Solar energetic particles and coronal interplanetary radio bursts

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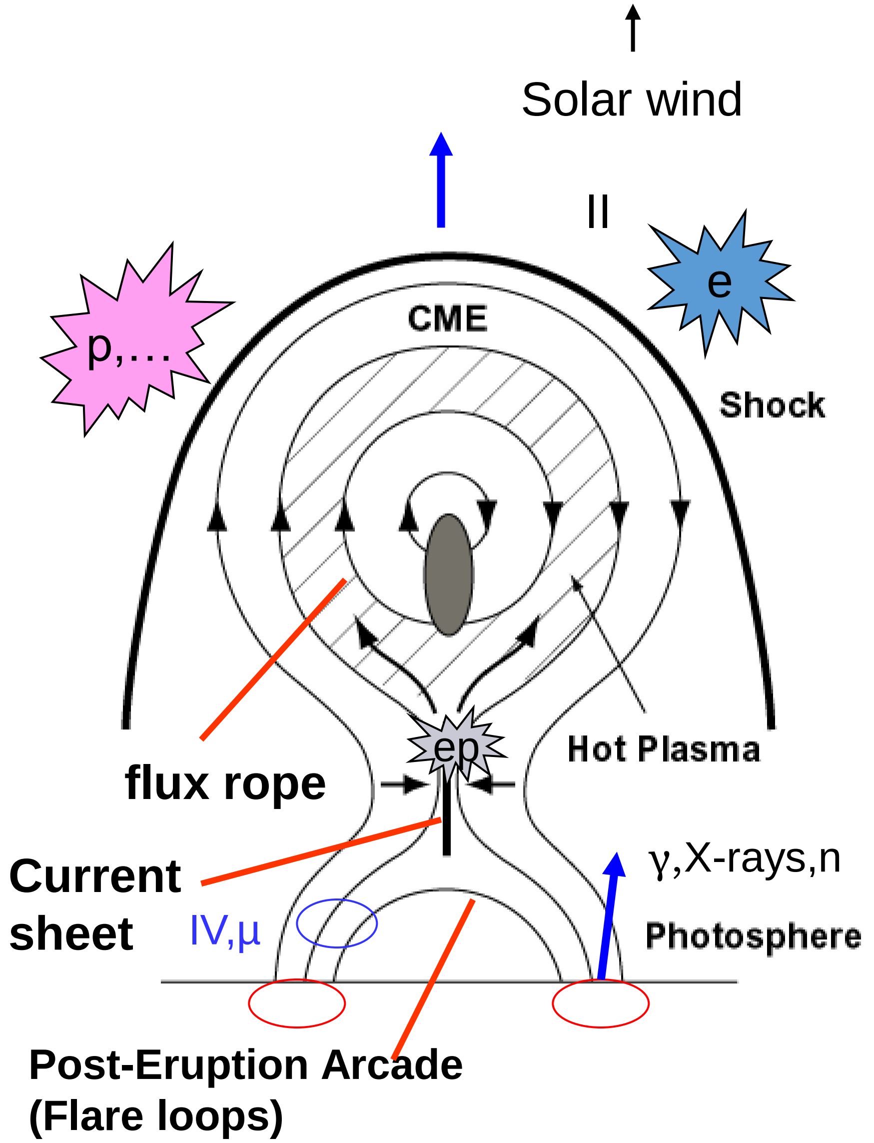
Particle Energization Sites

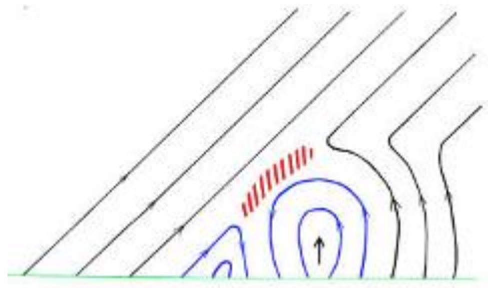
Energy release on the Sun
Solar eruptions
Noise storms
SEPs (ions, electrons)
In situ detection of particles
Inferred from electromagnetic emission

Electrons KeV to 100s of MeV, protons of keV to tens of GeV from the Sun

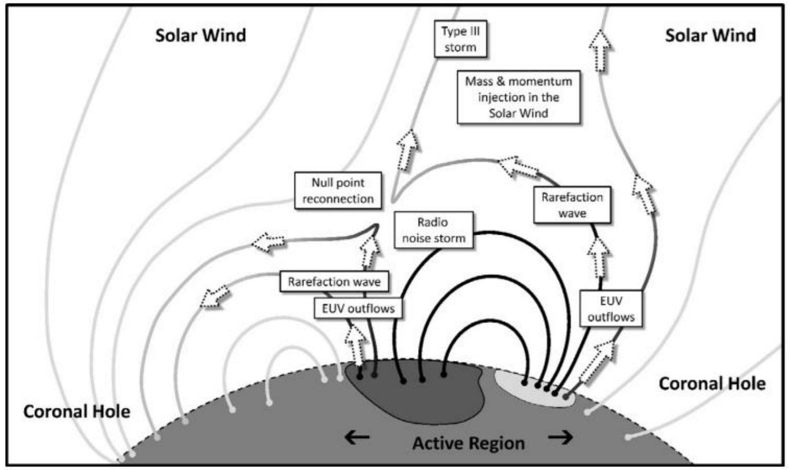
Coronal thermal particles have an energy of ~175 eV



Gopalswamy 2006

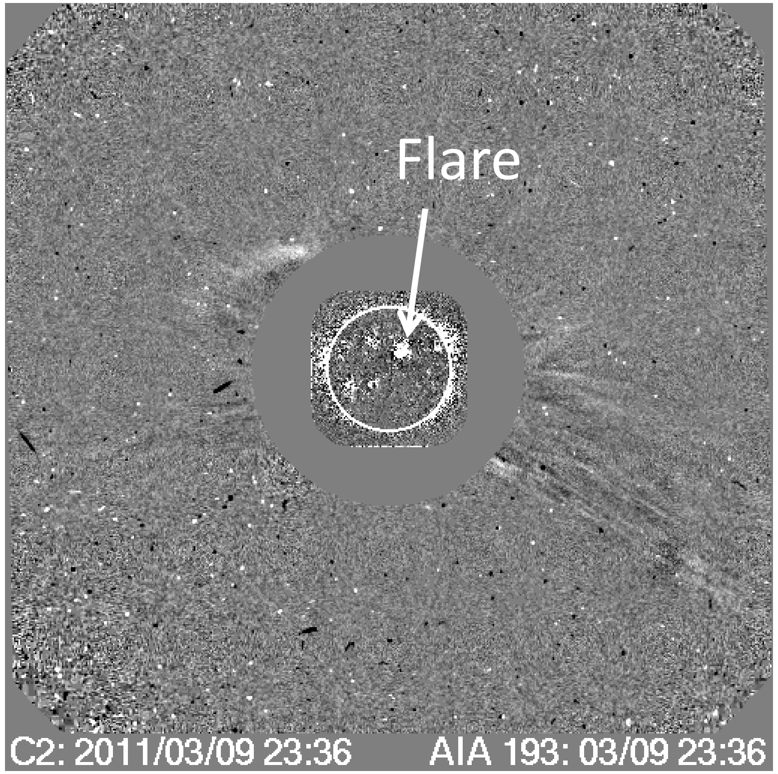


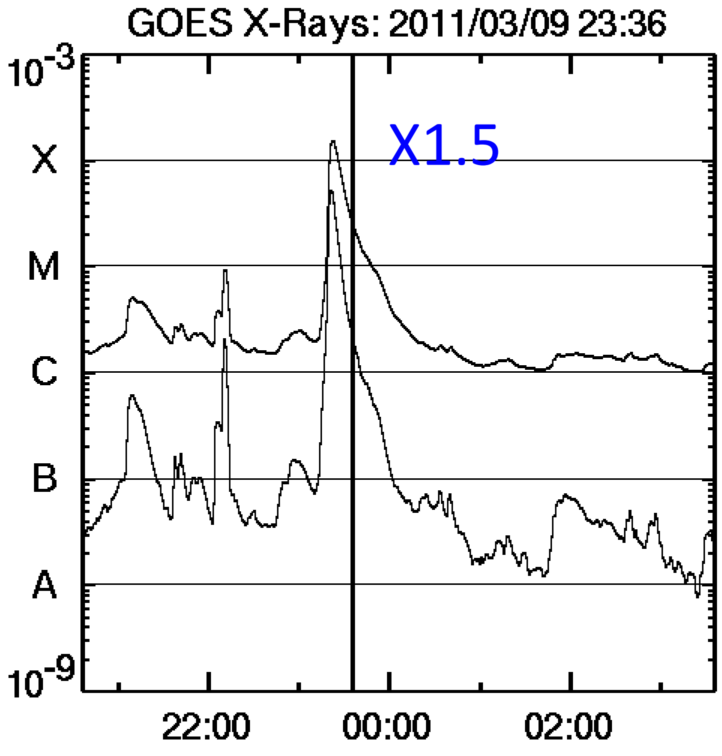
impulsive SEP events associated with jets
Jets are similar to CMEs, except open field line are involved

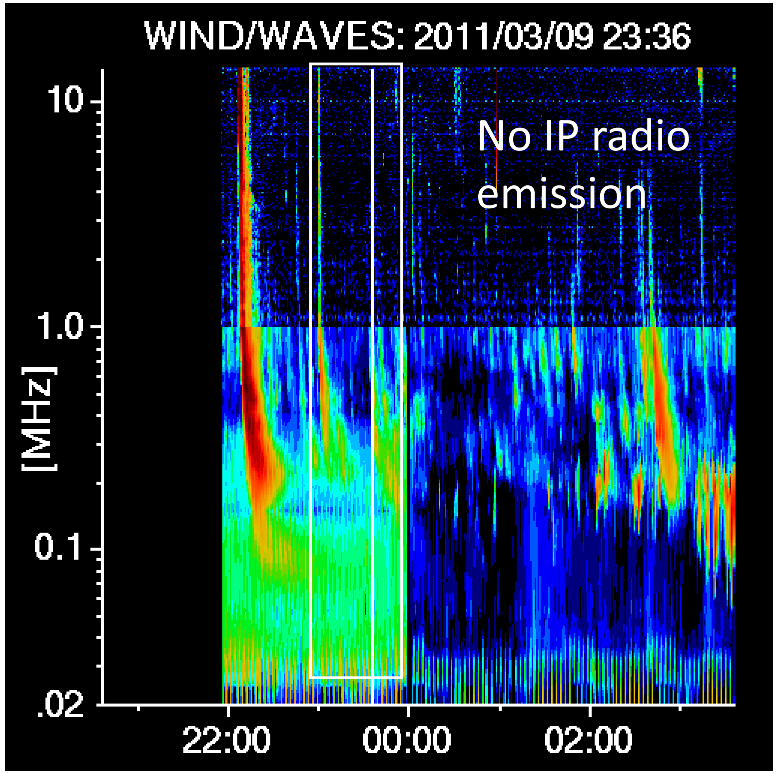


Del Zanna et al. 2011

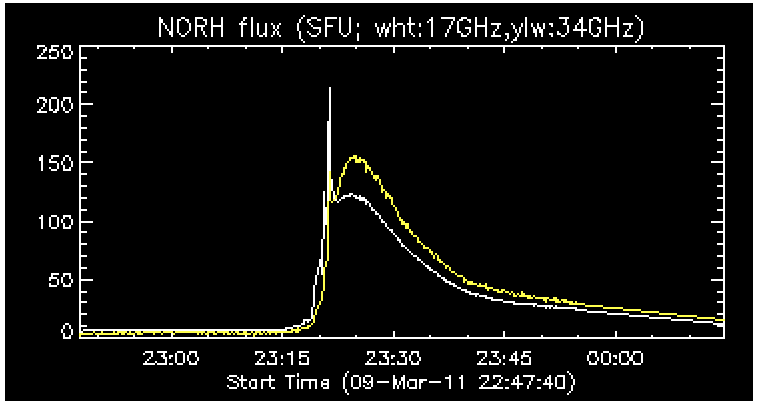
Confined Flare: No mass motion

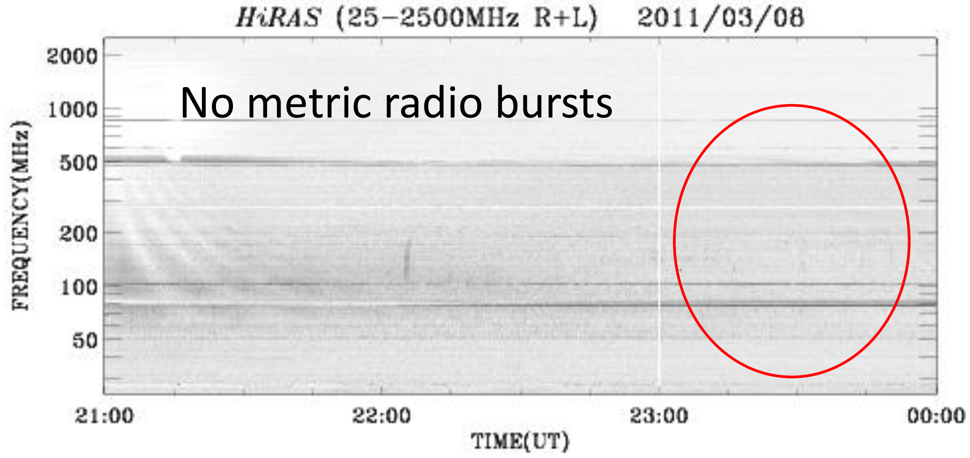




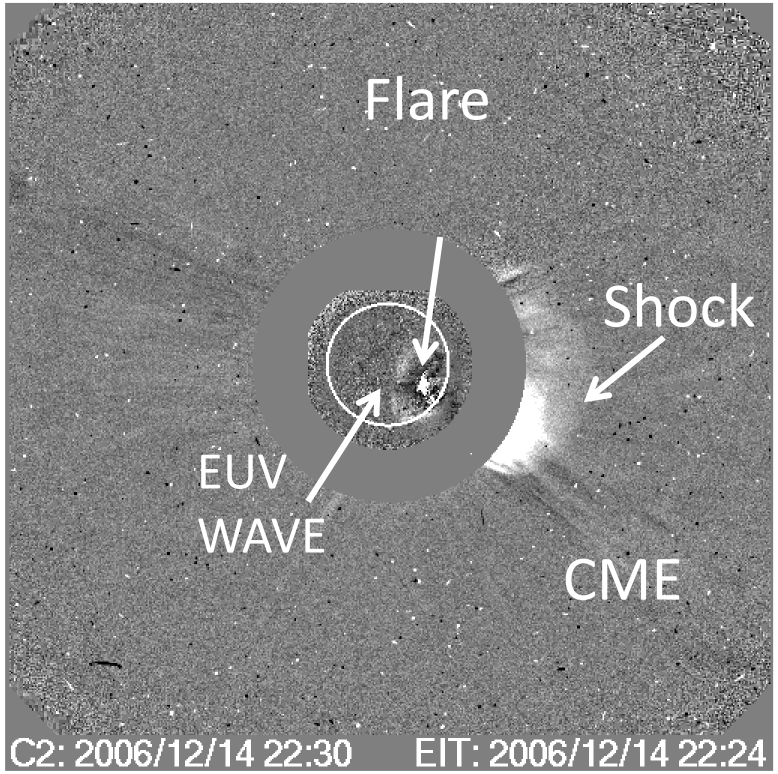


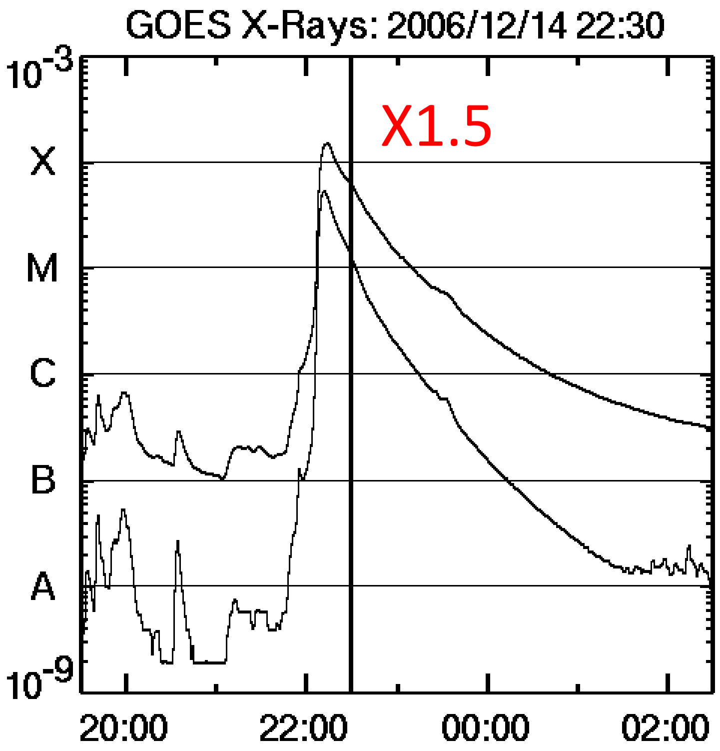
- Microwave burst, X-rays → nonthermal electrons propagating toward the Sun
- No metric radio bursts → no electrons away from the Sun
- No Interplanetary radio emission
- No SEP event

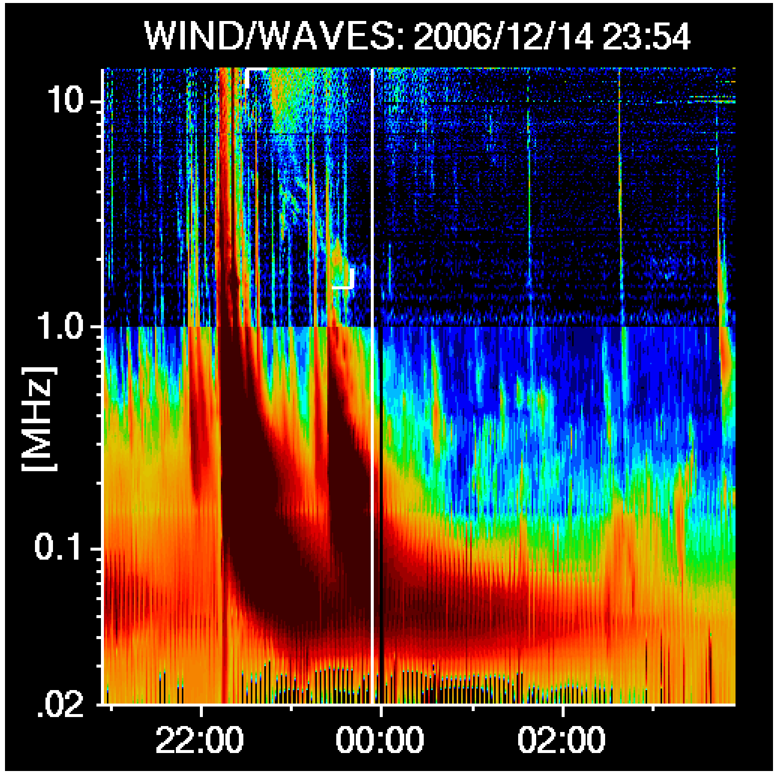




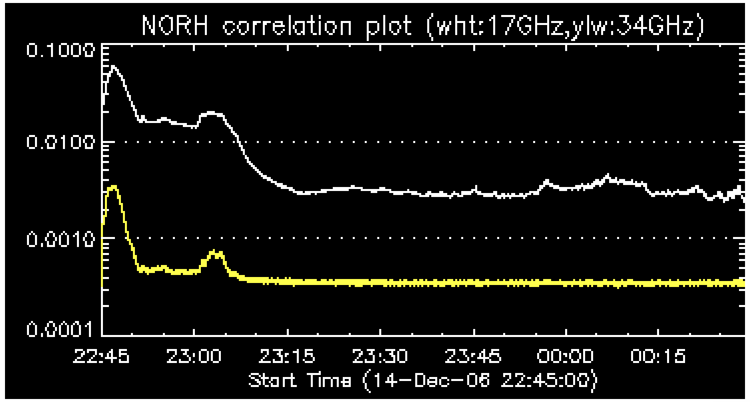
Eruptive Flare: CME involved

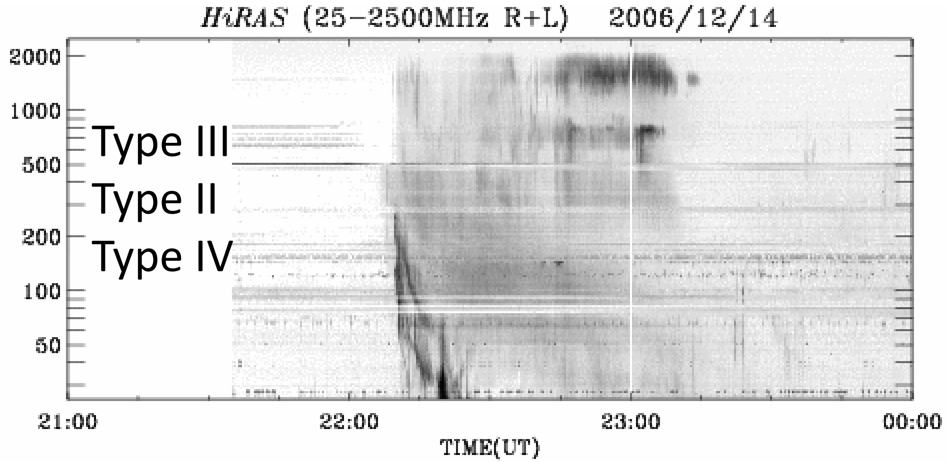




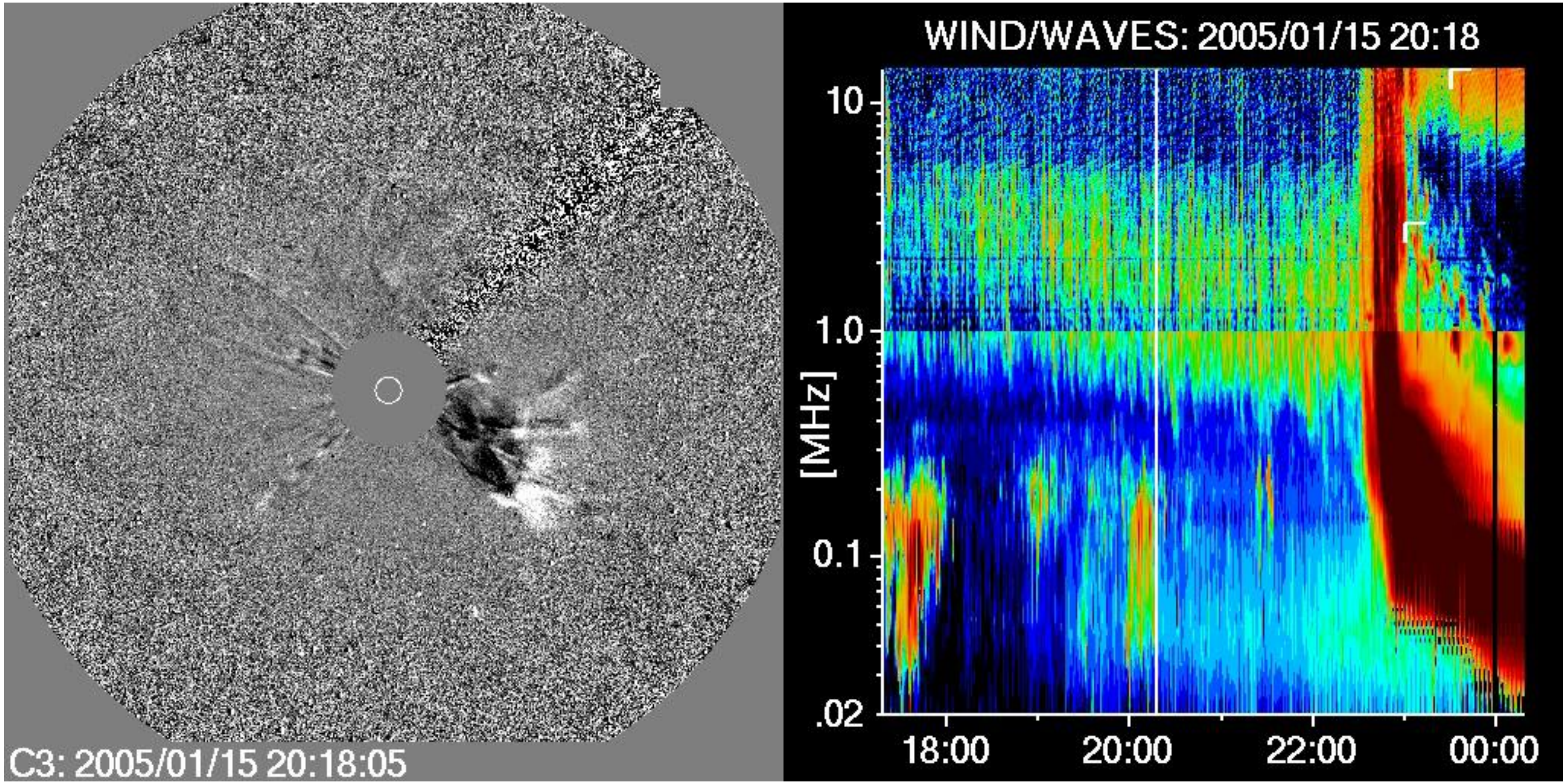


- Radio bursts → nonthermal electrons propagating away from the Sun
- X-ray emission → electrons propagating toward the Sun
- Interplanetary type II
- Large SEP event



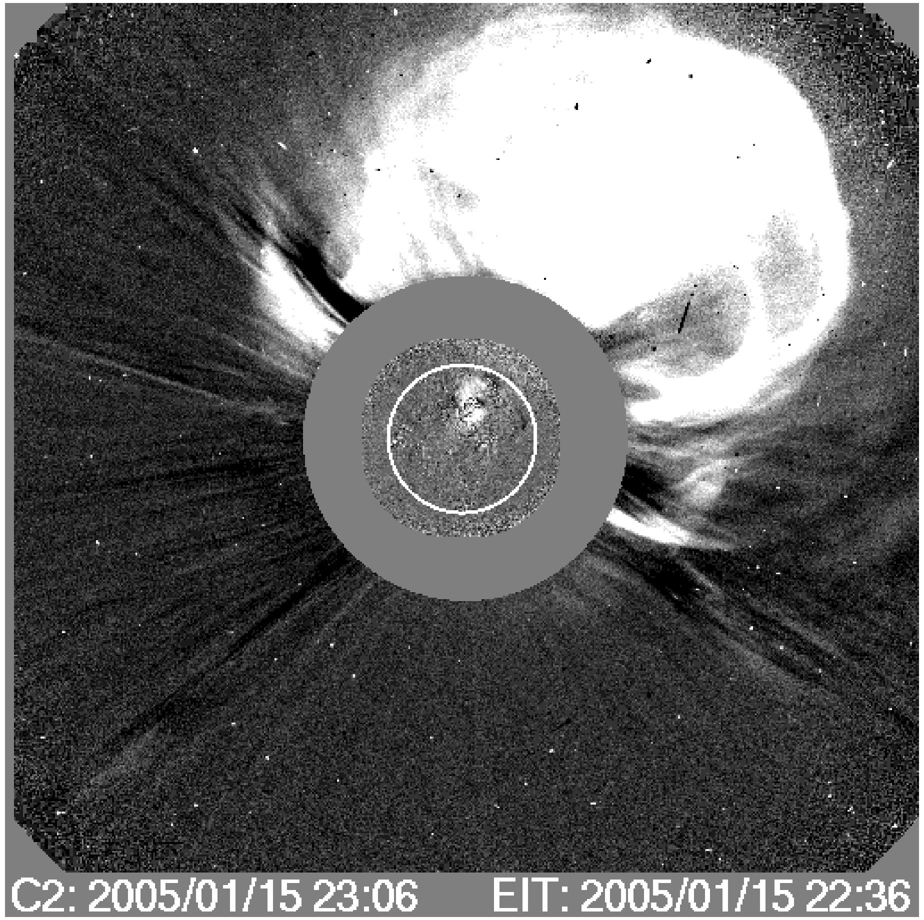


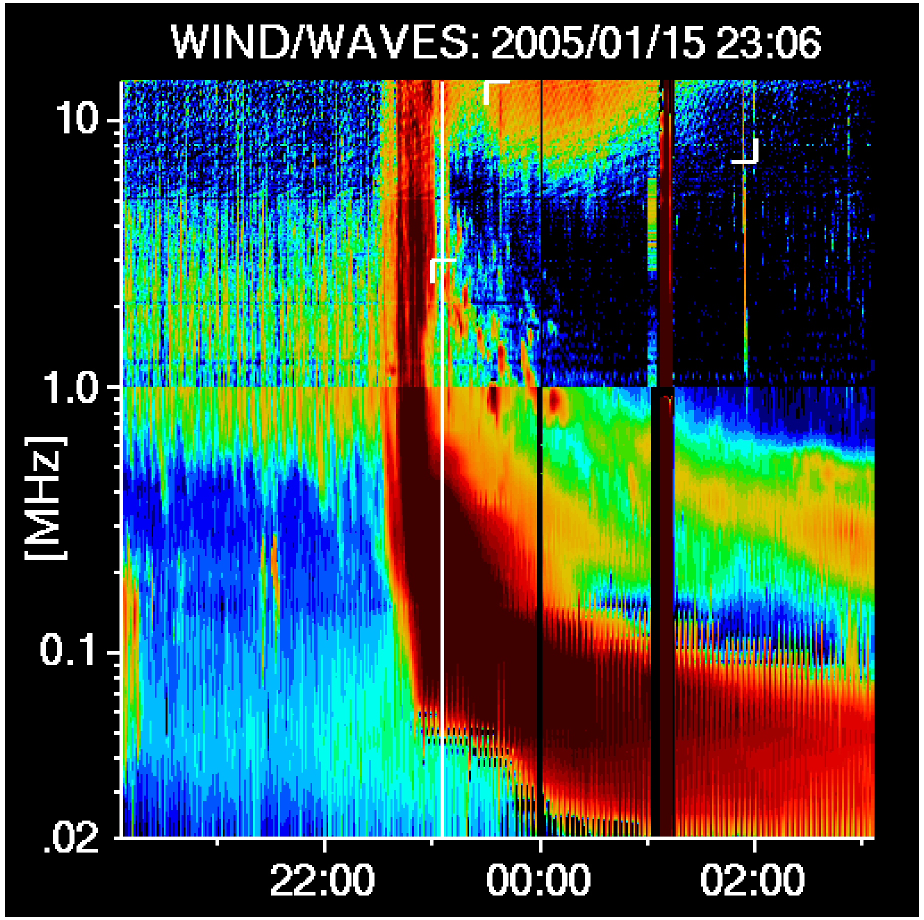
Interplanetary Shock and Radio Burst

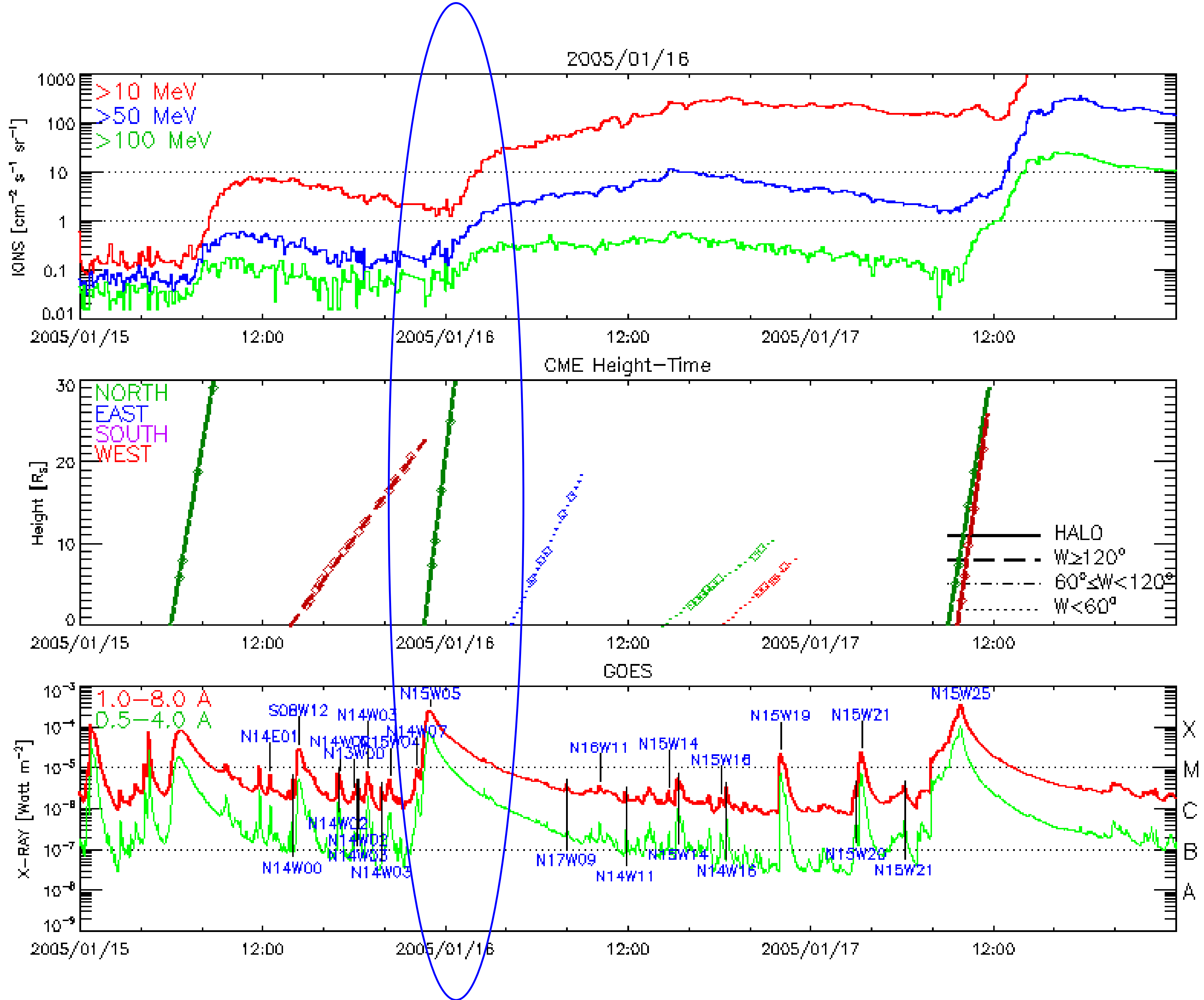


Cane et al. 1987; Reiner et al. 1997; Bougeret et al. 1998; Gopalswamy et al. 2001; 2004; 2005, 2011

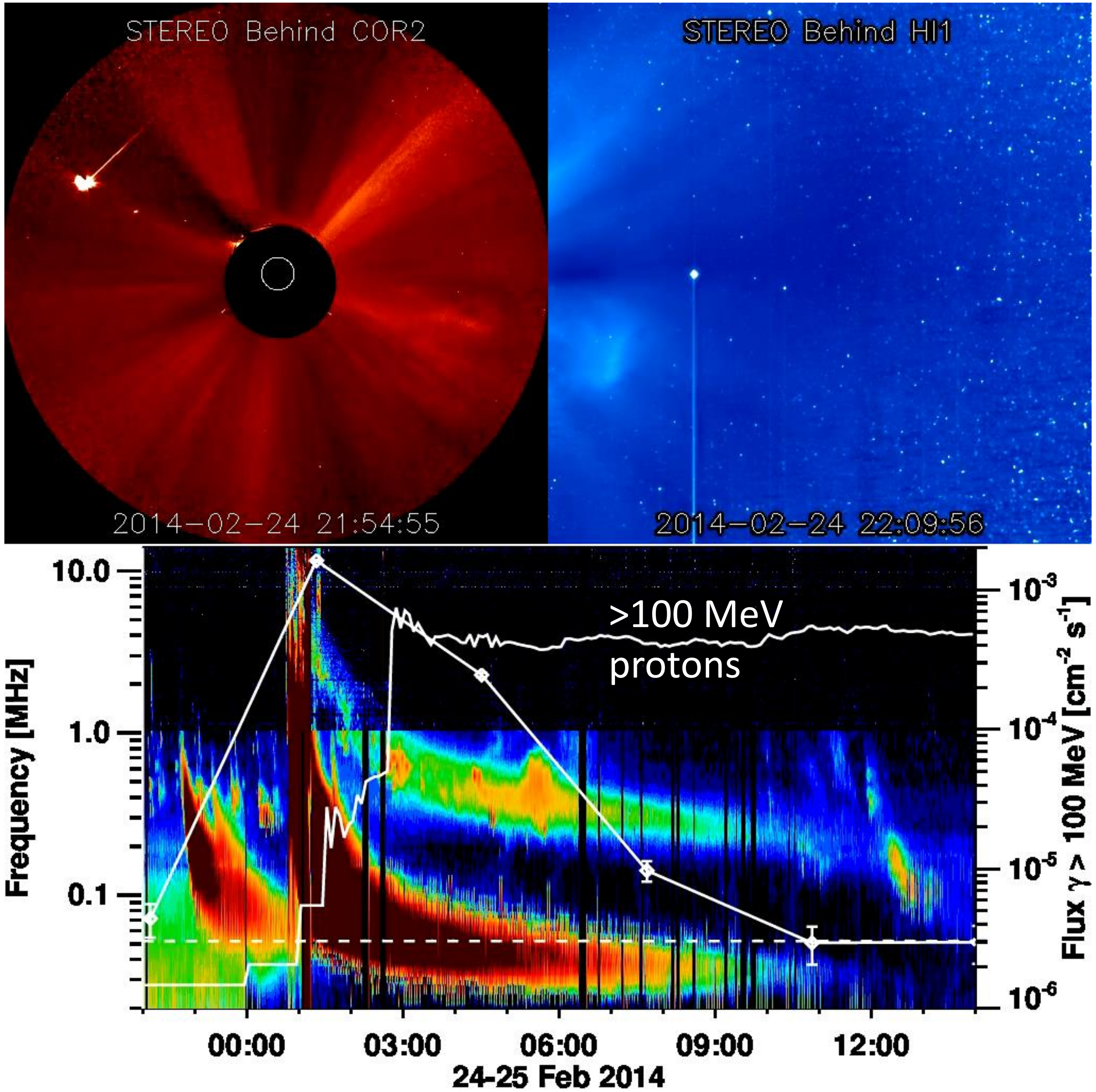
CME & IP radio bursts



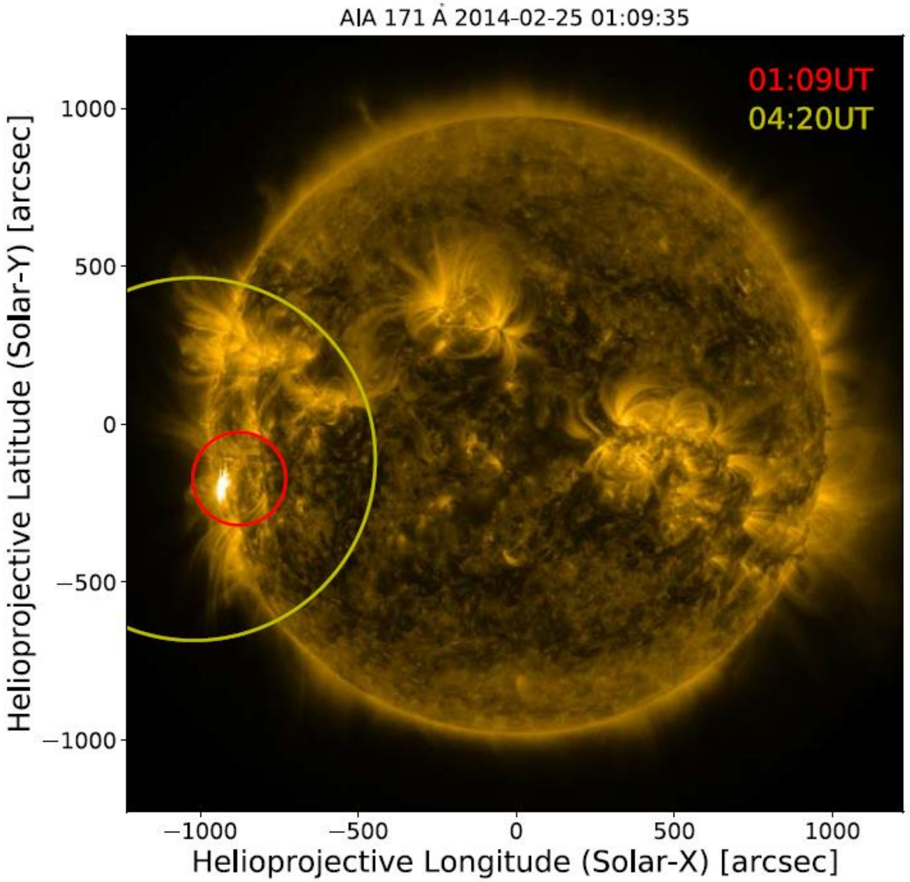



2005/01/16
>10 MeV
>50 MeV
>100 MeV
IONS [cm^-2 s^-1 sr^-1]
1000
100
10
1
0.1
0.01
2005/01/15
12:00
2005/01/16
12:00
2005/01/17
12:00
CME Height-Time
NORTH
EAST
SOUTH
WEST
Height [Rs]
30
20
10
0
HALO
W≥120°
60°≤W<120°
W<60°
GOES
1.0-8.0 A
0.5-4.0 A
X-RAY [Watt m^-2]
X
M
C
B
A
N15W05
S08W12
N14W03
N14E01
N14W07
N15W04
N13W00
N16W11
N15W14
N15W18
N15W19
N15W21
N15W25
N14W02
N14W00
N14W03
N17W09
N14W11
N15W14
N14W18
N15W20
N15W21

- SGRE ends when Type II ends
- CME at ~65 Rs when type II & SGRE end
- Large distances also indicated by the ending frequency of type II (~200 kHz)
- Copious >100 MeV particles from STEREO-B

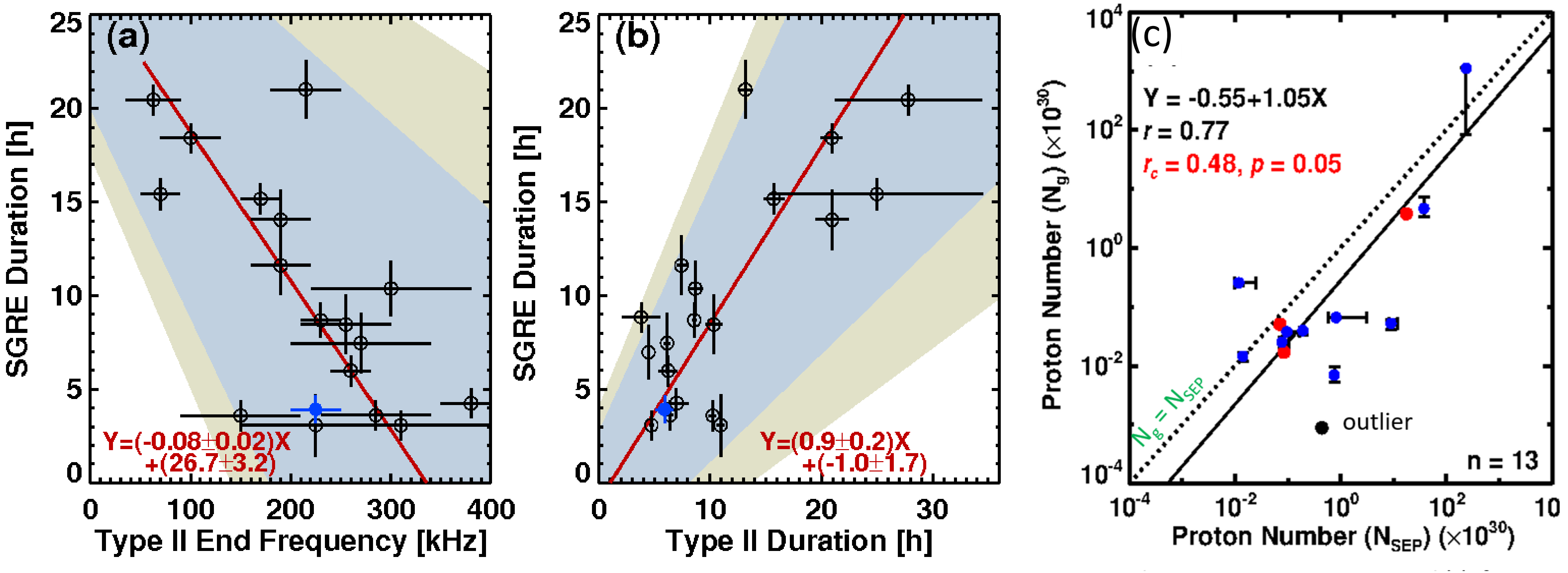


Gopalswamy+ 2018

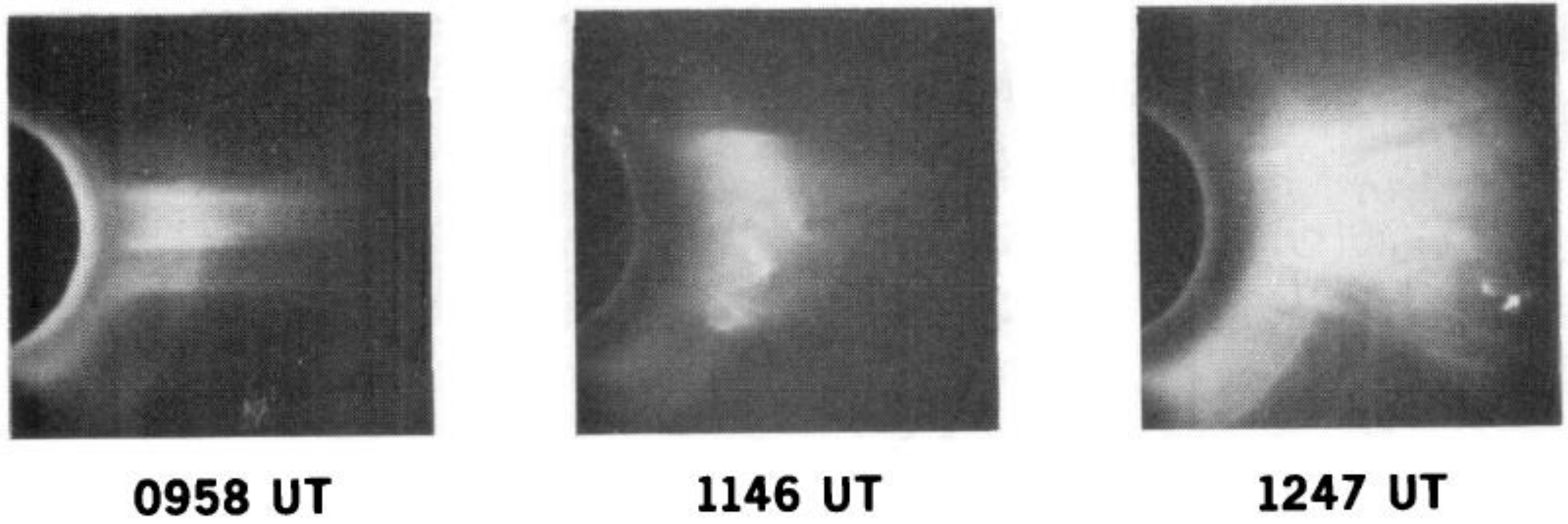


Ajello+ 2021

Type II burst, SEP Event, and SGRE Events linked by CME-driven shocks



Gopalswamy et al. 2018; 2021

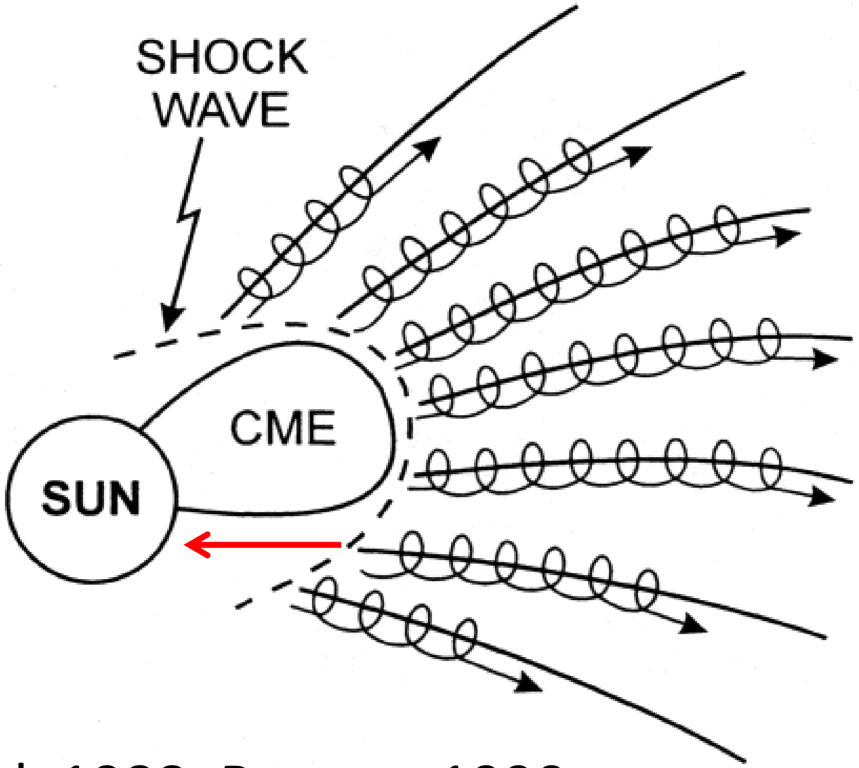


S. W. Kahler

Skylab CME on January 15, 1974

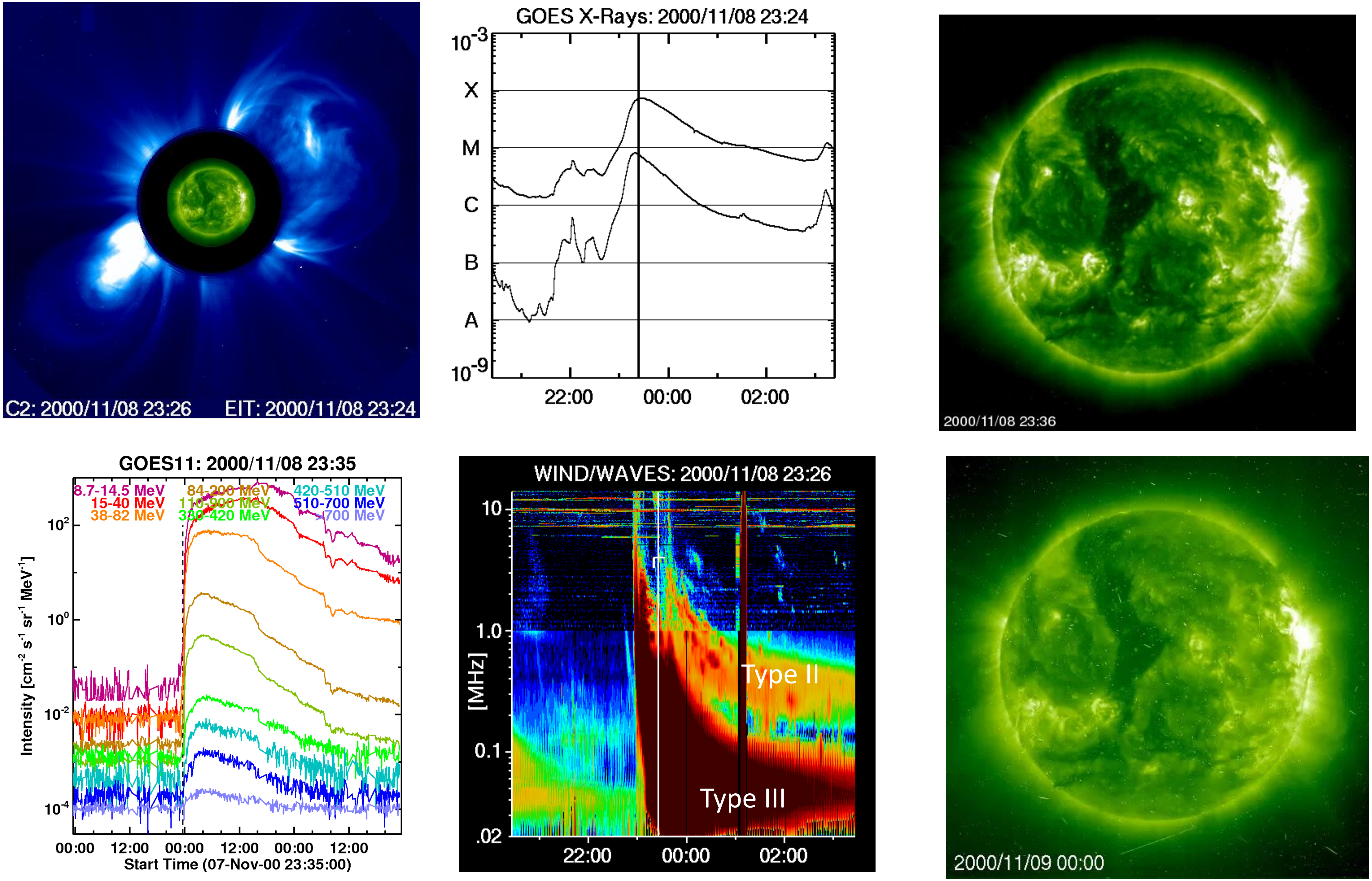
Studied 16 Skylab CMEs; 14 had SEP events
Found correlation between CME speed and SEP intensity

"We suggest that energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections"



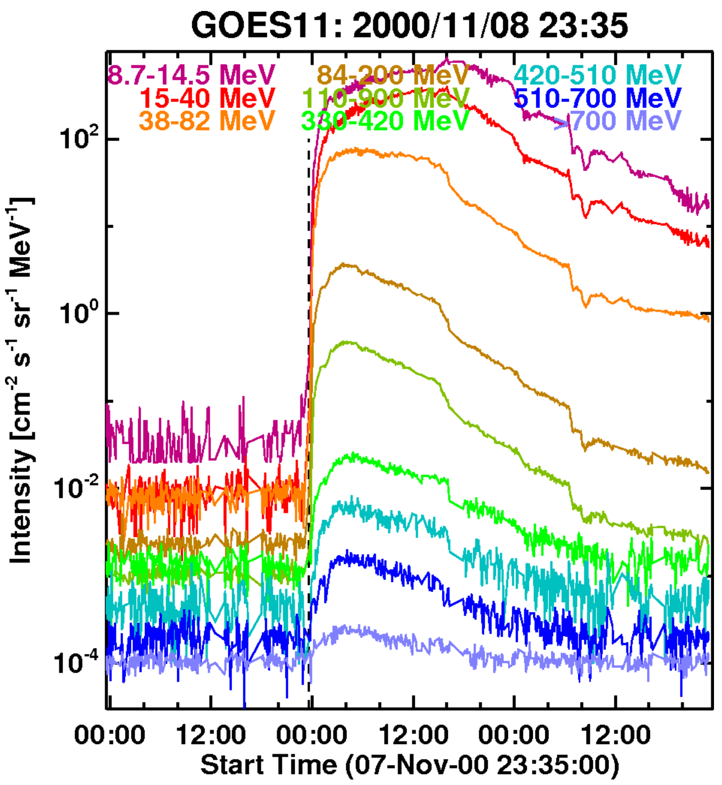
Kahler, Hildner, & Van Hollebeke (1978)

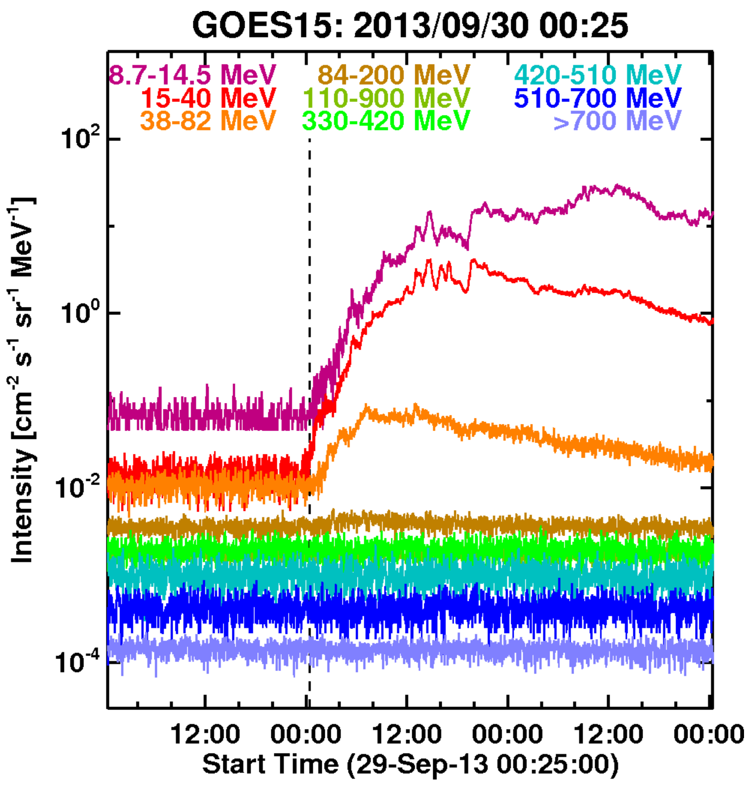
Rao et al. 1967 for ESPs; Cliver et al. 1982 for GLEs; Cane et al. 1988; Reames 1990

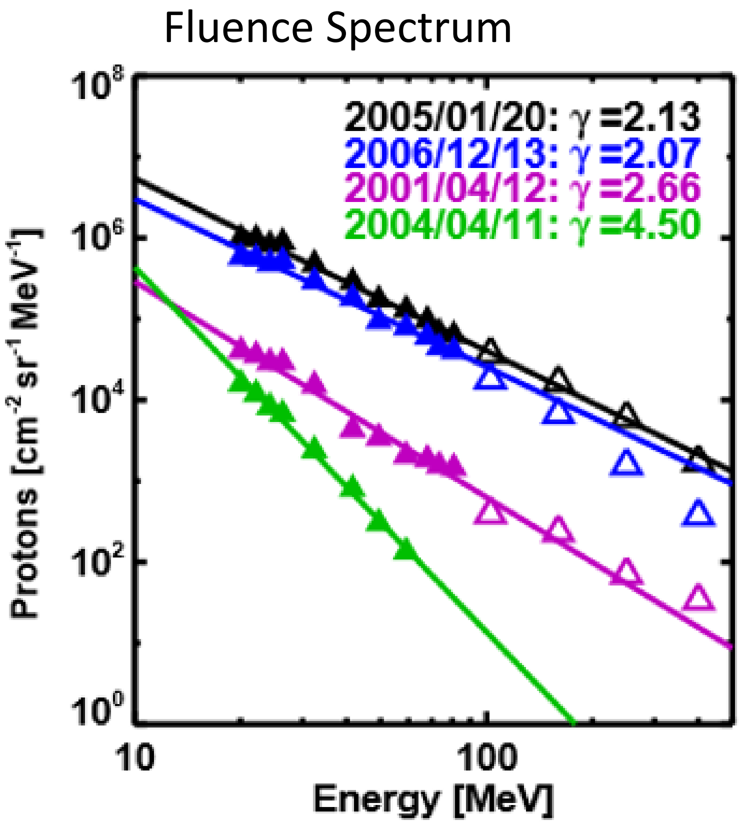


C2: 2000/11/08 23:26
EIT: 2000/11/08 23:24
GOES X-Rays: 2000/11/08 23:24
10^-3
X
M
C
B
A
10^-9
22:00
00:00
02:00
2000/11/08 23:36
GOES11: 2000/11/08 23:35
8.7-14.5 MeV
15-40 MeV
38-82 MeV
84-200 MeV
110-900 MeV
330-420 MeV
420-510 MeV
510-700 MeV
>700 MeV
Intensity [cm^-2 s^-1 sr^-1 MeV^-1]
10^2
10^0
10^-2
10^-4
00:00
12:00
00:00
12:00
00:00
12:00
Start Time (07-Nov-00 23:35:00)
WIND/WAVES: 2000/11/08 23:26
10
1.0
0.1
.02
[MHz]
Type II
Type III
22:00
00:00
02:00
2000/11/09 00:00

SEP Intensity, Energy Range, Spectrum



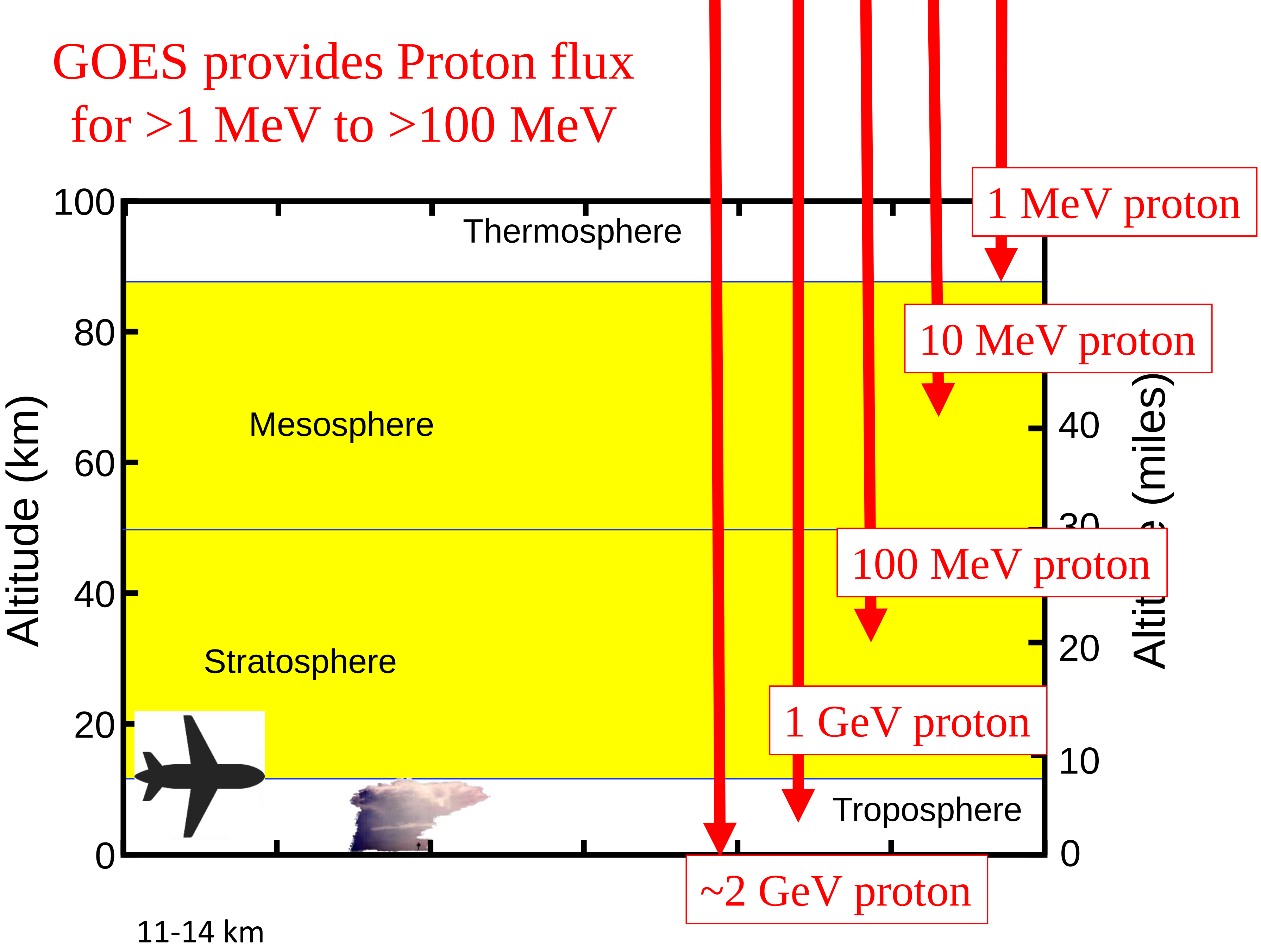




Intensity

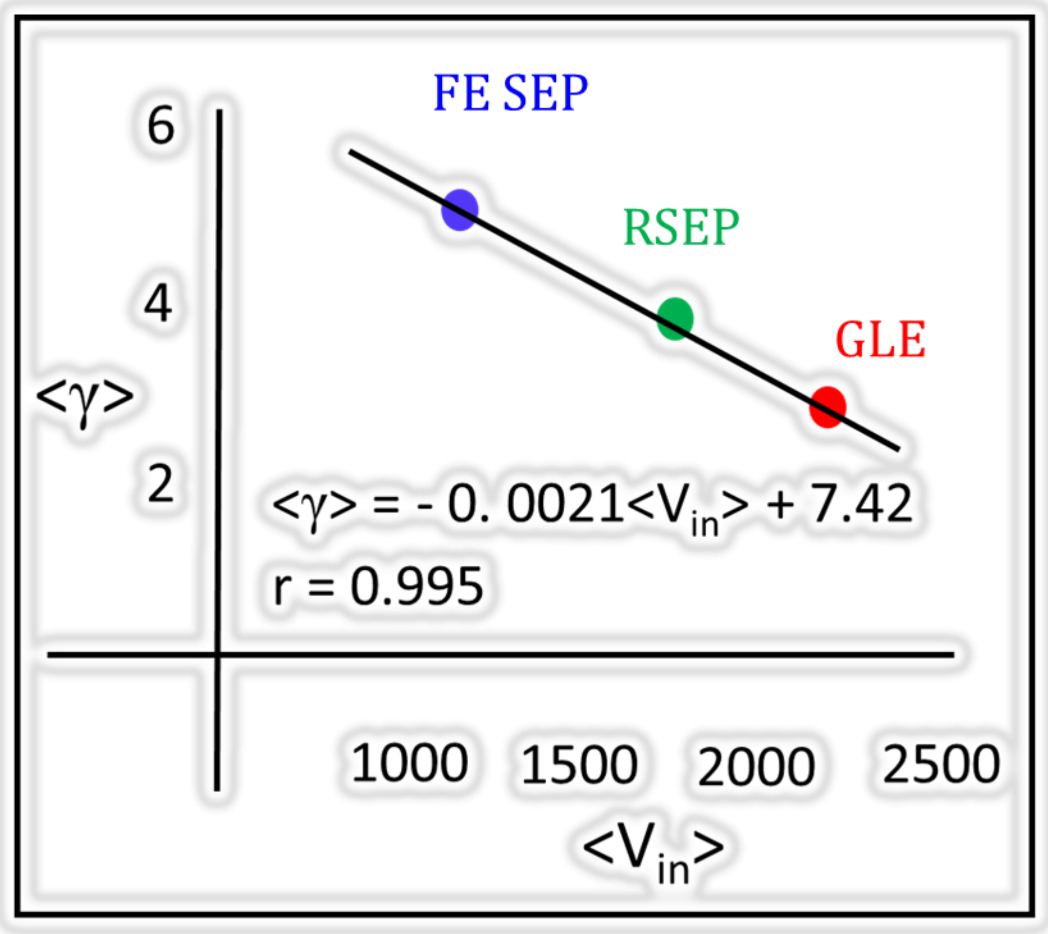
Spectrum

GOES provides Proton flux for >1 MeV to >100 MeV



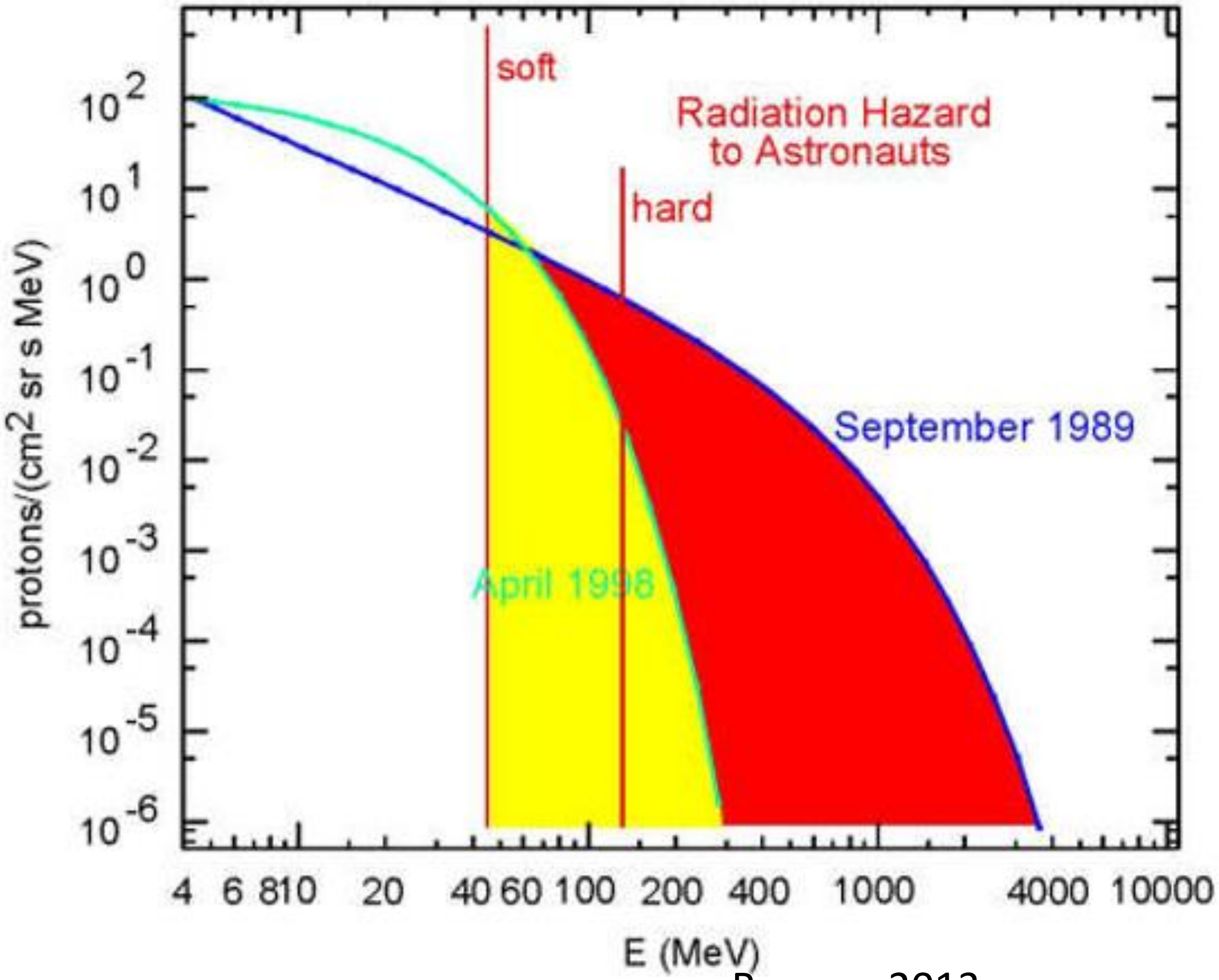
Particles hit the airplane material and produce secondaries, which affect crew and passengers in polar route

Hard Spectrum Events are more hazardous



CME Kinematics determines the spectral shape

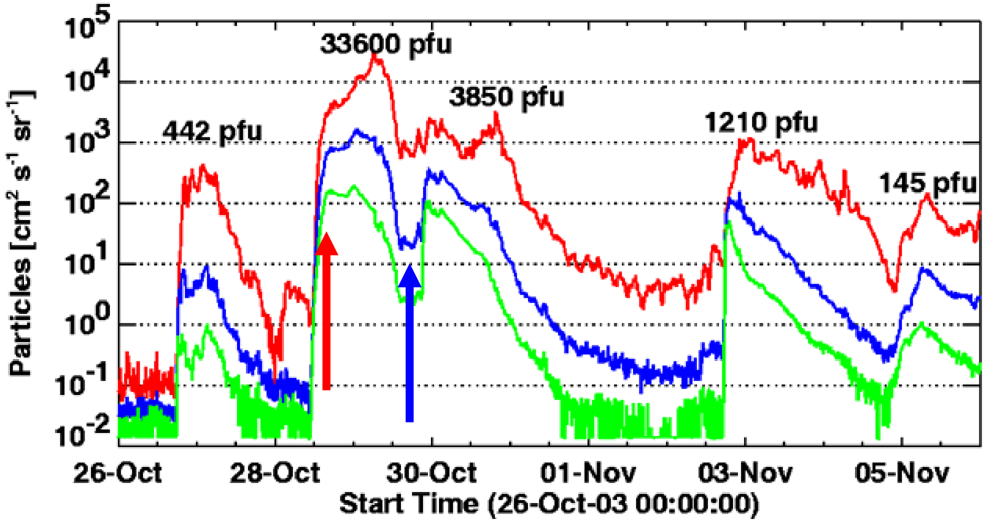
Gopalswamy et al. 2016



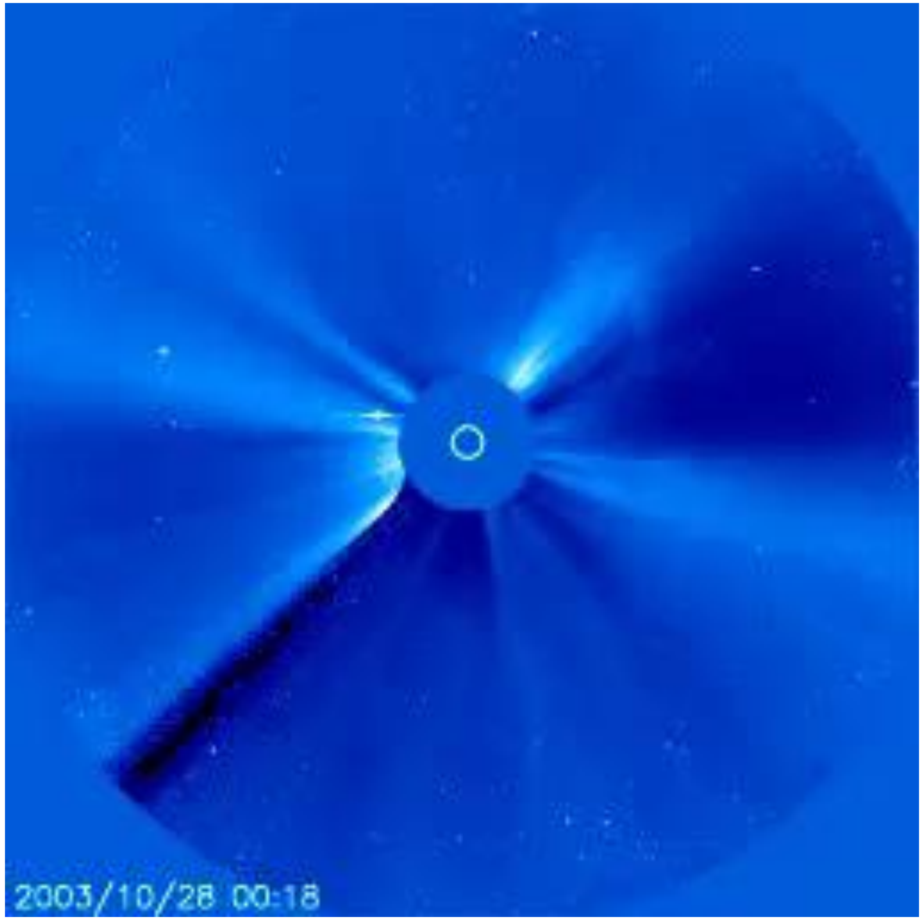
Reames 2013

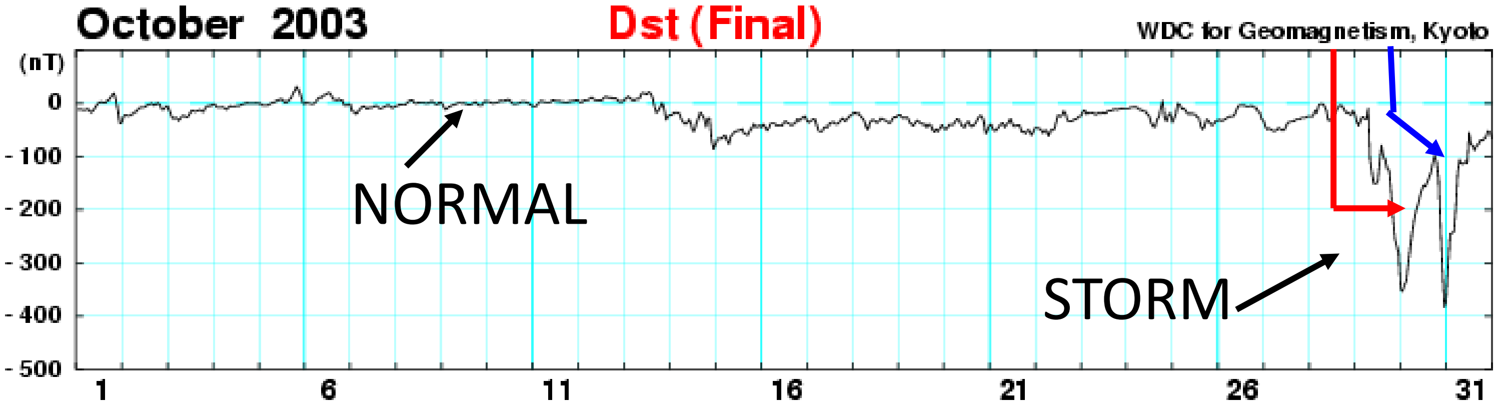
Double Whammy: Geomagnetic Storms & SEPs

Some times eruptions occur in quick succession maintaining elevated level of particle radiation
Gopalswamy et al. 2005



Two halo CMEs: 10/28 and 10/29 2003

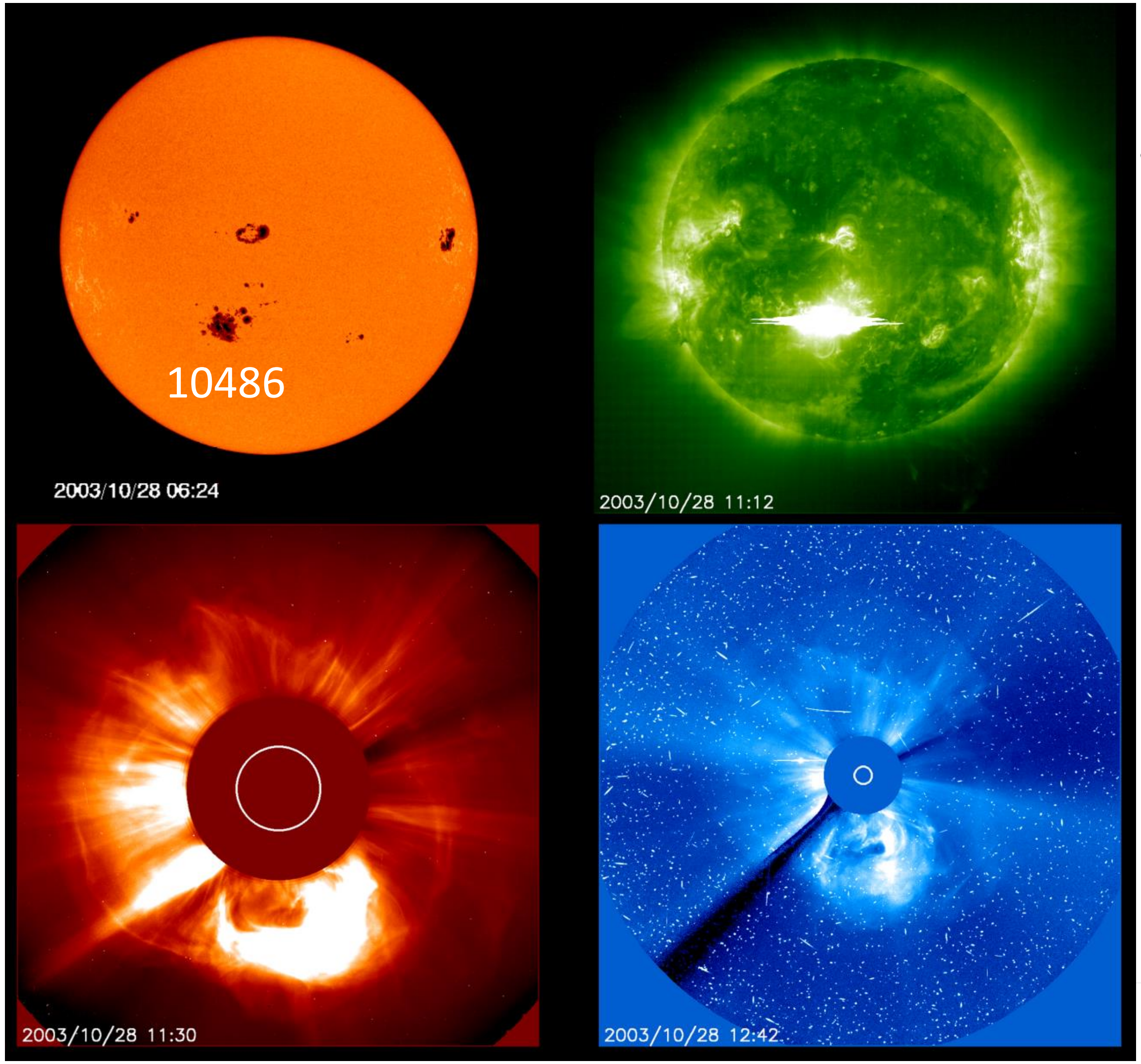


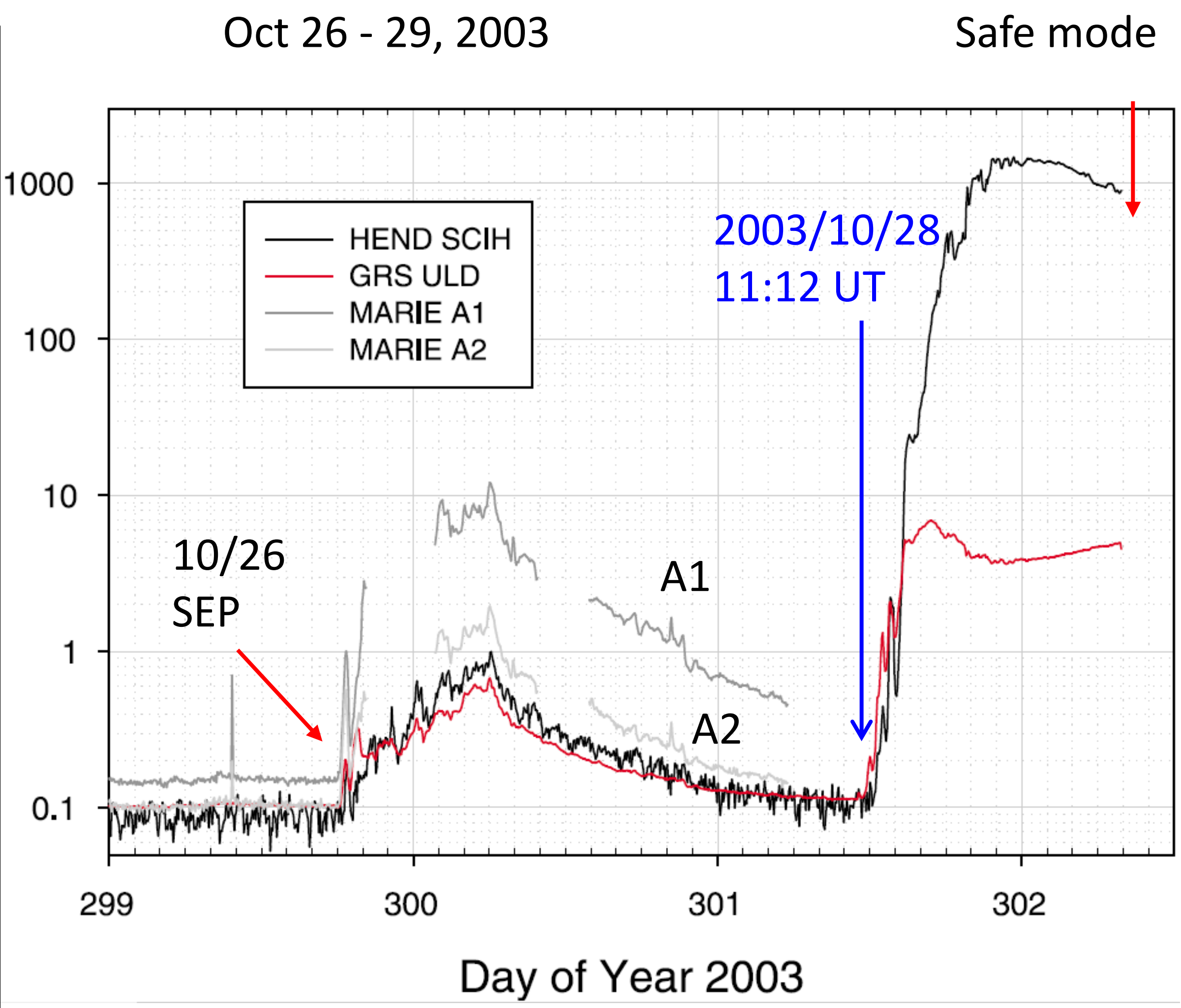


Transformer oil heated by 10° in Sweden; 50,000 people in Malmo had power blackout

SOHO/LASCO

The MARIE Slayer: 2003 Oct 28 Halloween Storm

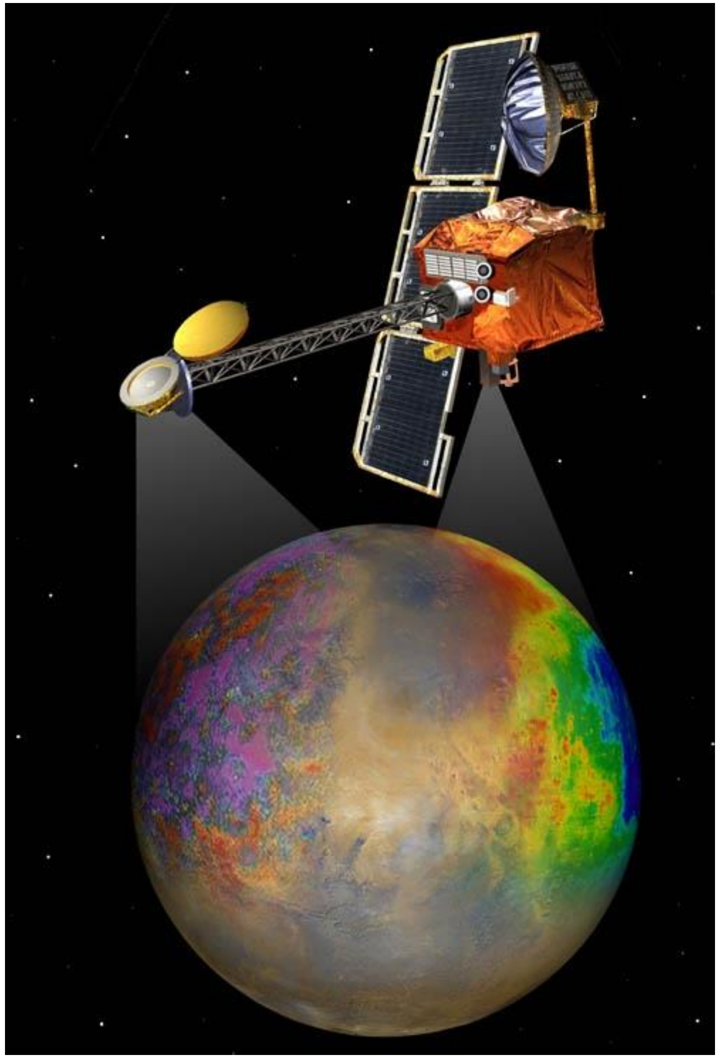




Zeitlin+2010

MARIE: The Martian Radiation Environment Experiment

Nozomi



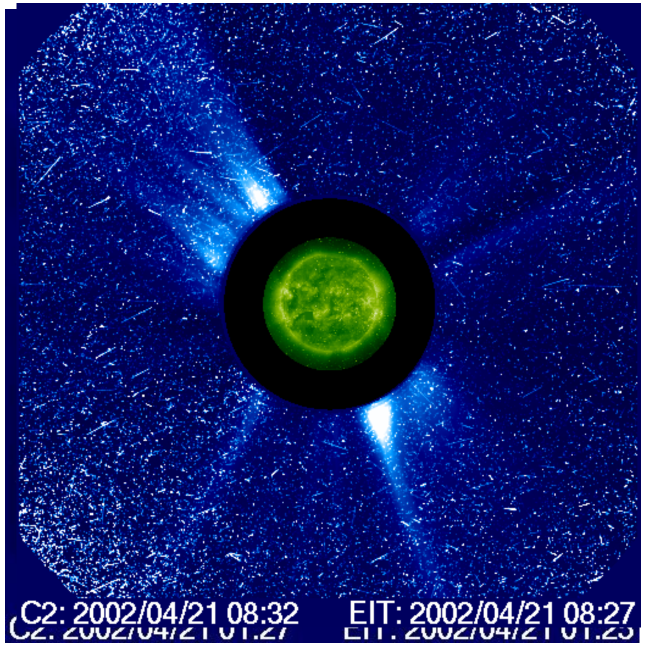
Mars Odyssey

The MARIE instrument on Mars Odyssey observed the radiation levels on the way to Mars and in orbit, so that future mission designers could plan the trips of human explorers to Mars.

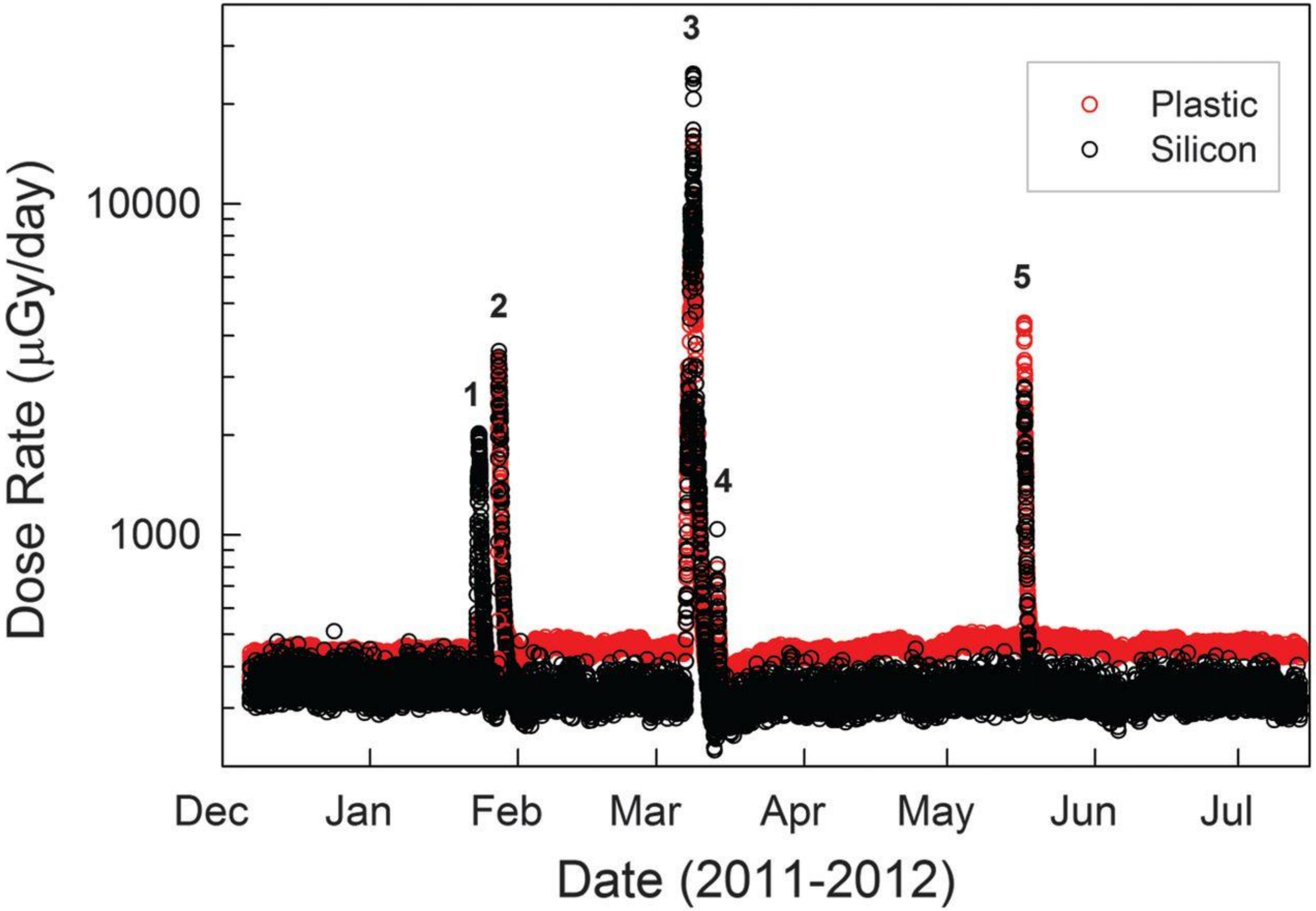
One of the October 2003 SEP events rendered MARIE inoperative. It is ironic, as MARIE was designed to measure the radiation environment at Mars.

Radiation Assessment Detector (RAD) on board the Curiosity rover (Mars Science Laboratory) Indicates that a 360-day round trip would add a dosage of ~660 mSv. (Zeitlin et al. 2013)

This is ~66% of astronaut's entire career exposure limit (1000 mSv)



Curiosity provides Radiation info for a Mars Trip

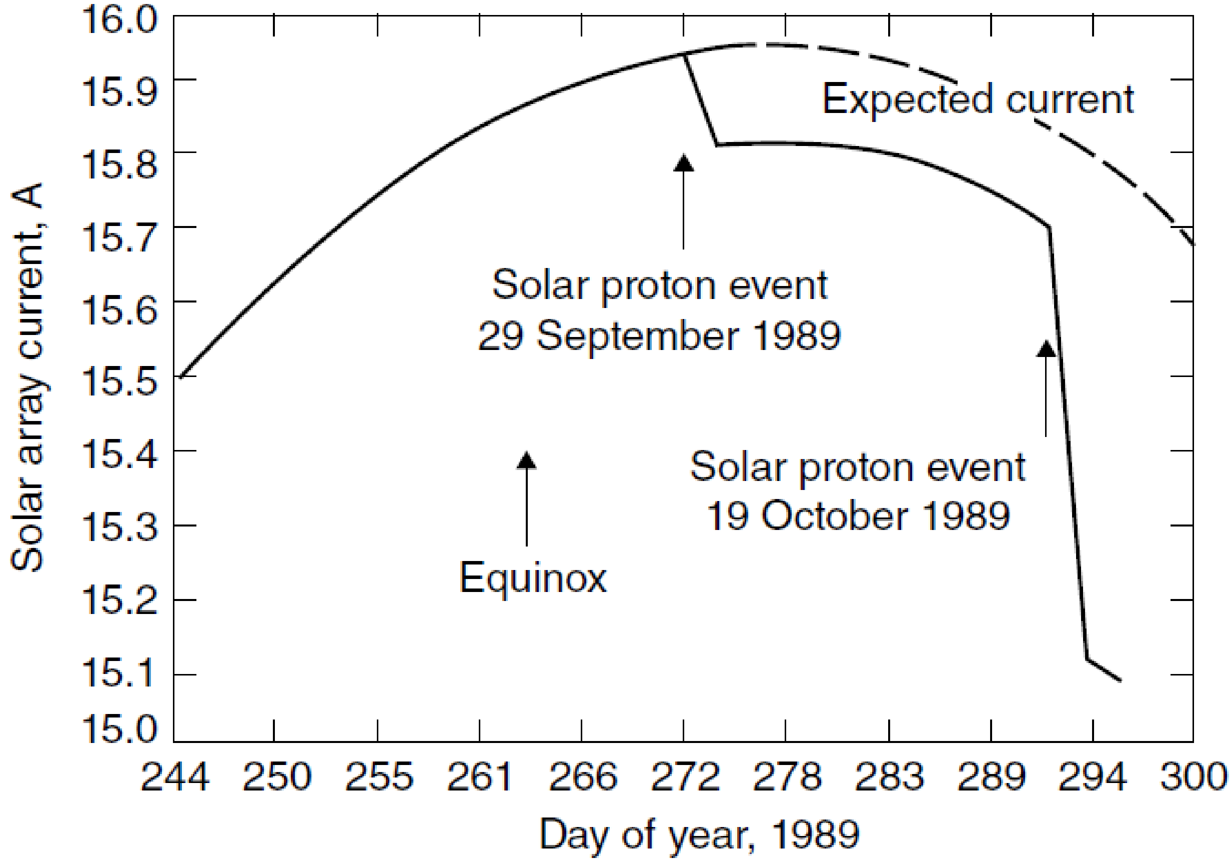


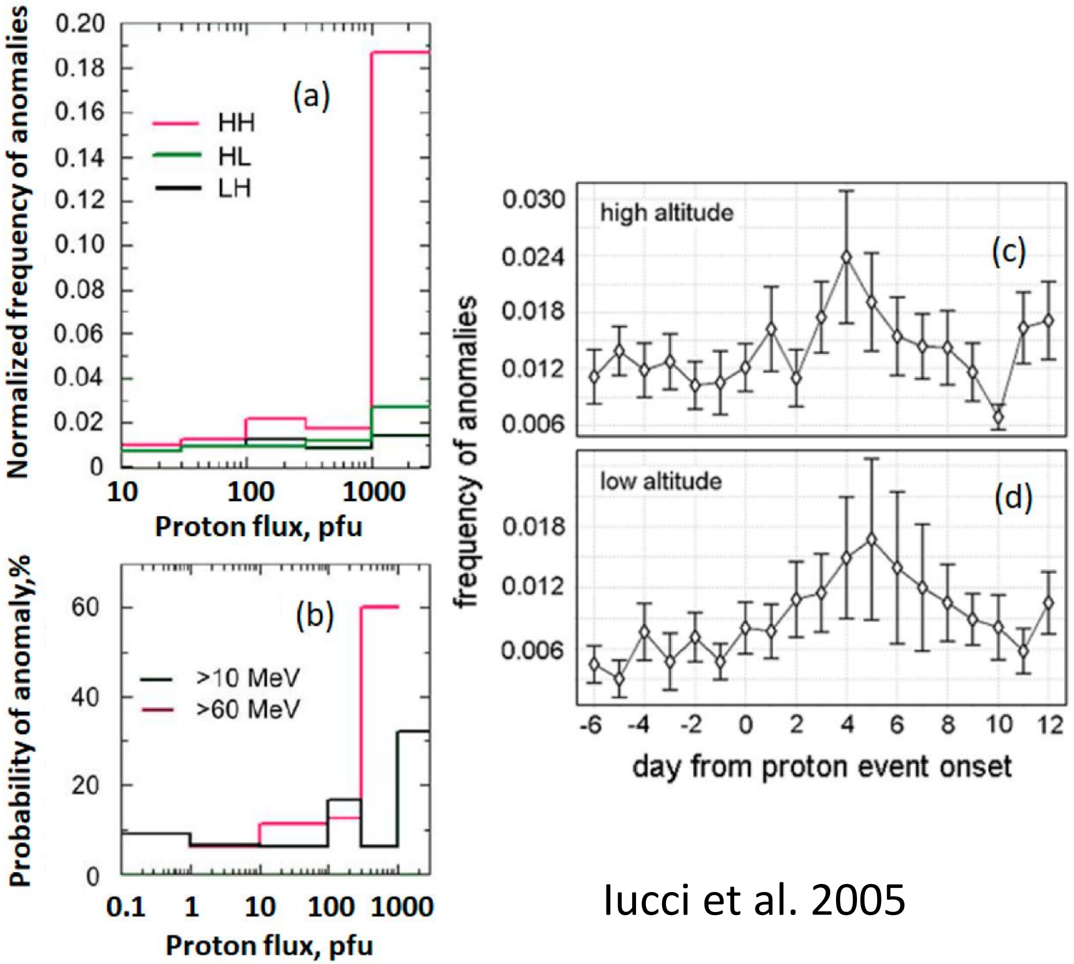
Radiation Assessment Detector on Mars Science Laboratory (RAD/MSL)

RAD mounted on the top deck of Curiosity rover

Data collection:
6 December 2011 to 14 July 2012
1.84 mSv/day due to GCRs
Total: 660 mSv; 5.4% due to SEPs

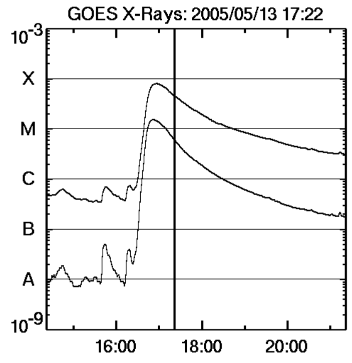
S/C Anomaly & SEPs

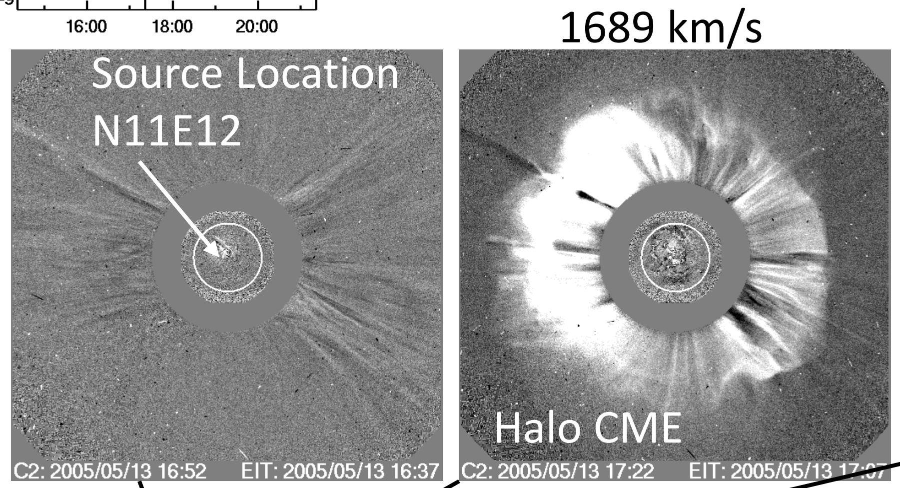


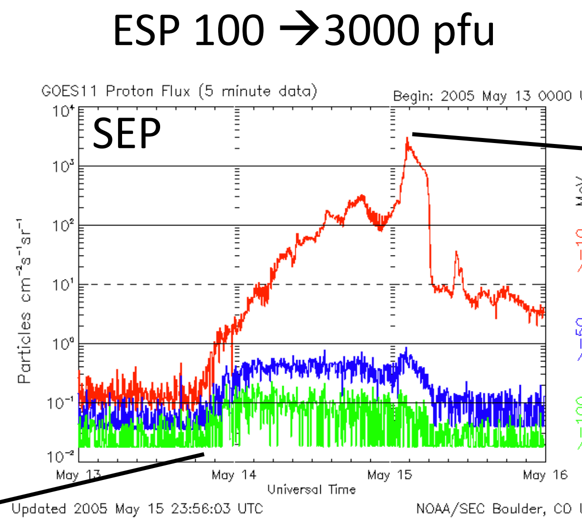


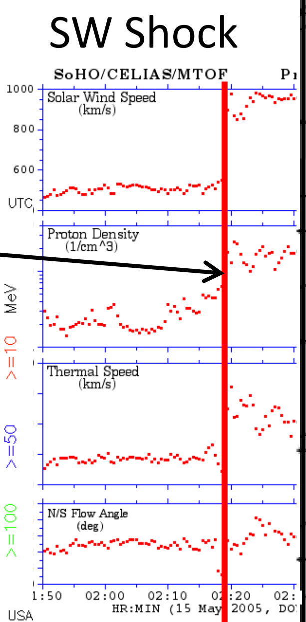
Iucci et al. 2005

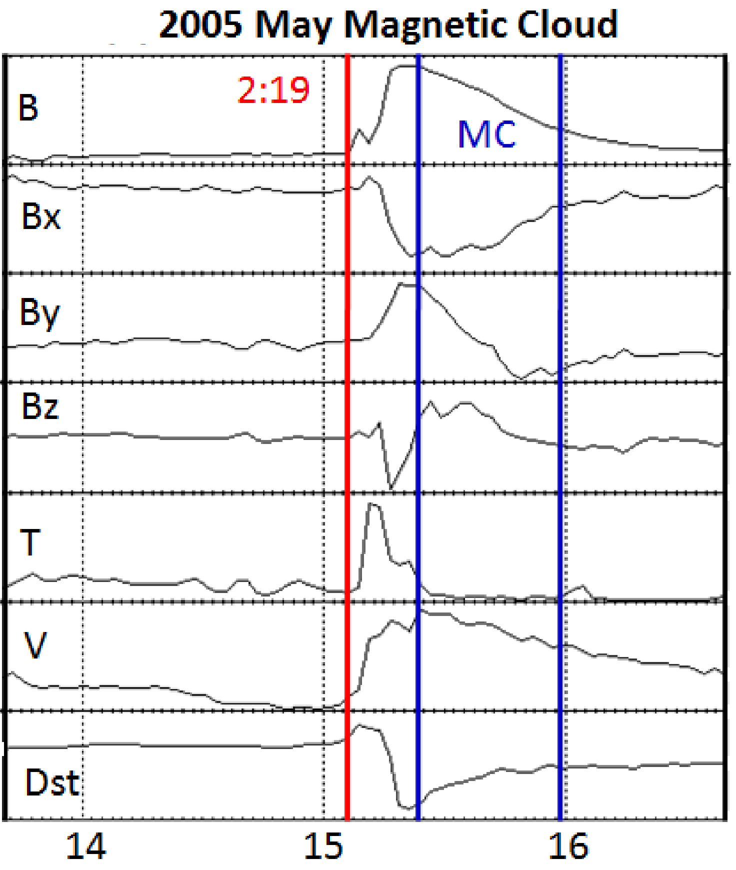
Range of Phenomena: 2005 May 13 CME

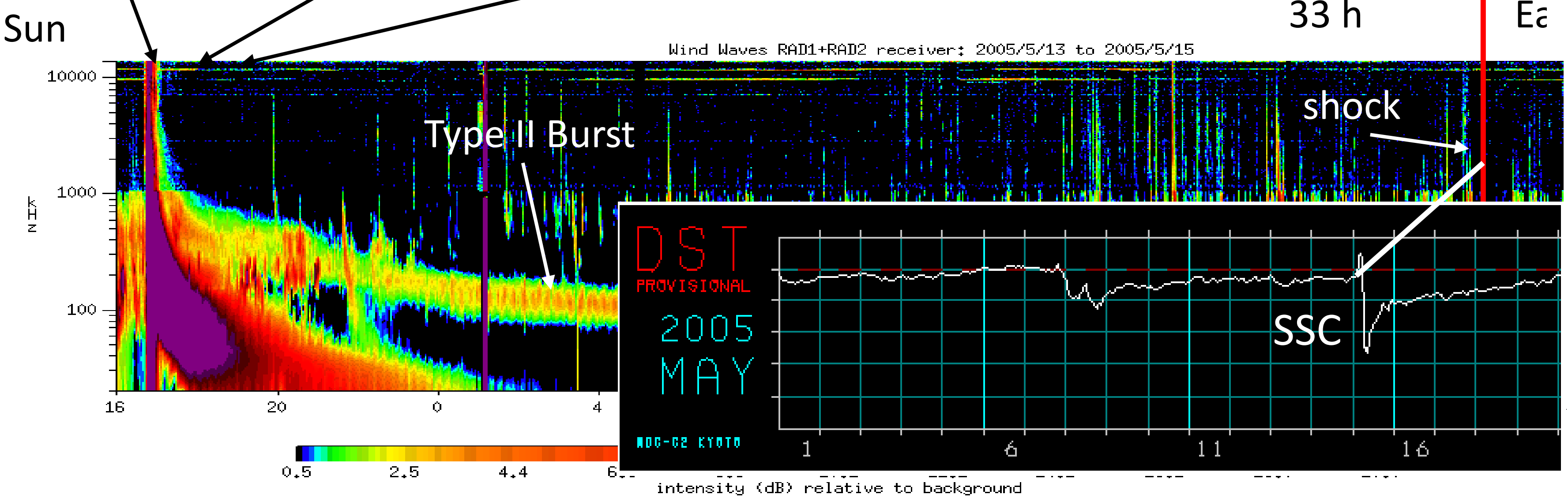






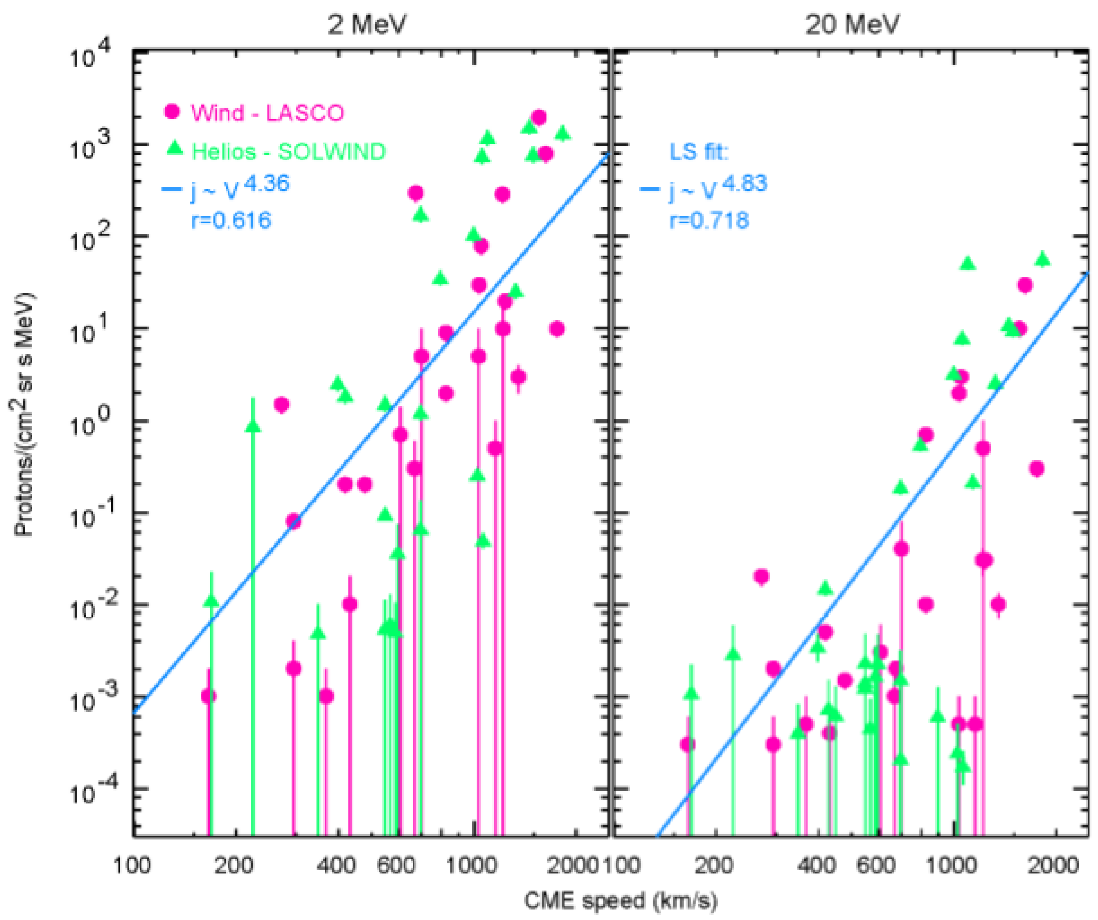




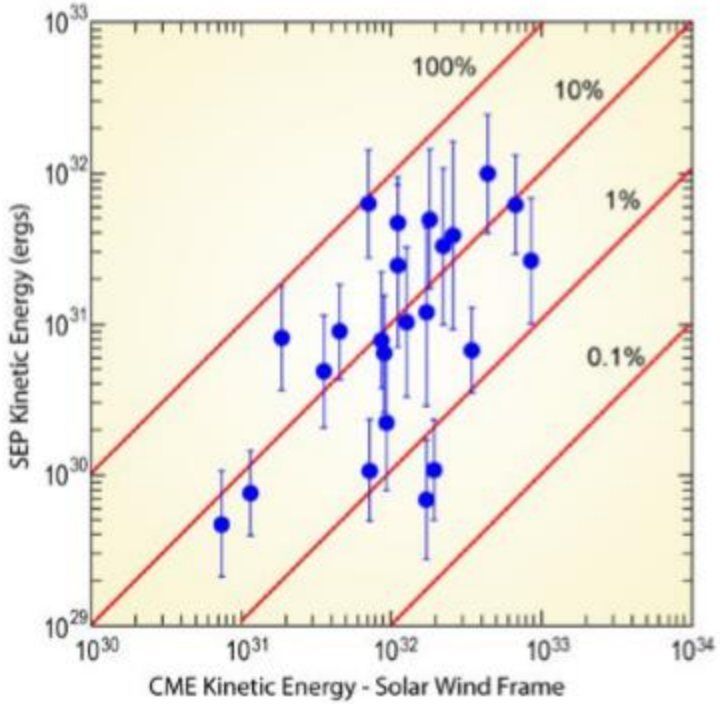


in-situ "view"
of the CME

SEP Intensity vs. CME Speed



Kahler 2001

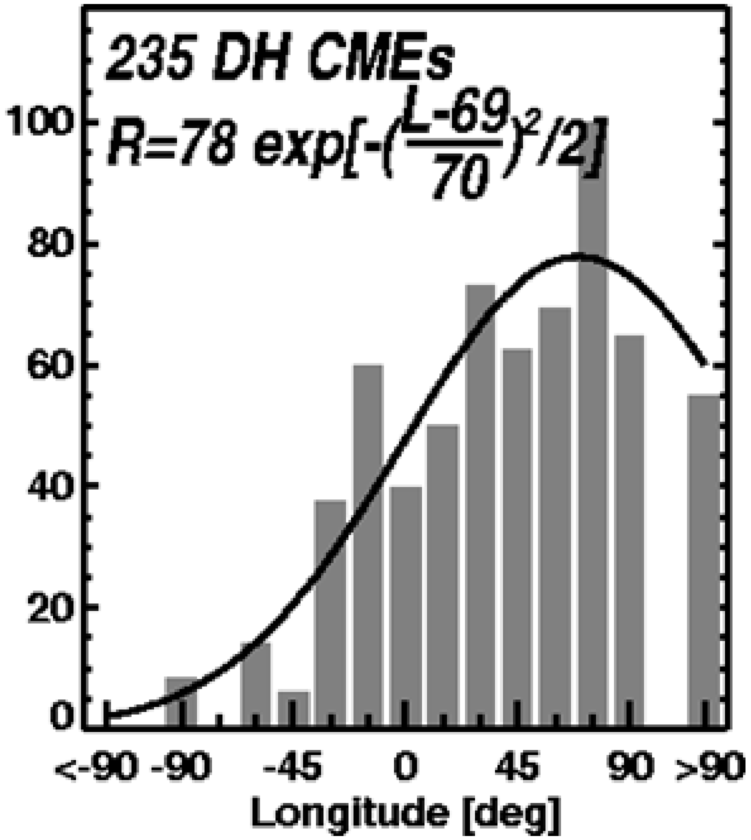


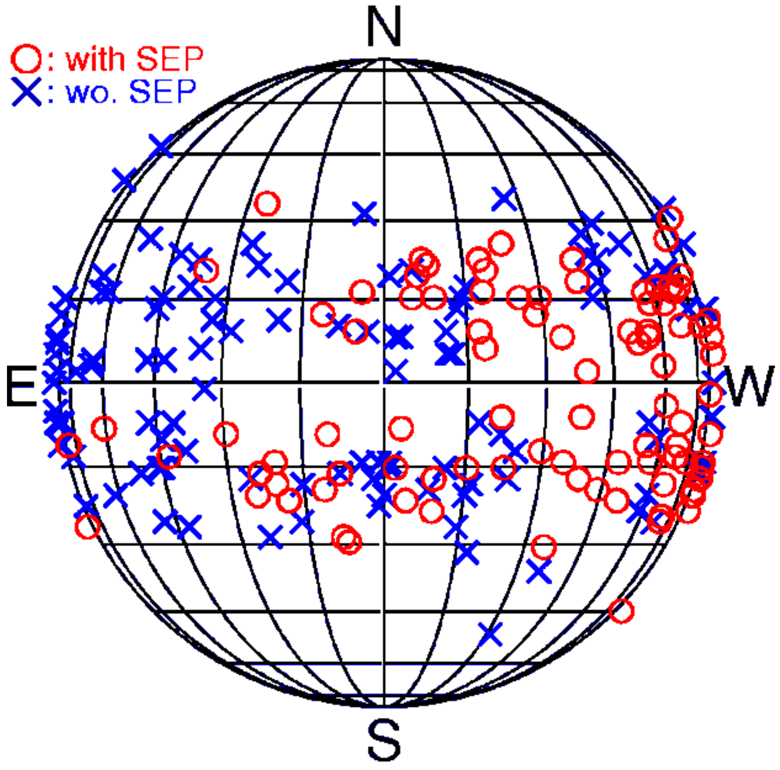
Mewaldt 2008

- SEP Intensity correlated with CME speed → strong evidence for acceleration by CME shocks
- Large Scatter

- Source and Environmental factors
- Connectivity
- CME interaction

More on Connectivity: CMEs Associated with Type II Bursts and SEPs





Sources of CMEs associated with type II bursts at f < 14 MHz (Decameter-hectometer and longer wavelengths)

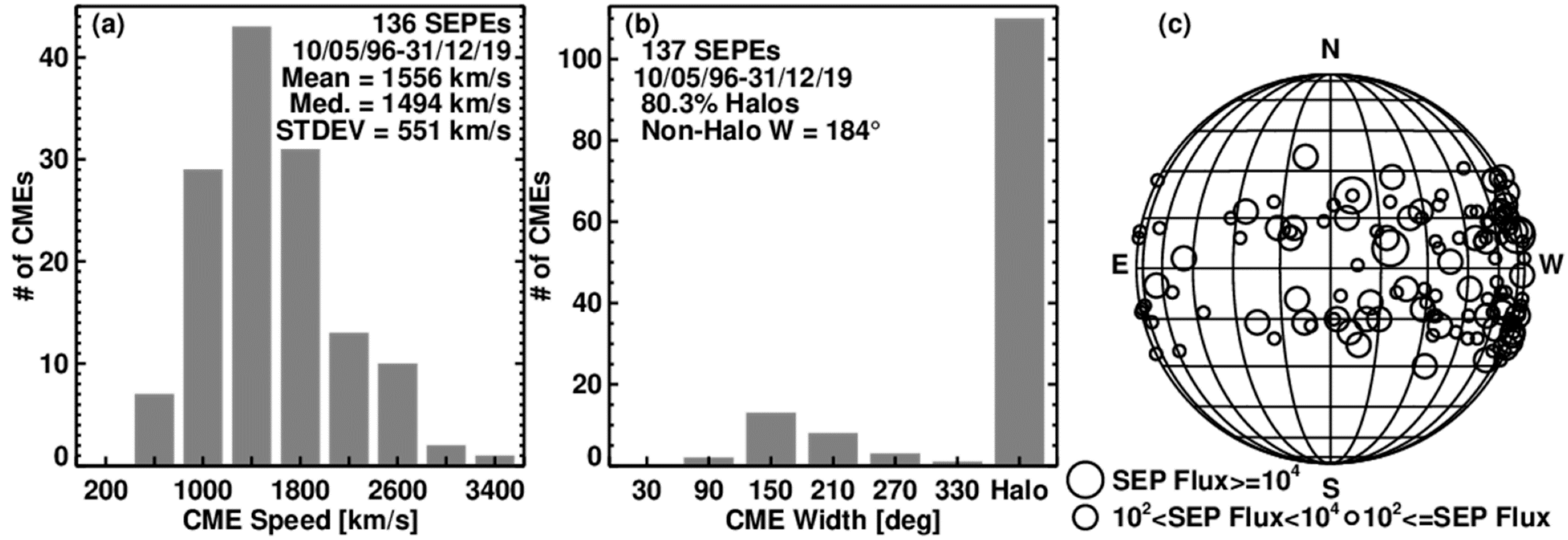
Type II bursts from the western hemisphere are likely to be associated SEPs due to better magnetic connectivity

Type II bursts from the eastern hemisphere are associated with SEPs that do not arrive at Earth (e.g., STEREO B)

Type II bursts and SEPs are due to the same shocks

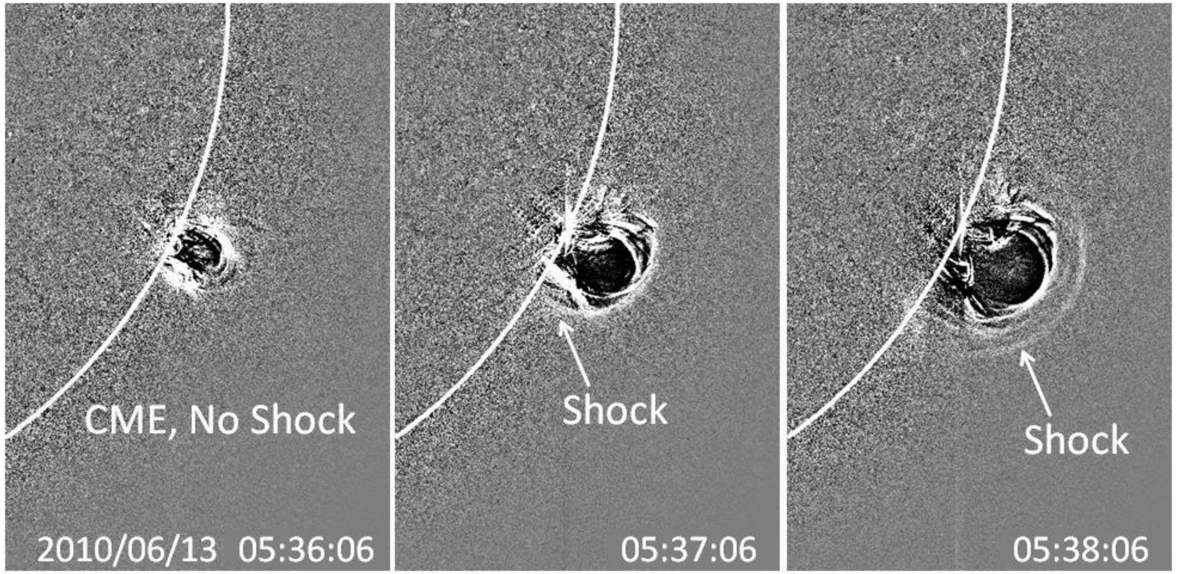
Gopalswamy et al. 2008 Ann Geo

CMEs producing Large SEP Events

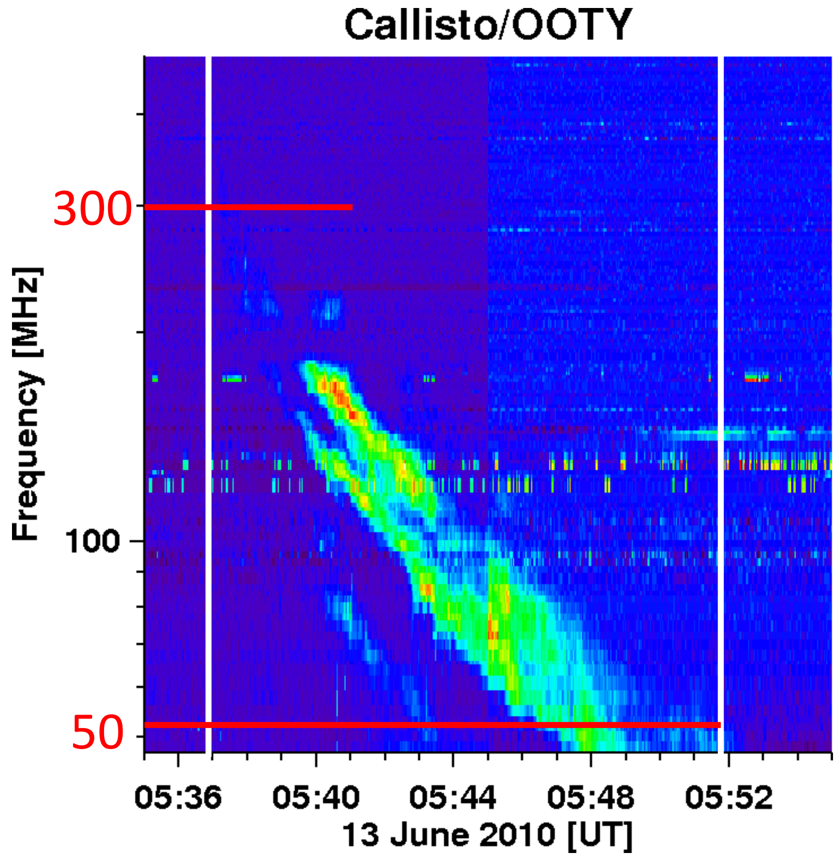


- SEP Events are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Shock-driving capability of CMEs key for SEPs

Shock Source: coronal mass ejections



Solar Dynamics Observatory (EUV 193 Å)



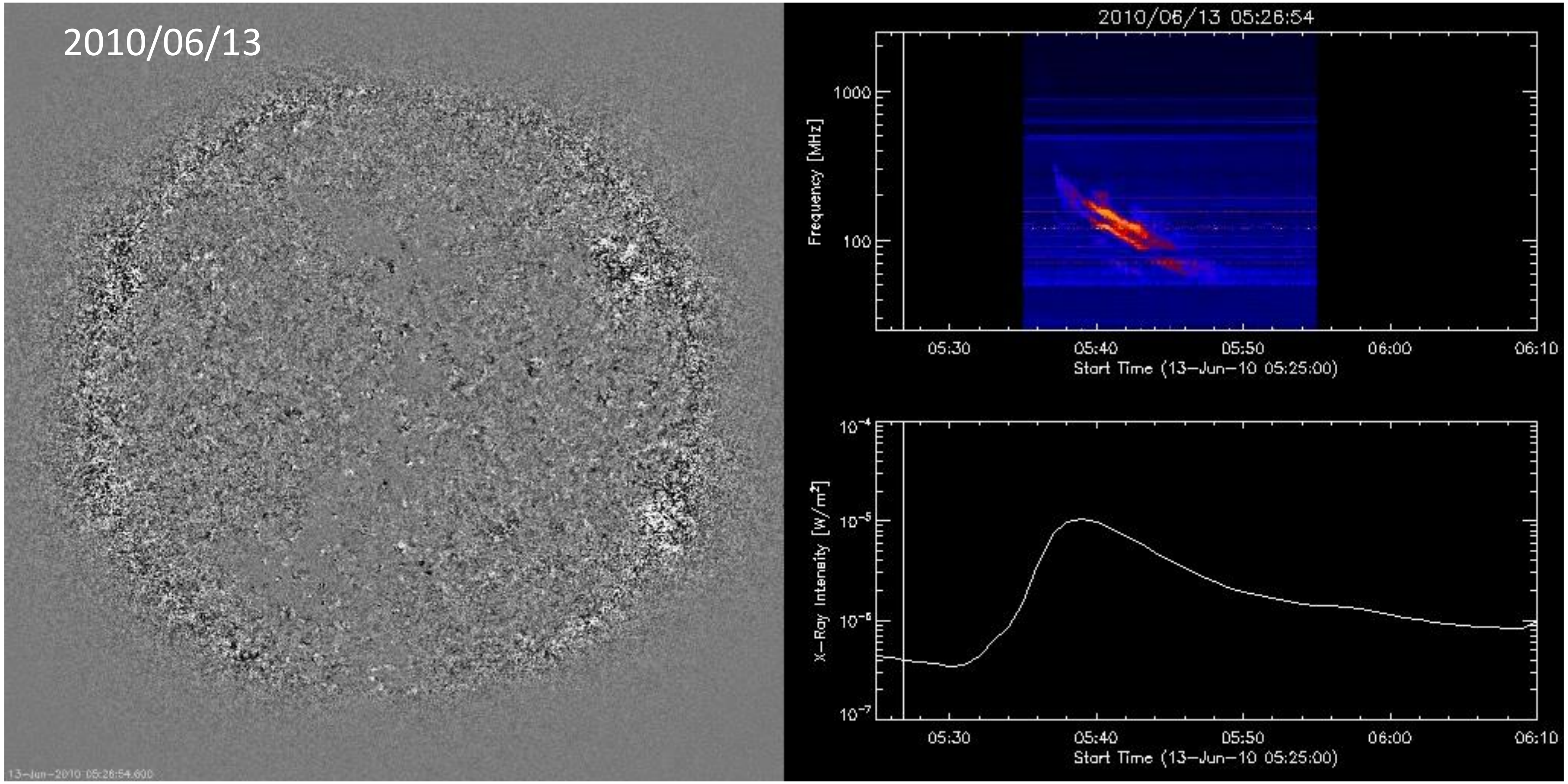
Type II burst starts exactly at the time the shock appears in the corona at 1.19 Rs (this is the leading edge method)

We can probe the coronal medium as well as the shock structure by combining type II and EUV/coronagraph observations

$df/dt = 0.28$ MHz/s; $(1/f)df/dt = (0.28/175)\ s^{-1}$

$V = 600$ km/s; $L = 189{,}000$ km

Where does the shock form? Or What is the shock/CME height when the type II bursts starts?

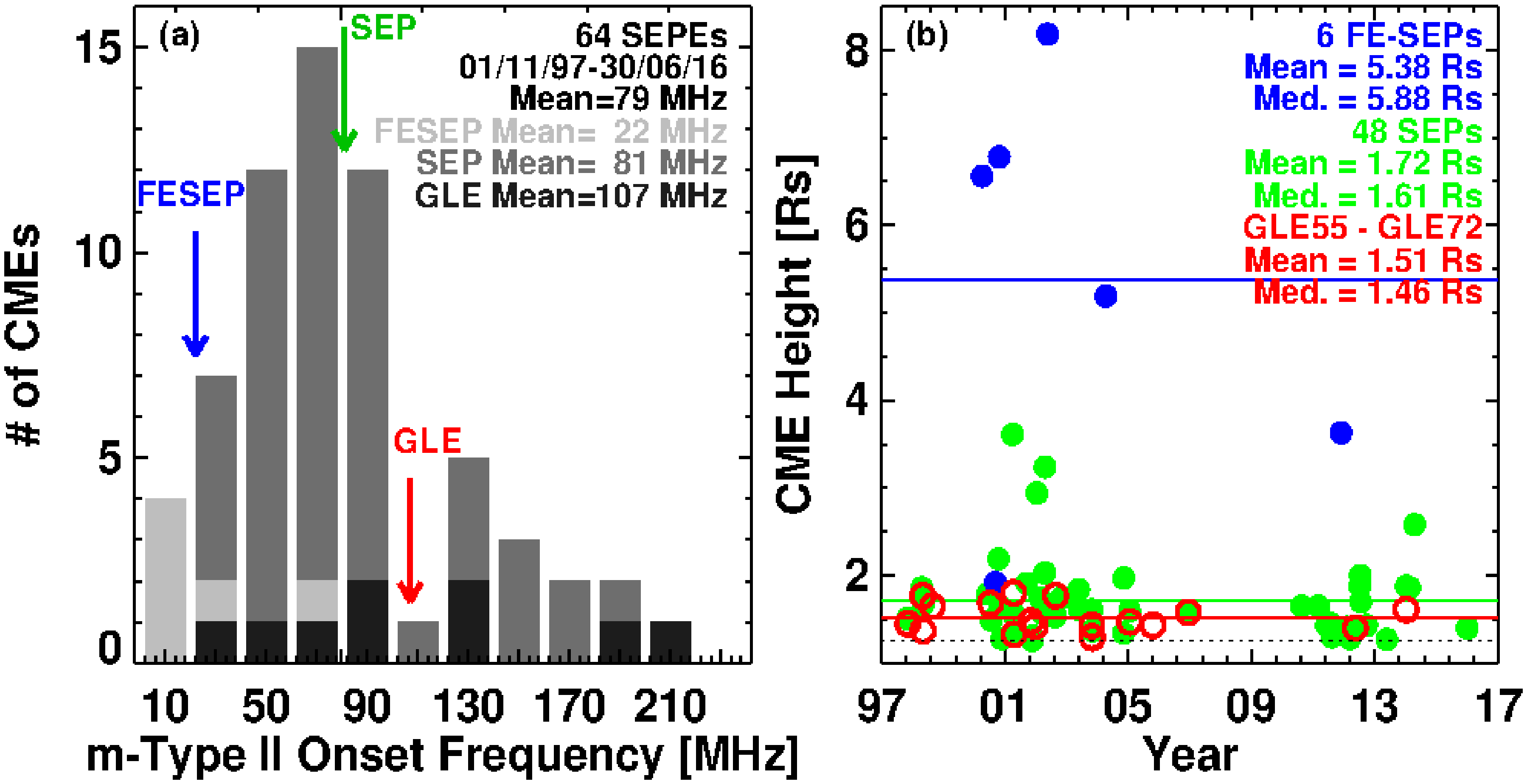


CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs

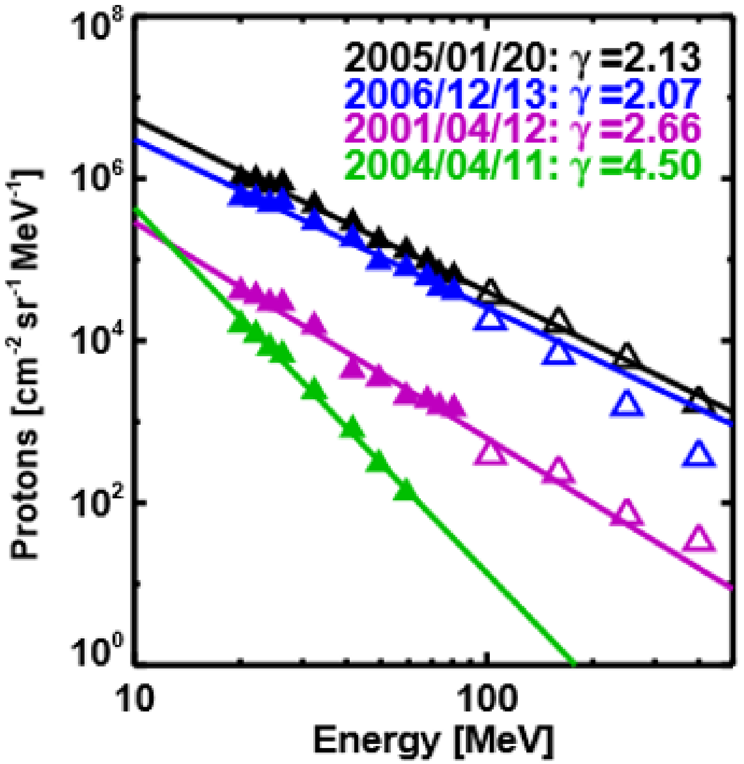
f_p = 150 MHz → n_p =2.8x10^8 cm^{-3}

Gopalswamy et al., 2012 ApJ

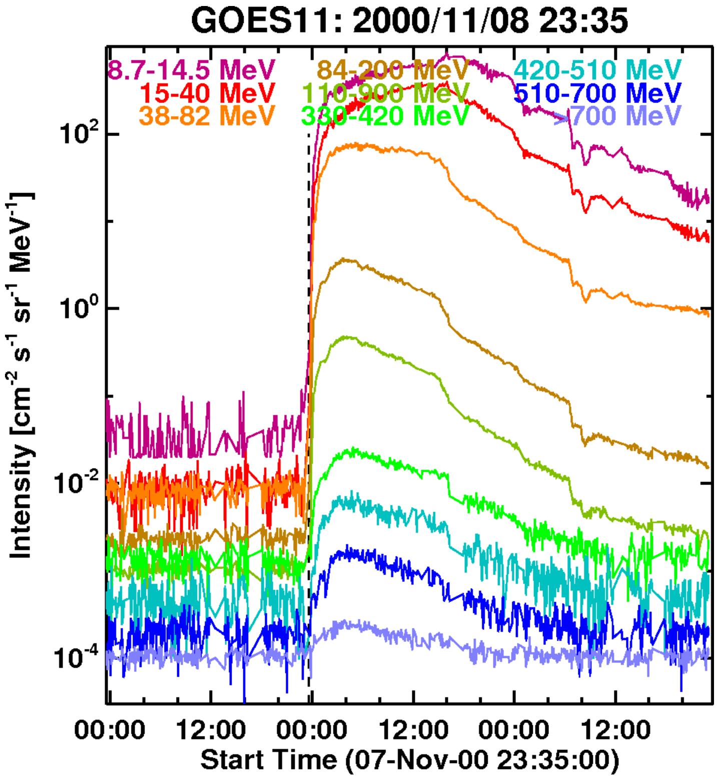
It Matters Where the Shocks Form

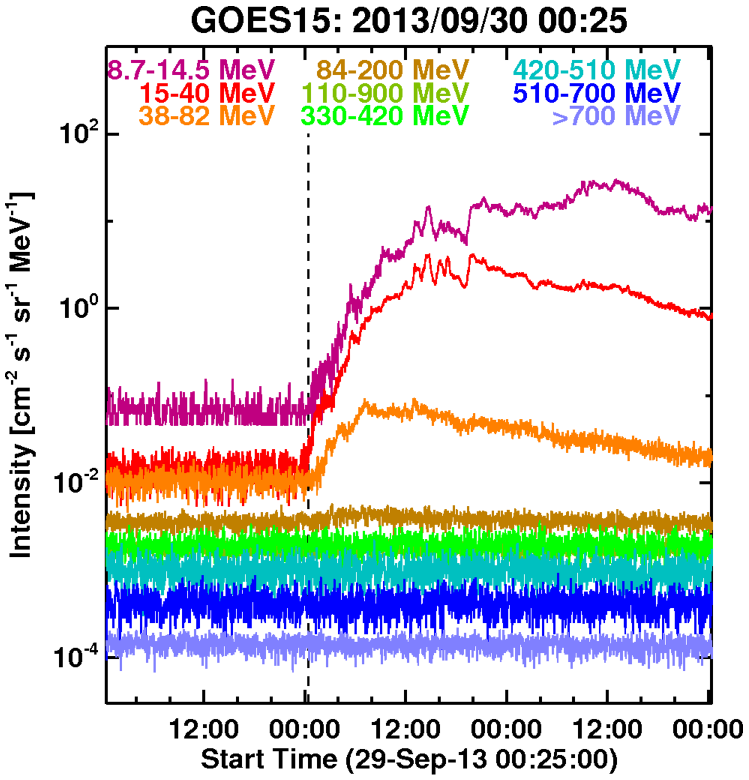


Fluence Spectrum

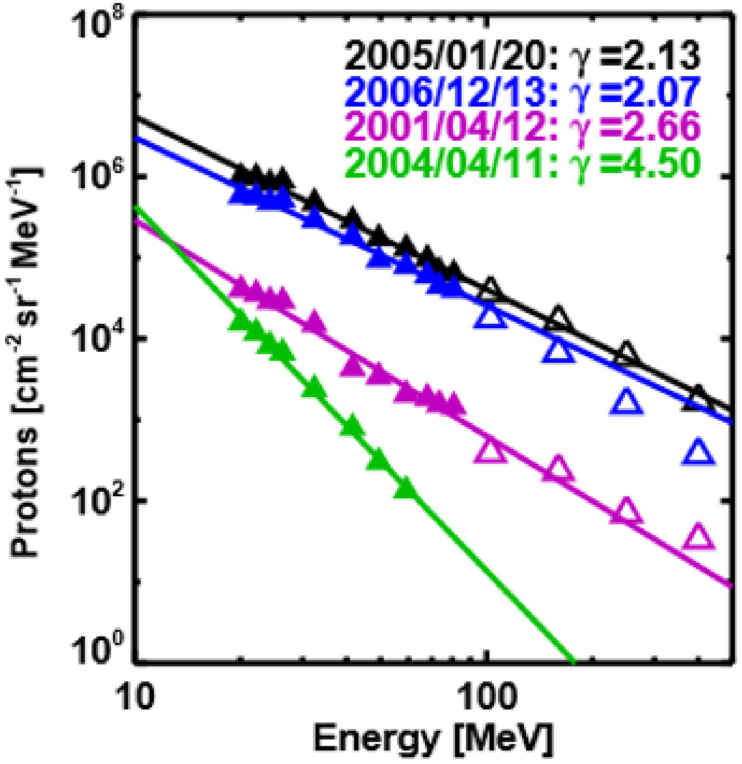


SEP Intensity, Energy Range, Spectrum





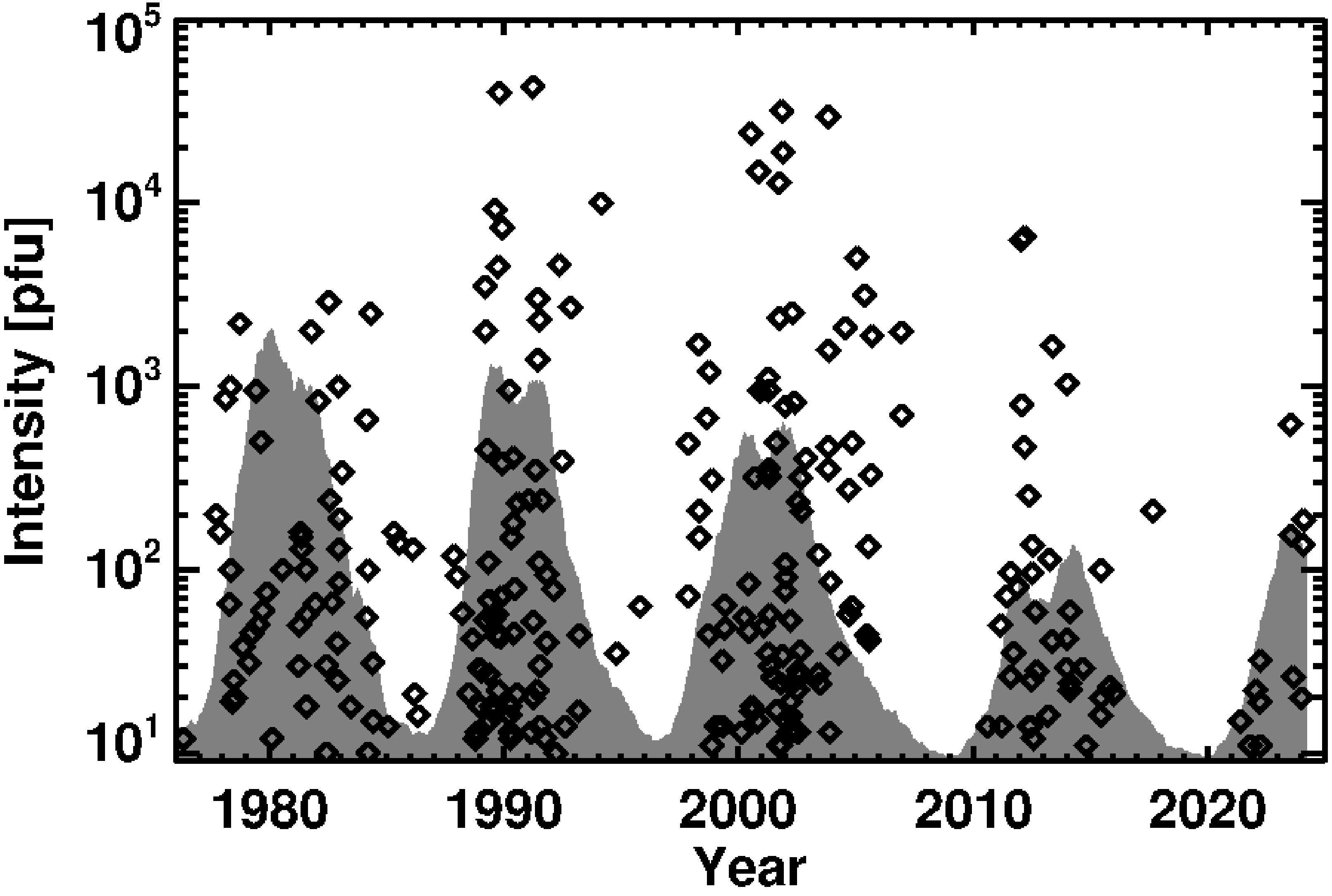
Fluence Spectrum



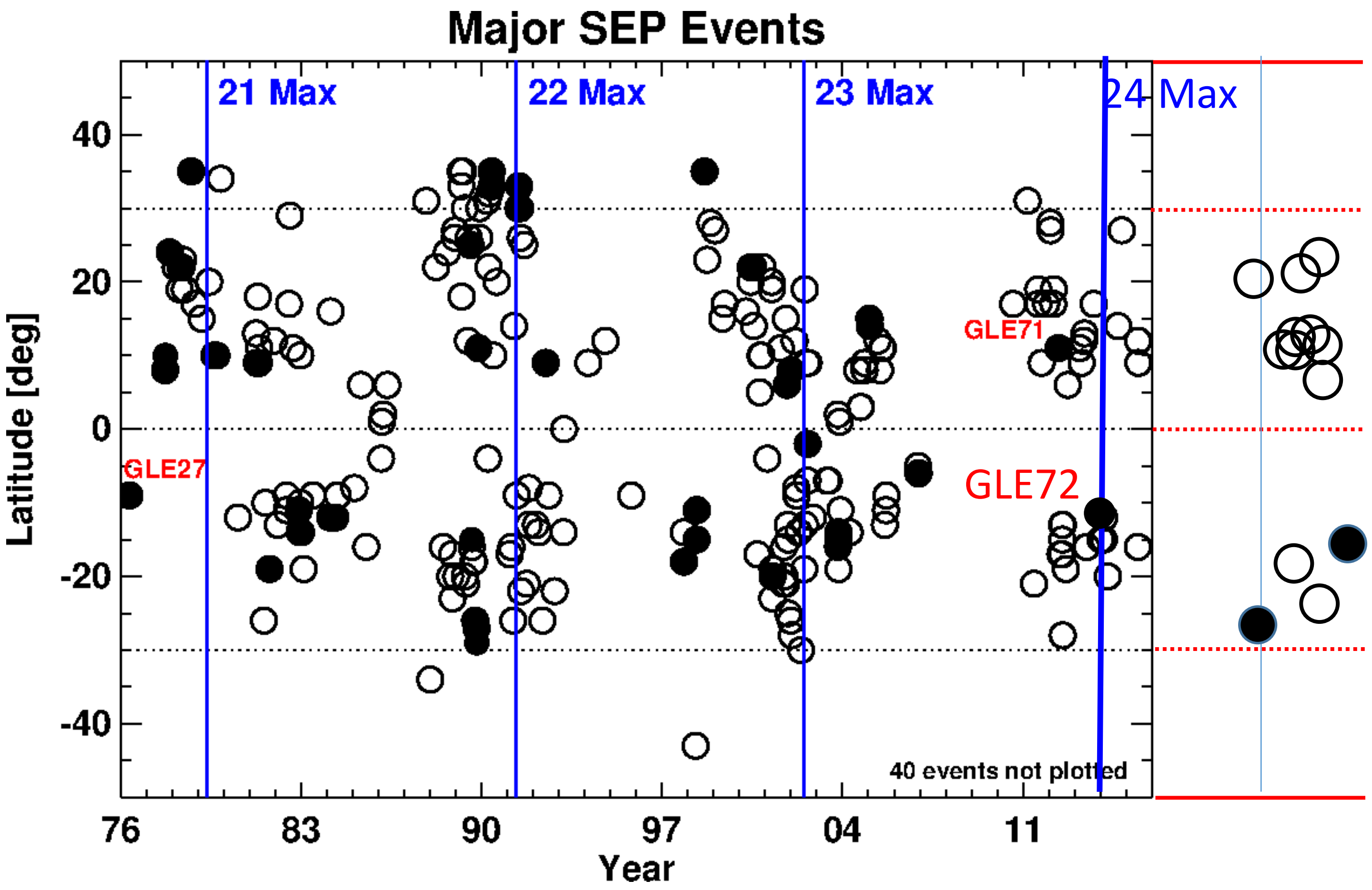
Intensity

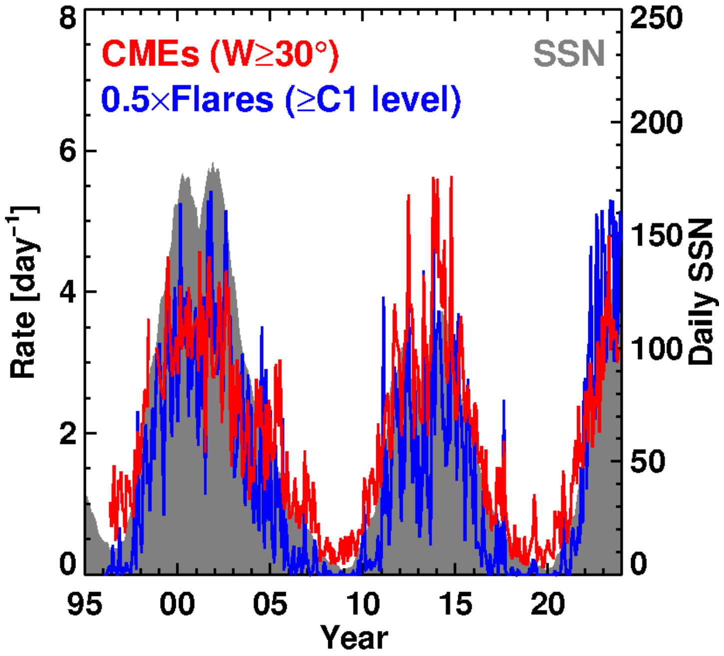
Spectrum

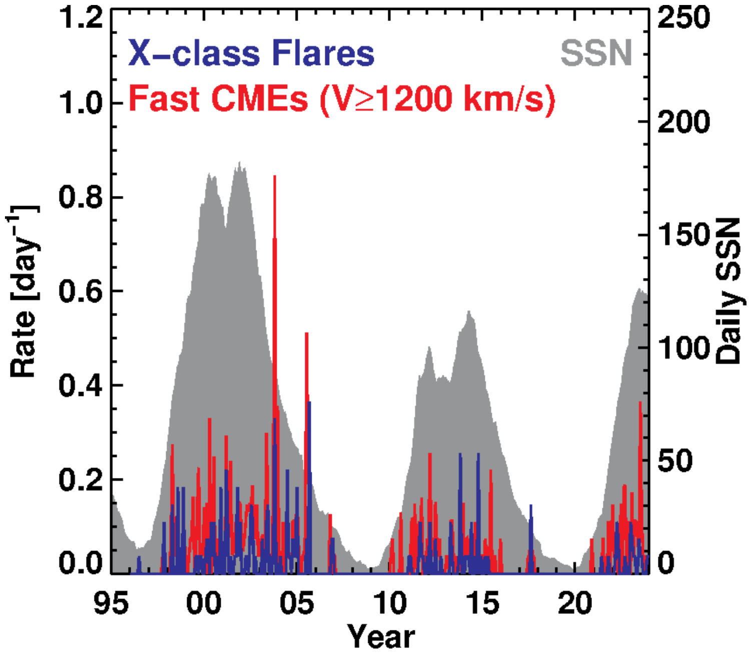
Solar Cycle Variation



Locations of CMEs that Produced SEP Events



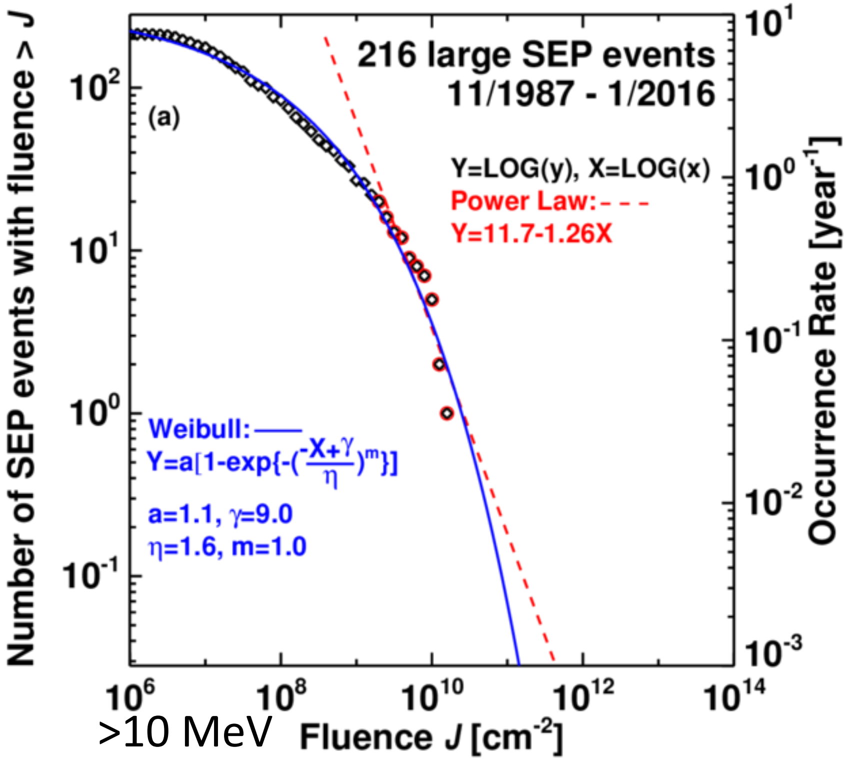


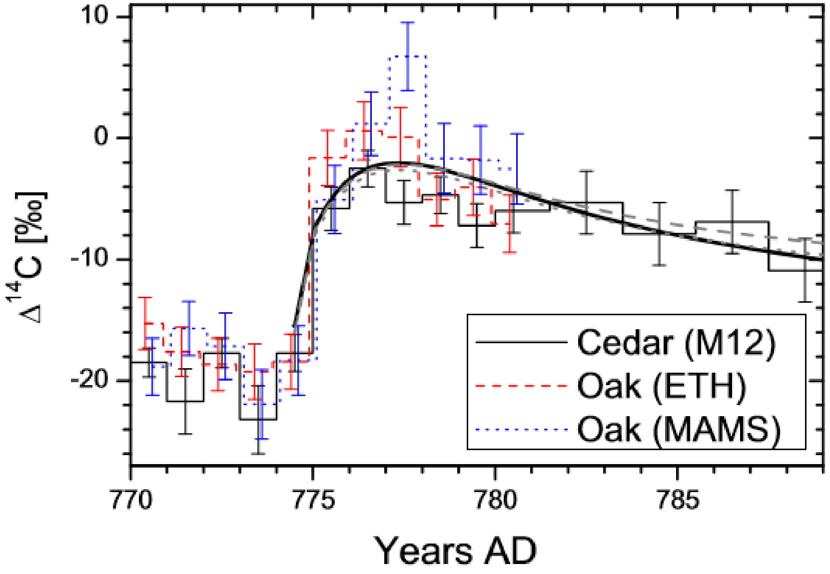


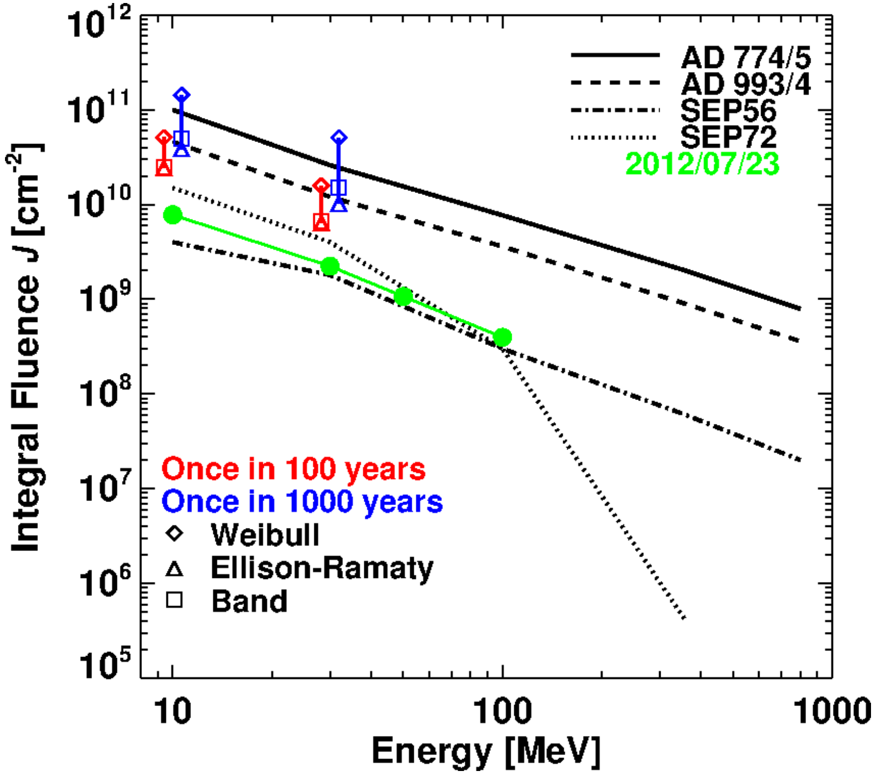
- More SEP events around solar maximum
- GLE events are very rare
- Paucity of high-energy SEP events in cycle-24

Extreme SEP Events

Usoskin et al. 2013







Miyake et al. 2012; Mekhaldi et al. 2015

Summary

- The large SEP events are caused by energetic CME-driven shocks
- Radio bursts are indicative of electron acceleration; also accompanied by ion acceleration (SEPs)
- The SEP spectrum is important in assessing their space weather impact
- Flare reconnection also causes particle acceleration, but the contribution to SEPs in space is unclear
- Most SEP events are produced during solar maximum (when there is high level of magnetic energy available for powering CMEs)
- There are not many high-energy SEP events in cycles 24 and 25 – consequence of a weak heliosphere

Notes

- Atomic mass unit (amu) = 1/12 the mass of 12C
- It is close enough to nucleon masses
- MeV per nucleon in indistinguishable from MeV per amu for SEP studies
- Total energy $W = AM_u\gamma$; $M_u = m_u c^2 = 931.494$ MeV
- $\gamma = (1- \beta^2)^{-1/2}$; $\beta = v/c$
- Kinetic energy $\mathcal{E} = AM_u(\gamma -1)$

^{3}He-Rich Events

Flare-accelerated particles at 1 AU

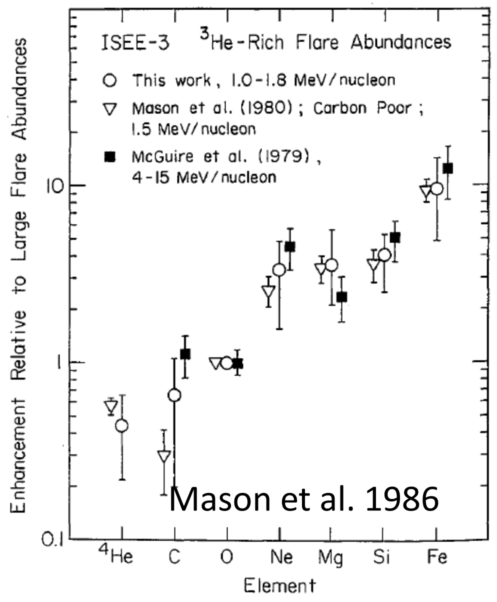
3He/4He > 0.1 (solar wind 5x10^{-4})

No CME association with ^{3}He-rich events

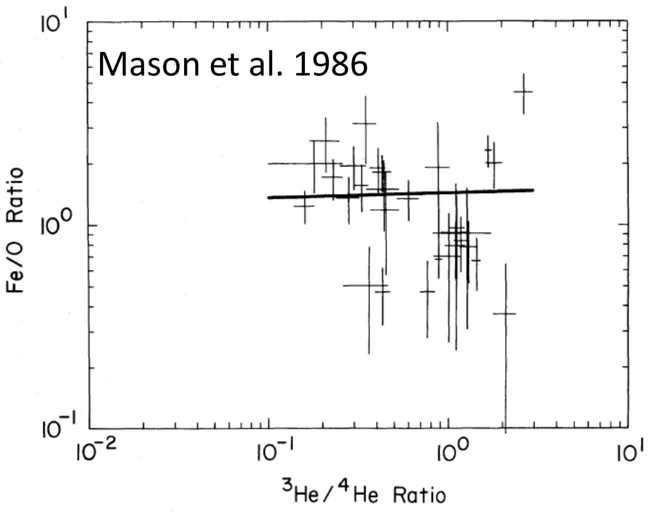
^{3}He-rich events associated with type III radio bursts produce by flare-accelerated electrons escaping into the IP space

Other heavy ions and the Fe/O-ratio enhanced

Enhancements of other heavy ions and Fe/O uncorrelated with ^{3}He/^{4}He



Mason et al. 1986



Mason et al. 1986

Shock Acceleration

Power-law energy spectrum in downstream region (Axford et al. 1977; Blandford & Ostriker 1978; Bell 1978; Lee 1983):

$$dJ/dE \propto E^{-\gamma}$$

Simple shock acceleration predicts independence of charge-to-mass ratio (Q/A)

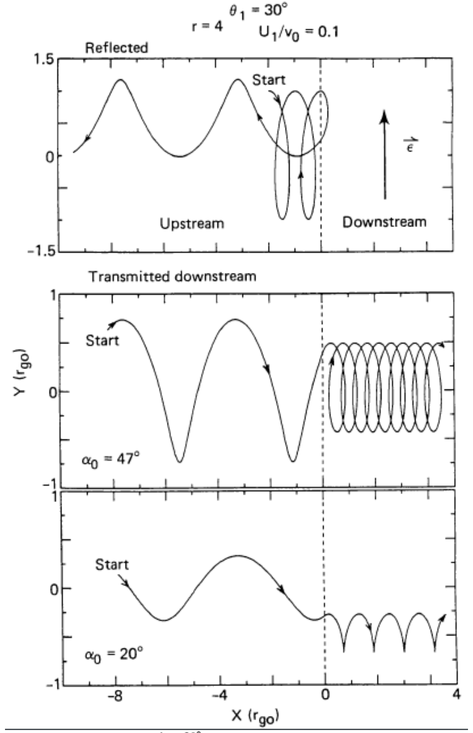
Shock lifetime and size limit the maximum energy of particles

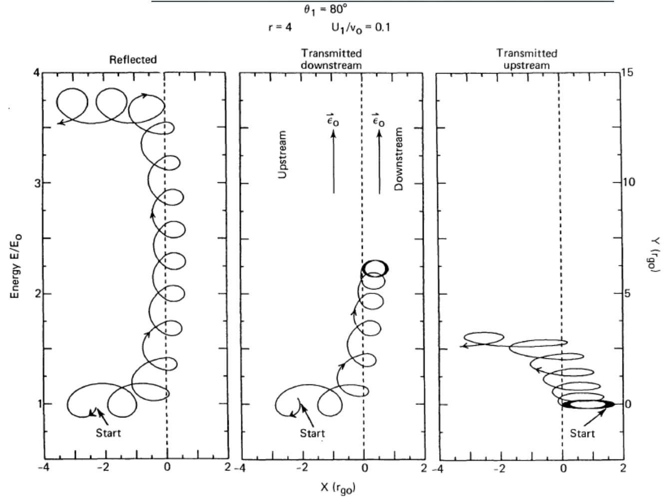
Diffusive shock acceleration (DSA):

- Quasi-parallel shock ($\theta_{BN} \leq 45°$)
- particles scattering between up- and downstream magnetic fluctuations (1st order Fermi acceleration)
- Slower acceleration rate
- Efficient scattering requires enhanced level of turbulence/waves

Shock drift acceleration (SDA):

- Quasi-perpendicular shock ($\theta_{BN} \geq 45°$)
- Induced electric field **E**=**V**×**B** at shock front
- Fast acceleration rate
- Higher maximum energy



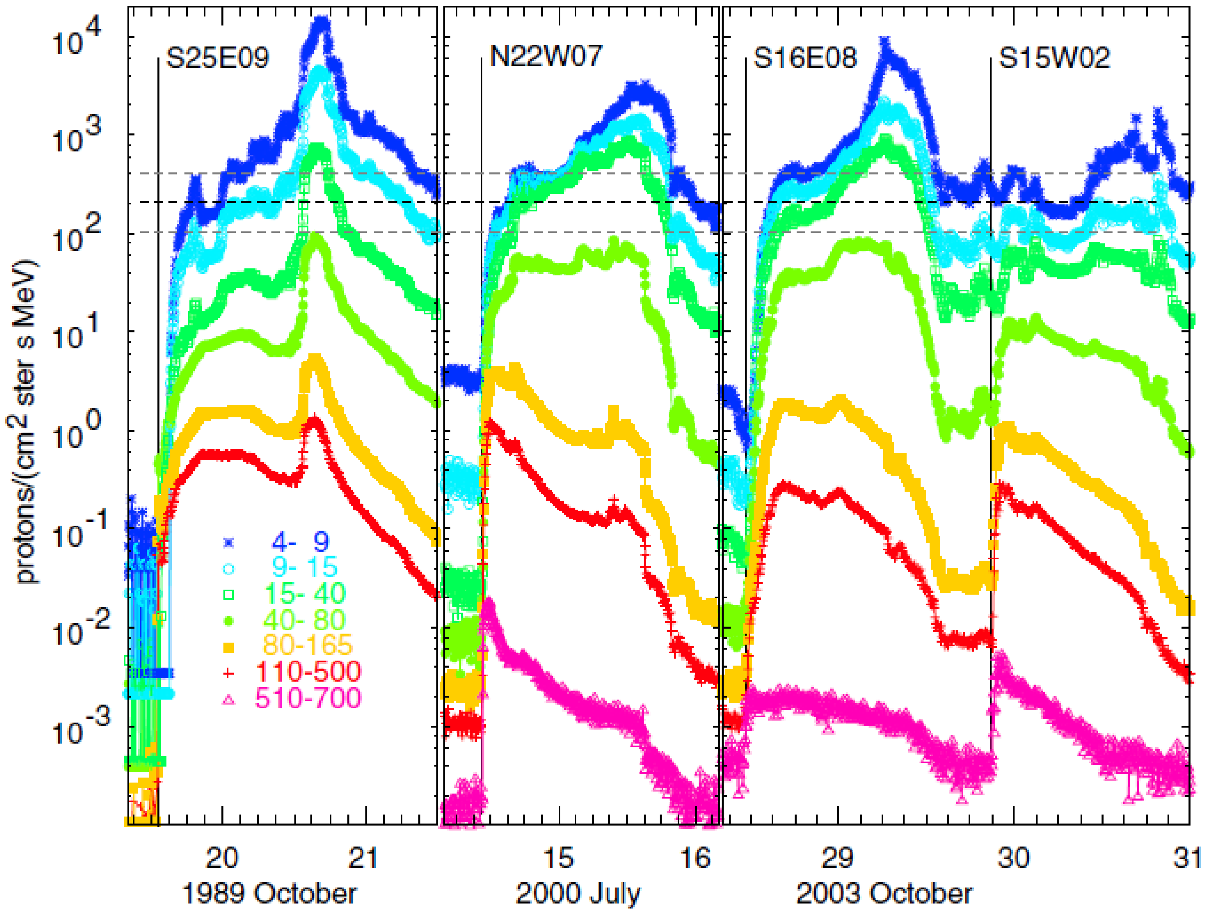


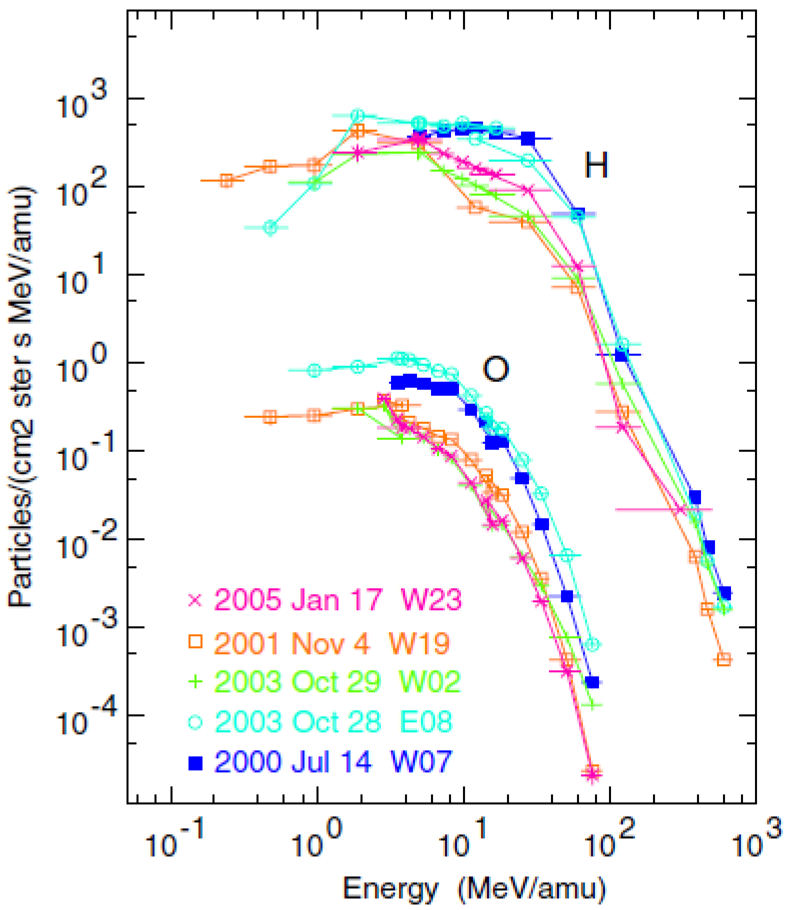
ϑ_{BN} is the angle between the shock normal and the direction of the upstream magnetic field

Decker 1988

Streaming-limited Intensities of SEP Events

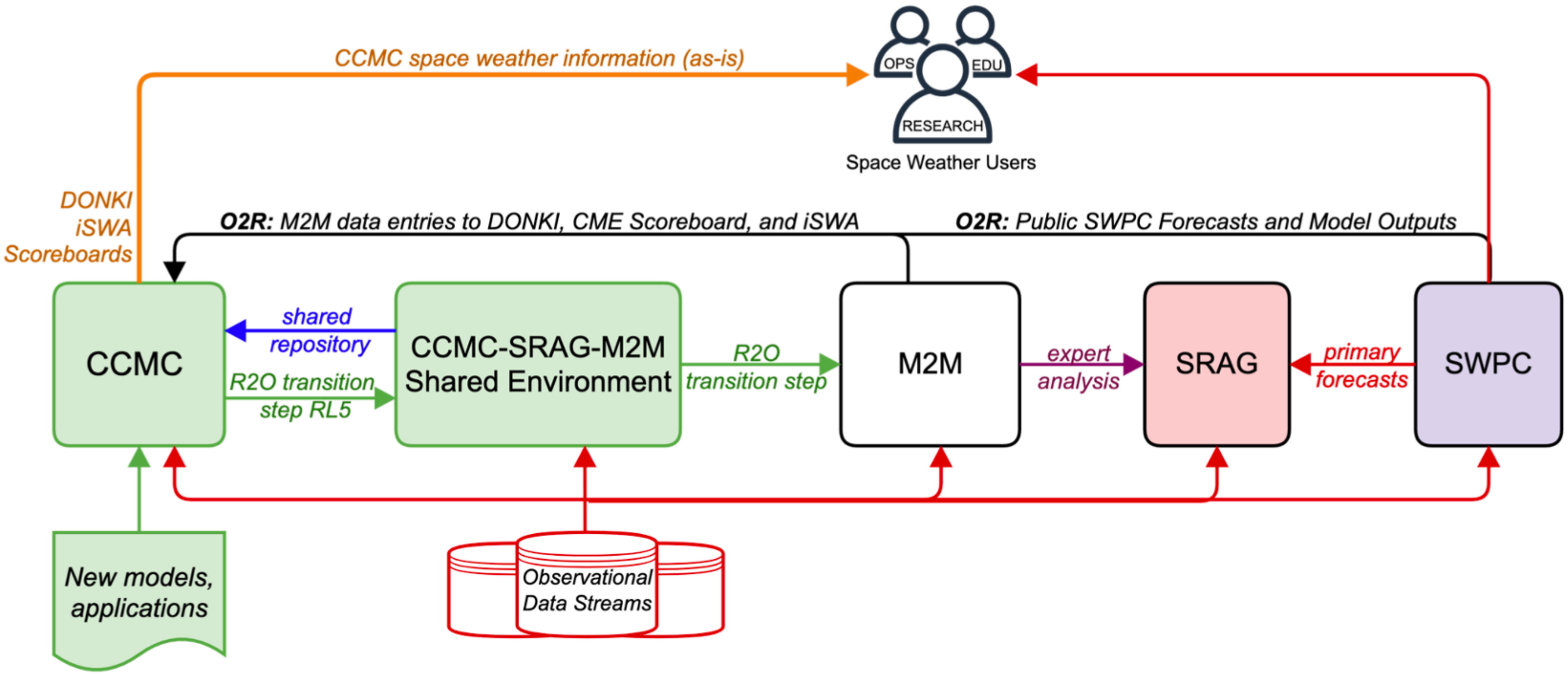
Reames & Ing 2010





- Plateau in lower energies after initial rise
- Tens of MeV protons cause Alfven waves, which throttle the lower energy particles (protons, He, Fe, O)

Max intensity ~400 H per (cm^2 s sr) in the energy range 5-20 MeV



Ishii et al. 2024

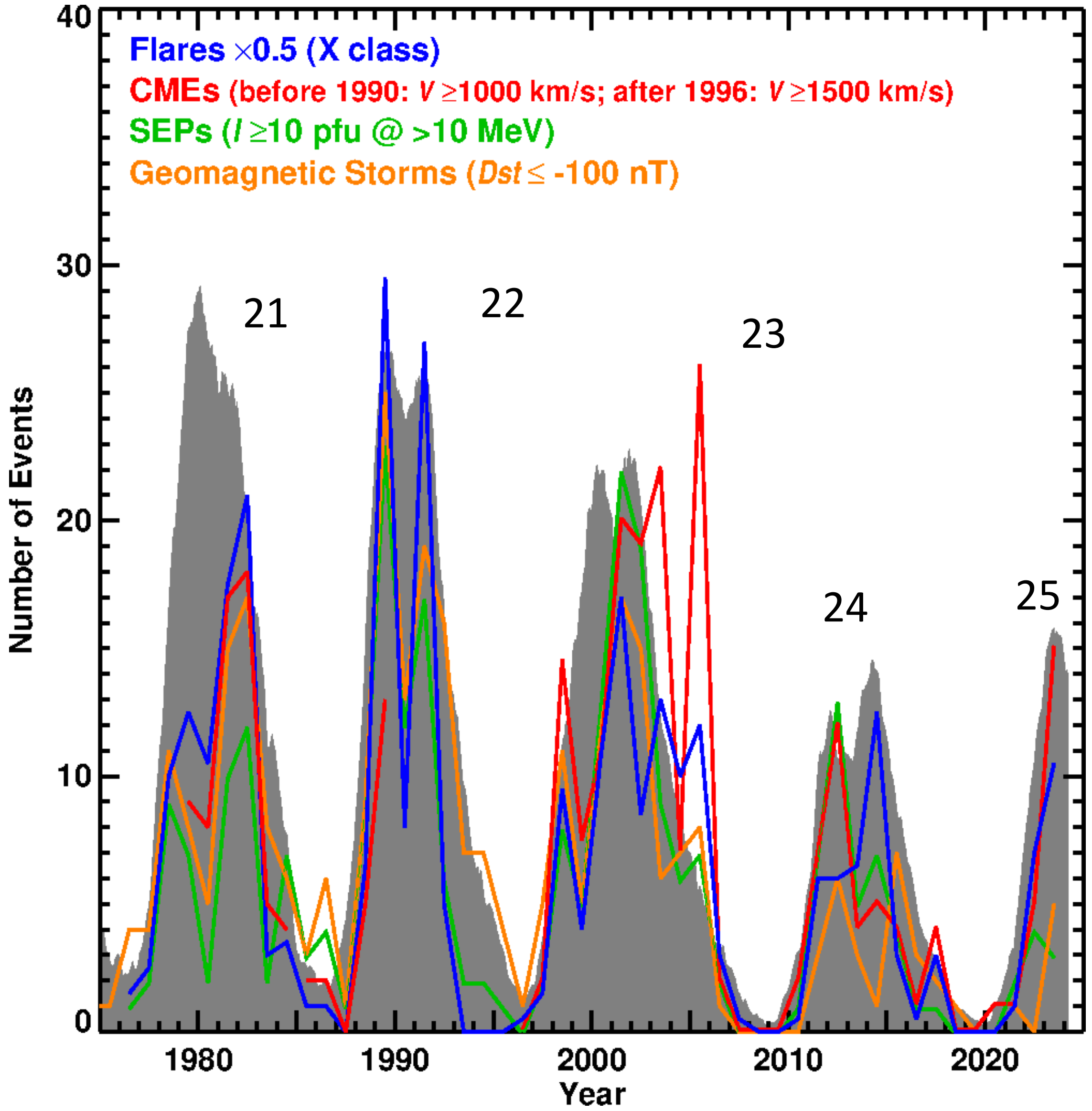
Overview

- What are solar energetic particle events?
- Coronal mass ejections (CMEs) and SEPs
- Brief History
- Radio bursts and shocks
- Properties of SEP-producing CMEs
- Height of shock formation
- Eruptive and confined flares
- Solar Cycle Variation of SEP events

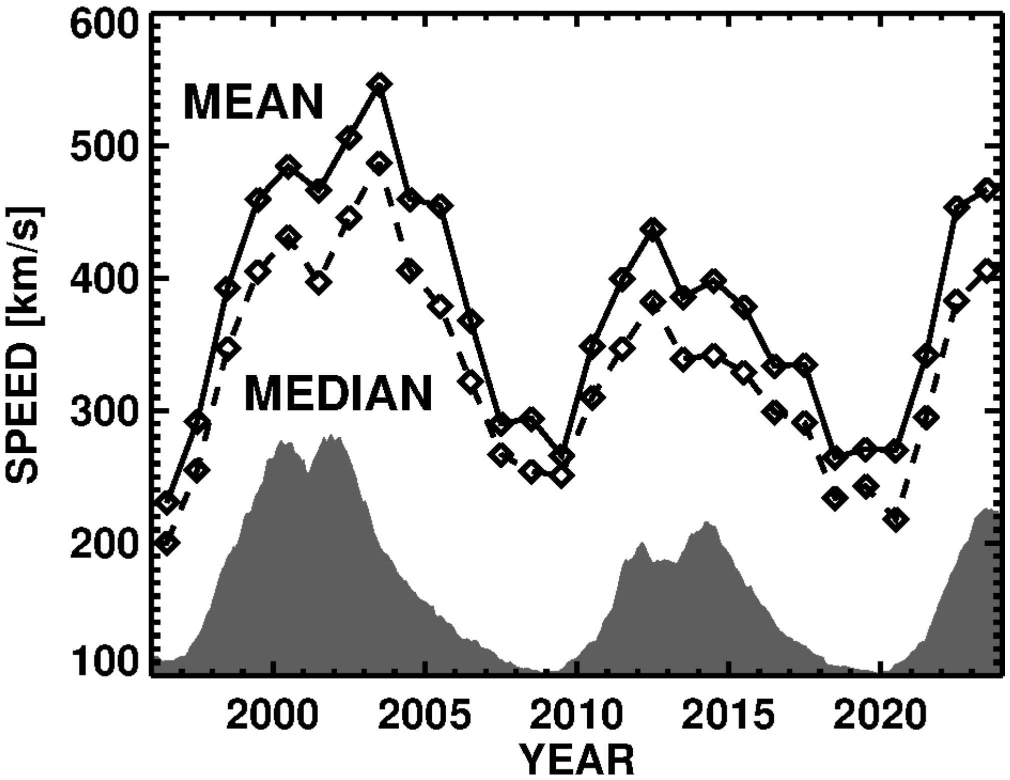
What are Energetic Particles?

- Speed of 2 MK protons: 129 km/s = 4.3e-4c [√(kT/m)]; T = 2 MK; ε_{th}= 175eV
- Speed of 2 MK electrons: 5547 km/s = 0.018c c = speed of light; m= mass
- 2 MK corresponds to an energy of 175 eV
- Nonthermal particles are energetic: $V \gg V_{th}$ or $\varepsilon \gg \varepsilon_{th}$
- Electrons KeV to 100s of MeV, protons of keV to tens of GeV from the Sun (1 GeV protons have a speed of ~0.875c = 260,000 km/s)
- Electrons and ions are detected by particle detectors; electrons are also inferred from their nonthermal radio emission
- Events involving emission of nonthermal particles are known as solar energetic particle (SEP) events. electrons, protons, He, Heavy ions
- Space weather community also uses the term solar proton events (SPEs) to specifically refer to energetic protons

SWx Sources: Solar Cycle Variation



- SWx in Cycles 24 &25 is clearly very mild
- CME and sunspot activity have discordant behavior between the two sunspot number peaks
- More fast CMEs during first peak, but a smaller SSN
- X-class flares are more during the second peak
- # of SEP events, magnetic storms similar to CMEs



Properties of CMEs Producing SEPs

- Need to be fast enough to drive a shock
- $V >> V_A \sim Bn^{-½}$
- The shock should be magnetically connected to the observer