

# Spectra and Properties of Ground-Level Events During Solar Cycle 23

R. A. Mewaldt\*, M. D. Looper†, C. M. S. Cohen\*, D. K. Haggerty†, A. W. Labrador\*, R. A. Leske\*, G. M. Mason‡, J. E. Mazur§ and T. T. von Rosenvinge¶

\*Caltech, Pasadena, California 91125 USA

†The Aerospace Corp., El Segundo, CA, 90245 USA

‡Johns Hopkins University, Laurel, MD, 20723 USA

§The Aerospace Corporation, Chantilly, VA, 20151 USA

¶NASA/Goddard Space Flight Center, Greenbelt, MD, 20771 USA

**Abstract.** We report spacecraft measurements of the energy spectra of solar protons and other solar particle properties during the 16 Ground Level Events (GLEs) of Solar Cycle 23. The measurements were made by seven instruments on the ACE, GOES, SAMPEX, and STEREO spacecraft and extend from  $\sim 0.1$  to  $\sim 700$  MeV. All of the proton spectra exhibit spectral breaks at energies ranging from  $\sim 2.4$  to  $\sim 33$  MeV and all are well fit by a double power-law shape. A comparison of GLE events with a sample of other SEP events shows that GLEs typically have harder spectra, with a mean slope of  $-3.17$  at  $>40$  MeV/nuc. On average, GLE events are enriched in species associated with impulsive  $^3\text{He}$ -rich SEP events, including enrichments in Ne/O, Fe/O,  $^{22}\text{Ne}/^{20}\text{Ne}$ , and elevated mean charge states of Fe. This paper discusses these and other properties of particles measured *in situ* in GLE events.

**Keywords:** Solar energetic particles, particle acceleration, solar particle composition

## I. INTRODUCTION

Ground-level events (GLEs) are large Solar Energetic Particle (SEP) events in which the intensity of high-energy solar protons is sufficient to rise above the galactic cosmic ray (GCR) background in one or more ground-based neutron monitors (e.g., [1]). For high-latitude neutron monitors, the threshold for H (or He) is set by the atmosphere thickness at  $\sim 500$ - $1000$  MeV/nuc, depending on altitude. GLEs are of space weather interest because they can present a risk to astronauts (and airline passengers). GLEs are of scientific interest because they represent examples of events in which the particle acceleration process has apparently been more efficient, lasted longer, or been more widespread than in 90% of more typical SEP events. During solar cycle 23 there were 16 GLEs, adding to the total of  $>60$  over the past  $\sim 75$  years. These 16 events were the subject of an interdisciplinary LWS CDAW workshop held in Palo Alto in January, 2009. In this paper we summarize spacecraft measurements of the proton energy spectra and other properties of the solar

TABLE I  
SOURCES OF ENERGETIC PARTICLE DATA FOR SEP ENERGY SPECTRA

Mission	Instrument	Species	Kinetic Energy MeV or MeV/n	Ref.
ACE	EPAM	H	0.03 to 5	[2]
	ULEIS	H to Fe	0.04 to 8	[3]
	SIS	He to Fe	8 to 100	[4]
GOES	EPS	H	8 to 200	[5]
	HEPAD		350-700	[5]
SAMPEX	PET	H	20-500	[6]
STEREO	LET	H	1.8-12	[7]
	HET	H	13-100	[8]

energetic particles (SEPs) observed in the GLEs of solar cycle 23.

## II. OBSERVATIONS

The spacecraft measurements reported here extend from  $\sim 50$  keV to  $\sim 700$  MeV for protons and from  $\sim 50$  keV/nuc to  $\sim 100$  MeV/nuc for heavier ions. They were made with instruments on NASAs ACE, SAMPEX, and STEREO missions and on NOAAs GOES-8, 10, and 11 missions, as summarized in Table 1. ACE provides continuous coverage of SEP events from L1 while SAMPEX is in an  $\sim 600$  km,  $82^\circ$  inclination orbit that provides two  $\sim 15$  minute high-latitude passes ( $>70^\circ$  invariant latitude) during each  $\sim 90$  minute orbit (e.g., [9]). During polar passes the instruments are zenith pointed. STEREO was launched in October, 2006, just in time to record the last GLE of solar cycle 23. The twin STEREO spacecraft are now separating from Earth at  $22.5^\circ$  per year.

NOAAs GOES-8, 10, and 11 satellites are in geosynchronous orbit at  $L = 6.6$  where geomagnetic effects are relatively small for protons  $>10$  MeV. Data reported here are from the EPS and HEPAD sensors [5]. Use of GOES proton spectra from  $\sim 10$  to  $\sim 200$  MeV is described in Mewaldt et al. [9]. The HEPAD spectra from 350 to 700 MeV have been corrected as described in Smart & Shea [10].

Figure 1 shows energy spectra for two GLE events. For all events we have fit the proton spectra from  $\sim 0.1$  to  $\sim 500$  MeV/nuc using the Ellison-Ramaty [11]

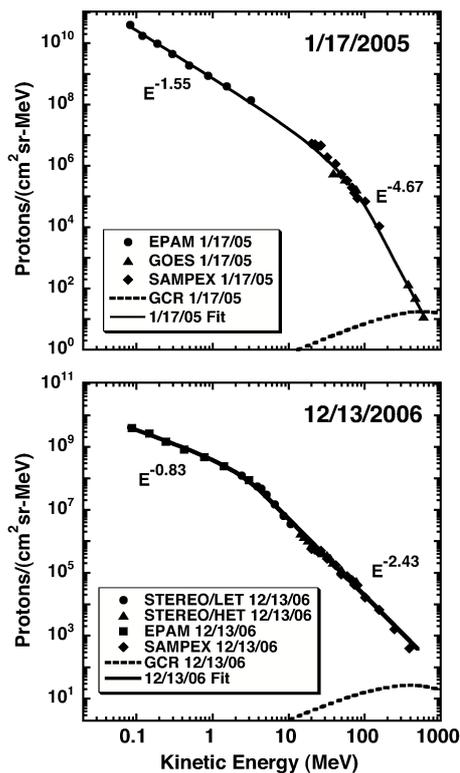


Fig. 1. Proton fluence spectra for two GLEs are fit with the double power-law form of [12]. Also indicated are the approximate cosmic-ray proton fluence for these time periods and the asymptotic slopes of the two power-laws.

form (power-law with an exponential cutoff), and the double power-law form of Band et al. [12]. All sixteen spectra have breaks with break energies (defined by the intersection of the two power laws) that range from 2.4 to 33 MeV. In all cases the double power law form fit best, as was also found for the five Halloween 2003 events [9]. In Figure 2 the range of spectral indices above the break for the 16 GLE fits is compared with those for 22 large non-GLE events fit with the same function. On average, GLE spectra are significantly harder than those of typical SEP events.

### III. OTHER PROPERTIES OF GROUND LEVEL SEP EVENTS

In this section we compare some properties of GLEs with those of other large (non-GLE) SEP events. If particular GLE characteristics or signatures can be identified they may provide clues to why the acceleration process in these events is apparently more efficient than in typical SEP events. Some of these properties are summarized in Table II (see also [31]).

The Fe/O ratio is often used to characterize SEP events because it may be a diagnostic of flare material. In Figure 3 the  $> 30$  MeV proton fluence is plotted versus the Fe/O ratio at 25-80 MeV/nuc. Note that Fe/O varies by a factor of  $\sim 100$  or more in both samples, including a roughly equal number of Fe-rich and Fe-poor events

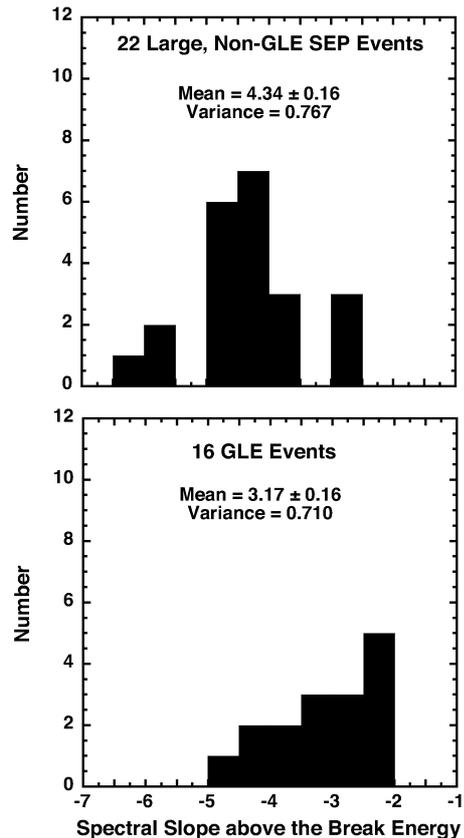


Fig. 2. Comparison of the high-energy spectral indices (above the break; see Figure 1) based on fits to 22 non-GLEs and 16 GLE events. The mean and variance of the distributions are indicated.

relative to coronal abundances. It is also interesting that these two samples span much the same range of  $>30$  MeV proton fluences. Some non-GLE events in the top of Figure 3 have 100 to 500 times the  $>30$  MeV proton fluence of some GLE events in the bottom panel, yet they fail to be identified as GLEs. This failure is presumably due to spectral differences (see Figure 2) as well as to the much more gradual time profiles of eastern hemisphere events, which may have large fluences, but never reach peak intensities that stand out above the  $>1$  GeV GCR background. One noticeable feature is that Fe-rich GLEs, on average, have 1-2 orders of magnitude smaller  $>30$  MeV proton fluences than the Fe-poor GLEs, as is also seen for non-GLE events [24]. It would be interesting to investigate whether this is a result of spectral differences, composition differences, or both.

A second signature of flare material is Ne/O [13], [14]. Figure 4 illustrates that Fe/O and Ne/O are correlated for most events with  $\text{Fe/O} > \sim 0.15$ , while for  $\text{Fe/O} < 0.1$  the Ne/O ratio appears to level off at a value similar to the coronal ratio [14]. Compared to the average SEP abundances at 5-12 MeV/nuc [15], 11 of the 16 GLEs are Fe-rich and 10 are Ne-rich. Although not shown here, the mean  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio for GLE events is also enriched by a factor of  $\sim 1.5$  with respect to the solar-wind ratio, and enriched by  $\sim 27\%$  relative to the mean

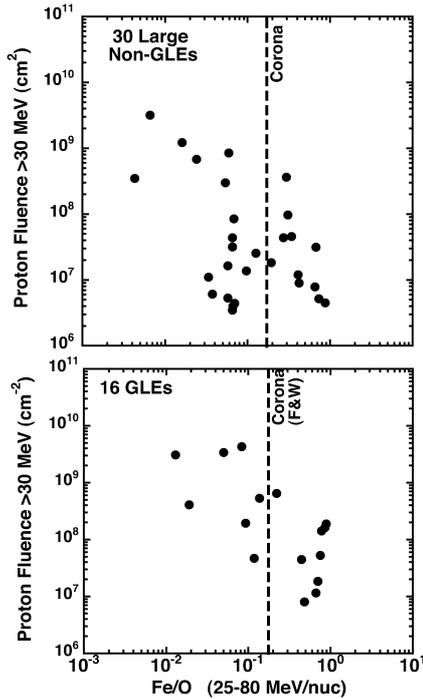


Fig. 3. Plot of the  $>30$  MeV proton fluence measured by GOES versus the Fe/O ratio measured by ACE/SIS for 30 non-GLEs (top panel) and 16 GLEs (bottom panel). The coronal ratio of Feldman and Widing [23] based on spectroscopic data is also indicated.

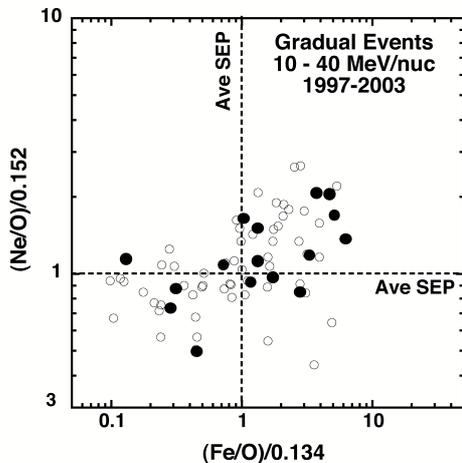


Fig. 4. Plot of Ne/O vs. Fe/O for 16 GLEs (big circles) and 26 non-GLEs (open circles). Based on ACE/SIS data (see also [14]). The dashed lines show average SEP abundances of Reames (1995).

of 26 non-GLE events.

In the energy range  $>20$  MeV/nuc the mean ionic charge states of SEPs can be measured using the geomagnetic technique [16]. Figure 5 compares the mean charge state of Fe,  $\langle Q_{Fe} \rangle$ , for nine GLEs and nine non-GLEs. Included are SAMPEX measurements using the geomagnetic technique [17] and three values obtained by indirect approaches based on fitting the composition and spectra of heavy ions [18], [19]. Note that the mean value of  $\langle Q_{Fe} \rangle$  for the GLEs is marginally greater than that for non-GLE events (by  $\sim 1.4\sigma$ ), and that the range

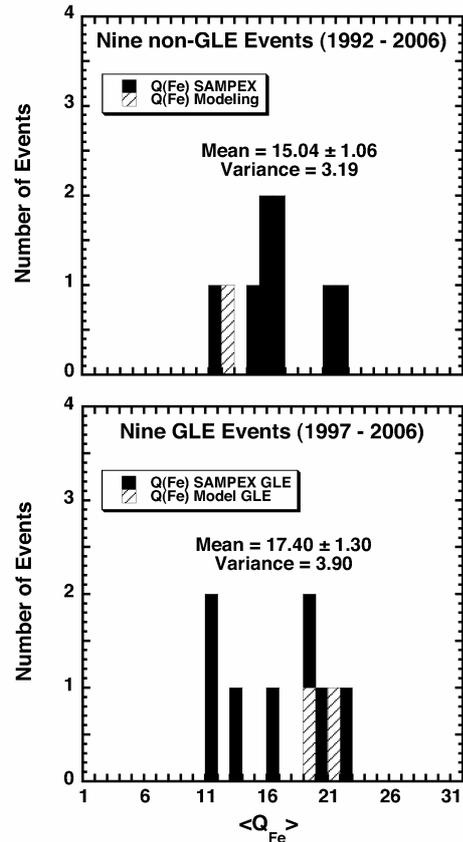


Fig. 5. Histograms of the mean ionic charge state of SEP Fe  $\langle Q_{Fe} \rangle$  for non-GLEs and GLEs, as determined using the geomagnetic method (Labrador et al. 2005) and by modeling SEP composition and spectra ([18], [21]). The mean and variance of the distributions are indicated. Uncertainties in individual events are typically  $\sim 2$  charge units.

is similar.

#### IV. DISCUSSION

The comparisons presented here indicate that, on average, the 16 GLEs of solar cycle 23 are rather similar to other large SEP events. The only significant difference is in the spectral index above the spectral break in the proton spectrum (typically  $>30$  MeV for protons), which is  $-3.17$  for GLEs, compared to  $-4.34$  for non-GLEs. This harder spectrum allows smaller SEP events to supply many more protons  $>0.5$  GeV using the same amount of energy from the accelerator as is measured in larger events. Giacalone [20] has shown that shock acceleration at quasi-perpendicular shocks can proceed much more rapidly and provide a harder spectral index than at parallel shocks. In addition, Tylka et al. [21], [22] have suggested that acceleration at quasi-perpendicular shocks can also explain the enrichment of Fe and other heavy species (discussed below) if quasi-perpendicular shocks have a higher injection threshold, such that they accelerate mainly suprathermal ions.

Many GLEs exhibit properties generally associated with flare material as observed in impulsive ( $^3\text{He}$ -rich) SEP events [18], [24] including enrichments in Fe/O, Ne/O,  $^{22}\text{Ne}/^{20}\text{Ne}$ , and highly ionized charge states of

TABLE II  
GLE EVENTS FROM SOLAR CYCLE 23 ALONG WITH SELECTED PROPERTIES.

Date	X-ray Intensity	Location <sup>a</sup>	>30 MeV Fluence <sup>b</sup>	Spectral G1 <sup>c</sup>	Spectral G2 <sup>c</sup>	Fe/O 25-80 MeV/n	Ne/O 10-30 MeV/n
11/6/97	X9.4	S18W63	1.63 e+08	1.03	2.44	0.857	0.259
5/2/98	X1.1	S15W15	1.85 e+07	1.94	2.70	0.701	0.331
5/6/98	X2.7	S11W65	8.02 e+06	1.04	2.89	0.481	0.317
8/24/98	X1.0	N35E09	4.69 e+07	1.35	3.85	0.118	0.172
7/14/00	X5.7	N22W07	4.31 e+09	1.09	3.78	0.083	0.159
4/15/01	X14	S20W85	1.45 e+08	1.12	2.09	0.776	0.175
4/18/01	?	S23W117	4.48 e+07	1.30	2.43	0.444	0.167
11/4/01	X1.0	N06W18	3.40 e+09	1.19	4.50	0.050	0.186
12/26/01	M7.1	N08W54	1.16 e+07	1.52	3.13	0.662	0.130
8/24/02	X3.1	S02W81	5.30 e+07	1.25	2.90	0.753	0.148
10/28/03	X17	S20E02	3.07 e+09	1.03	4.36	0.013	0.109
10/29/03	X10	S19W09	5.34 e+08	1.10	3.15	0.137	0.241
11/2/03	X8.3	S18W59	1.95 e+08	1.09	3.44	0.092	0.131
1/17/05	X3.8	N14W25	6.50 e+08	1.55	4.67	0.019	0.179
1/20/05	X7.1	N14W61	4.10 e+08	0.98	2.14	0.221	0.228
12/13/06	X3.4	S06W23	1.67 e+08	0.83	2.43	0.884	0.205

<sup>a</sup> Flare locations from [31].

<sup>b</sup> Units for the proton fluences (measured by GOES) are protons/(cm<sup>2</sup>sr-MeV).

<sup>c</sup> G1 & G2 are preliminary spectral indices above & below the break.

Fe. Indeed, many GLE events have <sup>3</sup>He/<sup>4</sup>He ratios significantly greater than in the solar wind, as is often seen in other large events (e.g., citecoh99,can03). While GLEs appear to include a greater fraction of events with these properties, the differences do not appear to be significant.

Following work by Dietrich and Lopate [25], Tylka et al. [21] reported that 33 of 38 GLEs observed from 1976 through 2003 had Fe/O ratios that were enriched by a factor of  $\geq 2$  at 40 MeV/nuc or higher with respect to the average SEP abundances of Reames [15], in which Fe/O = 0.134. Their survey included SIS data from 13 of the 16 events from solar cycle 23. In the 25-80 MeV/nuc interval only 50% of the 16 GLEs in Table 2 show this enrichment, although an Fe enrichment could be present at higher energies.

Among the possibilities suggested to explain flare signatures in SEP events associated with both large flares and fast CMEs are the following: 1) shock acceleration of remnant suprathermal ions in the interplanetary medium left from previous impulsive SEPs [26], [21]; (2) mixed contributions from escaping flare-accelerated particles and CME shock-accelerated particles [27], [28]; (3) shock acceleration of a mixture of solar wind and escaping flare particles [29]; and (4) acceleration of a mixture of suprathermals and CME ejecta [14]. Li and Mewaldt [30] discuss a model where CME and flare-accelerated material may be shock-accelerated when two closely-spaced CMEs interact. The data presented here do not rule out any of these possibilities.

Now that the twin STEREO spacecraft are separated by  $>90^\circ$ , it will be interesting to study solar cycle 24 GLE events from three separated locations, which may put these ideas to a better test.

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