

Solar Energetic Particles (SEPs)

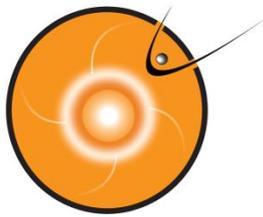
Yihua Zheng

Acknowledge: Rebekah Evans

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

June 2, 2015

SW REDI Boot Camp



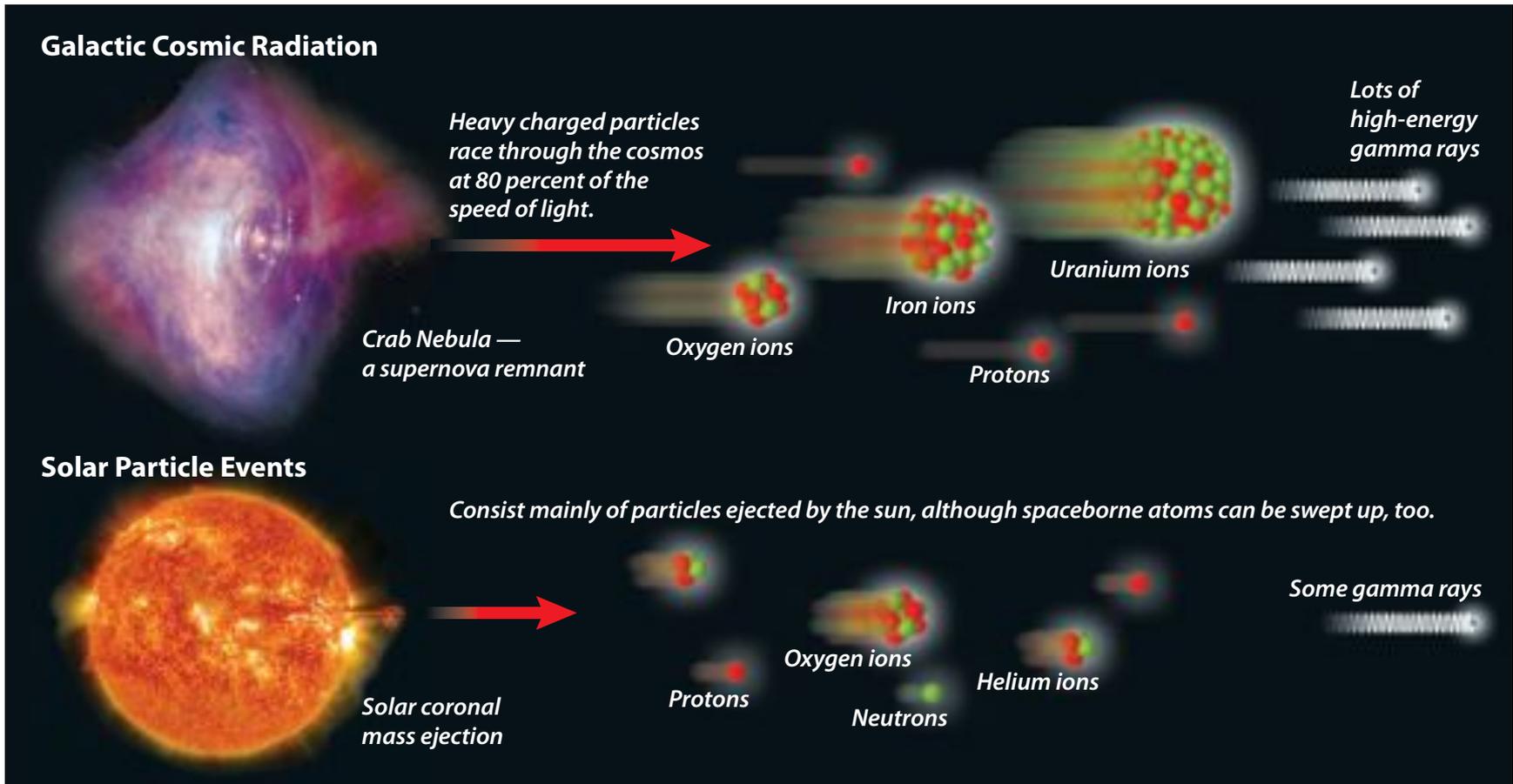
SEPs – important source of space radiation: hard to predict

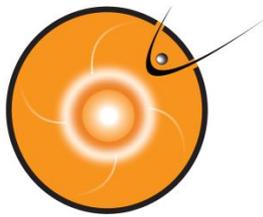


Deep space dangers

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

Galactic Cosmic Radiation (another source)





SEPs: What are they?

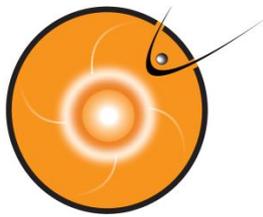


Definition:

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!).

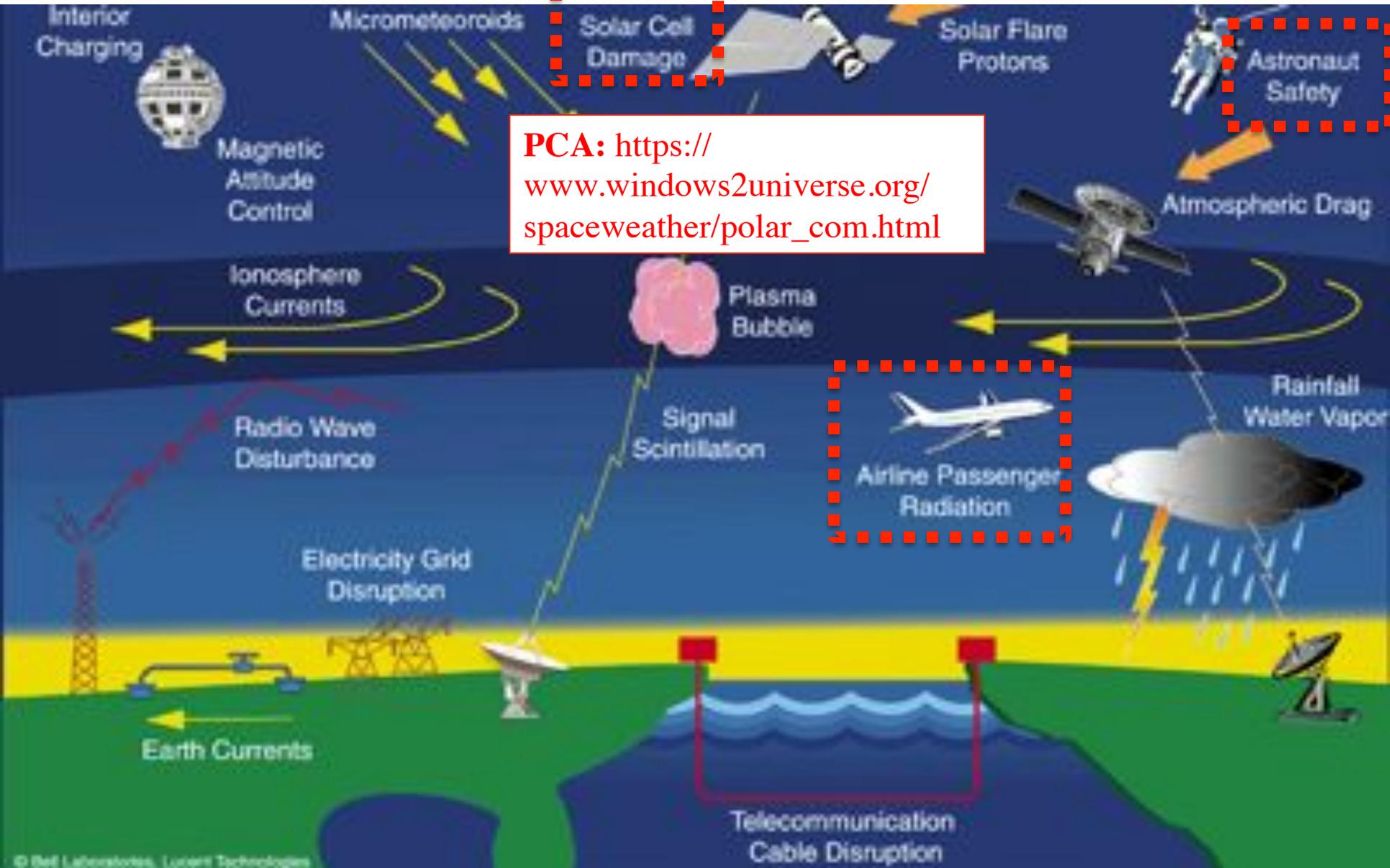
They can travel from the Sun to the Earth in one hour or less!

The term “SEP” usually refers to protons.

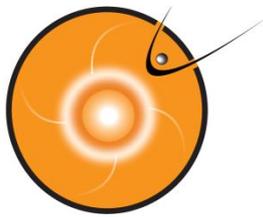


Why do we care?

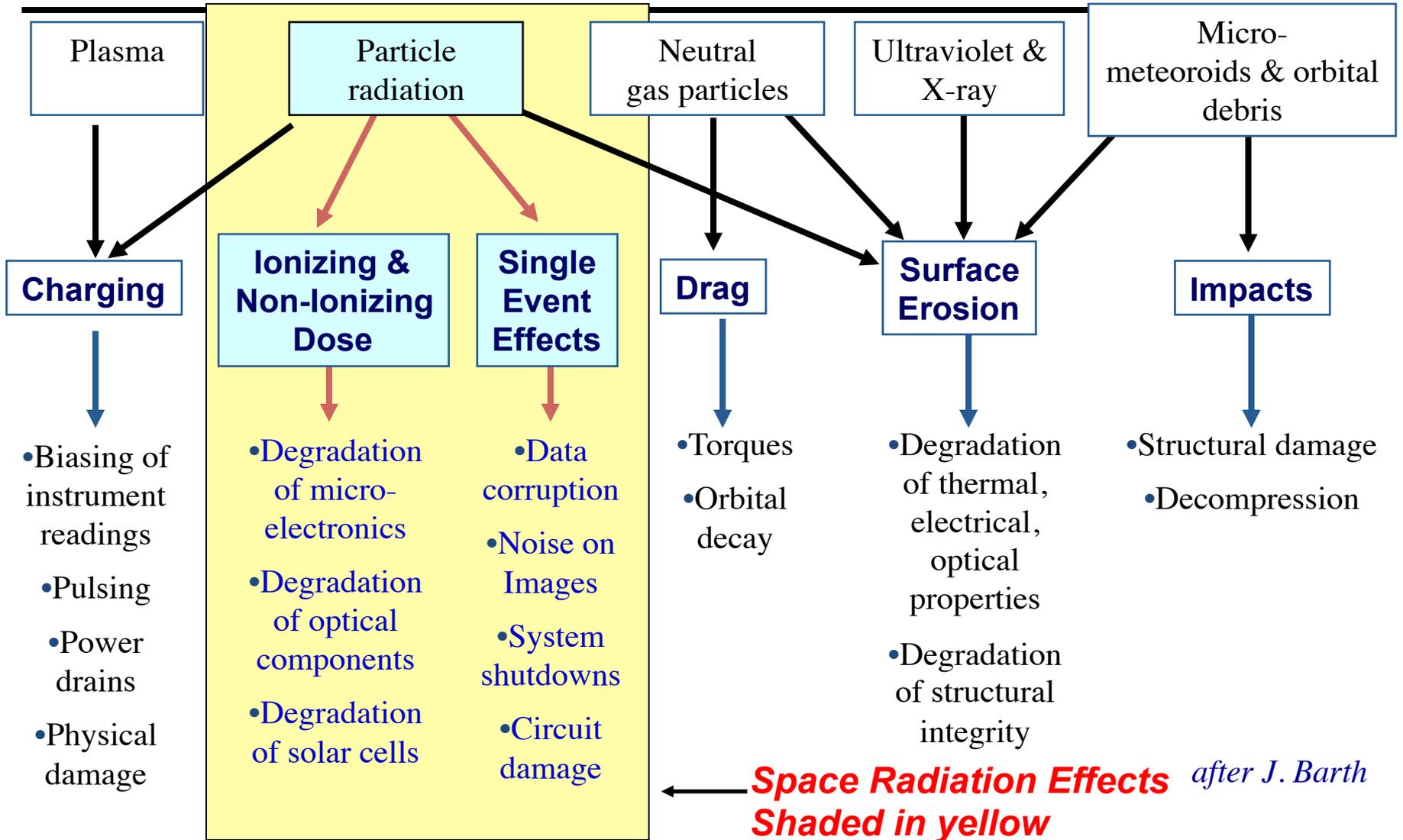
Radiation hazards for spacecraft, human in space and airline passenger safety, PCA (polar cap absorption)



PCA: https://www.windows2universe.org/spaceweather/polar_com.html



Space Environments and Effects on Spacecraft



Plasma

Particle radiation

Neutral gas particles

Ultra-violet & X-ray

Micro-meteoroids & orbital debris

Charging

Ionizing & Non-Ionizing Dose

Single Event Effects

Drag

Surface Erosion

Impacts

- Biasing of instrument readings
- Pulsing
- Power drains
- Physical damage

- Degradation of micro-electronics
- Degradation of optical components
- Degradation of solar cells

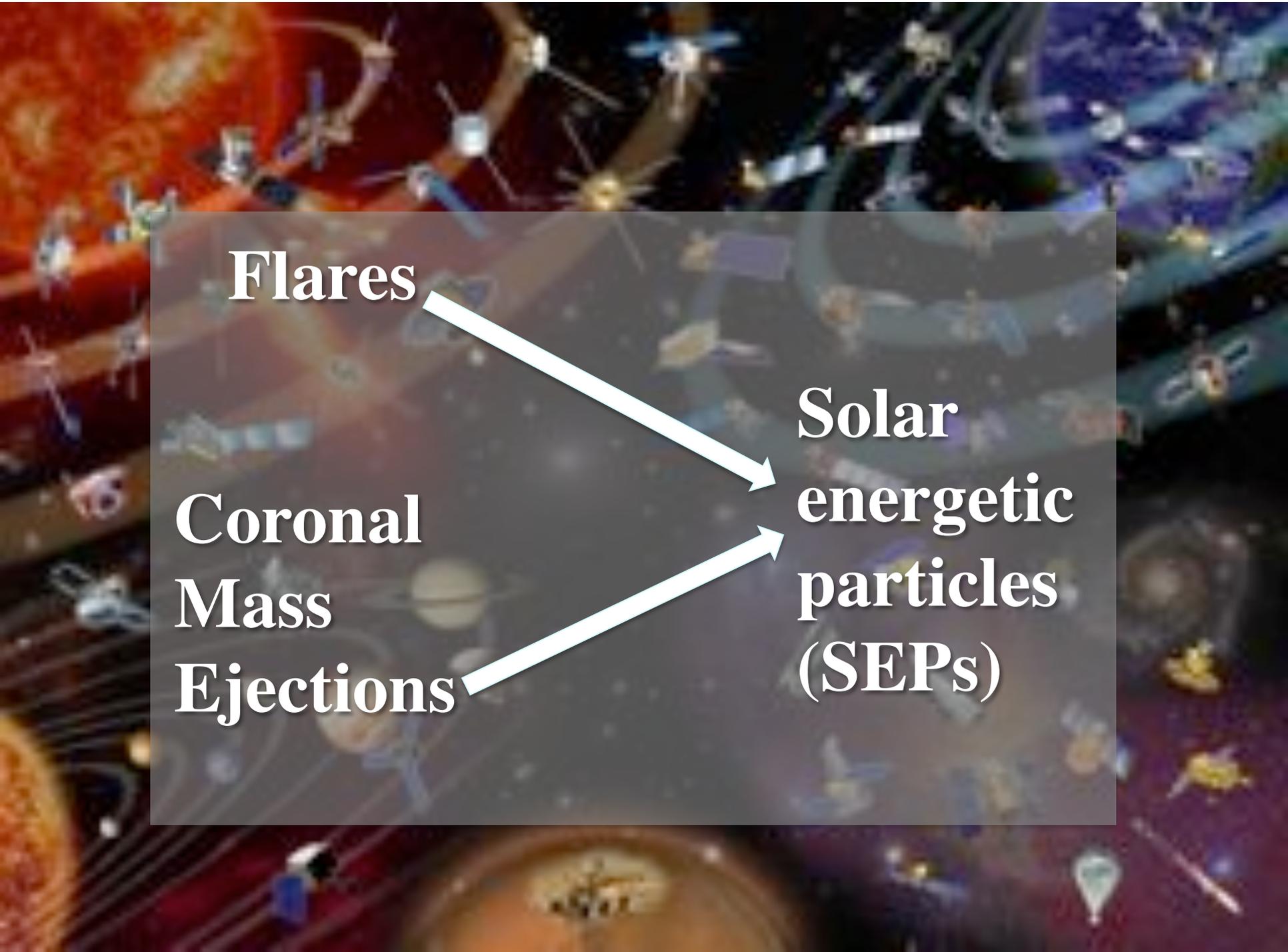
- Data corruption
- Noise on Images
- System shutdowns
- Circuit damage

- Torques
- Orbital decay

- Degradation of thermal, electrical, optical properties
- Degradation of structural integrity

- Structural damage
- Decompression

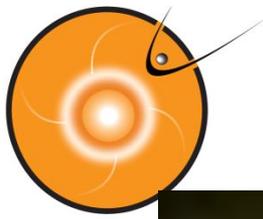
Space Radiation Effects after J. Barth
Shaded in yellow



Flares

**Coronal
Mass
Ejections**

**Solar
energetic
particles
(SEPs)**

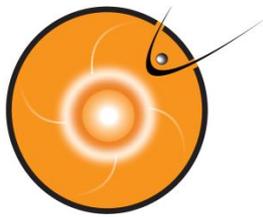


SEPs: ion radiation storms

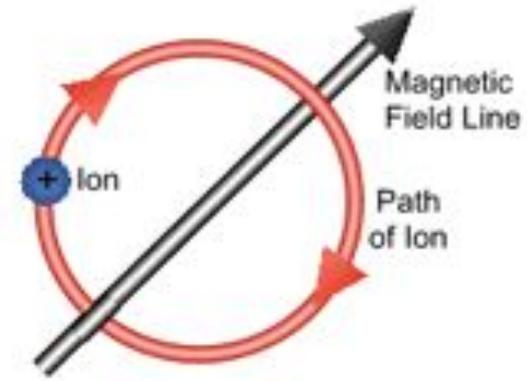
Potentially affect everywhere in the solar system



Courtesy: SVS@ NASA/GSFC



Magnetic fields guide SEPs



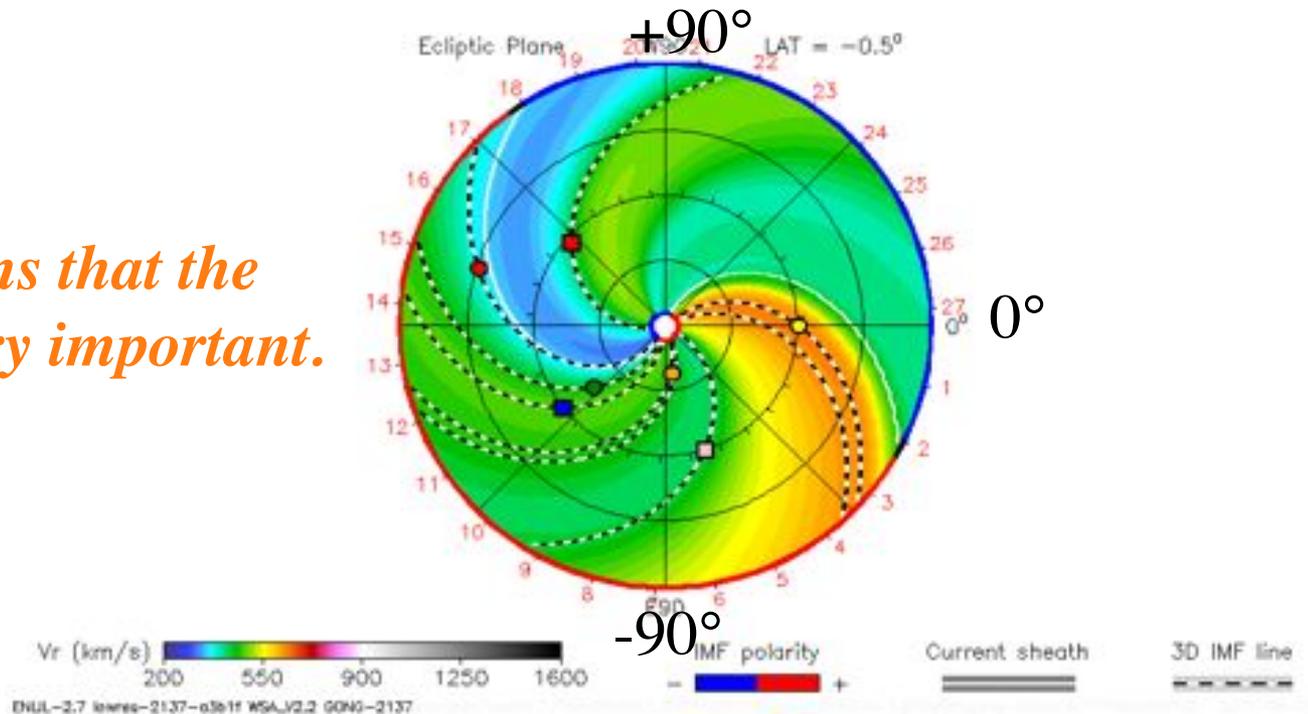
Charged particle motion* is confined by the magnetic field.

2013-06-02T12:00

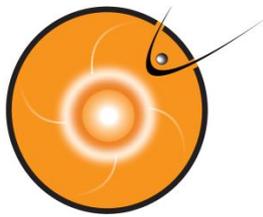
2013-05-10T18 +22.73 days

Earth Mars Mercury Venus Juno Spitzer Stereo_A Stereo_B

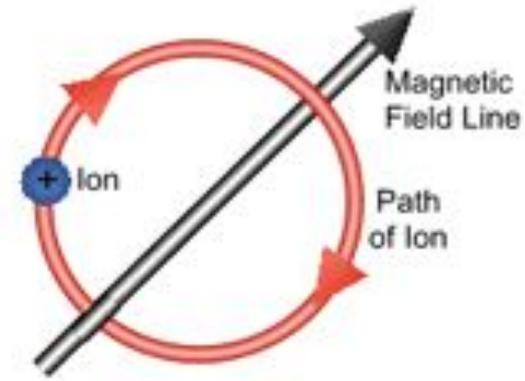
This means that the source is very important.



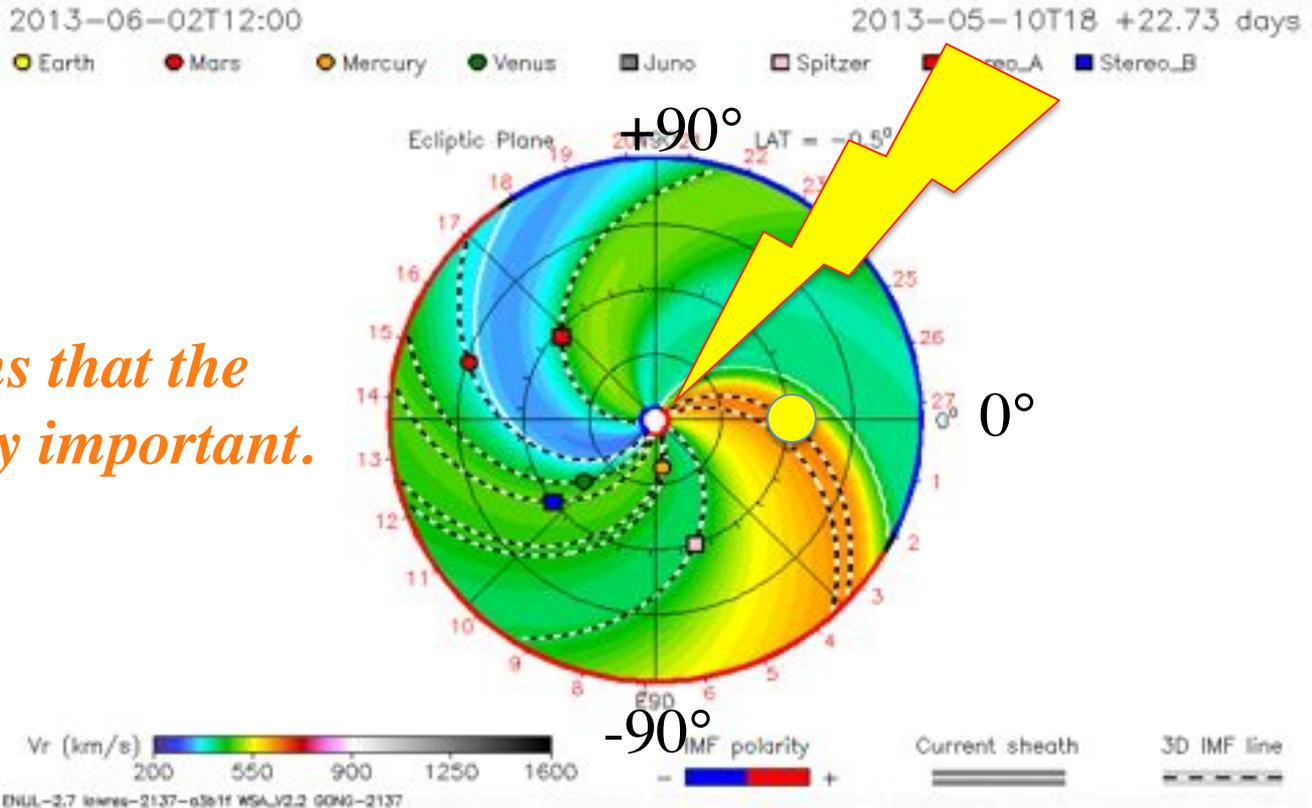
*in a substantially strong B



Magnetic fields guide SEPs/ magnetic connectivity

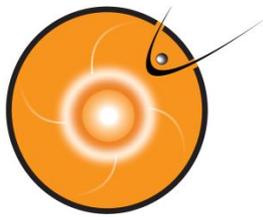


Charged particle motion* is confined by the magnetic field.

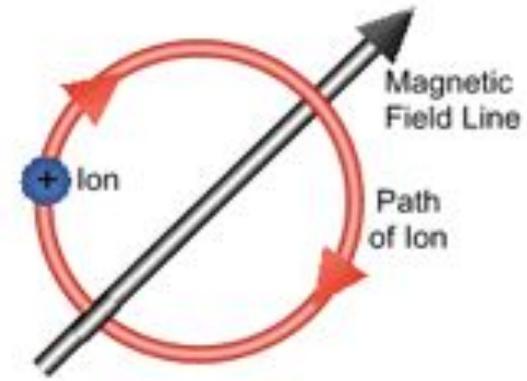


This means that the source is very important.

*in a substantially strong B



Magnetic fields guide SEPs



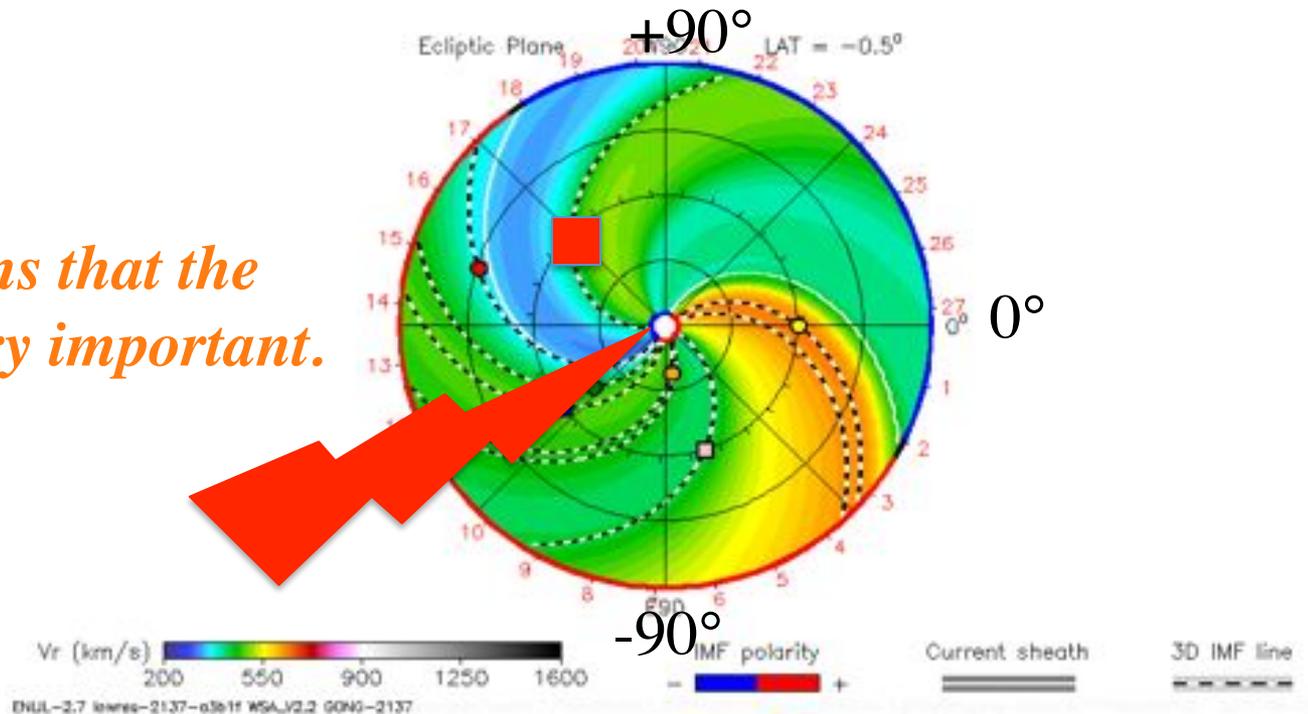
Charged particle motion* is confined by the magnetic field.

2013-06-02T12:00

2013-05-10T18 +22.73 days

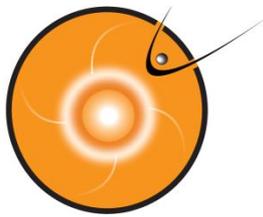
Earth Mars Mercury Venus Juno Spitzer Stereo_A Stereo_B

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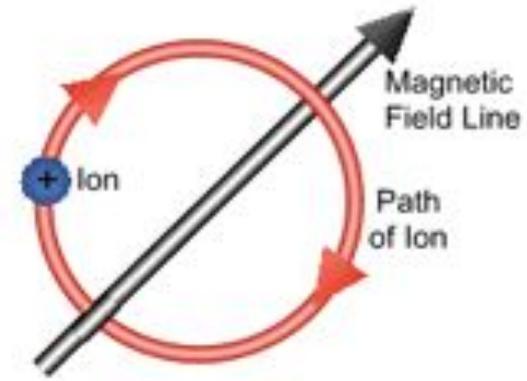


ENLIL-3.7 lines-2137-03b1f WSA_V2.2 GONG-2137

*in a substantially strong B



Magnetic fields guide SEPs



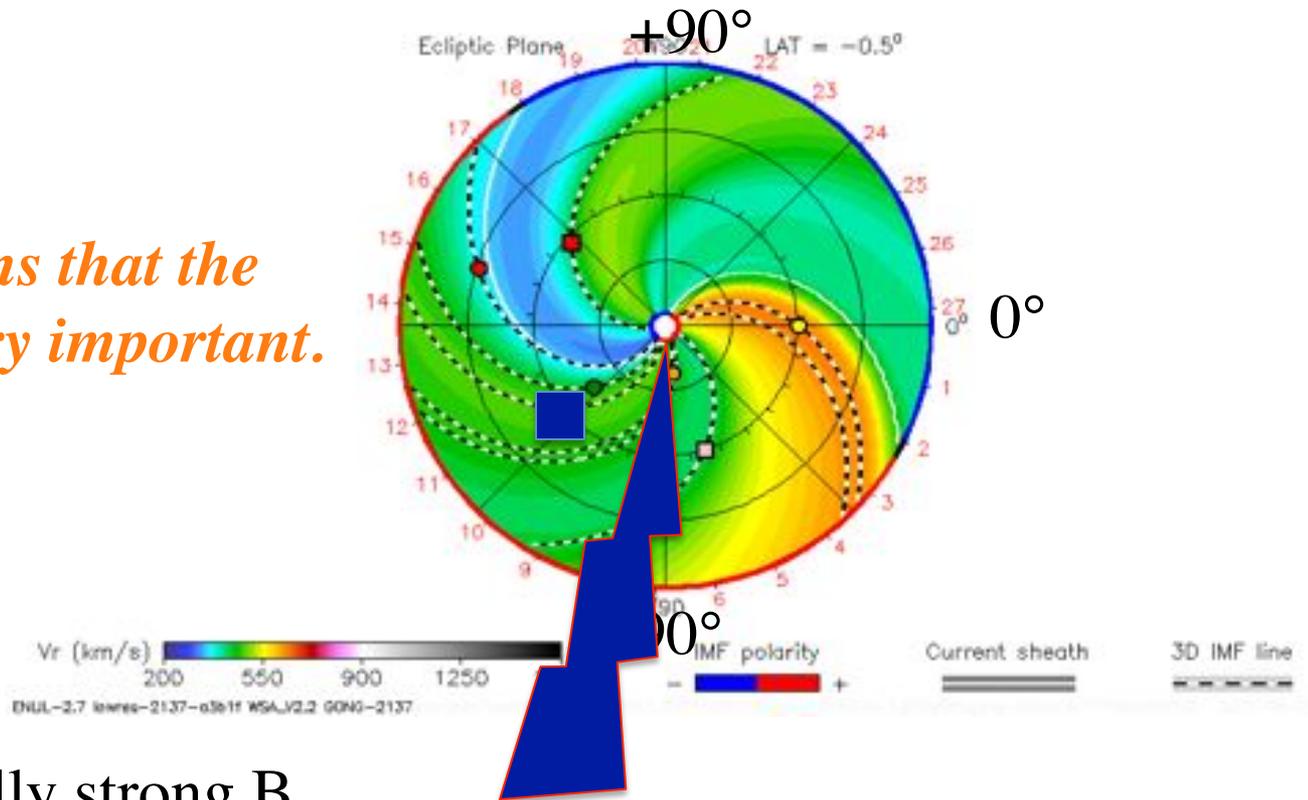
Charged particle motion* is confined by the magnetic field.

2013-06-02T12:00

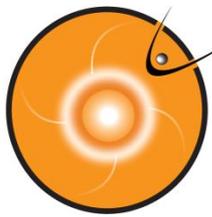
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Earth Mars Mercury Venus Juno Spitzer Stereo_A Stereo_B

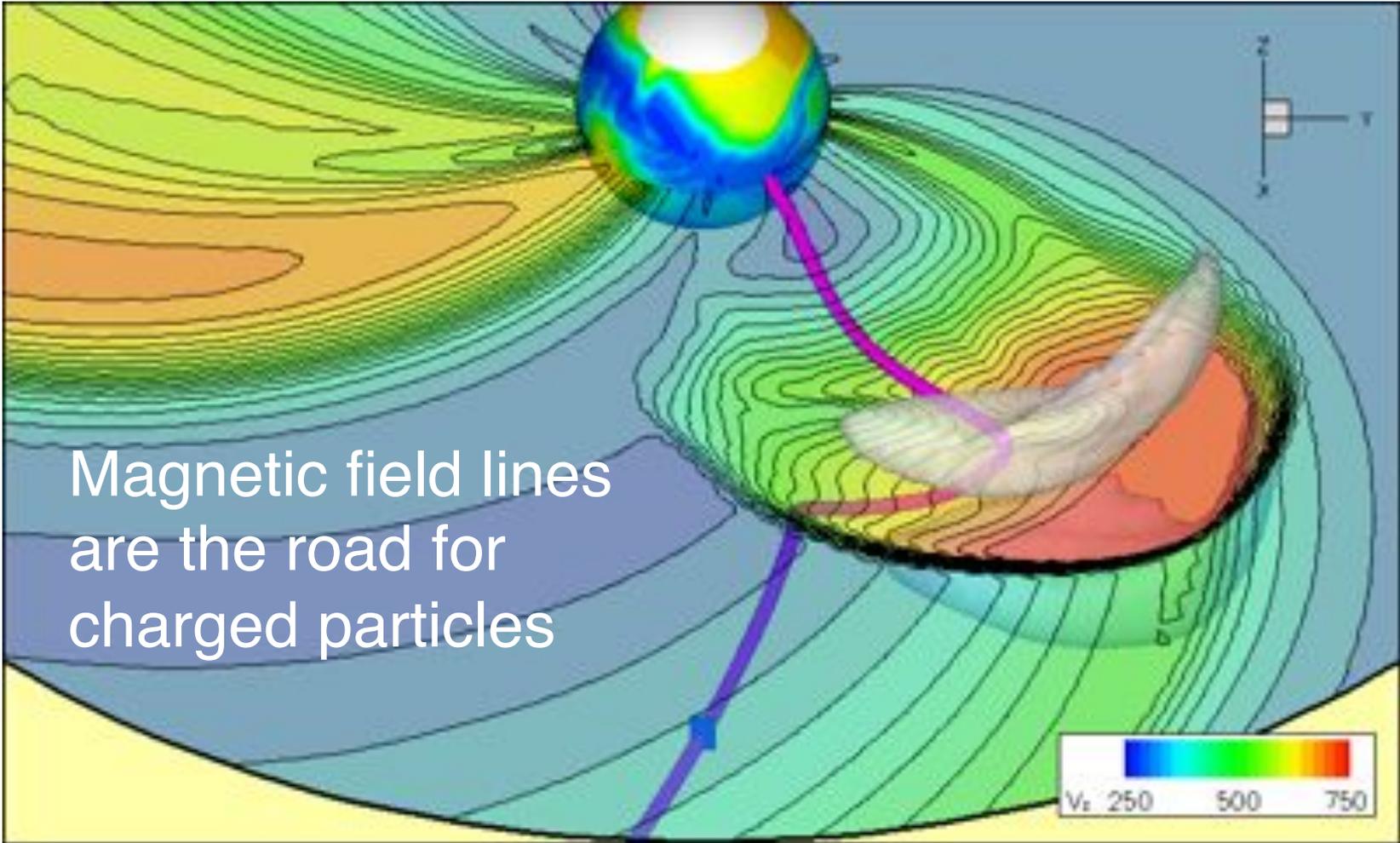
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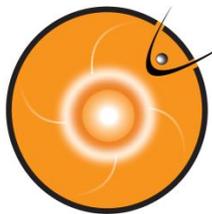


*in a substantially strong B

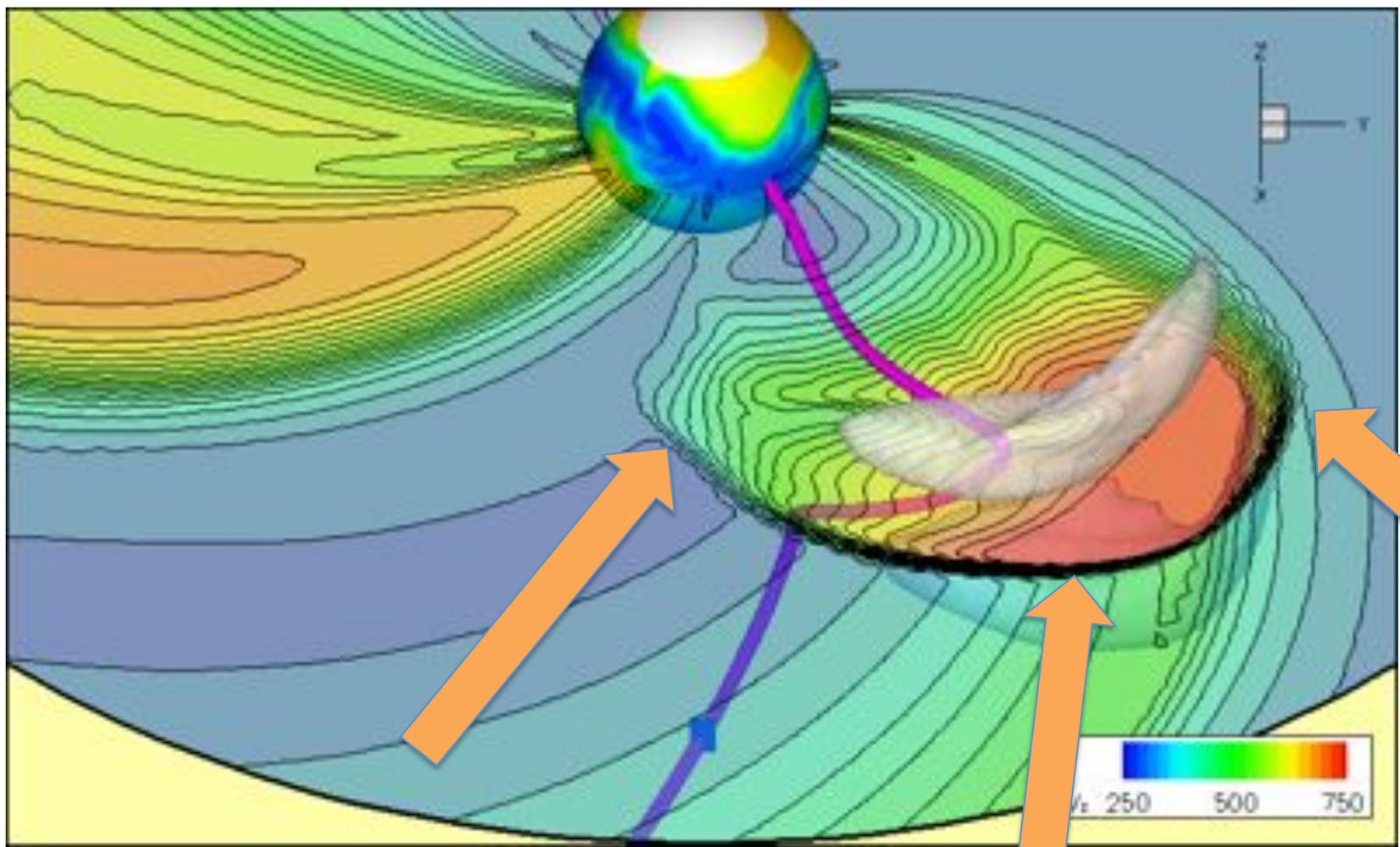


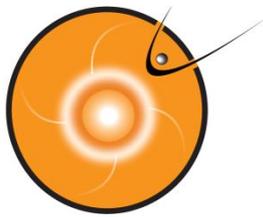
CMEs Can Widen Longitudinal Extent of SEP Events





CMEs Can Widen Longitudinal Extent of SEP Events





How Do We Monitor SEP Levels?

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

Track the particle flux at different locations.

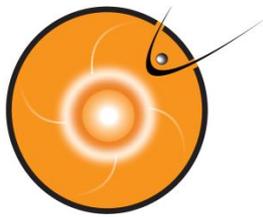
Flux units: pfu, pfu/MeV

- **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



Event magnitudes:

> 10 MeV/nucleon integral
fluence: can exceed 10^9 cm^{-2}

> 10 MeV/nucleon peak flux: can
exceed $10^5 \text{ cm}^{-2}\text{s}^{-1}$



PARTICLE SNOW!



Coronagraph acting as particle detector

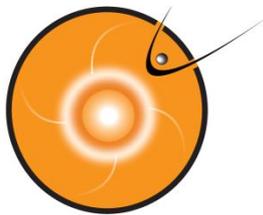
Flare peaked at 01:47 UT



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

One hour later

*SOHO/LASCO C3
May 17 03:00 UT*



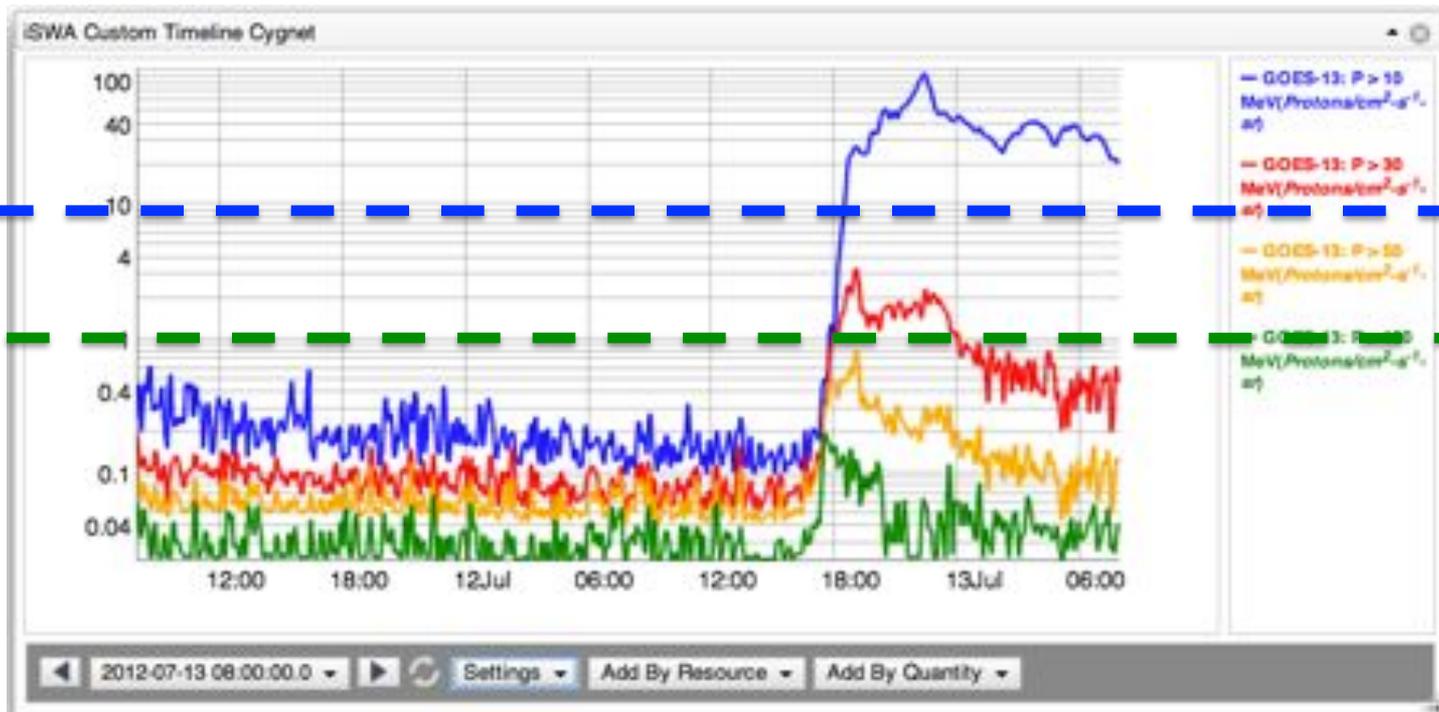
How do we define an SEP Event?



SWRC: SEP event detections are defined as:

GOES Proton $E > 10$ MeV channel > 10 pfu

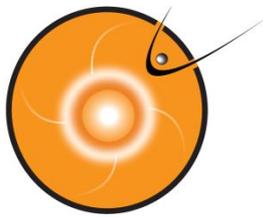
GOES Proton $E > 100$ MeV channel > 1 pfu



How Do We Quantify an SEP Event?

NOAA Space Weather Scale for Solar Radiation Storms

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**)
S5	Extreme	<p>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.***</p> <p>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.</p> <p>Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.</p>	10^5	Fewer than 1 per cycle
S4	Severe	<p>Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p>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.</p> <p>Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</p>	10^4	3 per cycle
S3	Strong	<p>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.***</p> <p>Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.</p> <p>Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.</p>	10^3	10 per cycle
S2	Moderate	<p>Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***</p> <p>Satellite operations: infrequent single-event upsets possible.</p> <p>Other systems: small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.</p>	10^2	25 per cycle
S1	Minor	<p>Biological: none.</p> <p>Satellite operations: none.</p> <p>Other systems: minor impacts on HF radio in the polar regions.</p>	10	50 per cycle



Human Safety in Space

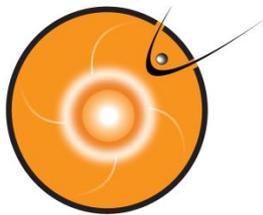


- GCR
- **SEP**

Johnson Space Center/Space Radiation
Analysis Group (SRAG)

Limit: the > 100 MeV flux exceeding 1 pfu
(1 pfu = 1 particle flux unit = $1/\text{cm}^2/\text{sec}/\text{sr}$)

- All clear (EVA –extravehicular activity)

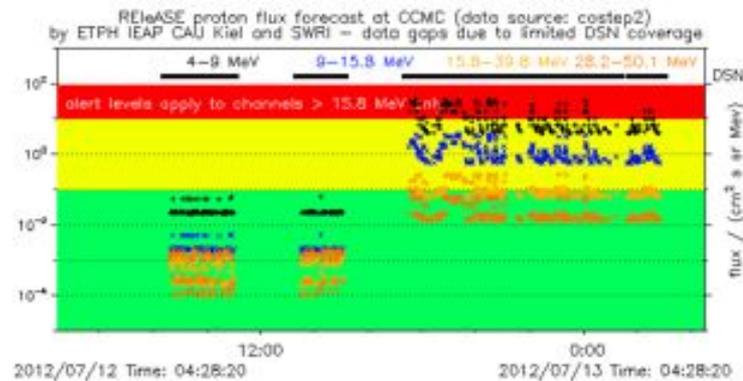
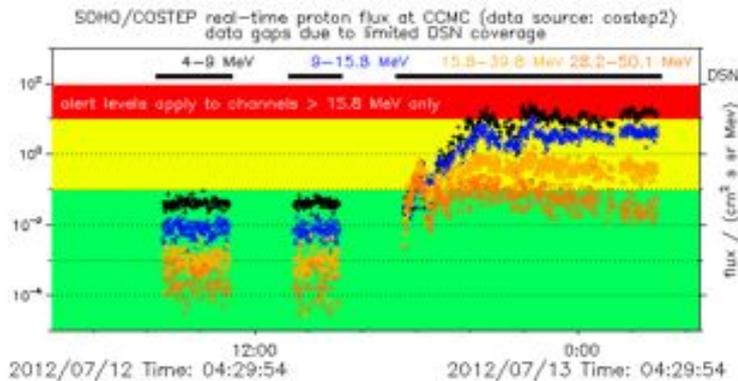
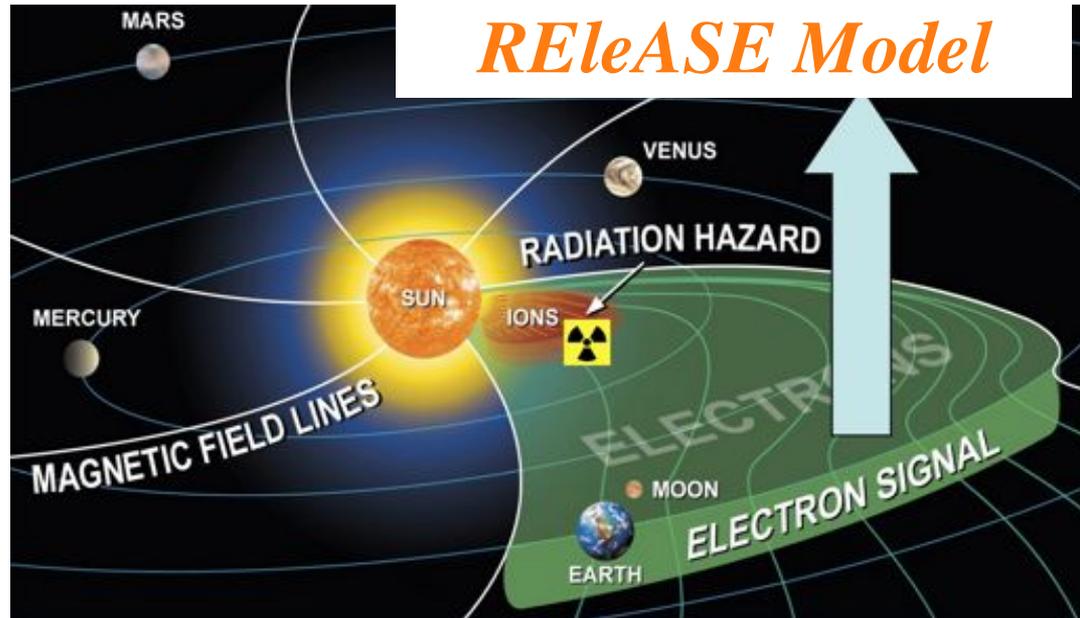


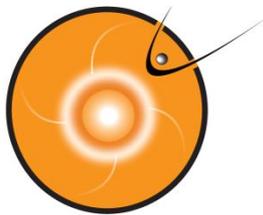
Can we predict SEP events?



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

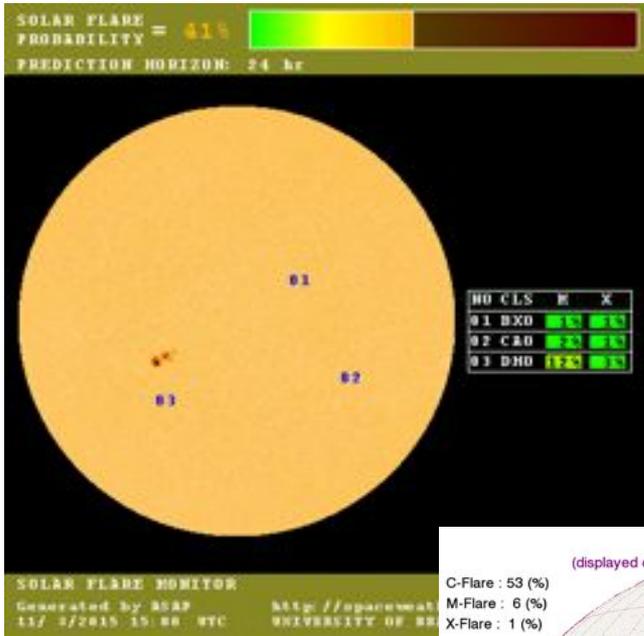
Data source: SOHO
COSTEP





SEP prediction (active region)

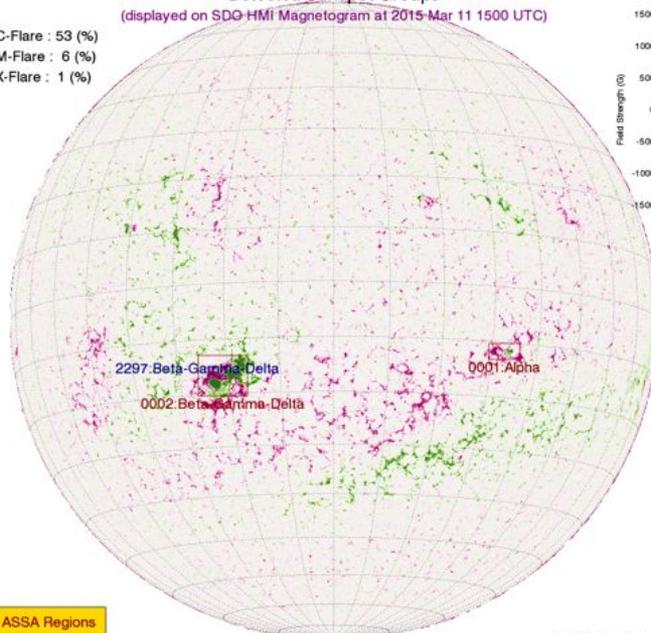
x2.2 flare on march 11, 2015



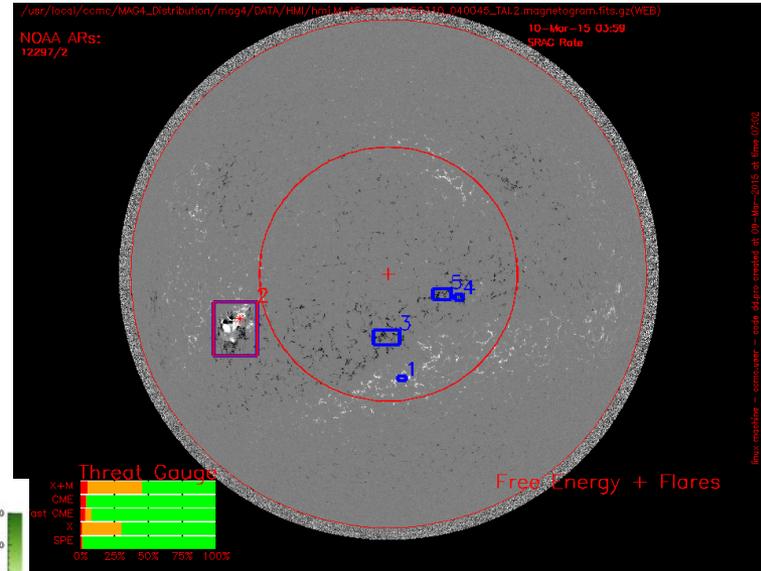
ASAP

Detected Sunspot Groups
(displayed on SDG-HMI Magnetogram at 2015-Mar 11 1500 UTC)

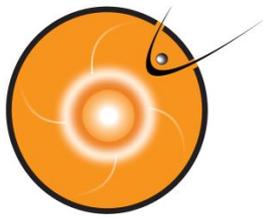
C-Flare : 53 (%)
M-Flare : 6 (%)
X-Flare : 1 (%)



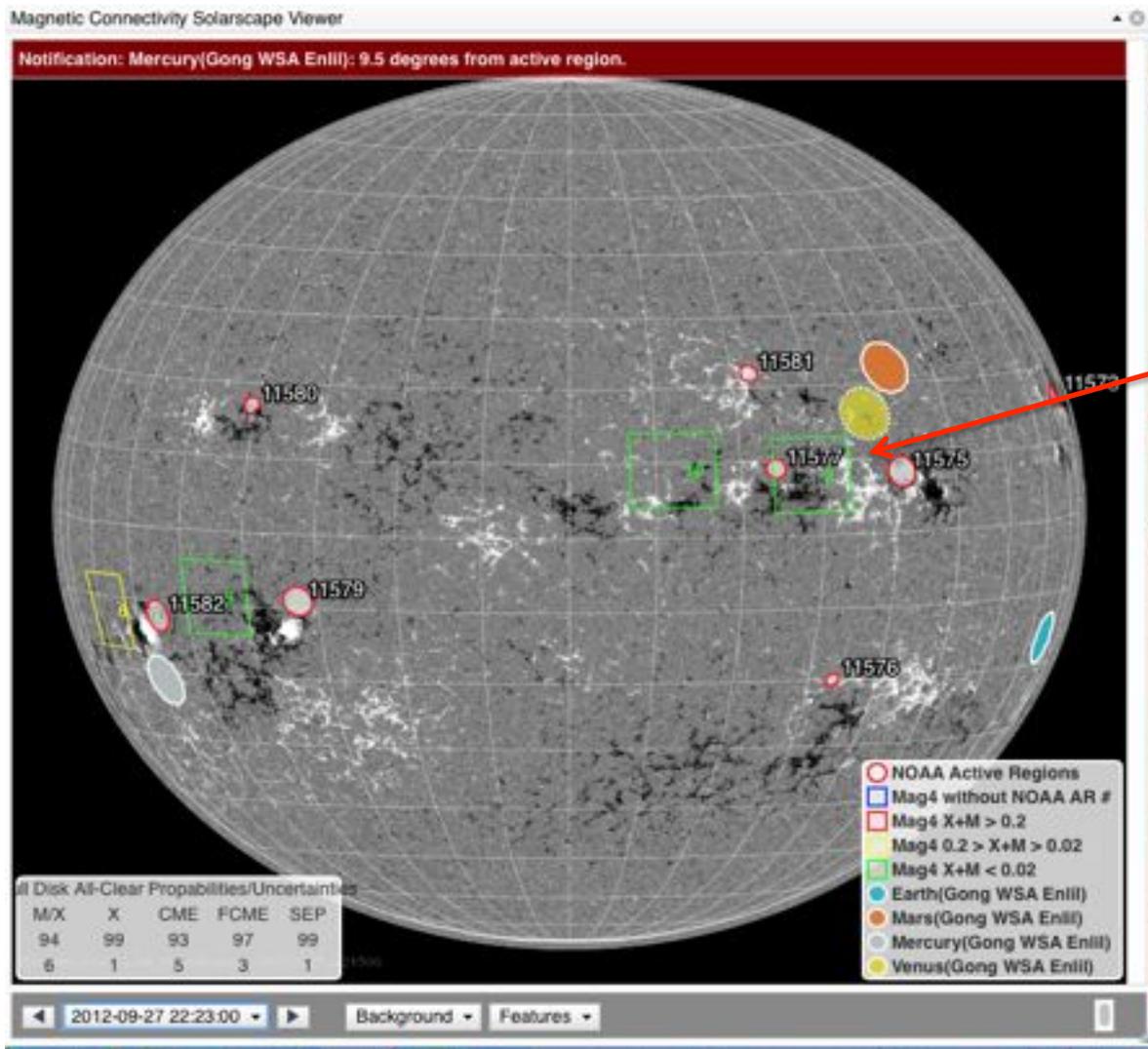
ASSA



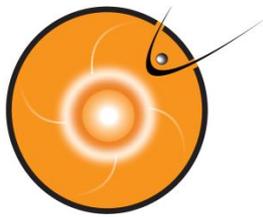
MAG4



Solarscape/magnetic connectivity



C3.7 class flare
AR 11577



How Often Do SEP Events Occur?



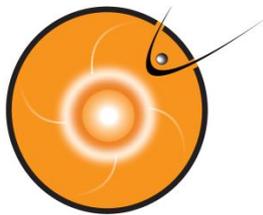
SEP event detections in the near-Earth environment (GOES 13, Proton $E > 10$ MeV channel)

2007-2009: Zero Events - Solar Minimum Indeed!

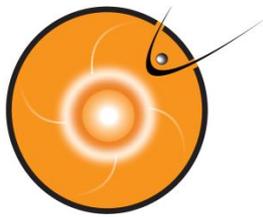
Total Events



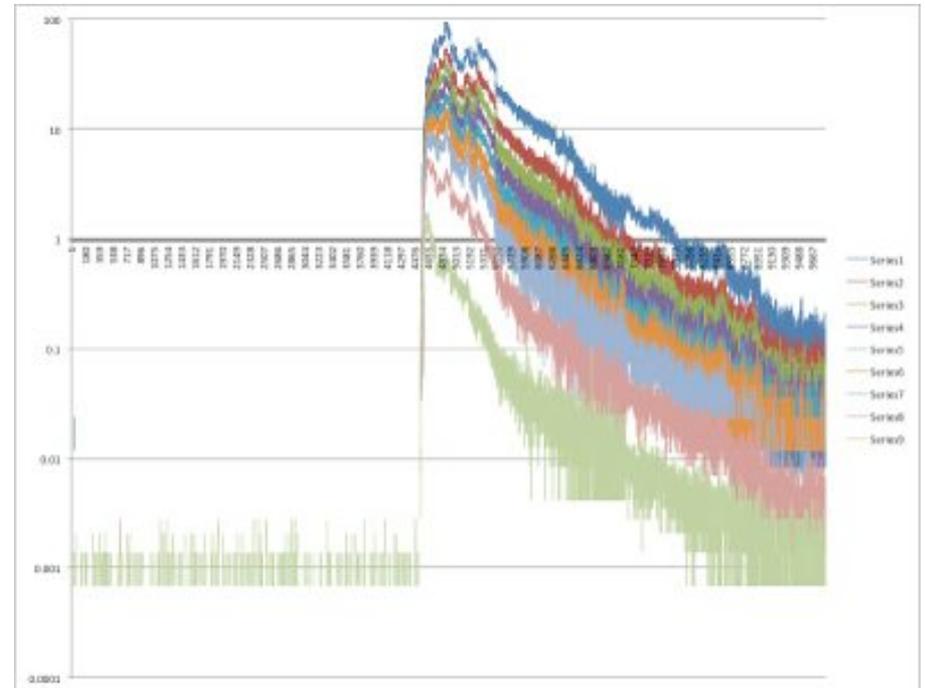
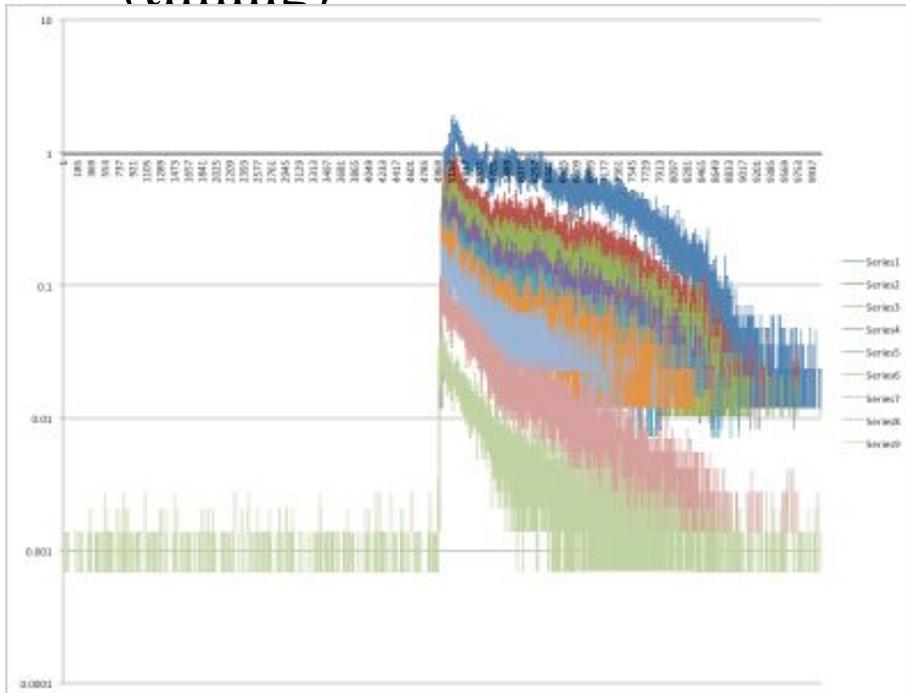
*Since March 2011
STEREO A: 16
STEREO B: 11*

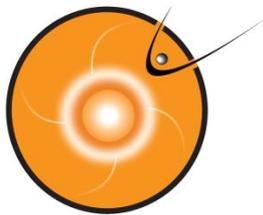


*Recognizing profile shapes of SEP flux and
associating it with the source/driver*

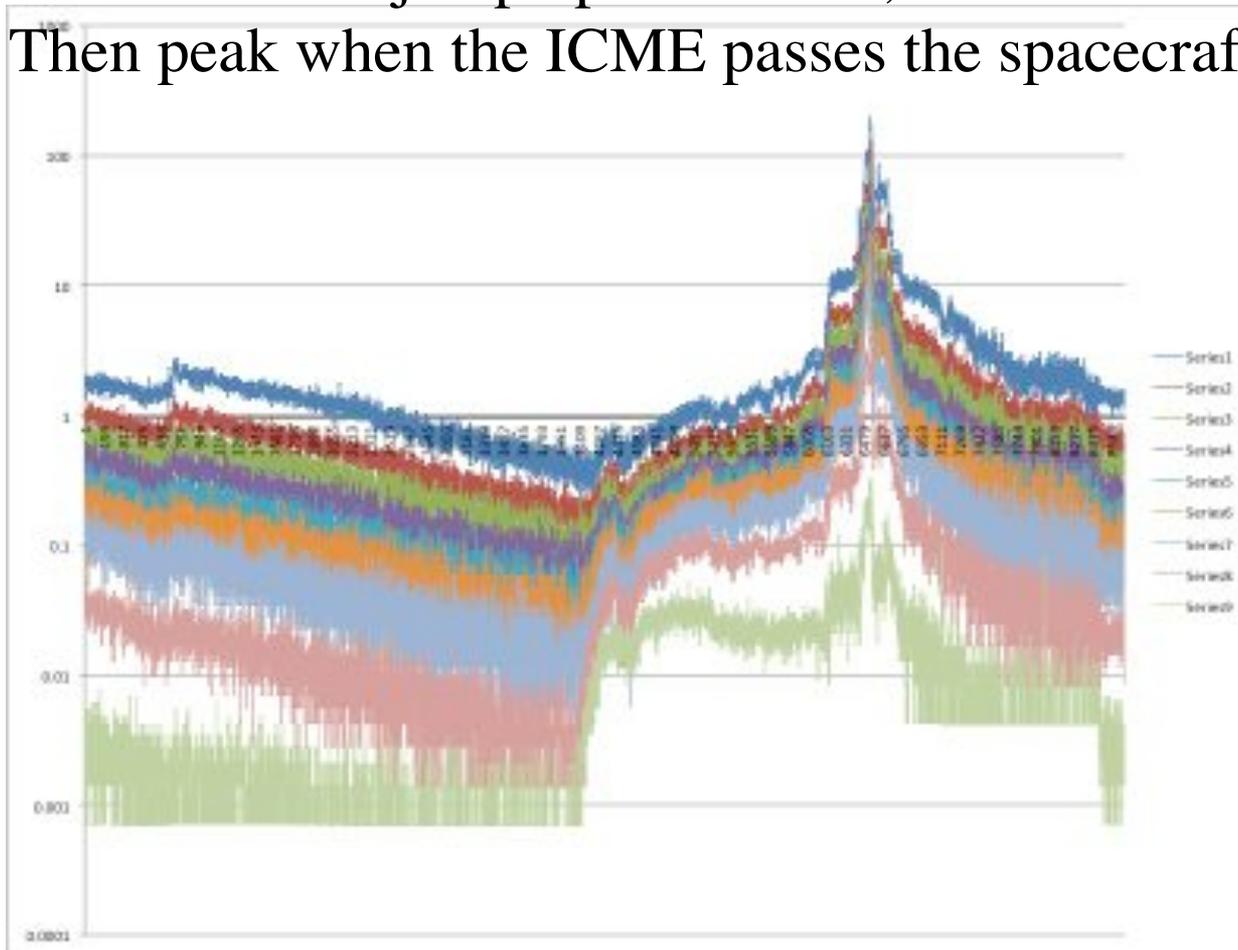


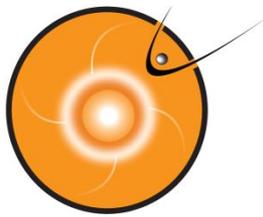
Impulsive: The “peak at the beginning due to flare, fall off” – indicates how well connected you are to the source (timing)



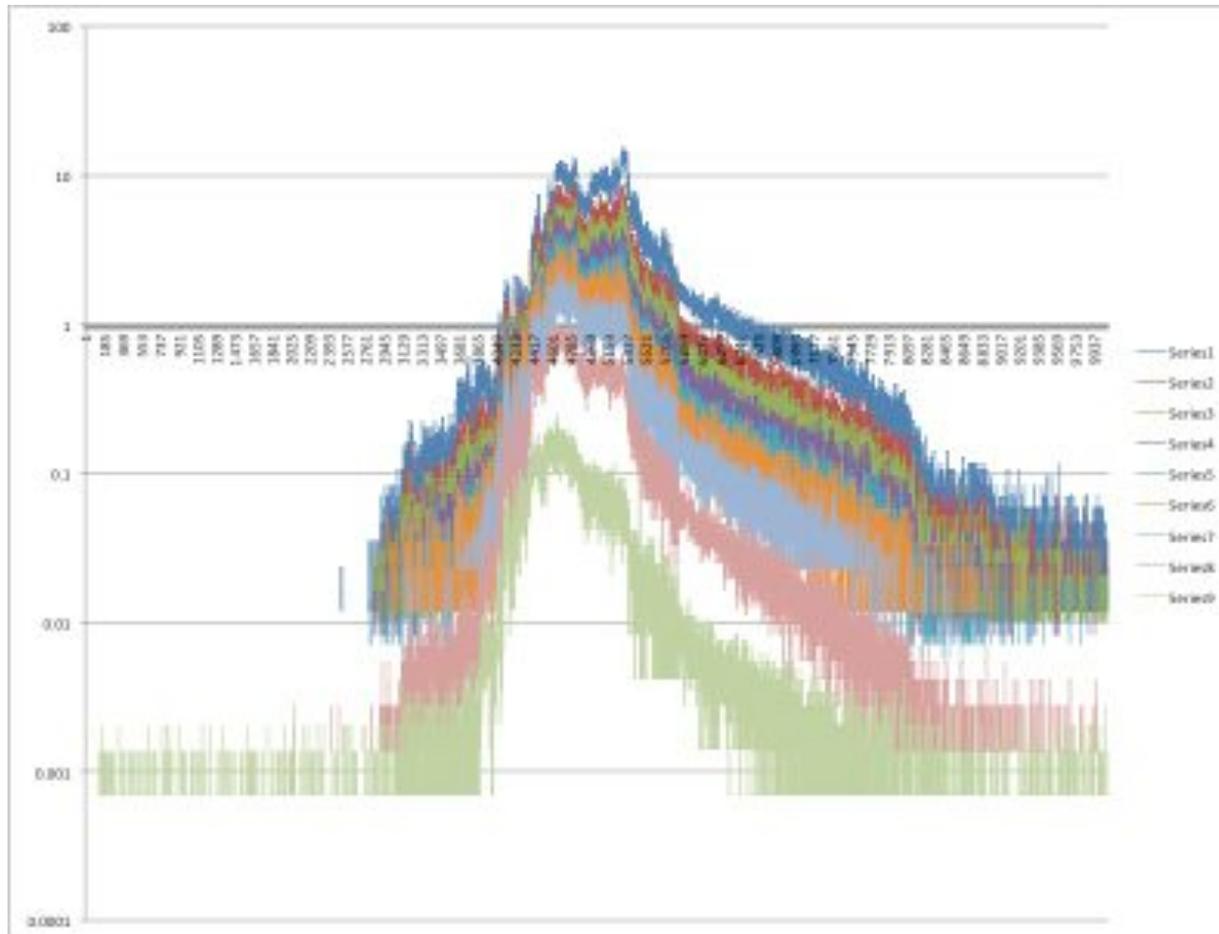


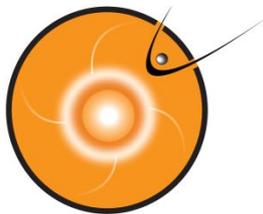
Gradual: The “jump up from flare, slow rise
Then peak when the ICME passes the spacecraft”





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”





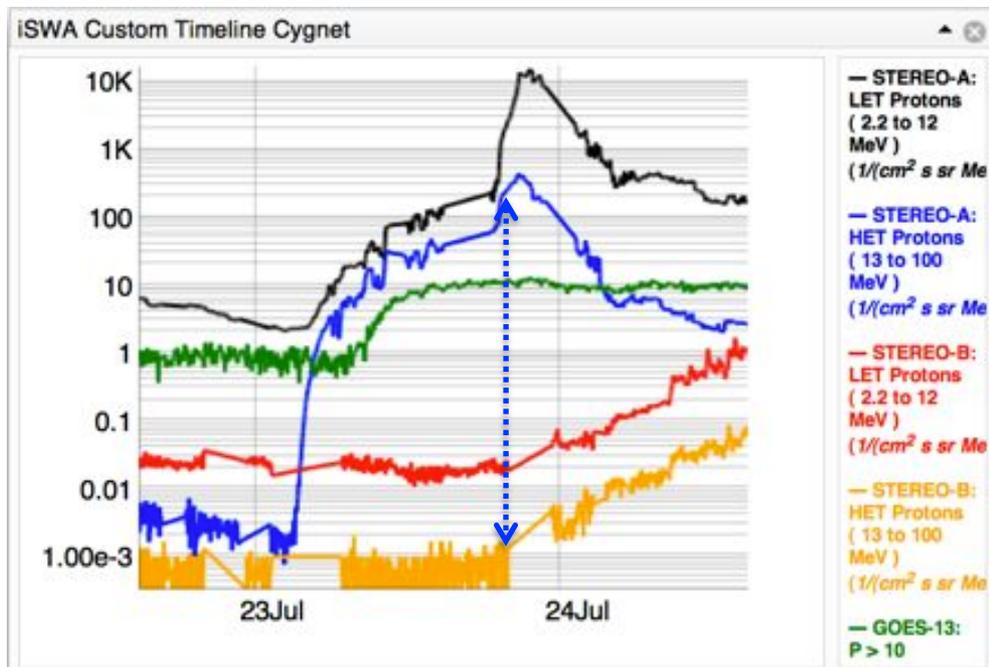
July 23, 2012



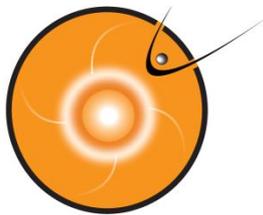
Example where it reaches one spacecraft, then later another...



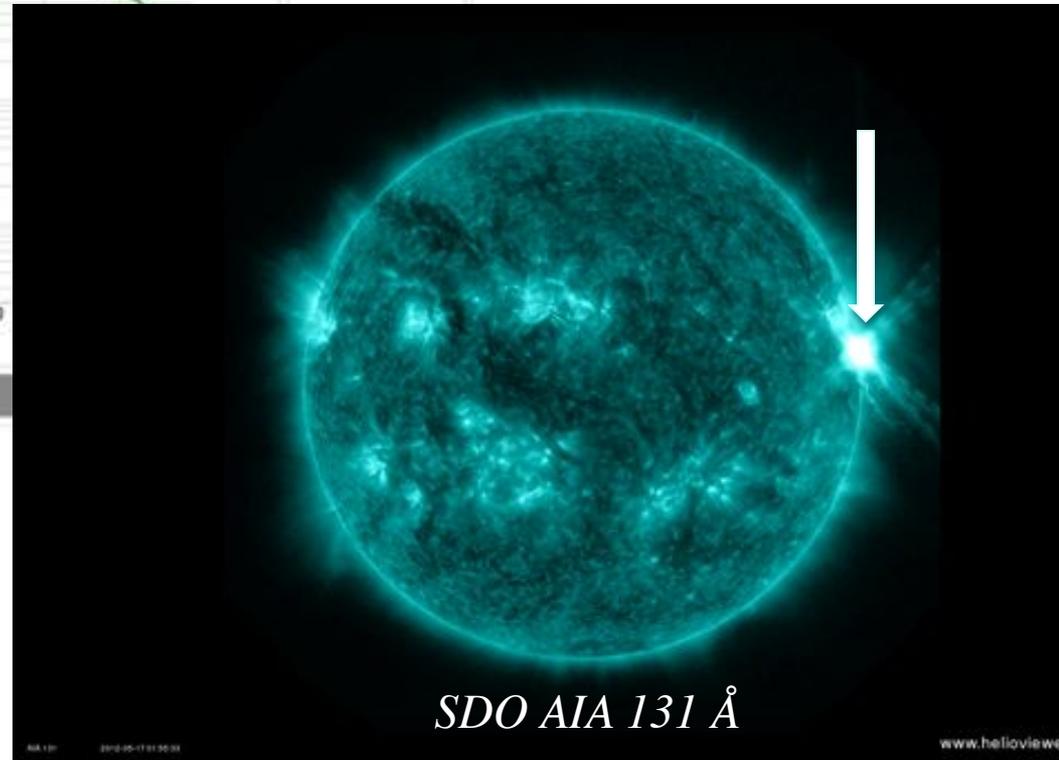
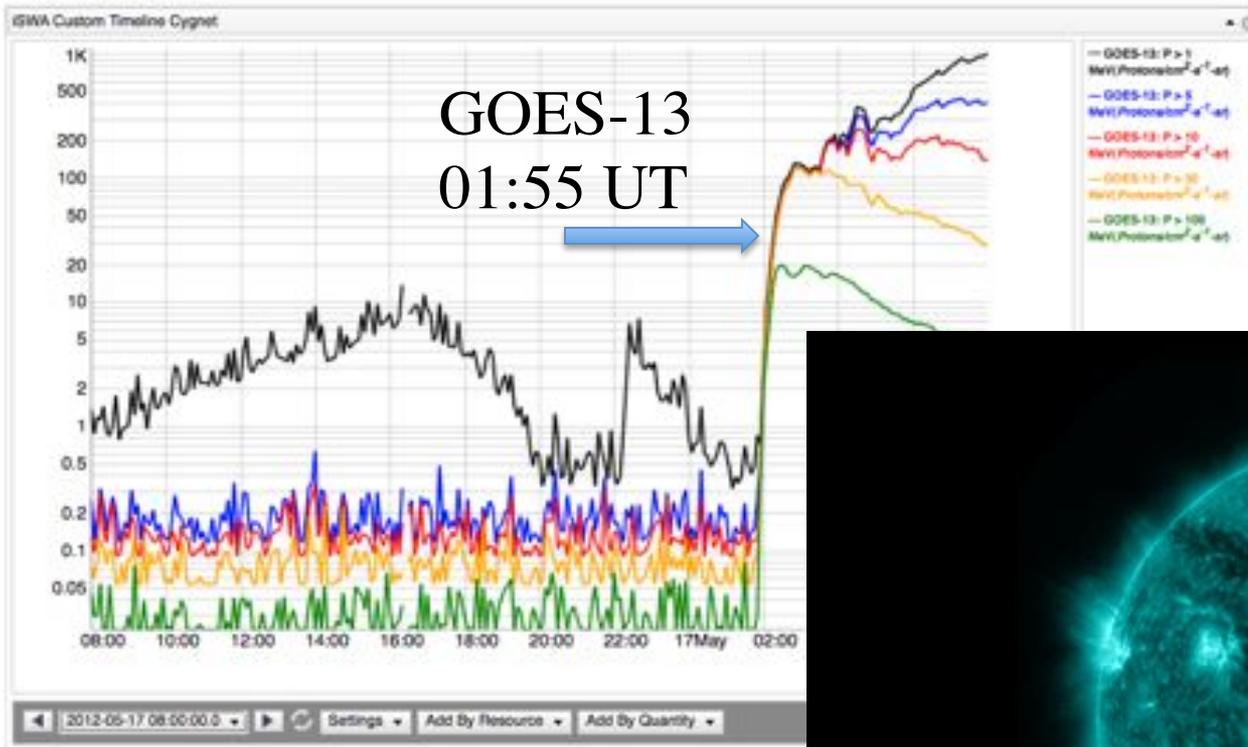
July 23 flare as seen in STEREO A EUVI 195



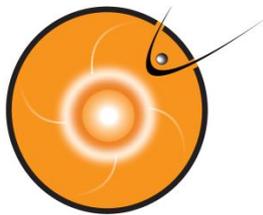
Increase of more than 5 orders of magnitude at STEREO A
SEP event also detected by GOES, and later enhancement seen at STEREO B (possibly due to IPS)



For Earth – Best Connection is 45-60 degree west



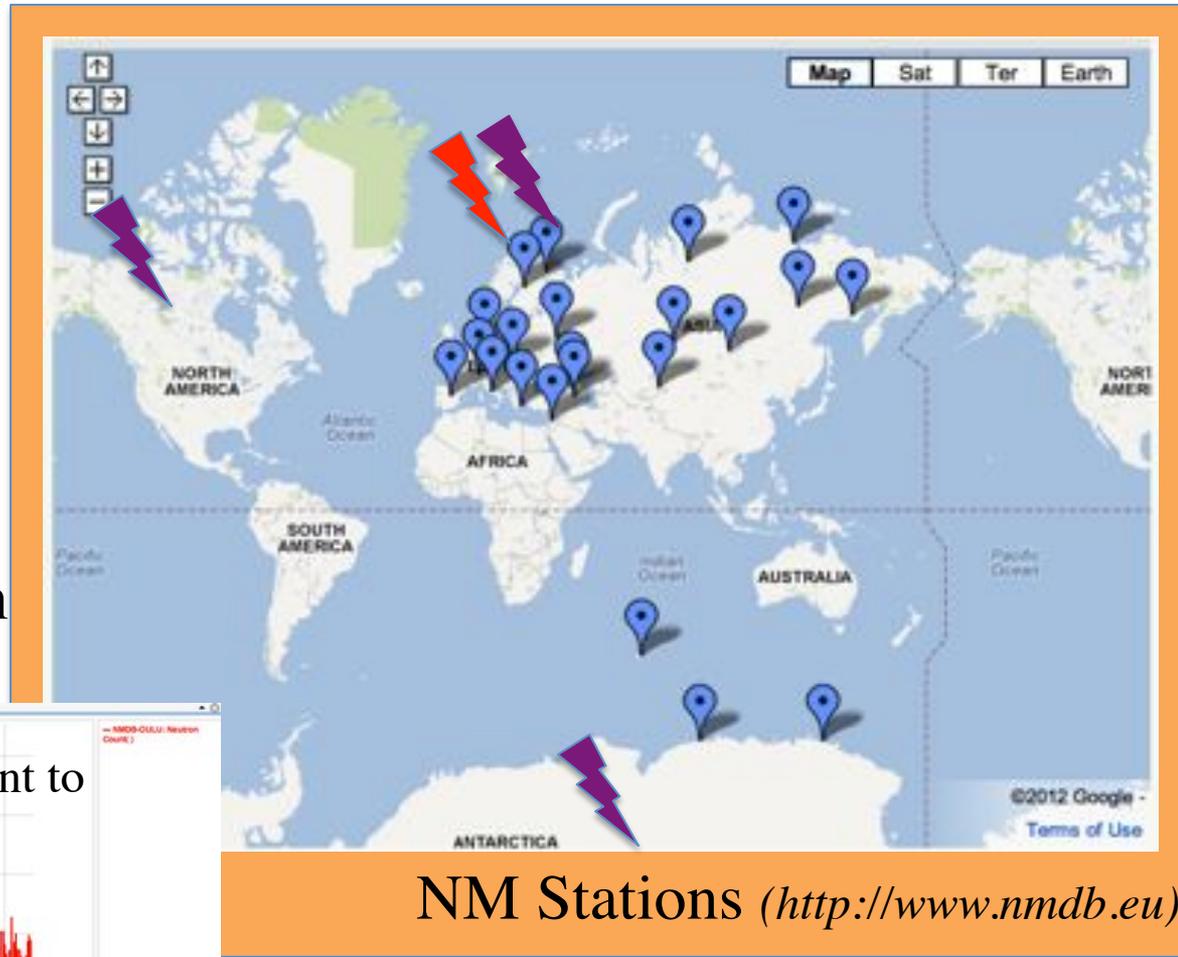
Energetic proton fluxes elevated for >12 hours



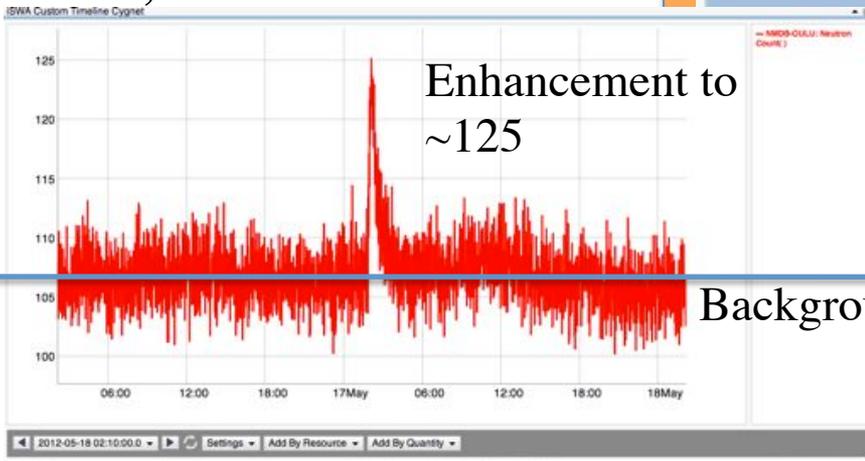
Ground Level Enhancement



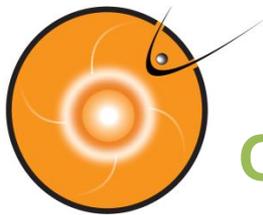
A subset of SEP events, a GLE event occurs when extremely high energy protons (>500 MeV/nuc) penetrate the Earth's atmosphere. Collisions with atoms generate secondary particles that are measured at neutron monitoring (NM) stations on the ground.



Neutron Monitoring Station in Oulu, Finland



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

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 ID	Onset		Max Int (%) ^a	Flare GOES		CME POS speed (km/s)	Width (deg)
	Date	Time ^b		Class	Location		
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

^aAccording to the Oulu Neutron Monitor

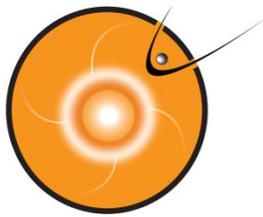
^bNo SOHO LASCO data

^cFrom Gopalswamy et al. (2010). There are different estimates (see Grechnev et al. 2008)

Nitta et al. 2012

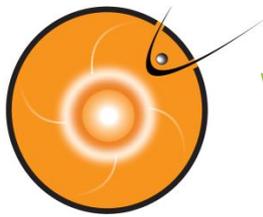
CME-driven shocks are thought to play important role in low (<3R_s) corona

- Only imaged in mid-high corona (*Ontiveros & Vourlidas 2009*)
- Type II radio bursts
- Multiple CME events – doesn't apply for May 17 event

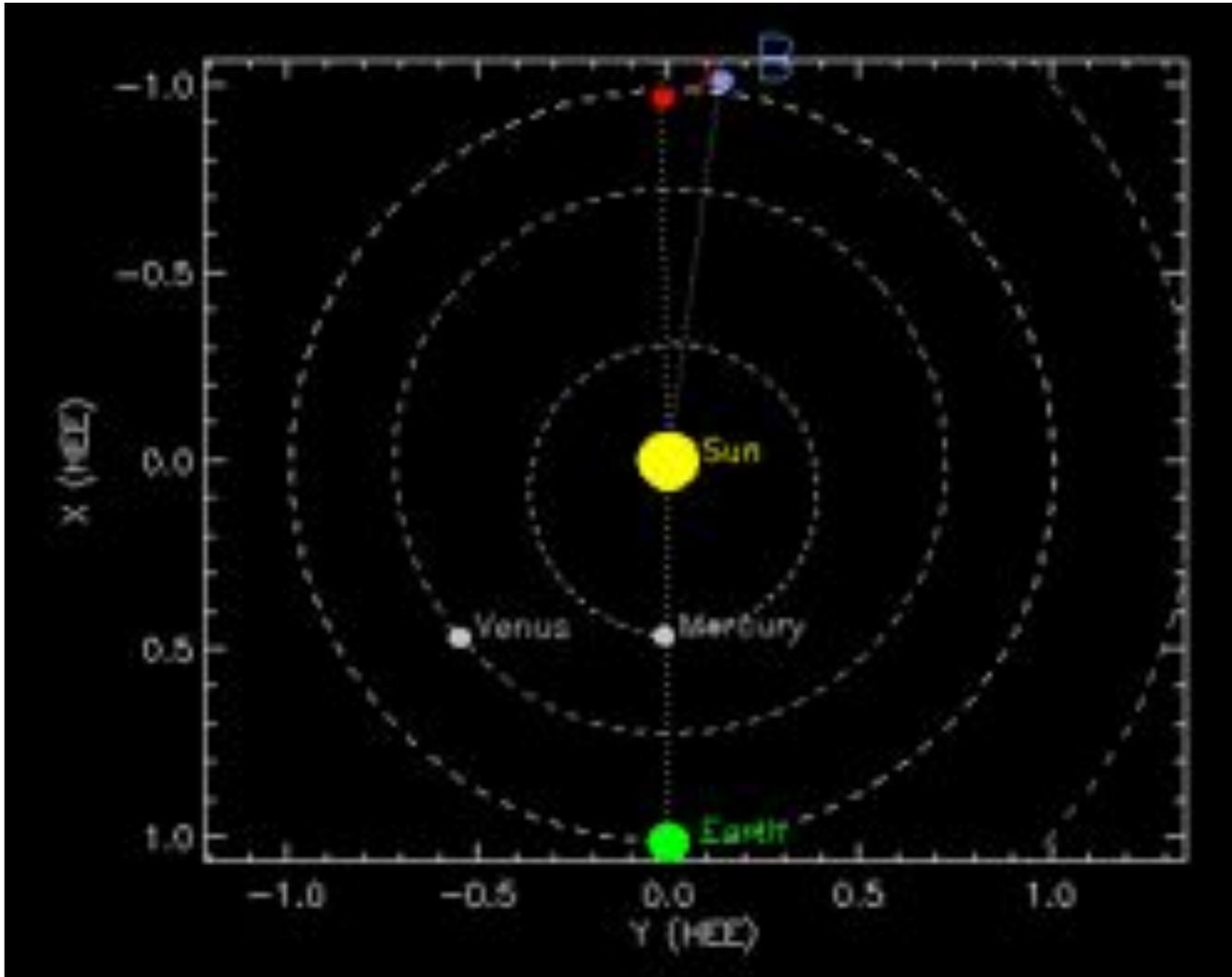


Exceptions to every rule!

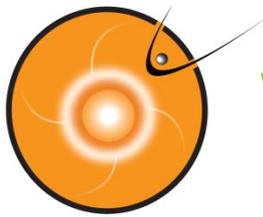
September 28, 2012 – whole heliosphere event – C3.7 flare



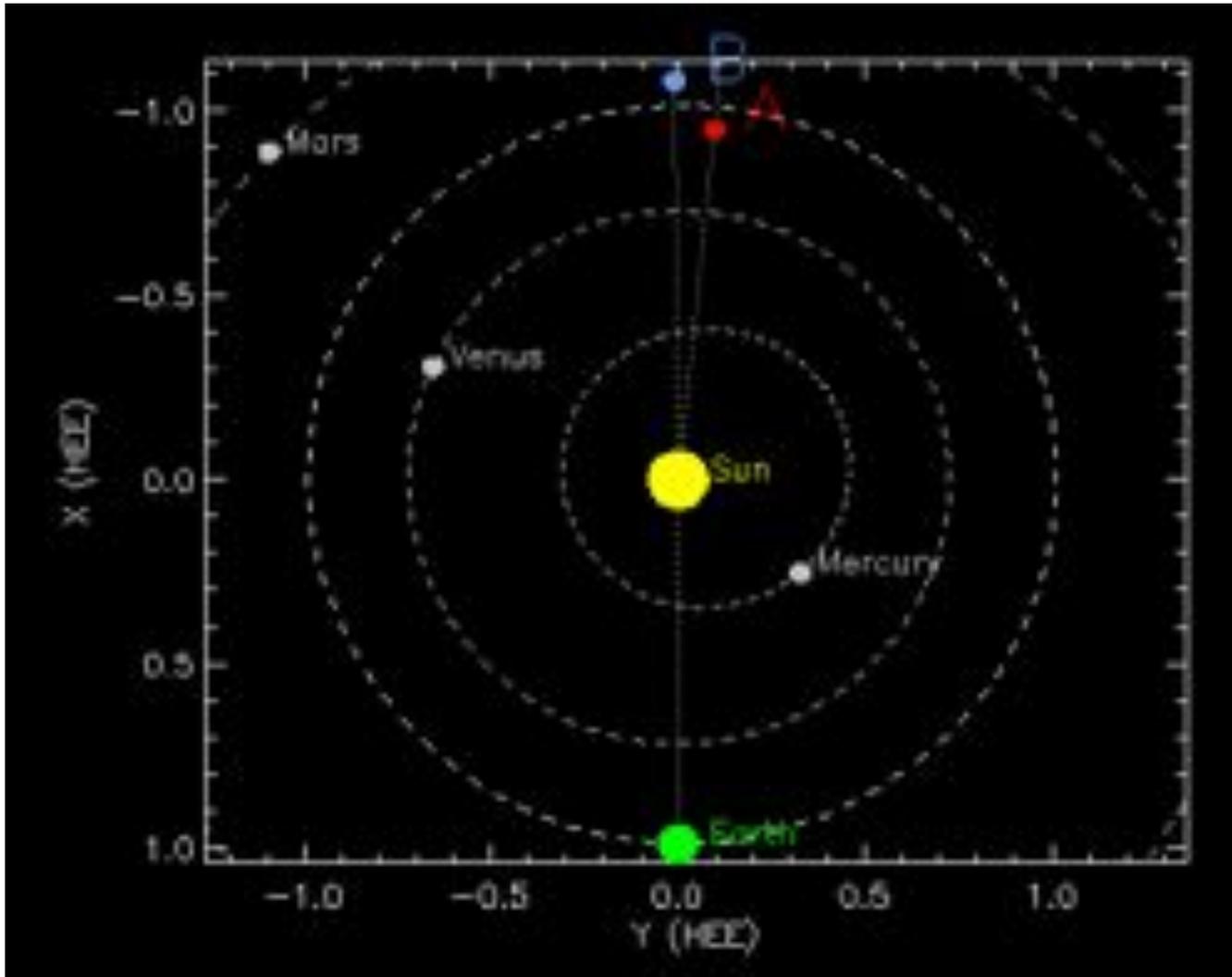
Where are NASA assets now?



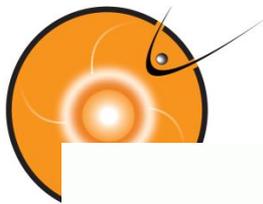
May 29, 2015



Where are NASA assets now?

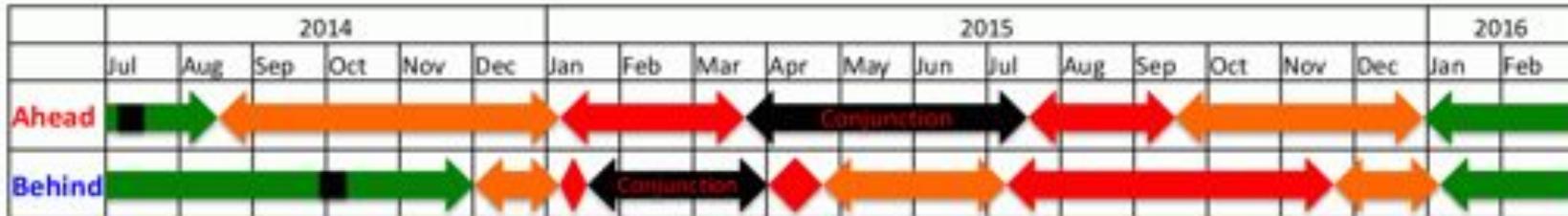


Feb 14, 2015



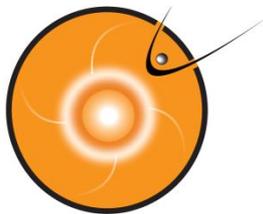
STEREO

STEREO SOLAR CONJUNCTION SCHEDULE



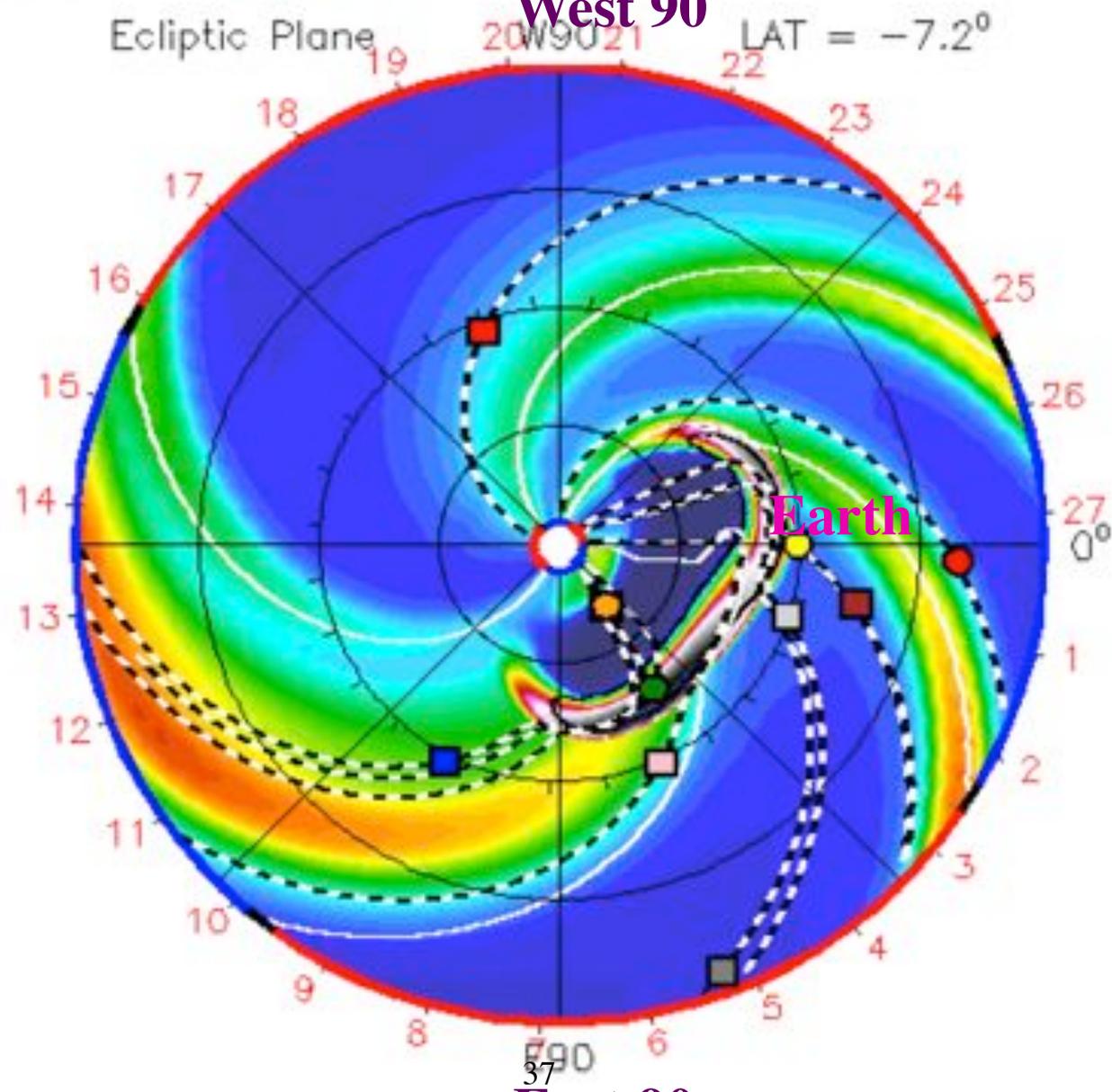
Event	kbps	Ahead	Behind
Instrument Off (Spacecraft Test)	0	6-Jul-2014	29-Sep-14
Nominal Science	120	15-Jul-2014	6-Oct-2014
HGA on 1 st Side Lobe	7.4	20-Aug-2014	1-Dec-2014
HGA on 2 nd Side Lobe	1.7	5-Jan-2015	6-Jan-2015
Instrument Off	0	22-Mar-2015	20-Jan-2015
HGA on 2 nd Side Lobe	1.7	14-Jul-2015	30-Mar-2015
HGA on 1 st Side Lobe	7.4	24-Sep-2015	25-Apr-2015
HGA on 2 nd Side Lobe (Behind Only)	1.7	NA	8-Jul-2015
HGA on 1 st Side Lobe (Behind Only)	7.4	NA	20-Nov-2015
Instrument Recommissioning	120	31-Dec-2015	5-Jan-2016

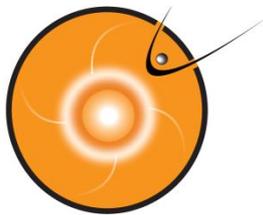
14-Nov-2014 : all dates subject to change (SPACECRAFT HEALTH IS PRIORITY ONE)



- Earth (Yellow circle)
- Mars (Red circle)
- Mercury (Orange circle)
- Venus (Green circle)
- Spitzer (Pink square)
- Stereo_A (Red square)
- Stereo_B (Blue square)

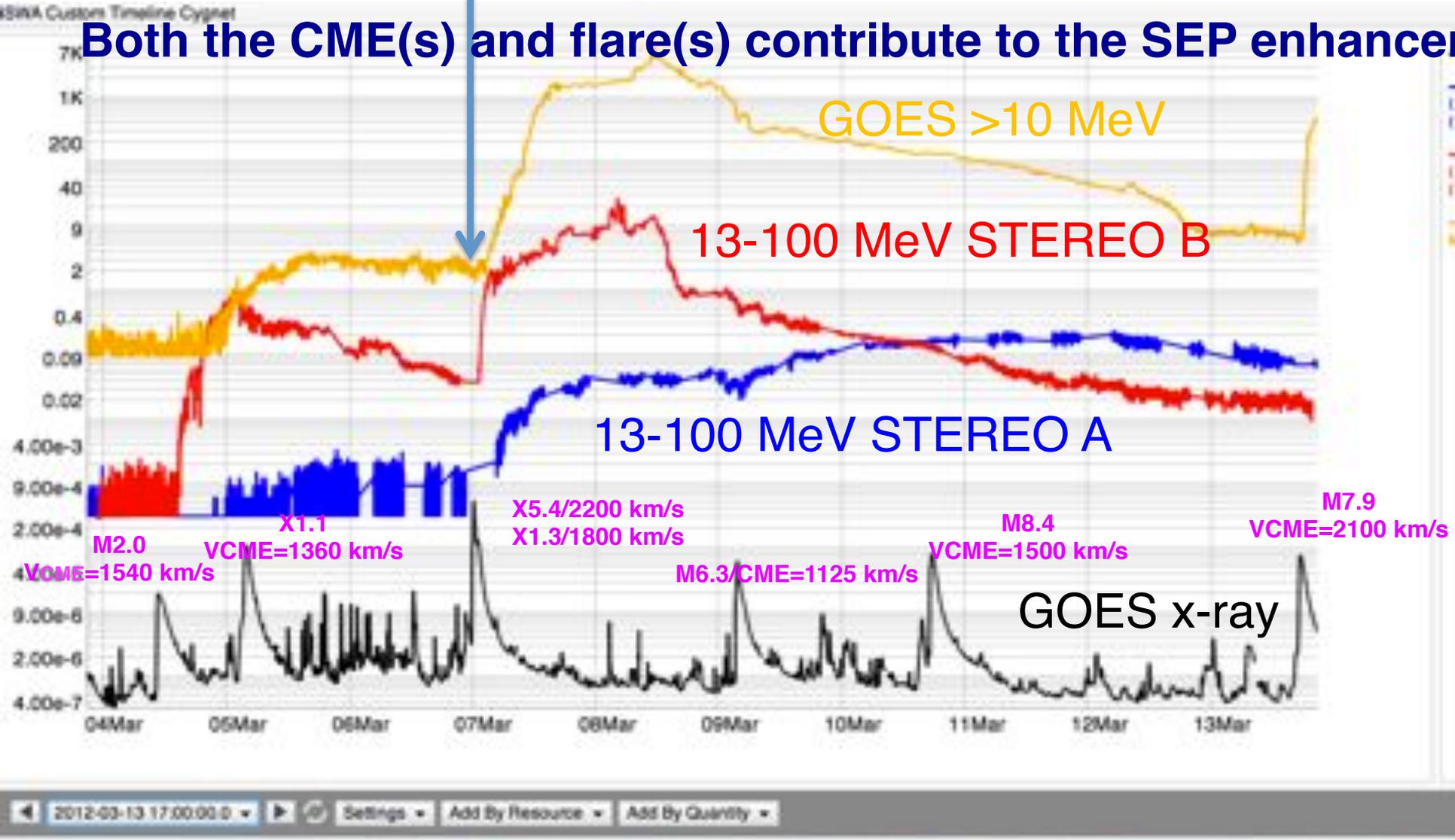
West 90

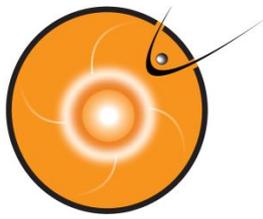




SEP: proton radiation

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





SEP Layout

http://bit.ly/alert_SEP_layout