Solar Energetic Particles (SEPs)

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Goals: identify SEPs in data, their drivers, and characteristics

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SW REDI Boot Camp
What are they?

**Definition:**
Energetic charged particles (such as electrons and protons) traveling much faster than ambient particles in the space plasma, at a % of the speed of light (relativistic!)

Elemental composition* (may vary event by event)
- 96.4% protons
- 3.5% alpha particles
- 0.1% heavier ions (not to be neglected!)

Energies: up to ~ GeV/nucleon

They can travel from the Sun to the Earth in one hour or less!

The term SEP usually refers to protons (even though “p” is particle)
Why do we care?

NASA Johnson Space Center/Space Radiation Analysis Group (SRAG)
Flares

Coronal Mass Ejections

Solar energetic particles (SEPs)

Generally, fast and strong drivers lead to strong SEP events, but there are other factors to consider...
Charged particle motion* is confined by the magnetic field.

*Magnetic fields guide SEPs

*in a substantially strong B
Magnetic fields guide SEPs

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This means that the source is very important.

*Magnetic Connectivity*

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Magnetic field lines are the road for charged particles.

*Magnetic Connectivity*
CMEs Can Widen Longitudinal Extent of SEP Events

*Magnetic Connectivity*
How Do We Monitor SEP Levels?

*Track the particle flux at different locations.*

*Units: pfu, pfu/MeV*

(1 pfu = 1 particle flux unit = 1/cm²/sec/sr)

- **Heliosphere with STEREO In-situ Measurements of Particles and CME Transients (IMPACT)**
  - Differential energy band; example energy range: 13-100 MeV
- **Upstream of Earth with SOHO/COSTEP**
  - Differential energy bands; example energy range: 15.8-39.8 MeV
- **Geostationary Orbit with GOES**
  - Integral flux, example energy ranges: >10 MeV, >100 MeV
How Do We Monitor SEP Levels?

Track the particle flux at different locations.

*Flux units: pfu, pfu/MeV*

Another useful quantity:

*Fluence = flux integrated over the entire event - dose*

Important for biological effects (flights)

Event magnitudes:

- $> 10 \text{ MeV/nucleon integral fluence: can exceed } 10^9 \text{ cm}^{-2}$
- $> 10 \text{ MeV/nucleon peak flux: can exceed } 10^5 \text{ cm}^{-2}\text{s}^{-1}$
Coronagraph acting as particle detector – SNOW!

Flare peaked at 01:47 UT

SDO AIA 131 Å + SOHO/LASCO C2
May 17 02:00 UT

One hour later

SOHO/LASCO C3
May 17 03:00 UT
How do we define an SEP Event?

At the SWRC, SEP events are defined as:

- GOES Proton $E > 10 \text{ MeV}$ channel $> 10 \text{ pfu}$
- GOES Proton $E > 100 \text{ MeV}$ channel $> 1 \text{ pfu}$
- SOHO Proton, $>15.8 \text{ MeV}$ channel $> 0.1 \text{ pfu}/\text{MeV}$
- STEREO Impact $13-100 \text{ MeV}$ channel $> 0.1 \text{ pfu}/\text{MeV}$
# How Do We Quantify an SEP Event?

## NOAA Space Weather Scale for Solar Radiation Storms

<table>
<thead>
<tr>
<th>Scale</th>
<th>Descriptor</th>
<th>Duration of event will influence severity of effects</th>
<th>Physical measure</th>
<th>Average Frequency (1 cycle = 11 years)</th>
</tr>
</thead>
</table>
| S 5   | Extreme    | **Biological:** unavoidable high radiation hazard to astronauts on EVA (extravehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***  
**Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.  
**Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult. | Flux level of $\geq 10$ MeV particles (ions)* | $10^5$ | Fewer than 1 per cycle |
| S 4   | Severe     | **Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***  
**Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.  
**Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely. | $10^4$ | 3 per cycle |
| S 3   | Strong     | **Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***  
**Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.  
**Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely. | $10^3$ | 10 per cycle |
| S 2   | Moderate   | **Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***  
**Satellite operations:** infrequent single-event upsets possible.  
**Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected. | $10^2$ | 25 per cycle |
| S 1   | Minor      | **Biological:** none.  
**Satellite operations:** none.  
**Other systems:** minor impacts on HF radio in the polar regions. | 10 | 50 per cycle |
How Often Do SEP Events Occur?

SEP event detections in the near-Earth environment
(GOES 13, Proton E > 10 MeV channel)


Total Events (Earth)

- 2013 (Jan-May)
- 2012
- 2011
- 2010

Since March 2011
STEREO A: 16
STEREO B: 11
Can we forecast SEP events?

Uses detection of high energy *electrons* to predict arrival of high energy *protons*.

Data source: SOHO/COSTEP

**REeleASE Model**
Recognizing profile shapes of SEP flux and associations with the driver(s)
The peak at the beginning due to flare, fall off – indicates how well connected you are to the source (timing)

Impulsive SEP event
Gradual SEP event

Slow rise, then peak when the ICME passes the spacecraft
Gradual SEP event

Slow rise, then peak when the ICME passes the spacecraft
Multiple SEP event

Another event occurs before the first ends
July 23, 2012

July 23 flare as seen in STEREO A EUVI 195

Increase of more than 5 orders of magnitude at STEREO A SEP event also detected by GOES, and later enhancement seen at STEREO B (possibly due to IPS)
July 23, 2012

July 23 CME as modeled with WSA-ENLIL + cone

Increase of more than 5 orders of magnitude at STEREO A SEP event also detected by GOES, and later enhancement seen at STEREO B (possibly due to IPS)
Energetic proton fluxes elevated for >12 hours
A subset of SEP events, a GLE event occurs when extremely high energy protons (>500 MeV/nuc) penetrate the Earth’s atmosphere. Collisions with atoms generate secondary particles that are measured at neutron monitoring (NM) stations on the ground.

**Neutron Monitoring Station in Oulu, Finland**

Enhancement to ~125

Background ~105

NM Stations ([http://www.nmdb.eu](http://www.nmdb.eu))
What causes strong SEP events?

Complexity of AR
- Most young, more compact

Magnetic connectivity of AR
- About ~50% are well connected

Magnitude of flare
- Average X3.8, but as low as M7.1
- Long duration

Magnitude of CME
- Range of speeds (~2,000 km/s average, but four events <1,500 km/s)

Seed particles
- Known to have harder spectrum

Table 1: GLE events and associated flares and CMEs (adopted from Gopalswamy et al. 2010)

<table>
<thead>
<tr>
<th>ID</th>
<th>Onset</th>
<th>Time</th>
<th>Max</th>
<th>Int (%)</th>
<th>Flare Class</th>
<th>Location</th>
<th>CME</th>
<th>POG speed km/s</th>
<th>Width (deg)</th>
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<tbody>
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<td>12:10</td>
<td>11.3</td>
<td></td>
<td>X9.4</td>
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<td></td>
<td>1556</td>
<td>360</td>
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<td>6.8</td>
<td></td>
<td>X1.1</td>
<td>S15W15</td>
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</tr>
</tbody>
</table>

Nitta et al. 2012


According to the Oulu Neutron Monitor
bNo SOHO LASCO data
cFrom Gopalswamy et al. (2010). There are different estimates (see Grechnev et al. 2008)
Where are NASA assets now?

Mars

180°

+90°

-90°

Sun

Mercury

Venus

Earth

A
• SEP events are associated with flares and CMEs
• Charged particles travel along magnetic field lines, and so magnetic connectivity is important
• Monitor energetic protons in the magnetosphere, upstream of the Earth, and in the heliosphere
• An event occurs when the flux increases by ~2 orders of magnitude above background levels
• Can last days
• Space weather effects include biological, spacecraft damage