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Key Points:
- The 10 September 2017 event proton spectrum was a broken power law, typical of ground-level events but softer than usual at high energies
- Due to the event's high break energy, the 100-MeV proton fluence was within a factor of 4.5 of the largest ground-level events of cycle 23
- STEREO observed events larger than the largest cycle 23 ground-level event, but the top 10 events were smaller in cycle 24 than cycle 23

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The Ground-Level Enhancement Event of September 2017 and Other Large Solar Energetic Particle Events of Cycle 24

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Abstract The 10 September 2017 solar energetic particle (SEP) event was the largest since June 2015 and one of only two ground-level enhancement (GLE) events of solar cycle 24. GLE events are subset of large SEP events (~15% of events identified by Space Weather Prediction Center) with particularly hard spectra, making them a substantial space weather hazard to space-based instrumentation and exposed astronauts. We present analysis of the 10 September 2017 event and compare it to the other cycle 24 GLE events, to those of cycle 23, and also to two extreme SEP events observed by Solar Terrestrial Relations Observatory (STEREO). We find the 10 September 2017 event had a broken power law spectrum typical of GLE events but was softer than average at high energies. However, it was hard at low energies with a relatively high break energy, which led to 100-MeV proton fluences within a factor of 4.5 of the largest cycle 23 GLE events. The composition was nominal, except for a low Fe/O ratio, which has also been seen in large SEP events this cycle, but is somewhat atypical of the cycle 23 GLE events. The extreme events seen by STEREO exhibited very hard high-energy spectra, with one event producing ~80-MeV proton fluences larger than the largest cycle 23 GLE event. However, even including STEREO events, the top 10 largest cycle 24 events are, on average, 2.4 times smaller than the top 10 of cycle 23 based on >10-MeV proton fluences.

1. Introduction

Ground-level enhancement (GLE) events are a particular category of extreme solar energetic particle (SEP) events. In such events there are a sufficient number of energetic ions above ~500 MeV, which interact with the Earth's atmosphere to create quantities of secondary neutrons and/or muons measurable by ground-based instrumentation. In comparison with other SEP events identified as being of *space weather interest* (i.e., having >10 particles per centimeter squared-steradian-second-mega-electronvolt at energies >10 MeV, also commonly referred to as *Geostationary Operational Environmental Satellite* [*GOES*] *events*), GLE events typically have significantly harder spectra with an average power law index of −3.18 at energies >40 MeV (Mewaldt et al., 2012). The combined hard spectra and large intensity of >50-MeV/nuc ions makes GLE events a particular danger to space-based instrumentation and exposed astronauts (Shea & Smart, 2012).

Due to these space weather concerns, there has been significant effort over the last few decades to determine the specific conditions that produce GLE events (see, e.g., Gopalswamy, Xie, et al., 2014; Kahler et al., 2012; Nitta et al., 2012; Reames, 2009; and references therein). Through the combined analysis of coronagraph observations of coronal mass ejections (CMEs), radio bursts, and SEP onset times (e.g., Gopalswamy et al., 2012; Reames, 2009), it has been determined that GLE events tend to be associated with the faster CMEs (>2,000 km/s on average), intense X-ray flares, large active regions that are magnetically well connected to the Earth, and shock acceleration at low altitudes (e.g., <3 R_S). Unfortunately, partly due to their relative rarity (only 46 out of 261 GOES events from 1976 to 2017 were GLE events), determining a specific set of conditions that can be used to predict the occurrence of a GLE event remains elusive (e.g., Kahler et al., 2011; Nitta et al., 2012) and our current ability to predict the characteristics (e.g., composition, spectral index, and peak intensity) of an ensuing GLE event remains virtually nonexistent.

Since the launch of the twin STEREO spacecraft, the opportunity to measure SEP events has increased to include events beyond the subset of those observed along the Sun-Earth line. Although, by definition, GLE events can only be detected by Earth-based instrumentation, several extreme SEP events have been measured by STEREO SEP sensors, which had harder spectra and higher >50-MeV fluences than the GLE

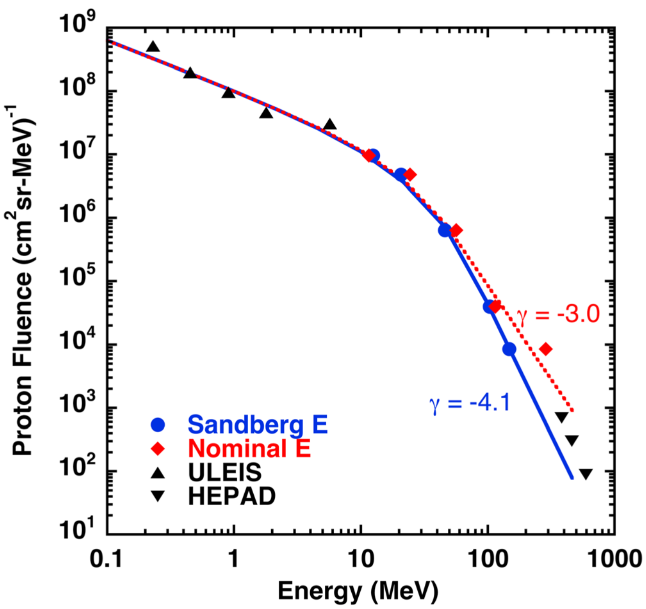

Figure 1. Event-integrated proton fluences versus energy using the nominal GOES/EPS energy values (red diamonds) and using the recommended GOES/EPS effective energy values (blue circles) at energies ~10–100 MeV. The lower-energy data are from ACE/ULEIS (triangles) and the highest-energy data are from GOES/HEPAD (inverted triangles). The two Band fits (solid and dashed lines) do not use the GOES/HEPAD data and indicate the influence of the different EPS energy values on the high-energy spectral index. ACE = Advanced Composition Explorer; EPS = energetic particle sensors; GOES = Geostationary Operational Environmental Satellite; HEPAD = High Energy Proton and Alpha Detector; ULEIS = Ultra-Low Energy Isotope Spectrometer.

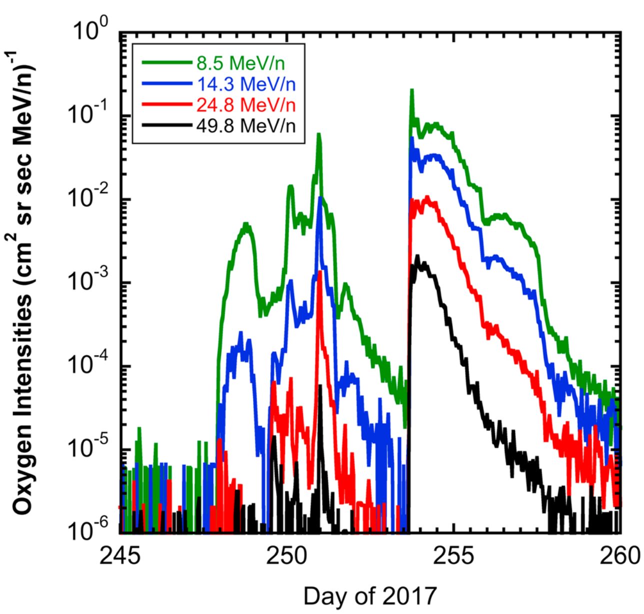

Figure 2. Oxygen intensities versus time for the period of 2–17 September 2017 for four energies as measured by Advanced Composition Explorer/Solar Isotope Spectrometer. Several solar energetic particle events can be identified with the largest being the 10 September event.

events of 13 December 2006 and 17 May 2012, suggesting that they would have been GLE events had they been Earth-directed (Cohen et al., 2017). The study of such events increases the limited database of GLE-like events, furthering our understanding of this space weather hazard.

This is particularly the case for the current solar cycle (cycle 24) in which only two GLE events have been identified. Several aspects of cycle 24 have been shown to be significantly weaker than those of cycle 23, including the solar wind speed and the magnetic field strength (see, e.g., McComas et al., 2013). The number of large SEP events is no exception (Gopalswamy, Akiyama, et al., 2014; Mewaldt et al., 2017), with the decrease in GLE events being particularly strong (two in cycle 24 vs. 16 in cycle 23; gle.oulu.fi). In this paper we focus not only on the most recent GLE event on 10 September 2017, comparing its properties to the GLE events of cycle 23 and the other cycle 24 event of 17 May 2012, but also present data from the extreme SEP events observed by STEREO and discuss the top 10 SEP events of cycles 23 and 24.

2. Observations

2.1. Instrumentation

Since 1976 National Oceanic and Atmospheric Administration (NOAA)'s series of GOES satellites have provided continuous monitoring of solar energetic protons in the near-Earth environment from ~4 to 700 MeV. These data are used by solar, atmospheric, and magnetospheric scientists for a wide range of scientific studies and by a broad spectrum of government and industrial users for space weather research, forecasts, and warnings. As many studies of the acceleration, transport, and effects of SEPs include GOES data to complement and extend observations made with space instruments flown by National Aeronautics and Space Administration (NASA), European Space Agency, and other space agencies, an accurate calibration of the GOES intensities and energy intervals reported by NOAA is essential. In the past few years there have been several important papers that bear on the calibration of the GOES energetic particle instruments.

Rodriguez et al. (2014) carried out careful intercalibrations of the energetic particle sensors (EPS; Onsager et al., 1996) flown on the GOES-8 to GOES-15 satellites. It is well known that in the geostationary orbits occupied by GOES the lowest energy channels P2 (nominally 4–9 MeV) and P3 (9–15 MeV) are typically affected by the geomagnetic cutoff during geomagnetically quiet periods. However, observations have shown that during periods when the solar-wind dynamic pressure exceeds 5–10 nPa the GOES proton fluxes become isotropic, indicating that they are no longer affected by the geomagnetic cutoff. Focusing on such periods, Rodriguez et al. made extensive intercomparisons of the responses of the multiple GOES satellites in orbit and showed that the integral channels of EPS on GOES-8 to GOES-15 used for real-time solar radiation alerts were intercalibrated to within 10%. The differential channels were found to agree to within 20% (sometimes to within 1%). This paper provided confidence that one can intercompare GOES SEP data from one solar cycle to the next without danger of large intercalibration effects.

In a second key paper Sandberg et al. (2014) carried out an extensive intercalibration of the EPS on GOES-5, GOES-6, GOES-7, GOES-8, and GOES-11 from a few MeV up to several hundred MeV. They compared EPS data

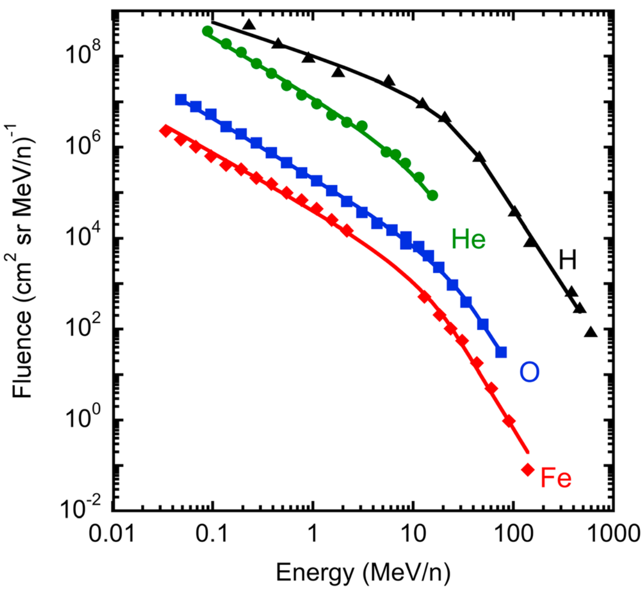

Figure 3. Event-integrated fluences versus energy for H (from GOES-13), He, O, and Fe (from the Advanced Composition Explorer) in the 10 September 2017 event (points). The Band fits are indicated by the lines. The lack of high-energy He is due to raised detector thresholds on Advanced Composition Explorer/Solar Isotope Spectrometer.

with energetic proton data from the NASA IMP-8 Goddard Medium Energy Experiment during 1984 through 2001. From these comparisons they derived *effective energy values* and estimated *effective energy ranges* for channels P2 to P7 on each of GOES-5, GOES-6, GOES-7, GOES-8, and GOES-11.

The Sandberg et al. results produced significantly lower effective energies than NOAA had been using to produce GOES integral fluxes. The median ratios of the standard NOAA integral fluxes to those derived using the Sandberg et al. effective energies were found to be 1.1, 1.7, 2.1, and 2.9 for >10-, >30-, >60-, and >100-MeV protons. A comparison of the effective GOES fluxes with STEREO low-energy telescope (LET; Mewaldt et al., 2008) and high-energy telescope (HET; von Rosenvinge et al., 2008) data from the December 2006 solar particle events provided validation of the new effective energies and also demonstrated good consistency between the long-term IMP-8 Goddard Medium Energy Experiment and the STEREO LET and HET solar proton data sets (see also Mewaldt, Cohen, Leske, et al., 2015). Thus, it was recommended that the GOES integral fluxes publicly available through NOAA be normalized by these factors to obtain more accurate values. In this paper we have represented the nominal energy intervals for GOES-11, and GOES-13 by their effective energy values, which were slightly updated during the construction of the European Space Agency Solar Energetic Particle Environment Modelling reference data set v2.0 (Heynderickx et al., 2016).

During the final preparation of this paper we were made aware of a recent paper by Bruno (2017). He made an extensive comparison of data from the High Energy Proton and Alpha Detector (HEPAD; Onsager et al., 1996) on GOES and from the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA; Adriani et al., 2009). Using the procedure introduced by Sandberg et al., he derived new *effective* energies for HEPAD. The HEPAD proton data released by NOAA span energies of 330 to 700 MeV and are included (when significantly above the galactic cosmic ray background) in several of our spectra for the largest solar proton events (e.g., Figures 3 and 5), including the 10 September 2017 event. The Bruno paper makes an important step in calibrating the GOES H and He response up to Giga-electron volts per nucleon energies.

For our study we have combined the differential GOES/EPS and HEPAD proton data, utilizing the effective energy values proposed by Sandberg et al., with proton measurements made by the Ultra-Low Energy Isotope Spectrometer (ULEIS; Mason et al., 1998) on the Advanced Composition Explorer (ACE), the Electron Proton Helium Instrument (EPHIN; Müller-Mellin et al., 1995) on the Solar and Heliospheric Observatory (SOHO), and the Proton Electron Telescope (PET; Cook et al., 1993) on the Solar, Anomalous, and Magnetospheric Particle Explorer to obtain complete proton spectra near Earth. Proton measurements from the STEREO spacecraft were made by the LET and HET sensors. We have also made use of the integral >10-MeV proton fluxes as recalibrated by Rodriguez et al. (2017). We note that in events for which there are no suitable HEPAD data, the high-energy portion of the spectrum can be significantly altered by the revised EPS energies. As an illustration, the proton spectrum for the 10 September 2017 event is plotted in Figure 1 with both sets of EPS energies. The Band fits are done without considering the HEPAD data and show that the old GOES energies result in a harder spectrum (by almost a full unit, i.e., −2.8 vs. −3.7). Most of the events in this study were measured by GOES-8 or GOES-11. By interchanging the effective energies of the two spacecraft we also find that their >10-MeV fluences agree to within 6%.

Table 1
10 Sept 2017 Band Fit Parameters

Element	Amp	γ_A	γ_B	E_0
H	$(1.06 \pm 0.05) \times 10^8$	-0.73 ± 0.04	-3.39 ± 0.05	19.1 ± 1.5
He	$(1.30 \pm 0.04) \times 10^7$	-1.30 ± 0.02	[a]	[a]
C	$(6.95 \pm 0.23) \times 10^4$	-1.28 ± 0.03	-3.65 ± 1.5	24.5 ± 2.3
N	$(2.90 \pm 0.13) \times 10^4$	-1.17 ± 0.04	-3.04 ± 0.15	14.4 ± 1.6
O	$(2.14 \pm 0.07) \times 10^5$	-1.31 ± 0.03	-3.36 ± 0.26	21.2 ± 1.7
Ne	$(3.60 \pm 0.15) \times 10^4$	-1.24 ± 0.03	-3.10 ± 0.17	18.7 ± 1.8
Mg	$(3.85 \pm 0.15) \times 10^4$	-1.23 ± 0.03	-3.39 ± 0.19	19.1 ± 1.5
Si	$(4.69 \pm 0.20) \times 10^4$	-1.18 ± 0.04	-3.34 ± 0.12	12.9 ± 1.1
S	$(1.21 \pm 0.08) \times 10^4$	-1.28 ± 0.05	-3.33 ± 0.17	13.5 ± 1.7
Ca	$(3.70 \pm 0.31) \times 10^3$	-1.32 ± 0.06	-3.53 ± 0.37	15.4 ± 2.3
Fe	$(4.29 \pm 0.24) \times 10^4$	-1.25 ± 0.04	-3.61 ± 0.11	11.9 ± 1.1

[a]The lack of high energy He does not allow for a determination of these parameters.

The heavy-ion SEP data used here are from ULEIS and the Solar Isotope Spectrometer (SIS; Stone et al., 1998) on ACE and LET on STEREO. Heavy-ion measurements from ULEIS and SIS have been intercalibrated several

Table 2
10 Sept 2017 Composition (12–45 MeV/n)

Element	X/O	Uncert	X/O norm[a]
C	0.39	0.0021	0.84
N	0.12	0.0010	0.97
O	≡1	—	1
Ne	0.18	0.0013	1.2
Mg	0.20	0.0014	1.0
Si	0.16	0.0012	1.1
S	0.03	0.0006	0.94
Ca	0.01	0.0003	0.94
Fe	0.10	0.0010	0.75

[a]Normalized to the solar energetic particle abundances of Reames (1998).

times and generally yield excellent agreement; while the LET observations were compared to those of ULEIS + SIS in the December 2006 events (when the STEREO spacecraft were still close to Earth), allowing intercalibration between the three spacecraft.

2.2. 10 September 2017 GLE Event

The activity leading to the 10 September 2017 GLE event has been described in detail in this issue and elsewhere, including observations in ultraviolet (Seaton & Darnel, 2018), the early dynamical evolution of the CME and influence of preceding CMEs (Gopalswamy et al., 2018; Guo et al., 2018), the relative role of shocks versus flares in the acceleration of particles (Zhao et al., 2018), and even the resulting *ground-level event* on Mars (Guo et al., 2018; Schwadron et al., 2018). Here we give only a brief summary. Active region 12673 emerged on the disk on 28 August and produced 27 M-class and four X-class flares, including the largest X-ray flare (X9.3) of solar cycle 24, before rotating over the west limb of the Sun. During this period it also generated four CMEs with velocities >1,000 km/s and widths >120°. Thus, it is not surprising that multiple SEP events were also observed by near-Earth spacecraft (Figure 2). The SEP event of 10 September 2017 was classified as a GLE event when at least 20 neutron monitors registered clear count rate increases (see, e.g., gle.oulu.fi) and was the largest SEP event in >10-MeV proton peak intensities since June 2015 (umbra.nascom.nasa.gov/SEP).

The event-integrated fluence spectra for H, He, O, and Fe for the 10 September GLE event as measured by GOES-13, EPHIN, ULEIS, and SIS are shown in Figure 3. Fitting the spectra with the broken power law Band function (Band et al., 1993) reveals similar spectral indices for all species below the spectral break (except H) as well as above the spectral break. Unfortunately, since January 2016, the thresholds on the front detectors of SIS have been raised, which eliminates the higher-energy He measurements, so the >20-MeV/nuc portion of the He spectrum is not available for the 10 September event. The complete set of Band parameters for the dominant elements between H and Fe are given in Table 1. The heavy-ion spectra have been integrated from 12 to 45 MeV/nuc to obtain the abundance ratios relative to oxygen given in Table 2.

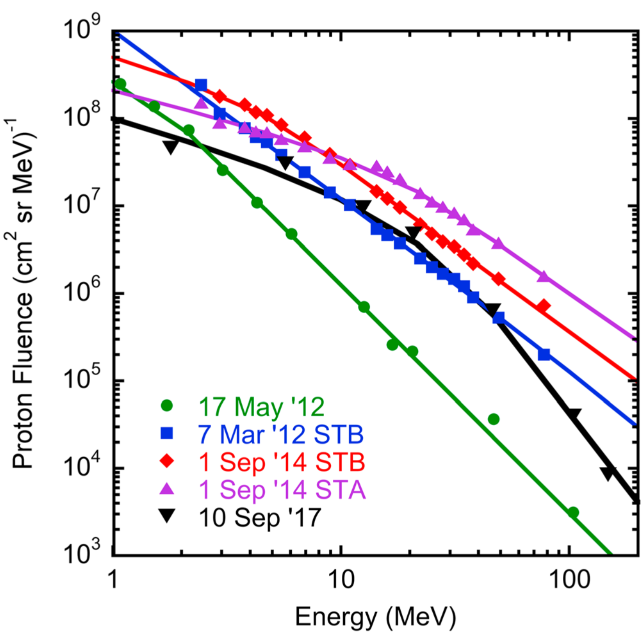

Figure 4. Event-integrated proton fluences versus energy for the two cycle 24 GLE events (17 May 2012 and 10 September 2017 from GOES-13) and the two extreme STEREO events (7 March 2012 and 1 September 2014, which was observed by both STEREO spacecraft). The STEREO spectra are extremely hard above ~20 MeV; both GLE events are softer.

2.3. Extreme STEREO SEP Events

In a study of extreme events observed by STEREO, Cohen et al. (2017) searched for events that had daily intensities of >10-MeV protons similar to or greater than those measured during the 13 December 2006 GLE event. They selected five events that had fluences at ~80 MeV, which were greater than that of the 17 May 2012 GLE event (which was somewhat smaller than the 13 December 2006 event). Of these five events, the 7 March 2012 event observed by STEREO-B and the 1 September 2014 event as observed by both STEREOs had sufficiently hard spectra above 20 MeV that extrapolation to 500 MeV suggested the events would have created GLE events if they had been directed toward Earth. These three spectra are compared to the two cycle 24 GLE events (17 May 2012 and 10 September 2017) in Figure 4.

Although the 23 July 2012 event, observed by STEREO-A, was one of the largest events of the current cycle at 10 MeV (see, e.g., Joyce et al., 2015; Mewaldt, Cohen, Leske, et al., 2015; Gopalswamy et al., 2016), the event-integrated proton spectrum analyzed by Cohen et al. clearly showed a spectral break at ~25 MeV. Unfortunately, the available measurements (up to 100 MeV) do not provide enough information above the spectral break to accurately extrapolate the spectrum out to 500 MeV; the data are well described by both the Band function and the Ellison-Ramaty form (a power law multiplied by an exponential; Ellison & Ramaty,

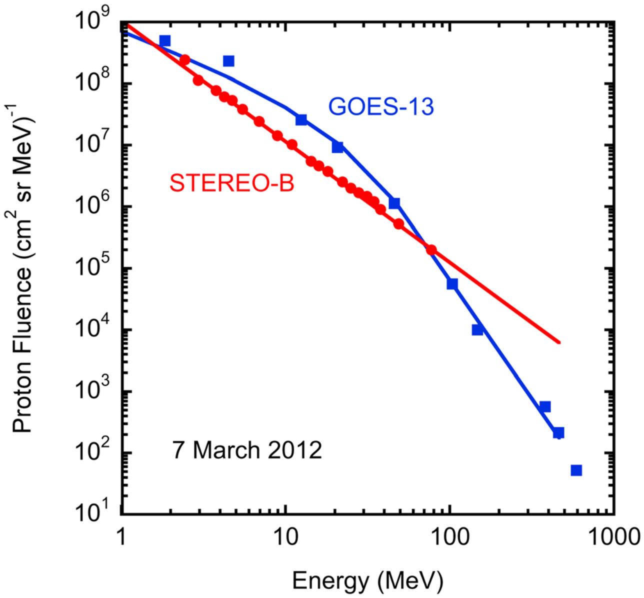

Figure 5. Event-integrated proton fluences versus energy for the 7 March 2012 event as observed by GOES-13 and STEREO-B. Band fits are indicated by the lines and suggest that the event was larger at STEREO-B for energies >100 MeV. GOES = Geostationary Operational Environmental Satellite; STEREO = Solar Terrestrial Relations Observatory.

1985); however, the high-energy spectral index of the Band function is not constrained by the data. Extrapolating to 500 MeV using the Ellison-Ramaty form yields a fluence well below that of the 17 May 2012 and 13 December 2006 GLE events, while an extrapolation of the Band function is not possible due to the unconstrained spectral index. Hence, in our discussion of STEREO events that might have created GLE events if differently directed, we do not include the 23 July 2012 event and focus on the previously mentioned STEREO events, which exhibited clearly defined power laws above 30 MeV that can be reasonably extrapolated.

The 7 March 2012 event was a large event at Earth as well as at STEREO-B. It has been dubbed a *sub-GLE* by Mishev et al. (2017; see Poluianov et al., 2017, for the proposed definition of sub-GLE). The high-energy portion of the proton spectrum measured by STEREO-B is significantly harder than that observed by GOES-13, possibly because at E27 it was a *western* event for STEREO-B but an *eastern* event as viewed by GOES (Figure 5). The 1 September 2014 event was large at both STEREOs but, likely due to its solar source location of E108, it was a small event at Earth; it did not exceed the threshold for being identified as a GOES event. As many of the characteristics of these two events, as measured by STEREO, are similar to those of other GLE events (Cohen et al., 2017; Mewaldt et al., 2012), and as cycle 24 has a dearth of GLE events, we will include the 7 March 2012 and 1 September 2014 STEREO events in our discussion of the cycle 24 GLE events below.

3. Discussion

Table 3 lists the top 10 events of cycle 23 as determined by the fluence of >10-MeV protons, which can be compared to those of cycle 24 given in Table 4. These fluences were calculated from integral intensities provided by NOAA (and corrected as recommended by Rodriguez et al., 2017) using the primary GOES satellite at the time of the event. Most of the cycle 23 data were from GOES-8 and GOES-11 and the cycle 24 data are from GOES-11 and GOES-13. We have not attempted to correct for variations in the local geomagnetic cutoff. In cycle 24 we have additional observations from the two STEREO spacecraft, also located near 1 AU but not near the Sun-Earth line. This additional observational capability allows the identification of other large events (e.g., 1 September 2014); Table 5 lists the top 10 cycle 24 events after including the STEREO observations. The STEREO fluences are a combination of data from LET (1.8–12 MeV) and HET (13.6–100 MeV), where the LET data have been extrapolated to 13.6 MeV to fill the energy gap between the two instruments. For better comparison with GOES, we have also extrapolated the HET data to 500 MeV assuming the observed power law at high energies continues. Although we do not know if the spectra roll over above 100 MeV, we believe the assumption introduces a small uncertainty.

Table 3
Top 10 Cycle 23 Events

Event date	>10-MeV H fluence (cm^{-2})
7/14/00	1.50×10^{10}
11/4/01	1.38×10^{10}
10/28/03	1.06×10^{10}
11/08/00	9.82×10^{9}
11/22/01	7.37×10^{9}
9/24/01	6.74×10^{9}
4/21/02	2.60×10^{9}
1/17/05	2.24×10^{9}
10/29/03	1.96×10^{9}
12/05/06	1.84×10^{9}

The most direct comparison between solar cycle 23 and cycle 24 is through Tables 3 and 4, that is, using GOES observations only. This clearly shows that cycle 24 has not produced events as large as cycle 23 did. This is consistent with the overall distribution of event sizes and total proton fluence in each cycle as examined by Mewaldt, Cohen, Mason, et al. (2015). While some of the largest events in cycle 24 were not directed toward Earth, for example, 23 July 2012 and 1 September 2014, even including the STEREO observations in the top 10 list (Table 5) does not change the conclusion that the conditions of cycle 23 yielded larger SEP events (on average a factor of 2.4 bigger). As suggested by Mewaldt et al. (2017) this may be a result of the lower interplanetary density of suprathermal seed particles, combined with a lower magnetic field strength in cycle 24 (see also Gopalswamy, Akiyama, et al., 2014; Vainio et al., 2017).

Table 4
Top 10 Cycle 24 Events at Earth

Event date	>10-MeV H fluence (cm^{-2})
1/23/12	3.44×10^9
3/7/12	3.40×10^9
1/7/14	1.33×10^9
9/10/17	1.25×10^9
5/22/13	9.55×10^8
1/27/12	5.28×10^8
9/5/17	3.82×10^8
6/21/15	2.55×10^8
2/25/14	2.02×10^8
9/30/13	1.82×10^8

Table 5
Top 10 Cycle 24 Events at Earth and Solar Terrestrial Relations Observatory

Event date	>10-MeV H fluence (cm^{-2})
9/1/14	7.71×10^9 (STA)
7/23/12	6.65×10^9 (STA)
1/23/12	3.44×10^9
3/7/12	3.40×10^9
9/22/11	2.64×10^9 (STB)
6/4/11	1.63×10^9 (STA)
1/7/14	1.33×10^9
9/10/17	1.25×10^9
8/31/12	1.03×10^9 (STB)
11/7/13	1.03×10^9 (STB)

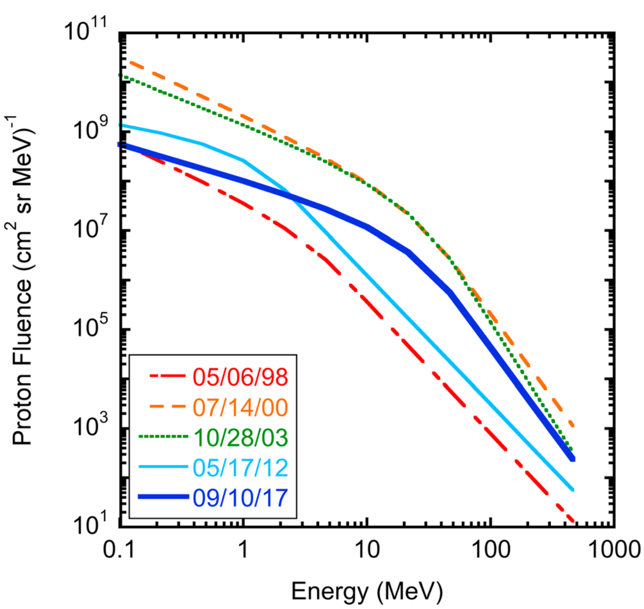

Figure 6. Band fits of the event-integrated proton fluences versus energy for the ground-level enhancement events of cycle 24 (solid lines; from GOES-13) and the smallest (6 May 1998) and two largest (14 July 2000 and 28 October 2003) ground-level enhancement events of cycle 23 (from GOES-8).

Figure 6 compares the two cycle 24 GLE events to the smallest (6 May 1998) and two of the largest (14 July 2000 and 28 October 2003) GLE events of cycle 23. Both cycle 24 events are well within the range of the cycle 23 GLE events, although falling toward the low end at energies below a few MeV. The relatively hard spectrum at low energies combined with a high break energy of 10 September 2017 results in it being only a factor of ~4.5 smaller than 14 July 2000, the largest of cycle 23, at energies >100 MeV. While the two cycle 24 events have similar spectral indices below ~1 MeV, the 10 September 2017 event has a higher break energy than 17 May 2012; however, above the break, the September event is significantly softer. The GLE event survey of Mewaldt et al. (2012) showed that the spectral indices above the break ranged from −4.6 to −2.1 for the cycle 23 events. The index of the 10 September 2017 event of −3.4 (for H, Table 1) is within this range but softer than the mean of −3.18 and the median of −2.94 (see also Gopalswamy et al., 2018). This is consistent with cycle 24 being one of the weaker cycles from the standpoint of solar energetic particles.

Interestingly, if one were to also consider the extreme STEREO events shown in Figure 4, the 1 September 2014 event might be larger than the 14 July 2000 GLE event. However, without proton measurements above 100 MeV it is impossible to determine how far the hard spectrum would extend in energy before rolling over. The 7 March 2012 event was measured by both GOES and STEREO-B. Although in >10-MeV fluence, it was larger at GOES, Figure 5 shows that STEREO-B observed a significantly harder spectrum above 10 MeV. Again, we are limited to energies <100 MeV for the STEREO observations, but extrapolation of the measured power law (with index of −2.1) would suggest the event was significantly larger at STEREO-B at energies above 100 MeV. As 7 March 2012 did produce some responses in the neutron monitors, but not enough to be officially recognized as a GLE event, it would appear that had Earth been located where STEREO-B was during the event, we might have had another cycle 24 GLE event. Regardless, the STEREO observations of 1 September 2014 and 7 March 2012 suggest that the conditions of cycle 24 were conducive to creating GLE-sized SEP events more often than just in the two instances of 17 May 2012 and 10 September 2017.

Mewaldt et al. (2012) showed that as a population, cycle 23 GLE events tended to have higher Fe/O ratios than large, non-GLE SEP events. In Figure 7 we compare the Fe/O abundance ratios obtained over 12–45 MeV/nuc for the GLE events of cycles 23 and 24, as well as the two STEREO extreme events from Figure 4. Of the cycle 24 events, only the 17 May 2012 event has a higher than average Fe/O ratio (we use the average SEP value obtained by Reames, 1998, at 5–12 MeV/nuc for comparison, as indicated by the vertical line in Figure 7). Although the statistics for the cycle 24 events are extremely limited, it does not appear that the cycle 23 tendency of having higher Fe/O ratios in GLE events is present in cycle 24. This is perhaps not surprising as the fluence of 10- to 30-MeV/nuc SEP Fe was an order of magnitude lower in the first half of cycle 24 compared to the first half of cycle 23, whereas the fluence of SEP O was depleted by a factor of ~5 (Mewaldt, Cohen, Mason, et al., 2015). Similarly the density of Fe suprathermal particles was a factor of 7 lower in cycle 24 and suprathermal O was depleted by a factor of 3.2 (Mewaldt, Cohen, Mason, et al., 2015). Thus, cycle 24 had a suprathermal population with a

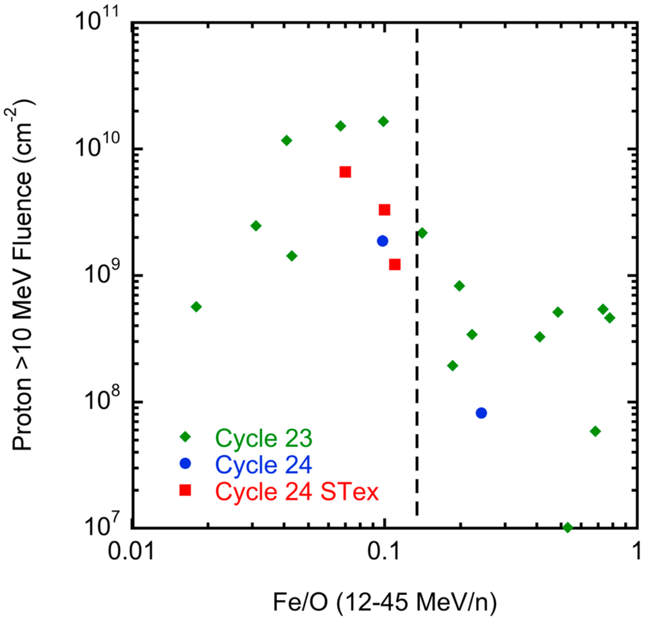

Figure 7. Event-integrated proton fluences versus event-integrated, 12–45 MeV/nuc Fe/O abundance ratios for the GLE events of cycle 23 (green diamonds), the GLE events of cycle 24 (blue circles) and the extreme events of STEREO (red squares; note both STEREO-A and STEREO-B values are plotted for the 1 September 2014 event). The 10 September 2017 event is the blue circle near the center of the plot. The vertical line indicates the average SEP Fe/O value as reported by Reames (1998).

lower average Fe/O ratio as compared to cycle 23, which may be directly reflected in the composition of the SEP events, including the GLE and STEREO extreme events.

In Table 2, the full composition of the 10 September 2017 event is also given relative to the average SEP values of Reames (1998). It is readily apparent that, aside from Fe, the abundance ratios are fairly nominal.

4. Summary

The 10 September 2017 event was one of only two GLE events of solar cycle 24 and was the largest GOES event since June 2015. Although the high-energy portion of the 10 September 2017 proton spectrum was softer than many of the GLE events observed in cycle 23 (and the GLE event of 17 May 2012), the hard low-energy portion plus a relatively high break energy resulted in it being within a factor of ~4.5 of the largest GLE events of cycle 23 at energies >100 MeV. The heavy-ion composition of the event is unremarkable in that it is generally within 10–20% of the average values for large SEP events, with the exception of Fe. Although many of the cycle 23 GLE events had higher than average Fe/O ratios, the Fe/O ratio in the 10 September 2017 GLE event was lower than average (by ~25%). This may be primarily a consequence of the suprathermal population having a lower Fe/O ratio in cycle 24 and is consistent with a general trend for large SEP events this cycle.

Although there have been only two identified GLE events in cycle 24, as compared to 16 in the previous cycle, several extreme events were observed away from Earth by the STEREO spacecraft. At least two of these had spectra hard enough at 100 MeV to suggest that they might have been GLE events had Earth been at the location of STEREO during the events. However, even when accounting for these events, the top 10 cycle 24 events were on average smaller by a factor of 2.4 in terms of their >10-MeV proton fluence than the top 10 events of cycle 23.

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