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A 360° Survey of Solar Energetic Particle Events and One Extreme Event

R. A. Mewaldt*[1], C. M. S. Cohen[1], G. M. Mason[2], T.T. von Rosenvinge[3], and A. Vourlidas[2]

[1]*California Institute of Technology, Pasadena, CA 91125 USA*
[2]*Johns Hopkins University/Applied Physics Laboratory, Laurel MD 20723, USA*
[3]*NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA*

E-mail: rmewaldt@srl.caltech.edu, cohen@srl.caltech.edu, Glenn.Mason@jhuapl.edu, tycho. t. vonRosenvinge@NASA.gov, Gang.Li@UAH.edu, Charles.Smith@UNH.edu

We report on a 3-point longitudinal survey of Solar Energetic Particle (SEP) events during 2010-2014 using data from the STEREO and near-Earth spacecraft. During the period from August 2010 through September 2014 a total of 77 SEP events were identified with >10 MeV proton intensities that exceeded the NOAA criterion of >10 protons/(cm^{2}sr-s), including 37 events at STEREO-A and 36 each at GOES and STEREO-A. Thirty-seven percent of the events reached this threshold intensity at more than one location. Unexpected solar activity in December 2006 provided an opportunity to cross-calibrate the STEREO and GOES sensors, demonstrating that the >10 MeV response for GOES was ~5%-8% greater than for the STEREOs, while the STEREO A&B responses agreed to within 2%. The July 23, 2012 event observed by STEREO-A was found to be the most intense SEP event in more than 20 years. We present observations of the longitude distribution of SEP events and fluences and compare properties of the July 23, 2012 event with those of the largest events of earlier solar cycles.

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1. Introduction

Solar Cycle 24 (SC24) has provided a unique opportunity to measure Solar Energetic Particle (SEP) Events over ~360° in longitude by combining data from NASA's twin STEREO spacecraft and near-Earth spacecraft like GOES, ACE, and SOHO. It is found that SEPs are distributed more quickly and broadly in longitude than was appreciated from single-point measurements (e.g., [1-6]). This paper reports a survey of large SEP events from 3 points of view as the STEREO A and B spacecraft (STA and STB) moved away from Earth at ~22.5° per year. From 2010 through September, 2014 we identified 36 events at Earth that met the NOAA criterion of ≥10 protons/(cm^{2}sr-s) with >10 MeV, referred to as 10 proton flux units (PFU). Using STEREO data we extend the survey of space-weather SEP events in longitude by identifying 71 events that exceed 10 PFU at 1, 2, or 3 locations.

Previous multi-spacecraft surveys of SC24 SEP events have studied small ^{3}He-rich and electron events [1-4] and larger proton events from ~15 to 53 MeV [4-6]. The latter two surveys found longitude distributions somewhat broader than an earlier IMP-8/Helios study [7]. In addition, there are numerous reports that solar activity (including sunspot number, X-class flares, and fast CMEs) is reduced in SC24 [e.g. 8, 9]. In particular, there has been a significant decrease in the number of ground-level enhancement (GLE) events [9]. This paper compares SEP event frequency over three decades in intensity and with three earlier solar cycles.

2. Sources of Data

The near-Earth SEP measurements for this survey were made by the EPS sensor on NOAA's Geostationary Orbiting Environmental Satellites in Geosynchronous orbit (GOES [10]). In addition, data from the Electron Proton and Alpha Monitor (EPAM), and Ultra-Low-Energy Isotope Spectrometer (ULEIS) on ACE and Electron-Proton-Helium Instrument (EPHIN) on SOHO helped identify event onsets and Energetic Storm Particle (ESP) events. The STEREO measurements were made by the High Energy Telescopes (HET [11]) and Low-Energy Telescopes (LET [12]), which together measure protons from ~2 to 100 MeV. In addition lower-energy data from the Solar Electron-Proton Telescope (SEPT) were consulted.

The NOAA criterion for a solar proton event "affecting the Earth environment" is three consecutive 5-minute intervals with ≥10-MeV proton intensities ≥10 PFU. NOAA then tabulates the peak 5-minute intensity. Since a NOAA SEP event continues until the intensity drops below 10 PFU, it may combine contributions from multiple large solar eruptions. NOAA data identify 259 such "GOES events" at Earth from 1976 through September 2014. For STEREO we use 1-hour averages to categorize the peak intensity of solar proton events and 5-minute data to verify if any of the five NOAA intensity levels is satisfied [see http://www.swpc.noaa.gov/noaa-scales-explanation and additional discussion in Section 2.1].

2.1 Calibration Issues

In comparing GOES and STEREO data it is important to check whether geometry factors and energy thresholds are accurately cross-calibrated. Lario et al. [5] compared 15-40 MeV and 25-53 MeV GOES/EPS proton data with STEREO HET data from the December 2006 SEP events when all spacecraft were near Earth and deduced that GOES data should be divided by ~1.6 to achieve agreement. Sandberg et al. [13]) redefined the energy limits of the GOES differential channels by comparison with IMP-8/GME data. It is not obvious how to apply their results to our study that uses GOES integral channel data.

We have cross-calibrated GOES-11, STA and STB >10 MeV data using 144 consecutive hour averages from December 6 through December 11, 2006 when the STEREOs were in Earth orbit and reasonably close to GOES. This comparison is complicated because the STB spacecraft was flying upside down at the time and did not have the same field of view with respect to the Sun as STA [14]. The GOES-11 >10 MeV integral data give mean ratios to STEREO 10-100 MeV proton intensities of 1.075 ± 0.011 for STA and 1.055 ± 0.011 for STB. The mean 10-100 MeV STB/STA ratio was 1.021 ± 0.004, indicating good intercalibration of the STB/STA LET and HET sensors (but note the field of view difference). The GOES-11 >100 MeV proton rate was 1.30% of the >10 MeV rate for these days. However, the >100 MeV/>10 MeV fluence ratio was only 0.67% in SEP events from 8/2010 to 9/2014. We have therefore compared GOES >10 MeV intensities to STEREO 10-100 MeV intensities, realizing that in large SEP events STEREO may miss ~1% of the peak intensity, a difference small compared to the ~5% - 8% GOES excess determined above.

Rodriguez, Krosschell and Green [15] showed that GOES low-energy intensities (<40 MeV) are typically reduced by the geomagnetic cutoff unless the solar wind dynamic pressure is ≥5 nPa. They also concluded that GOES integral rates are calibrated to within 10% from one GOES to the next. Using OMNI data we identified 17 hours of the 144 hours in which the solar wind dynamic pressure was ≥5 nPa. For these 17 hours the GOES/STA and GOES/STB >10 MeV proton ratios were both 1.13. This suggests that GOES and STEREO >10 MeV integral rates agree better than GOES/STEREO differential rates (see [5, 13]). Typical geomagnetic effects apparently help bring GOES and STEREO >10 MeV intensities into better agreement.

3. Observations

Hourly-average proton intensities from STB, GOES, and STA are shown in Figure 1. The plotted STEREO data (from the LET and HET sensors), show 10-100 MeV intensities while the GOES data are for >10 MeV (as noted above, the effect of excluding >100 MeV protons on STEREO is typically <1%). These intensities are compared with the NOAA Solar Radiation Storm scale for solar proton events [http://www.swpc.noaa.gov/noaa-scales-explanation]. Table 1 summarizes the number of events that exceeded 10 PFU at 1, 2, and all 3 locations (two August 2010 events are not shown in Figure 1 but are included in Table 1). We identify two GOES events in 2012 (in agreement with [9]) that are not included by NOAA. If, instead of requiring>10 PFU at each spacecraft we simply require a detectable >10 MeV increase at each location, the 3-spacecraft event total would be ~50 [6].

If the GOES response is ~5%-8% greater than that of other near-Earth spacecraft we can ask if this affects the event totals in Figure 1 and Table 1. Surprisingly, if we correct for this effect all 36 GOES events still have peak intensities >10 PFU and only the GOES 7 January 2014 event would be reassigned from “Strong” to “Moderate”. However, we choose not to make such corrections because the GOES record has been established since 1976 and the integral proton intensities from the GOES satellites are intercalibrated to within <10% [14].

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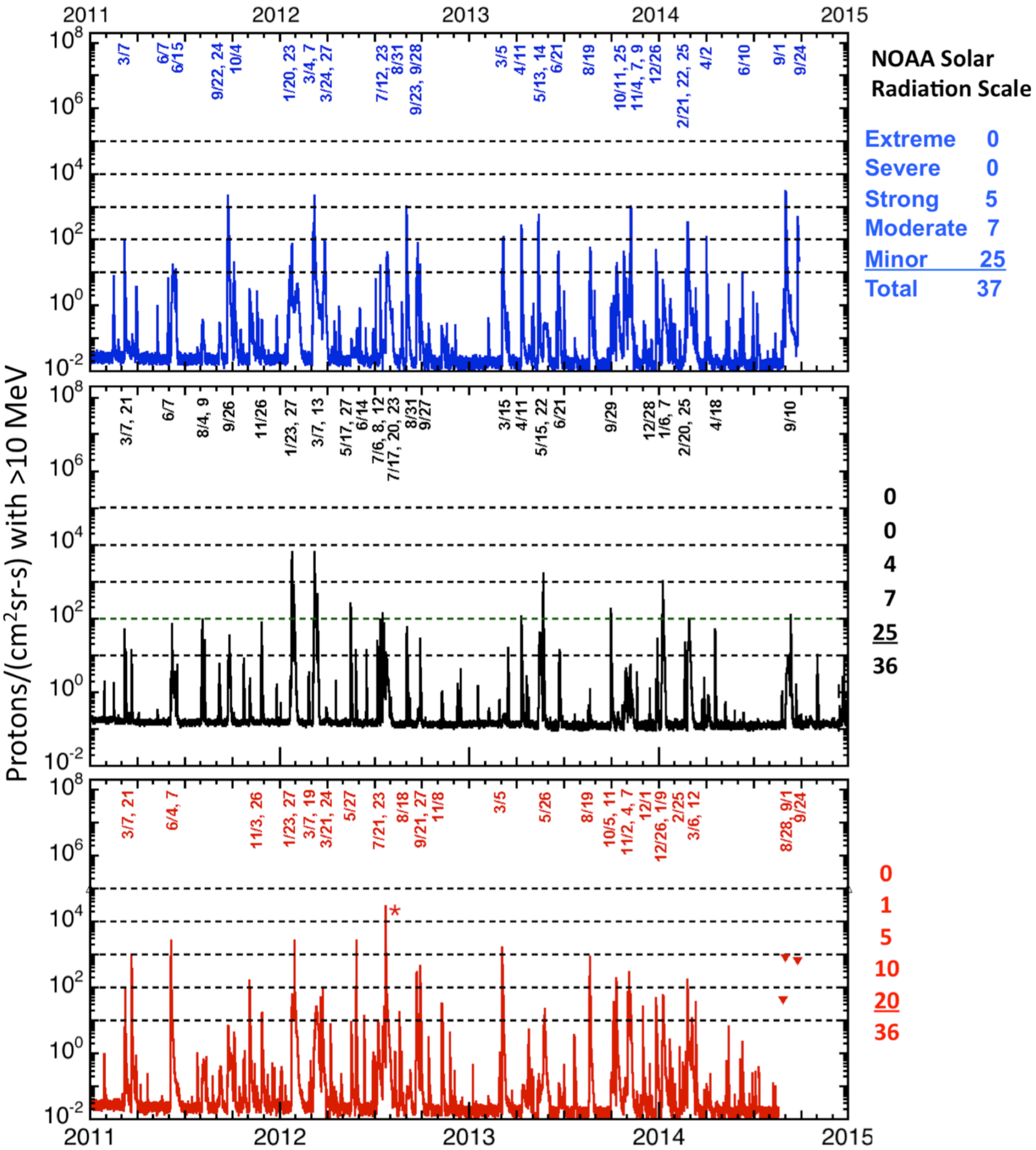

Figure 1: Hour-average intensities of >10 MeV protons measured by STEREO-B (top panel), GOES (middle), and STEREO-A (bottom) from January, 2011 to September 29, 2014. These intensities are compared with NOAA's 5-level Space Weather scale for Solar Radiation Storms (see dotted lines and event totals for each spacecraft). The X-ray flare dates (or, in some cases CME dates) of events ≥10 PFU are listed at the top of each panel. STA observed the most intense SC24 event to date (July 23, 2012; see star). Lower limits are shown for 3 STA events observed in August and September 2014 with limited data coverage. For earlier versions of this survey see [8] and [4].

Table 1: Single and Multi-Spacecraft "GOES" Events: January 2010 – September 2014 (77 Total)						
B	**Earth**	**A**	**B+E**	**A+E**	**A+B**	**A+B+E**
17	**19**	**15**	**5**	**6**	**9**	**6**

As the STEREOs approached solar conjunction they were commanded into a low data-rate mode that only provided 1 or 2 several-hour contacts a day (starting with STEREO-A). Thus, the last three events on the STA panel are shown as upper limits. During this period STA Beacon data were recorded on-board for recovery following solar conjunction. From 3/21/2015 to July 2015 there was no downlink from STA and the SEP sensors were turned off. Unfortunately, during a test of the STB low-rate mode contact with STB was suddenly lost on 9/24/15. Repeated attempts to regain contact with STEREO-B have so far been unsuccesful.

3. Longitudinal and Radial Variations

A plot of the integrated >10 MeV proton fluence versus time at the three spacecraft demonstrates how long-term fluences can be dominated by a few very large events (Figure 2). Note that ~2/3 of the total fluence at GOES was accumulated in the first 3 months of 2012, including events on January 23, 27, and March 7. Later in 2012 STA observed the most intense SEP event in ~20 years, accounting for ~50% of the STA fluence as of September, 2014. Although the STB fluence lagged behind much of this time, the fluences at all three spacecraft were within 10% of each other in late September, 2014.

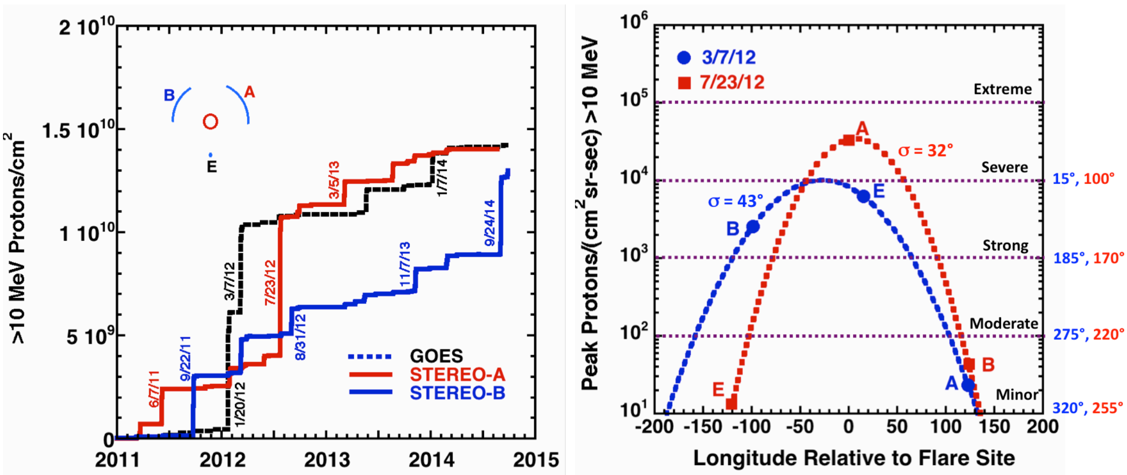

Figure 2a (left): Integrated fluence of >10 MeV protons at the 3 spacecraft from 1/1/11 to 9/29/14. Selected large events are labeled. The STA and STB locations are indicated at the upper left. This plot assumes the spacecraft are cross-calibrated (see Section 2.1 and [5]). Figure 2b (right): Gaussian fits to 3-point distributions of >10 MeV protons illustrate peak-intensity dependence on longitude for two large events. The July 23, 2012 event [15] was "Severe" over ~100° in longitude; much more than March 7, with a typical SEP width of σ = 43° [5,6]. However, March 7 registers "Strong" and "Moderate" over broader longitude ranges.

A significant fraction of these events originated behind the limb of the Sun as viewed by one of the observing spacecraft measuring >10 PFU. Using flare and CME locations we find that 17 ± 4% originated on the farside of the Sun, illustrating the value of a 360° view of the Sun. The maximum distance from the flare site was 155° (over west limb) and 136° (over the east limb). Without requiring a minimum intensity, Richardson et al. [6] found that ~30% of >25 MeV proton events originated beyond the limb.

The two STEREOs separate from Earth at ±22.5 ° per year and the average STA radial distance is ~4% inside 1 AU while STB averages ~4.4% beyond 1 AU. For 27-37 MeV protons Lario et al. [9] find radial gradients of $\sim R^{-1.1}$ for fluences and $\sim R^{-2}$ for peak intensities. Since the peak intensity distribution varies as $\sim I^{-0.4}$ (Figure 3) the STEREO and GOES event rates in Figure 1 may be biased by ±2% due to radial differences, and somewhat more for fluences. These bias estimates are small compared to statistical fluctuations in the event totals.

4. SEP Peak Intensity Distributions

It is generally known that solar cycle 24 has so far been less active than cycle 23 [8, 9]. To compare SC24 with earlier cycles we averaged the integral distribution of SEP peak intensities over the first 5.75 years of cycles 21-23 using GOES data and compared this with the SC24 integral distribution averaged over the GOES, STA, and STB locations (Figure 3).

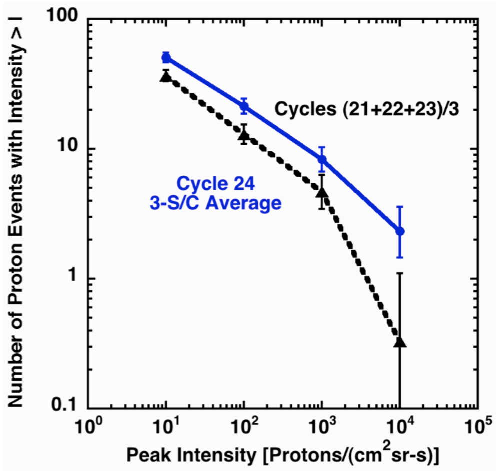

Figure 3: Integral distributions of SEP peak intensities during the first 5.75 years of each cycle. The mean number of events at the 3 locations in SC24 is compared with the mean of cycles 21, 22, and 23 at Earth. The slopes of the four points from cycles 21-23 and for the first 3 points of SC24 are both $\sim I^{-0.4}$. Note the large difference for peak intensities $>10^4$/(cm^{2}sr-s).

Although SEP event tabulations at these three locations are not independent [~37% of the 71 large SEP events reach 10 PFU at multiple spacecraft (Table 1)], averaging three locations is more representative of SC24 SEP activity than single-spacecraft data. The number of SEP events in SC24 is reduced in all four NOAA event categories, but the greatest difference is for "Severe" events, where only 1 event (July 23, 2012) reached $>10^4$ protons/(cm^{2}sr-s), compared to an expectation of seven events based on SEP activity in the first 5.75 years of Cycles 21 – 23. The lack of large SEP events in SC23 is also evident in Figure 4, which lists the Top 20 most intense solar proton events from 1976 to September 2014. Of the 259 events during this period the July 23, 2012 event would rank 3rd (had it been observed at Earth by GOES rather than at STA). Note that 8 of the top 20 events (and 6 of the top 8) occurred during cycle 23, while the only two from SC24 rank 12 and 13. This comparison clearly documents the relative lack of large solar proton events in SC24.

NOAA Top 20 Solar Proton Events
GOES >10 MeV Protons: 1976 – 2014
(Total of 259 Events)

Rank	Year	Month	Start	Intensity P/(cm2sr-s)
1	1991	Mar	23/0820	43000
2	1989	Oct	19/1305	40000
3	2001	Nov	04/1705	31700
4	2003	Oct	28/1215	29500
5	2000	Jul	14/1045	24000
6	2001	Nov	22/2320	18900
7	2000	Nov	Aug-50	14800
8	2001	Sep	24/1215	12900
9	1994	Feb	20/0300	10000
10	1989	Aug	12/1600	9200
11	1989	Nov	30/1345	7300
12	2012	Mar	07/0510	6530
13	2012	Jan	23/0530	6310
14	2005	Jan	16/0210	5040
15	1992	May	09/1005	4600
16	1989	Sep	29/1205	4500
17	1989	Mar	08/1735	3500
18	2005	May	14/0525	3140
19	1991	Jun	04/0820	3000
20	1982	Jul	11/0700	2900

July 23, 2012
= 35800
p/cm²sr-s

Cycle 23 events Cycle 24 events

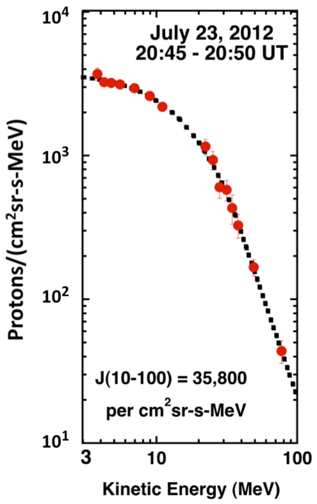

Figure 4: (left) A list of the 20 most intense solar proton events from 1976 through September 2014. The July 23, 2012 event would have placed 3rd had it occurred at Earth. (right) Peak 5-minute spectrum measured by the LET and HET sensors on STA [8].

5. Summary

After the first 5.75 years of solar cycles 21, 22, and 23 GOES had registered 31, 66, and 53 SEP events with >10 PFU, respectively. From this point of view the 34 (NOAA) or 36 (this paper) events in SC24 may not be surprising, but measuring essentially the same value at three locations does validate that SC24 is statistically less active than SC22 and SC23. Further evidence comes from the lack of "Severe" events (only 1 at 3 locations in SC24 versus an expected value of 7 based on cycles 21-23). For some reason SEPs are not being accelerated as high in energy in SC24 as in SC22 or SC23 (for more on this issue see [16]).

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