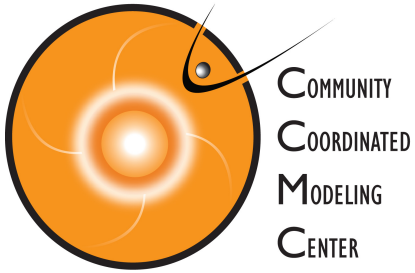
Flares, CMEs and SEPs



A. Taktakishvili

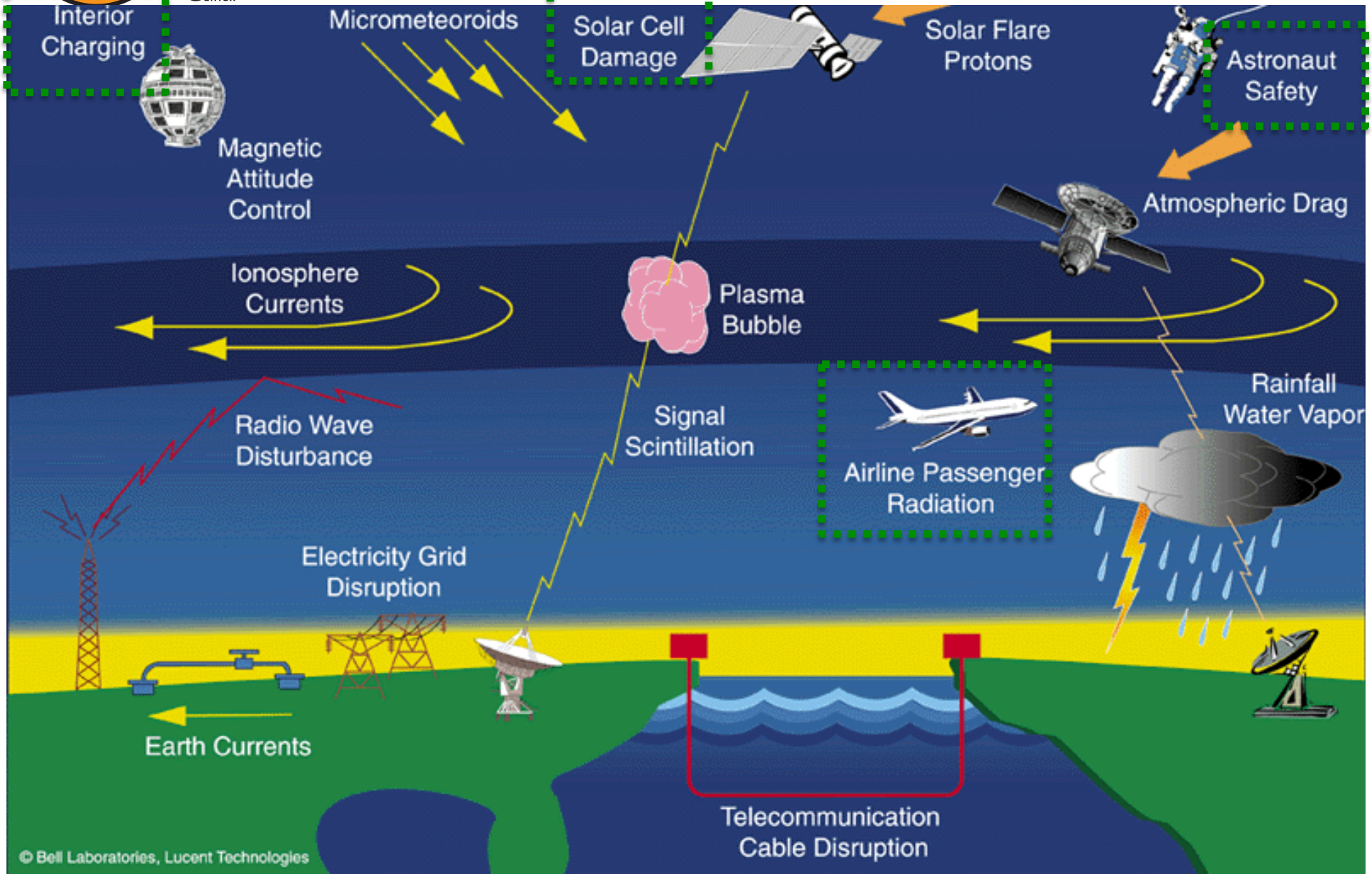
CCMC, SWRC

NASA Goddard Space Flight Center

NASA
Space
Weather
Research
Center

Community Coordinated Modeling Center

Why do we care?



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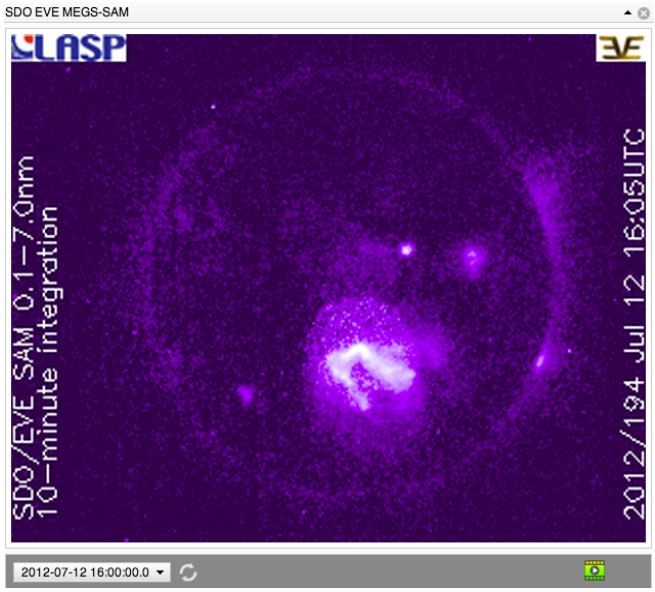
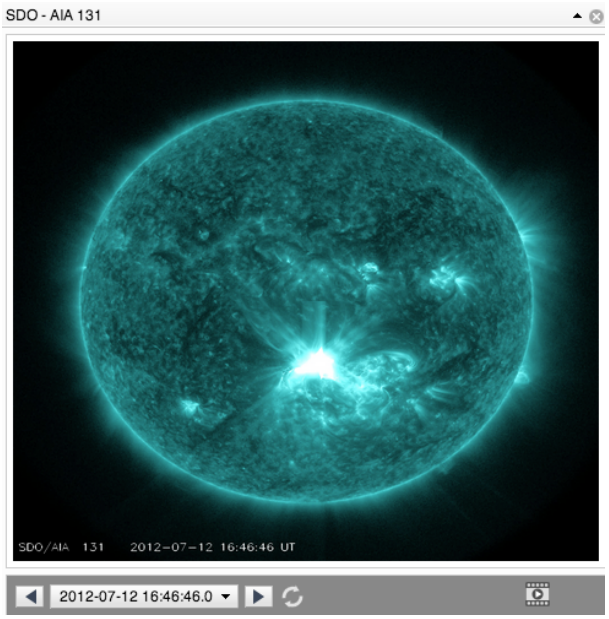
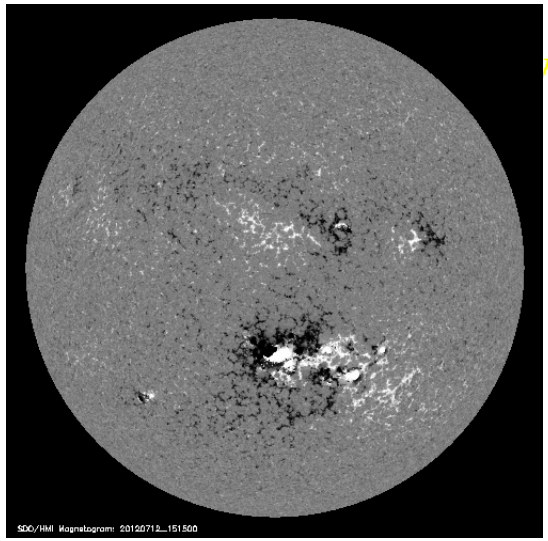
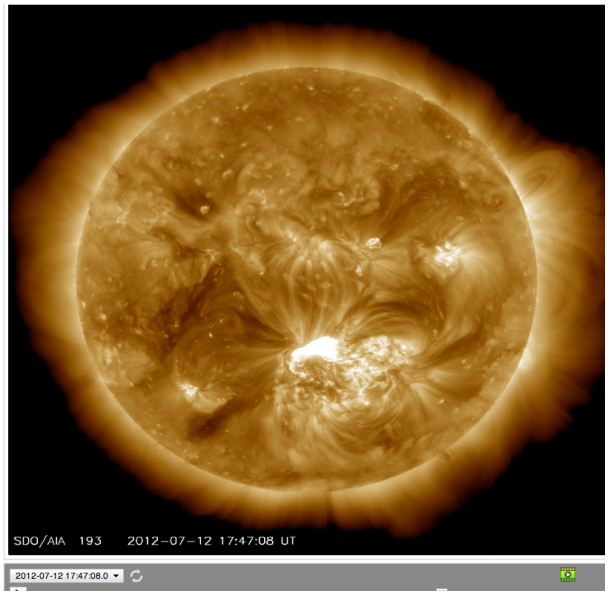
Solar Flare

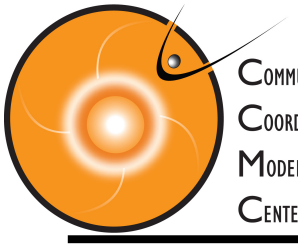


2012 July 12 X1.4 class flare







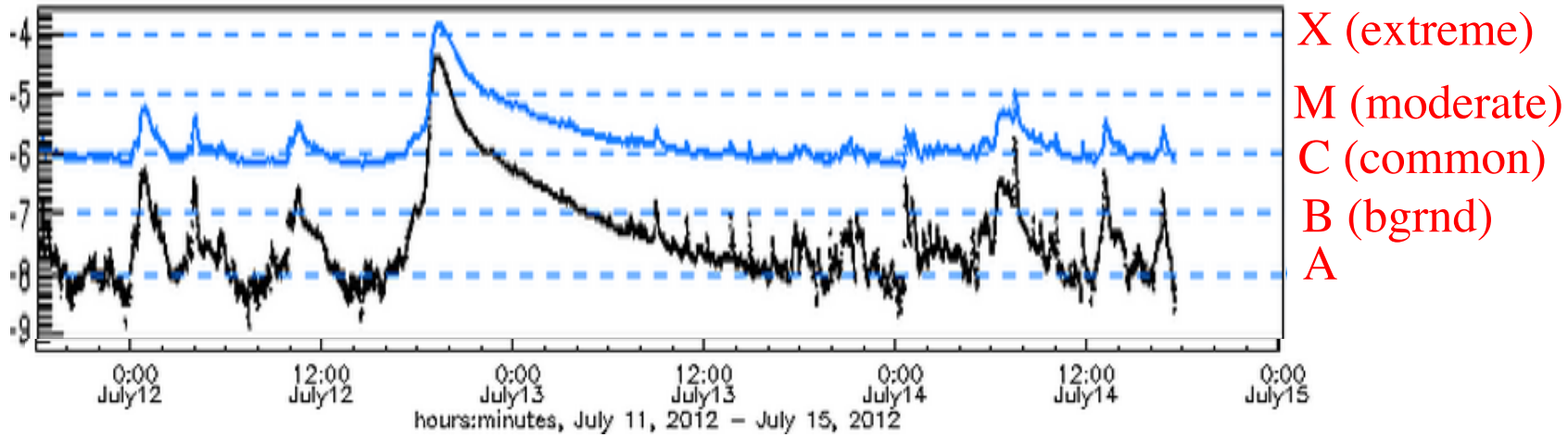


Solar Flare Class

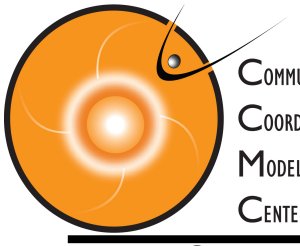
2012 July 12 X1.4 class flare

0.1-0.8 nm

0.05-0.4 nm

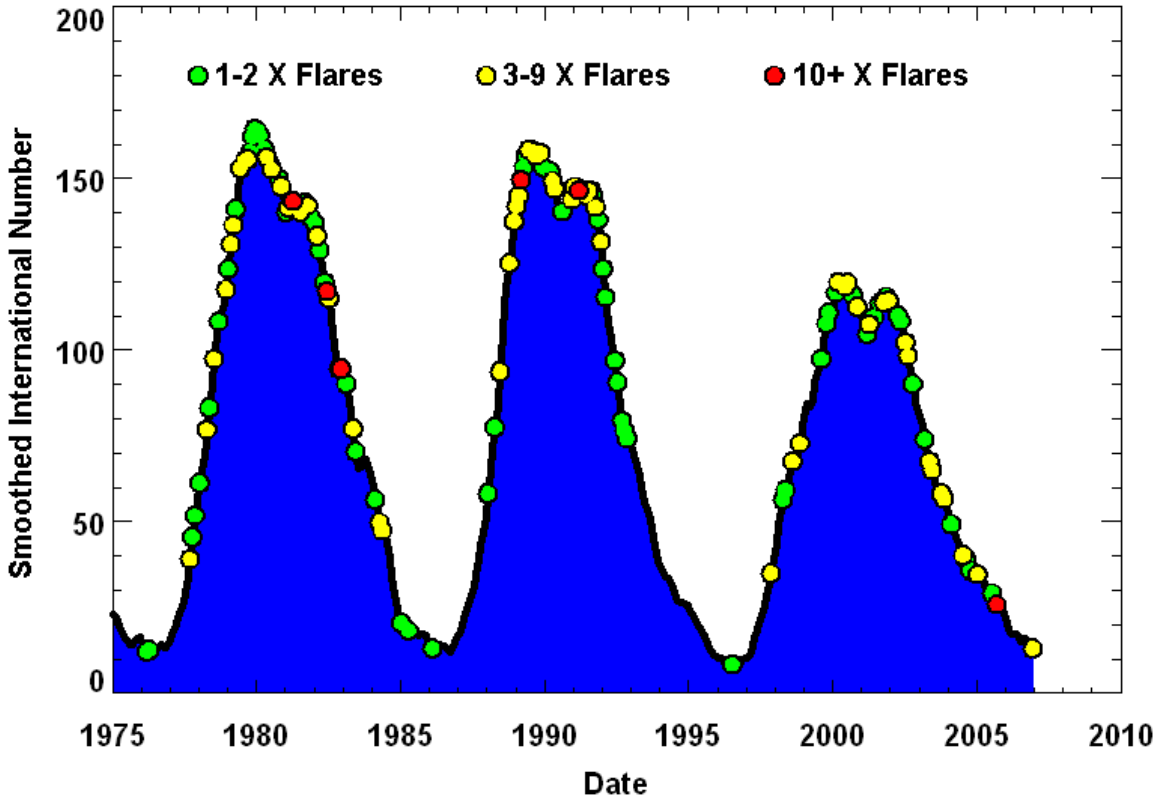


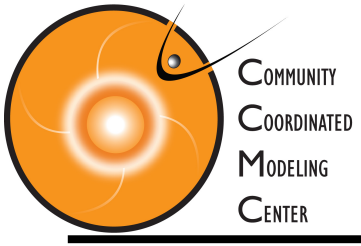
X1.4 class: flux(0.1-0.8nm)[Wm^2]=1.4*10^(-4)



Flares over the Solar cycle

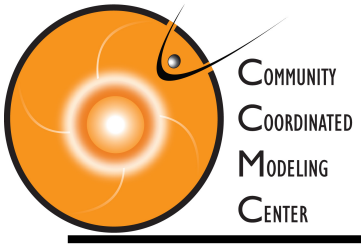
Solar flares have been monitored by x-ray detectors on GOES satellites since 1976. The number of X-Class flares per month increases with the number of sunspots but **big flares can occur anytime sunspots are present.**





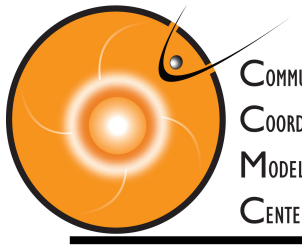
Flare: SWx impacts

- Cause radio blackout through changing the structures/composition of the ionosphere (sudden ionospheric disturbances) – X ray and EUV emissions, lasting minutes to hours
- Affect radio communications, GPS, directly by its radio noises at different wavelengths
- Contribute to SEP – proton radiation, lasting a couple of days



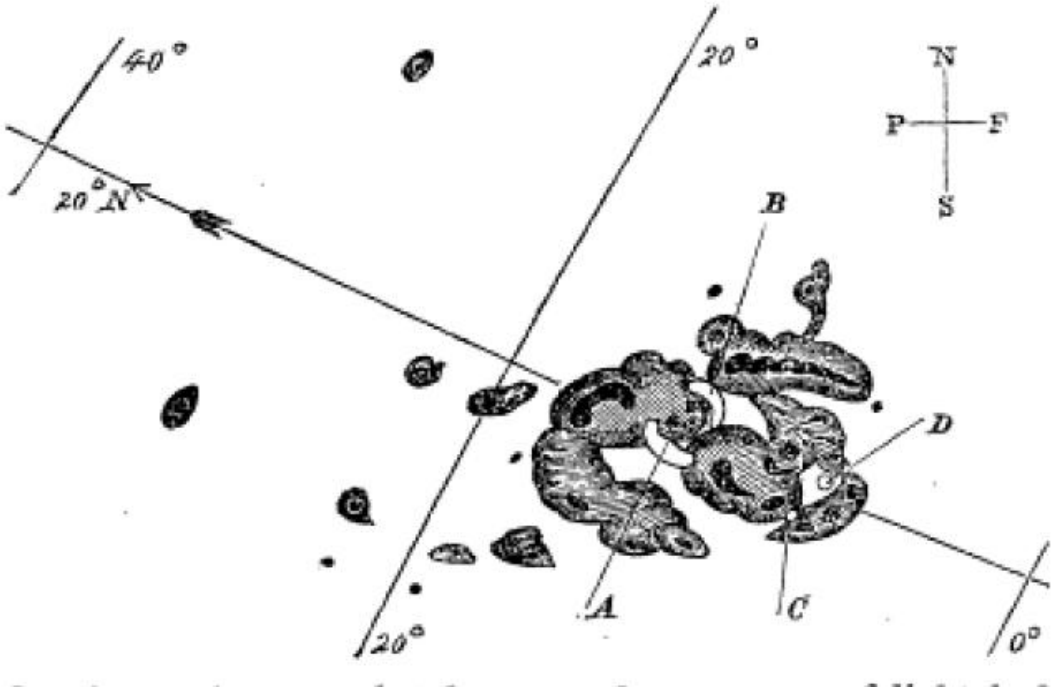
Flare Characteristics

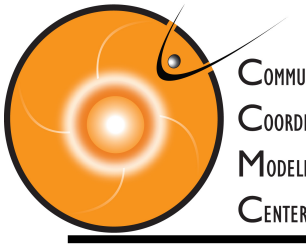
- Flares tend to occur in isolation, localized in space and time but with strong correlations; typically one active region will produce dozens of flares, especially during periods of flux emergence (often near the beginning of the lifetime of a given region, but not always). The most powerful events usually occur in active regions.



Solar Flare Discovered

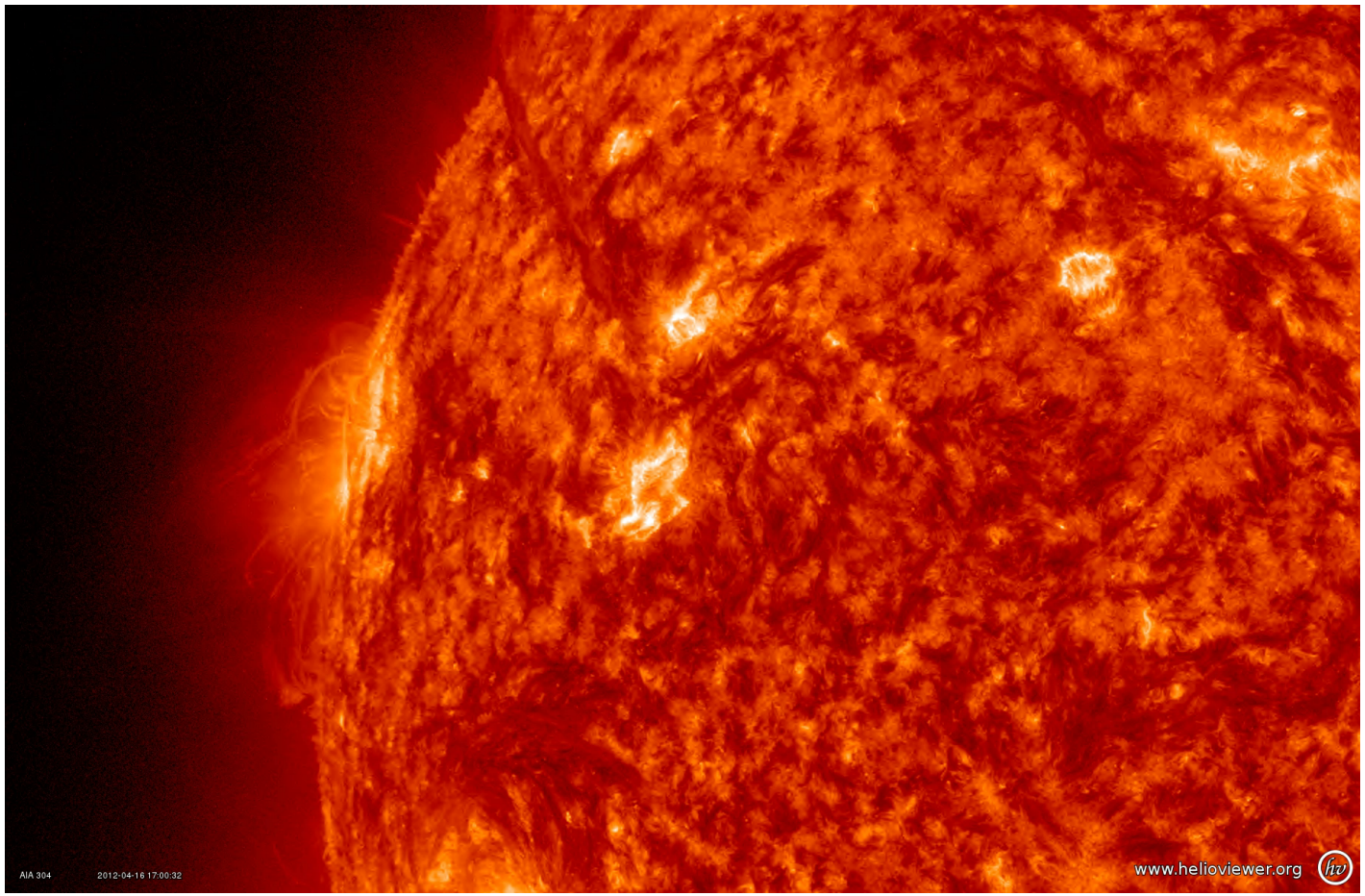
In 1859 Richard Carrington reported observing a large sunspot group on the afternoon of September 1st when "…*two patches of intensely bright and white light broke out*…"

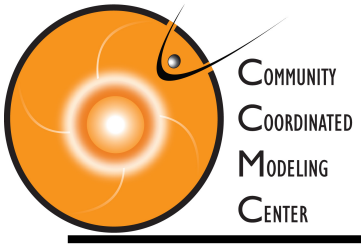




Coronal Mass Ejection

Coronal Mass Ejection – Reaches the Earth in 1-3 days





CME/flare

- The most energetic CMEs occur in close association with powerful flares. Nevertheless large-scale CMEs do occur in the absence of major flares even though these tend to be slower and less energetic.

- When strong flare/CME occurs, it gives off emission across the whole electromagnetic spectrum, at the same time energetic particles

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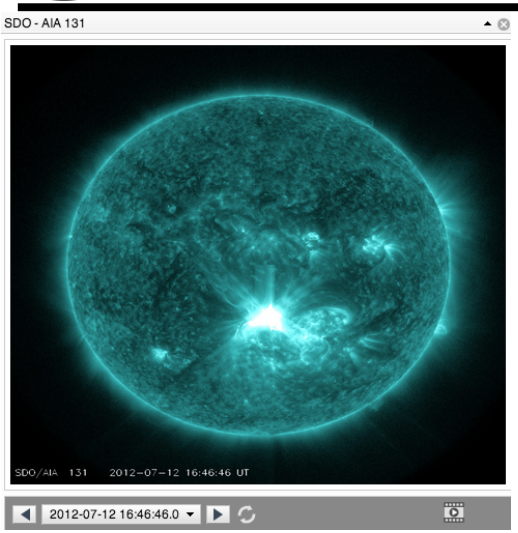
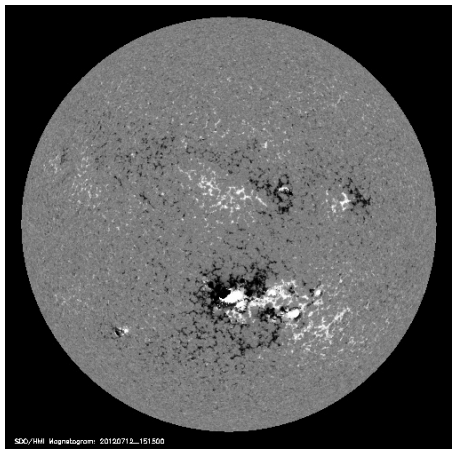
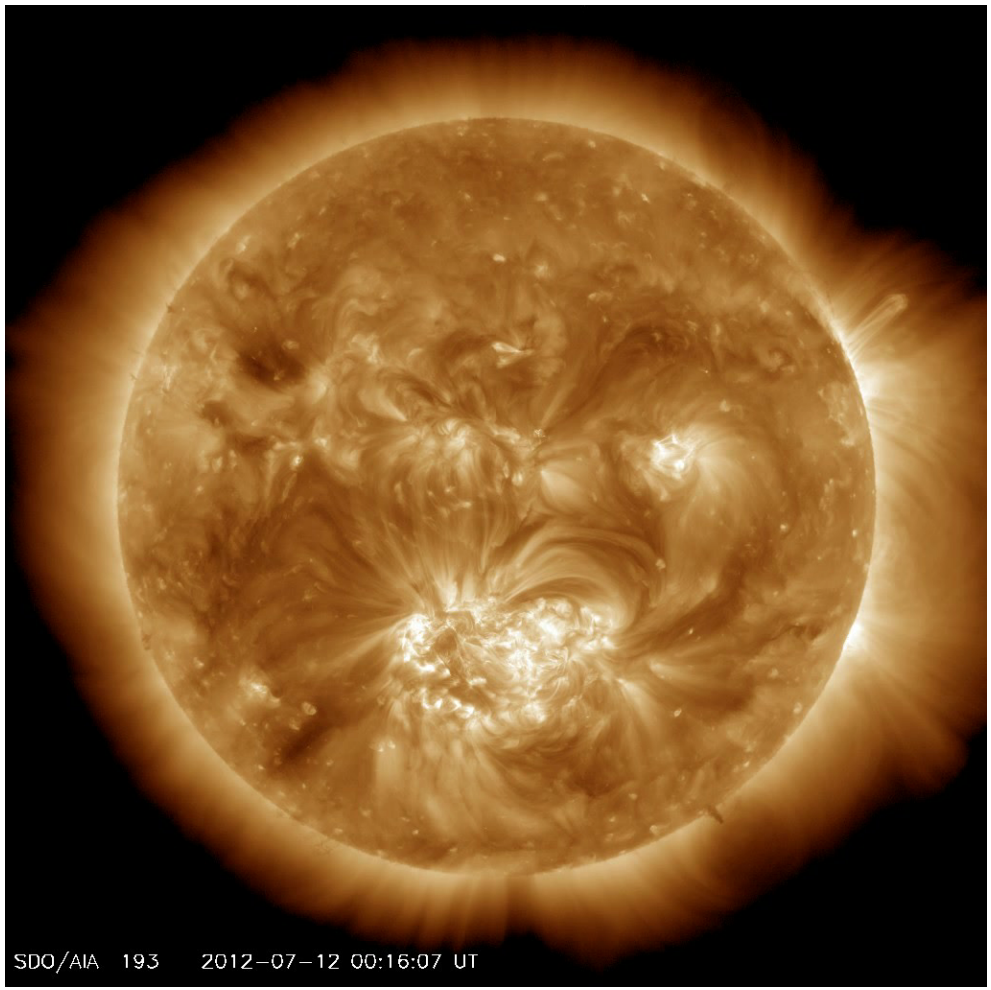
Most of the CMEs Originate From the Active Regions





2012 July 12 X1.4 class flare and a following CME



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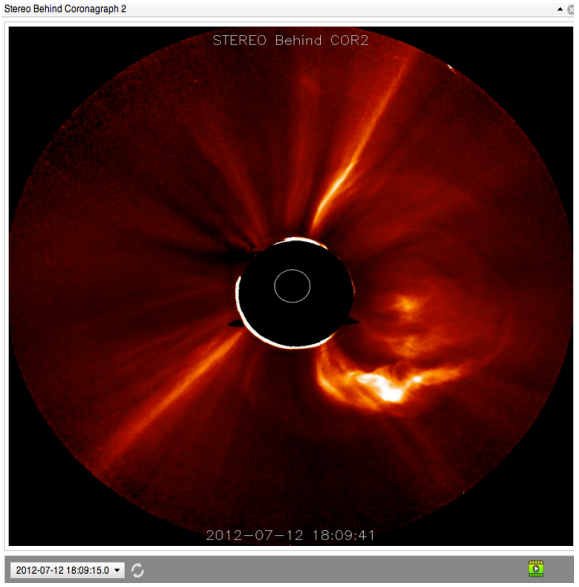
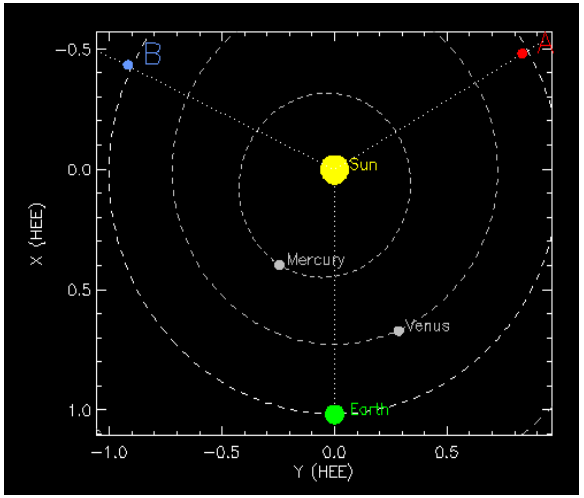
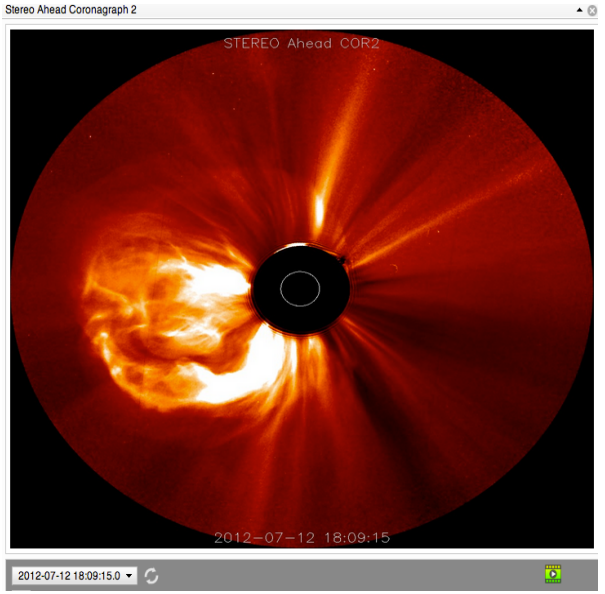
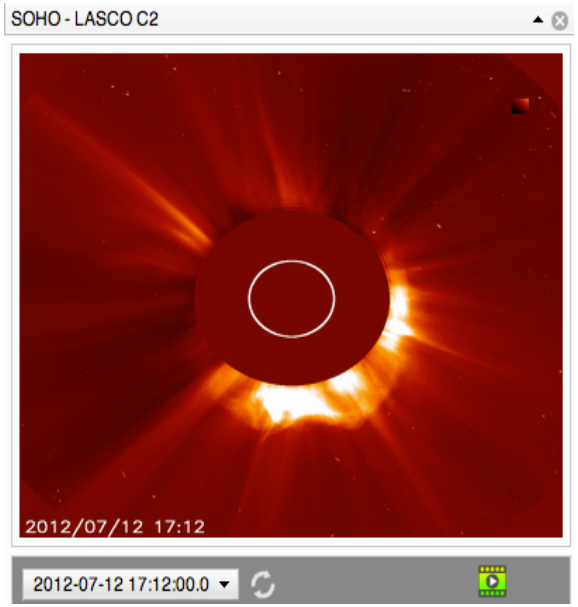
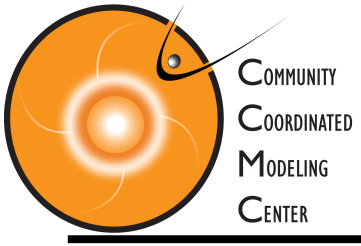
July 12, 2012CME Viewed by Coronagraph Imagers





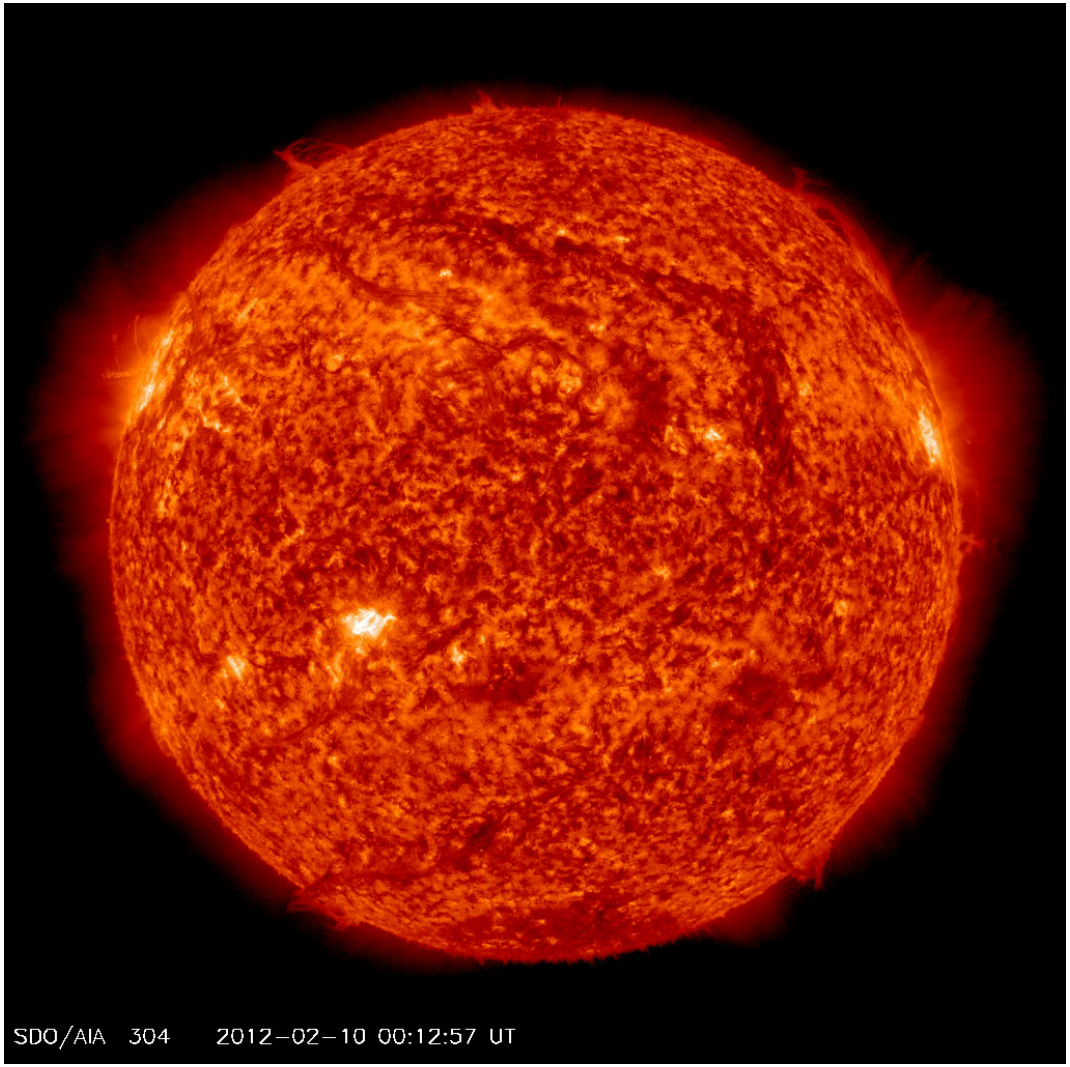


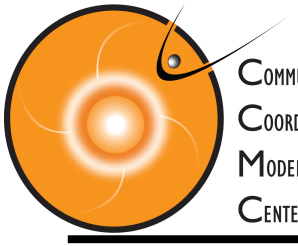




CME from a Filament Eruption

Northeast (upper left) quadrant starting around 19:00 UT on Feb 10, 2012





CME Properties

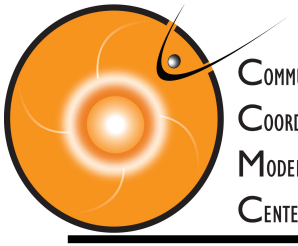
- Mass: ~$10^{15\text{-}16}$ g
- Speed: few hundred - 3000km/s

..or

- Mass: ~1 million Nimitz-class aircraft carriers
- Speed: 1.5 -10 million km/hour

Earth?

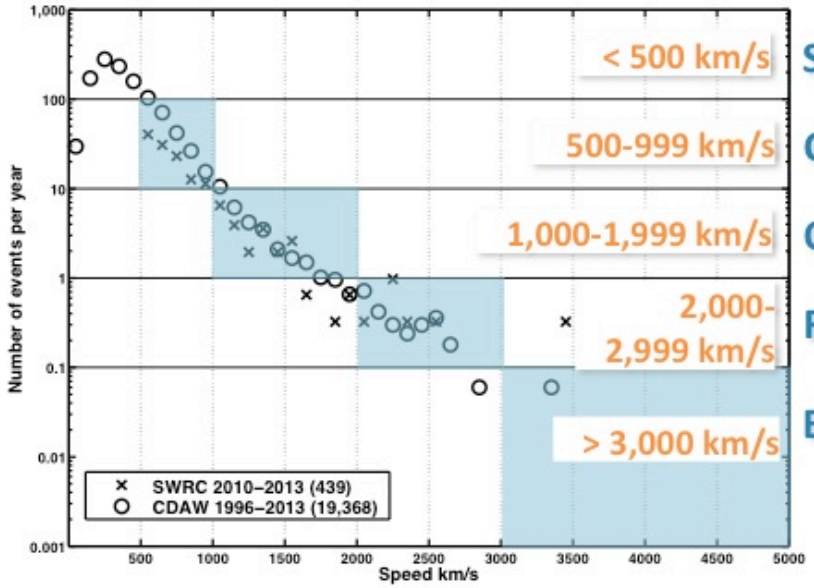
- Arrives to Earth in 1-2 days



CME SCORE

- A simple new category system for CMEs based on frequency of detection and speed
- Complements Flare Classes
- Applicable in space weather operations and research

Space Weather Research Center
CME SCORE Scale



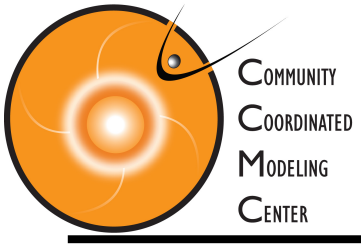
S-type

C-type (Common)

O-type (Occasional)

R-type (Rare)

ER-type (Extremely Rare)



SWx impacts of CME

- Contribute to SEP (particle radiation): 20-30 minutes from the occurrence of the CME/flare
- Result in a geomagnetic storm: takes 1-2 days arriving at Earth
- Result in electron radiation enhancement in the near-Earth space: takes 1-3 days

Affecting spacecraft electronics – surfacing charging/ internal charging, radio communication, navigation power grid, pipelines, and so on

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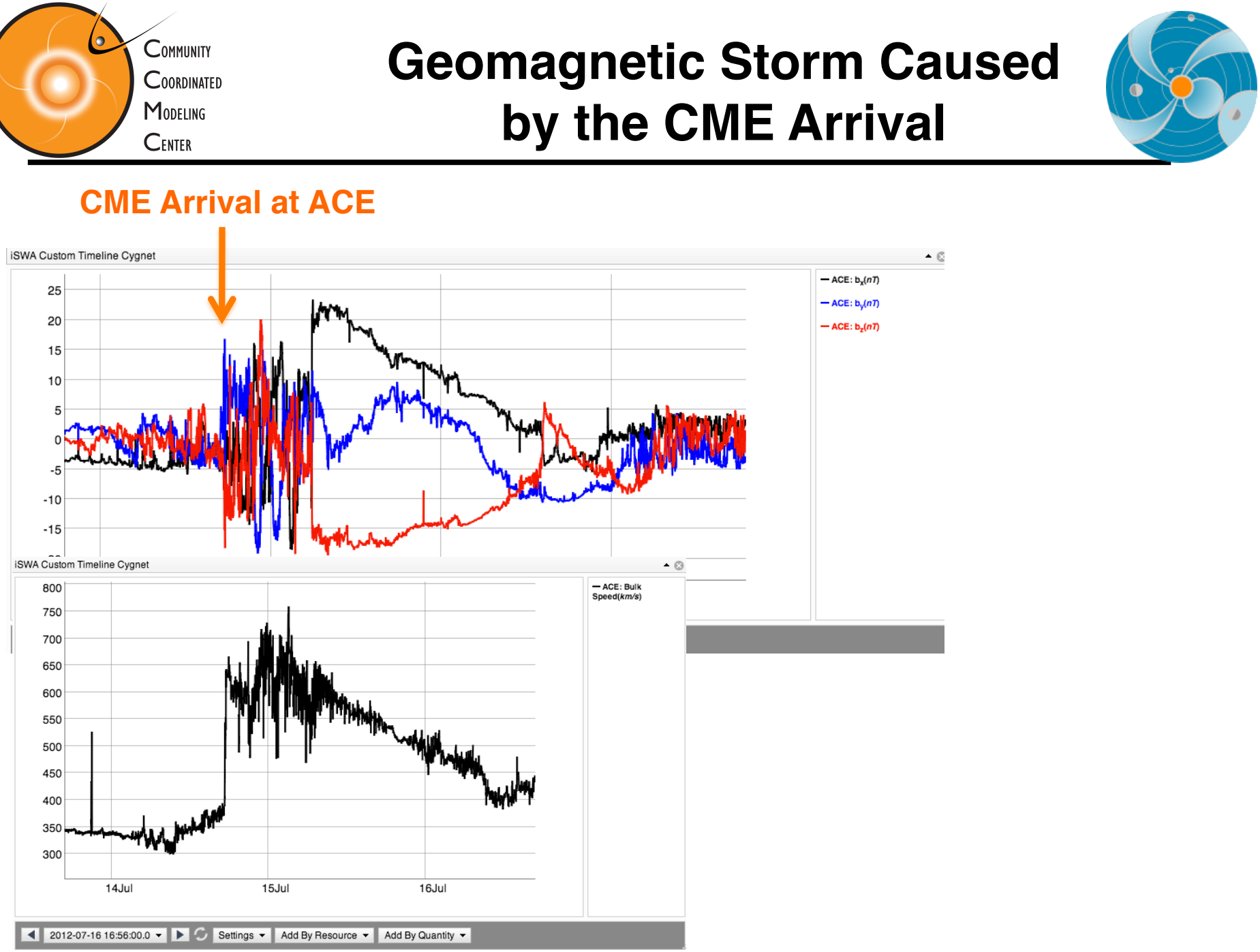
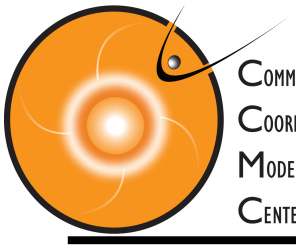
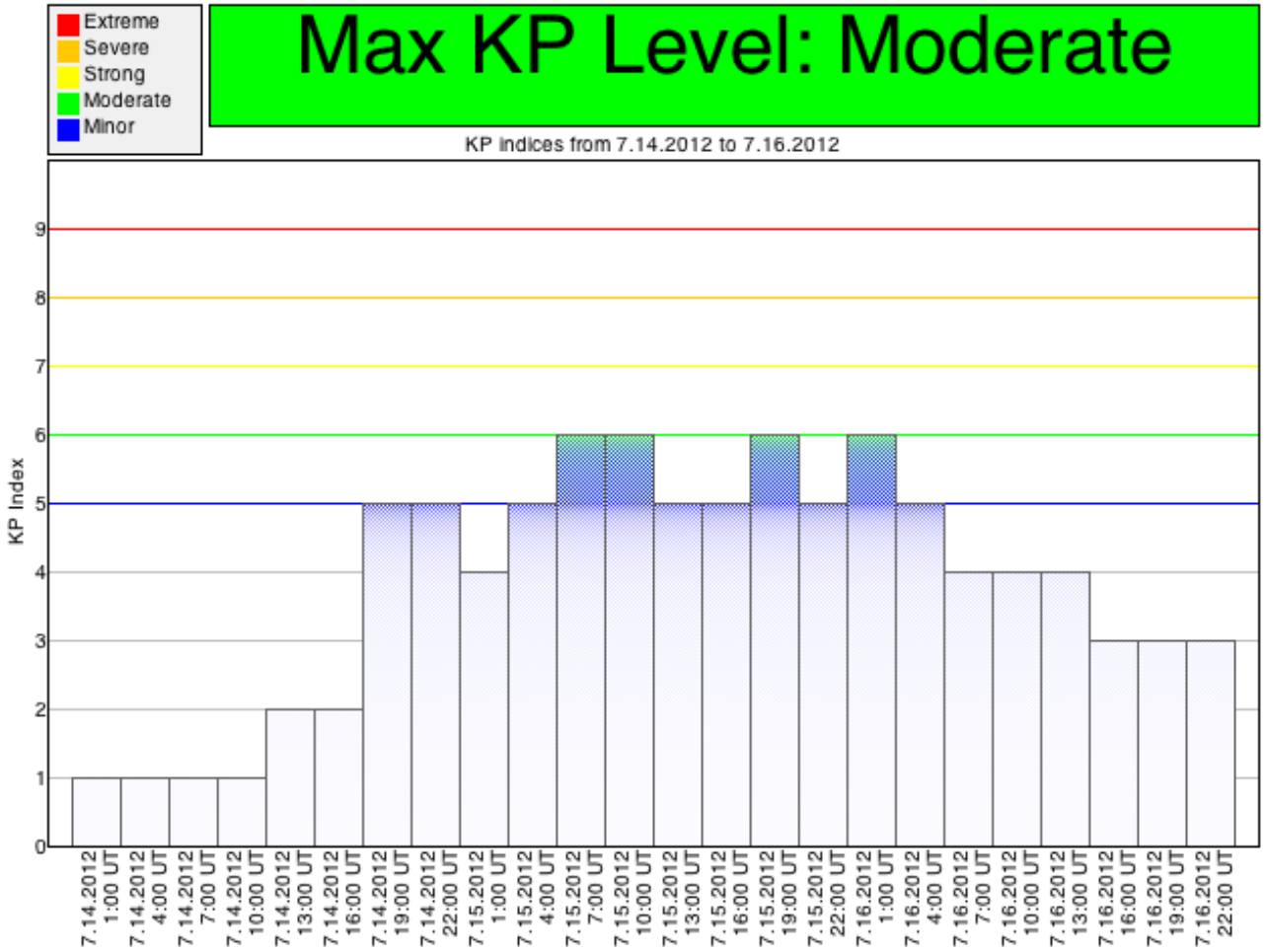
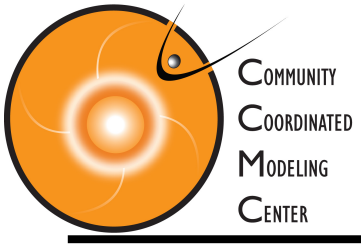
Geomagnetic Storm Caused by the CME Arrival





Geomagnetic Storm Caused by the CME Arrival





Physical Mechanism Behind the Flares and CMEs

It is believed that solar magnetic field, releases energy, accelerating solar plasma and causing flares and CMEs. Magnetic reconnection.

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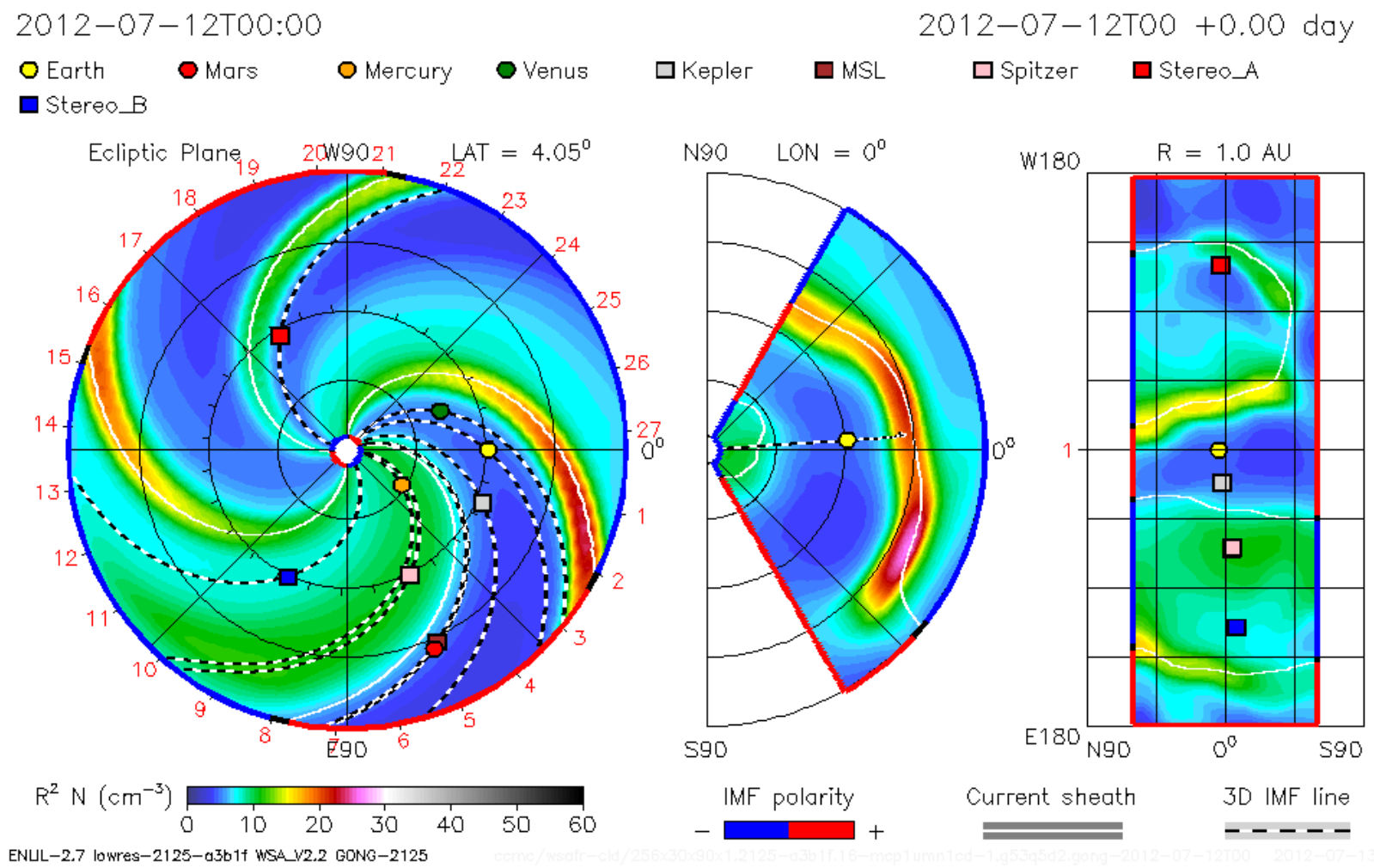
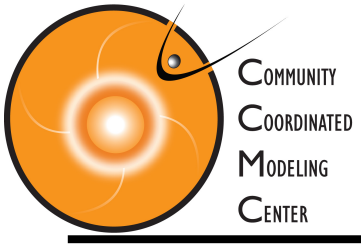
CME Modeling





Solar Energetic particles - 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!)

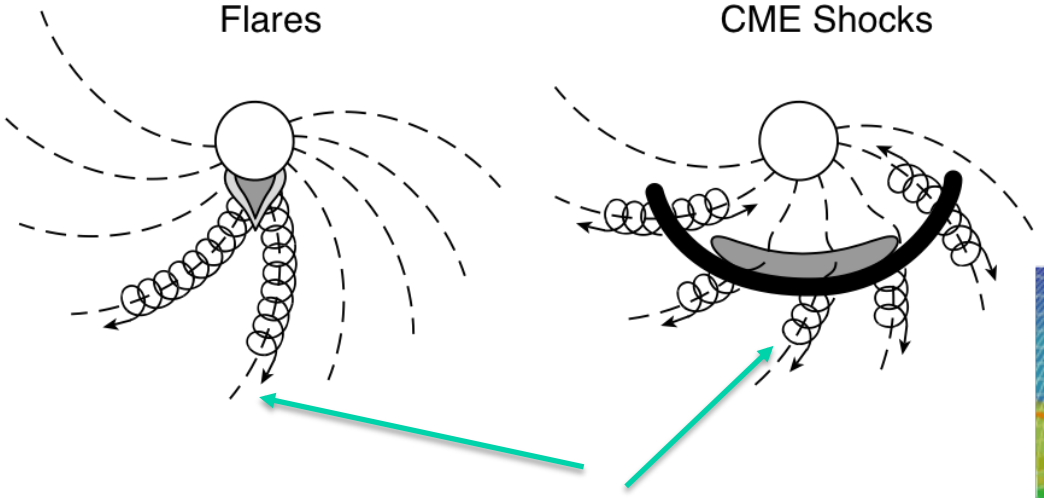
Energies: up to ~ GeV/nucleon

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

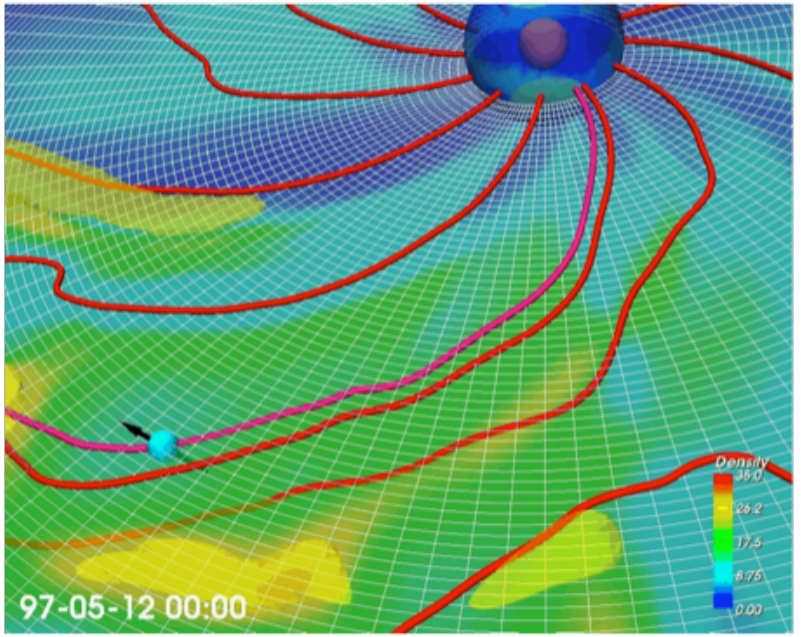
The term SEP usually refers to protons (even though “p” is particle)

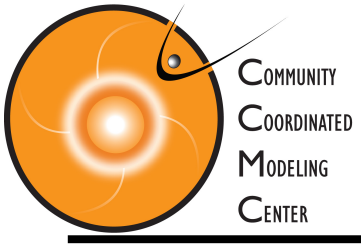
Flares, CMEs and SEPs and the Magnetic connectivity

When flare and CME occurs accelerated charged particles start to move along the interplanetary magnetic field lines.



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/cm^2/sec/sr)

- *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*

Fluence = flux integrated over the entire event - dose

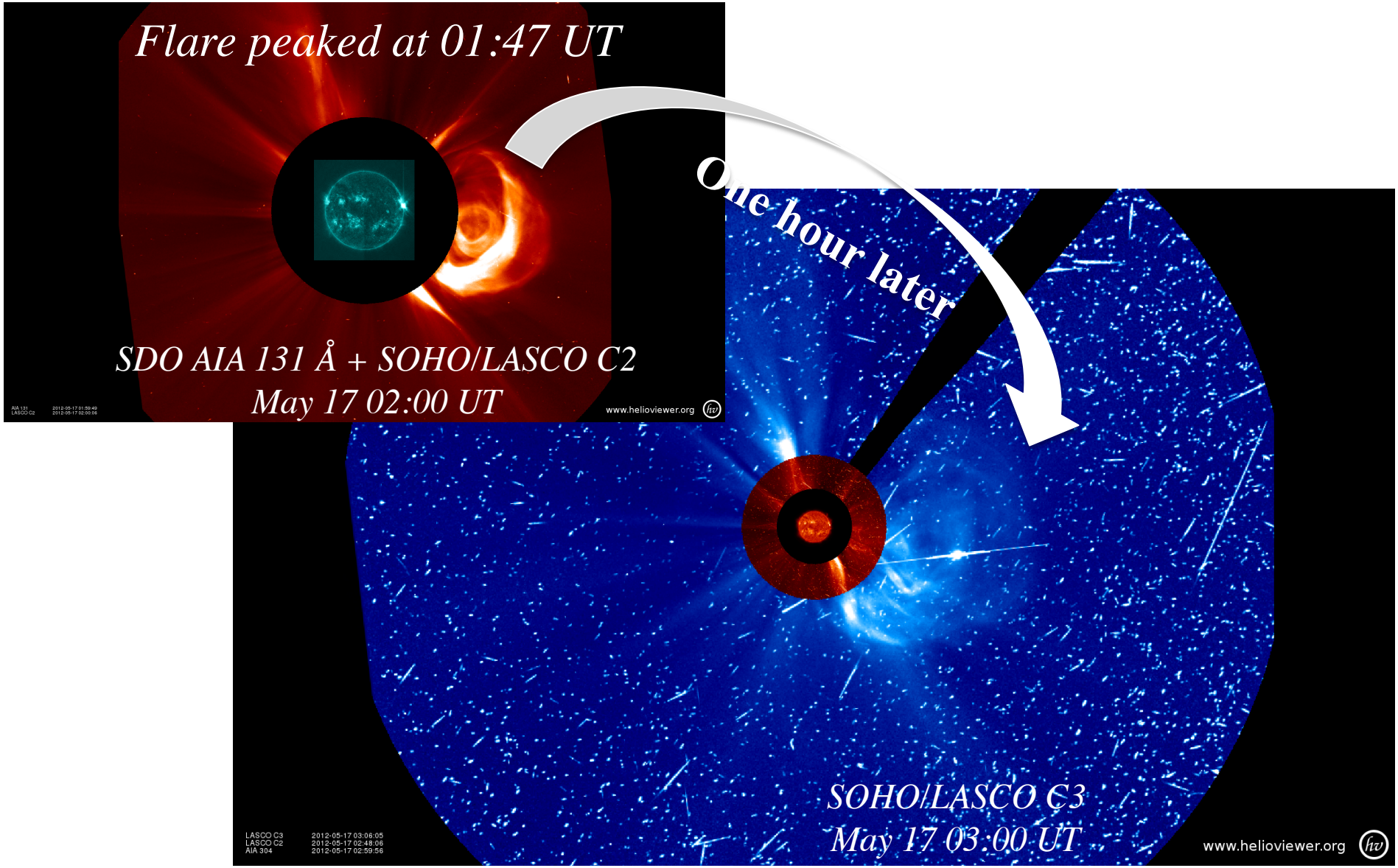
Important for biological effects (flights)

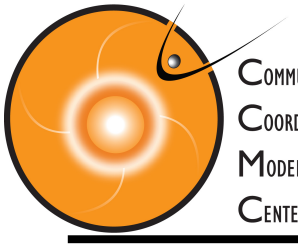
Event magnitudes:

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

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

Coronagraph acting as particle detector – SNOW!





How do we define an SEP Event?

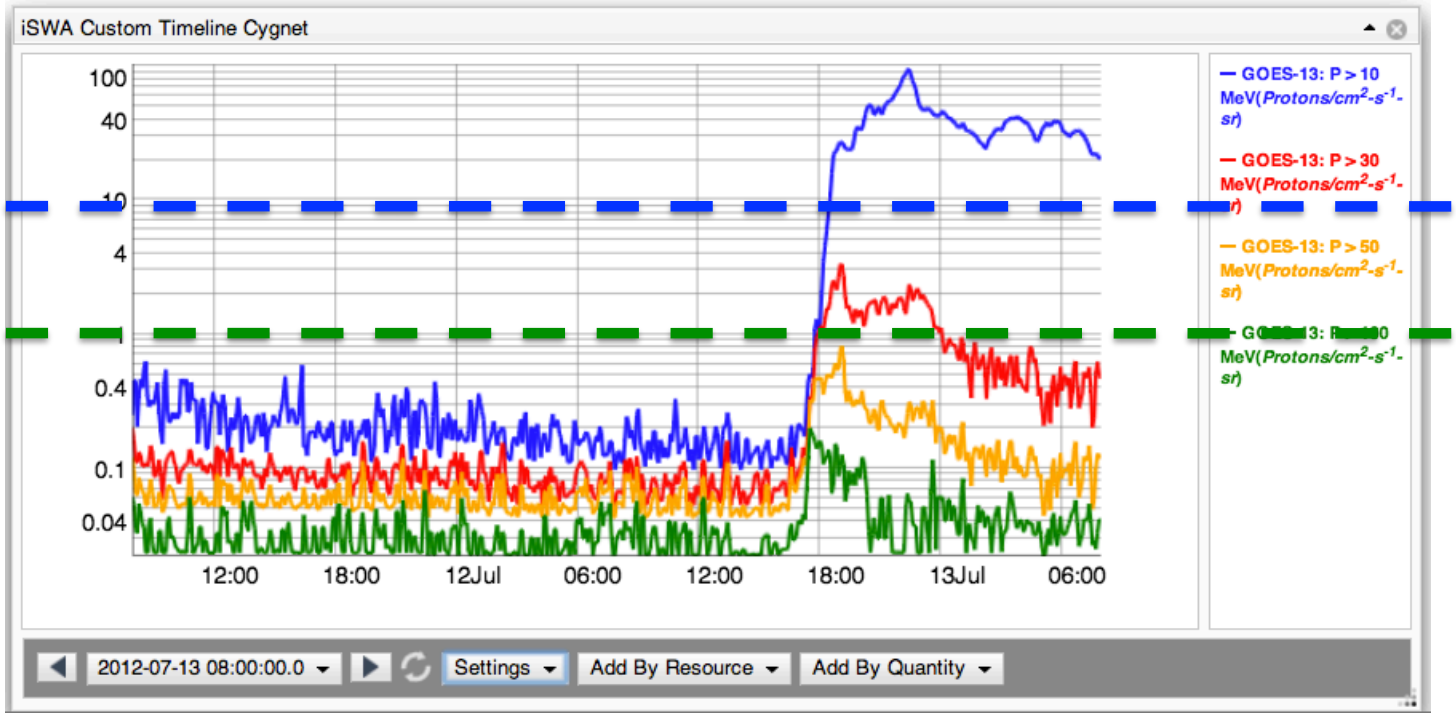
At the SWRC, SEP events are defined as:

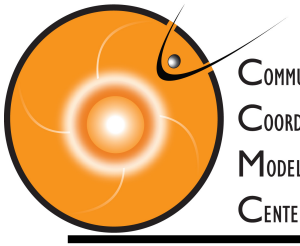
GOES Proton E > 10 MeV channel > 10 pfu

GOES Proton E > 100 MeV channel > 1 pfu

SOHO Proton, >15.8 MeV channel > 0.1 pfu/MeV

STEREO Impact 13-100 MeV channel > 0.1 pfu/MeV

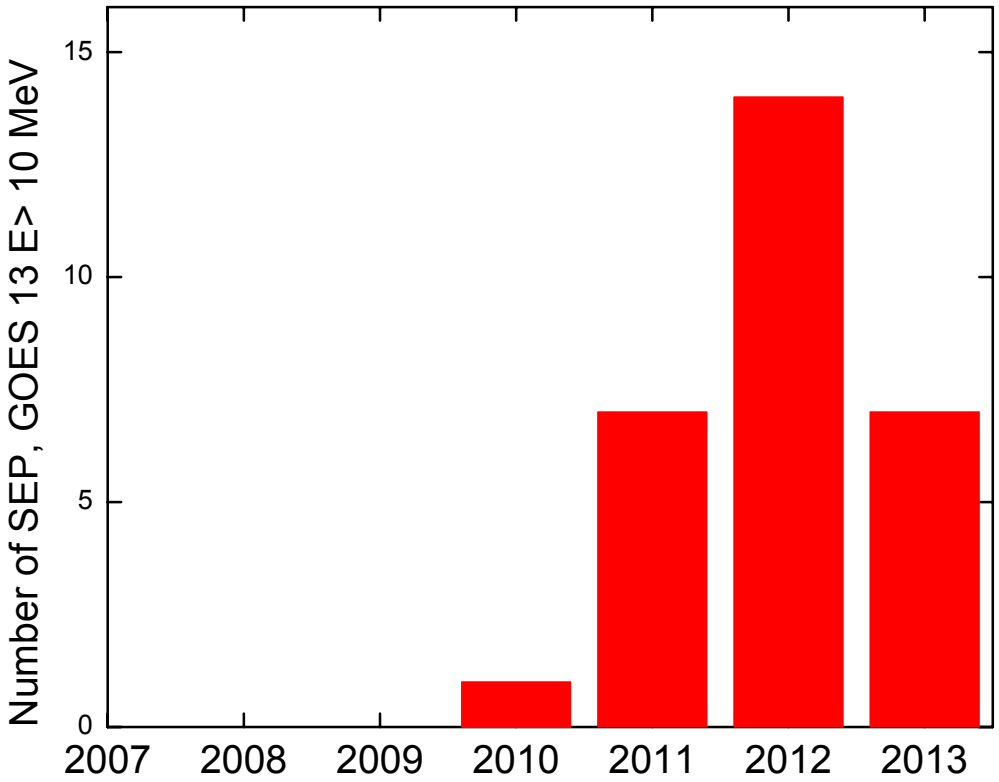




How Often Do SEP Events Occur?

SEP event detections in the near-Earth environment

(GOES 13, Proton E > 10 MeV channel)



2007-2009:
Zero Events –
Solar Minimum

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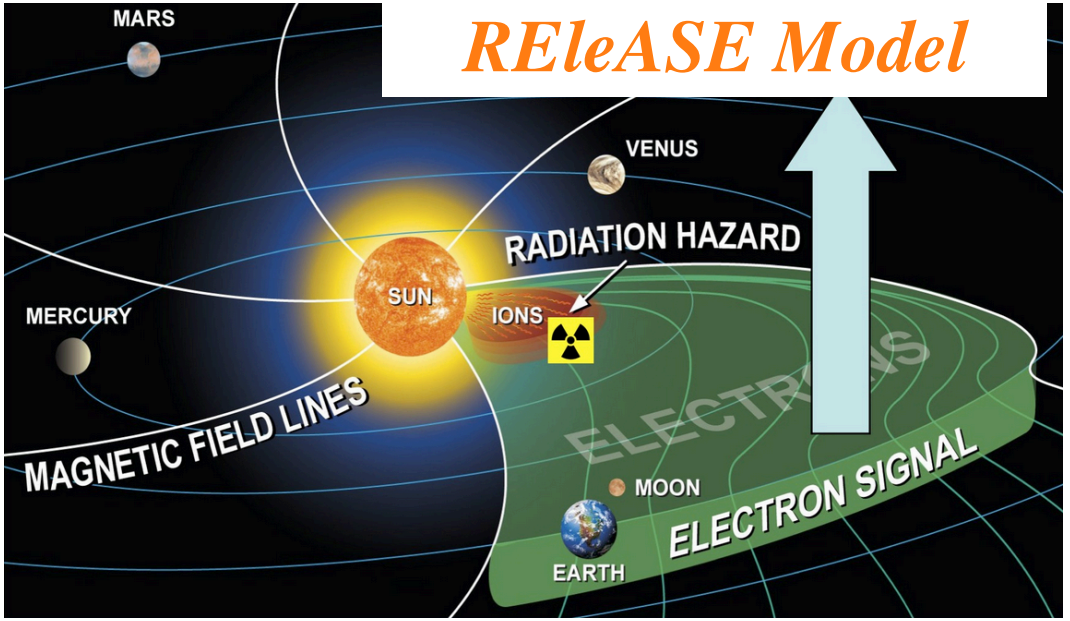
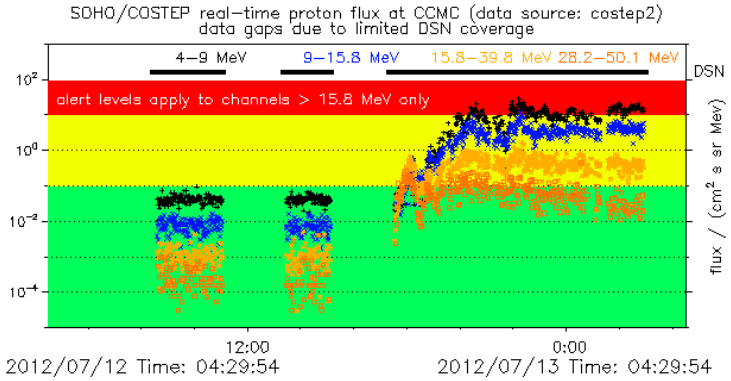
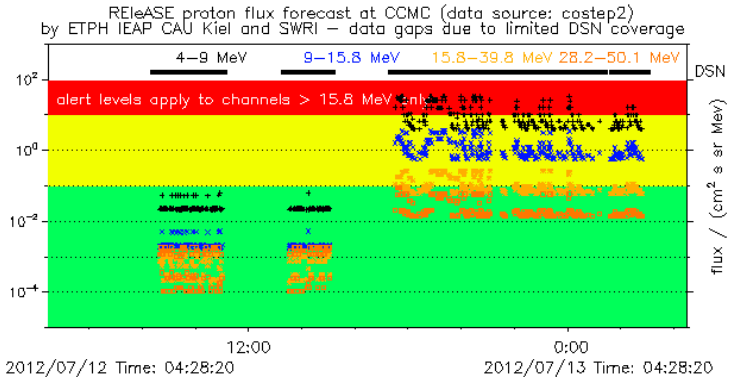
Can we forecast SEP events?

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

Data source: SOHO/ COSTEP







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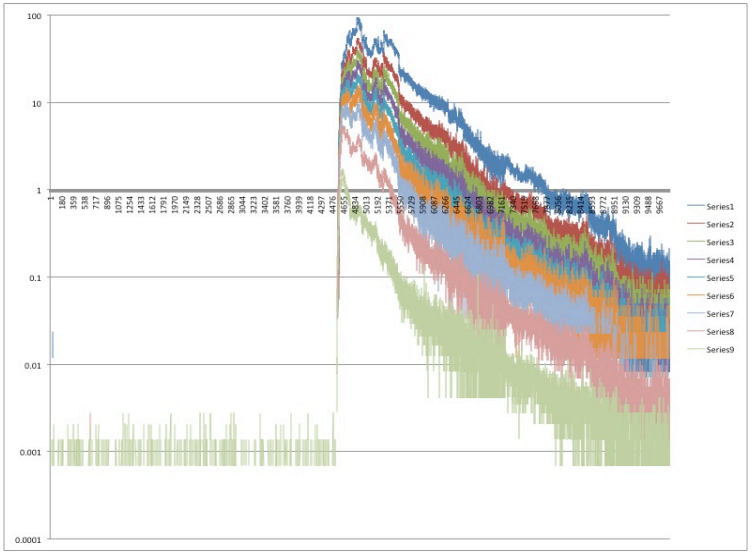
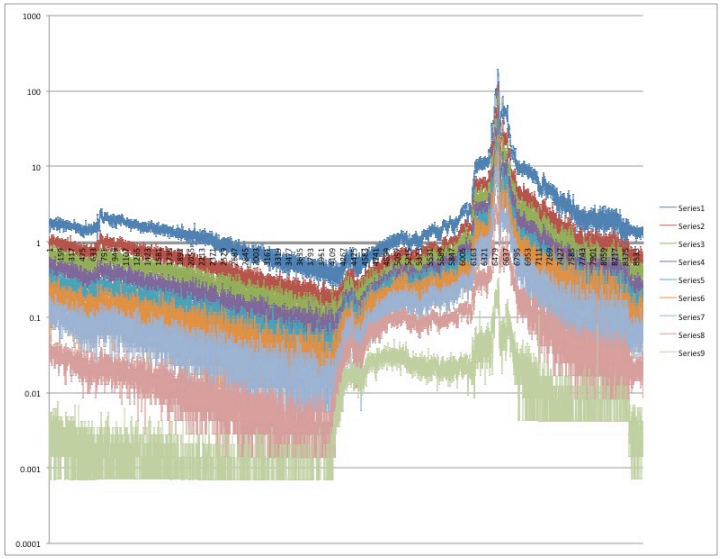
Profile Shapes of SEP Fluxes

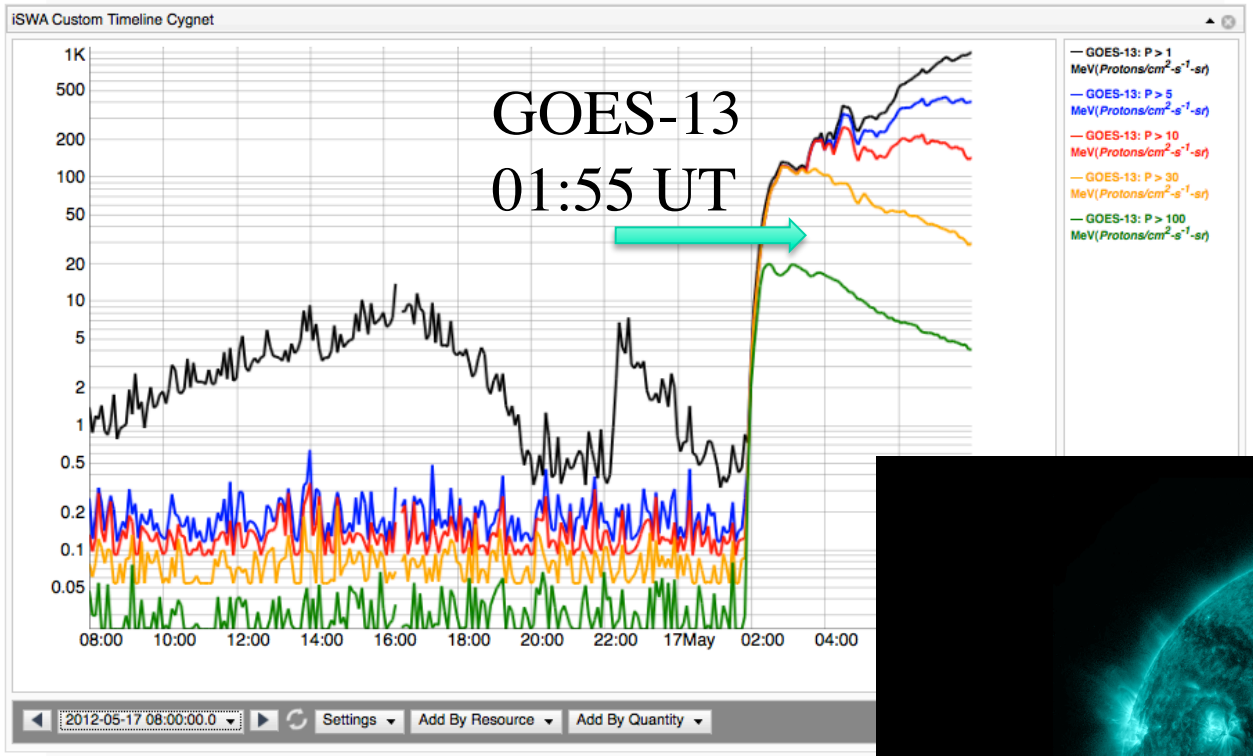


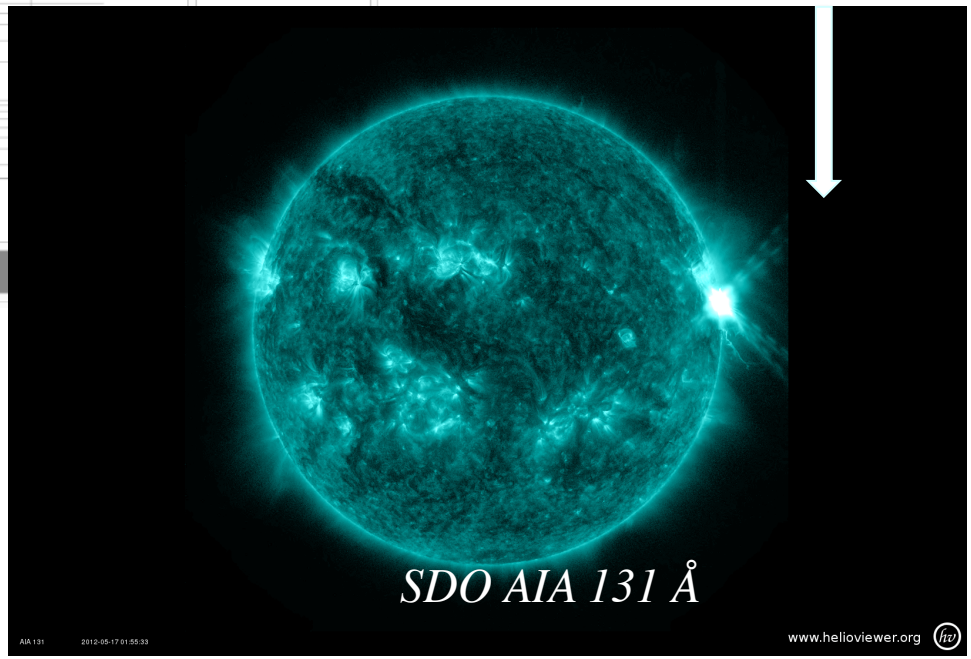
Impulsive SEP event - The peak at the beginning due to flare, all off – indicates how well connected you are to the source (timing)

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



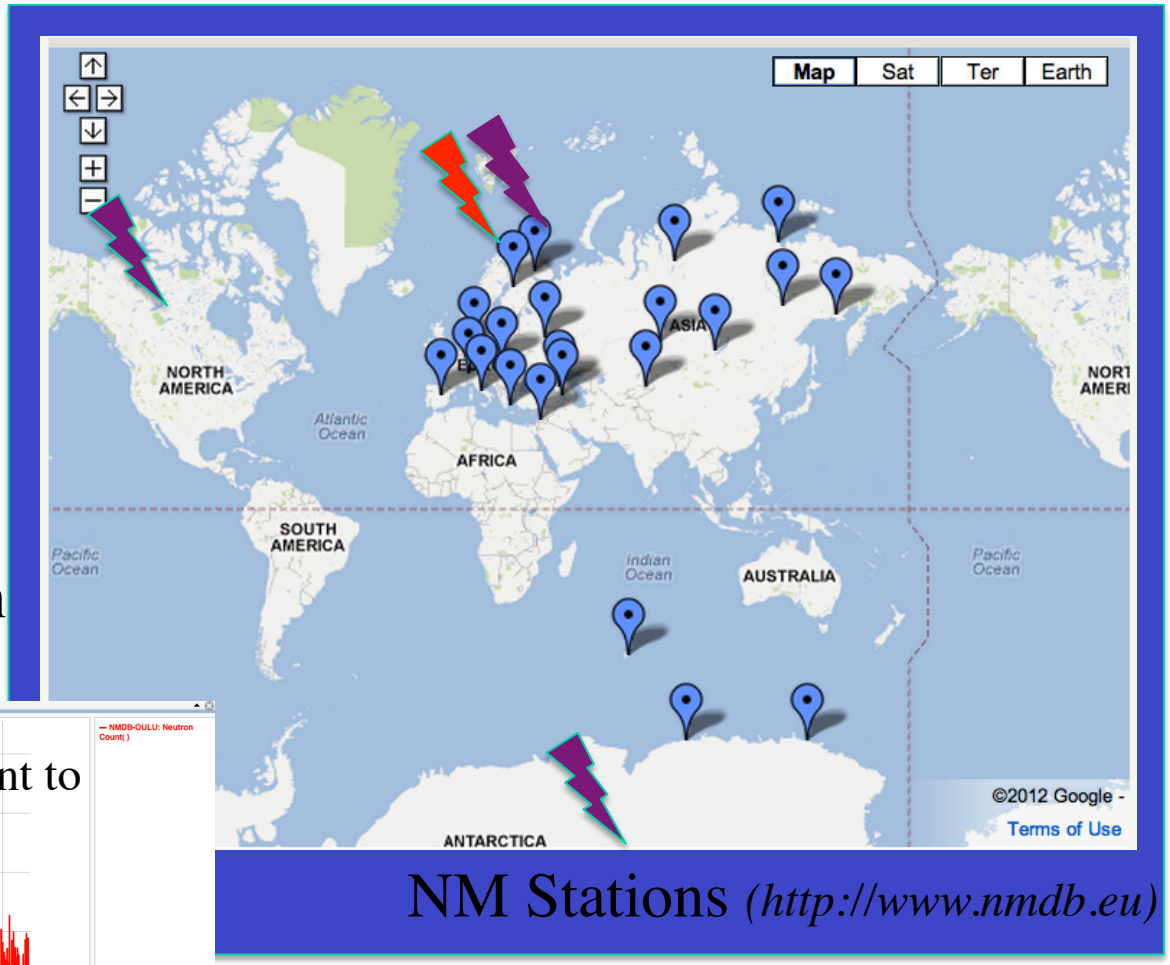
For Earth – Best Connection is Western Limb





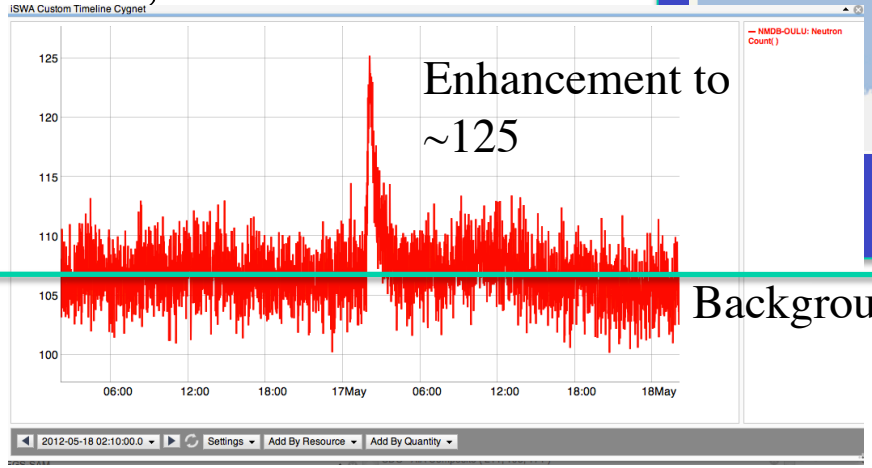
Energetic proton fluxes elevated for >12 hours

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.



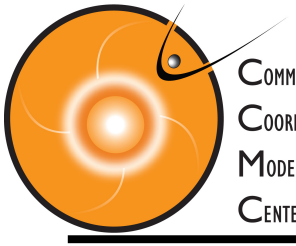
NM Stations *(http://www.nmdb.eu)*

Neutron Monitoring Station in Oulu, Finland



Enhancement to ~125

Background ~105



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)

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

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