:50.5 ± 0.5 for P > 4 GV) by seven minutes. Struminsky (2006) also made a detailed study of the high-energy electromagnetic emission associated with this event, and concluded that its close correlation with the solar proton flux near the Earth is evidence for prolonged and multiple proton acceleration in solar flares.

The propagation time for gamma rays is the light-transit time of 8 minutes and 20 s. The Parker spiral from Sun to Earth has a nominal length of 1.2 AU, and hence the propagation

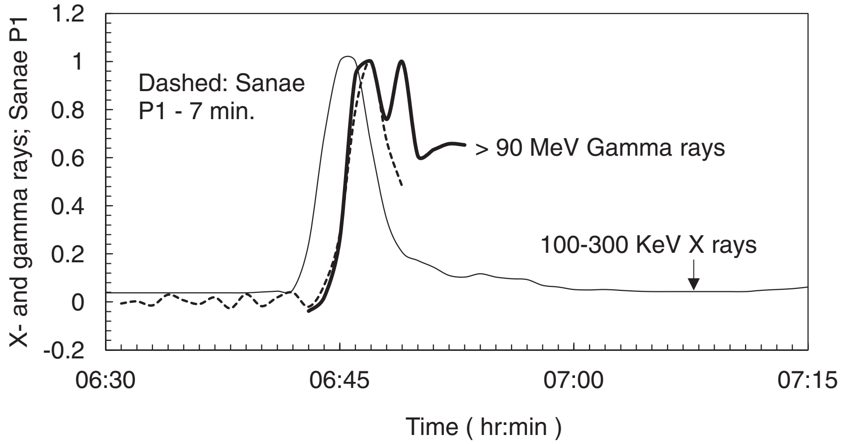

Figure 6. (Copied from Figure 10 of McCracken et al. 2008.) X-ray and gamma-ray emissions, observed by the *RHESSI* and *CORONAS-F* spacecraft, respectively, together with the P1 cosmic ray pulse observed by Sanae. This pulse is shifted backward in time by seven minutes. The horizontal scale is observation time at Earth. All profiles are normalized to their peak values. Copyright 2008 American Geophysical Union. Reproduced by permission of the American Geophysical Union.

time of the highly collimated relativistic charged particles along this field configuration will be ∼10 minutes. This is 1 minute 40 s longer than for gamma rays, and 20 s longer than for 1 GeV neutrons from the Sun. Hence in the two cases cited above, if the neutrons, gamma rays and charged particles left the vicinity of the Sun at the same instant, the delays of ∼7 and ∼12 minutes imply that charged particles propagated along highly distorted field lines with a total length of 1.8 and 2.4 AU in the two cases, while preserving fast rise and fall times as in Table 2. Such long path lengths are not inferred from so-called $1/v$ studies by, e.g. Reames (2009), and therefore it seems that the charged particles that did arrive at Earth were either accelerated later than the source particles for the neutrons and gamma rays, or that there was a storage mechanism in the near-solar magnetic fields for them before they were released.

Aschwanden (2012) has used the Neupert effect to estimate the intervals during which high-energy electrons were accelerated in association with 13 GLEs that occurred during solar cycle 23. He concluded that the observations were consistent with the “prompt” components of the subsequent GLEs having been accelerated in the lower corona in 11 out of the 13 events. For GLE 69 his estimates yield a delay of six minutes to the commencement of the HEI GLE, in good agreement with the delay in the case of the gamma-ray pulse discussed above. For GLE 60 and GLE 70, his estimates yield delays of 24 and 30 minutes to the initiation of the HEI GLE pulse. If we can associate the Neupert pulse with the acceleration of energetic SEP ions as well as electrons, this suggests that the HEI GLE particles frequently reach Earth 5–20 minutes after the electromagnetic and neutron pulses that herald the acceleration of relativistic electrons and ions in the corona. This time delay indicates trapping of the particles after acceleration.

Bieber et al. (2002, 2004, 2007) and Saiz et al. (2008) proposed that time delays of charged-particle peaks observed at Earth may be due to heliospheric magnetic field configurations that cause the particles to arrive at Earth along the “long” leg of a closed magnetic loop, or that they were reflected back inward from a highly turbulent region beyond 1 AU. Such an explanation must, however, successfully explain the rapid rise times, and even more the very short switch-off times of the HEI GLEs. This is difficult for spatially extended magnetic field configurations far away from the solar source.

9. THE CHARACTERISTICS OF THE HEI GLE

Based on the foregoing discussions and the data in Table 2, we now summarize the characteristics of the 10 large HEI GLEs in the archival record. As discussed previously, the evidence shows that the HEI GLE is a major component of the prompt component defined by Vashenyuk et al. (2006, 2011) and we use the spectral data from those studies in the following. The combined temporal characteristics (this paper) and spectra (Vashenyuk et al. 2011; Bombardieri et al. 2008) define important constraints that apply to any mechanism proposed to explain the initial impulsive phase of the GLE.

1. Large GLEs originating at $\geqslant 24^\circ$ West on the solar disk invariably commence with an HEI GLE. For the 10 events studied, the average duration of the impulsive event is 21 minutes.
2. The rise times are short, six being in the range three to seven minutes, with an average of seven minutes for all 10 events.
3. When high time-resolution data are available, the rise times are consistent with the simultaneous release of a pulse of both high (>5 GV) and low (1–2 GV) rigidities near the Sun, followed by velocity dispersion en route to Earth. This imposes constraints on the particle injection process: (a) either the particles have free access to the heliospheric field which implies that $P > 5$ GV particles must be accelerated to those rigidities within one minute; or (b), if the accelerated population is trapped prior to release, there is efficient trapping up to $P > 5$ GV, followed by simultaneous and efficient release over the range from 1 to >5 GV.
4. Some of the events exhibit a flat top for up to five minutes at all energies.
5. Following the peak, the intensity decreases very rapidly to 50% of the peak value; in five cases, the fall-time is between three and seven minutes, in each case being comparable to the rise time of that event. The average 50% fall time for all 10 events is ∼10 minutes.
6. The rise and fall times are marginally longer, by one to three minutes, for low rigidities (1–2 GV), compared to those at high rigidities, which is consistent with velocity dispersion.
7. The impulsive event is usually observed up to rigidities >5 GV and has extended to >20 GV twice, for GLEs 5

and 42. The rise time for GLE 5 at >13.5 GV is one of the fastest ever recorded (∼6 minutes), providing a strong constraint on the nature of the acceleration process.

8. On two occasions, for GLEs 69 and 48, freshly accelerated SEPs are known to have impacted on matter in the chromosphere 7 and 12 minutes, respectively, prior to the assumed departure of the impulsive SEP from the near-Sun environment. The delays from the start of the "Neupert pulses" for GLEs 60 and 70 are even longer, at 24 and 30 minutes, respectively. In a third case, for GLE 42, which occurred behind the limb, the timing is more complicated (see, e.g., Vestrand & Forrest 1993).
9. These 10 large HEI GLEs have all been associated with major flares or CME activity at $\geqslant 24^\circ$ W on the solar disk. All 10 exhibited the rapid fall times which we propose imposes strict constraints on any putative acceleration mechanism. Nine of these ten were followed by a slow worldwide GLE.

10. DISCUSSION

The following discussion is restricted to the HEI GLE, alone. It acknowledges that the slower rising, worldwide GLE is probably produced by first-order Fermi acceleration in the quasi-parallel shock ahead of the associated CME at ∼4 solar radii, e.g., McCracken et al. (2008), with an additional contribution from particles scattered out of the HEI GLE beam. It also recognizes the well-known distinction between the "prompt" and "gradual" SEP events observed at lower energies. In particular, it recalls that the "prompt" events are rich in ^{3}He, indicating an origin low in the corona. (We note that "prompt" and "gradual" in the context of SEP events initially referred to the onset or rate of rise of the soft X-ray emissions. Short duration X-ray events typically give rise to events rich in ^{3}He.)

We interpret the characteristics of the HEI GLE in terms of the available acceleration mechanisms. There are three distinct such mechanisms, namely first-order Fermi acceleration at the bow of an outward-moving shock front surrounding a CME, where the normal to the shock front is quasi-parallel to the ambient magnetic field; a similar acceleration when the CME shock normal is quasi-perpendicular to the field, as typically happens on its flanks; and acceleration in the reconnection region in the coronal magnetic fields that extend down to the solar flare observed in the chromosphere.

In first-order Fermi (or shock) acceleration in a quasi-parallel configuration the acceleration timescale is of the order of κ/V_s^2, where κ is the diffusion coefficient due to pitch-angle scattering of the particles along the magnetic field lines, and V_s is the shock speed. The relationship between diffusion coefficient and diffusion mean-free-path is $\kappa = v\lambda/3$, with v being the particle speed, and according to Caballero-Lopez et al. (2004) the typical mean-free-path at Earth that fits the galactic cosmic-ray modulation is $\lambda = 0.25P(\text{GV})$ AU. Using $V_s = 2000$ km s^{-1}, this leads to an acceleration timescale of $\tau_a = 10.4\beta P(\text{GV})$ days. Diffusion coefficients should scale approximately inversely proportional to B, and in the inner heliosphere the Parker spiral field scales as r^{-2}. Thus, the acceleration timescale at 4 solar radii, which is the typical distance where CME shocks have developed, is $\approx 0.16\beta P(\text{GV})$ hr. For ∼2 GV particles this implies an acceleration time of ∼15 minutes, which is consistent with what is observed for the typical worldwide GLE. For the HEI GLEs studied in this paper, where rigidities up to 20 GV have been observed, this estimate implies acceleration times of more than 3 hr, which is up to 60 times longer than the few to several minutes observed for the rise times Tr of the leading edges in Table 2. We note, however, that Ng & Reames (2008) argued that the acceleration timescale may be reduced by orders of magnitude through self-excitation of waves, and it would be desirable to model this in further detail for the events reported in this paper. As discussed below, the rapid fall times observed in all HEI GLEs may be incompatible with the Ng & Reames (2008) hypothesis.

The flanks of a CME will typically expand in the latitudinal and longitudinal directions across the solar surface. Hence, in these regions the magnetic field will more typically be quasi-perpendicular to the normal on the shock front. The diffusion coefficient perpendicular to the magnetic field, described by the nonlinear guiding center theory of Matthaeus et al. (2003), and mostly caused by random walk of field lines (e.g., Giacalone & Jokipii 1999), is typically 10–100 times smaller than the parallel coefficient due to pitch-angle scattering, This can bring the acceleration of 5–20 GV particles down to the order of a minute, which is sufficient to account for the short rise times of the HEI GLEs. Zank et al. (2007) have pointed out, however, that a drawback of the quasi-perpendicular scenario is that the maximum energies achieved are smaller than in quasi-parallel shocks because self-excited waves are not effective in the quasi-perpendicular acceleration case. Also, the injection energy threshold for quasi-perpendicular shocks is much higher than for quasi-parallel shocks. We note that for a CME shock both problems may be mitigated by particles that are pre-accelerated in the quasi-perpendicular front of the CME, and then "slide down" to the quasi-perpendicular flanks. This is the essence of the composite or mixed particle-acceleration model proposed by Li & Zank (2005) for SEP events.

In flare acceleration, the process occurs in the turbulent reconnection region above an expanding solar flare. A possible acceleration mechanism there is that of the contraction of elongated magnetic islands formed in this region, as proposed by Drake et al. (2006). The speed of contraction is the Alfvén speed, V_A, and in this case the acceleration timescale is l/V_A. It is also a first-order process because the islands will always contract (never expand). This is potentially much faster than the shock acceleration discussed above, because for typical values $V_A \sim 2000$ km s^{-1}, the timescale is $\tau_a = 0.25l$ s when the scale size of the islands, l, is expressed in solar radii. Typical values of l will be only a small fraction of a solar radius, and the highest energies observed are therefore not a problem for this mechanism.

The short fall-off times observed for the HEI GLEs are likely to impose constraints on any putative acceleration mechanism. For acceleration in a quasi-parallel shock at the nose of a CME, this would require that pre-existing and self-generated turbulence (as proposed by Ng & Reames 2008 to provide rapid particle acceleration), would switch off abruptly. It is not clear how this can happen. For a quasi-perpendicular shock such as on the flanks of a CME, it is conceivable that the shock front may connect and disconnect with open field lines that are connected to Earth, and so lead to both an abrupt switch-on and switch-off of the SEP pulse The quasi-perpendicular shock also has the advantage that particles are accelerated nearer to the lower corona, and if they propagate along the shock front into the Sun, they provide a natural explanation for the gamma rays and neutron pulses observed with some of the events.

The 7–12 minute delays from the arrival of the nuclear signals (and the Neupert pulse) and the HEI GLE may provide an important clue to the origin of the HEI pulse. Excluding the possibility of exceedingly long magnetic field lines of force leading back to the Sun, they indicate that a population of >1 GeV ions was accelerated in the corona 7–12 minutes before the HEI GLE pulse departed the vicinity of the Sun. In this time, the associated CME will have traveled 1–2 solar radii. The delays therefore suggest that (1) the acceleration occurs in a region of the corona without access to the open field, but with access to the chromosphere; (2) that the >1 GeV particles remain trapped in the coronal fields for ∼10 minutes or more; and (3) that the SEP particles of all rigidities are released into the open field simultaneously, possibly by a triggering action of the CME.

11. CONCLUSIONS

Using the database of 71 GLEs observed between 1942 and 2012, we have identified 10 short-lived, highly anisotropic pulses of cosmic rays with rigidities $P > 5$ GV that constitute the first phase of large GLEs. Their rise times of three to seven minutes, and precipitous fall-off times within another three to seven minutes puts them in a different category than the generally observed GLE which has a duration of several hours. The nine largest GLEs in the archival record that originated from activity $\geqslant 24^\circ$ W on the Sun exhibit this behavior. In most cases the short-lived pulse is followed by a more gradual GLE. On account of their impulsive nature, and extension to high energies, we have named these pulses the HEI GLE. We conclude that they are a subset of the PC defined by Vashenyuk et al. (2006). Their rapid fall times, and other features of their time profile, provide nine constraints given in Section 9 that must be met by any putative acceleration mechanism in addition to predicting the PC spectra given by Vashenyuk et al. (2011). Unlike previous papers, e.g., Bieber et al. (2002, 2004, 2007) and Saiz et al. (2008) we do not ascribe these pulses as due to transport effects in the heliospheric magnetic fields.

First-order Fermi acceleration in quasi-parallel and quasi-perpendicular CME shocks, as well as in reconnection regions above expanding solar flares, or a mixture thereof, offer plausible explanations for the effect. For the two cases where nuclear signals such as high-energy gamma rays and neutron pulses are available, the HEI GLE pulses are delayed by 7 and 12 minutes relative to these signals, and the origin of this delay as due to propagation delays in the heliospheric magnetic field or storage of freshly accelerated particles before their release onto field lines that are connected to Earth, is presently unresolved. This requires continued observations of the GLEs, together with ever-improving observations of the electromagnetic radiation as offered by current and next-generation spacecraft such as *SOHO*, *Stereo*, and the *Solar Probe*.

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