Solar Energetic Particles (SEPs)

Yihua Zheng and Rebekah M. Evans

Goals: identify SEPs in data, connect to drivers, identify characteristics of SEPs

June 3, 2014

SW REDI Boot Camp
DEFINING ACCEPTABLE RISK

Currently, NASA limits its astronauts to receiving 3 percent of the estimated lifetime radiation exposure. This is based on science that says exposure to 1 sievert of radiation increases a person’s risk for fatal cancer by 5 percent. How many “safe days” in space that translates to depends on the individual astronaut’s “age, gender, prior exposure, solar cycle and mission location,” according to Dr. Rich Williams, NASA’s chief health and medical officer. In an email he says, “For crew with no prior exposure, the number of estimated safe days can range from 180 to 1,600 days, for young females on deep space missions and older males on ISS missions respectively.”

This policy limits the number of individuals who would qualify for a long-term deep space mission, like one to Mars. “You don’t want to send a total rookie, you want somebody who’s been in space and knows what they are doing, that means probably that person already has significant exposure. If you already had exposure in space then you’re getting up to where your limit is,” says Dr. Dorit Donoviel, deputy chief scientist at the National Biomedical Research Institute in Houston, Texas, a nonprofit institute established by NASA in 1997 to address health-related issues of long-term spaceflight. Donoviel points out that this 3 percent policy would preclude women from going on a lot more missions, because women reach their maximal safe days in space sooner than men. That’s because women already have higher incidents of radiation-induced cancers, and on average they live five years longer than men, which gives more time to develop cancer.

Donoviel says one of the measures to take to protect the crew from galactic cosmic radiation would be to make the trip shorter. But so far, new propulsion technologies that would achieve that, or techniques to shield the spacecraft from galactic cosmic radiation, remain the stuff of science fiction: “Right now there are no lightweight solutions, in fact no ways to shield from galactic cosmic rays,” says Donoviel. The best solution, she says, may lie with pharmaceuticals.

Besides colorectal cancer risk, the Georgetown researchers looked at the sources: NASA SOHO solar observatory, NASA Hubble and Chandra images.

Deep space dangers

Mars explorers will need protection from galactic cosmic radiation, which researchers say would plow into cells like molecular artillery.
**What are they?**

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

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

The term “SEP” usually refers to protons.
Why do we care?

Radiation hazards for spacecraft, human in space and airline passenger safety
Space Environments and Effects on Spacecraft

- **Charging**
  - Biassing of instrument readings
  - Pulsing
  - Power drains
  - Physical damage

- **Particle radiation**
  - Degradation of micro-electronics
  - Degradation of optical components
  - Degradation of solar cells

- **Single Event Effects**
  - Data corruption
  - Noise on Images
  - System shutdowns
  - Circuit damage

- **Neutral gas particles**
  - Torques
  - Orbital decay

- **Ultraviolet & X-ray**
  - Degradation of thermal, electrical, optical properties
  - Degradation of structural integrity

- **Micro-meteoroids & orbital debris**
  - Structural damage
  - Decompression

**Space Radiation Effects** after J. Barth
Shaded in yellow
Solar energetic particles (SEPs)

Flares

Coronal Mass Ejections

Solar energetic particles (SEPs)
SEPs: ion radiation storms
Potentially affect everywhere in the solar system

Courtesy: SVS@ NASA/GSFC
Charged particle motion* is confined by the magnetic field. This means that the source is very important.

*in a substantially strong B
Magnetic fields guide SEPs

Charged particle motion* is confined by the magnetic field.

This means that the source is very important.

*in a substantially strong B

2013-06-02T12:00
Earth

2013-05-10T18 +22.73 days
Mars Mercury Venus Juno Spitzer Geo_A Geo_B

Ecliptic Plane

+90°

IMF polarity

0°

-90°

Vr (km/s)

Current sheath 3D IMF line
Magnetic fields guide SEPs

Charged particle motion* is confined by the magnetic field.

This means that the source is very important.

*in a substantially strong B
Charged particle motion* is confined by the magnetic field.

This means that the source is very important.

in a substantially strong B
Magnetic field lines are the road for charged particles.
CMEs Can Widen Longitudinal Extent of SEP Events
How Do We Monitor SEP Levels?

(1 pfu = 1 particle flux unit = 1/(cm^2/sec/sr))

Track the particle flux at different locations.

**Flux units: pfu, pfu/MeV**

- **Heliosphere with STEREO In-situ Measurements of Particles and CME Transients (IMPACT)**
  - Differential energy band; Units measured, some energy ranges are:
- **Upstream of Earth with SOHO/COSTEP**
  - Units measured, some energy ranges are:
- **Geostationary Orbit with GOES**
  - Integral flux, Units measured, some energy ranges are: pfu particle flux unit

Another useful quantity:

**Fluence = flux integrated over the entire event.**

Important for biological effects (flights)
Event magnitudes:
> 10 MeV/nucleon integral fluence: can exceed $10^9$ cm$^{-2}$
> 10 MeV/nucleon peak flux: can exceed $10^5$ cm$^{-2}$s$^{-1}$

SEP Intensity
PARTICLE SNOW!
Coronagraph acting as particle detector

Flare peaked at 01:47 UT

SOHO/LASCO C3
May 17 03:00 UT

SDO AIA 131 Å + SOHO/LASCO C2
May 17 02:00 UT
How do we define an SEP Event?

**SWRC: SEP event detections are defined as:**

- GOES Proton $E > 10$ MeV channel $> 10$ pfu
- GOES Proton $E > 100$ MeV channel $> 1$ pfu
# How Do We Quantify an SEP Event?

## NOAA Space Weather Scale for Solar Radiation Storms

<table>
<thead>
<tr>
<th>Category</th>
<th>Effect</th>
<th>Physical measure</th>
<th>Average Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>Descriptor</td>
<td>Duration of event will influence severity of effects</td>
<td>(1 cycle = 11 years)</td>
</tr>
<tr>
<td>Solar Radiation Storms</td>
<td>Flux level of ( \geq 10 ) MeV particles (ions)*</td>
<td>Number of events when flux level was met</td>
<td>(number of storm days)**</td>
</tr>
<tr>
<td>S 5</td>
<td>Extreme</td>
<td>Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</td>
<td>( \times 10^5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.</td>
<td></td>
</tr>
<tr>
<td>S 4</td>
<td>Severe</td>
<td>Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</td>
<td>( \times 10^4 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</td>
<td></td>
</tr>
<tr>
<td>S 3</td>
<td>Strong</td>
<td>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.***</td>
<td>( \times 10^3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.</td>
<td></td>
</tr>
<tr>
<td>S 2</td>
<td>Moderate</td>
<td>Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***</td>
<td>( \times 10^2 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Satellite operations: infrequent single-event upsets possible.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other systems: small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.</td>
<td></td>
</tr>
<tr>
<td>S 1</td>
<td>Minor</td>
<td>Biological: none.</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Satellite operations: none.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other systems: minor impacts on HF radio in the polar regions.</td>
<td></td>
</tr>
</tbody>
</table>
Human Safety in Space

- GCR
- SEP

Johnson Space Center/Space Radiation Analysis Group (SRAG)
Limit: the > 100 MeV flux exceeding 1 pfu
(1 pfu = 1 particle flux unit = 1/cm^2/sec/sr)

- All clear (EVA – extravehicular activity)
Can we predict SEP events?

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

Data source: SOHO COSTEP
How Often Do SEP Events Occur?

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


Since March 2011
STEREO A: 16
STEREO B: 11
Recognizing profile shapes of SEP flux and associating it with the source/driver
Impulsive: The “peak at the beginning due to flare, fall off” – indicates how well connected you are to the source (timing)
Gradual: The “jump up from flare, slow rise
Then peak when the ICME passes the spacecraft”
The “slow rise then peak, (slow rise can let you know that you are not well connected ICME doesn’t hit spacecraft so falls off”
The “multiple event weirdness”
July 23, 2012

Example where it reaches one spacecraft, then later another...

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 flare as seen in STEREO A EUVI 195
For Earth – Best Connection is 45-60 degree west

Energetic proton fluxes elevated for >12 hours

SDO AIA 131 Å
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)
What causes strongest SEP events? Or, how do the drivers relate to the SEP Flux?

Difficult to distinguish GLE from traditional SEP events:
- Complexity of Active Region (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


CME-driven shocks are thought to play important role in low (<3R_\text{s}) corona
- Only imaged in mid-high corona (Ontiveros & Vourlidas 2009)
- Type II radio bursts
- Multiple CME events – doesn’t apply for May 17 event
Exceptions to every rule!
September 28, 2012 – whole heliosphere event – C3.7 flare
Where are NASA assets now?

Mars and Earth are aligned! Share a similar magnetic connectivity.

We may lose real-time SEP at STEREOs.
SEP: proton radiation

Both the CME(s) and flare(s) contribute to the SEP enhancement.

GOES >10 MeV

13-100 MeV STEREO B

13-100 MeV STEREO A

GOES x-ray

M2.0 VCME=1360 km/s

X1.1

X5.4/2200 km/s

X1.3/1800 km/s

M6.3/CME=1125 km/s

M8.4 VCME=1500 km/s

M7.9 VCME=2100 km/s

Vc=1540 km/s

Vc=1800 km/s

Vc=1125 km/s

Vc=1500 km/s

Vc=2100 km/s

Both the CME(s) and flare(s) contribute to the SEP enhancement!
SEP Layout

Our goal is to understand extreme energetic particle events
We use a new solar wind model driven by Alfvén waves coupled to a kinetic model of particle acceleration and transport, acting on observed quiet time particle spectra (scaled back to the corona)
We find strong acceleration
Acceleration can vary wildly from different regions of the CME due to interaction with structures in the corona, so using a single CME speed as a hard predictor of particle acceleration will not work
Is it more about the magnetic connectivity of the observer than the properties of the CMEs and flares?
  – 2012 May 17 GLE event suggests it could be

The events from Solar Cycle 24 provide interesting cases to test our model – can we explain the May 17 and July 23 observations?