CMEs and SEPs

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2017 CCMC Bootcamp, Tuesday June 6

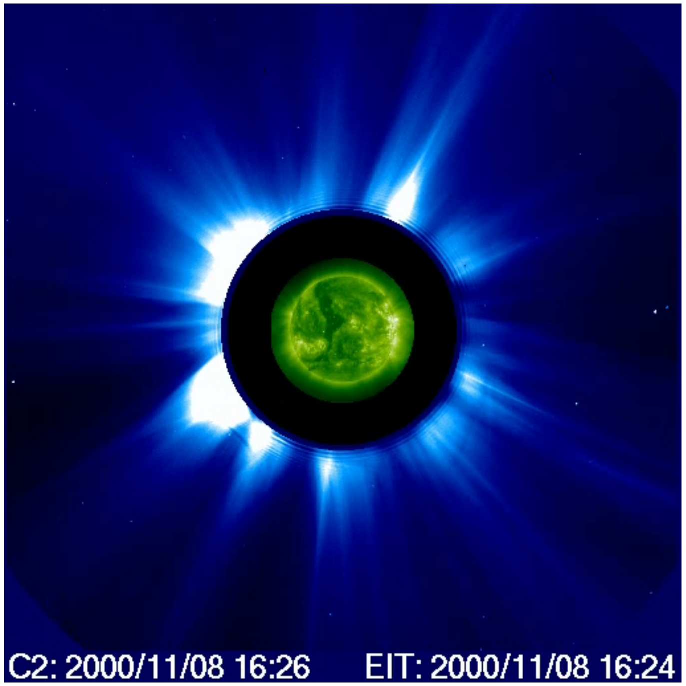
Overview

- What are solar energetic particle events?
- Coronal mass ejections (CMEs) and SEPs
- Brief History
- Radio bursts and shocks
- Properties of SEP-producing CMEs

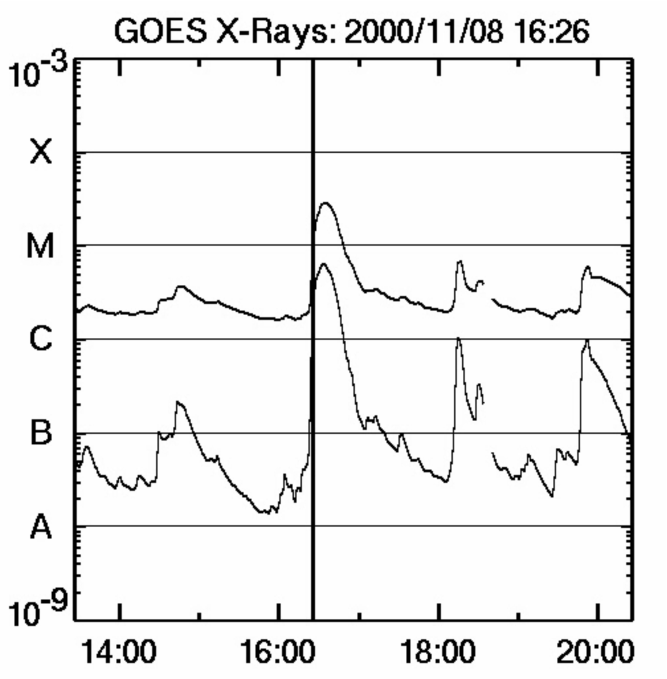
What are Energetic Particles?

- 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
- Space weather community also uses the term solar proton events (SPEs) to specifically refer to energetic protons

CMEs, Flares, SEPs



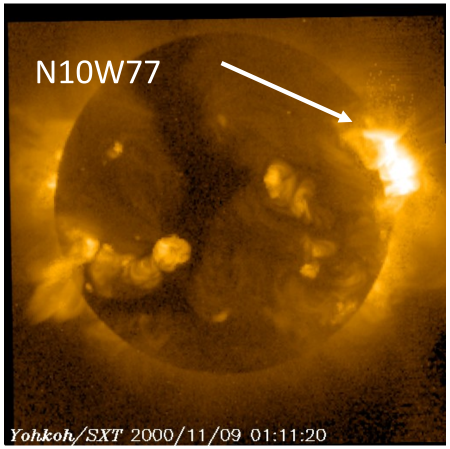
SOHO/LASCO and EIT



1-8 Å

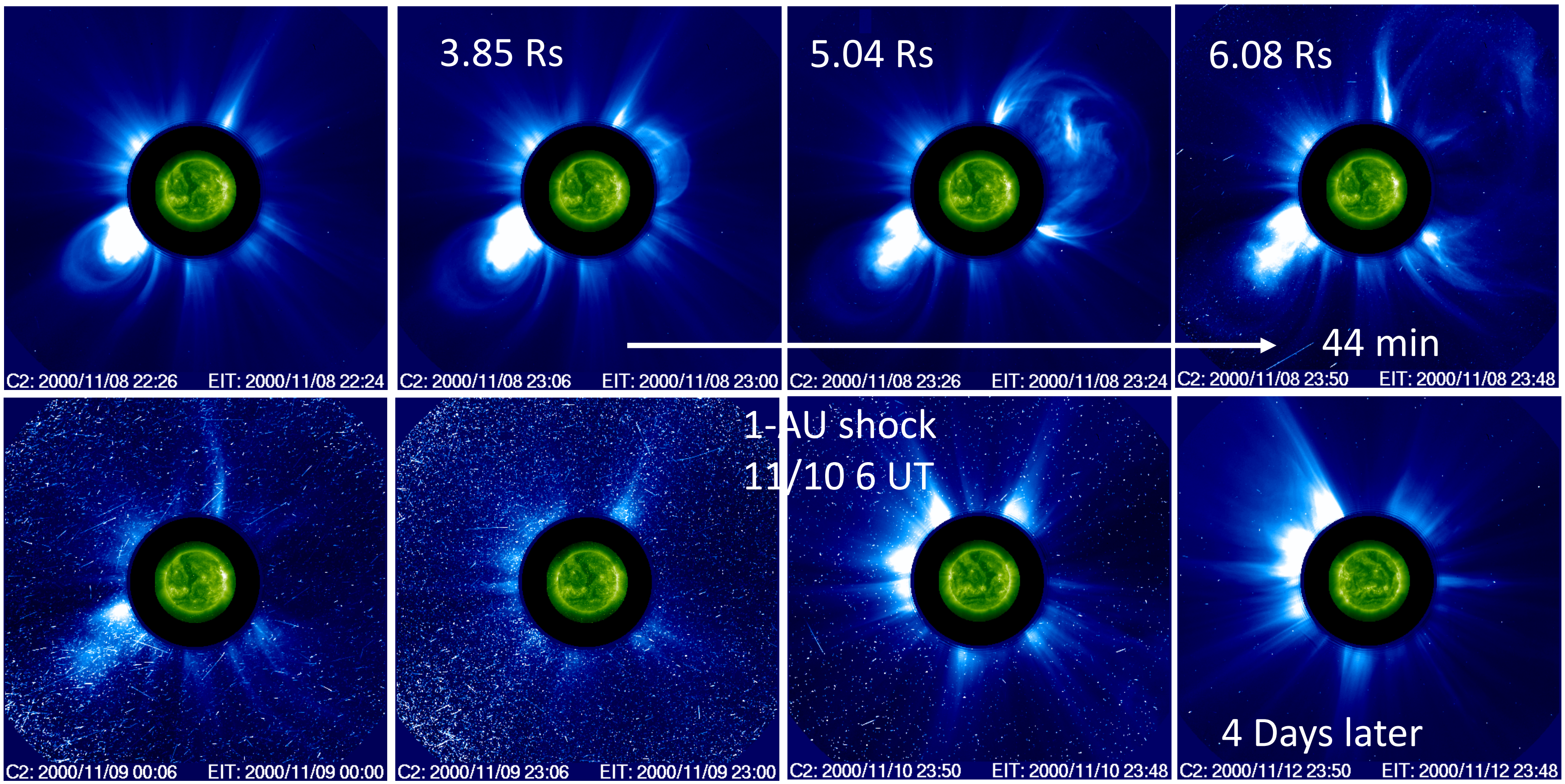
0.5-4 Å

http://cdaw.gsfc.nasa.gov

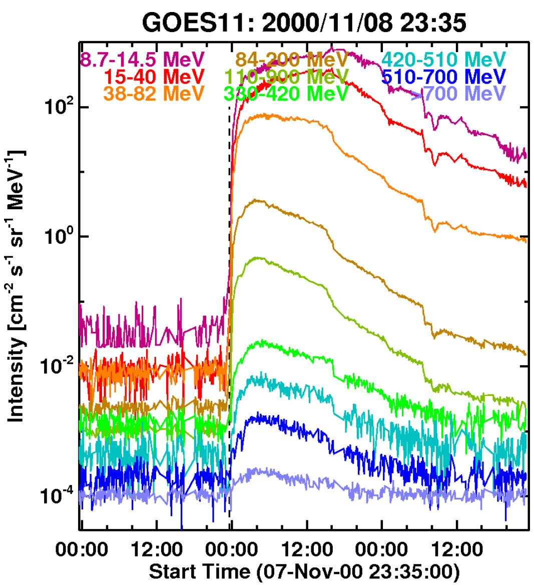


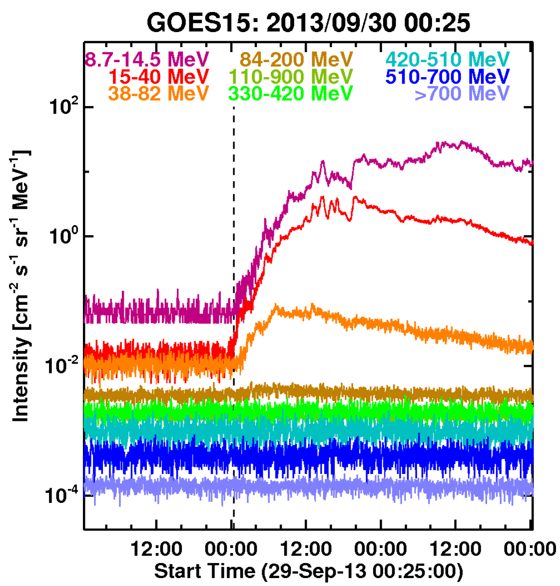
Yohkoh/SXT

Image Degradation due to Particle Impact

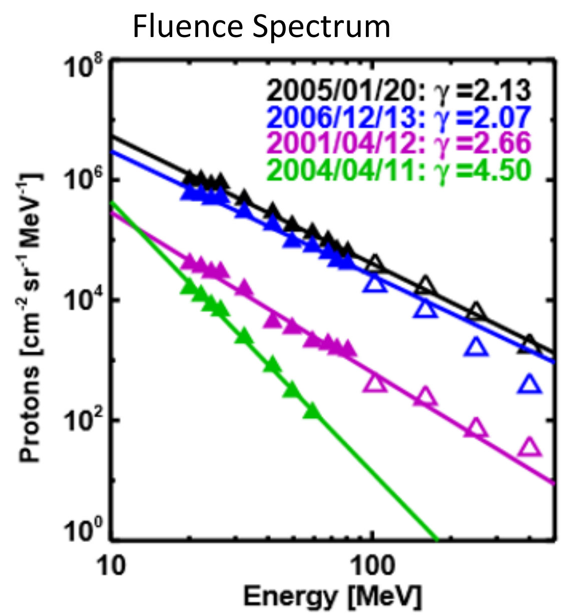


SEP Intensity, Energy Range, Spectrum





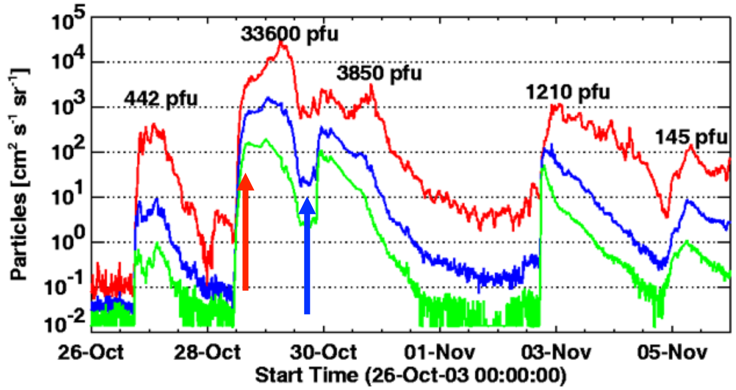
Intensity



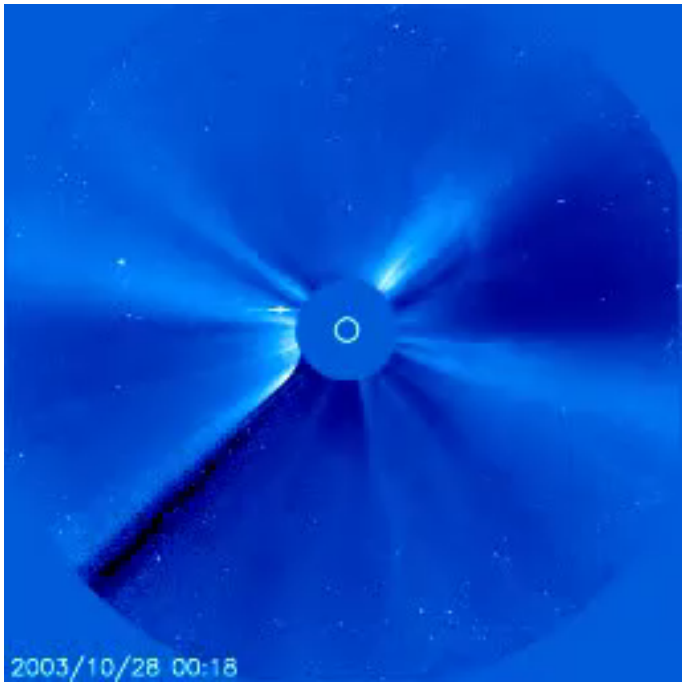
Spectrum

Double Whammy: Geomagnetic Storms & SEPs

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



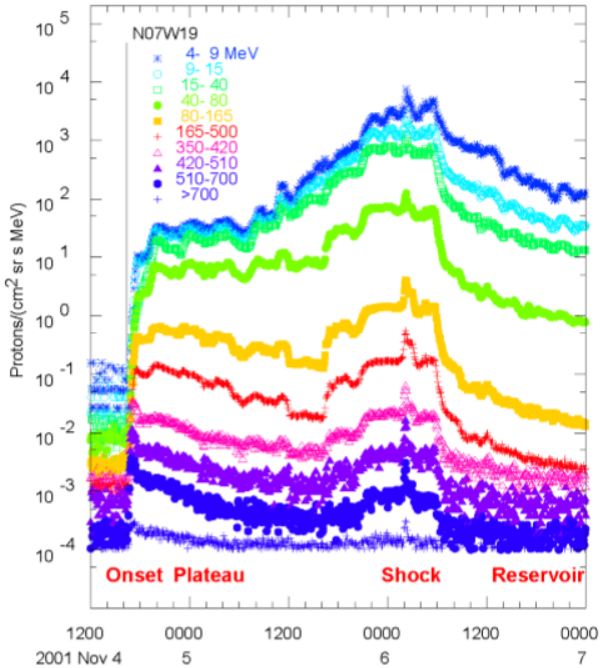
Two halo CMEs: 10/28 and 10/29 2003



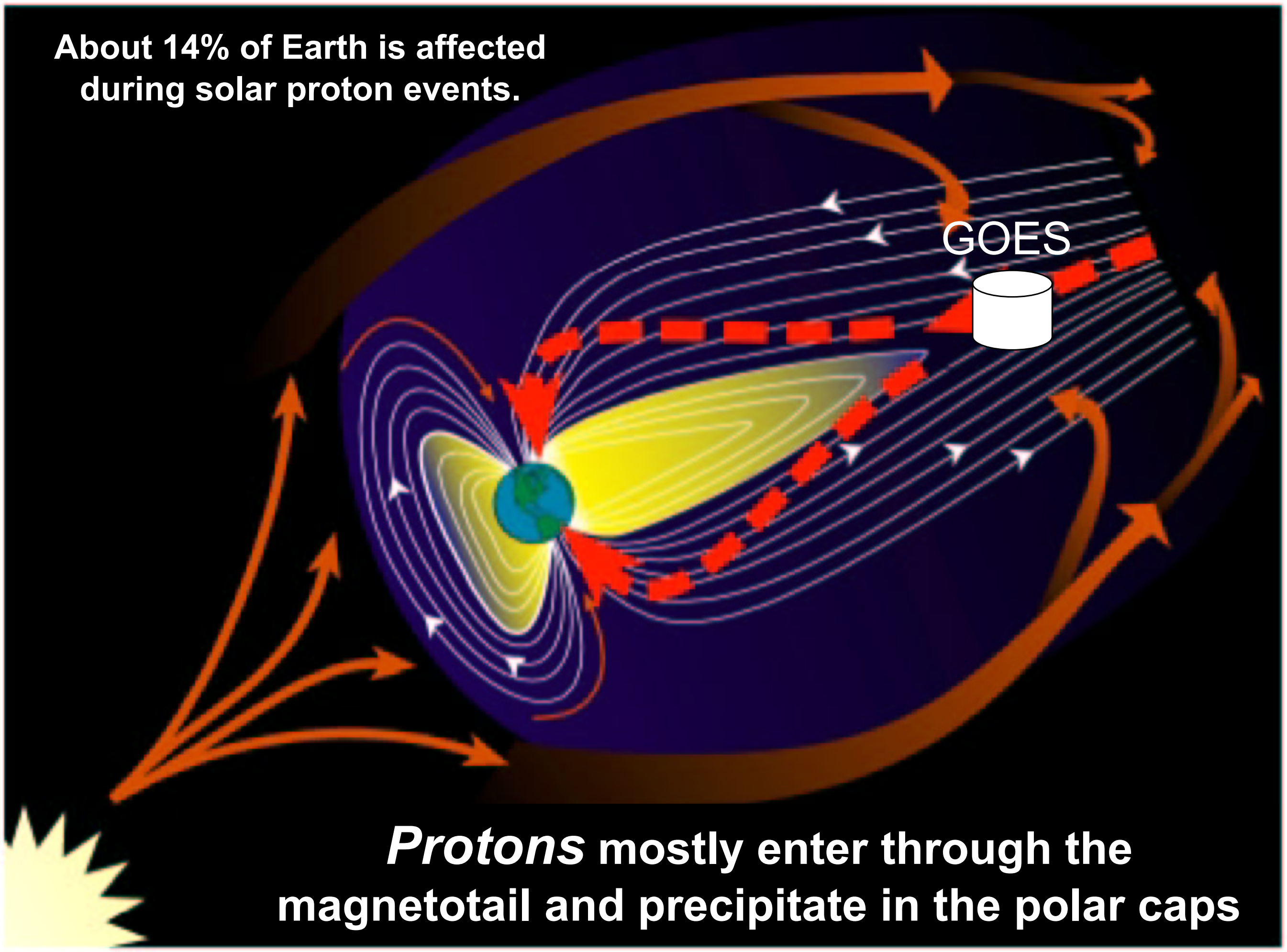
Transformer oil heated by 10° in Sweden; 50,000 people in Malmo had power blackout

SOHO/LASCO

General Time Profiles of SEP Events

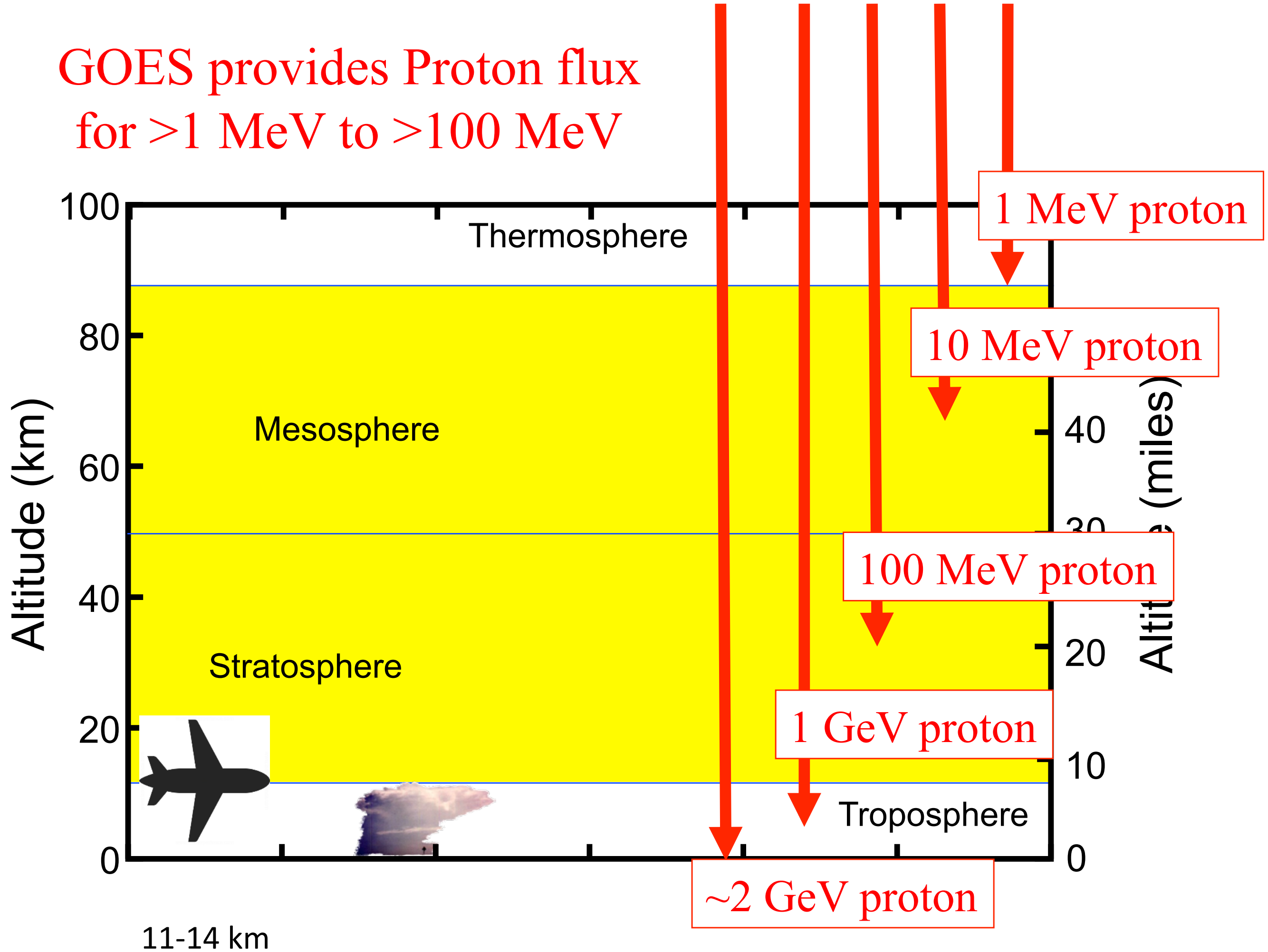


- Onset plateau due to waves trapping particles
- Peak when shock arrives at the detector
- Reservoir behind the shock

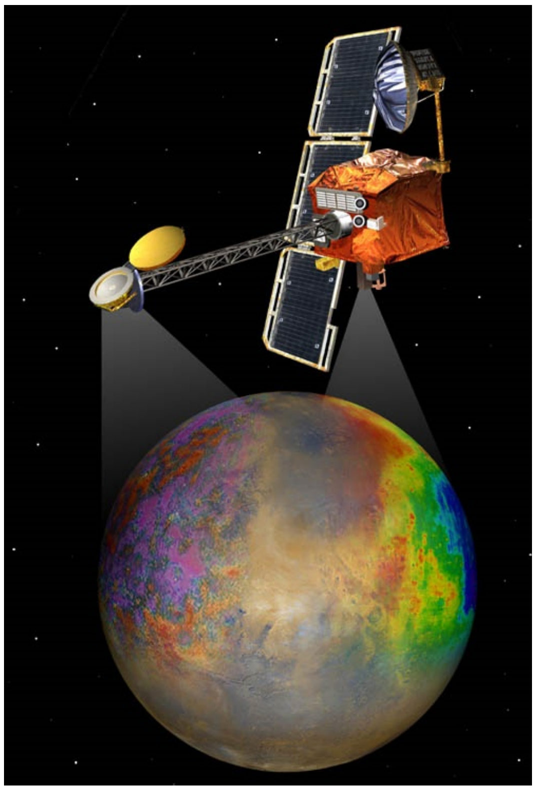


- Change in ionospheric conductivity
- Ozone depletion
- Radiation belt trapping and satellite anomalies

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



MARIE: The Martian Radiation Environment Experiment



Mars Odyssey

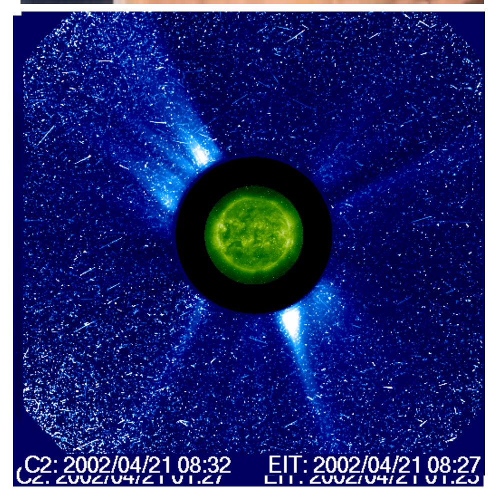
The MARIE instrument on Mars Odyssey observed the radiation levels on the way to Mars and in orbit, so that future mission designers could plan the trips of human explorers to Mars.

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

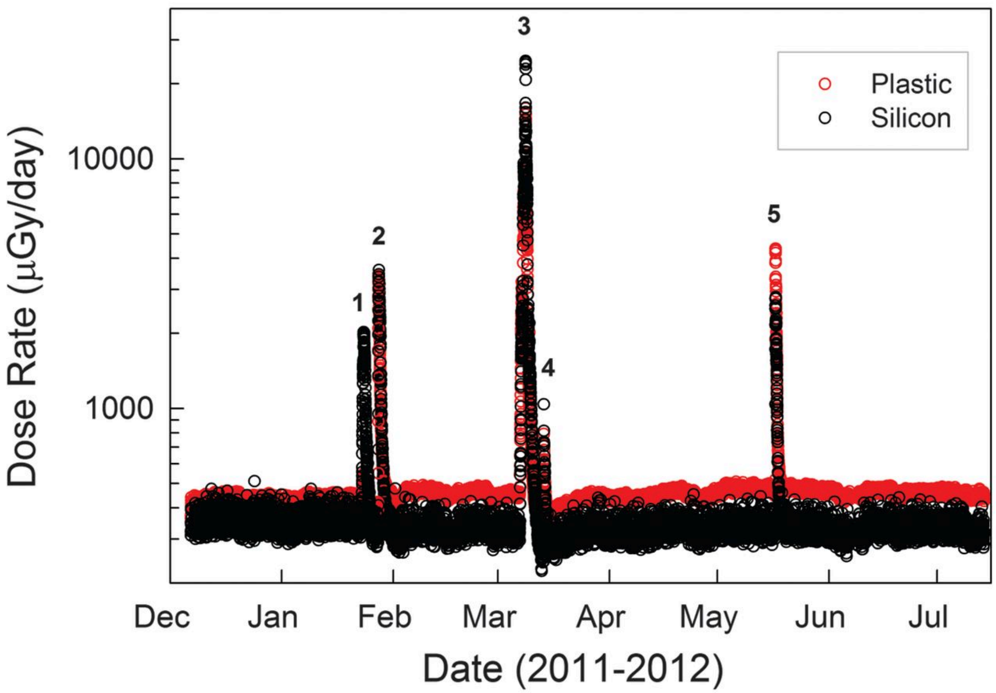
Radiation Assessment Detector (RAD) on board the Curiosity rover (Mars Science Laboratory) that a 360-day round trip would add a dosage of ~660 mSv. (Zeitlin et al. 2013)

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

Nozomi



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

Forbush Decrease, SEPs

Forbush (1946) Phys. Rev. Lett.

A full account of the experiment will be submitted for publication to the *Canadian Journal of Research*.

[1] C. Lapointe and F. Rasetti, Phys. Rev. 58, 554 (1940).
[2] John Marshall, Phys. Rev. 70, 107 (1946).
[3] J. Mattauch, *Kernphysikalische Tabellen* (Verlagsbuchhandlung Julius Springer, Berlin, 1942).

Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun

Scott E. Forbush
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

October 10, 1946

SEVERAL world-wide decreases in cosmic-ray intensity have been observed[1,2] during magnetic storms. These decreases have been ascribed[3] to ring currents, or their equivalents, required to account for the observed world-wide magnetic changes.

In about 10 years of continuous records of ionization in Compton-Bennett meters (shielded by 11-cm Pb) three obviously unusual increases in ionization have been noted. For Cheltenham, Maryland, geomagnetic latitude, $\Phi=50°$ N, these are shown in Fig. 1, in which the bi-hourly means were corrected for barometric pressure. Curves very similar to the upper one in Fig. 1 obtain[2] simultaneously for Godhavn, Greenland, $\Phi=78°$ N; and for Christchurch, New Zealand, $\Phi=48°$ S. Except for the absence of significant increases on February 28, 1942; March 7, 1942; and July 25, 1946, the curves for Huancayo, Peru, $\Phi=1°$ S, are otherwise quite similar to those for Cheltenham.

Figure 1 indicates each of the three unusual increases in cosmic-ray intensity began nearly simultaneously with a solar flare (bright chromospheric eruption)

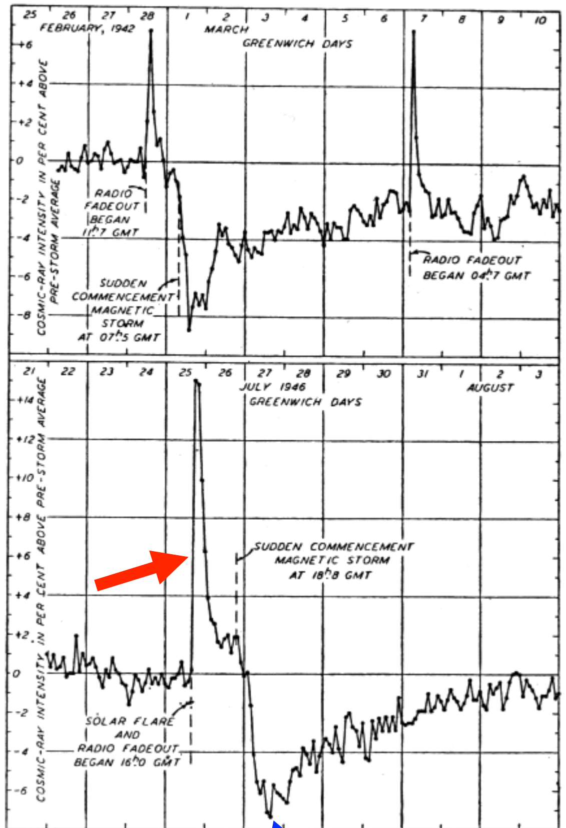
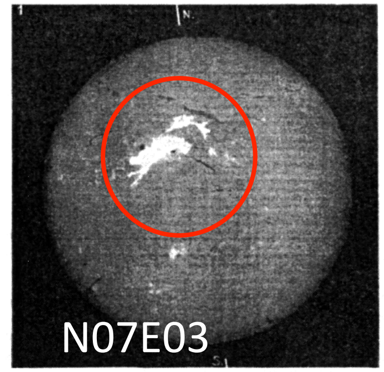


FIG. 1. Three unusual increases in cosmic-ray intensity at Cheltenham, Maryland, during solar flares and radio fadeouts.

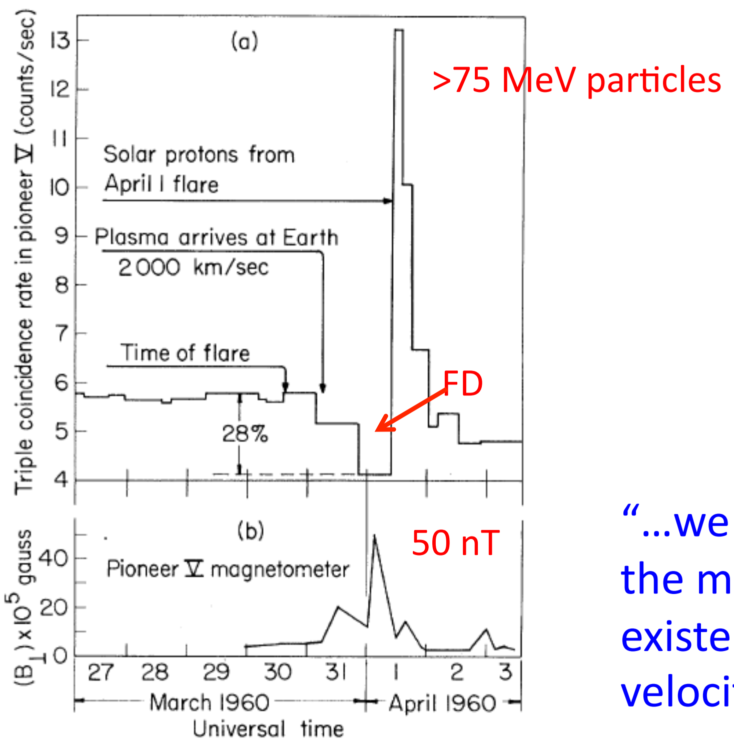
Forbush decrease (1937)



25 July 46 GLE Flare

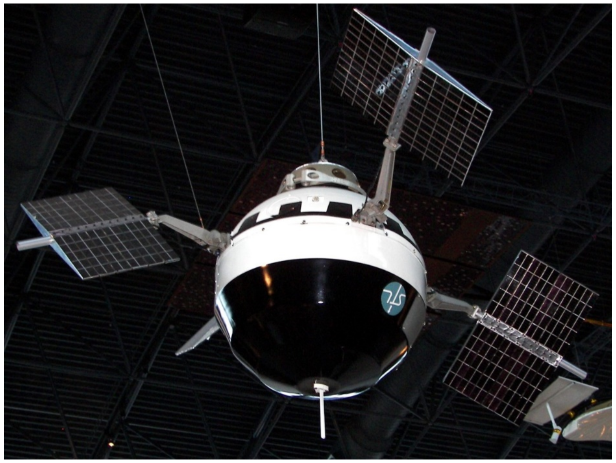
Scott E. Forbush
(1904-1984)

High Velocity Magnetized Plasma from the Sun



Fan, Meyer, Simpson, 1960 Phys Rev Lett

Pioneer 5
launch: 3/11/1960



"…we believe these Pioneer V results provide the most direct evidence to date for the existence of conducting gas ejected at high velocity from solar flares"

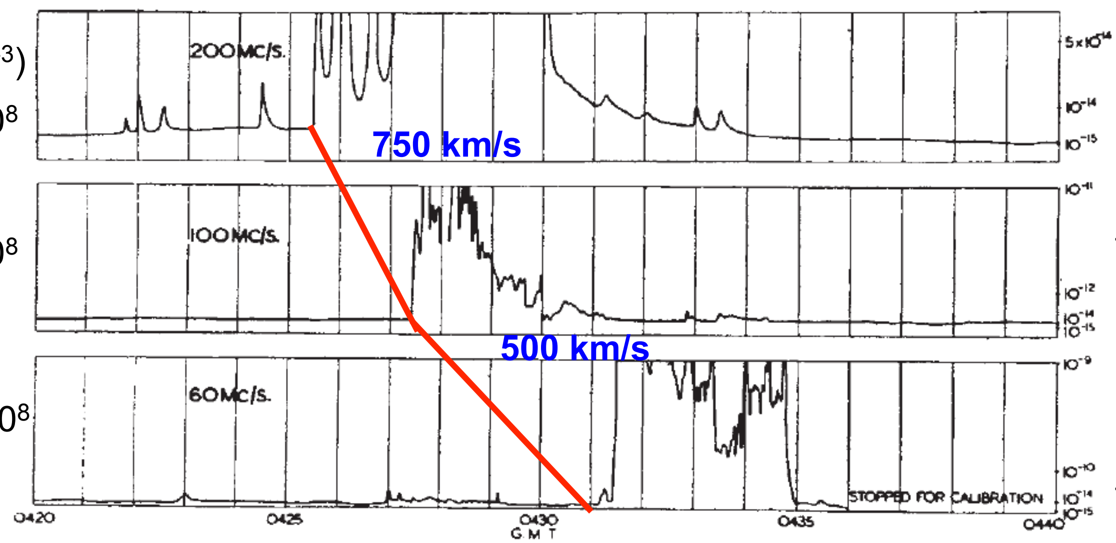
Radio Bursts Reveal Matter Leaving the Sun

The whole pattern drifts; 140 MHz in 6 min → df/dt = 0.4 MHz/s
"…the derived velocities are of the same order as that of prominence material…"

Ruby Payne-Scott
1912 – 1981

-Classified as type II radio bursts (Wild & McCready 1950)
-Caused by ~10 keV electrons accelerated in MHD shocks (Uchida 1960)
-Plasma emission mechanism (Ginzburg & Zhelezniakov 1958)
Nelson & Melrose (1985)

Plasma density (cm^{-3})
5.0 $\times 10^8$
1.2 $\times 10^8$
0.4 $\times 10^8$

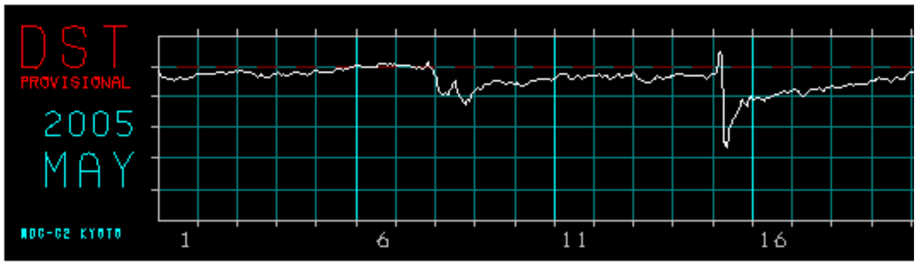


WATTS METRE^{-2}(MEGACYCLE/SEC)$^{-1}$

LARGE OUTBURST OF MARCH 8, 1947

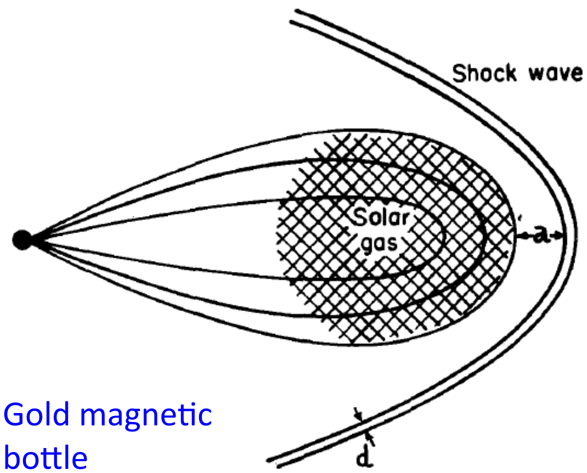
Payne-Scott, Yabsley & Bolton 1947, Nature 260, 256

Shocks in the IP medium



1953: Gold proposed Interplanetary shock to explain the Sudden Commencement

T. Gold (1920 – 2004)



Gold magnetic bottle

1962: "Idealized configuration in space, showing solar plasma cloud, the drawn-out field and the shock wave ahead"

MHD shock theory: de Hoffmann & Teller 1950
Parker applied it to interplanetary shocks in 1963

Radio Bursts: Nonthermal Electrons from the Sun

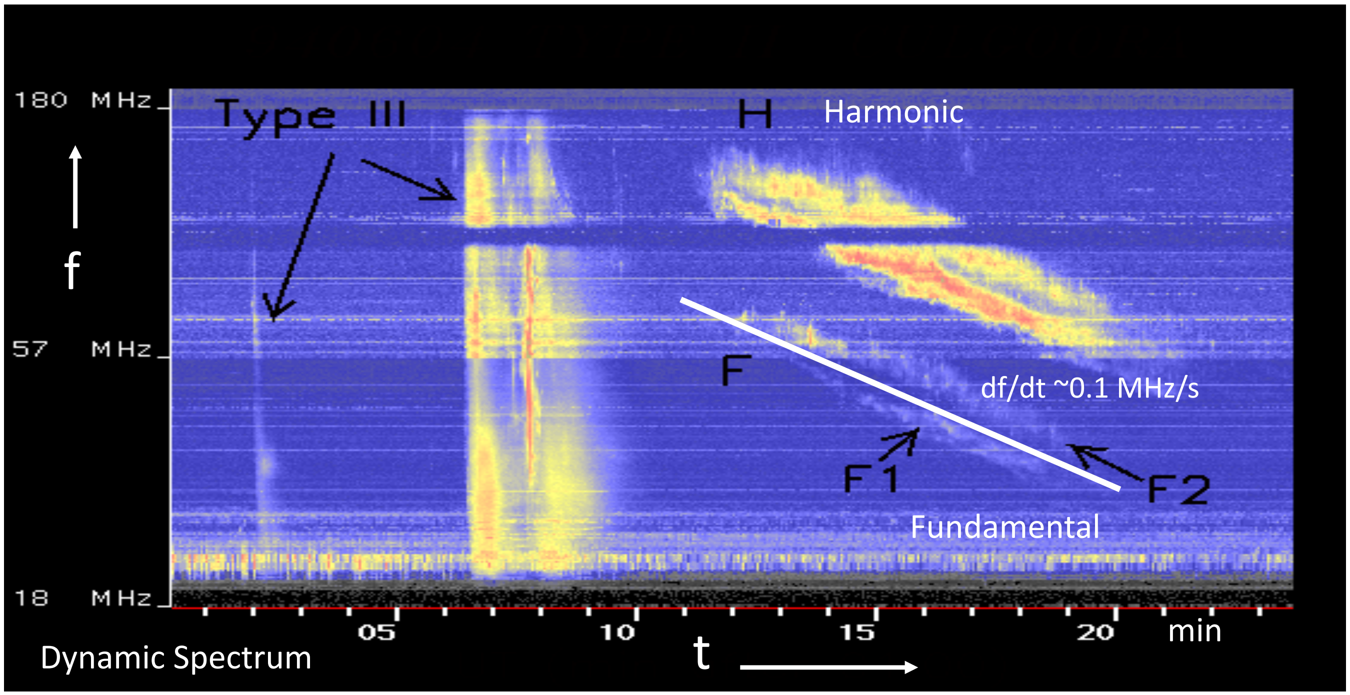
Type III (electron beams) v ~ 0.3 c

Type II (shocks) v >/~ 600 km/s

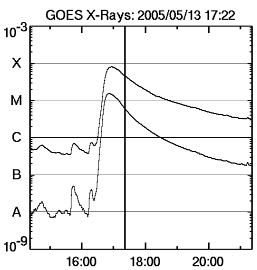
$df/dt = df/dr.dr/dt = (V/2)\, f\, n^{-1}(dn/dr)$

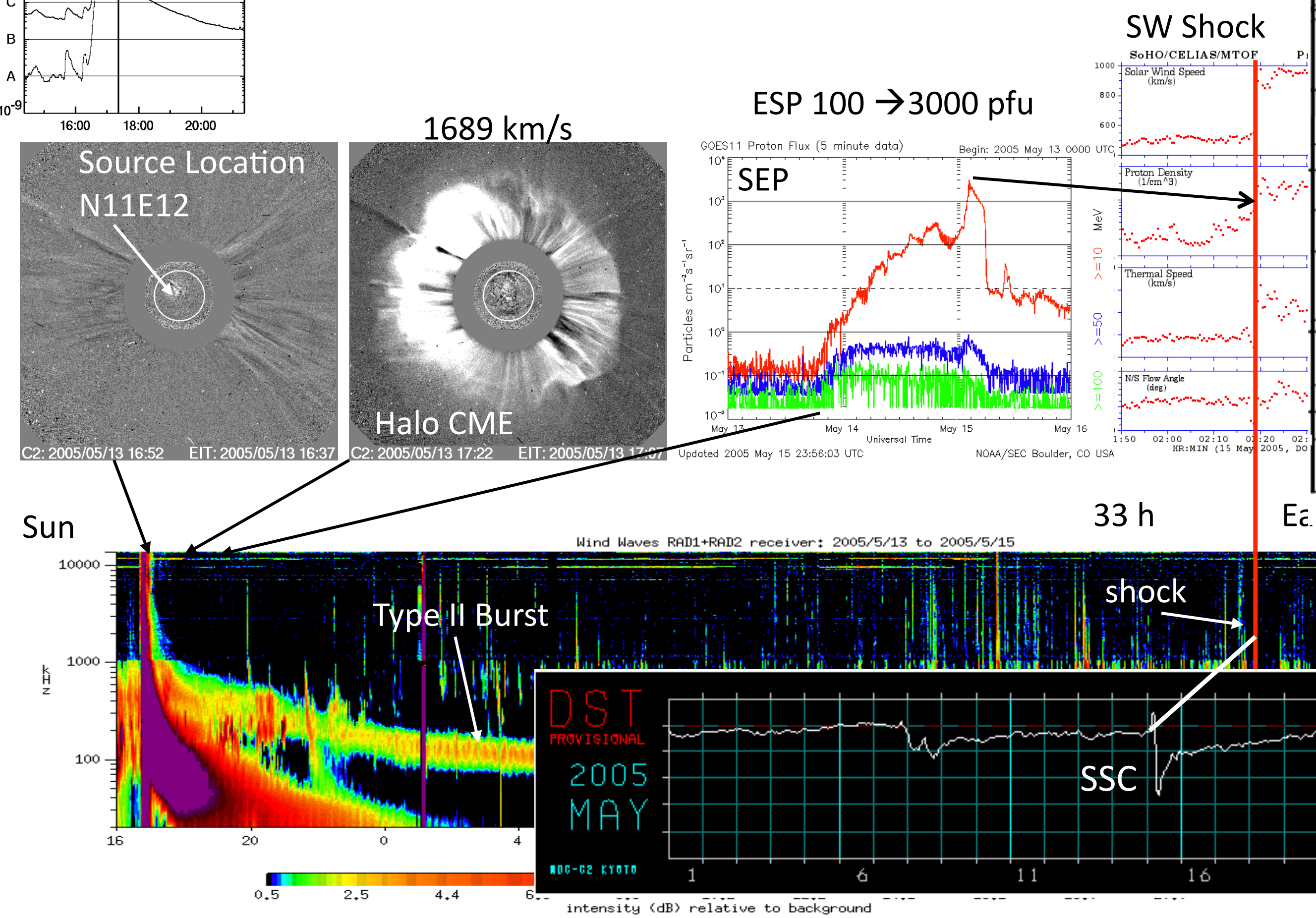
$V = 2L(d\ln f/dt)$

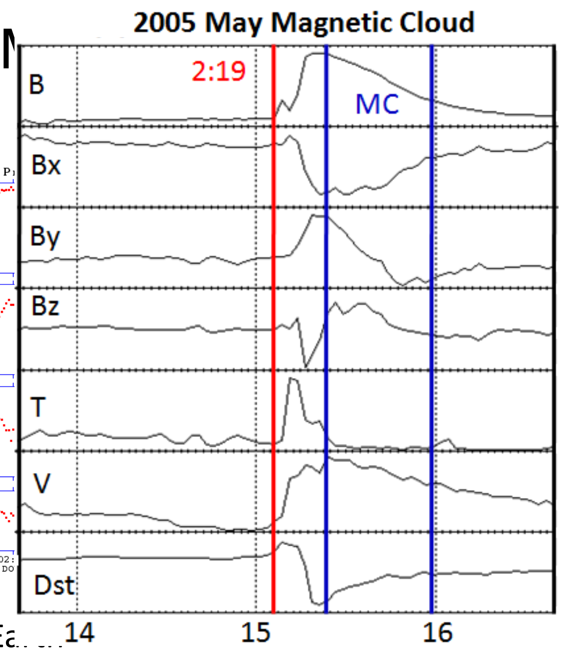
$f \sim n^{1/2}$ (plasma frequency)



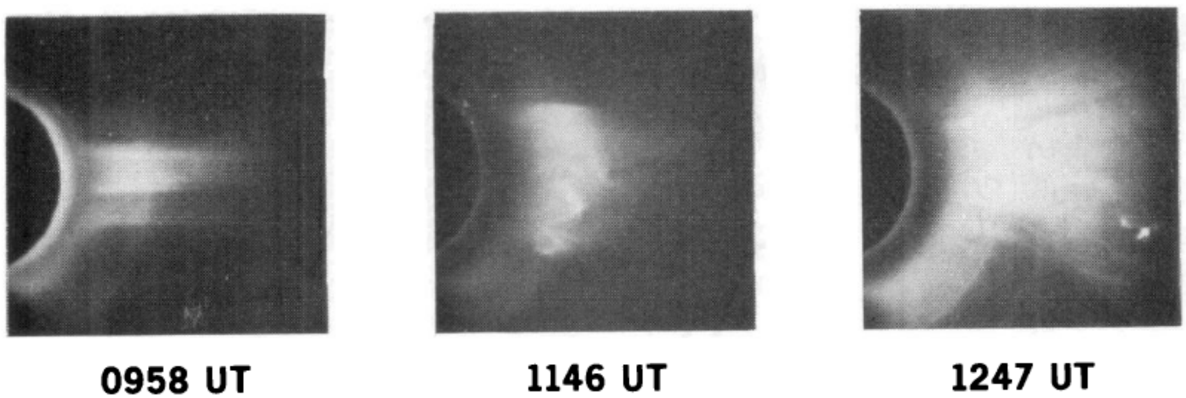
Range of Phenomena: 2005 May 13 CME





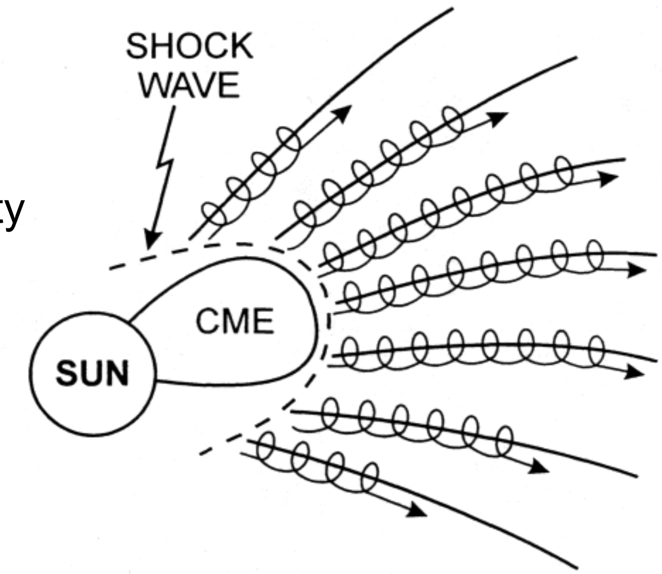


in-situ "view" of the CME



Skylab CME on January 15, 1974

S. W. Kahler



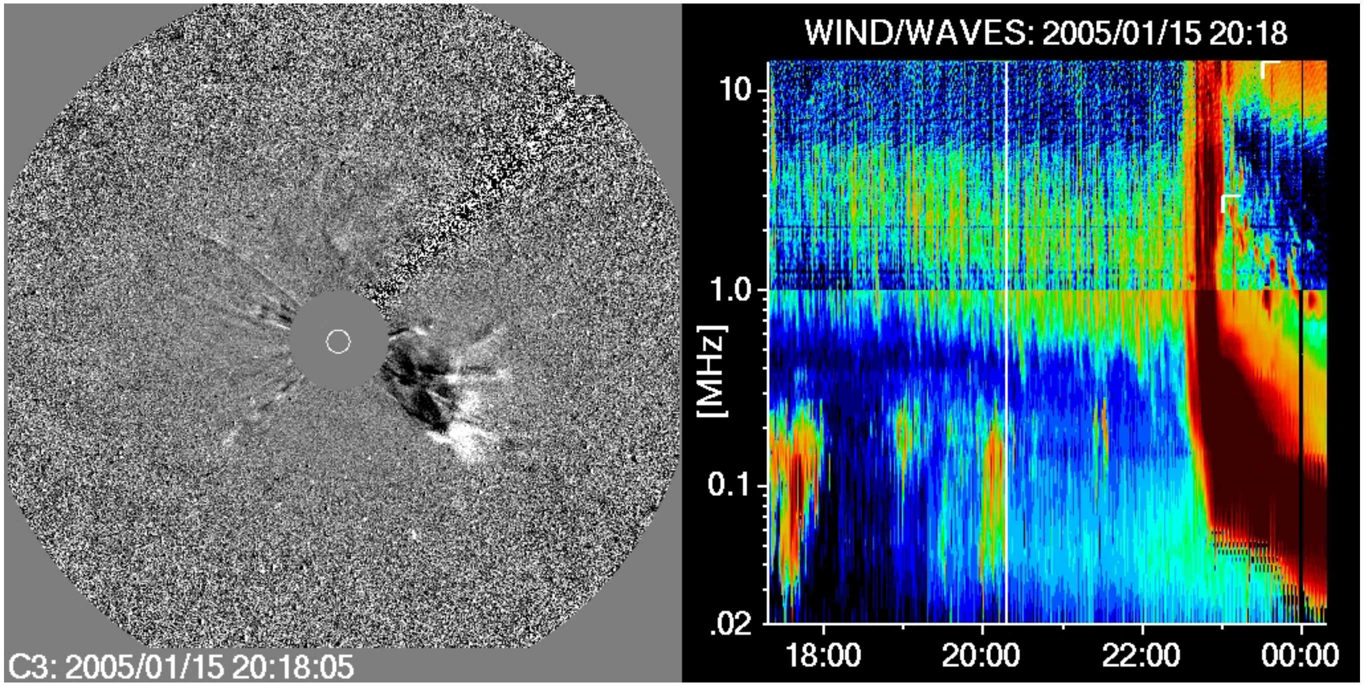
Studied 16 Skylab CMEs; 14 had SEP events
Found correlation between CME speed and SEP intensity

"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)

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

Interplanetary Shock and Radio Burst

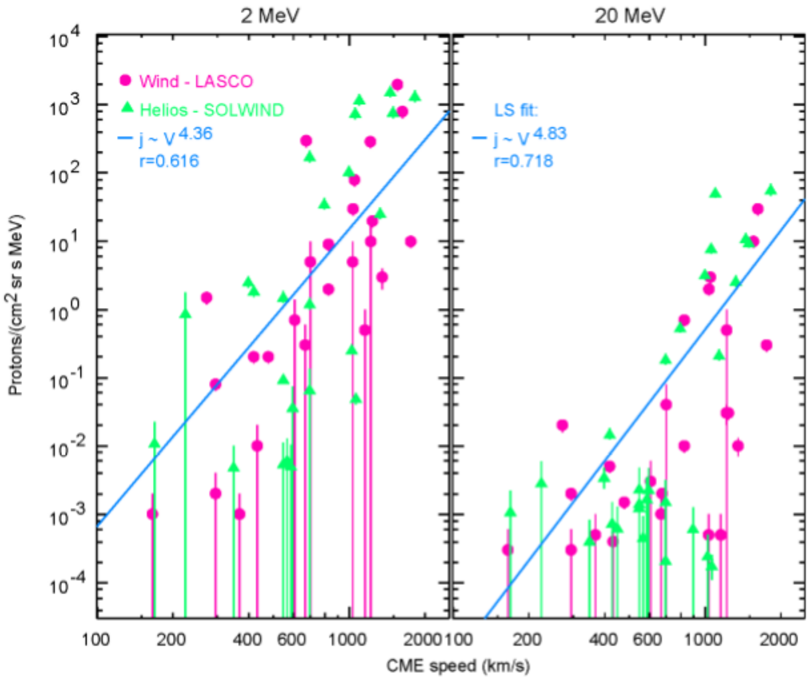


Cane et al. 1987; Reiner et al. 1997; Bougeret et al. 1998; Gopalswamy et al. 2001; 2004; 2005, 2011

Properties of CMEs Producing SEPs

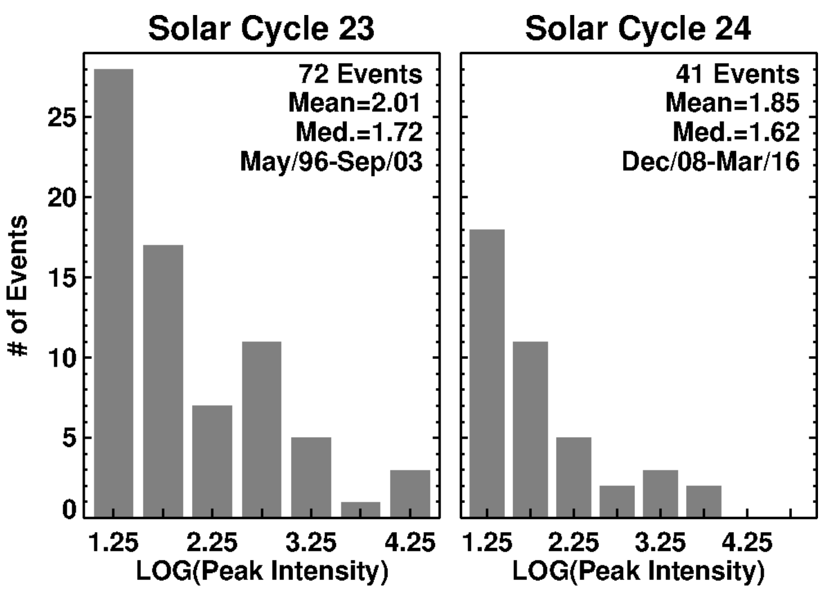
- Need to be fast enough to drive a shock
- The shock should be magnetically connected to the observer

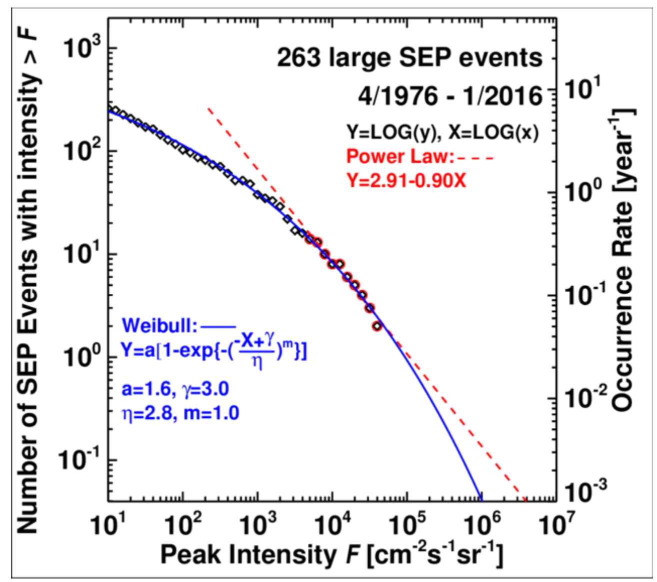
SEP Intensity vs. CME Speed



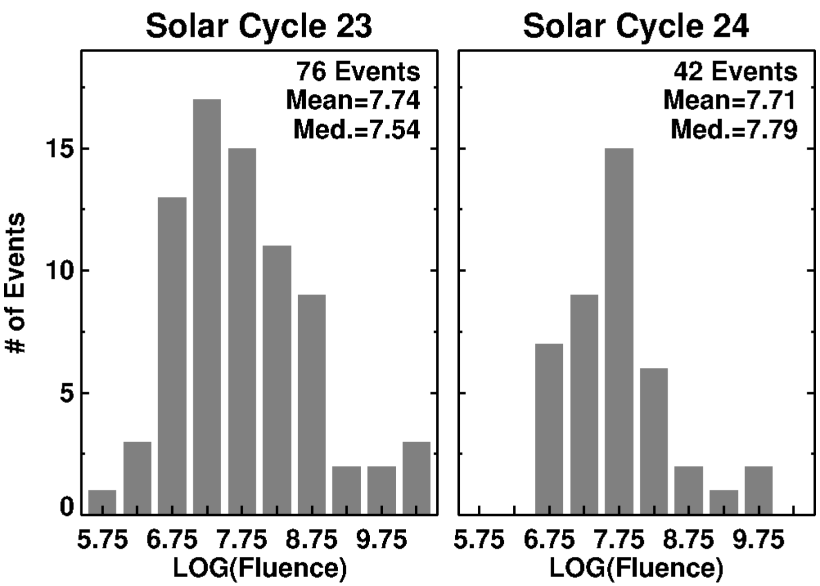
SEP Intensity correlated with CME speed
Large Scatter
Source and Environmental factors connectivity

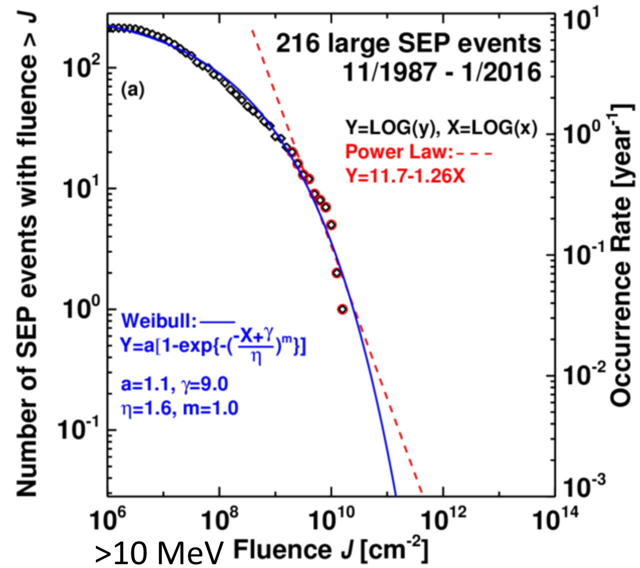
SEP Intensity and Fluence



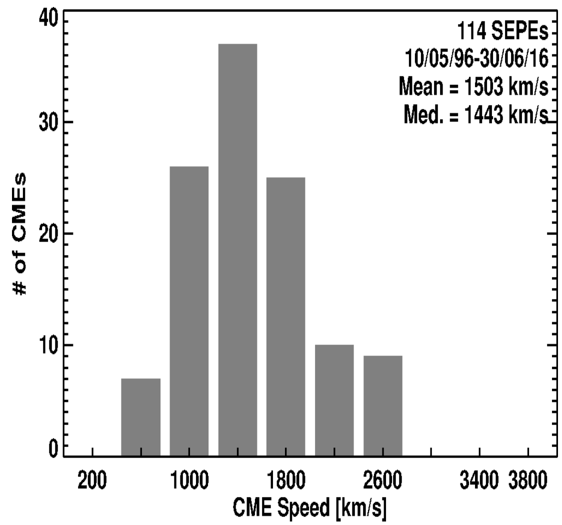


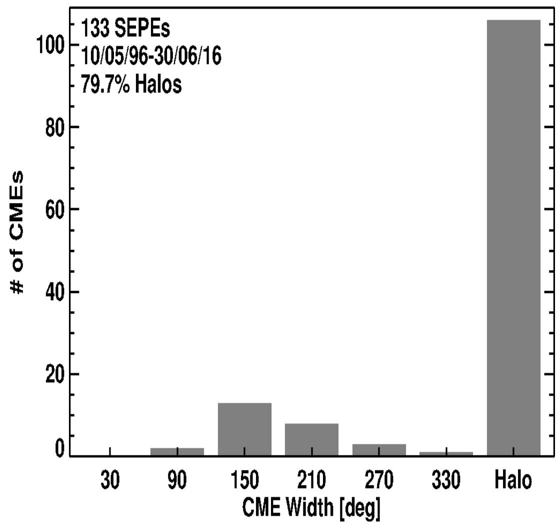
SEP Intensity and Fluence

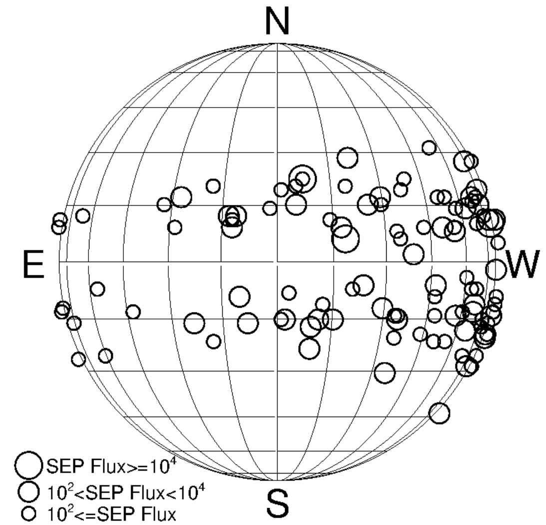




Properties of CMEs producing Large SEP Events

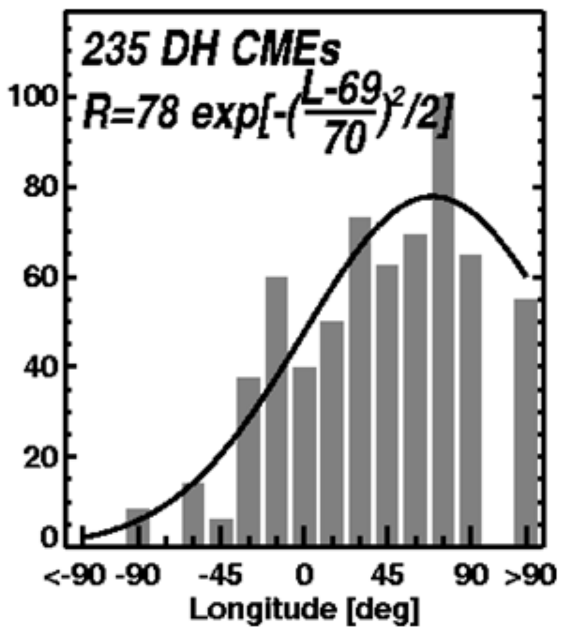


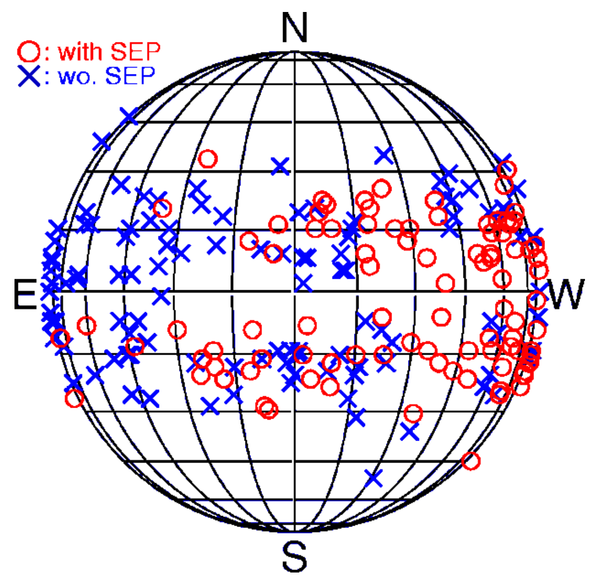




- SEP Events are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Shock-driving capability of CMEs key for SEPs

CMEs Associated with Type II Bursts and SEPs





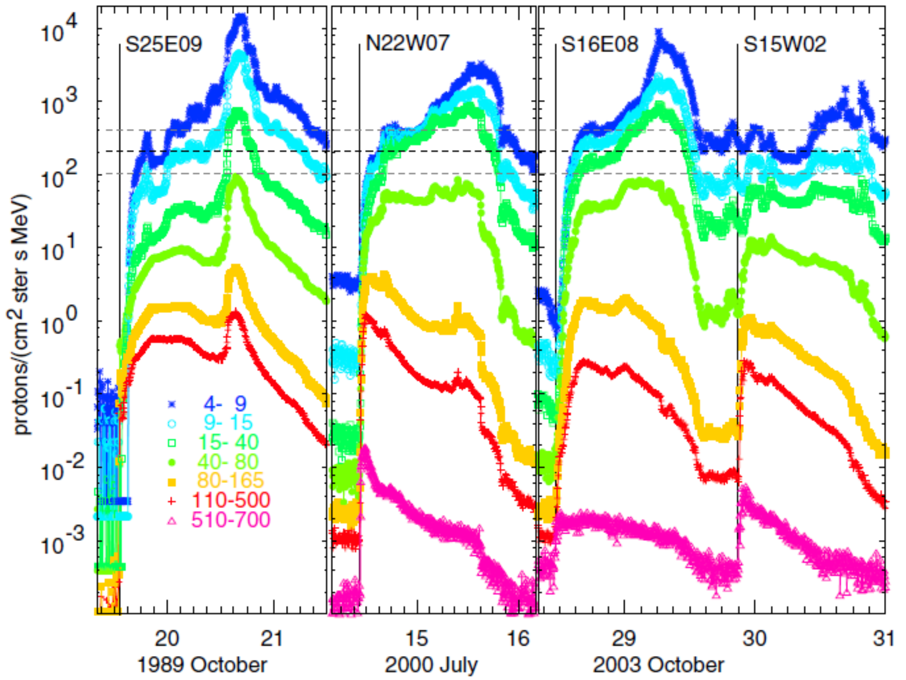
Sources of CMEs associated with type II bursts at f < 14 MHz (Decameter-hectometer and longer wavelengths)

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)

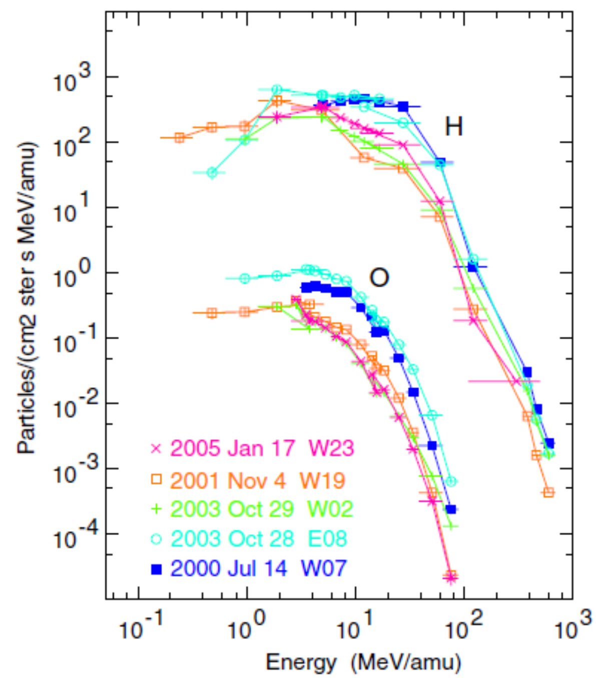
Gopalswamy et al. 2008 Ann Geo

Steaming-limited Intensities of SEP Events



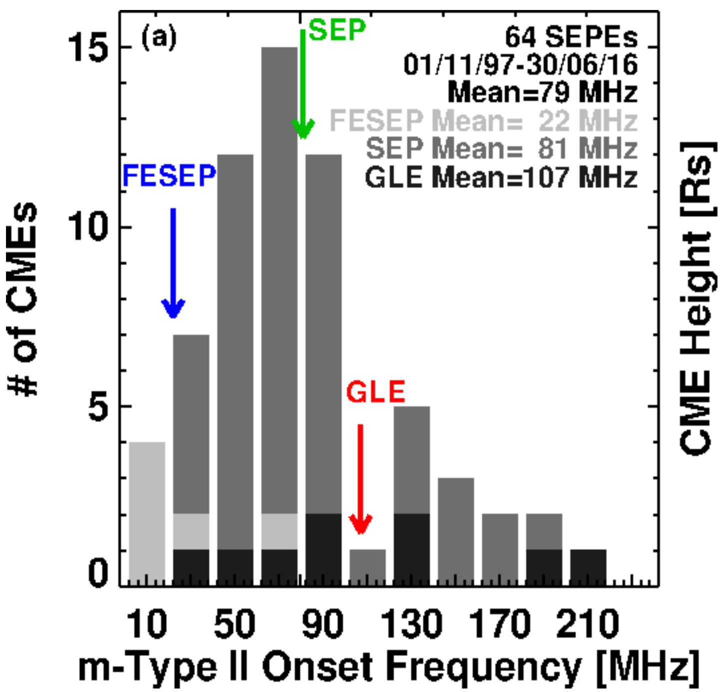
- Plateau in lower energies after initial rise
- Tens of MeV protons cause Alfven waves, which throttle the lower energy particles (protons, He, Fe, O)

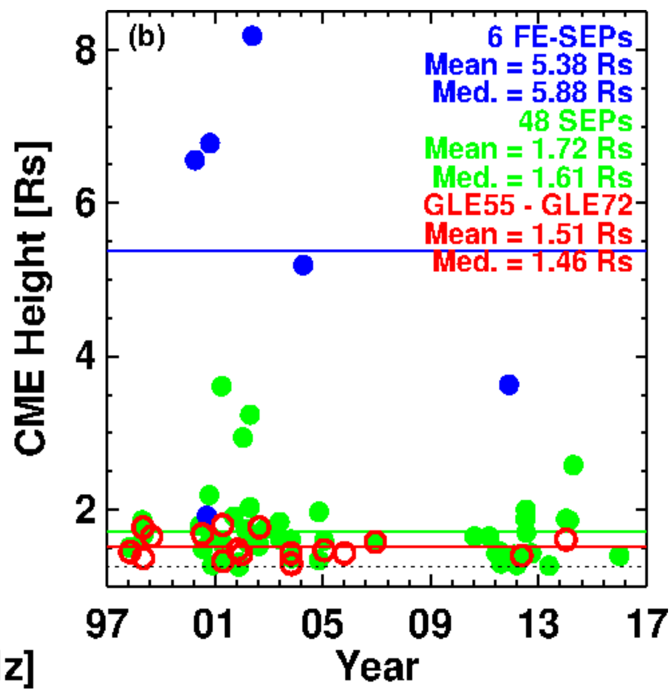
Reames & Ing 2010

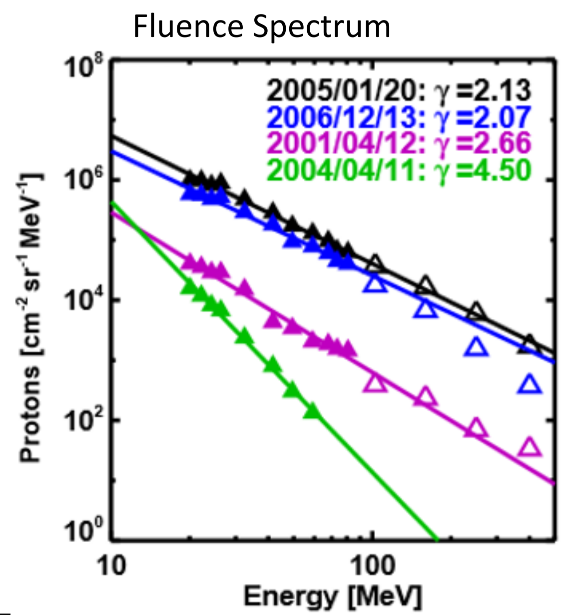


Max intensity ~400 H per (cm^2 s sr) in the energy range 5-20 MeV

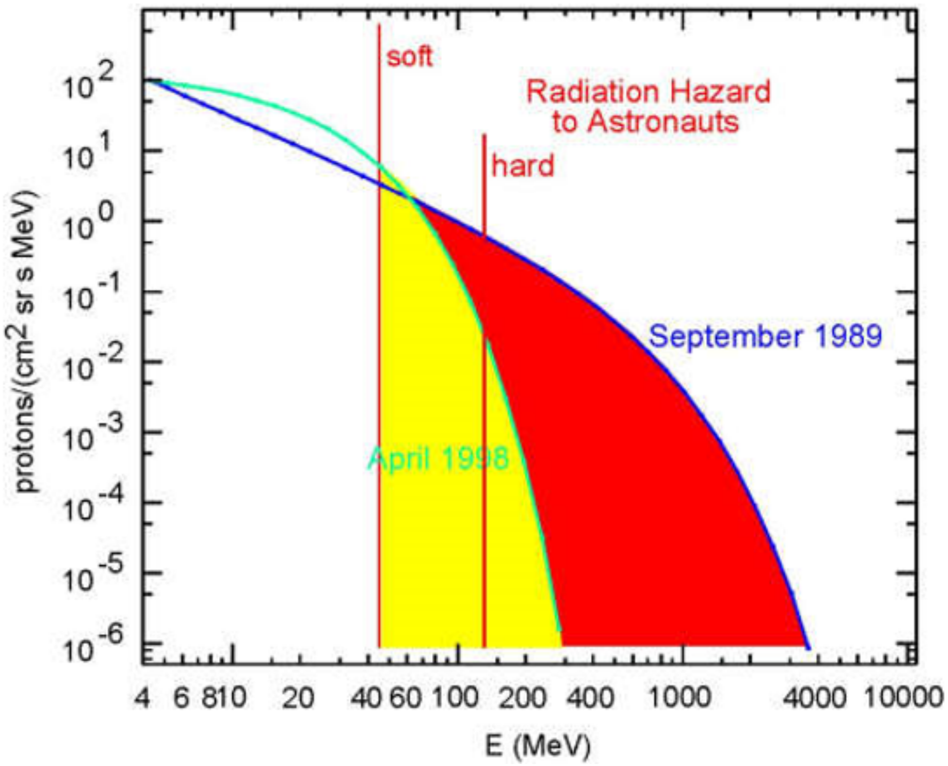
It Matters Where the Shocks Form







Hard Spectrum Events are more hazardous

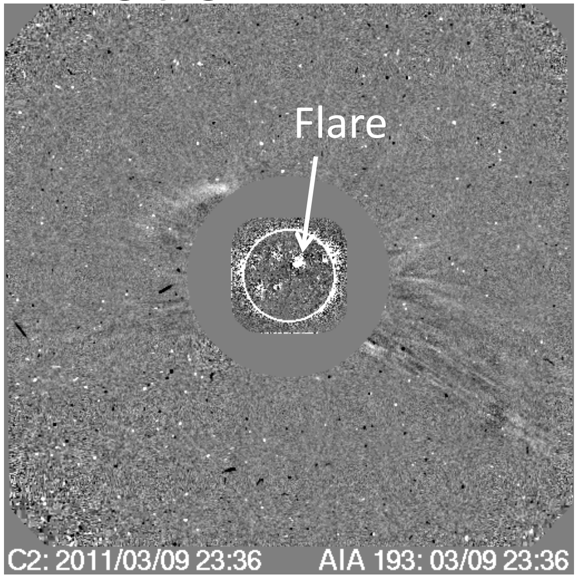


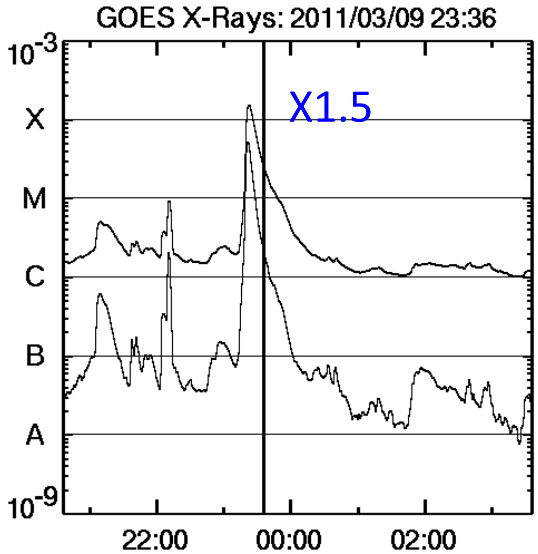
Reames 2013

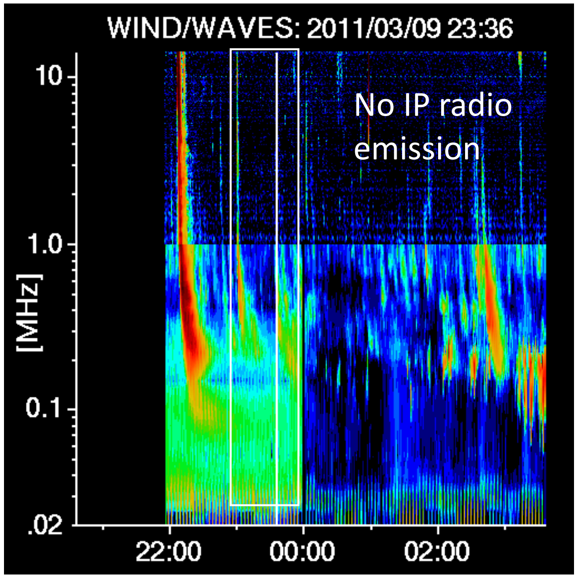
Two mechanisms of particle acceleration

- Confined flares: Particle acceleration in flares
- CMEs associated with filament eruption outside Active regions: particle acceleration in shocks; ESP events

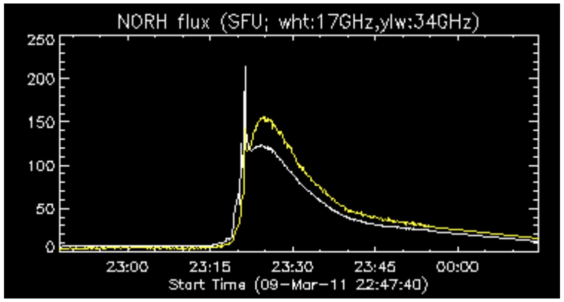
Confined Flare: No mass motion

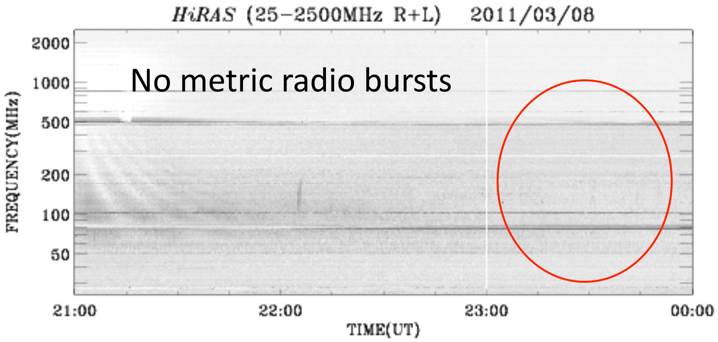




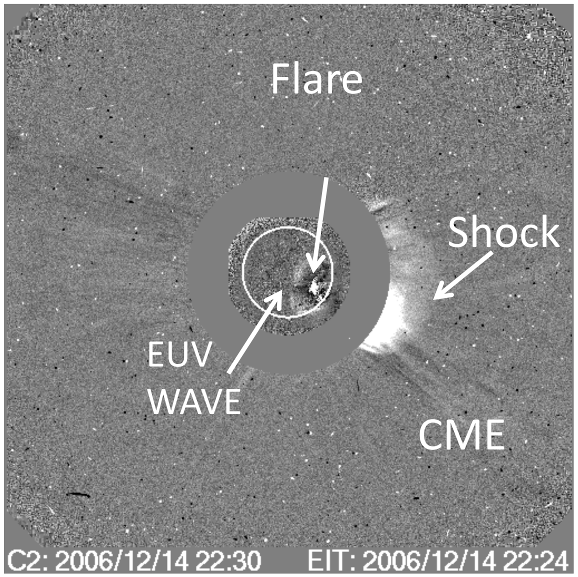


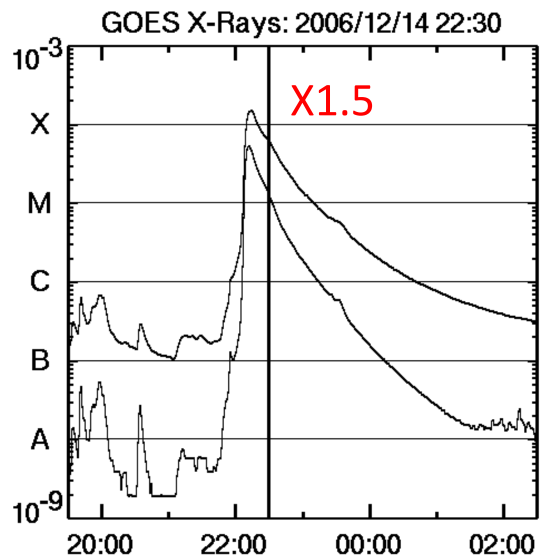
- Microwave burst, X-rays → nonthermal electrons propagating toward the Sun
- No metric radio bursts → no electrons away from the Sun
- No Interplanetary radio emission
- No SEP event

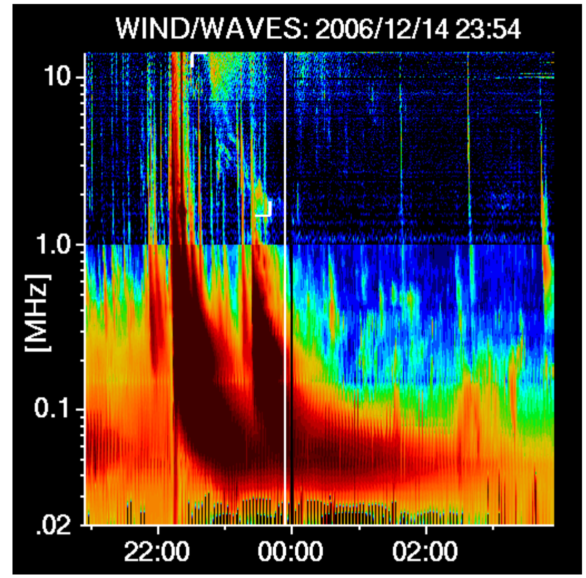




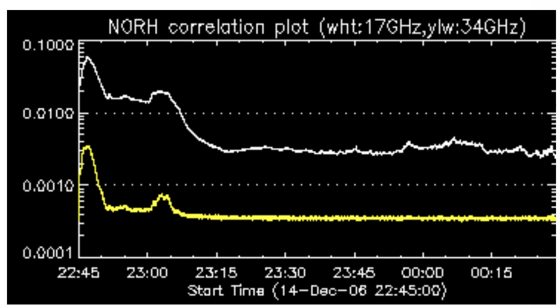
Eruptive Flare: CME involved

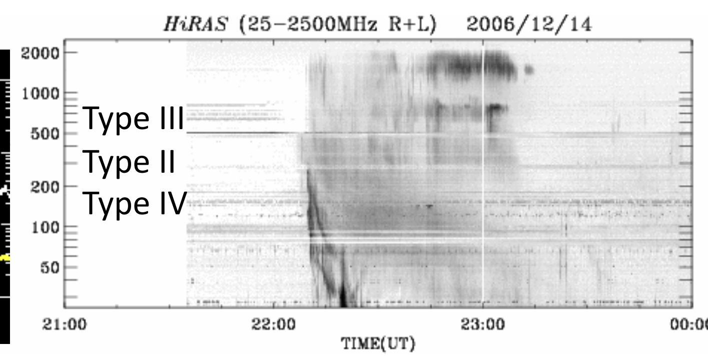




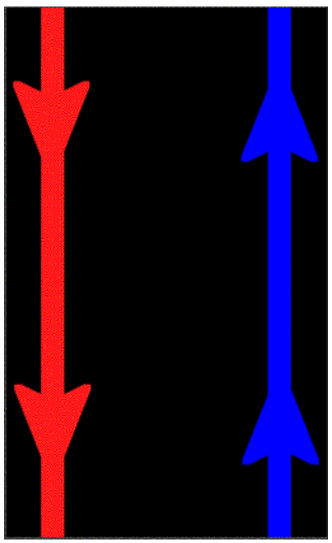


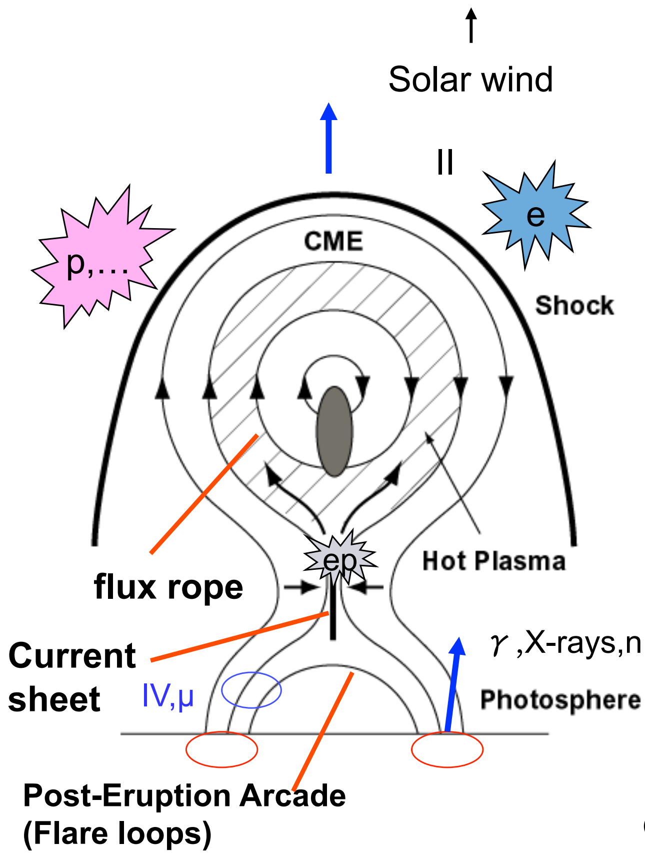
- Radio bursts → nonthermal electrons propagating away from the Sun
- X-ray emission → electrons propagating toward the Sun
- Interplanetary type II
- Large SEP event

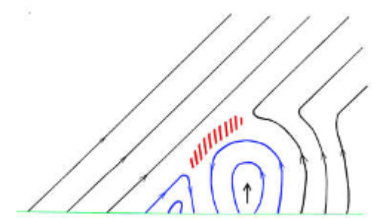




A Generic CME



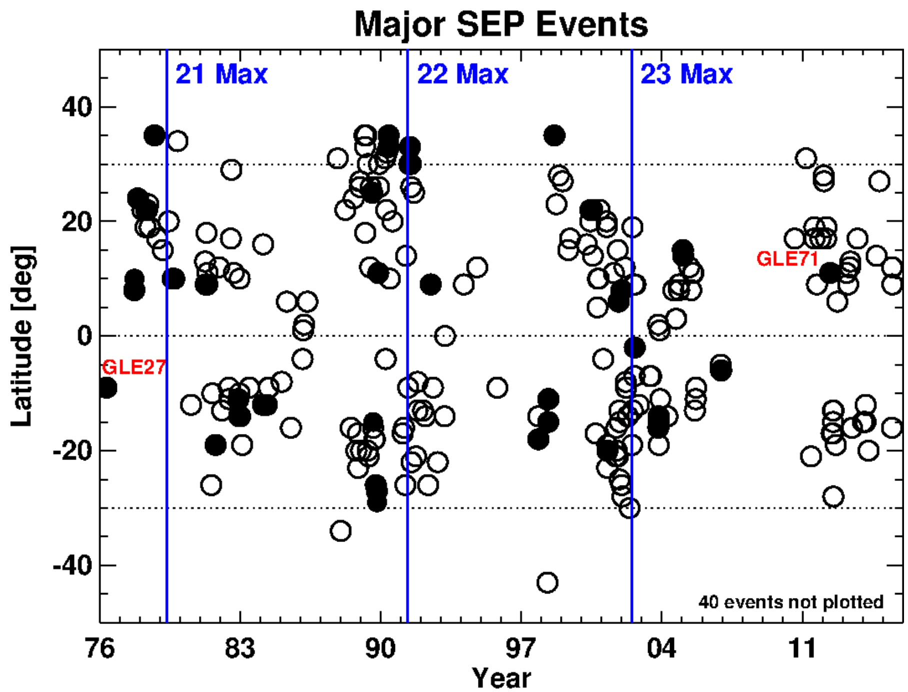




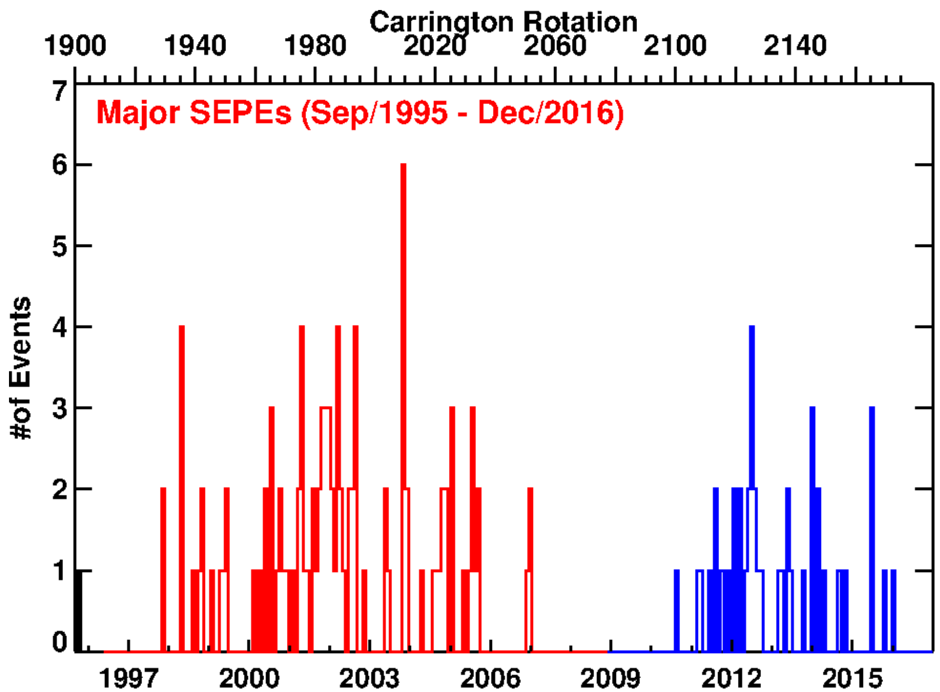
impulsive events
associated with jets

Gopalswamy 2006
adapted from Martens & Kuin 1989

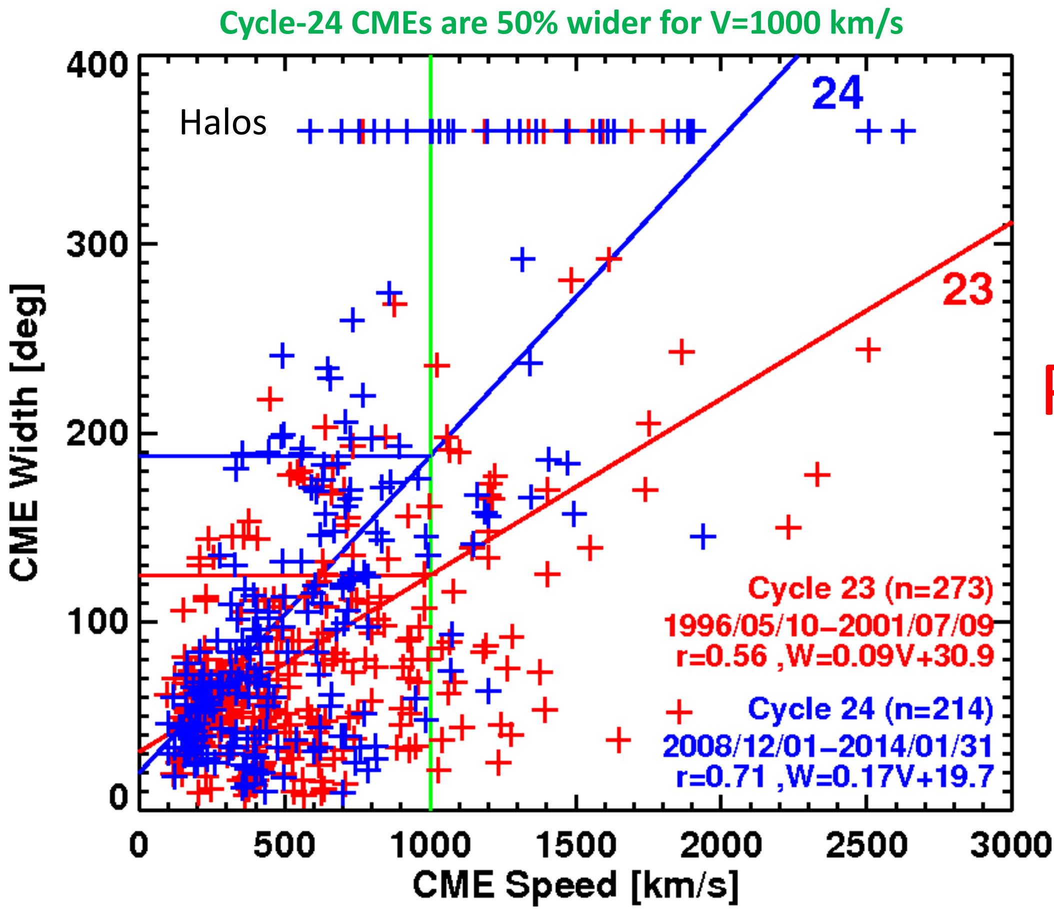
Solar Cycle Variation

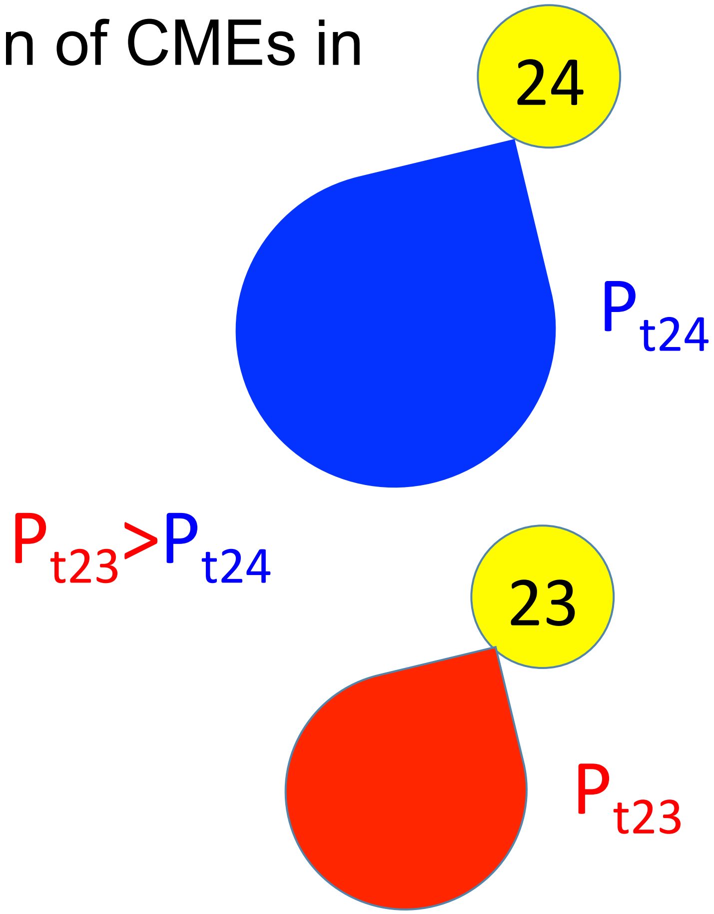


Major SEP Events
21 Max
22 Max
23 Max
GLE27
GLE71
40 events not plotted
Latitude [deg]
Year
40
20
0
-20
-40
76
83
90
97
04
11


Carrington Rotation
1900
1940
1980
2020
2060
2100
2140
Major SEPEs (Sep/1995 - Dec/2016)
#of Events
0
1
2
3
4
5
6
7
1997
2000
2003
2006
2009
2012
2015

Why Low VBz? Anomalous Expansion of CMEs in Cycle 24





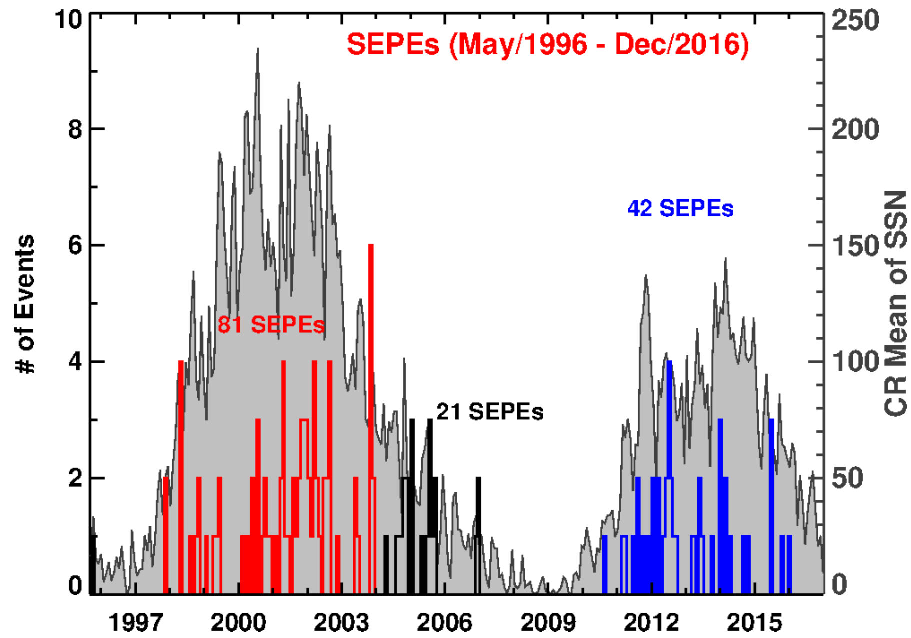
Slope is significantly different
For a given speed, cycle 24 CMEs are wider

Solar Energetic Particles

SEPs	Cycle 23*	Cycle24	Ratio
>10 MeV	81 (0.73/ SSN)	42 (0.67/SSN)	0.52
>500 MeV	27 (0.24/ SSN)	9 (0.14/SSN)	0.33
>700 MeV (GLE)	13 (0.12/SSN)	2 (0.03/SSN)	0.15

- Low-energy SEP events drop (48%) ~ to SSN
- >500 MeV SEP events dropped by 67%
- >700 MeV SEPs dropped by 85%
- These cannot be explained by the 34% drop in FW CMEs

>10 MeV SEP events



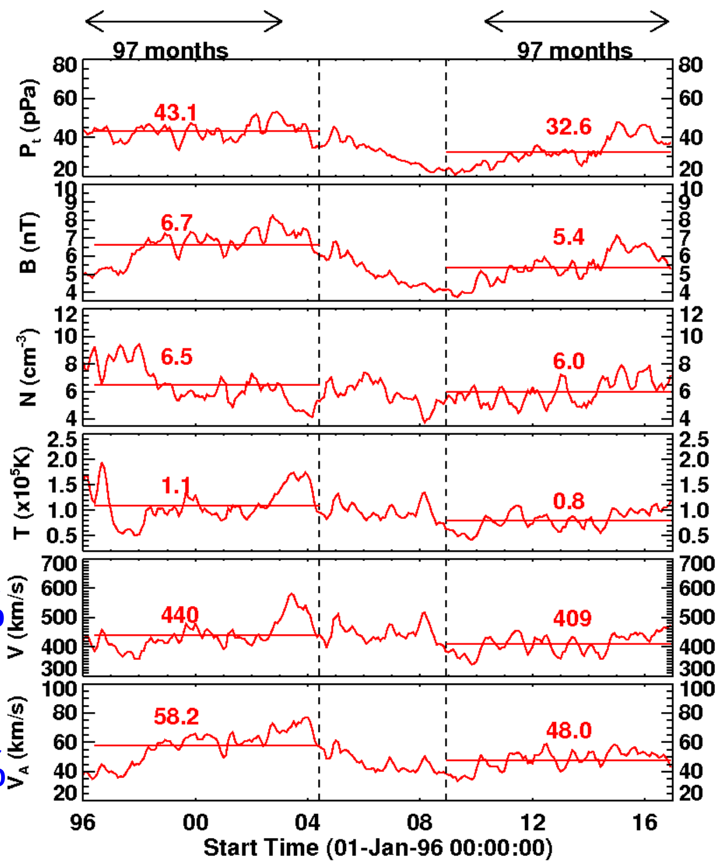
24%

19%

8%

28%

18%



Gopalswamy et al. 2014 GRL (updated)

State of the Heliosphere

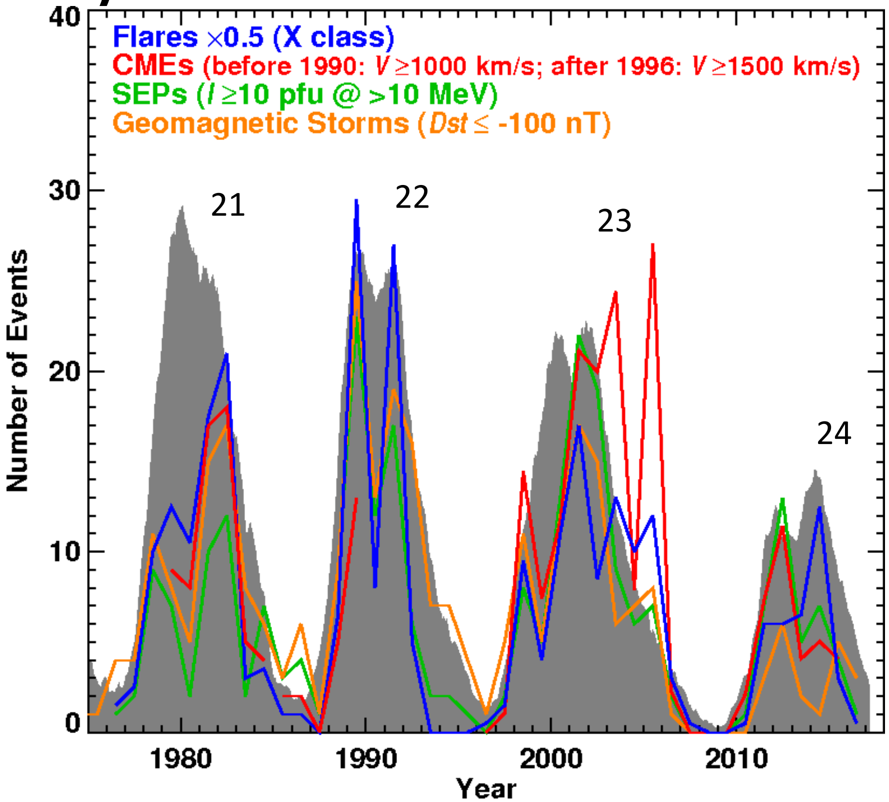
Parameter	SC 23	SC 24	% Decline
Pt (pPa)	43.1	32.6	24
B (nT)	6.7	5.40	19
N (cm^-3)	6.5	6.0	8
T (x10^5 K)	1.1	0.8	28
Va (km/s)	58.2	48.0	18

- Reduced B
- Reduced acceleration efficiency (Kirk, 1994)
  $dE/dt \propto B$ (rate of energy gain)

- Reduced Alfven speed near Sun

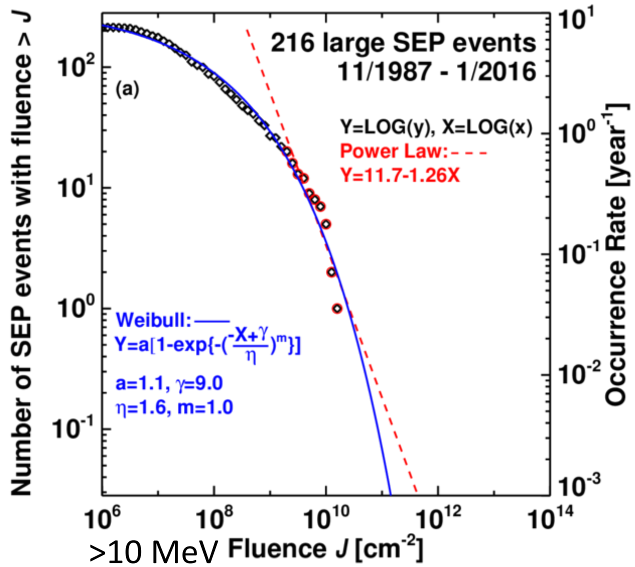
→No major reduction in the # SEP Events

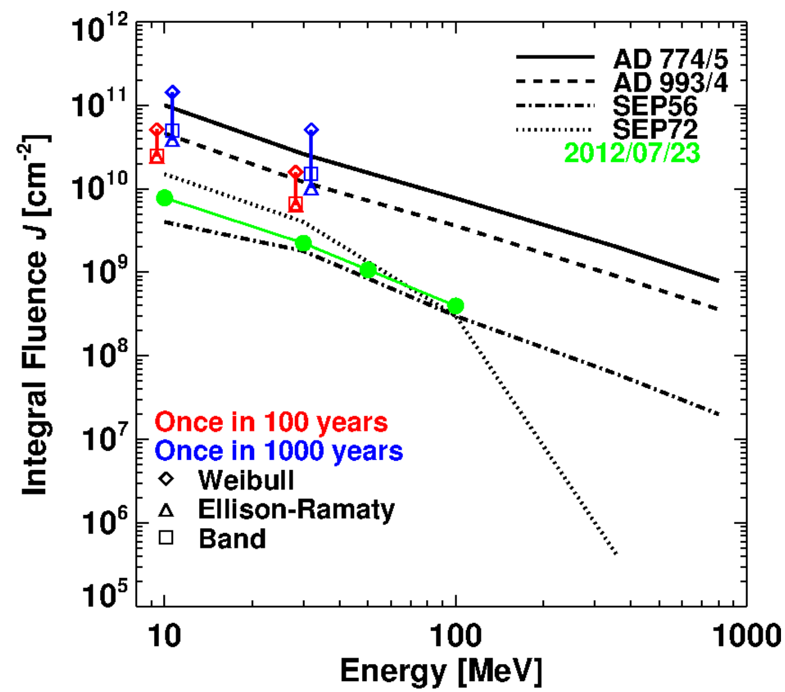
SWx Sources: Cycle 24 Compared to Previous Cycles



- SWx in Cycle 24 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

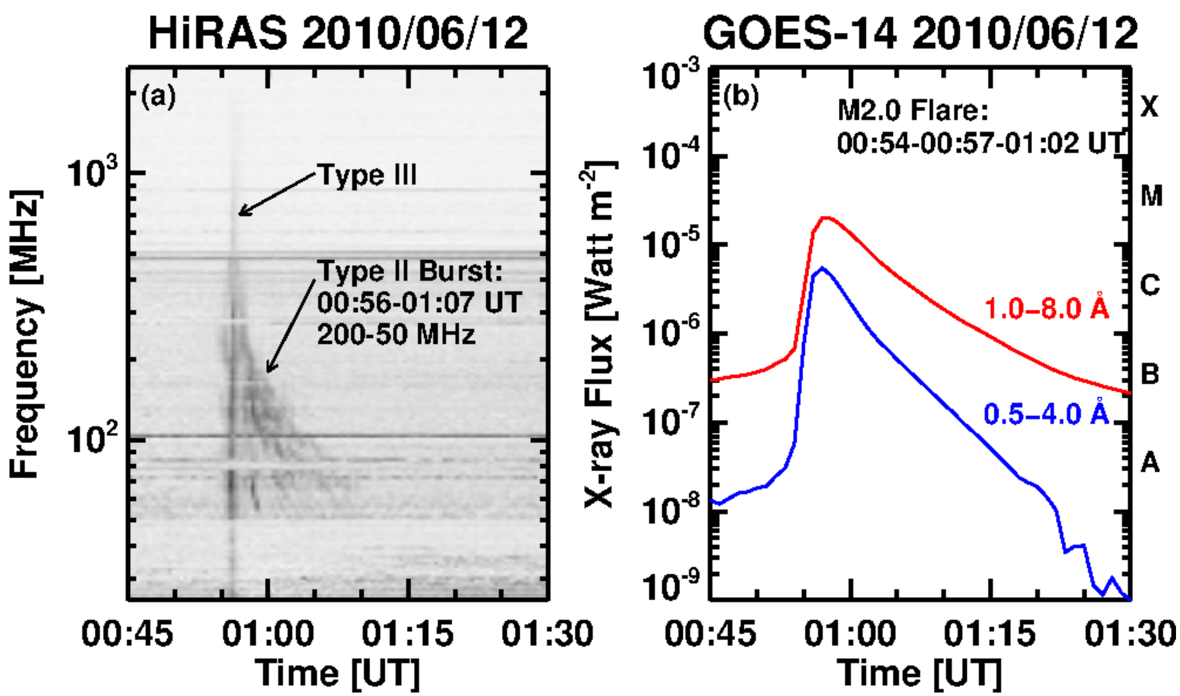
Extreme SEP Events



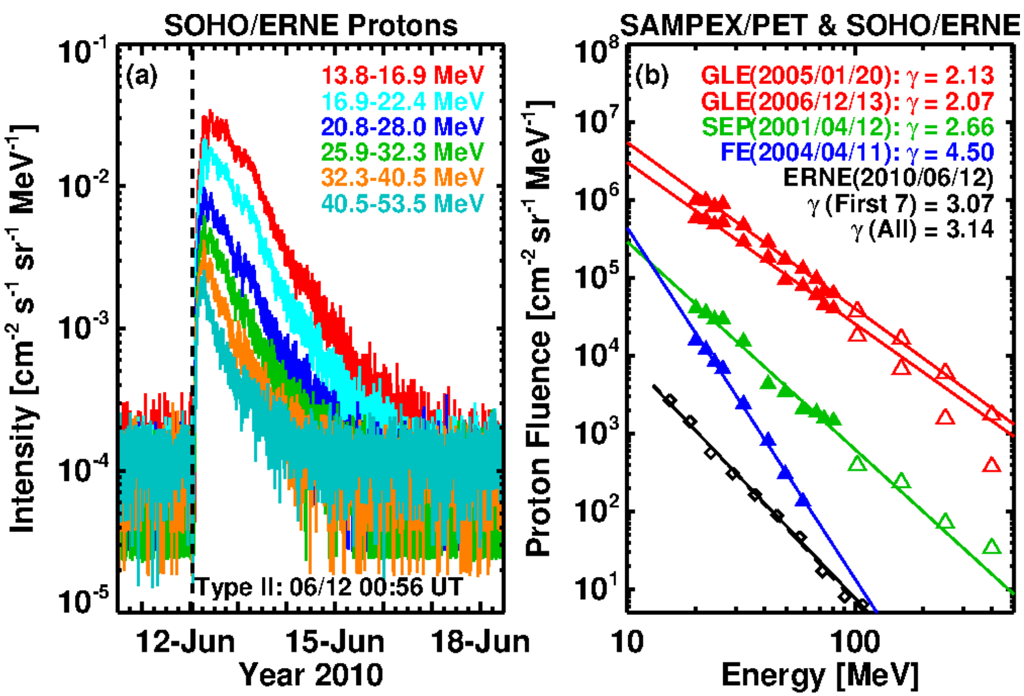


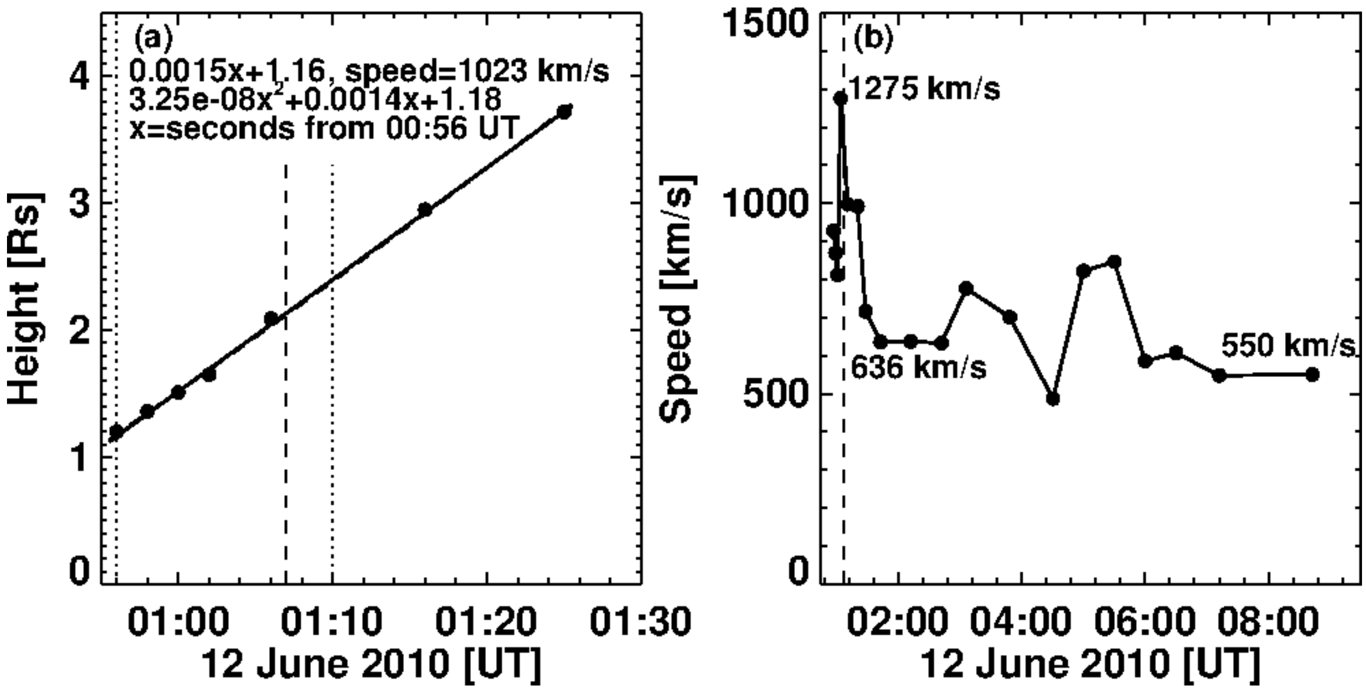
Miyake et al. 2012; Mekhaldi et al. 2015

Back up Slides



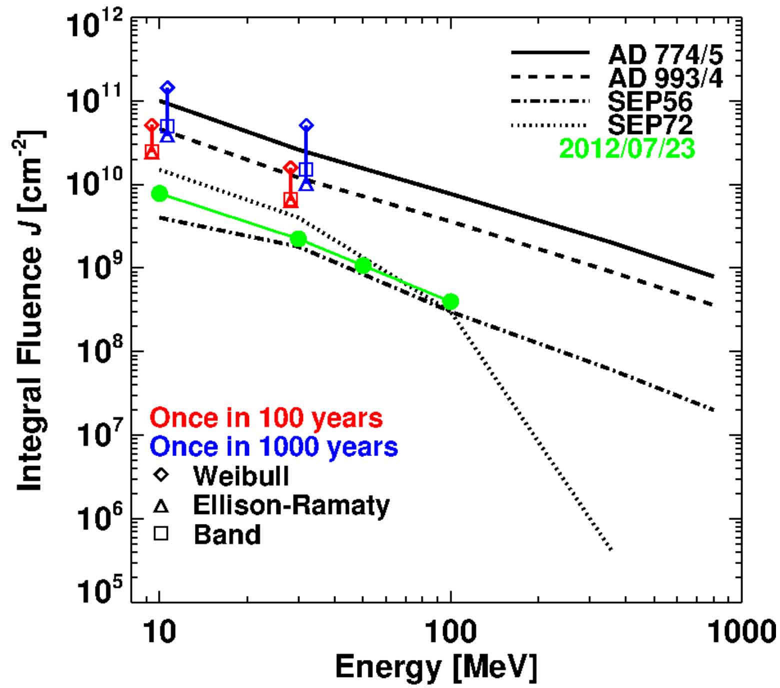
HiRAS 2010/06/12
(a)
Type III
Type II Burst:
00:56-01:07 UT
200-50 MHz
Frequency [MHz]
10^3
10^2
00:45
01:00
01:15
01:30
Time [UT]
GOES-14 2010/06/12
(b)
M2.0 Flare:
00:54-00:57-01:02 UT
X-ray Flux [Watt m^{-2}]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
X
M
C
B
A
1.0–8.0 Å
0.5–4.0 Å
00:45
01:00
01:15
01:30
Time [UT]

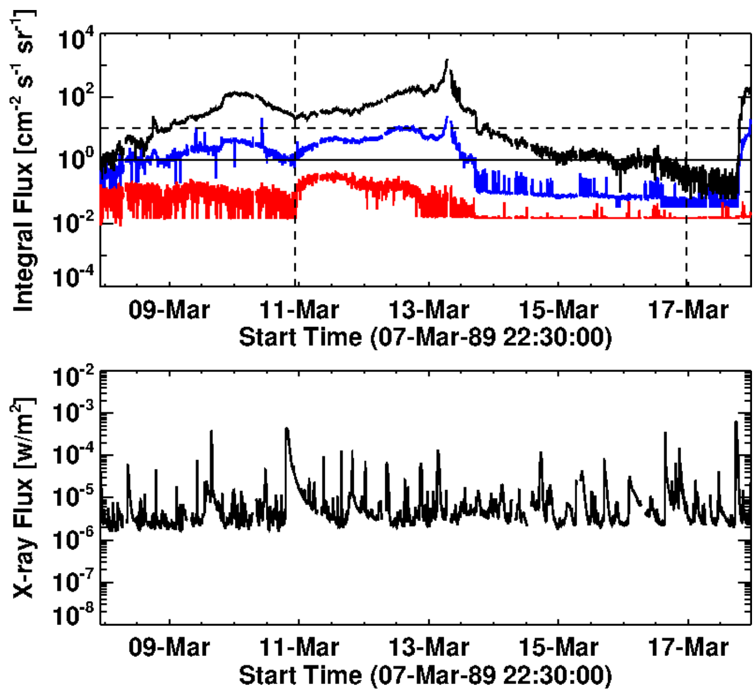

SOHO/ERNE Protons
(a)
13.8-16.9 MeV
16.9-22.4 MeV
20.8-28.0 MeV
25.9-32.3 MeV
32.3-40.5 MeV
40.5-53.5 MeV
Type II: 06/12 00:56 UT
Intensity [cm^{-2} s^{-1} sr^{-1} MeV^{-1}]
12-Jun
15-Jun
18-Jun
Year 2010
SAMPEX/PET & SOHO/ERNE
(b)
GLE(2005/01/20): γ = 2.13
GLE(2006/12/13): γ = 2.07
SEP(2001/04/12): γ = 2.66
FE(2004/04/11): γ = 4.50
ERNE(2010/06/12)
γ (First 7) = 3.07
γ (All) = 3.14
Proton Fluence [cm^{-2} sr^{-1} MeV^{-1}]
Energy [MeV]



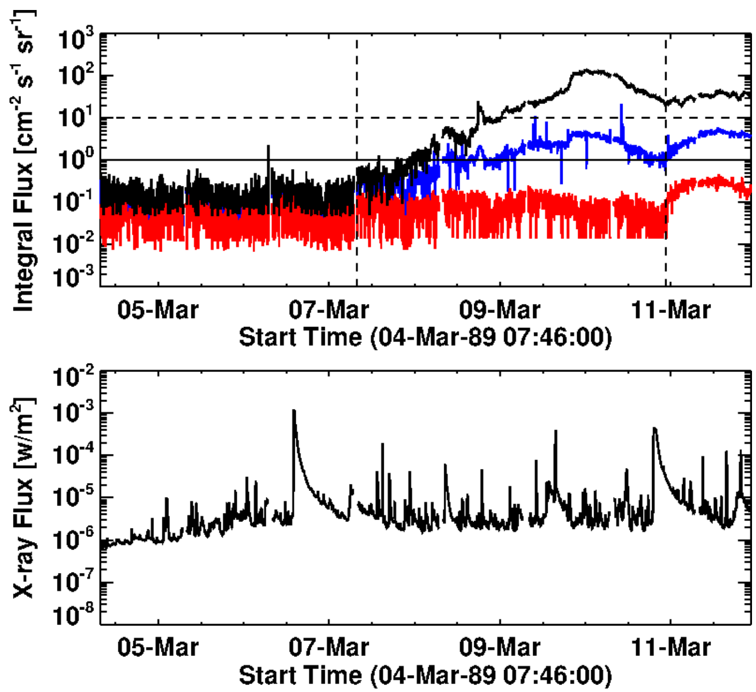
(a)
0.0015x+1.16, speed=1023 km/s
3.25e-08x^2+0.0014x+1.18
x=seconds from 00:56 UT
Height [Rs]
0
1
2
3
4
01:00
01:10
01:20
01:30
12 June 2010 [UT]
(b)
1275 km/s
636 km/s
550 km/s
Speed [km/s]
0
500
1000
1500
02:00
04:00
06:00
08:00
12 June 2010 [UT]

Extreme SEP Events





Integral Flux [cm^{-2} s^{-1} sr^{-1}]
10^4
10^2
10^0
10^{-2}
10^{-4}
09-Mar
11-Mar
13-Mar
15-Mar
17-Mar
Start Time (07-Mar-89 22:30:00)
X-ray Flux [w/m^2]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
09-Mar
11-Mar
13-Mar
15-Mar
17-Mar
Start Time (07-Mar-89 22:30:00)



Integral Flux [cm^{-2} s^{-1} sr^{-1}]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
05-Mar
07-Mar
09-Mar
11-Mar
Start Time (04-Mar-89 07:46:00)
X-ray Flux [w/m^{2}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
05-Mar
07-Mar
09-Mar
11-Mar
Start Time (04-Mar-89 07:46:00)

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

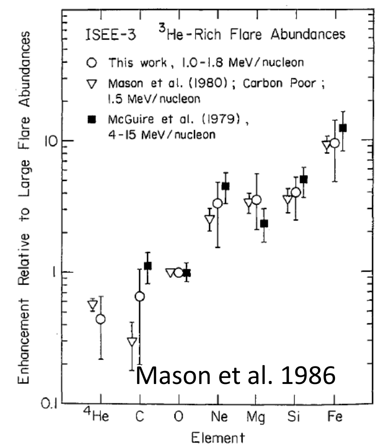
3He/4He > 0.1 (solar wind 5x10^{-4})

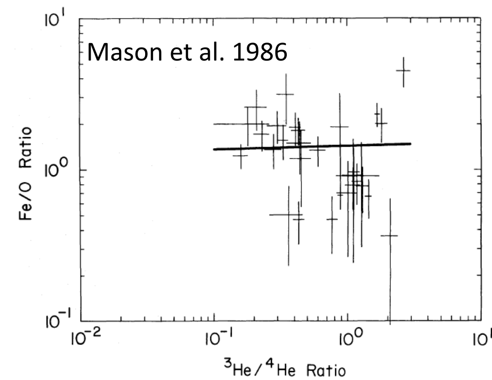
No CME association with ^{3}He-rich events

^{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





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

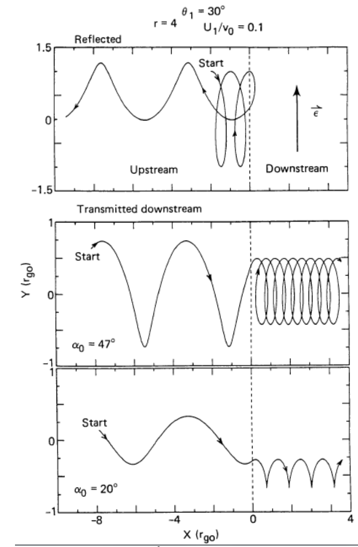
Shock drift acceleration (SDA):

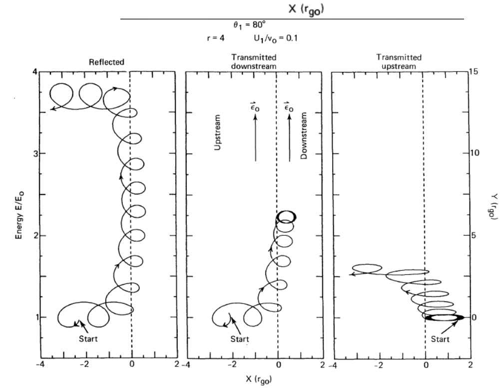
Quasi-perpendicular shock ($\theta_{BN} \geq 45°$)

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