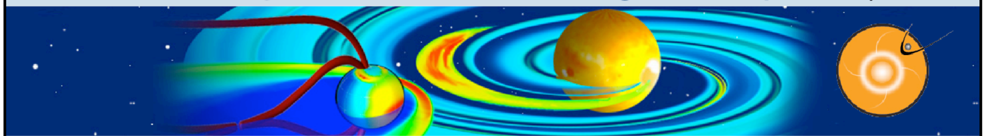
Community Coordinated Modeling Center (CCMC)



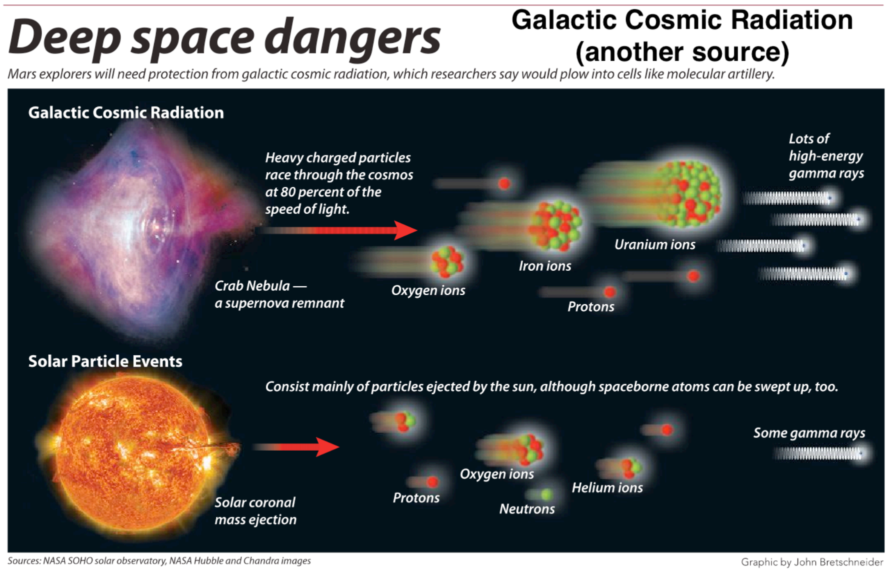
Introduction to Space Weather: Tools and Concepts

Solar Energetic Particles (SEPs) and Impacts

Yihua Zheng & CCMC Team

Science for Space Weather, Jan 24 – 29, 2016, Goa, India

SEPs – important source of space radiation: hard to predict



The main contributors to space radiation are Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs).

The earliest detection of SEPs by Forbush (1946) led to the term 'solar cosmic rays'. With what we know now about physical processes involved in the generation, acceleration and transport of GCRs and SEPs, the similarities in their initial names are more than just superficial. SEPs are usually associated with solar eruptions such as flares and Coronal Mass Ejections (CMEs).

Besides similarities, there are number of differences. GCRs have energies (10^8 – 10^20 eV/nucleon) much higher than SEPs (10^6 – 10^10 eV/nucleon). GCRs ions are typically GeV (giga electron volt) and above while SEP ions are in the energy range of a few MeV to hundreds MeV. For some extreme SEP events, ions can be accelerated to GeVs and higher. In the near-Earth's environment, GCR flux is at continuous background levels while SEP fluxes are highly dynamic and can vary several orders of magnitude in a short timescale. During large solar energetic particle (SEP) events the intensity of >100 MeV protons hitting the upper atmosphere can be >1000 times that of GCR protons.

SEPs: What are they?

Definition:

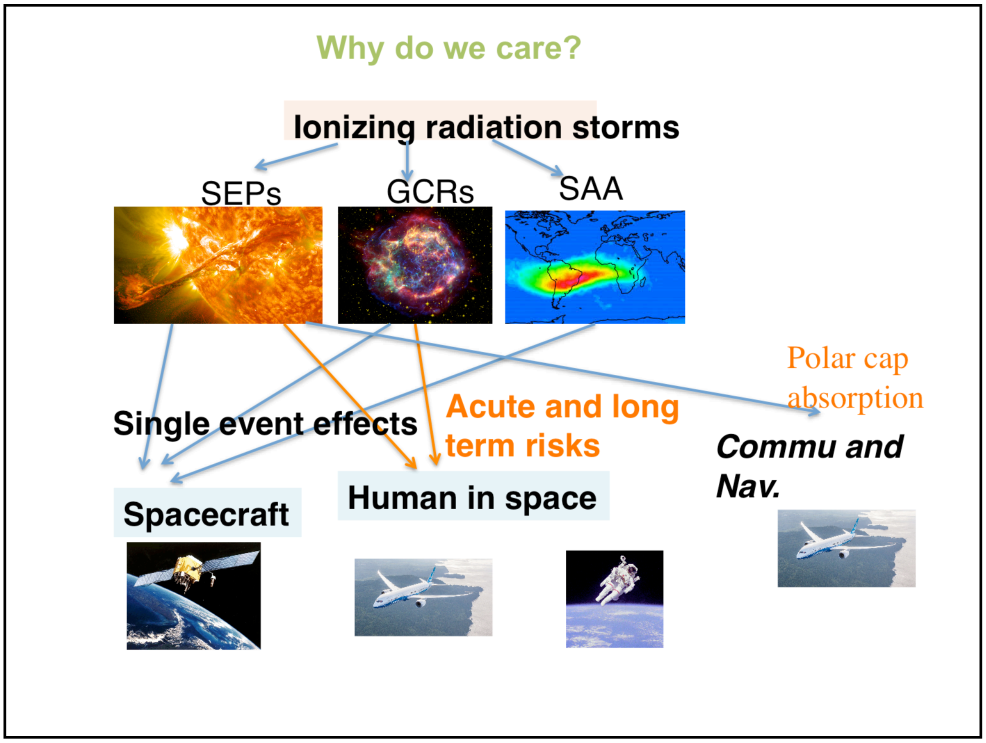
Energetic charged particles (such as electrons protons and other heavy ions) traveling much faster than ambient particles in the space plasma, at a fraction of the speed of light (relativistic!).

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

The term "SEP" usually refers to protons.

An SEP event is an enhancement in the radiation environment.

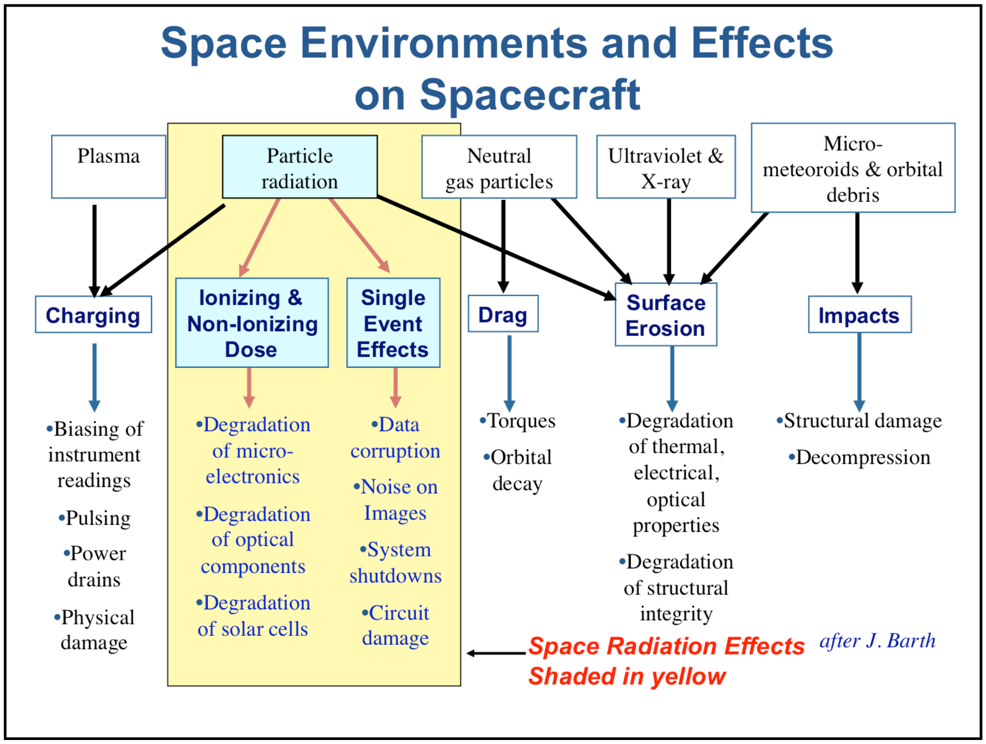
SEPs are usually associated with solar eruptions such as flares and Coronal Mass Ejections (CMEs). Even though historically SEP events have been classified into two groups only with the impulsive ones that are associated with flares and gradual ones associated with CMEs [e.g., Reames, 1999]. Later research [e.g., Kallenrode, 2003, Cane et al., 2010] shows that rather than a simple dichotomy of two classes of SEP events, both flare and CME shock acceleration can contribute in the largest SEP events. Regardless of the roles of flares and CMEs in leading to a SEP event, both these phenomena obtain their energy from the same solar magnetic field, very similar to particle acceleration process associated with GCRs where particles gain energies from strong magnetic fields at supernova remnant shocks.



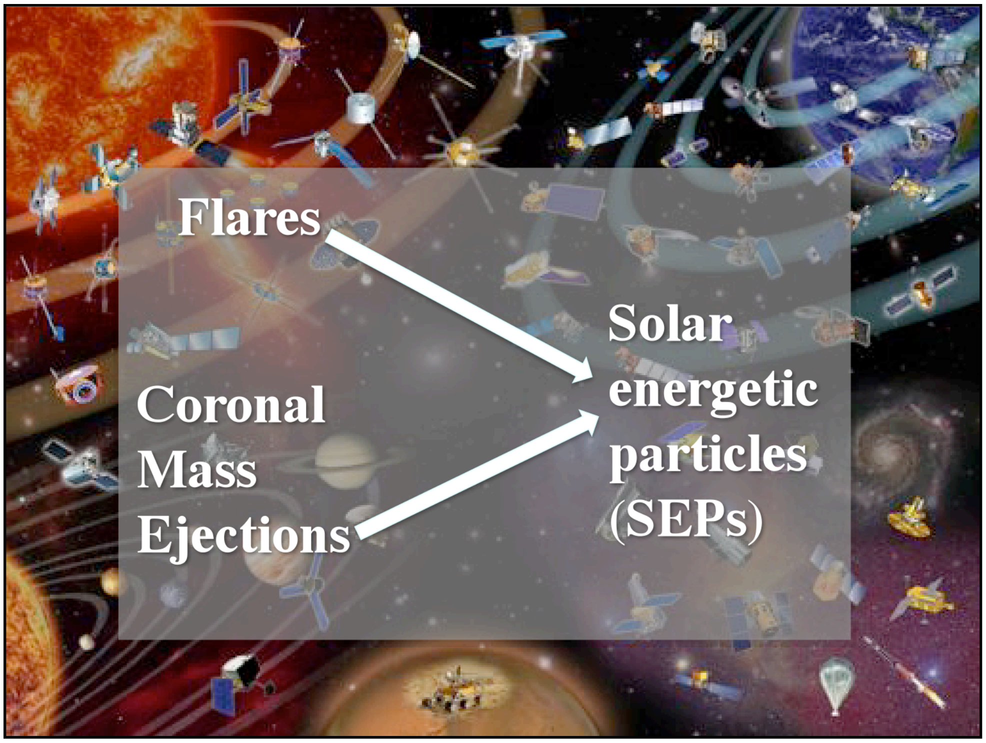
The main contributors to space radiation are Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs). Both can have deleterious effects on humans and technological assets/spacecraft components in space. From human perspective, space radiation can have acute in-flight effects, long-term cancer risks and risks on CNS (Central Nervous System) and cardiovascular system. From space hardware/components perspective, space radiation can cause cumulative degradation such as total ionizing dose (TID) and displacement damage dose (DDD) and transient effects such as single event effects (SEEs), all of which can be destructive. Supernova Remnants are believed to be the most plausible sources of GCRs. GCRs can have particles up to very high energies (- eV/nucleon). The latter is the more unpredictable of the two and is associated with most energetic solar eruptions: flares and coronal mass ejections; at the same time, SPEs are capable of inducing acute and profound effects on humans and on spacecraft components. Penetrating particle radiation from SPEs adversely affects aircraft avionics, communication and navigation, and potentially the health of airline crews and passengers on polar flights. SPEs also constitute major hazards for astronauts performing EVAs (Extra-Vehicular Activities) on board the International Space Station (ISS).

SAA: Since the geomagnetic field is not a perfect dipole, the inner radiation belt gets closer to the Earth over the South Atlantic Ocean, which is called the South Atlantic Anomaly (SAA).

Trapped proton sources are cosmic ray albedo neutron decay (CRAND). Calculated intensities at energies $\leq$100 MeV and for $L \geq 1.3$ are dominated by solar protons, CRAND being the dominant source otherwise.



This is overview of spacecraft environments and effects on satellites. The yellow highlighted region pertains to effects of space radiation from SEPs and GCRs.



At the SWRC, our goal is to monitor the space environment for NASA robotic mission operators.

For spacecraft outside of a protective planetary magnetosphere, the energetic particles very potential for damage.

The sources are both flares, CMEs. You remember that a flare is a rapid release of energy, which can be transferred to particles as kinetic energy. CMEs can drive shock waves, and shock waves are also efficient particle accelerators.

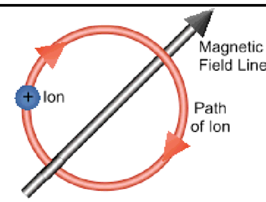
Note: for all the SEP events that exceed our threshold, there is accompanying CME(s). CMEs are very important for those SEP events of space weather significance.

SEPs: ion radiation storms

Potentially affect everywhere in the solar system

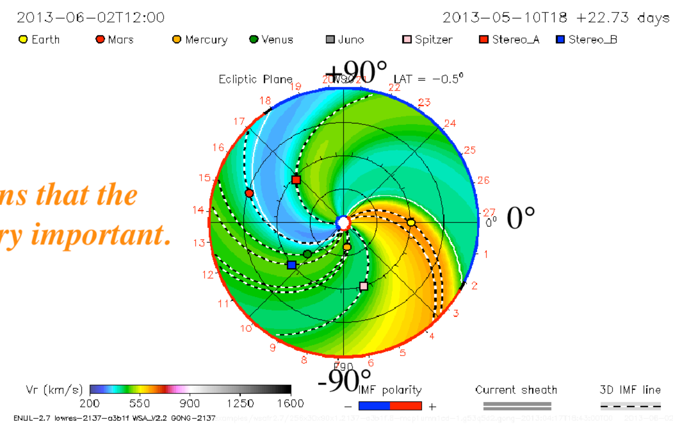
SEPs: applicable and potentially damaging everywhere that they have influence

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

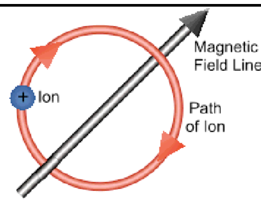
ENLIL

Charged particles, when the magnetic field is above some certain threshold, are tied to magnetic field lines. They will propagate along the magnetic field lines.

As we discussed earlier, because the Sun rotates, the interplanetary magnetic field takes a spiral shape in the equatorial plane. Use these lines to see where the soure regions can be for these spacecraft.

Just flares/source region connection

Magnetic fields guide SEPs/ magnetic connectivity



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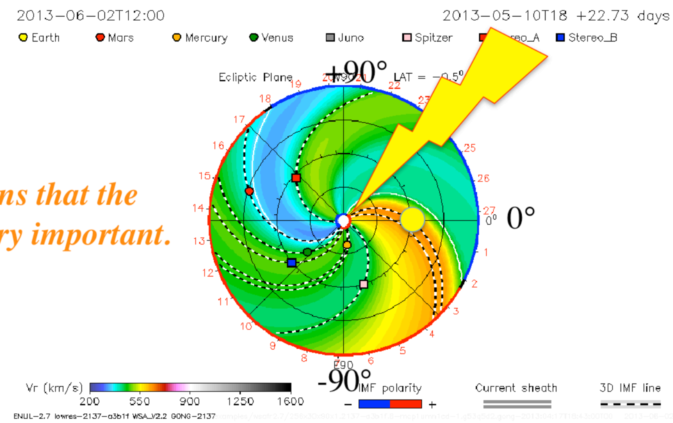

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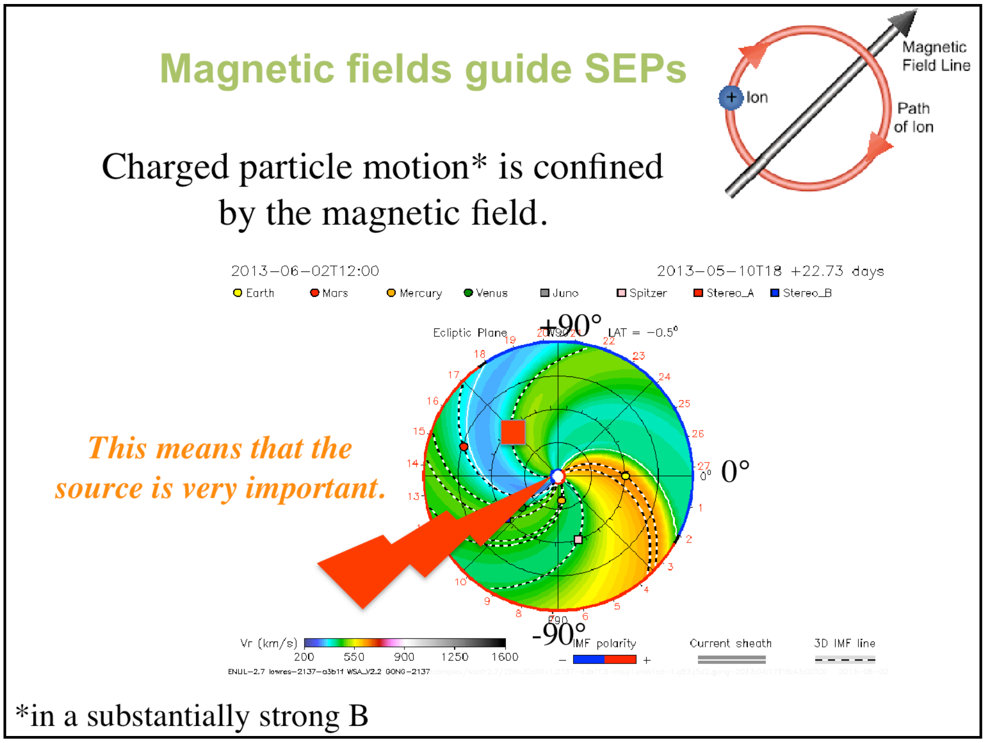

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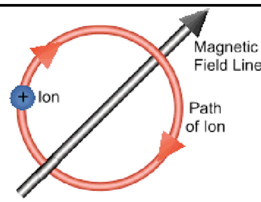
Magnetic fields guide SEPs



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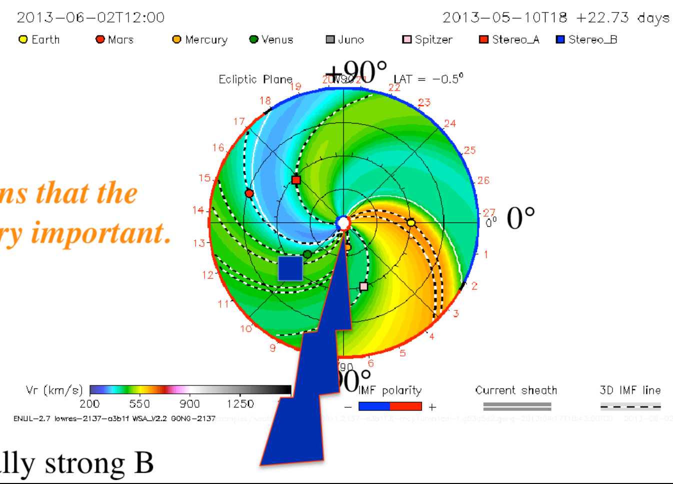
This means that the source is very important.



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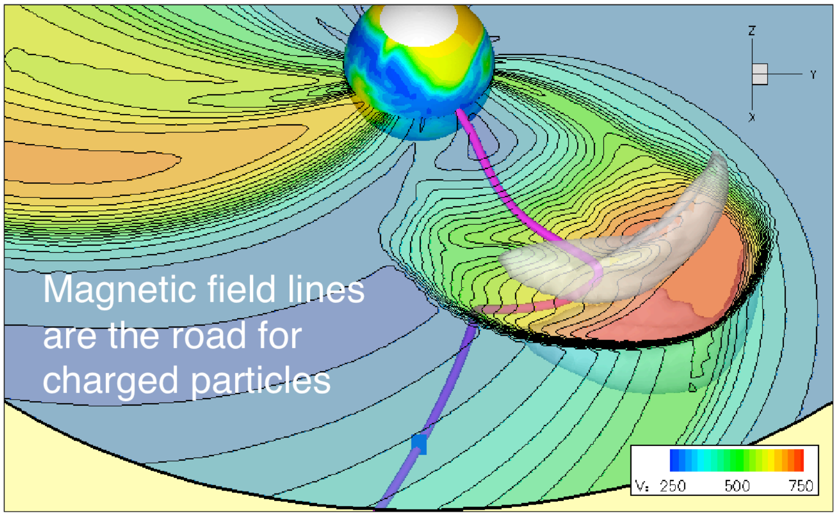
Just flares/source region connection

CMEs Can Widen Longitudinal Extent of SEP Events

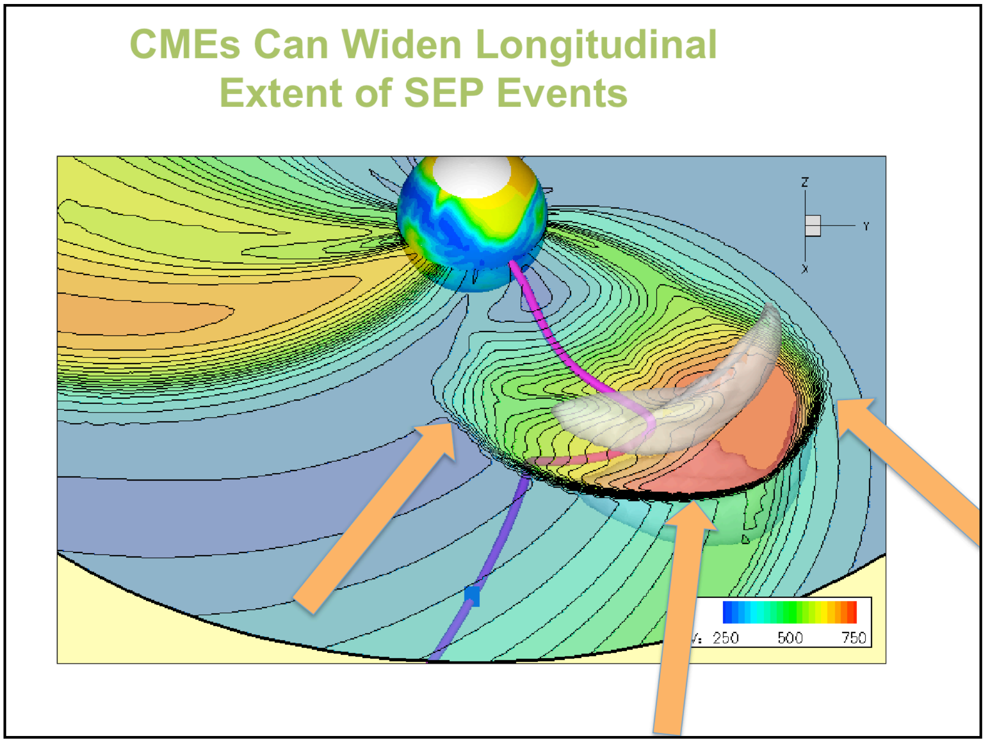


If particles do not easily cross from one magnetic field line to another, it may seem like all SEP events would then be very narrow in longitude.

However, a CME can play a role not only in accelerating the particles, but also in distributing them over a wide range of longitudes, as we can see here in this simulation.

Here is a simulation that shows us what that might look like.

So, remember, when there is a cme, it can widen the area of the SEPs.



If particles do not easily cross from one magnetic field line to another, it may seem like all SEP events would then be very narrow in longitude.

However, a CME can play a role not only in accelerating the particles, but also in distributing them over a wide range of longitudes, as we can see here in this simulation. Sandro said how CMEs can be greater than 100 in width, so it is possible for the same SEP event to be seen at multiple locations.

Here is a simulation that shows us what that might look like.

So, remember, when there is a cme, it can widen the area of the SEPs.

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)

SEP intensity is usually measured in differential flux, differential energy flux or fluence

Converting between the two is important to know in order to quantify the relative strengths.

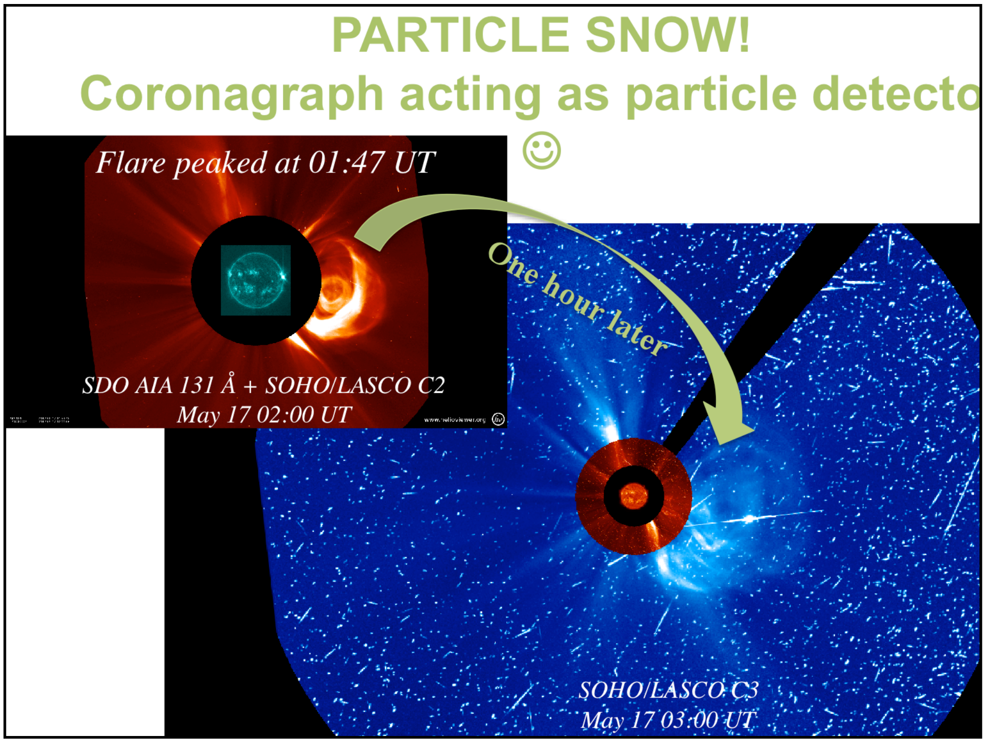
SEP Intensity

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 is usually measured in differential flux, differential energy flux or fluence

The extreme values of SEP events



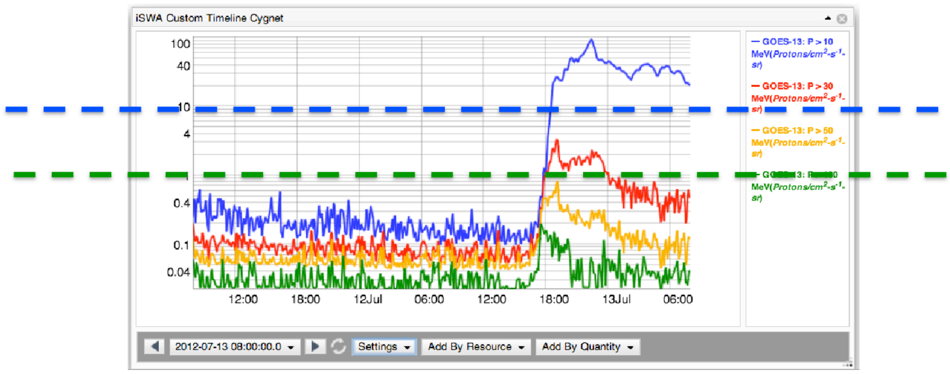
Another way that we “see” SEPs are in images, for example, coronagraphs. Here you can see the ‘snow’ of particles hitting the detector.

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



Here is an example of an event where the 10 MeV limit was met, but not the 100 MeV.

SOHO: > 15.8 MeV proton channels 0.1 pfu/MeV.

How Do We Quantify an SEP Event?

NOAA Space Weather Scale for Solar Radiation Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Solar Radiation Storms			Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S 5	Extreme	**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.*** **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.	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

NOAA/SWPC's classification of SEP events – based on the flux level of the >10 MeV integral proton flux level.

Note: this is a simplified classification system. Impacts depend on multiple factors, such as spectra of an event.

Human Safety in Space

- GCR
- **SEP**

Johnson Space Center/Space Radiation Analysis Group (SRAG)

Limit: the > 100 MeV flux exceeding 1pfu

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

- All clear (EVA –extravehicular activity)

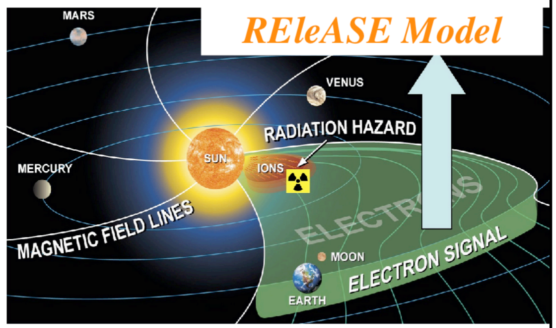
19

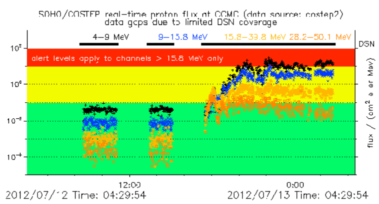
For humans in space, higher energy particles are more relevant. The >100 MeV proton flux is used.

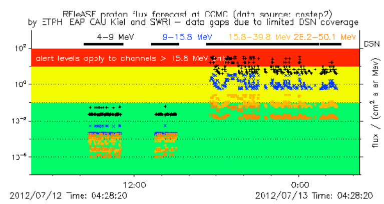
Can we predict SEP events?

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

Data source: SOHO COSTEP



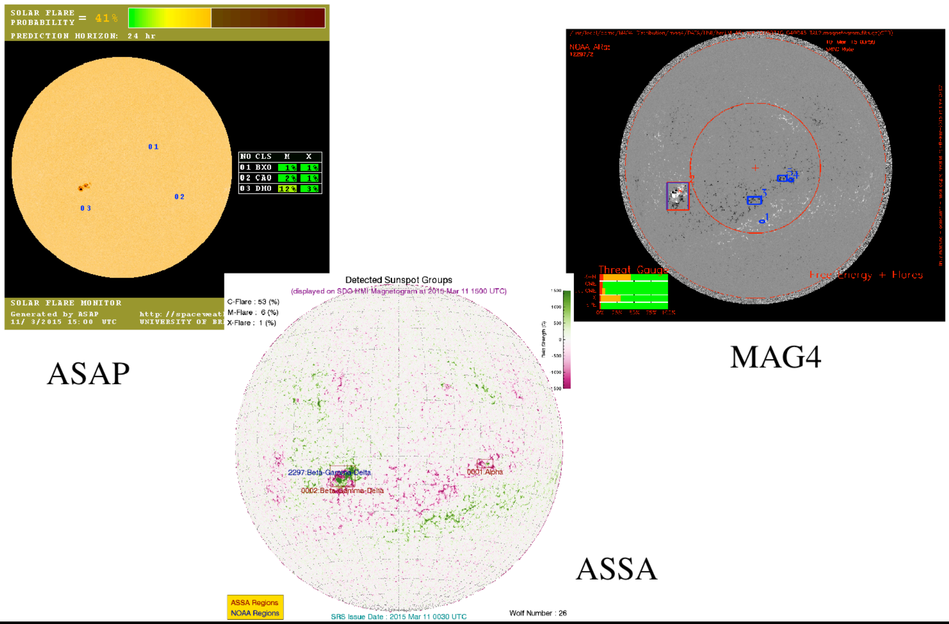




http://iswa.gsfc.nasa.gov/wiki/index.php/SOHO/Costep_Proton_Flux_-_Forecast

SEP Prediction (active region)

x2.2 flare on march 11, 2015

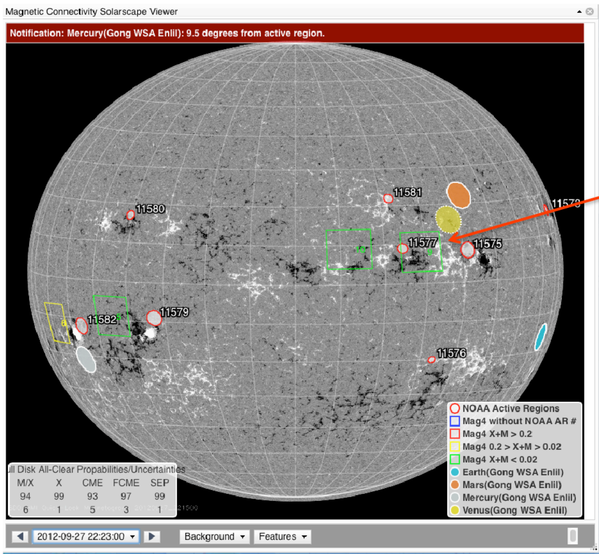


Intensity: X2.2 class
Source region S16E26 (12297)

SEP prediction – characterization of active regions, not so accurate/reliable

This event: strong flare – little enhancement in SEP fluxes

Solarscape/magnetic connectivity

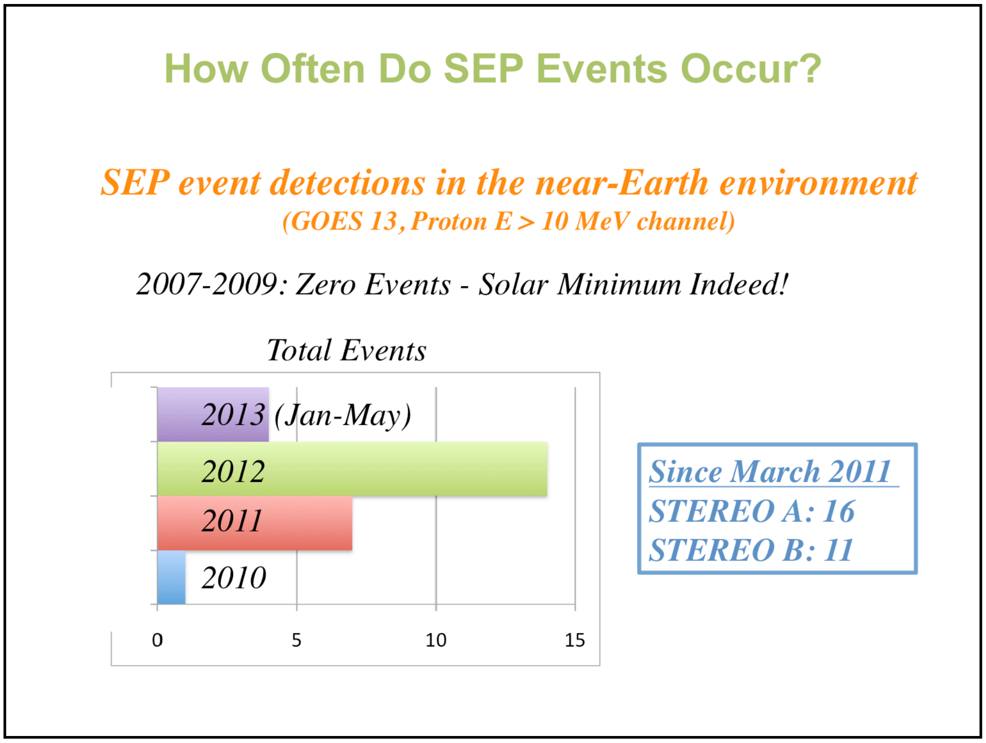


C3.7 class flare
AR 11577

20120927_2336 2012/09/27 23:36:00 00:34:00 23:57:00 C3.7 N09W32 (1577)
LDE: long duration event N09W32

This C-class flare and CME result in a SEP event at STEREO A and Earth

Earth-directed. Hemispheric wave, asymmetric halo

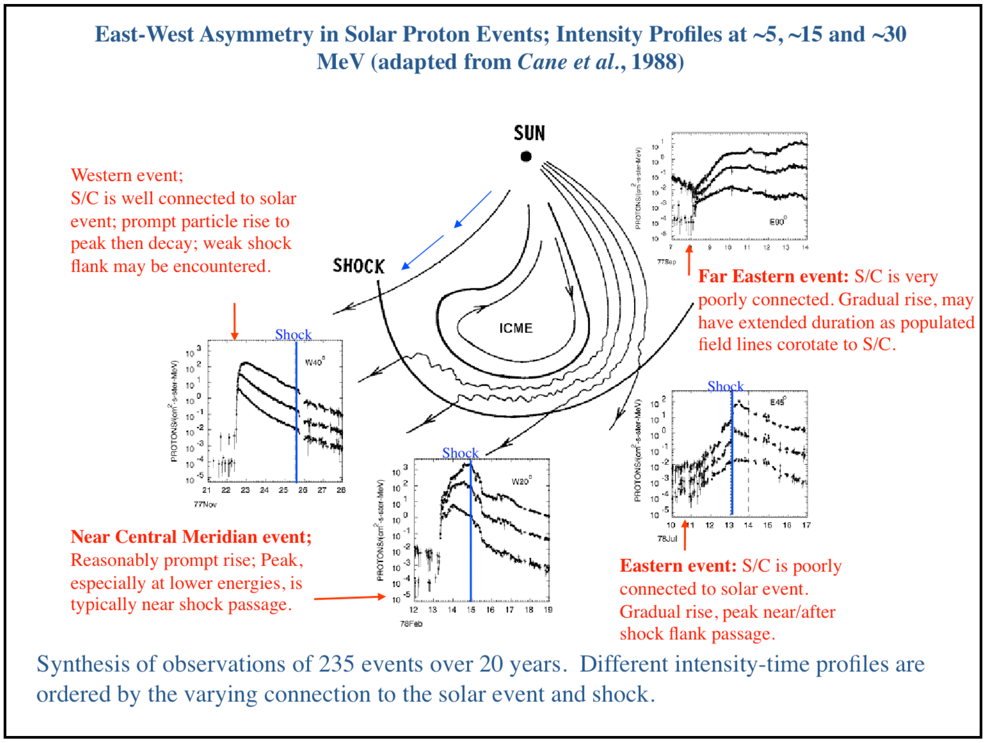


If you are speaking about one specific location in the heliosphere, for example, just at the Earth, then during solar minimum, there can be only a few or even none in a year. During higher activity times, there can be about one per month or so.

However, there can be many more SEP events happening at other locations, or that we simply are not measuring – remember how that sometimes events can be focused in space!

With only four events in the first 5 months of 2013, things are a little more quiet than we would have guessed.

Recognizing profile shapes of SEP flux and associating it with the source/driver



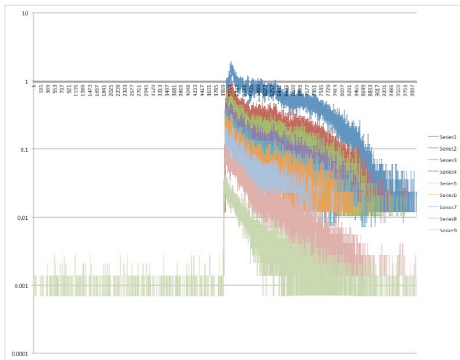
The profile of a proton event depends on the longitude of the solar event relative to the observer.

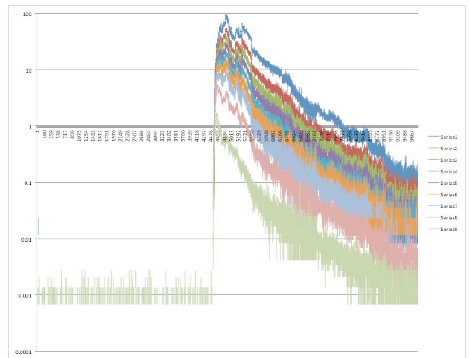
The major controlling agent is the existence of an interplanetary (IP) shock.

Cane and Lario, 2006

Cane et al., 1988

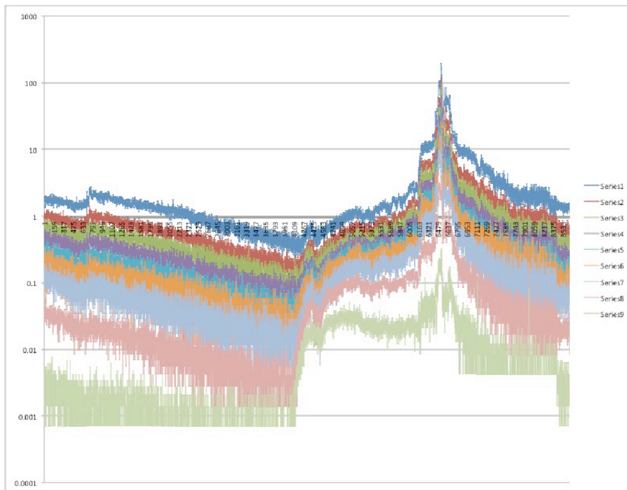
Impulsive: The "peak at the beginning due to flare, fall off" – indicates how well connected you are to the source (timing)





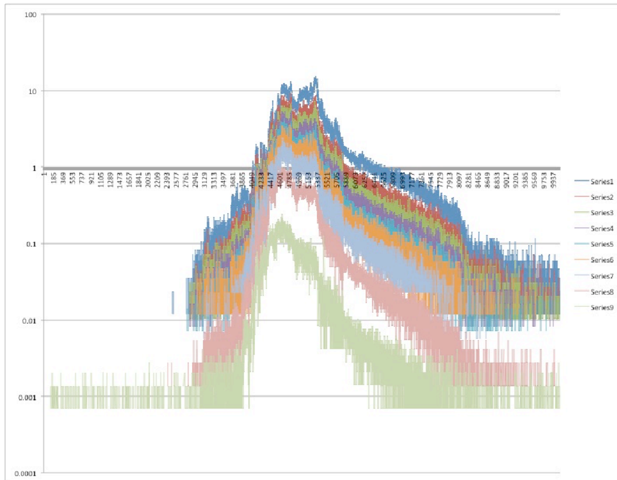
Well-connected events

Gradual: The "jump up from flare/CME, slow rise
Then peak when the ICME passes the spacecraft"



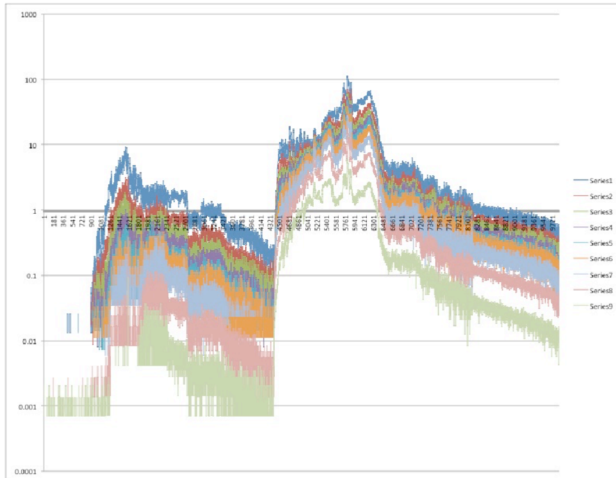
The peak is often called ESP – (Energetic Storm Particles) component (due to the CME arrival).

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”



When the observer is not magnetically well-connected to the source region - an eastern event

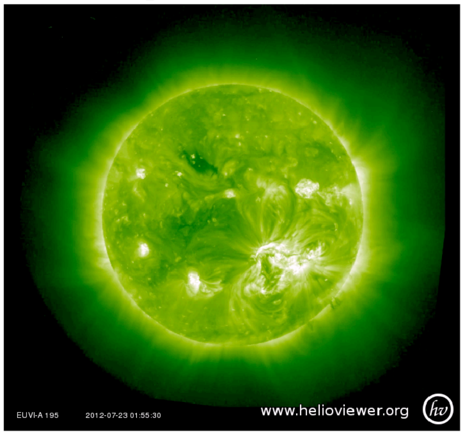
The “multiple event weirdness”



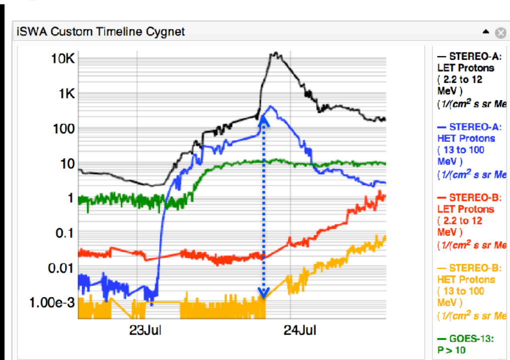
Temporal profile can be complicated with a series of SEP events – multiple events in a row

July 23, 2012

Example where is reaches one spacecraft, then later another…

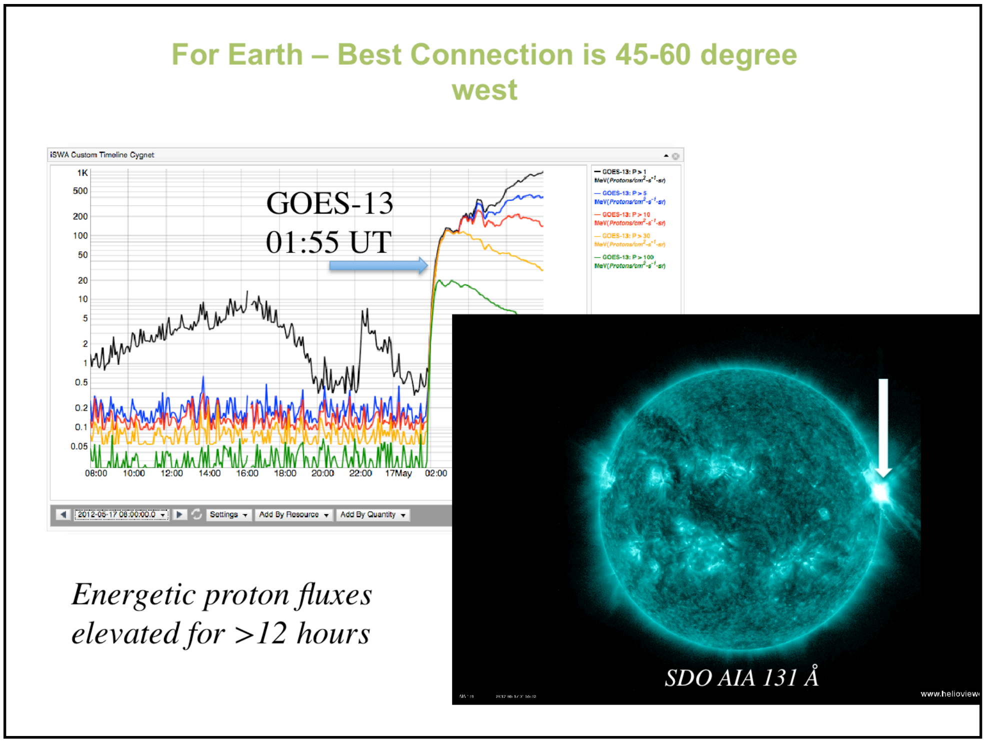


July 23 flare as seen in
STEREO A EUVI 195

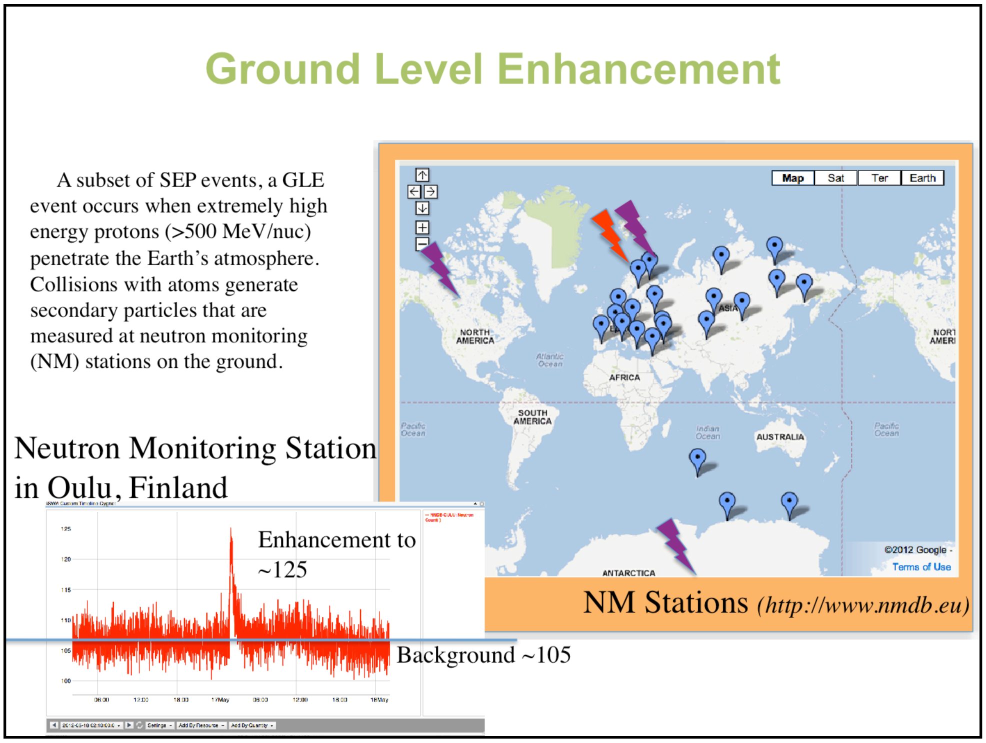


Increase of more than 5 orders of magnitude at STEREO A
SEP event also detected by GOES, and later enhancement seen at STEREO B (possibly due to IPS)

On July 23rd it really put on a show.



Not only were the >10 Mev channel elevated well above our threshold, but the >50 and >100 channels as well, which tell us that this event was very efficient at accelerating the highest energy particles.



The most extreme events…

This suspicious was confirmed by the detection of neutron enhancement at 4 stations. Those neutrons are reaction particles from relativistic protons

Add arrows to mark stations that observed May 17 GLE – what WAS THE TIME????

Save discussion of GLE events in SC 23 and characteristics of GLEs until 2nd half of talk. First half should only be observations!

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

Gopalswamy et al. 2012, Li et al. 2012, Mewaldt et al. 2012

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

GLE				Flare		CME	
Onset			Max	GOES		POS	Width
ID	Date	Time[a]	Int (%)[a]	Class	Location	speed (km/s)	(degs)
55	1997/11/06	12:10	11.3	X9.4	S18W63	1556	360
56	1998/05/02	13:55	6.8	X1.1	S15W15	938	360
57	1998/05/06	08:25	4.2	X2.7	S11W66	1099	190
58	1998/08/24	22:50	3.3	X1.0	N35E09	–[b]	–[b]
59	2000/07/14	10:30	29.3	X5.7	N22W07	1674	360
60	2001/04/15	14:00	56.7	X14	S20W85	1199	167
61	2001/04/18	02:35	13.8	C2.2	S20W116	2465	360
62	2001/11/04	17:00	3.3	X1.0	N06W18	1810	360
63	2001/12/26	05:30	7.2	M7.1	N05W54	1446	>212
64	2002/08/24	01:18	5.1	X3.1	S02W81	1913	360
65	2003/10/28	11:22	12.4	X17	S18E18	2459	360
66	2003/10/29	21:30	8.1	X10	S18W04	2029	360
67	2003/11/02	17:30	7.0	X8.3	S18W57	2598	360
68	2005/01/17	09:55	3.0	X3.8	N14W25	2547	360
69	2005/01/20	06:51	277.3	X7.1	N14W61	3242[c]	360
70	2006/12/13	02:45	92.3	X3.4	S06W23	1774	360

[a]According to the Oulu Neutron Monitor

[b]No SOHO LASCO data

[c]From Gopalswamy et al. (2010). There are different estimates (see Grechnev et al. 2008)

Nitta et al. 2012

CME-driven shocks are thought to play important role in low (<3R_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

Like I said, these events prompt more questions and more questions, so we want to look at all of the extreme events (GLE) and see if any characteristics of the solar part of the storm can tell us about what is happening. And the answer is that while there are trends, it's not true that strong flare cause GLEs, as you saw only M5 cause the May event, it's not the fastest and biggest CMEs.

Again I want to emphasize that these are all just speculations because most of the interesting stuff is happening in a region that is not well covered by coronagraphs.

End with: And so we are motivated to model the acceleration of particles by CME driven shocks in the low corona…

Comparing to previous AR1476 flares: Longer duration, but similar magnitude

March 7th event: flare and CME weaker, SEPs at Earth 20x weaker

Solar Cycle 23 GLE events: no CME in previous 24 hours (to generate seed particles)

What was special about this flare and CME to generate a GLE?

Timing: CME erupted during rise time of flare

Connectivity: AR well connected to Earth

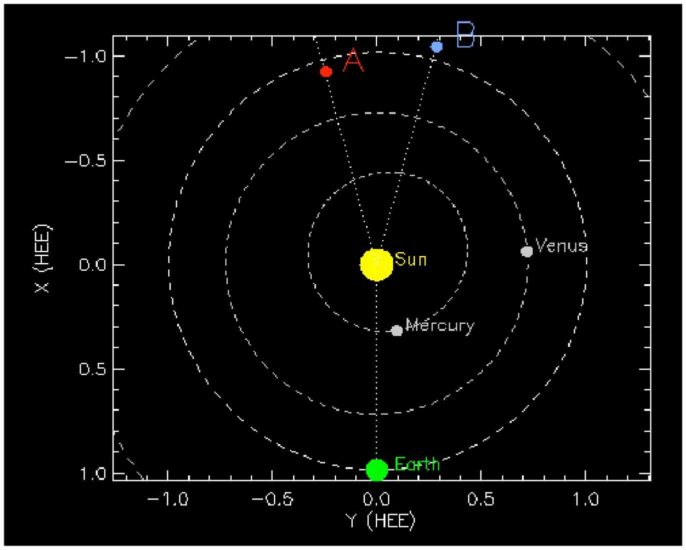
CME speed 1,500 km/s sufficient to drive shock in low corona (Evans et al. 2008)

Must have been very wide CME (to impact STEREO A and Earth)

As is common, they were not geoeffective (Kp max =4)

Possible Type II radio burst indicates CME driven shock

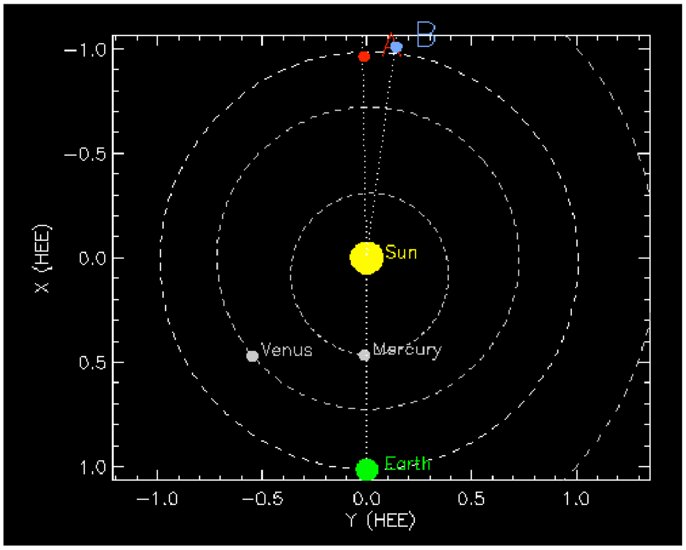
Where are NASA assets now?



Jan 18, 2016

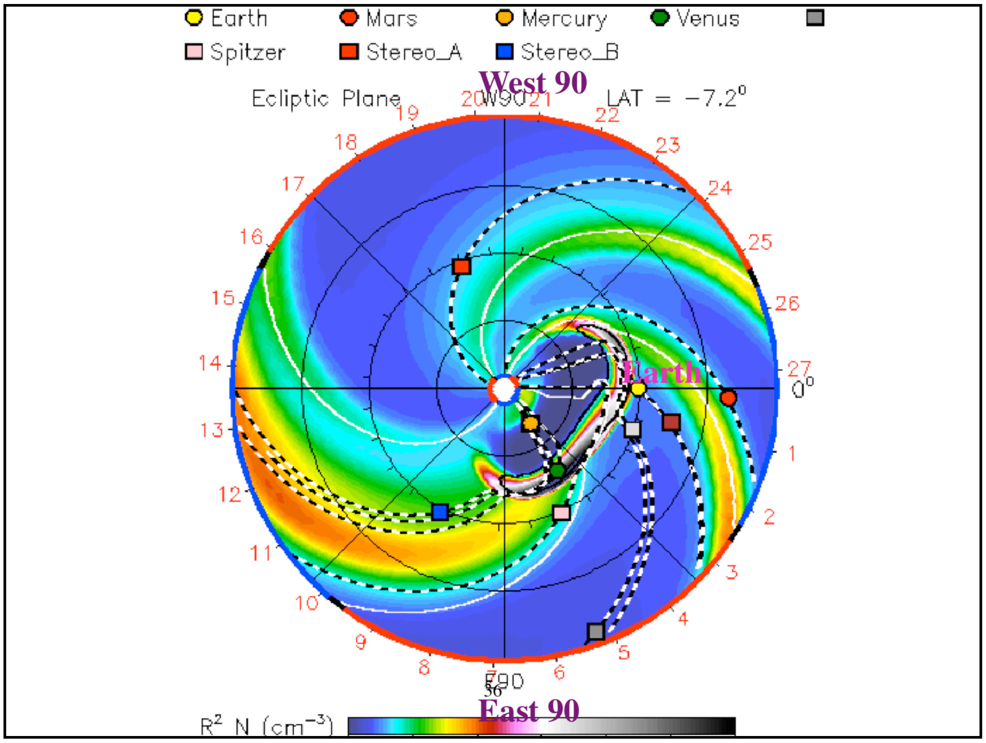
Explain the figure set up.

Where are NASA assets now?

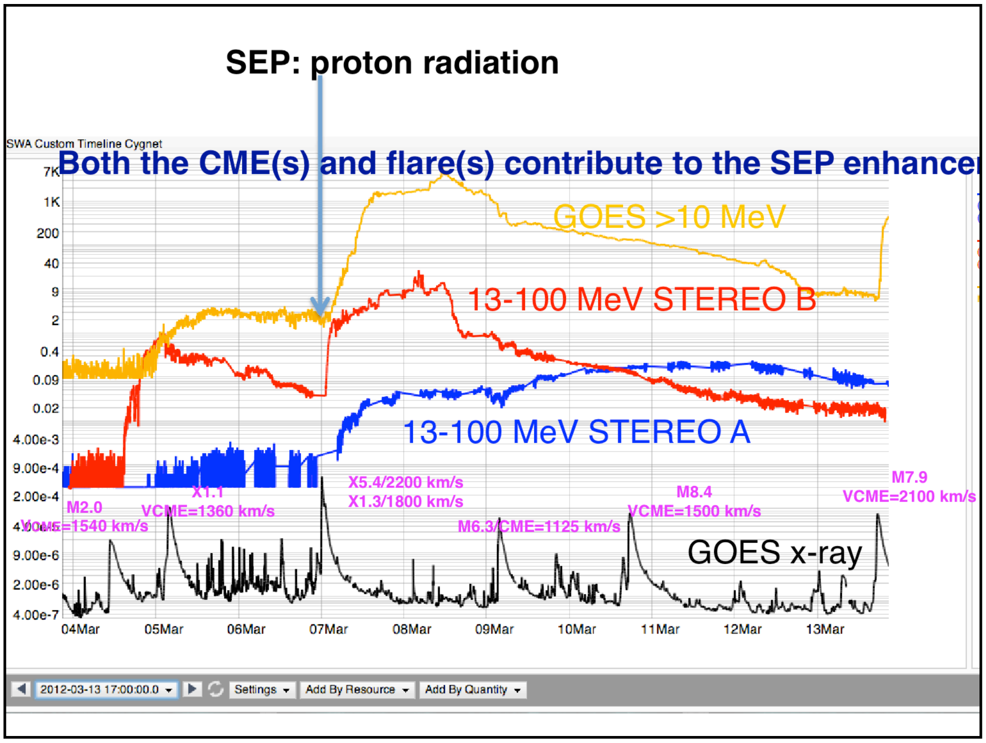


May 29, 2015

Explain the figure set up.



Simulation result of the March 7 2012 CMEs



Timeline of the event and SEP enhancement at multiple spacecraft for the 7 March 2012 event

SEP Layout

http://bit.ly/alert_SEP_layout

Exceptions to every rule!
September 28, 2012 – whole heliosphere event – C3.7 flare

20120927_2336 2012/09/27 23:36:00 00:34:00 23:57:00 C3.7 N09W32 (1577)
LDE longduration event N09W32

Earth-directed. Hemispheric wave, asymmetric halo