Solar Energetic Particles (SEPs) and Space Weather

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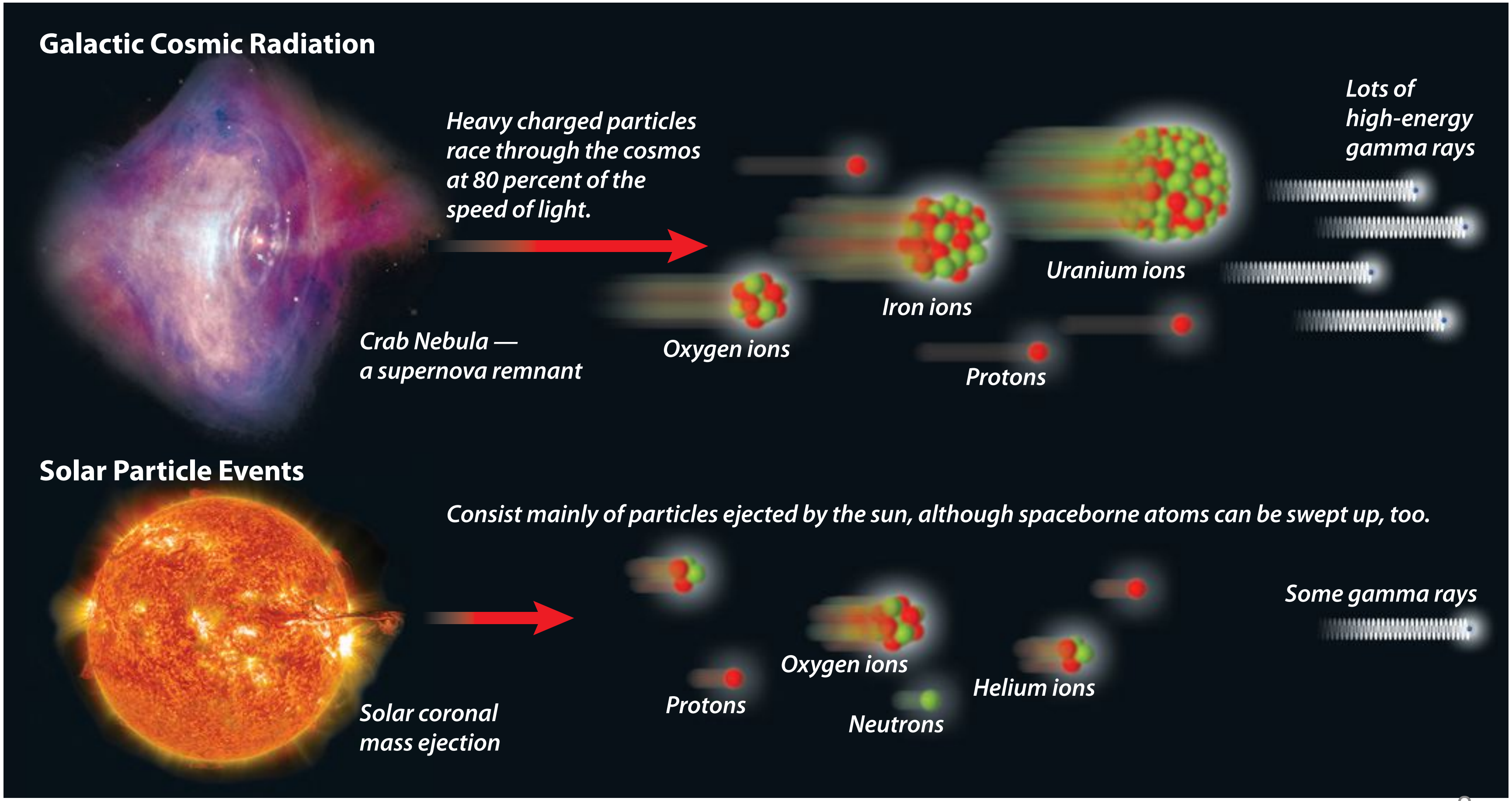
Acknowledge: M. Leila Mays

SEPs – Important Source of Space Radiation: Hard to Predict

Deep space dangers

Galactic Cosmic Radiation (GCR) -- another source

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

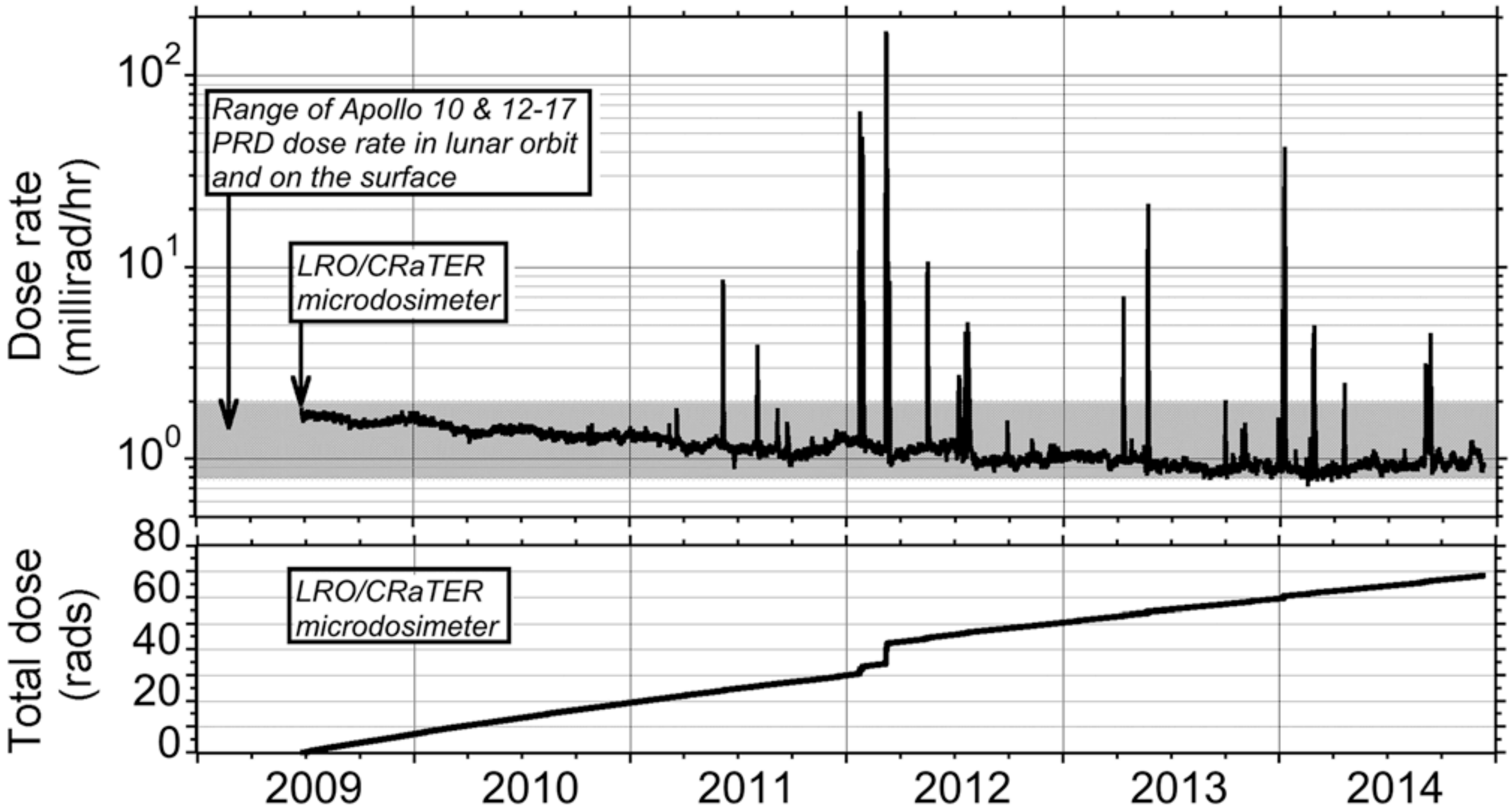


Sources: NASA SOHO solar observatory, NASA Hubble and Chandra images

Graphic by John Bretschneider

GCR versus SEP characteristics

Mazur et al. 2015. Figure 1



LRO (Lunar Reconnaissance Orbiter)/CRaTER (Cosmic Ray Telescope for the Effects of Radiation) microdosimeter measurements from launch in June 2009 to December 2014. Doses due to SEPs appear as spikes while those from GCRs is the slowly varying background.

Solar Energetic Particles

- **The Sun accelerates particles to near-relativistic speeds**
  - Particles include electrons, protons, ions
  - Near-relativistic speed = near the speed of light (c = 300,000 km/s)
  - Accelerated particle energies up to ~GeV ions.
  - Higher energy than ambient solar wind
- **Most of the acceleration happens close to the Sun (less than 10 Rs)**
- Particles can reach Earth's orbital distance (1 AU) in tens of minutes to hours

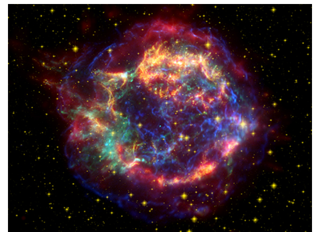
Ionizing Radiation Storms

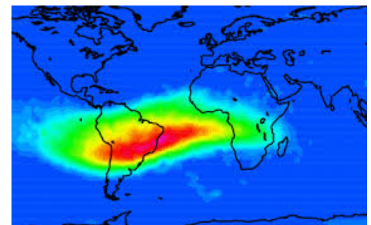
Why do we care?

SEPs

GCRs (Galactic Cosmic Rays)

SAA (South Atlantic Anomaly)





Polar Cap Absorption

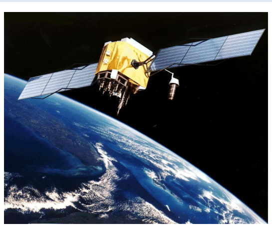
Single event effects

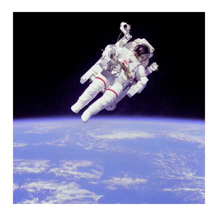
Acute and long term risks

Commu and Nav.

Spacecraft

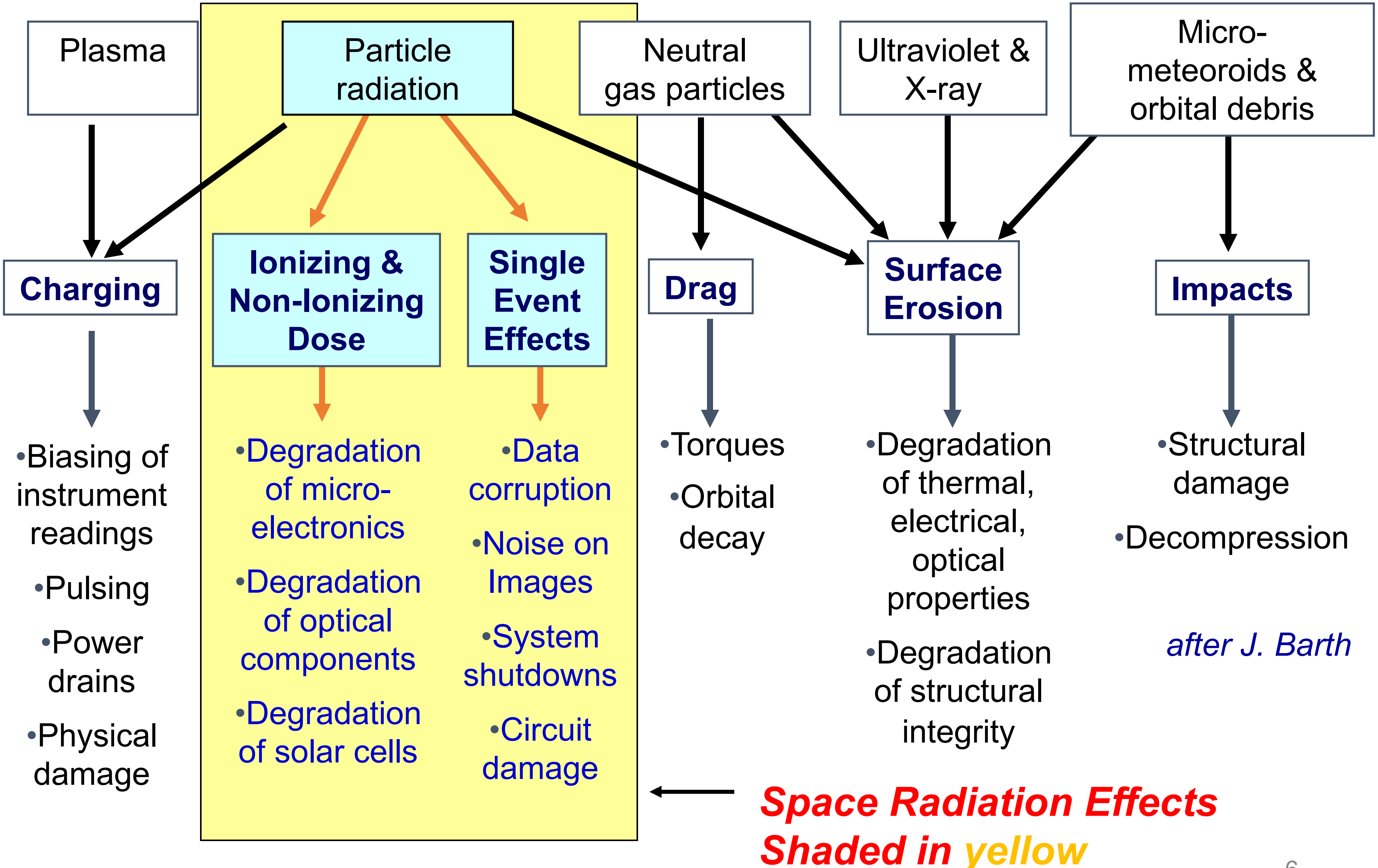
Human in space





Also: Total ionizing dose (TID) and displacement damage dose (DDD)

Space Environments and Effects on Spacecraft



Particle Energy Units

- The electronvolt (eV) is a unit of energy
- 1 eV = 1.6×10^{-19} Joules
- 1 MeV = 10^6 eV, 1 GeV = 10^9 eV

Examples:

- A 1 MeV proton is moving at 0.05c
- A 10 MeV proton is moving at 0.14c
- A 100 MeV proton is moving at 0.43c
- A 1 GeV proton is moving at 0.88c

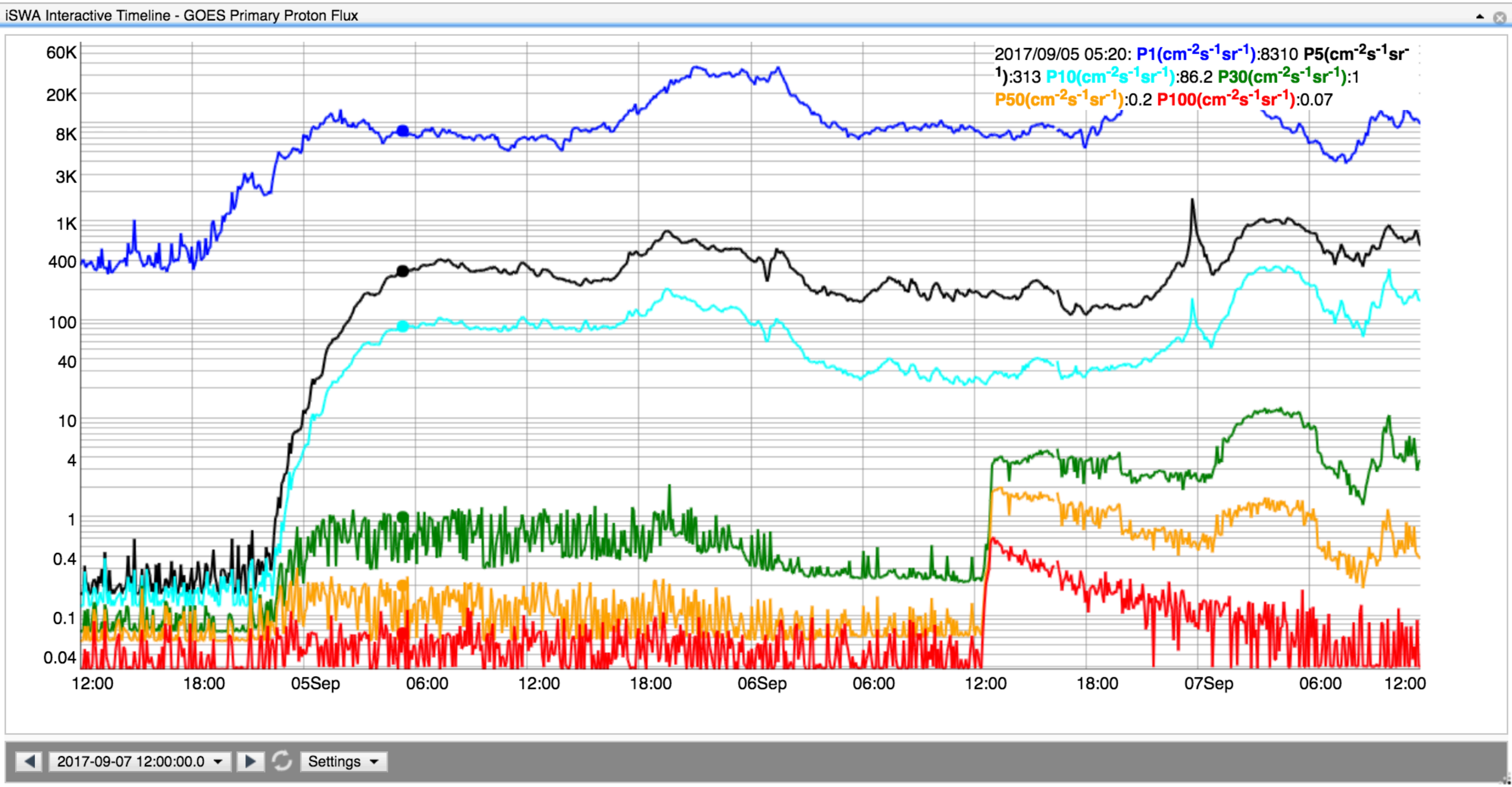
Flux Units

- pfu = particle flux unit
- 1 pfu = particles/(cm^2 sec sr)
- sr = steradian or square radian; unit of solid angle

SEPs: Potentially affect everywhere in the solar system

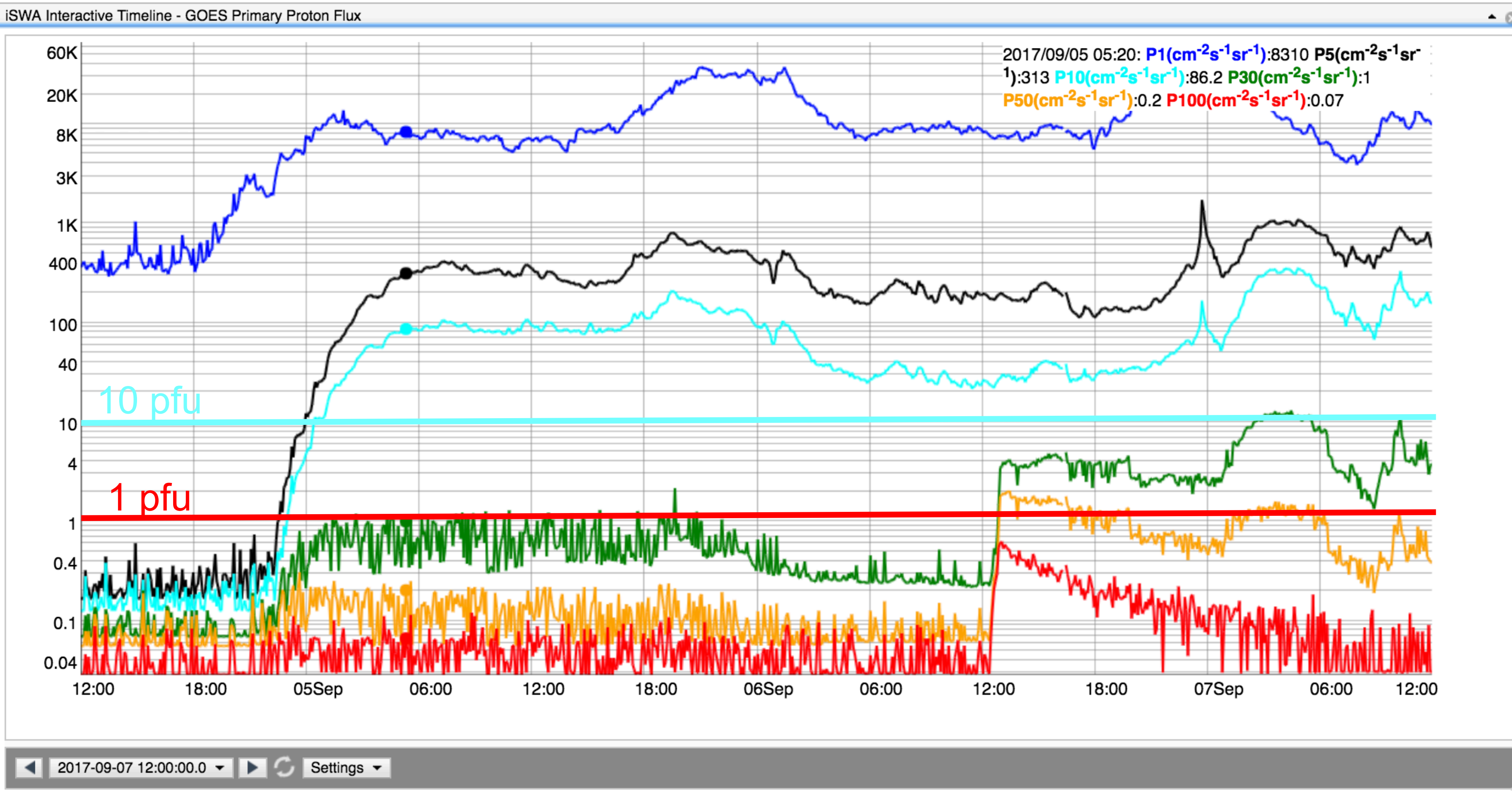
Courtesy: SVS@ NASA/GSFC

SEPs Observed by GOES: Proton Flux vs Time



integral proton flux (pfu) in 6 energy channels:
>1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV, >100 MeV

SEPs Observed by GOES: Proton Flux vs Time



integral proton flux (pfu) in 6 energy channels:

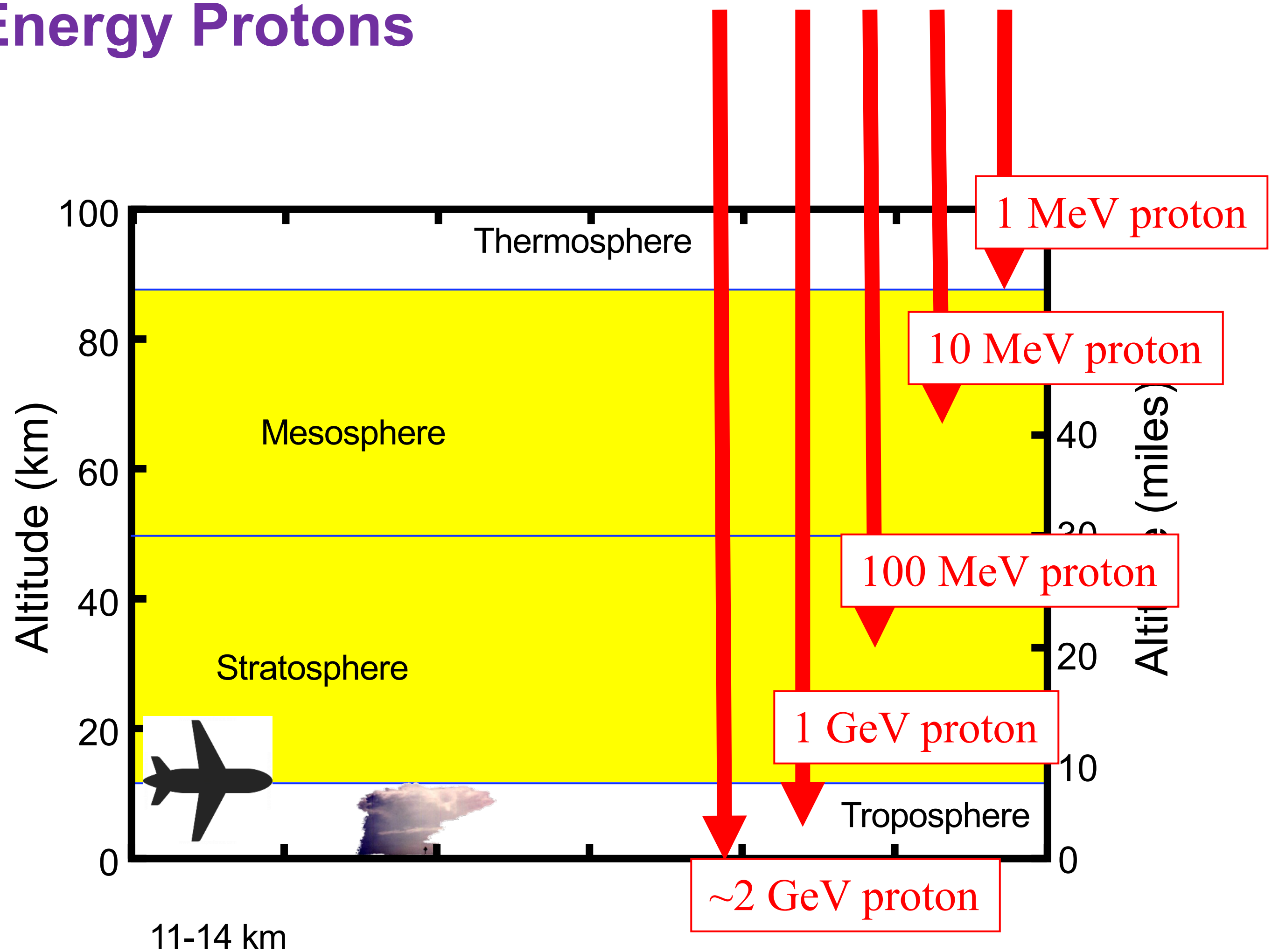
>1 MeV, >5 MeV, **>10 MeV**, >30 MeV, >50 MeV, **>100 MeV**

Notification threshold: 10pfu **1 pfu**

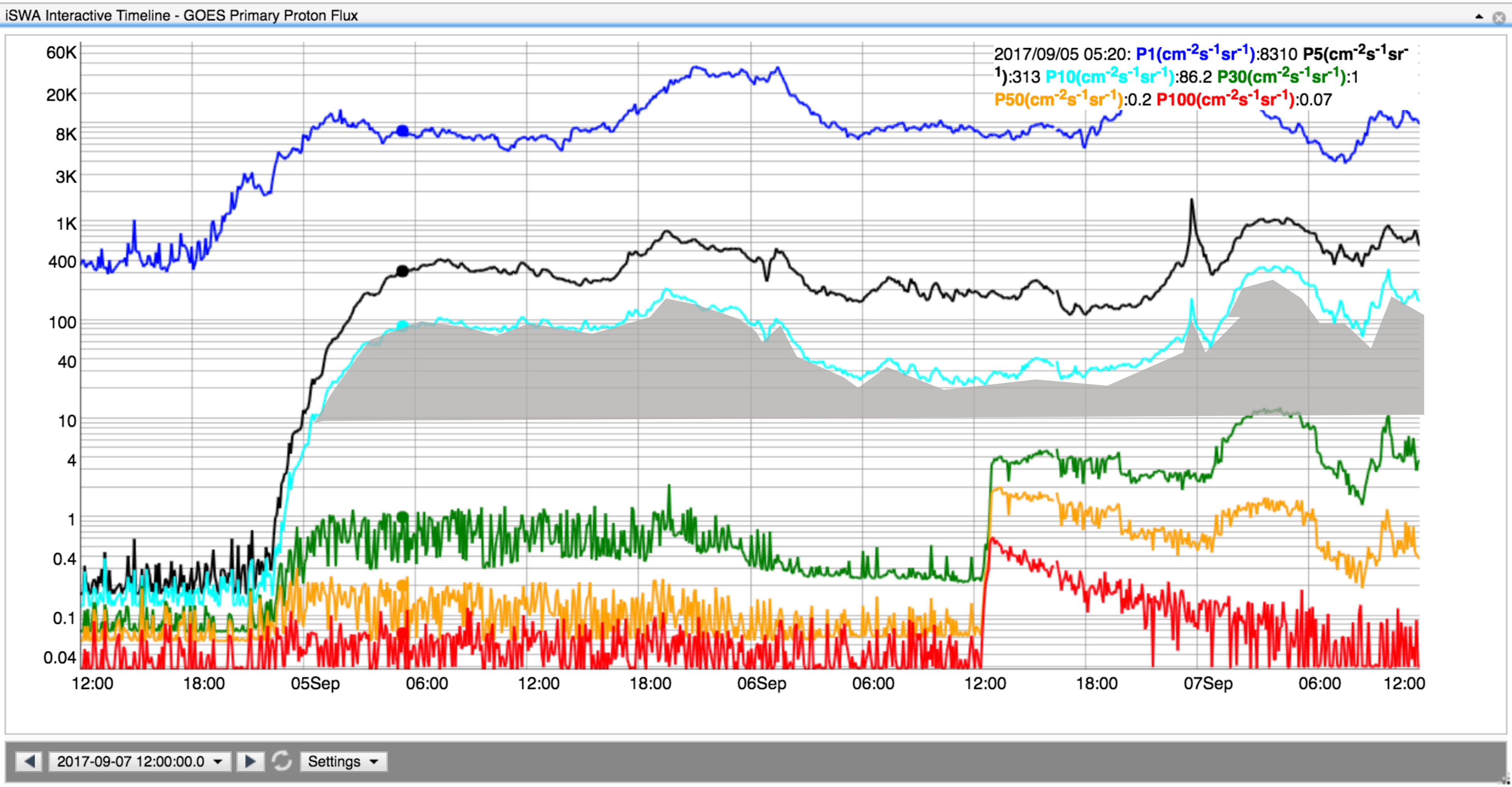
NOAA Space Weather Scale for Solar Radiation Storms

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

Penetration Depths of Different Energy Protons



Fluence=integrated proton flux over time, used to determine dose

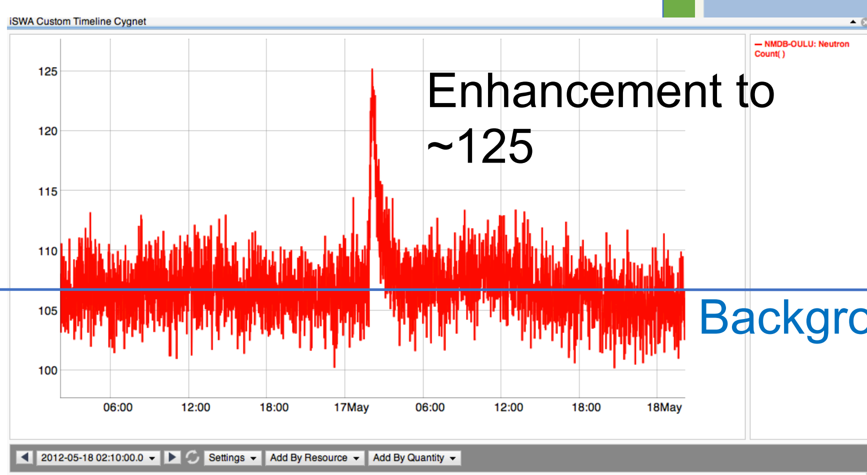


Sep 2017

Ground Level Enhancements

- GLEs = subset of SEP events
- high energy protons (>500 MeV/nuc)
- Reach Earth's surface.
- Collisions in the atmosphere generate secondary particles that are measured at neutron monitor stations on the ground.

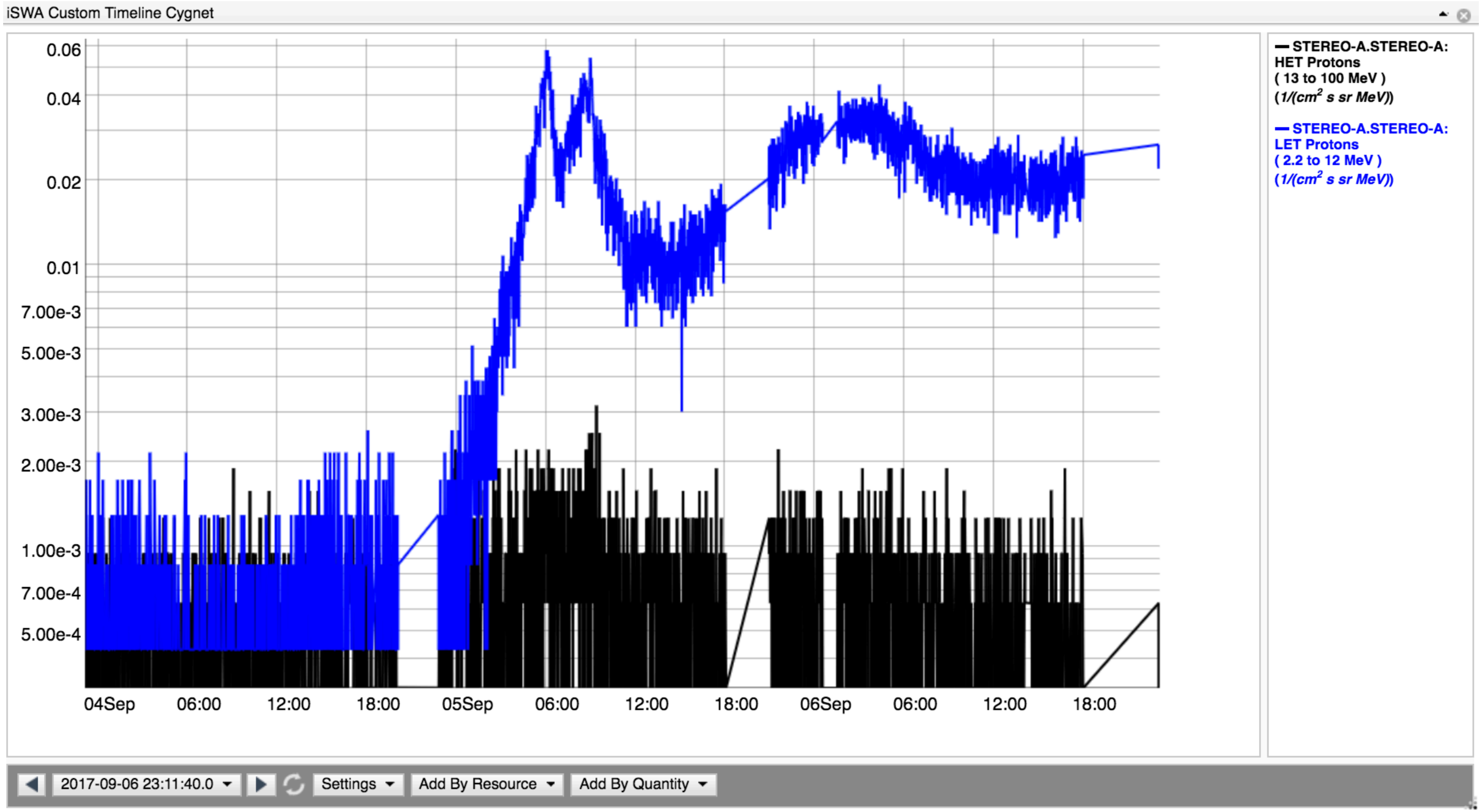
NM Stations *(http://www.nmdb.eu)*



Background ~105

Neutron Monitoring Station in Oulu, Finland

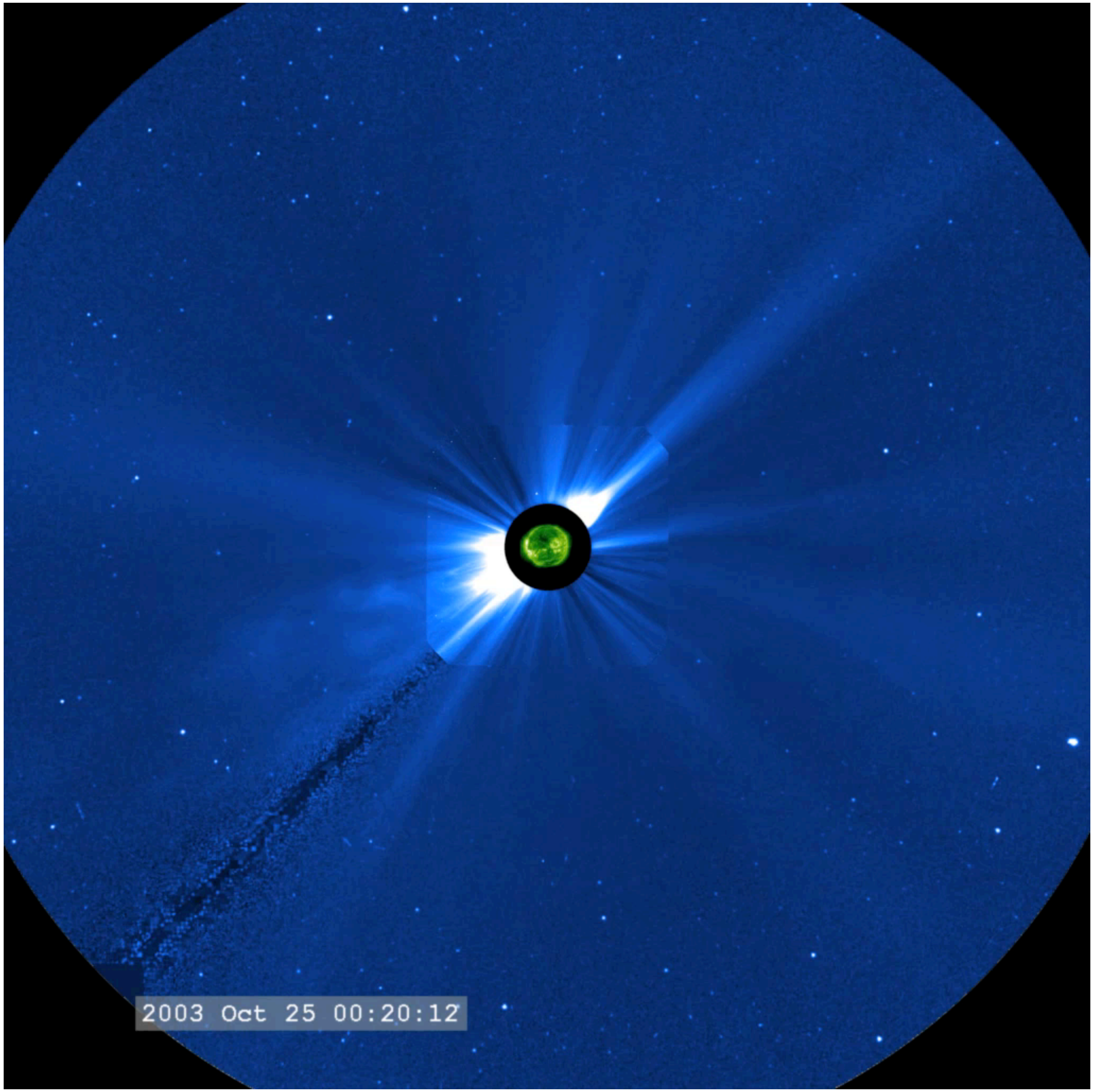
SEPs Observed by STEREO A: Proton Flux vs Time



differential proton flux (pfu/MeV) in 4 energy channels (two shown): 0.14-0.62 MeV, 0.62-2.22 MeV, **2.2-12 MeV**, **13-100 MeV**

Notification threshold: **0.1 pfu/MeV**

Solar Energetic Particles Hitting a Coronagraph



Navigate to this webpage:

http://qdle.net/24981545

What is a space weather effect from SEPs?

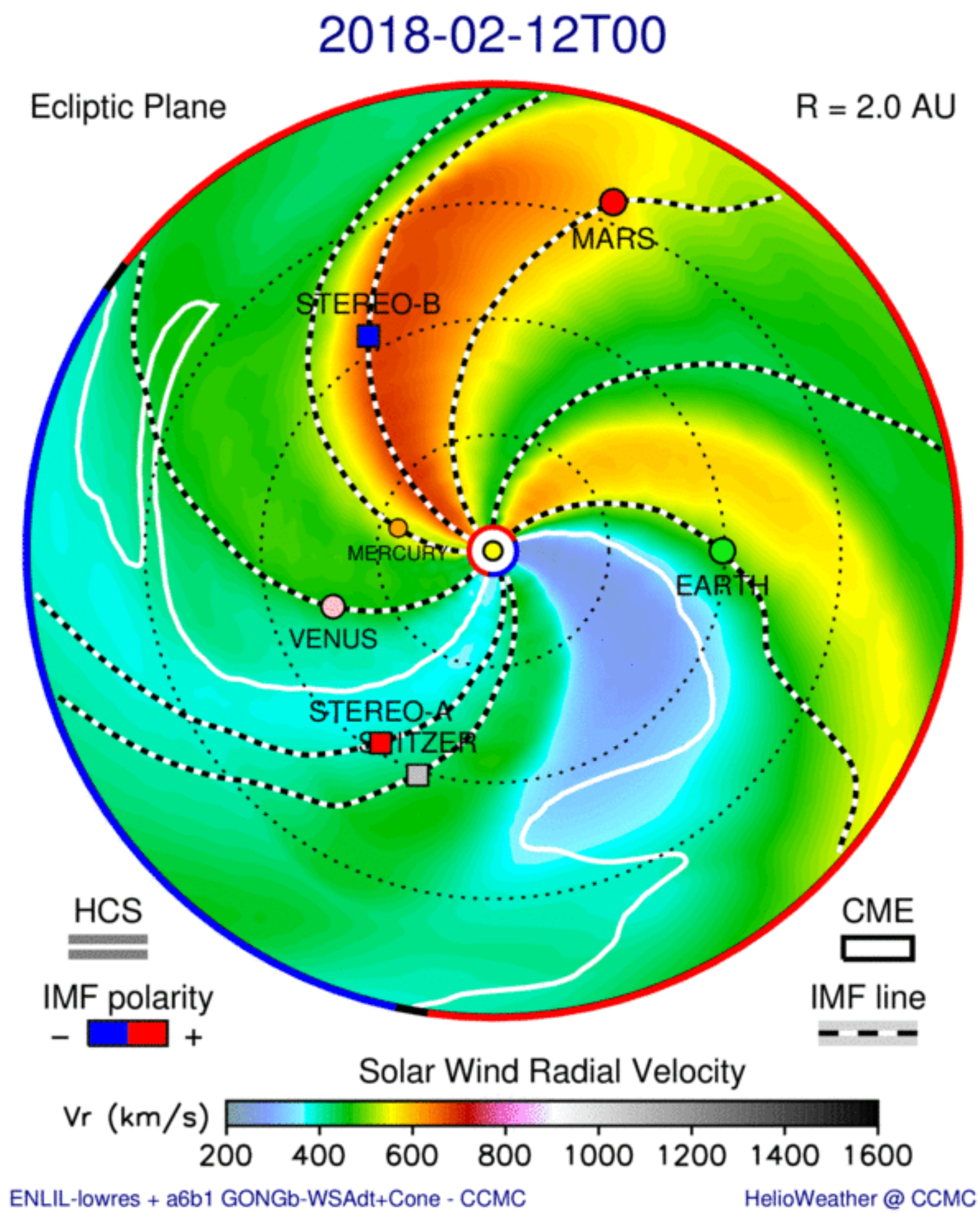
a) Increased radiation risk for astronauts on the ISS
b) Increased radiation risk for future human exploration missions throughout the solar system
c) Increased radiation risk for airline passengers and crew
d) Satellite solar panel degradation
e) Satellite processor and memory errors
f) All of the above

Answer the quiz here:

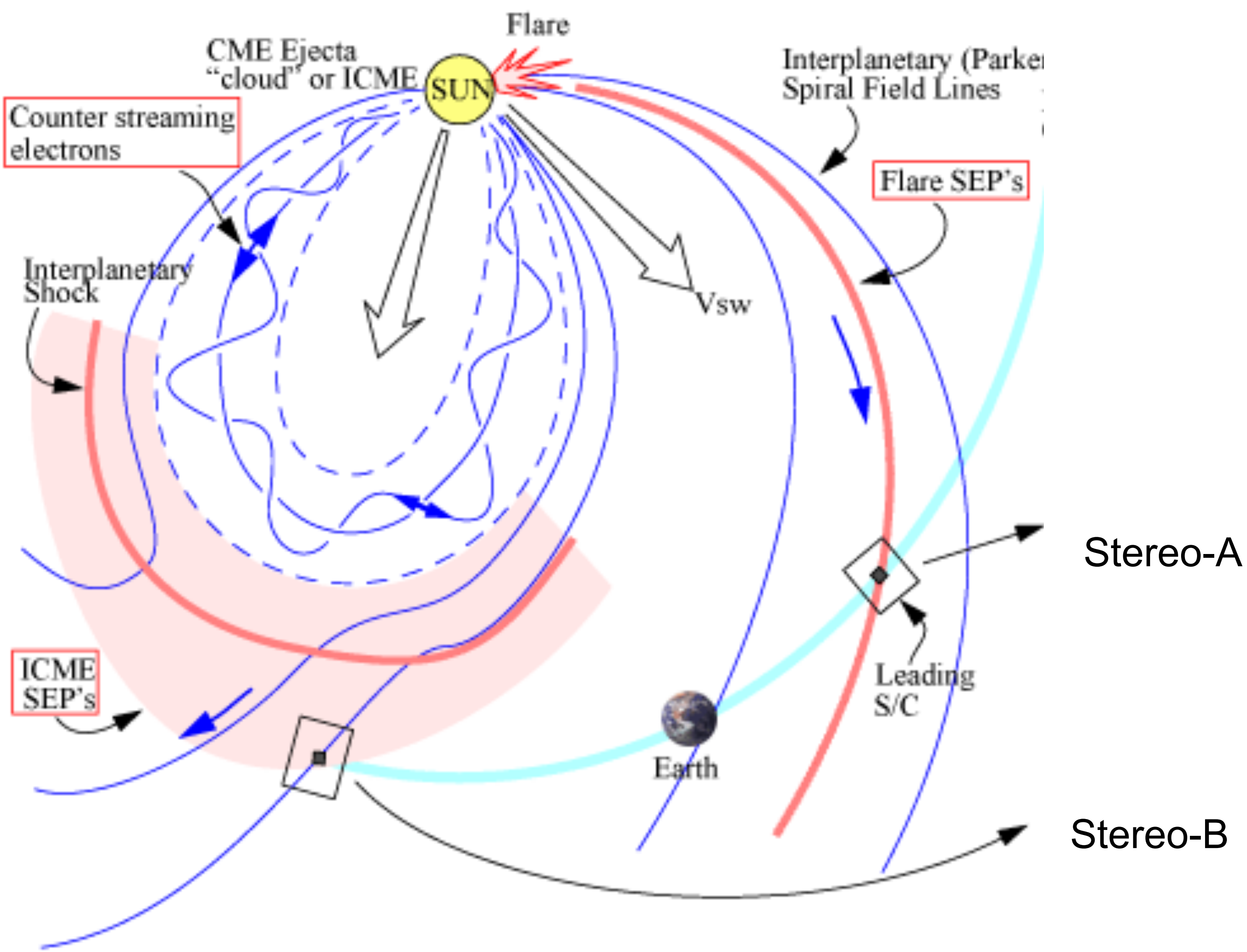
http://qdle.net/24981545

- The solar wind forms a spiral.
- The Sun's magnetic field also follows this spiral.
- Charged particles travel along these field lines (circling them)

  $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$



WSA-ENLIL model: Solar wind velocity contour plot in the ecliptic plane

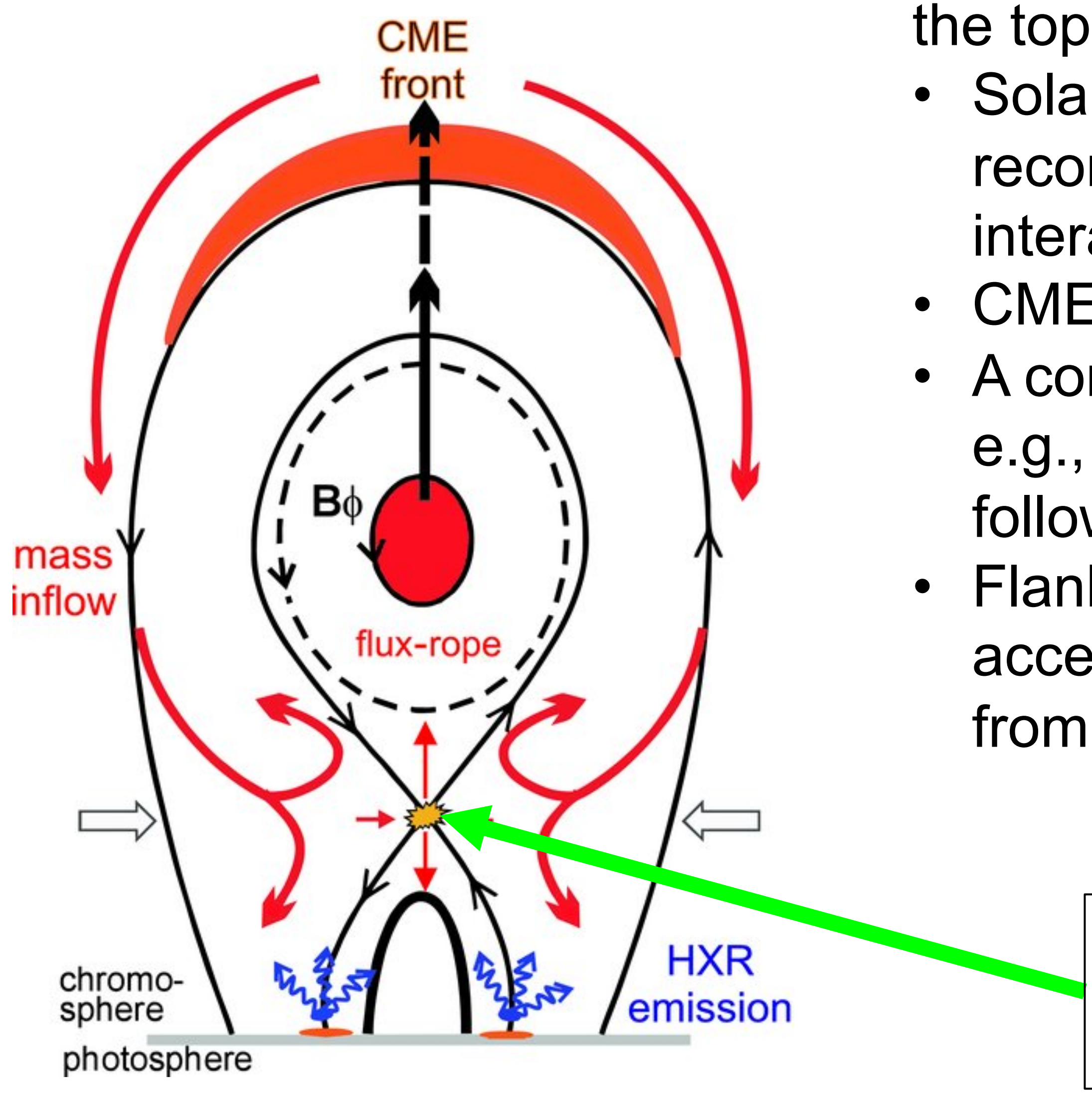


Slide from J. Luhmann

Acceleration Mechanisms are still the topic of heated debate

- Solar Flares (e.g., reconnection; wave-particle interactions)
- CME-driven shocks
- A combination of processes, e.g., initial flare acceleration followed by shock acceleration?
- Flanks of CME-driven shock accelerate seed population from *previous flares*.

Slide from I. G. Richardson



Adapted from Temmer et al., 2010

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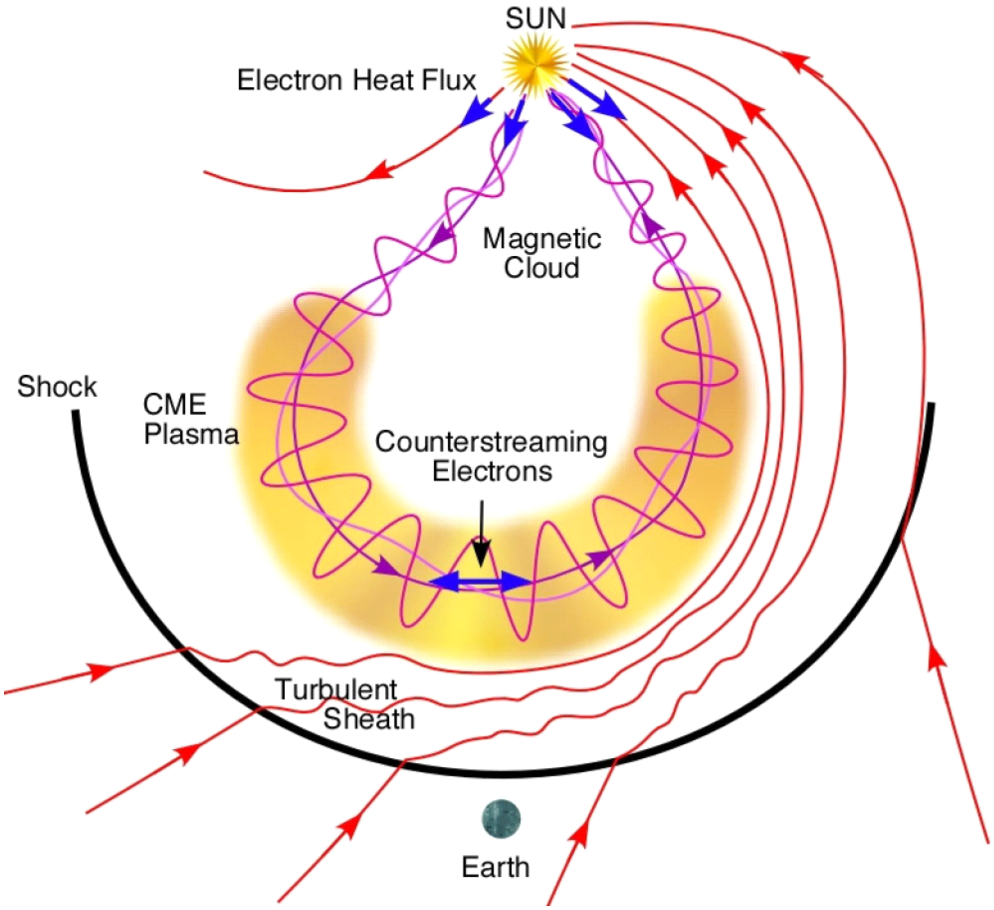
Particle acceleration by reconnection at neutral line below CME

Slide from I. G. Richardson

Shocks Associated With Interplanetary Coronal Mass Ejection (ICMEs) Can Accelerate Particles



Zurbuchen and Richardson, 2006

Shock is formed ahead of fast ICMEs

Shock may accelerate particles as it moves out through the solar wind

Observer's magnetic connectivity matters

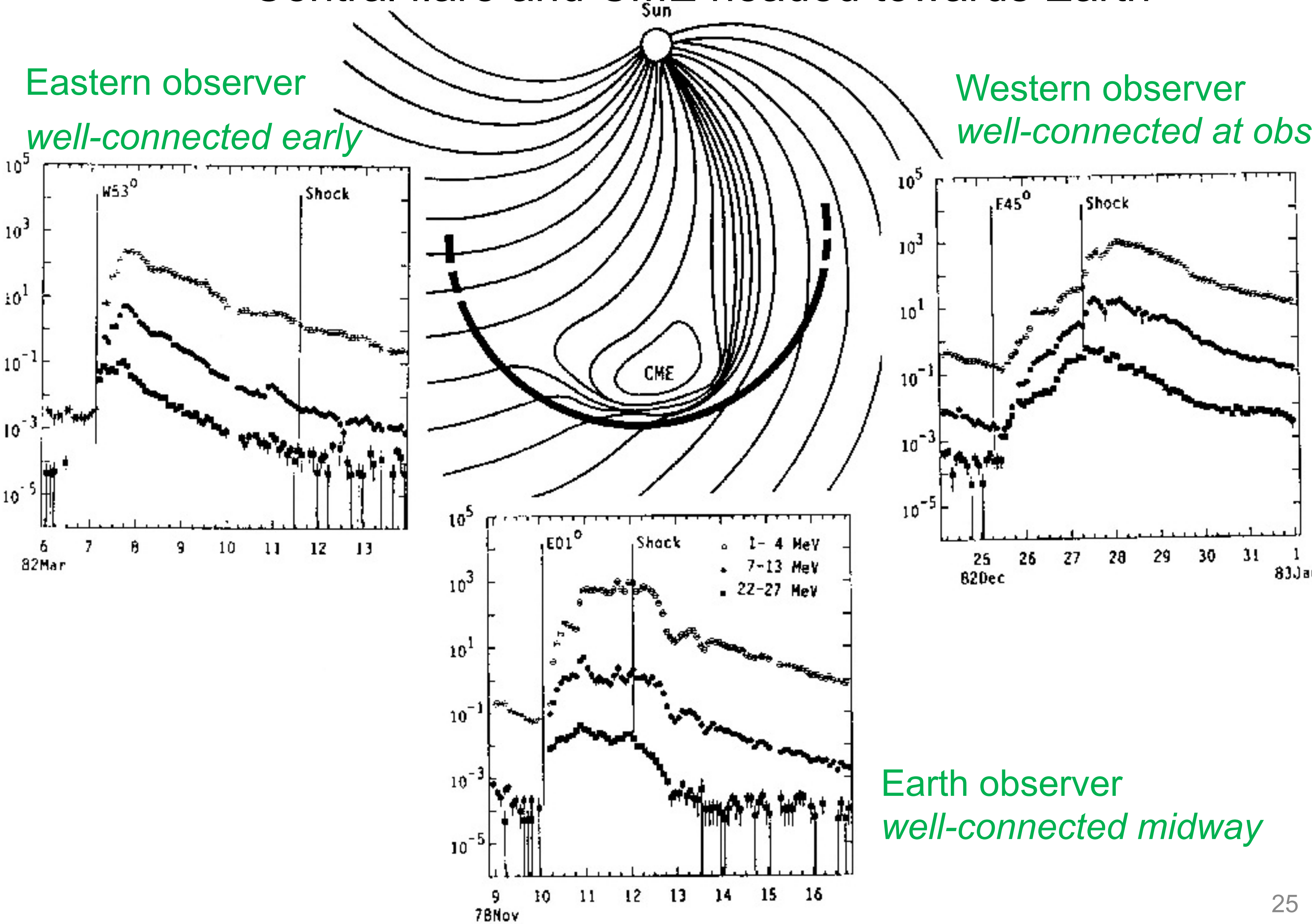
Slide from I. G. Richardson

Longitudinal Difference in Proton Flux Profiles

Central flare and CME headed towards Earth

Eastern observer
well-connected early

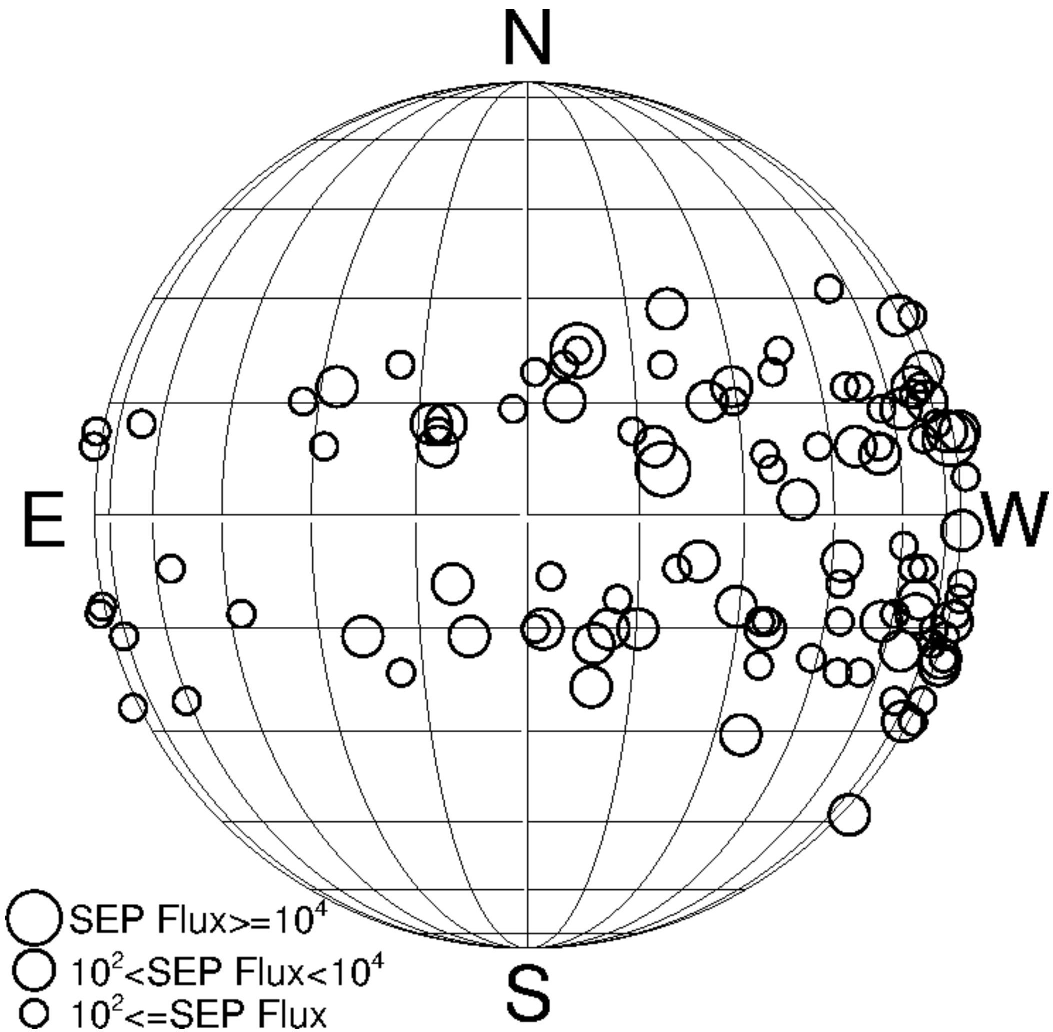
Western observer
well-connected at observer



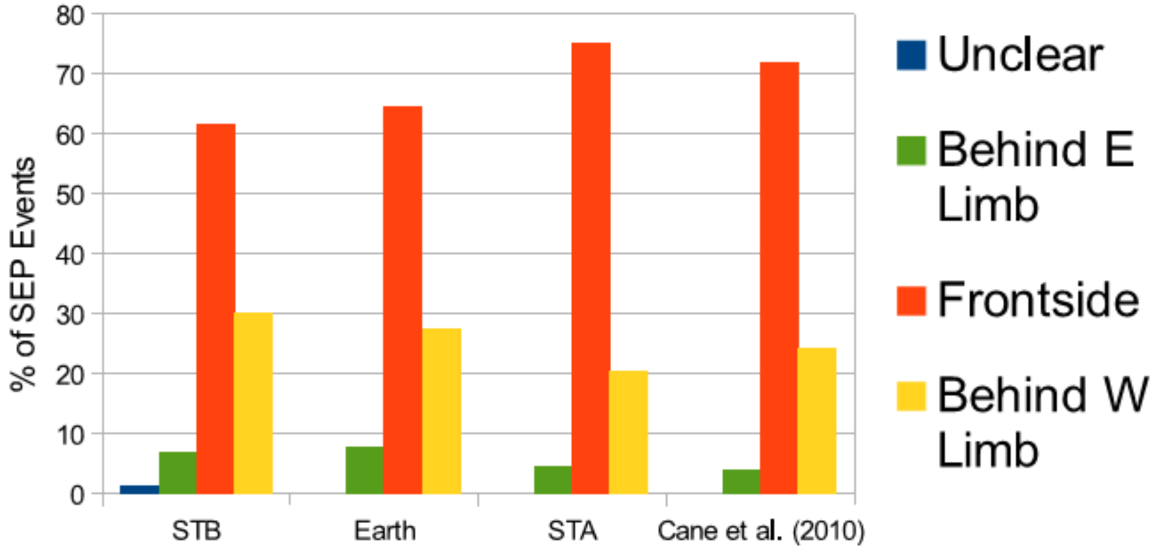
Earth observer
well-connected midway

(from Reames, Space Science Rev., 1999, adapted from Cane, Reames and von Rosenvinge, 1988)

Distribution of Front-side SEP Source Locations



How many ~25 MeV Proton Events Originate Behind the Limb of the Sun?



Around 25% of events originate behind the west limb and ~5% behind the east limb. Asymmetry reflects connection via the spiral interplanetary magnetic field.

Similar results for each spacecraft/location

Slide from I. G. Richardson

25 MeV Proton Event Statistics (*Richardson et al.,* 2014)

~99% are associated with cataloged CMEs

52% are associated with "full halo" CMEs in the CDAW LASCO catalog

Percentage associated with X-ray flares:

B-class	7%
C-class	37%
M-class	40%
X-class	16%

WIND/WAVES/SWAVES Radio observations

Type II 53%; IP type II (< 1 MHz) 33%

Type III 92%

Slide from I. G. Richardson

What is the solar source location for most SEPs with respect to an Earth observer?

a) From the backside of the Sun
b) From the western hemisphere and behind the western limb
c) From the eastern hemisphere
d) Behind the east limb

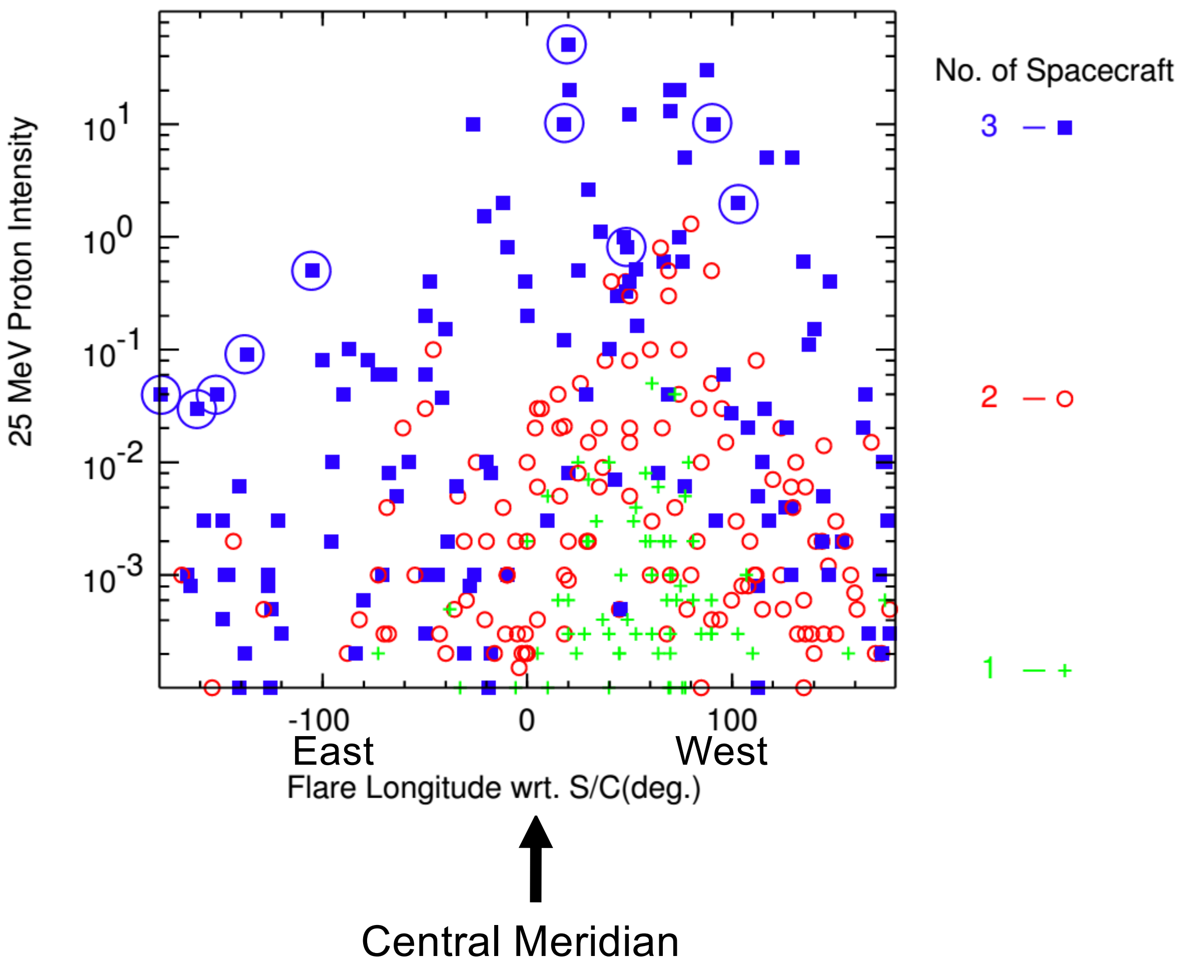
Answer the quiz here:
http://qdle.net/24981545

Why is the source location for most SEPs observed at Earth in the west?

a) There are more flares from the west limb
b) The solar cycle
c) There are more CMEs from the west limb
d) Favorable magnetic connectivity

Answer the quiz here:
http://qdle.net/24981545

Intensity of ~25 MeV Proton Events Plotted Against the Longitude of the Solar Event Relative to the Observing Spacecraft

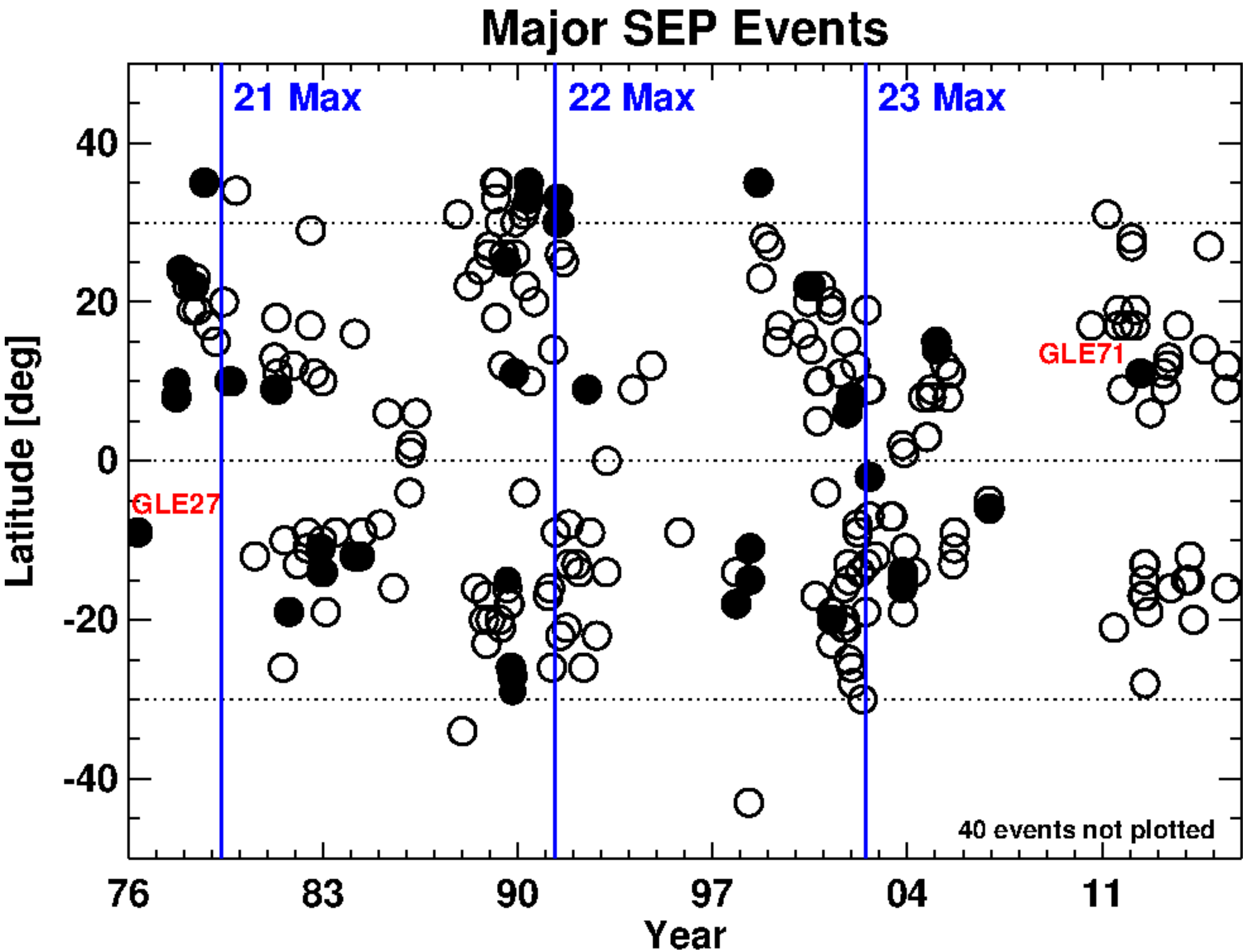


25 MeV Protons can be detected from anywhere on the Sun!

The intrinsic event intensity and spacecraft magnetic connection (~Parker spiral) are major influences on the observability of SEP events.

Richardson et al., 2014

Slide from I. G. Richardson



Slide from N. Gopalswamy

Why are there more SEPs near solar maximum?

a) Better connectivity
b) More flares and CMEs
c) More variable solar wind speed
d) Solar magnetic field strength

Answer the quiz here:
http://qdle.net/24981545

Historical Context

Table 5-2. ***Large SPEs during Solar Cycles 19 through 23 Corresponding to $\Phi_{30} > 10^9$ protons/cm^2***

Solar Cycle	SPE	$\Phi_{>30}$ protons/cm^2
19	11/12/1960	9.00×10^9
20	08/02/1972	5.00×10^9
22	10/19/1989	4.23×10^9
23	07/14/2000	3.74×10^9
23	10/26/2003	3.25×10^9
23	11/04/2001	2.92×10^9
19	07/10/1959	2.30×10^9
23	11/08/2000	2.27×10^9
22	03/23/1991	1.74×10^9
22	08/12/1989	1.51×10^9
22	09/29/1989	1.35×10^9
23	01/16/2005	1.04×10^9
19	02/23/1956	1.00×10^9

Apollo Era Overview

Parameters are averaged over **1-day**.

Conditions appear far more erratic on these timescales.

Declining phase of the Solar Cycle evident in $F_{10.7}$, but not in any other parameter.

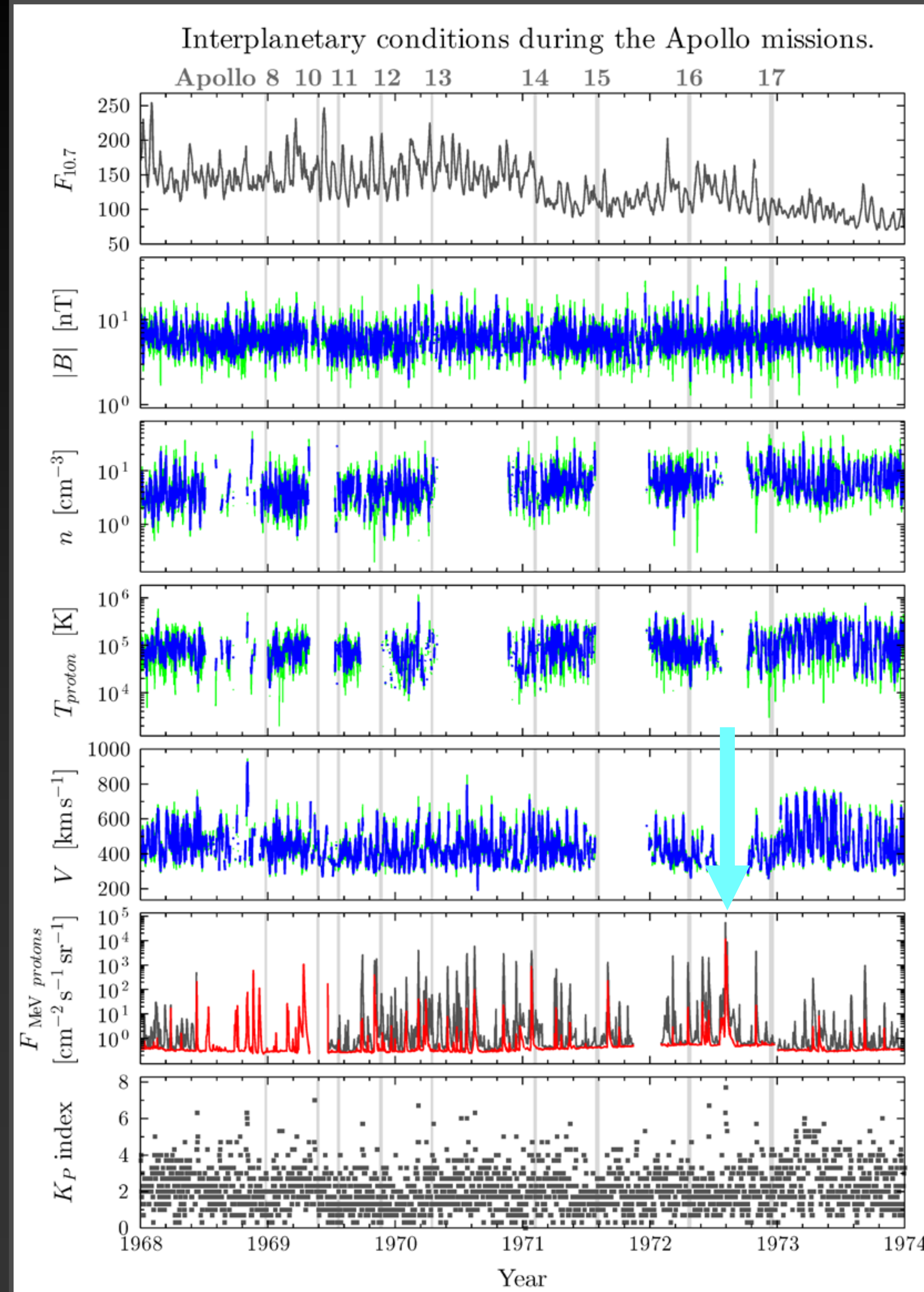
Fortuitously, the Apollo missions mostly flew during relatively quiet conditions.

Minor exceptions.

Apollo 12: High solar UV

Apollo 16: Energetic protons

Stubbs et al., 2012



Apollo Radiation Hazards

Average radiation measured by passive dosimeters.

Max. operational dose (MOD) limit was set to 400 rads for skin and 50 rads for blood-forming organs during Apollo.

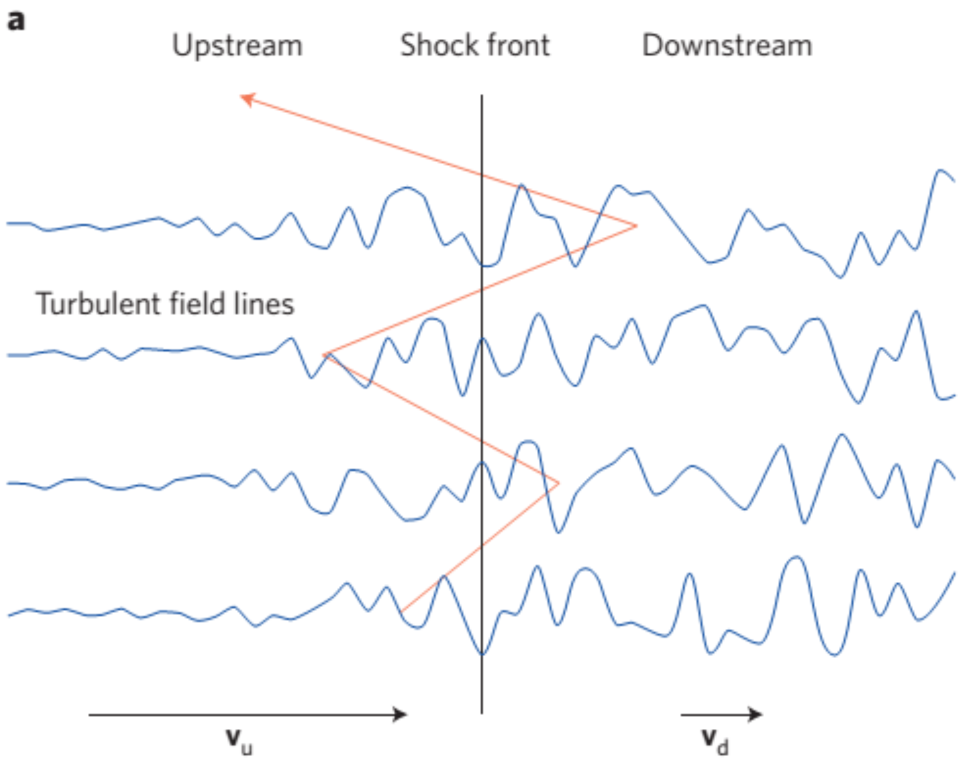
LRO: No additional shielding provided by the magnetosphere at lunar orbit (Case et al., 2010).

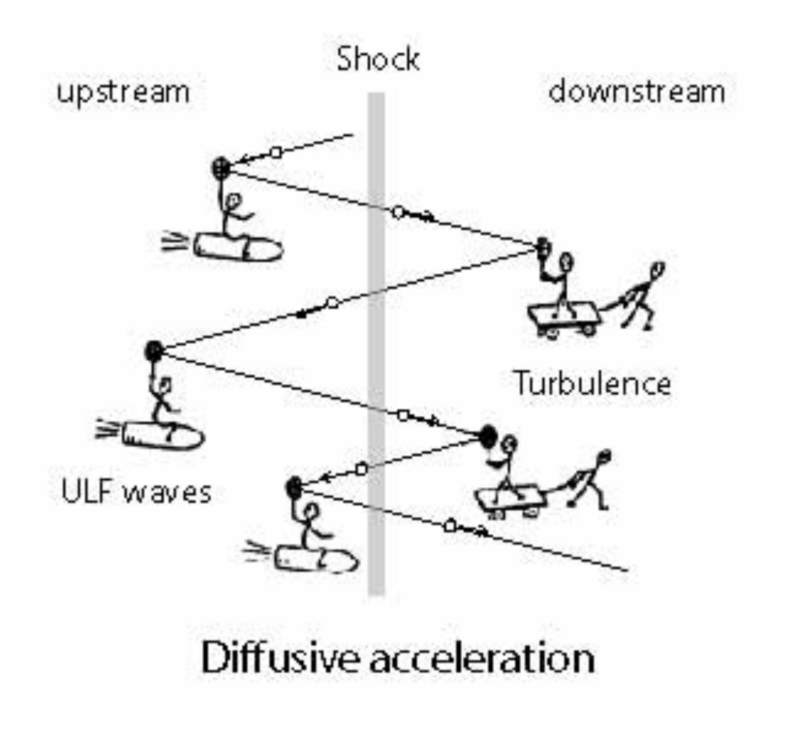
August 1972 event would have caused **moderate Acute Radiation Sickness (ARS)** without effective shielding and medical counter-measures (Hu et al., 2009).

Apollo Mission	Skin Dose, [rads (rem)]
8	0.16
10	0.48
11	0.18
12	0.58
13	0.24
14	1.14
15	0.30
16	0.51
17	0.55
August 1972	**~400!**

Stubbs et al., 2012

Particle Acceleration by Bouncing Between Converging Scattering Centers Upstream and Downstream of a Quasi-Parallel Shock (Diffusive Shock Acceleration)





M. Scholer

Quasi parallel = Upstream magnetic field ~parallel to shock normal.

Particle injection "problem" – particles must be able to propagate upstream of the shock (V_{sw} ~ 1 keV >> thermal energy))

Slide from I. G. Richardson

Particle Acceleration at a Quasi-Perpendicular Shock – Shock Drift Acceleration

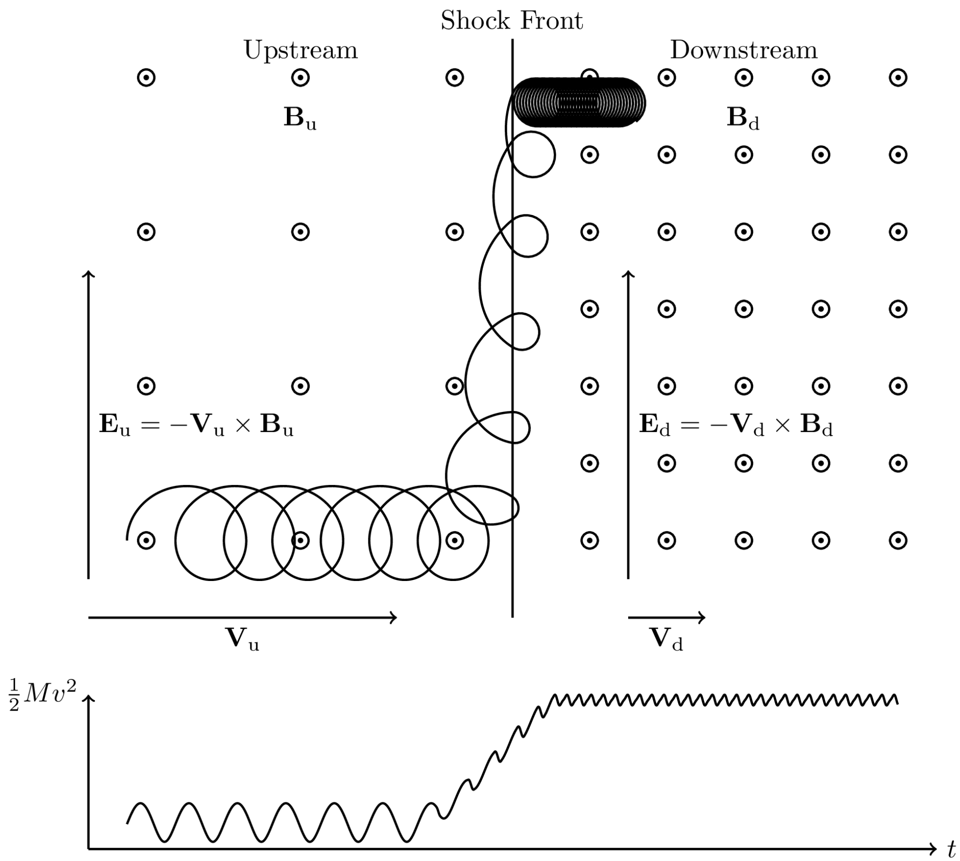


Figure by *M. Pulupa* after *Armstrong et al.*, 1985

Quasi perpendicular shock = Upstream magnetic field ~perpendicular to shock normal.

Process increases the particle velocity component perpendicular to B

Slide from I. G. Richardson

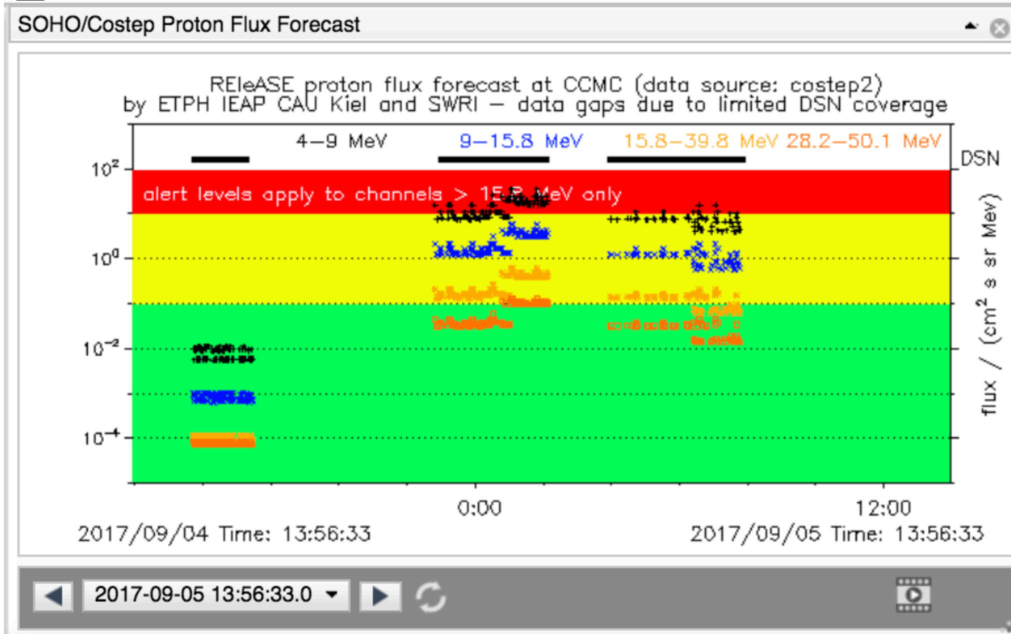
SEP Prediction at CCMC

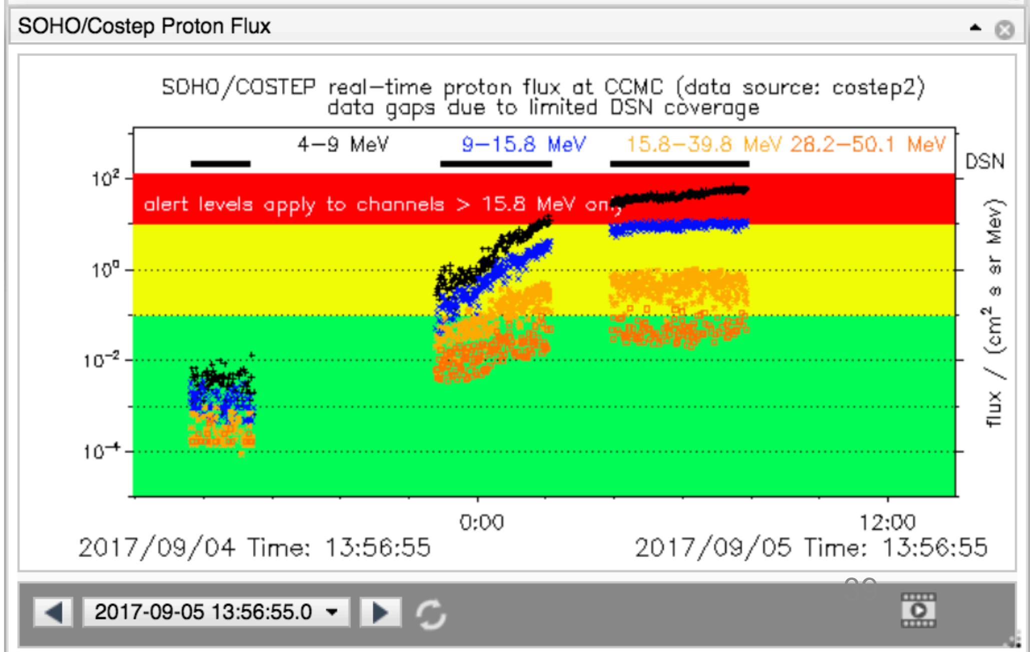
http://go.nasa.gov/2czfgmw

REleASE Model

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

Input data: SOHO COSTEP electron flux





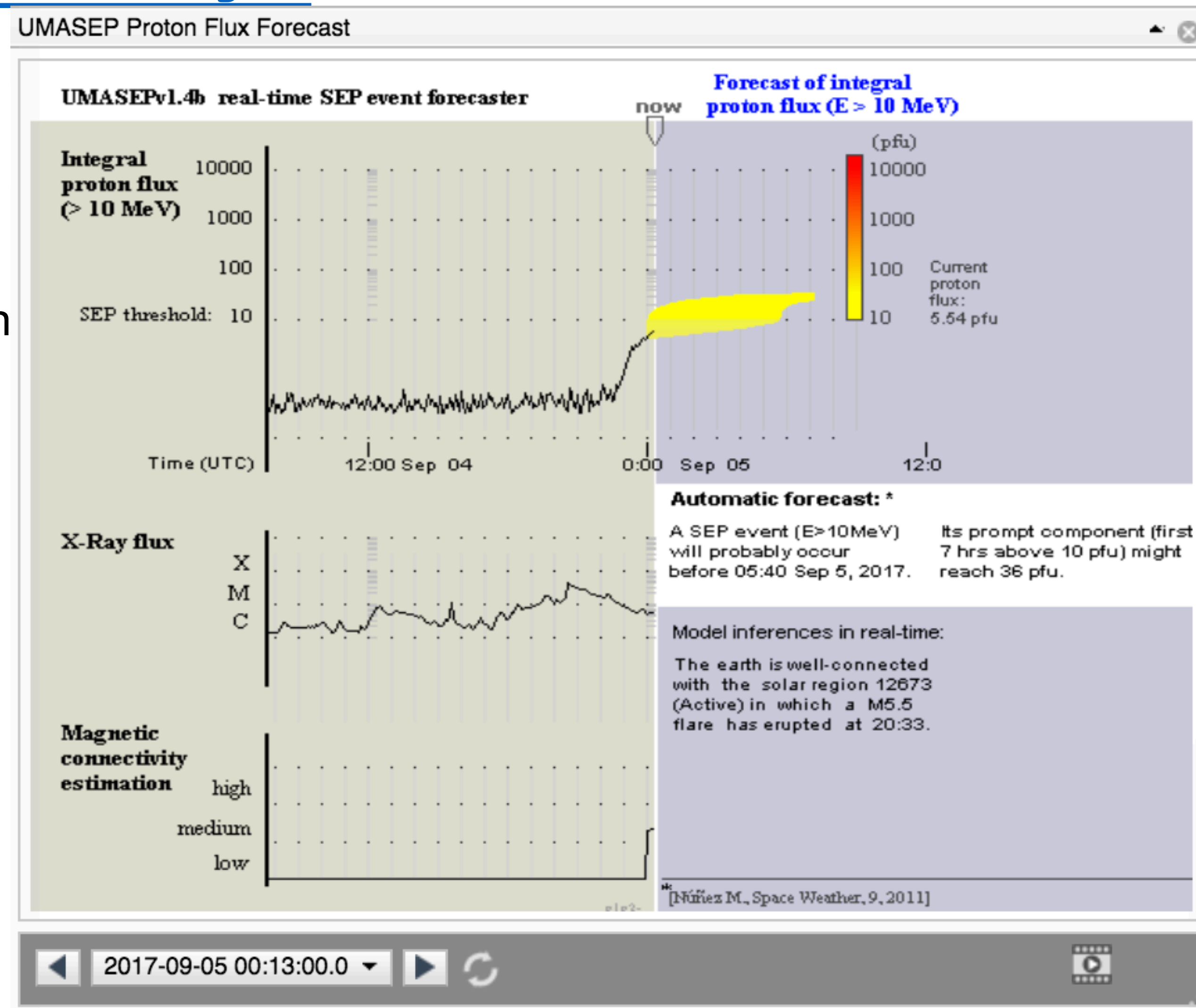
SEP Prediction at CCMC

http://go.nasa.gov/2czfgmw

UMASEP Model

Uses magnetic connectivity, current proton flux level to predict the peak flux

Input data: GOES X-ray flux, proton flux



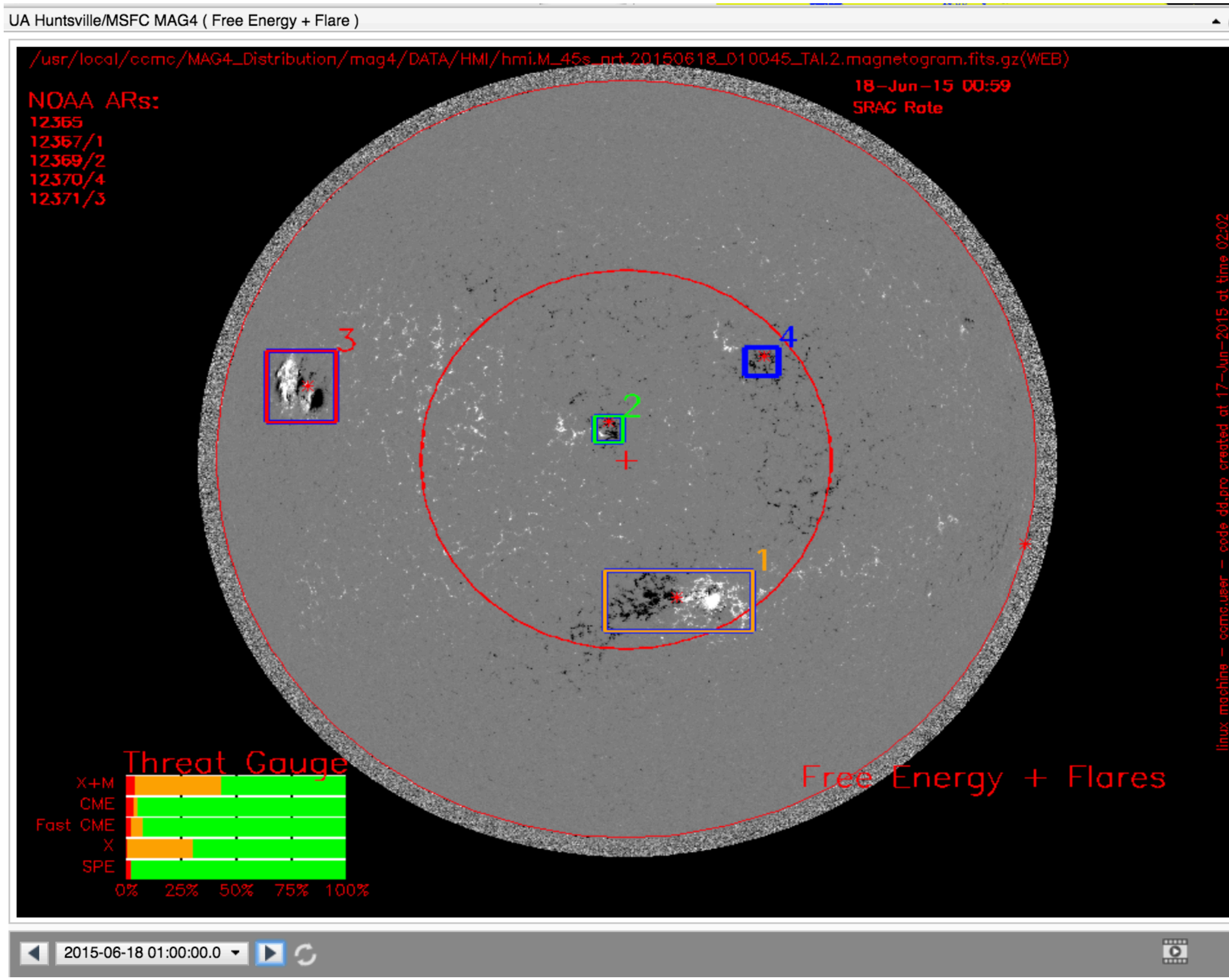
SEP Prediction at CCMC

http://go.nasa.gov/2czfgmw

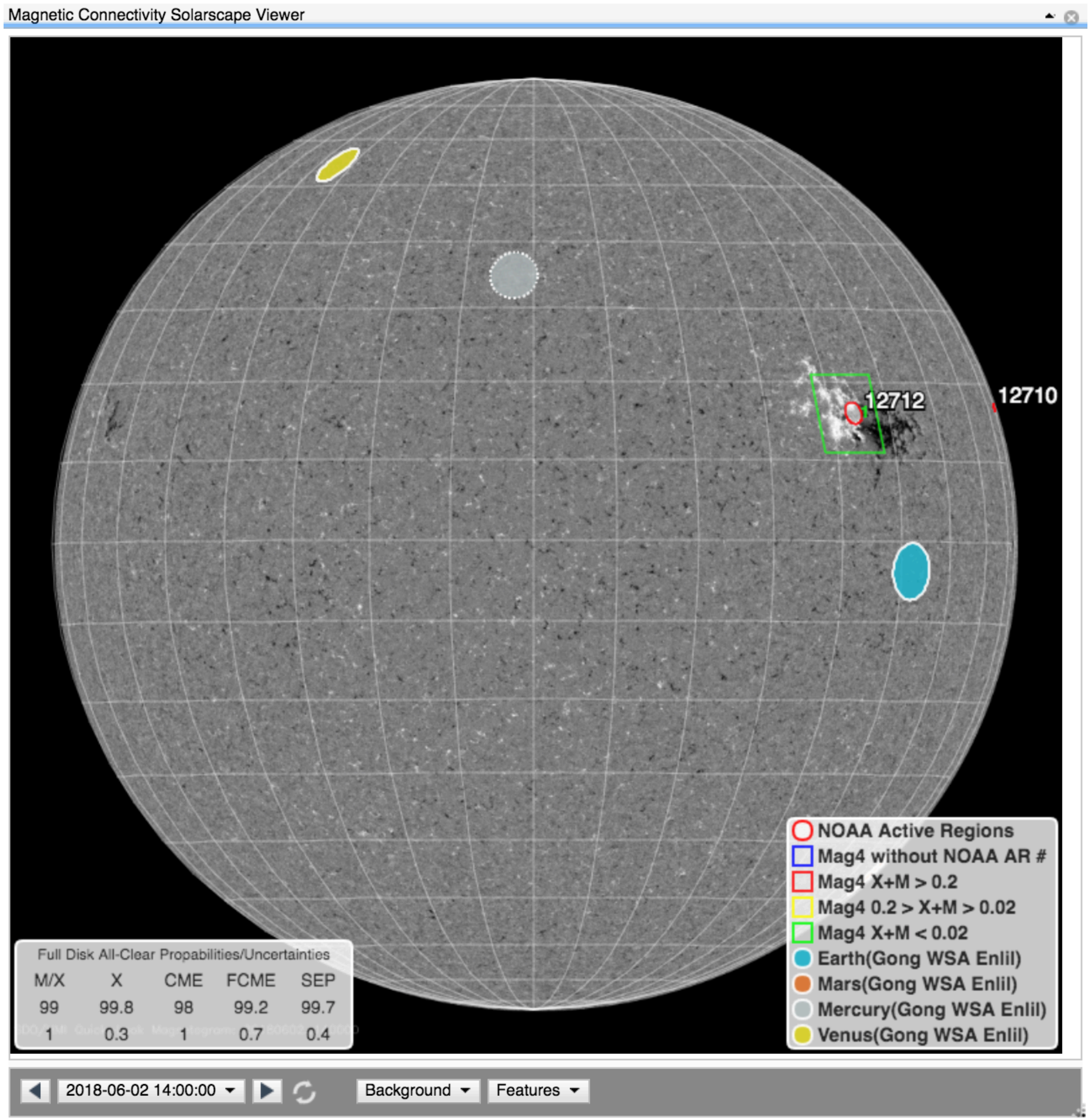
MAG4 Model

Uses active region properties and previous SEP events to produce a probabilistic forecast

Input data: SDO HMI magnetogram

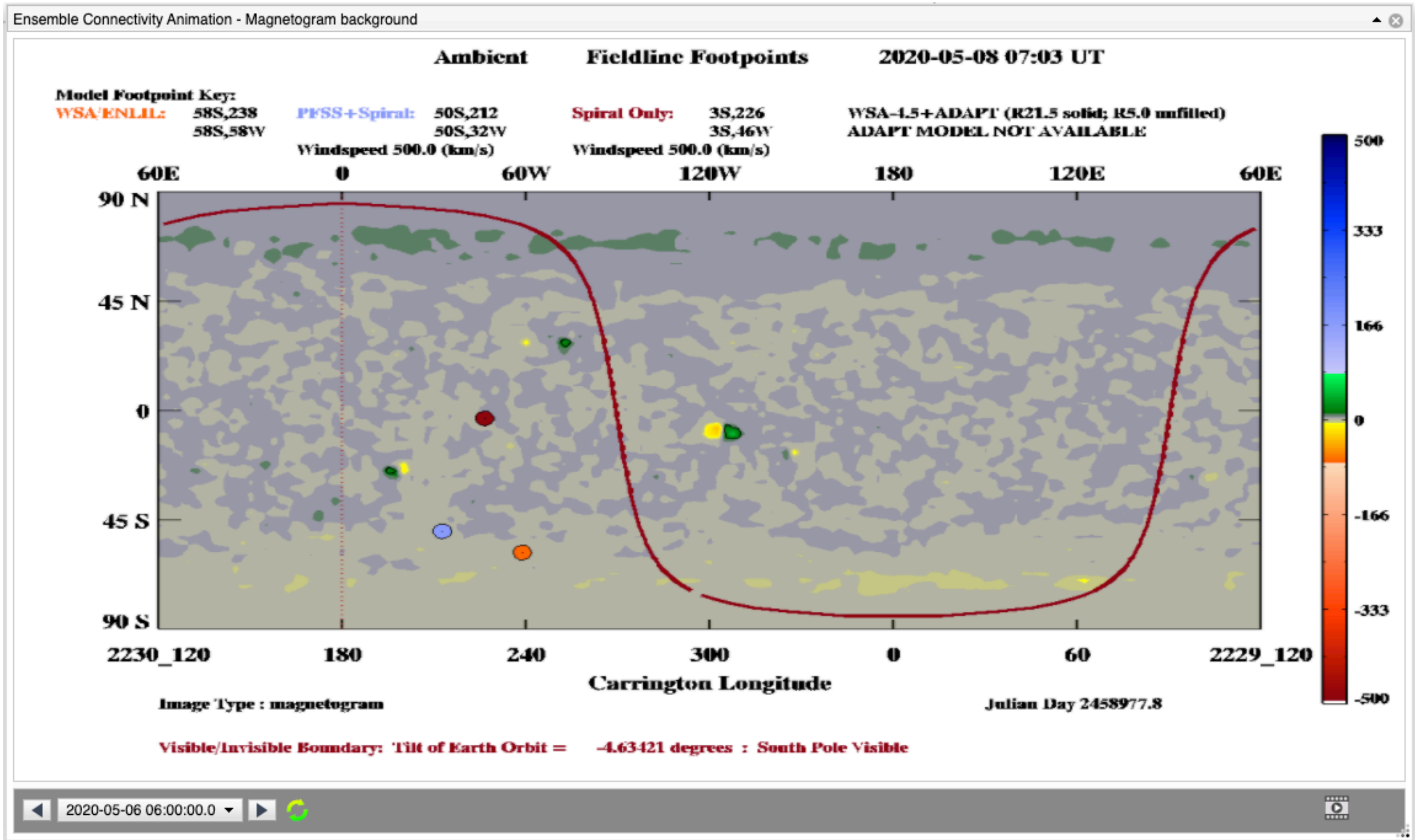


SEP Context at CCMC http://go.nasa.gov/2czfgmw



ISEP Products

https://bit.ly/ISEP-products



Joint product/capability development with JSC/SRAG (https://ccmc.gsfc.nasa.gov/isep/)