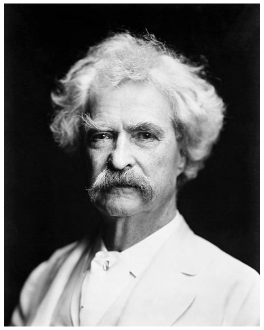
The Sun as the primary source of space weather

Nat Gopalswamy

NASA Goddard Space Flight Center

UN/Azerbaijan workshop on ISWI
2022 October 31 – Nov 4, Baku, Azerbaijan

Climate & Weather



Mark Twain
1835 - 1910

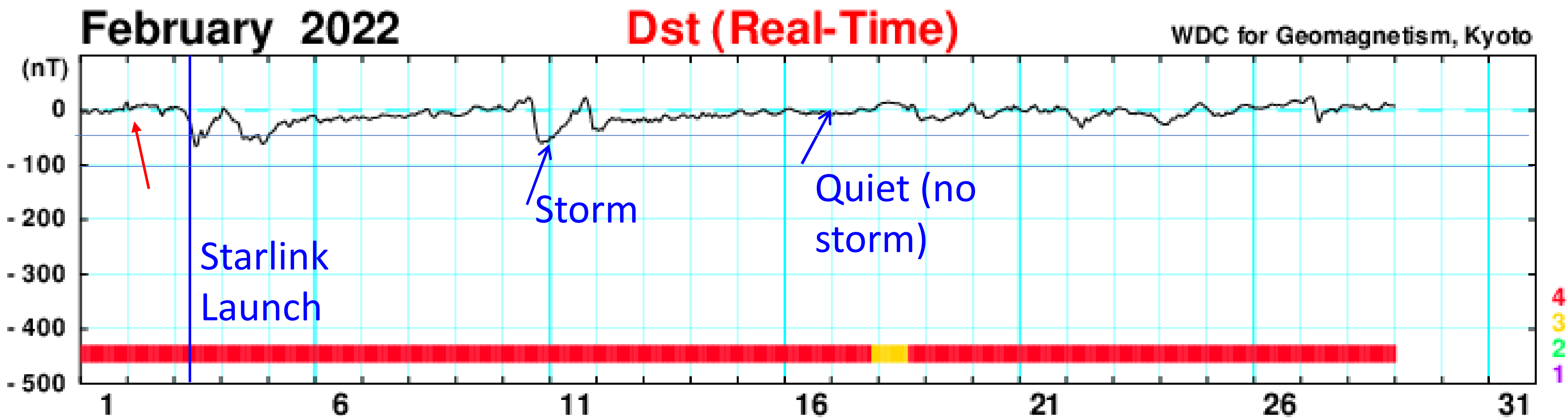
"Climate is what we expect, weather is what we get."

Terrestrial Weather:
Conditions in the atmosphere and on the ground
High winds, hail, excessive precipitation, and wildfires

Space weather:
conditions in space: ground, atmosphere, ionosphere, magnetosphere, interplanetary space and the Sun
Density, temperature, magnetic field, energetic particles: solar storms, particle storms

Normal, inconvenient, dangerous (as severity increases)

Mitigation, Prediction


February 2022
Dst (Real-Time)
WDC for Geomagnetism, Kyoto
(nT)
0
- 100
- 200
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- 400
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6
11
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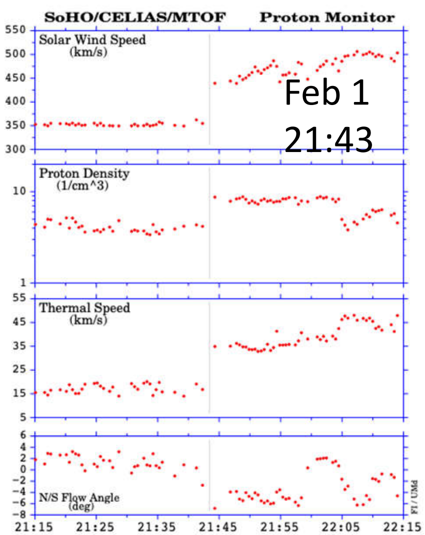
Starlink
Launch
Storm
Quiet (no
storm)


SoHO/CELIAS/MTOF
Proton Monitor
Solar Wind Speed
(km/s)
Feb 1
21:43
Proton Density
(1/cm^3)
Thermal Speed
(km/s)
N/S Flow Angle
(deg)
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21:55
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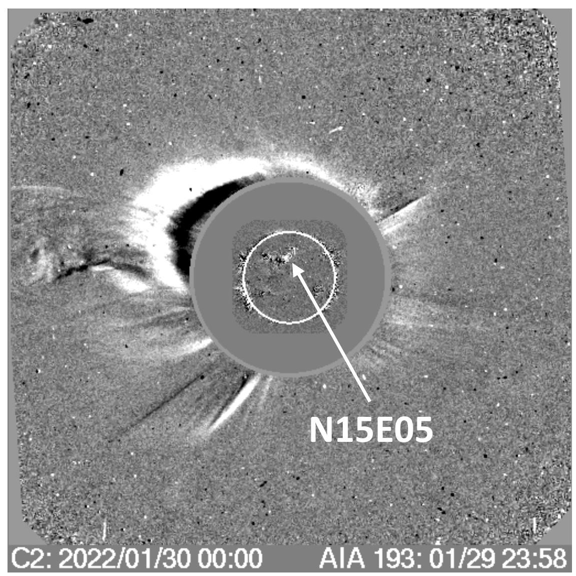
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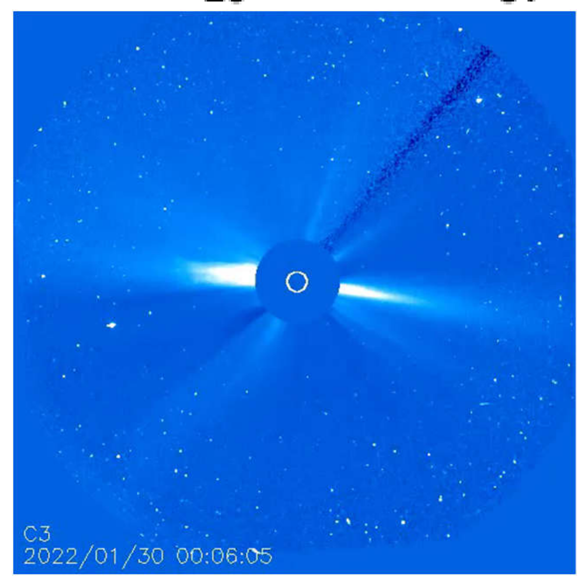
AIA 193: 01/29 23:58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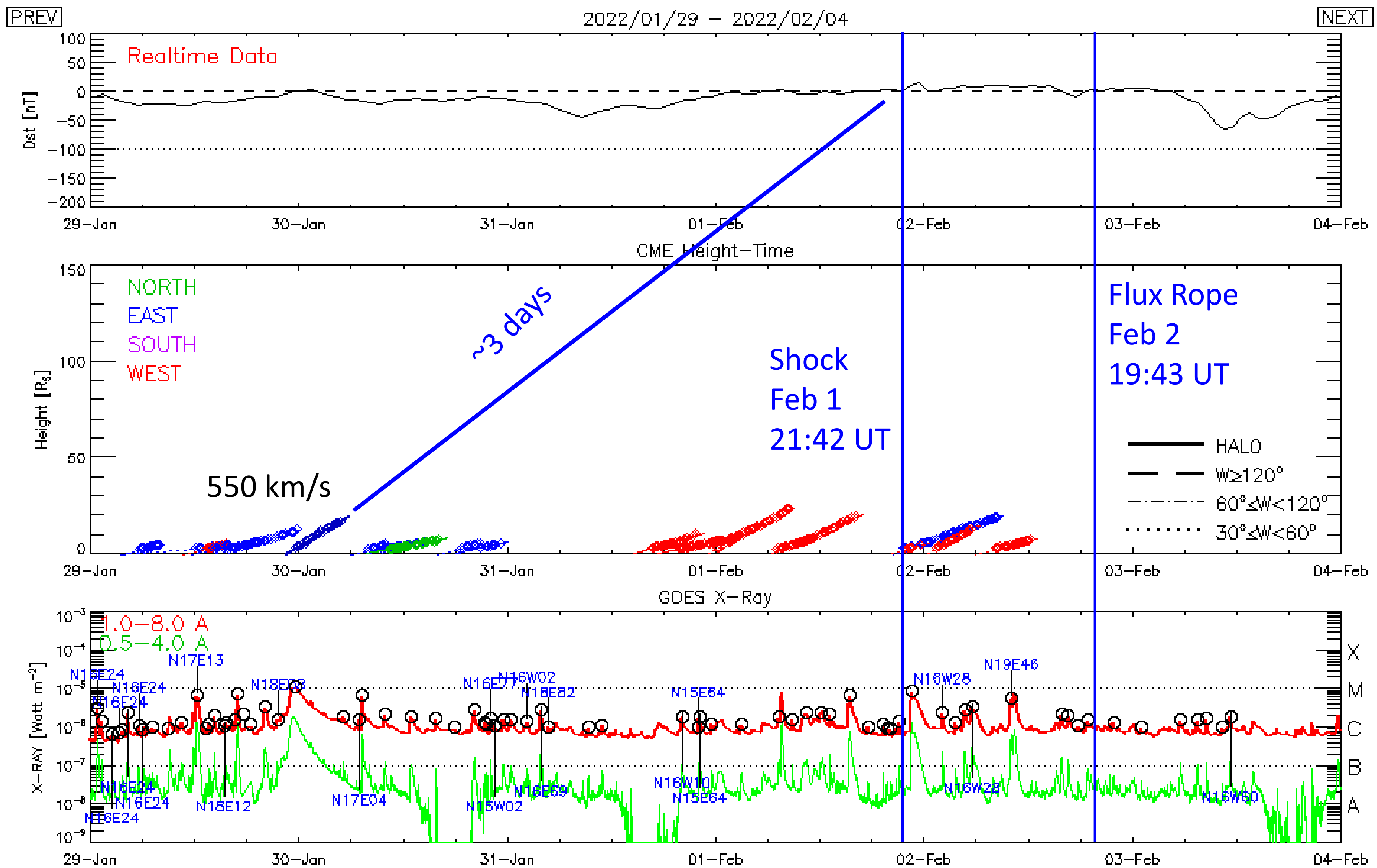
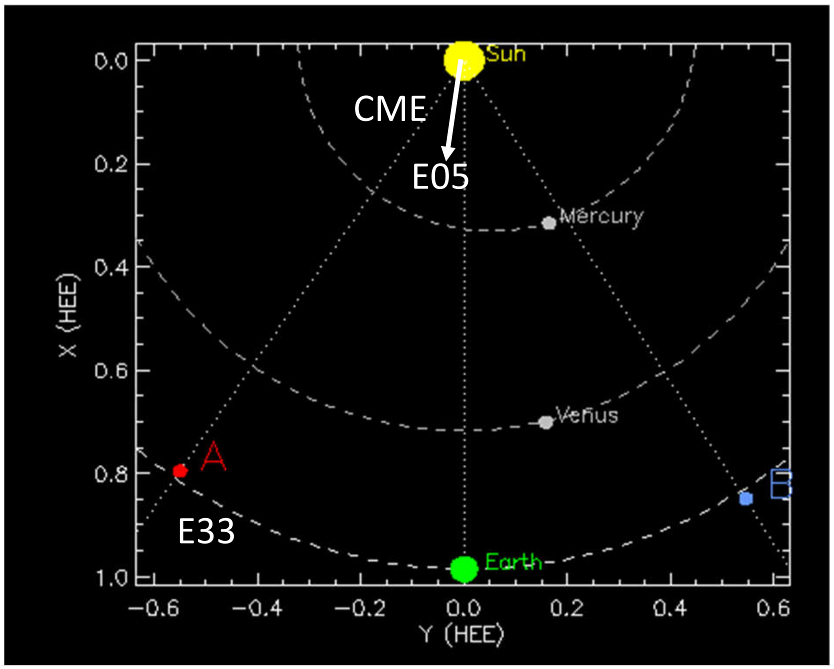
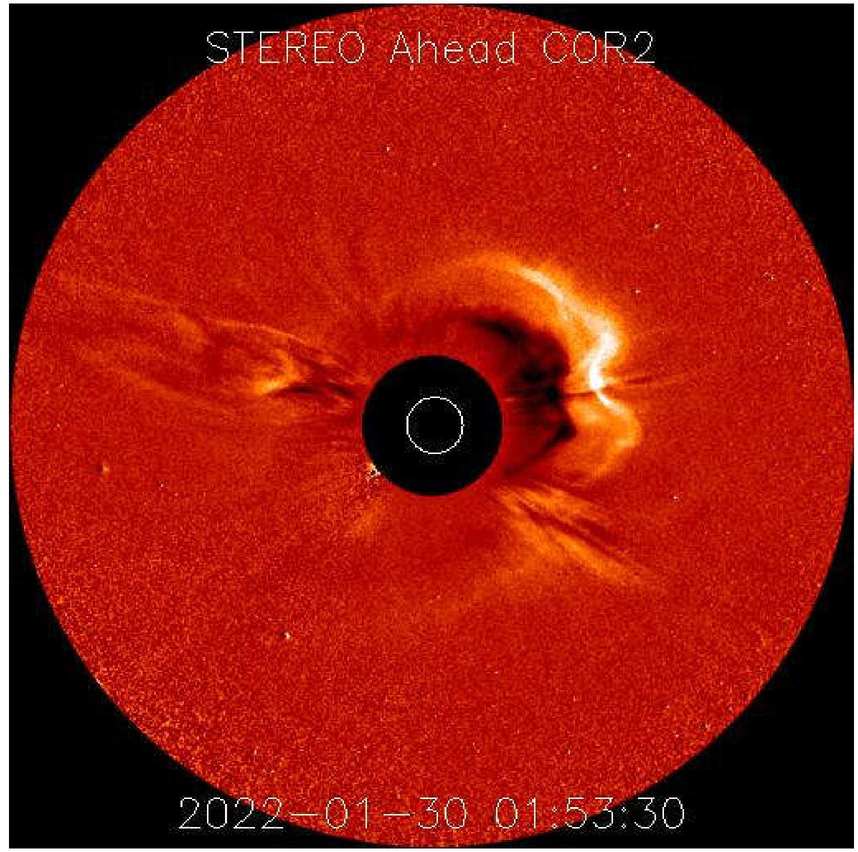


https://cdaw.gsfc.nasa.gov/CME_list/daily_plots/dsthtx/2022_01/dsthtx_20220129.html

Earth-directed CME

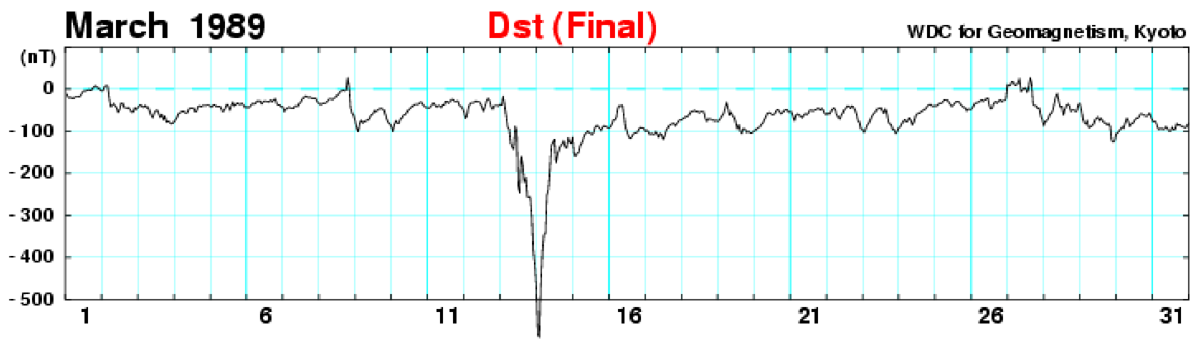




CME heading toward Earth

A Modern Superstorm

- Dst = -589 nT – 10 times more intense than the Starlink storm
- On March 13, 1989, at 2:44 am, a transformer failed. This led to a catastrophic collapse of the entire power grid of the HydroQuebec system.
- 6 million people suffered blackout for 9+ hours



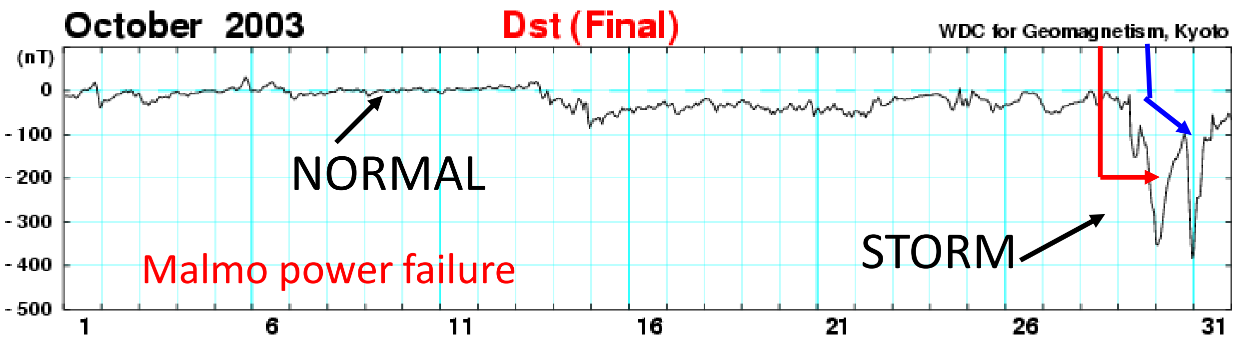
March 12 00:16 UT Eruption (1300 km/s)
Shock arrival: March 13 07:47 UT → 31.5 hrs

- 589 nT at 2 UT
on March 14

HydroQuebec Power Grid Failure

https://www.windows2universe.org/spaceweather/blackout.html

Two Recent SWx Events – Halloween 2003



http://wdc.kugi.kyoto-u.ac.jp/dstdir/

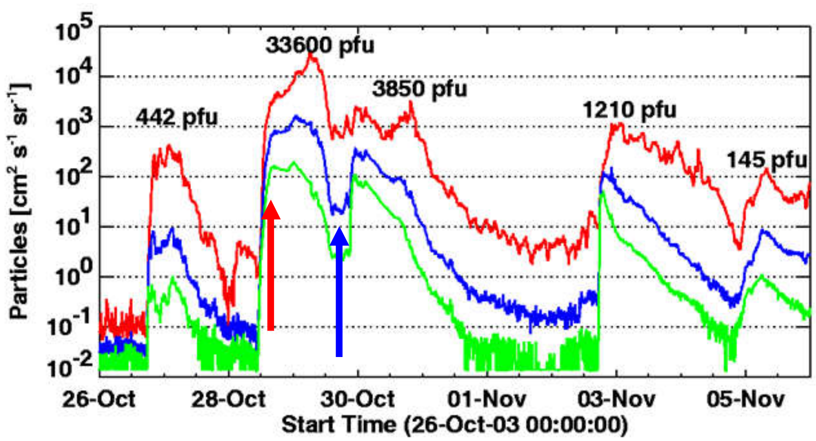
Transit under 19 hours

Particle radiation another huge hazard to human technology in space

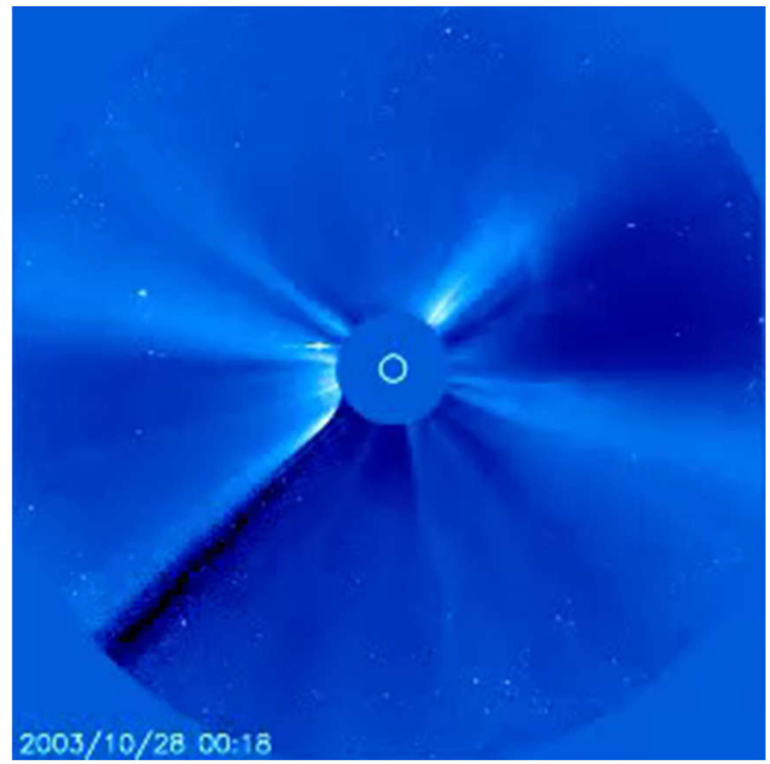
Mars mission affected

Gopalswamy et al. 2005

Double Whammy Events

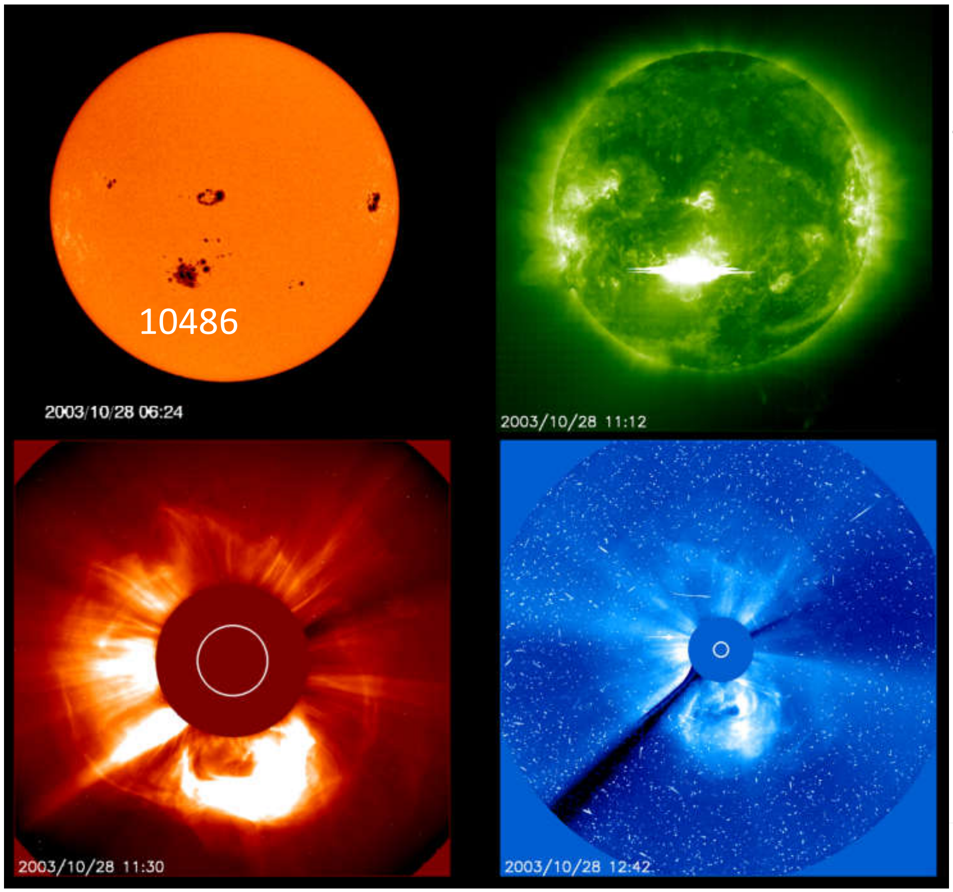


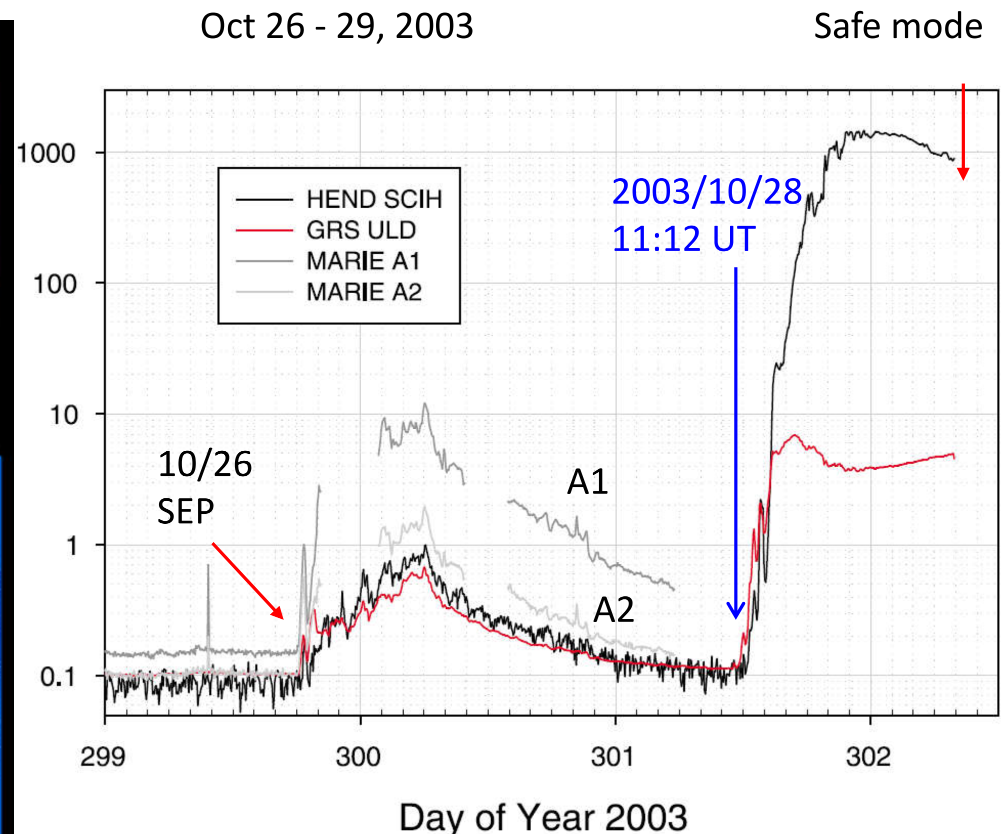
Two halo CMEs: 10/28 and 10/29 2003



SOHO/LASCO

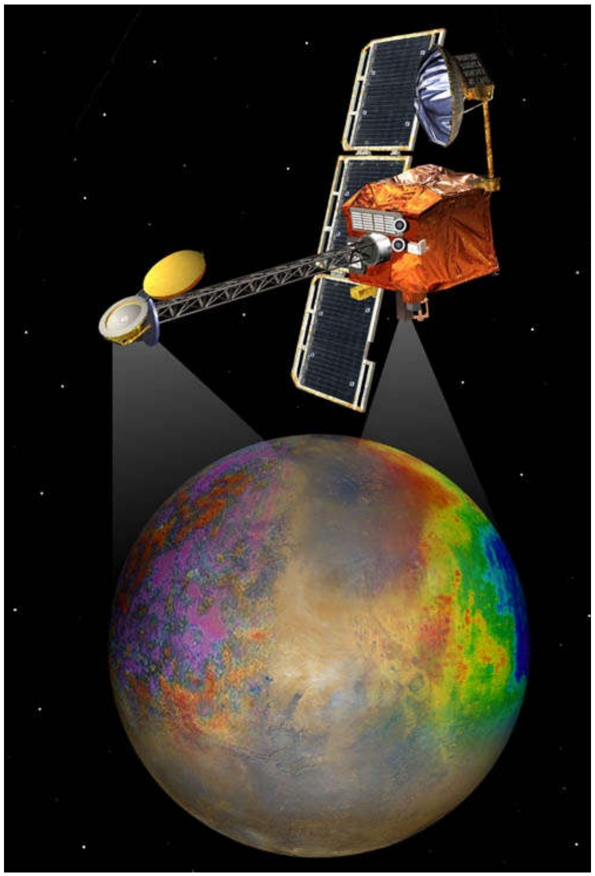
The MARIE Slayer: 2003 Oct 28 Halloween Storm





Zeitlin+2010

MARIE: The Martian Radiation Environment Experiment



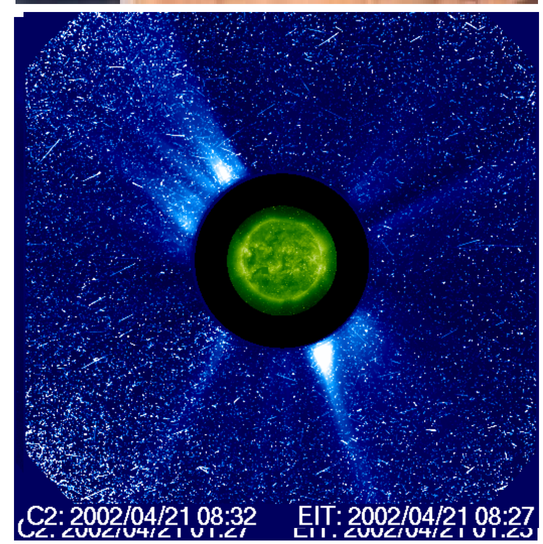
Mars Odyssey

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.

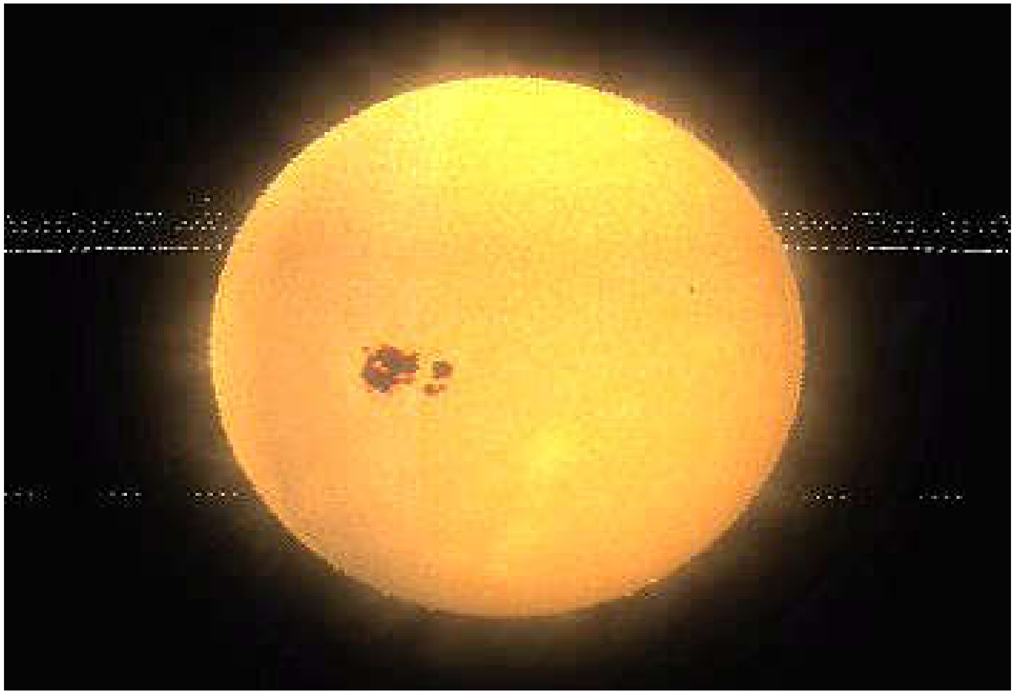
One of the October 2003 SEP events rendered MARIE inoperative. It is ironic, as MARIE was designed to measure the radiation environment at Mars.

The Japanese mission Nozomi was also destroyed by a particle storm that occurred on 2002 April 21

Nozomi



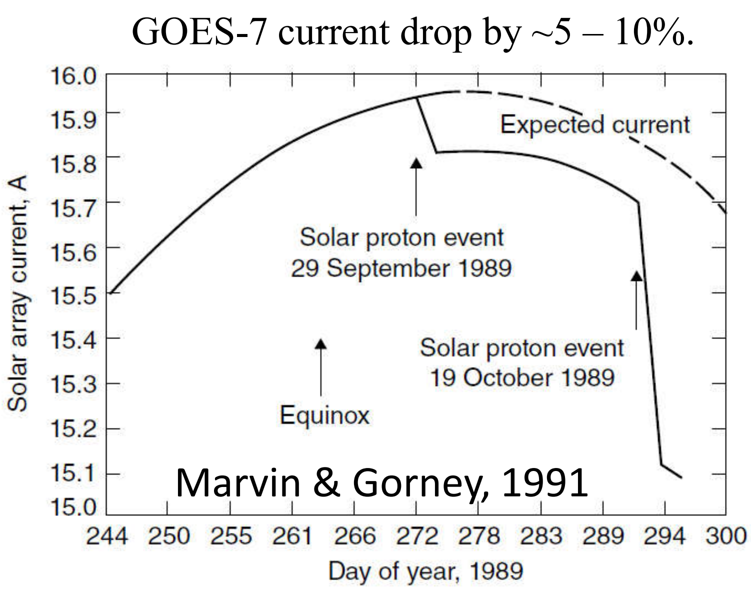
Animation of Halloween 2003 CMEs



Consequences of the CMEs were observed at Earth, Jupiter, Saturn and even at the edge of the solar system where the Voyagers were located. The CMEs took 6 months to reach the termination shock.

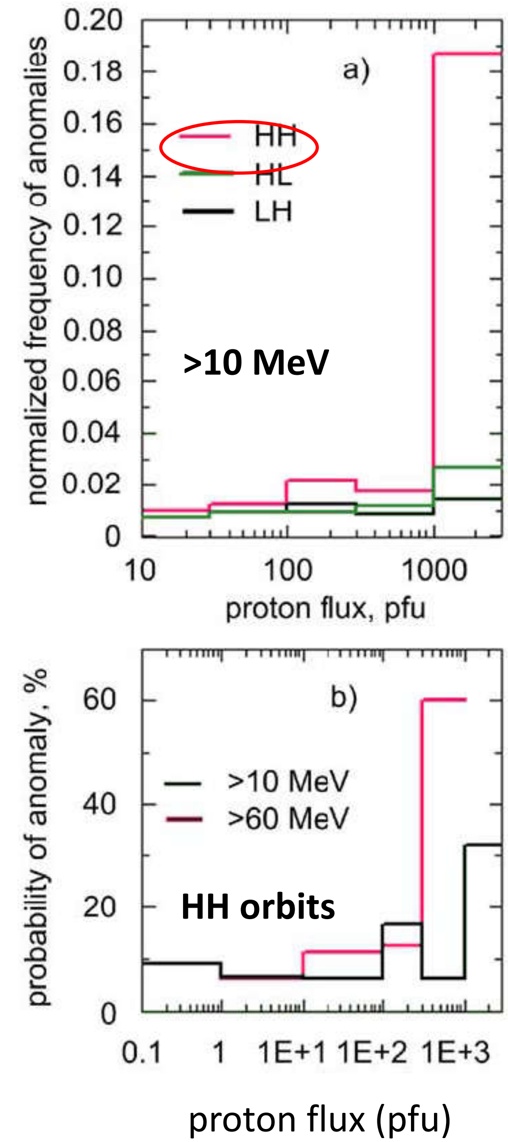
CMEs represent the most energetic phenomenon in the heliosphere

SEPs and S/C Anomalies



Major impact on solar arrays

- Anomaly frequency highest for HH (GNSS) orbits (0.19 vs. 0.01 for LH)
- The anomaly frequency rapidly increases with proton flux
- The probability of an anomaly for HH orbit is significantly higher for high proton flux and proton energy

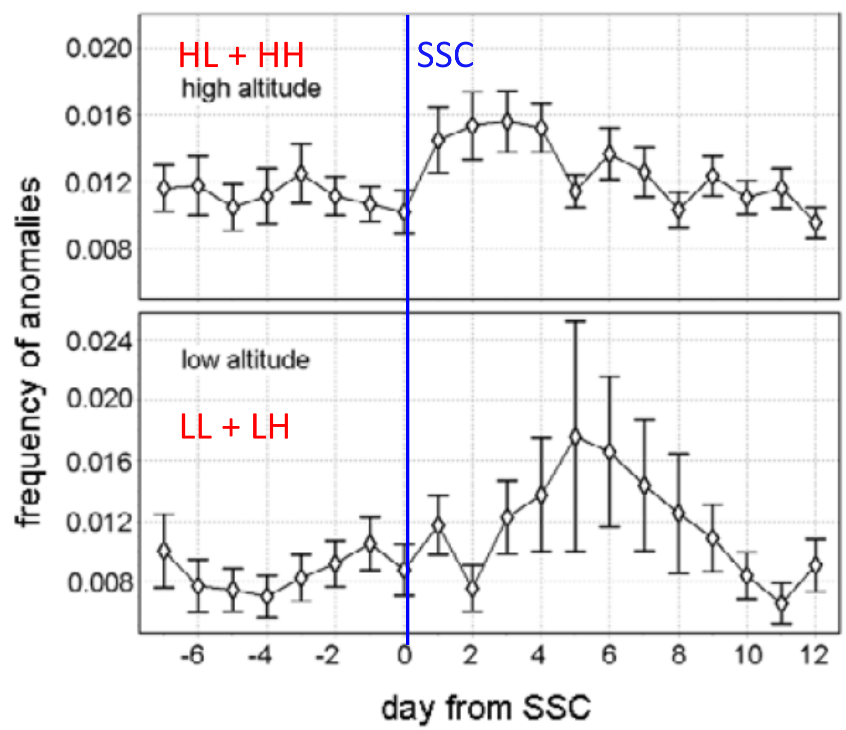


Iucci+ 2005

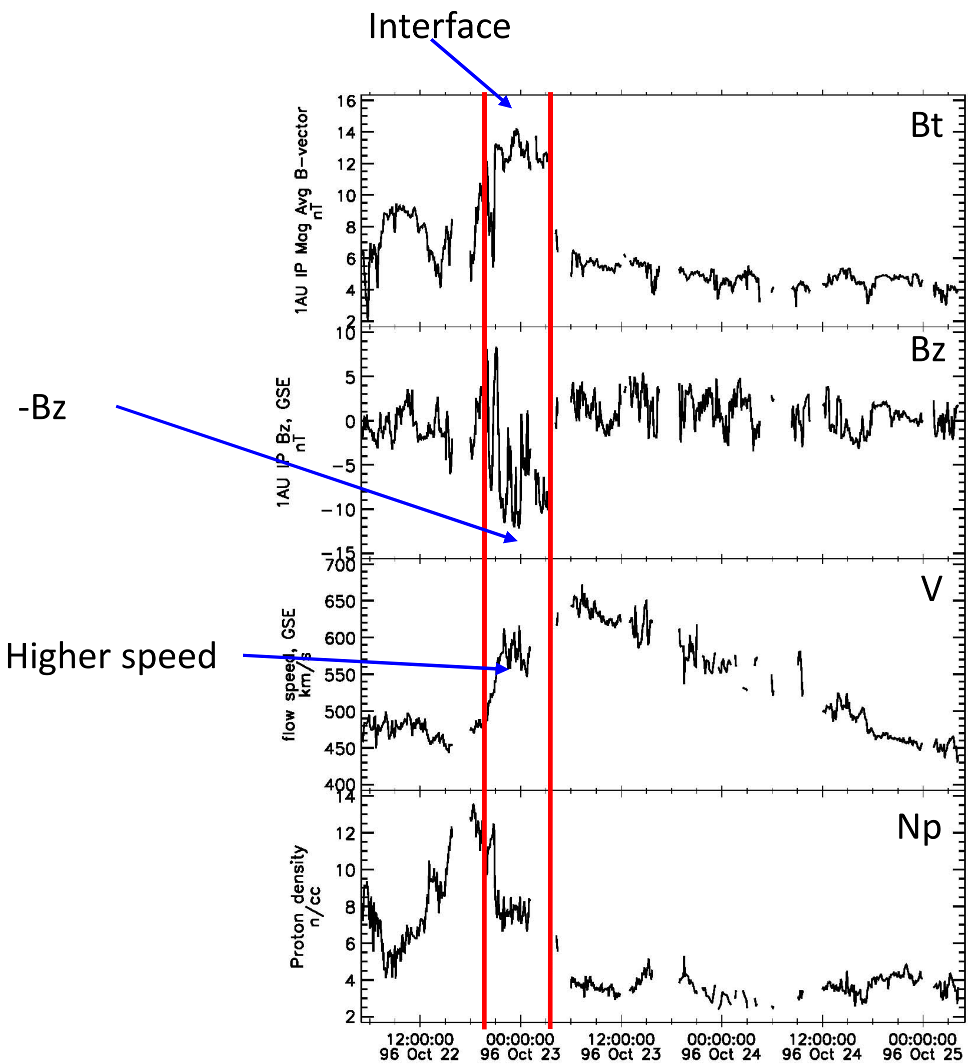
Geomagnetic Storms and Satellite Anomalies

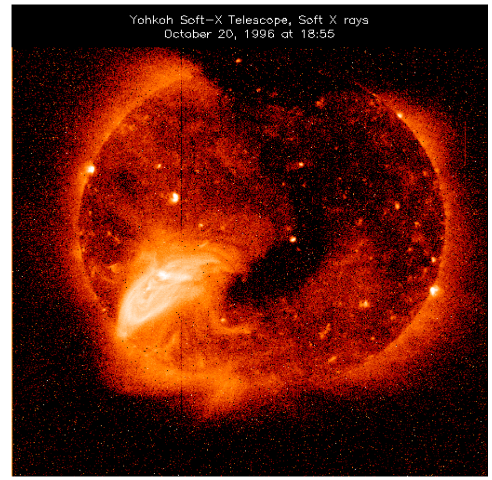
- Frequency of anomalies of High-altitude (low & high inclination) satellites peak in 2-4 days after the SSC
- The frequency of Low-altitude (low & high inclination) satellites peak in 5 days after the SSC

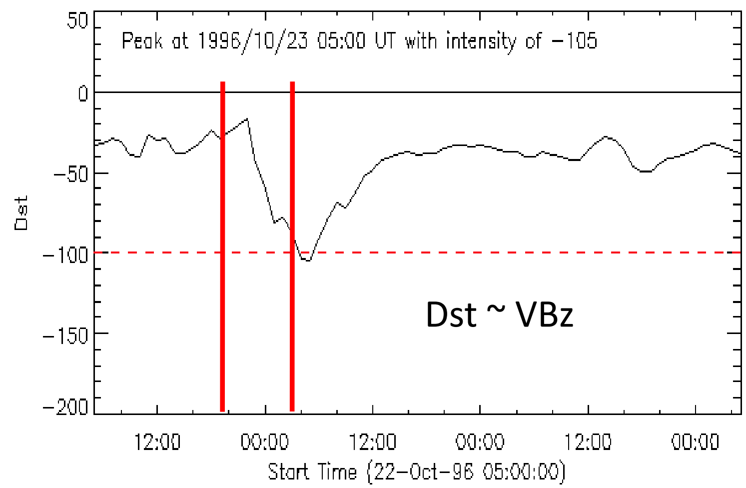
Number of anomalies per day per spacecraft



Iucci et al. 2005

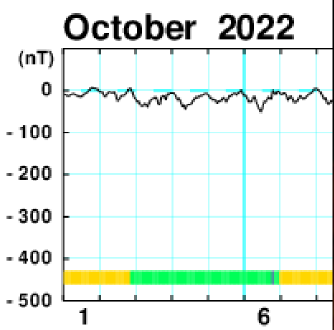


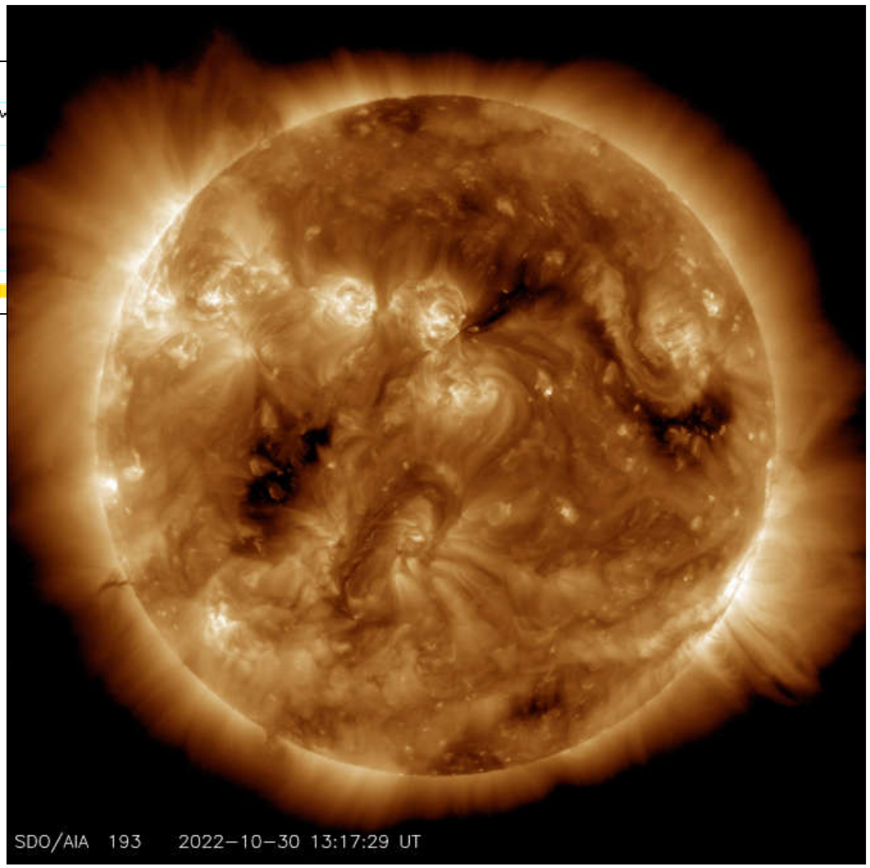


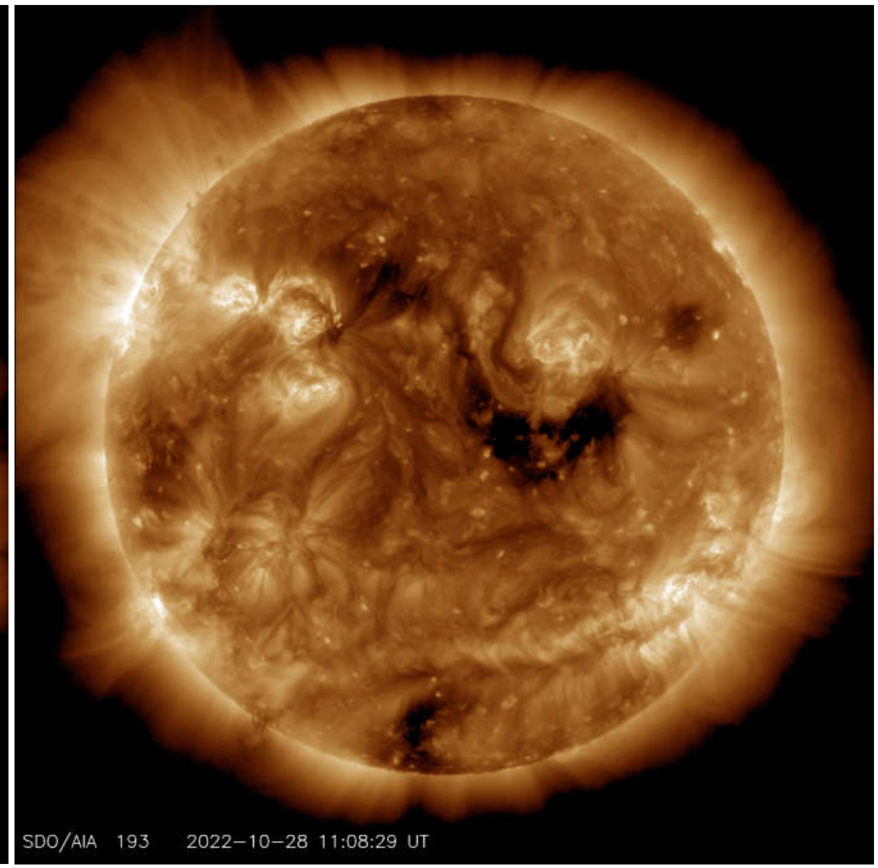


Gopalswamy, 2008

Recent Weak Storm due to the smiley CH







Electron energization following geomagnetic storms

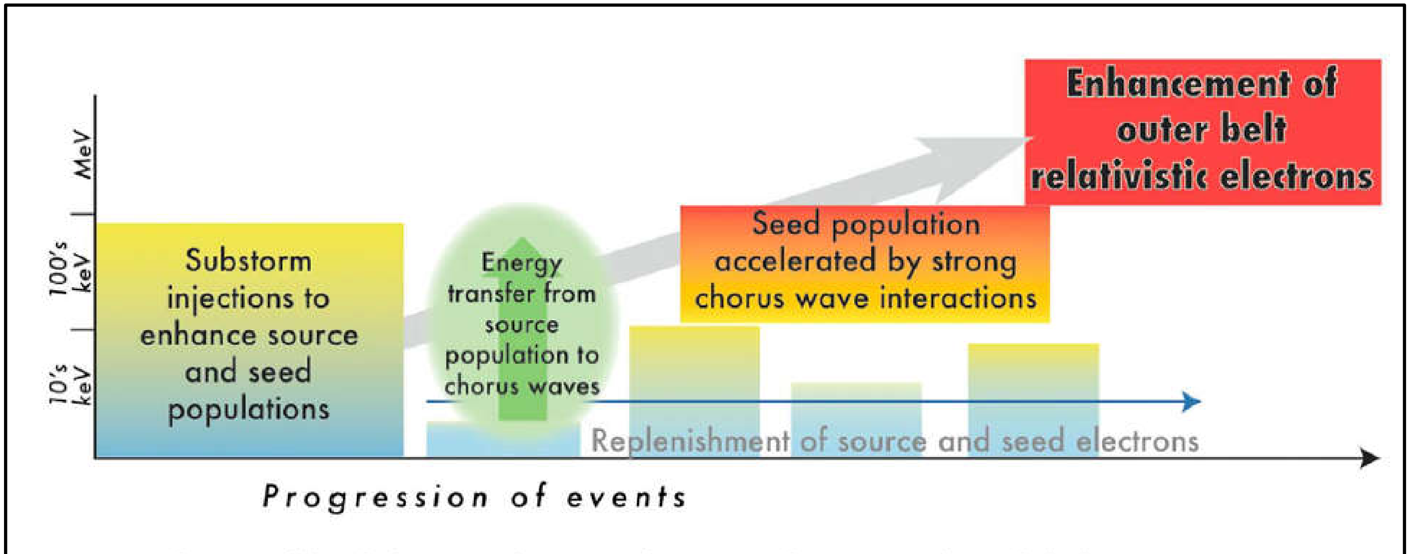
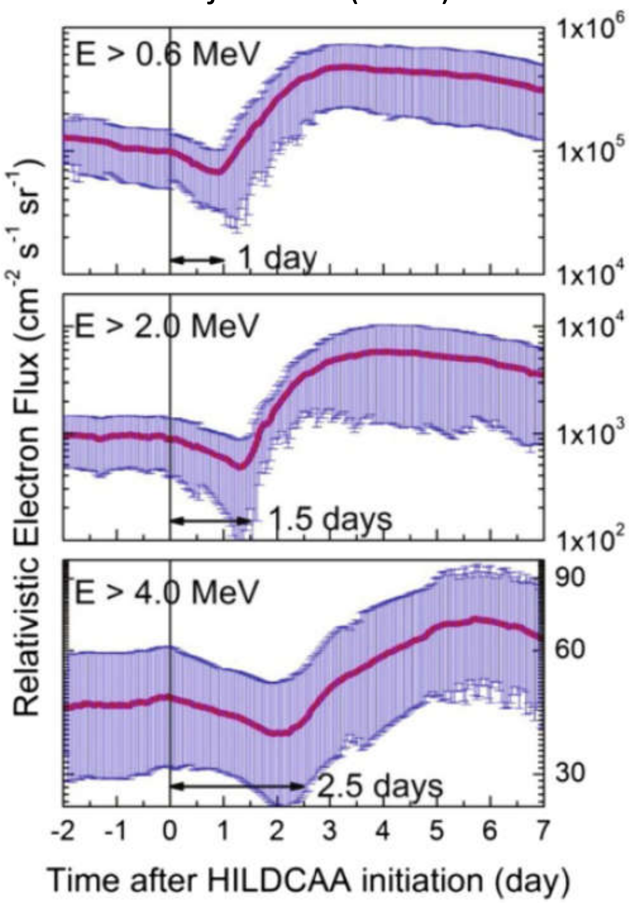


Figure 1. Schematic of the ideal setup and sequence for strong enhancement of outer belt electrons >1 MeV.

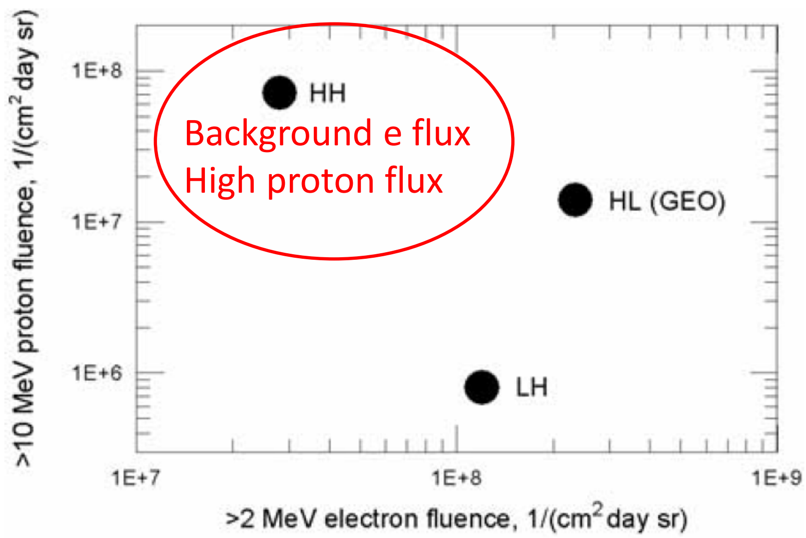
Jaynes et al. 2015

Hajra et al. (2014)



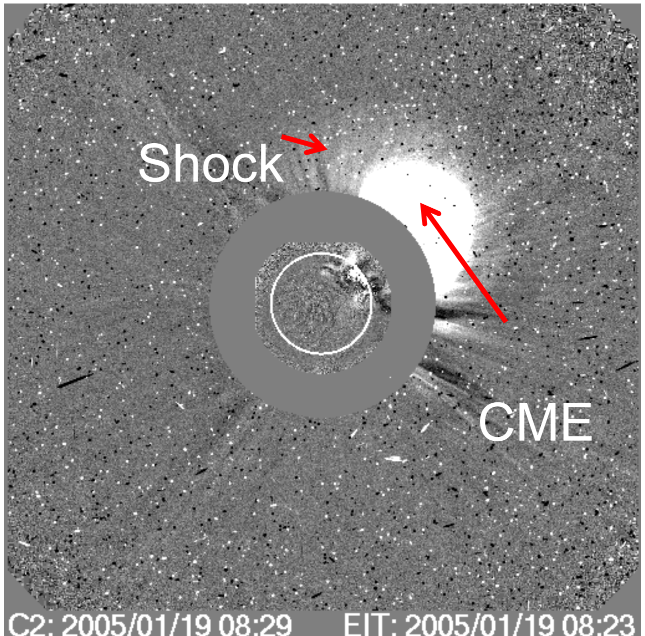
S/C anomalies due to protons and electrons

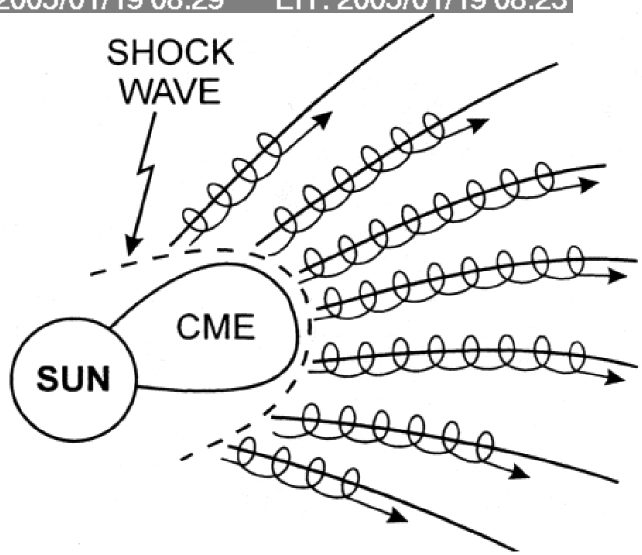
5700 anomalies: 1036 in HH from 13 S/C

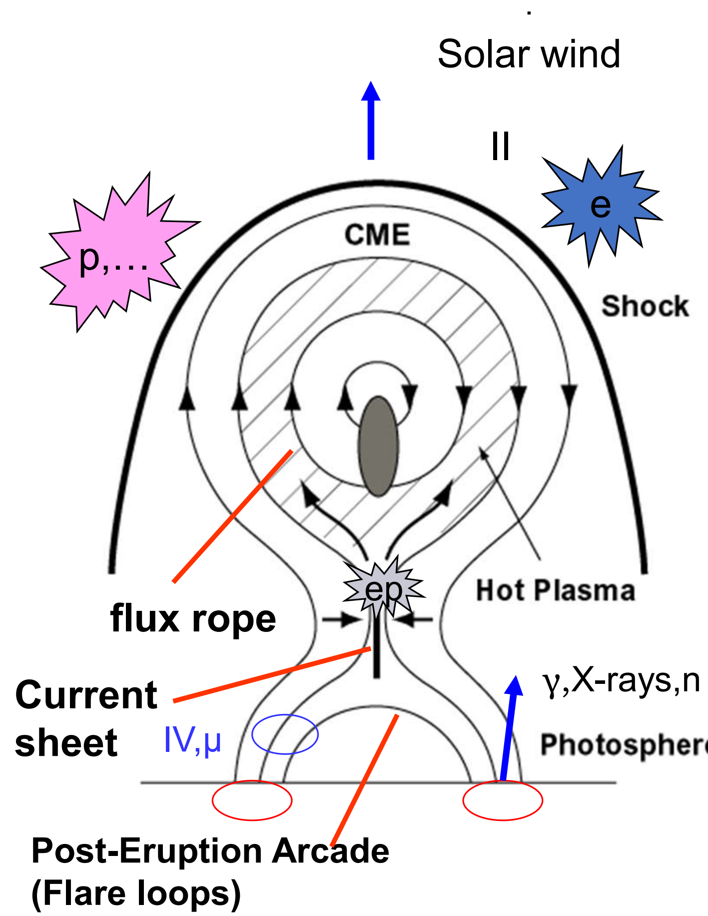


HH: High altitude (>15000 km),
high inclination (>55°)
Relevant to GNSS

Iucci et al. 2005

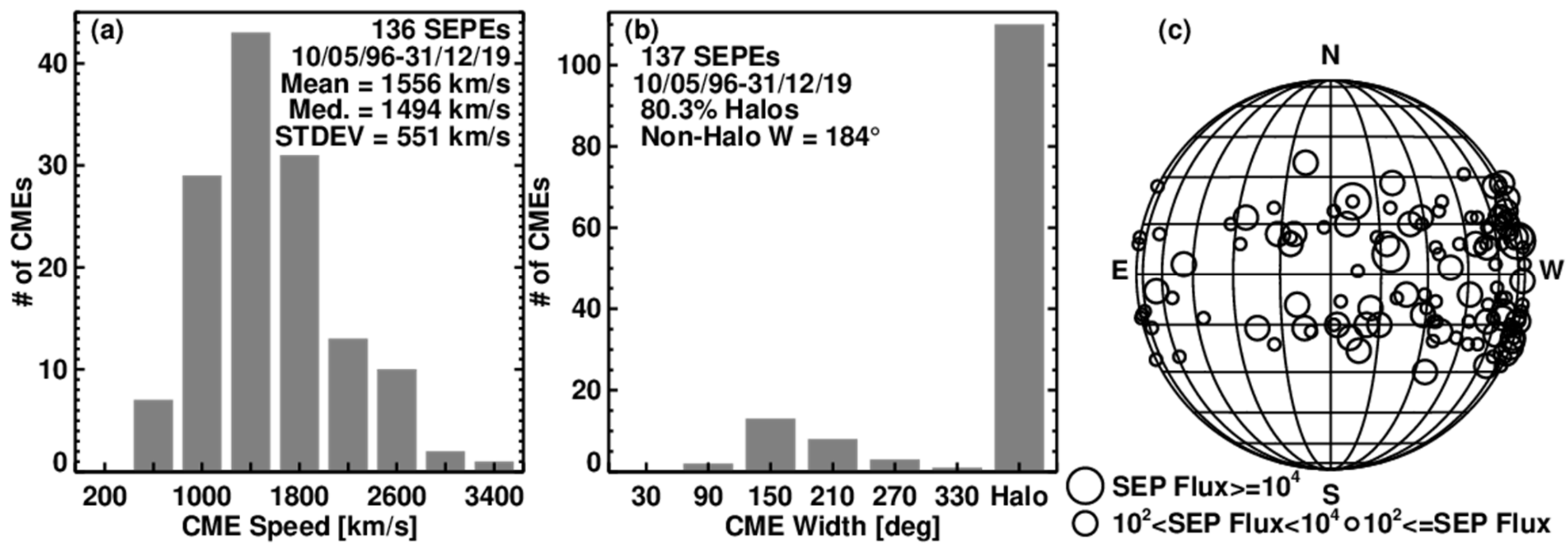






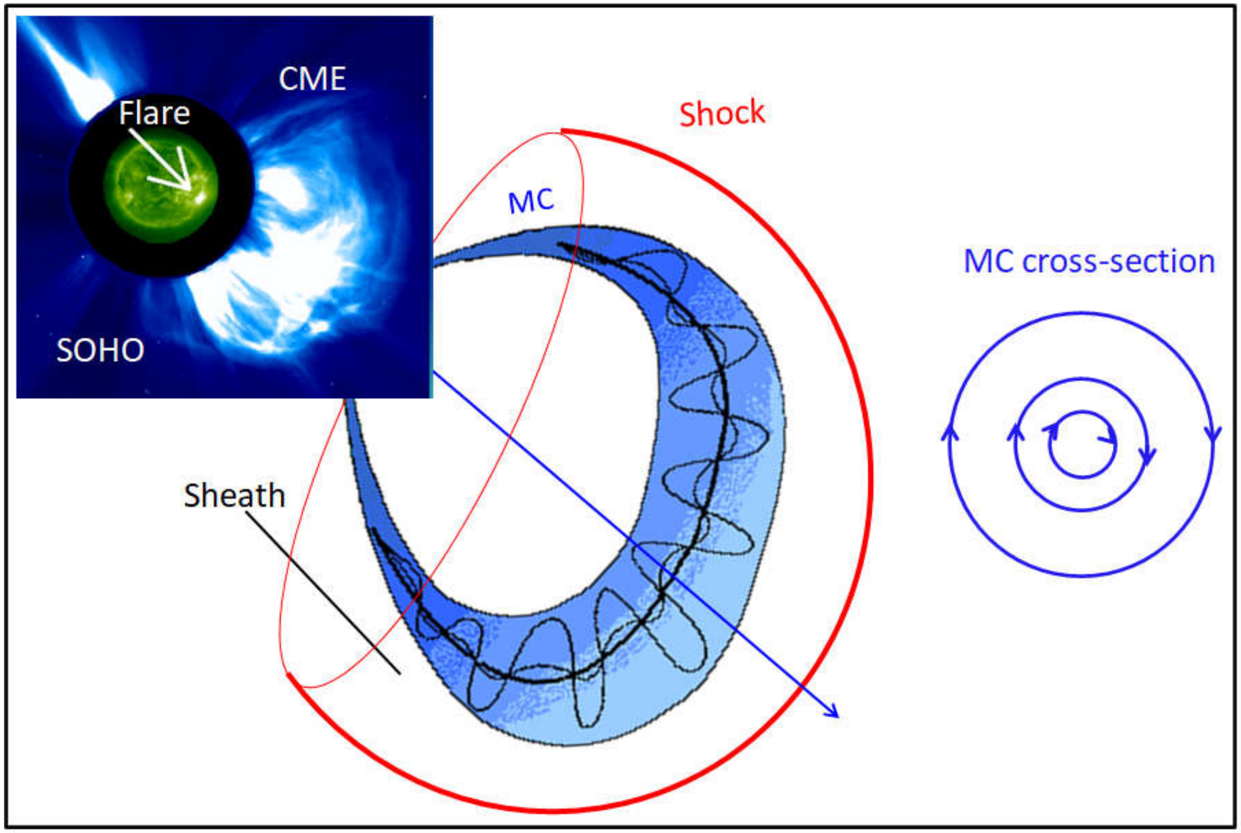
Kahler, Hildner, & Van Hollebeke (1978)

Properties of CMEs Producing Large SEP Events

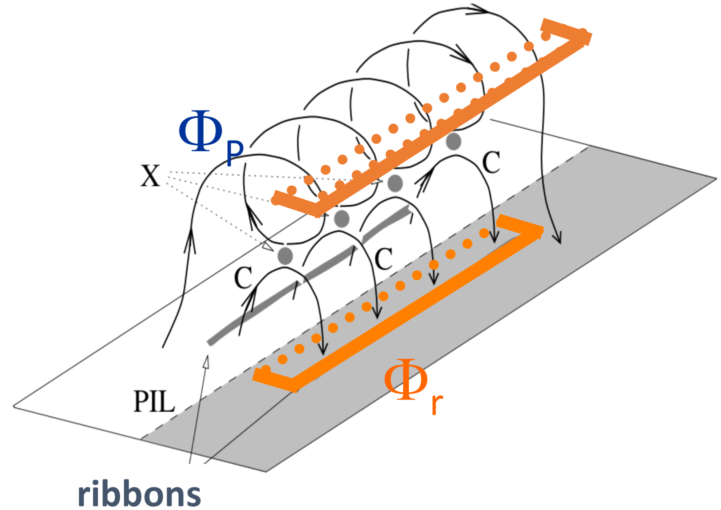


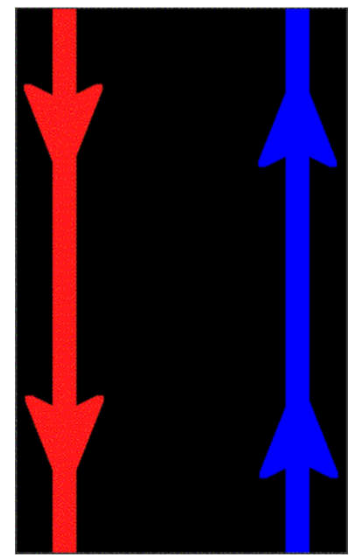
- SEP Events are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Shock-driving capability of CMEs key for SEPs

Typical speed: 400 km/s
Typical width 40 deg

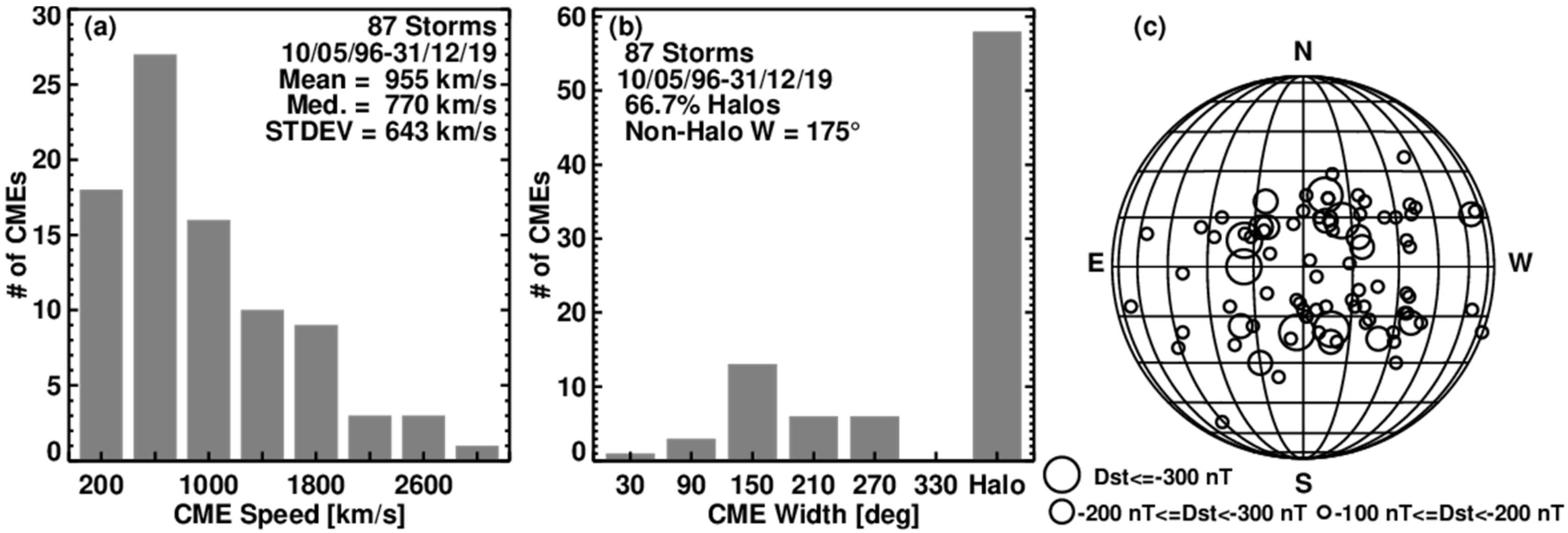


Magnetic flux rope and the shock sheath





Properties of CMEs Producing Large SEP Events



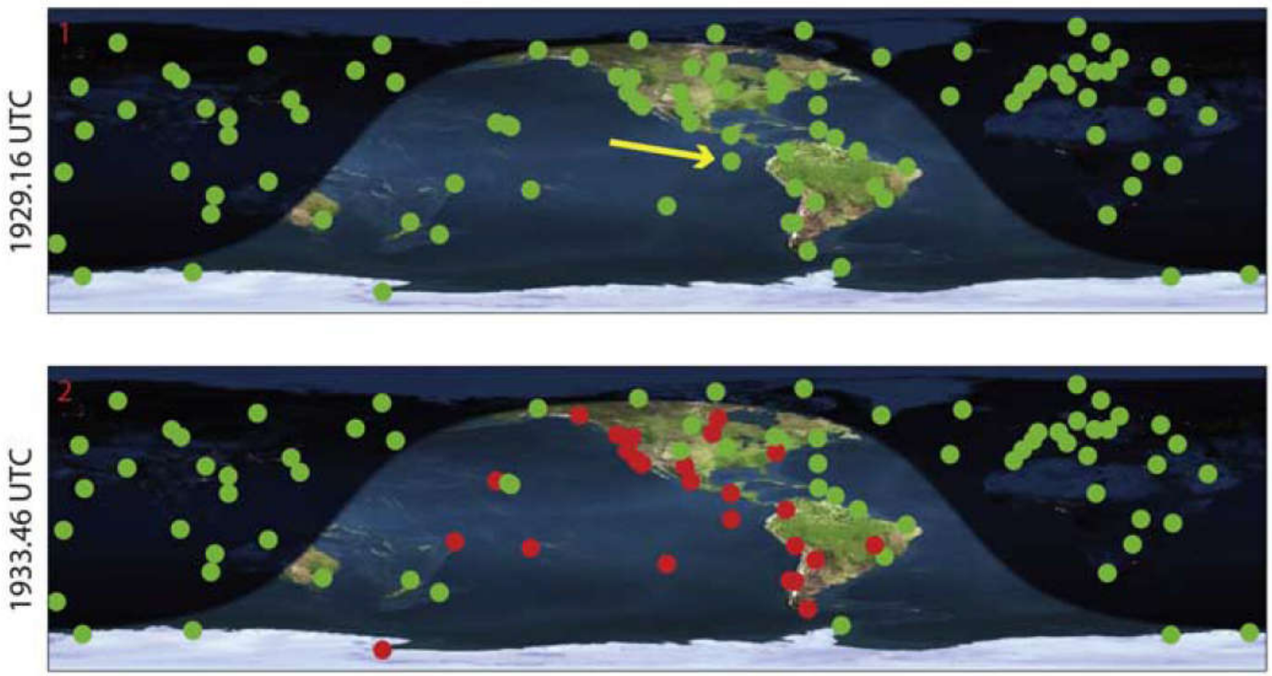
- Magnetic storms are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Southward IMF in CMEs key for magnetic storms

Typical speed: 400 km/s
Typical width 40 deg

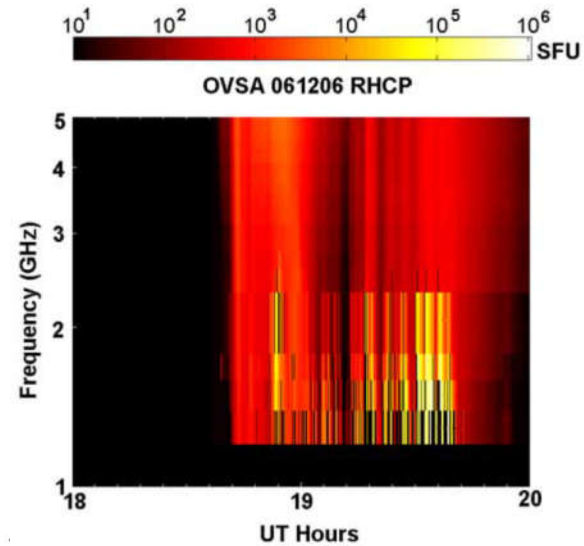
Solar Radio Burst Affecting GPS

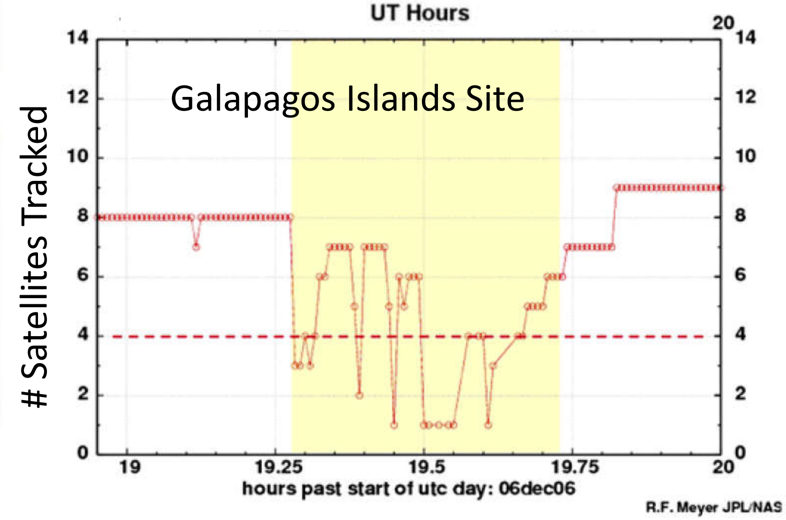
Microwave bursts are due to electrons accelerated in flaring regions

IGS Network Dual Frequency Code Observations, 6 December 2006



- Solar Radio Bursts affect the entire sunlit hemisphere
- Different from the frequent but localized ionospheric irregularities
- Civilian dual frequency GPS receivers were the most severely affected





Corrections require ≥4 satellites tracked

Cerruti et al. 2008 SpaWea

Radio Burst Interference with ATC Radar

'Solar storm' grounds Swedish air traffic

The Local
news@thelocal.se
@thelocalsweden

4 November 2015
17:01 CET+01:00

gothenburg
air
airports
solar storm

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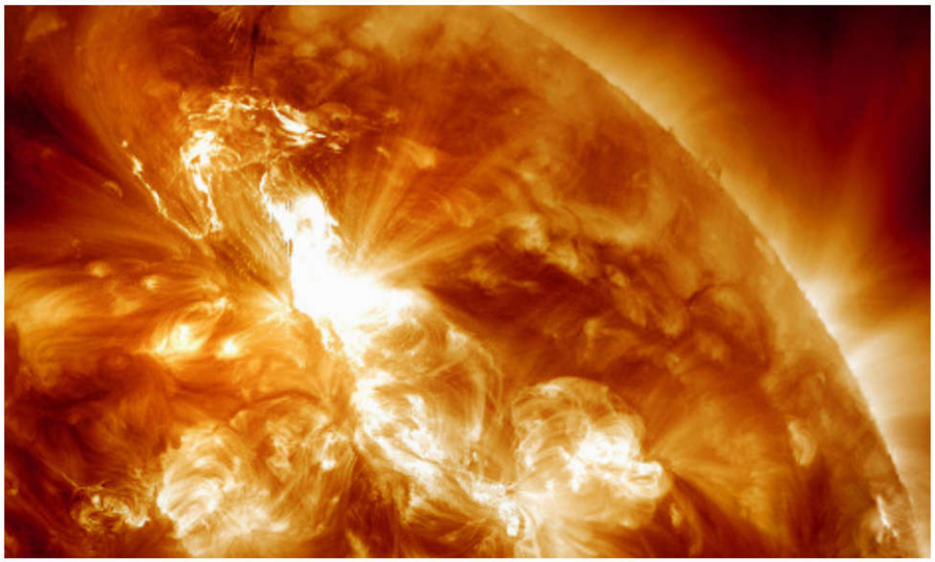
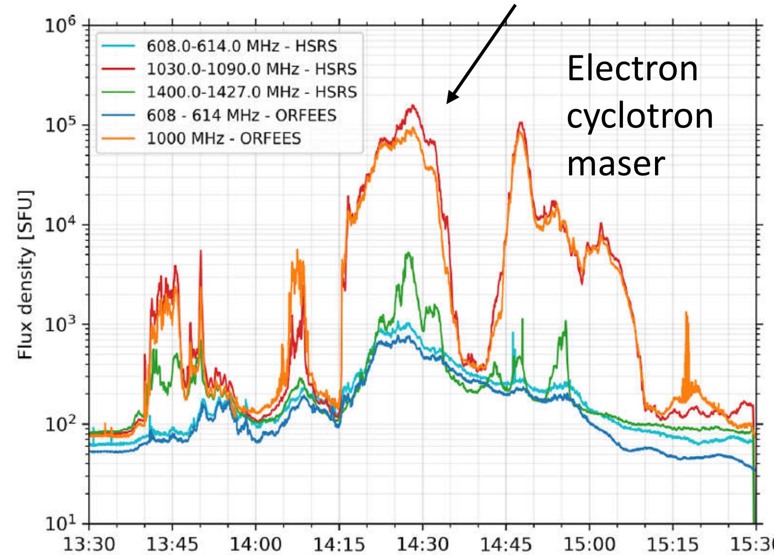


A solar flare erupting from the sun. Photo: AP Photo/NASA

Planes were grounded at some of Sweden's busiest airports on Wednesday afternoon because of a "solar storm" interfering with air traffic control radar systems, authorities said.

Secondary Surveillance Radars (SSR):
Operational frequencies: 1030 & 1090 MHz



Universal Time on 2015 Nov 04

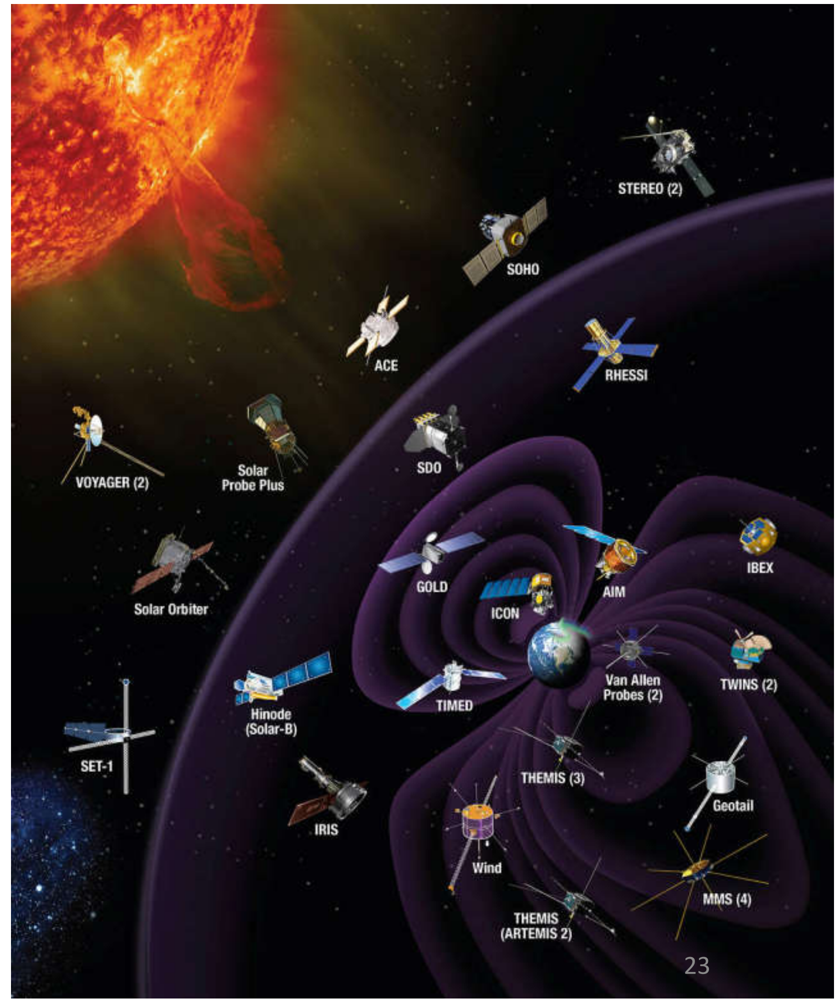
- Radar disturbances in Belgium, Sweden and Norway: false echoes when the airport antennas looked sunwards (2-12^o)
- Temporal association between periods of strongest disturbances and solar microwave bursts

Solar signal 34 dB above the interference level for the radar!

Marqué et al. 2018 JSWSC

The Heliophysics System Observatory

- How do flares and CMEs originate at the Sun?
- How do CMEs and CIRs evolve in the interplanetary medium?
- When do the transients start driving shocks?
- How to predict the arrival of transients at near-Earth space environment (CMEs, SEPs, shocks, CIRs)?
- What is the internal structure of CMEs and CIRs
- How are transients affected by solar cycle variation?
- Model development and validation using new data from space and ground

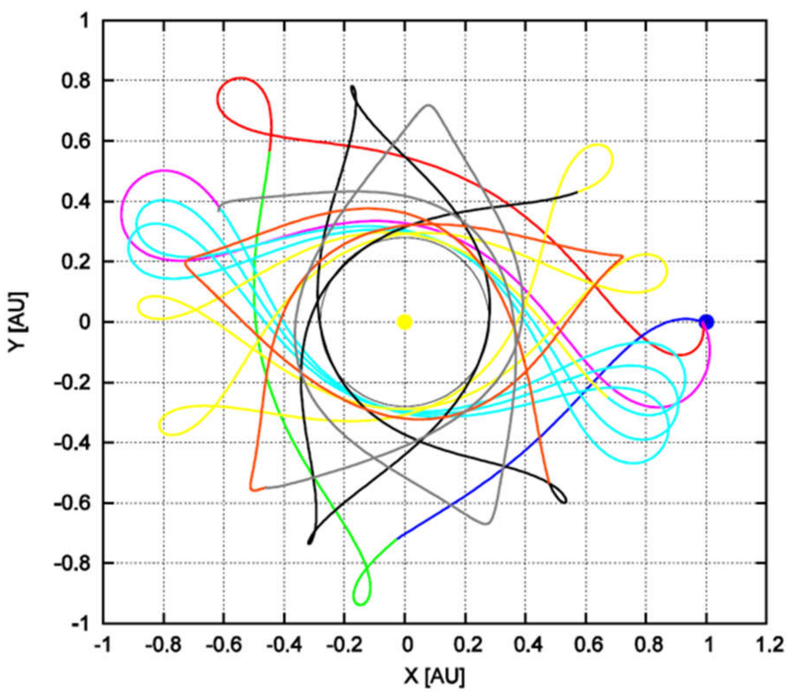


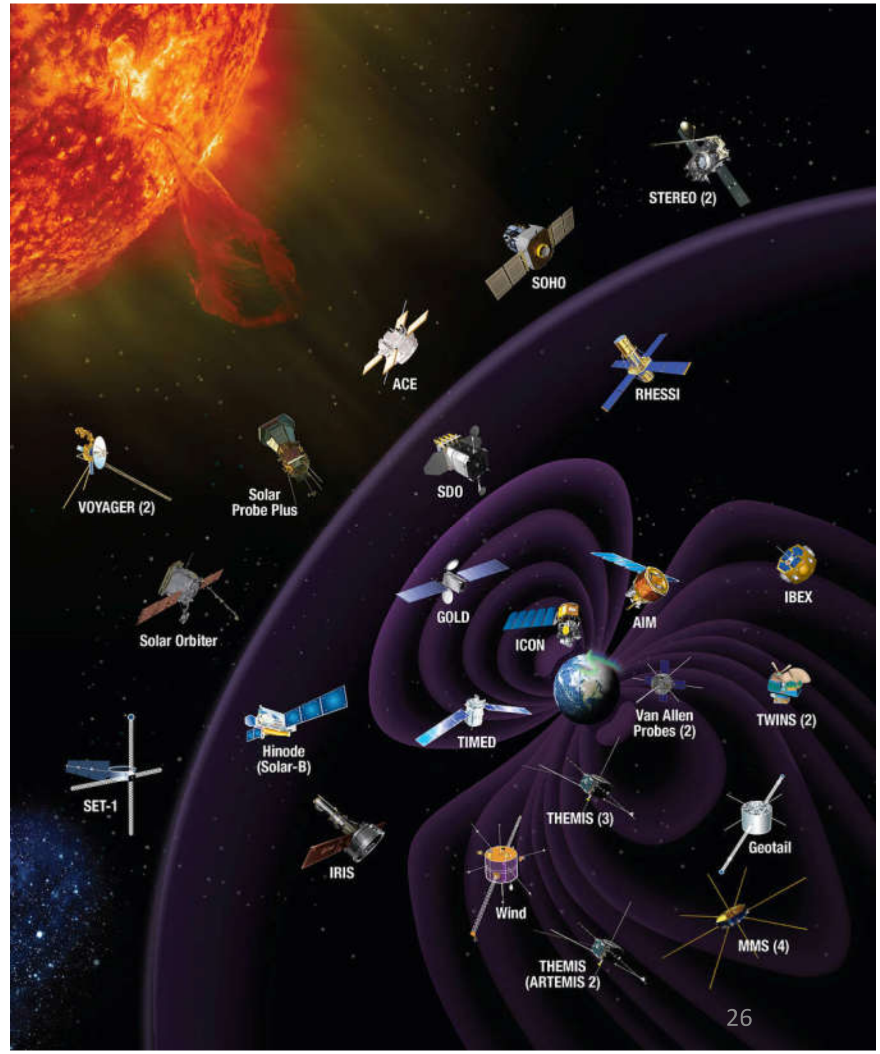
Summary

- Space weather is a unique field of research with scientific and practical importance.
- Most of the space weather is a consequence of variable energy flow from the Sun
- Upward energy flow from Earth and galactic cosmic rays contribute to space weather
- Coronal mass ejections, high speed streams, solar flares, and solar energetic particle events are the primary transients relevant for space weather

Back-up slides

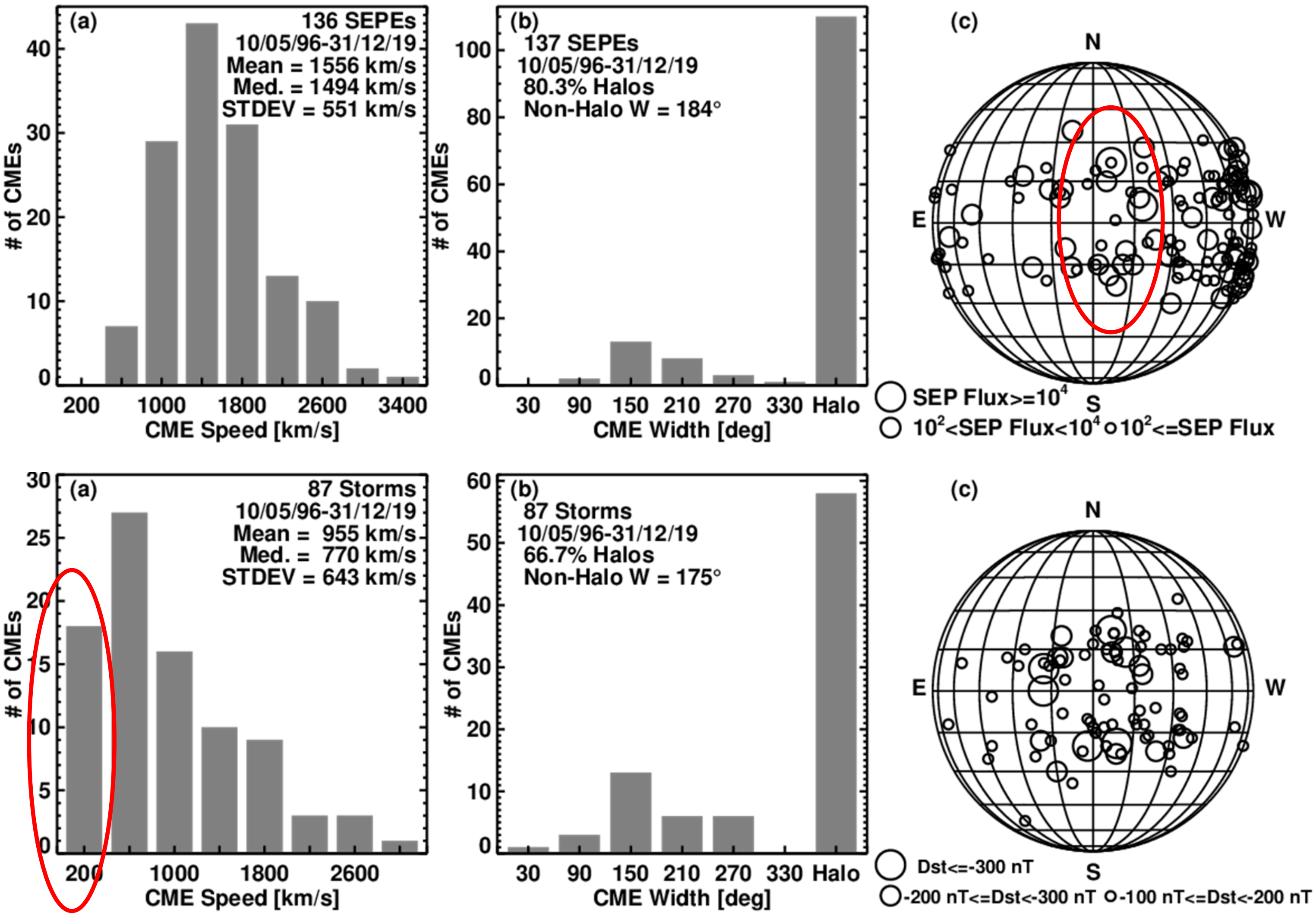
the Heliophysics System Observatory





SEP Events

Shock-driving CMEs

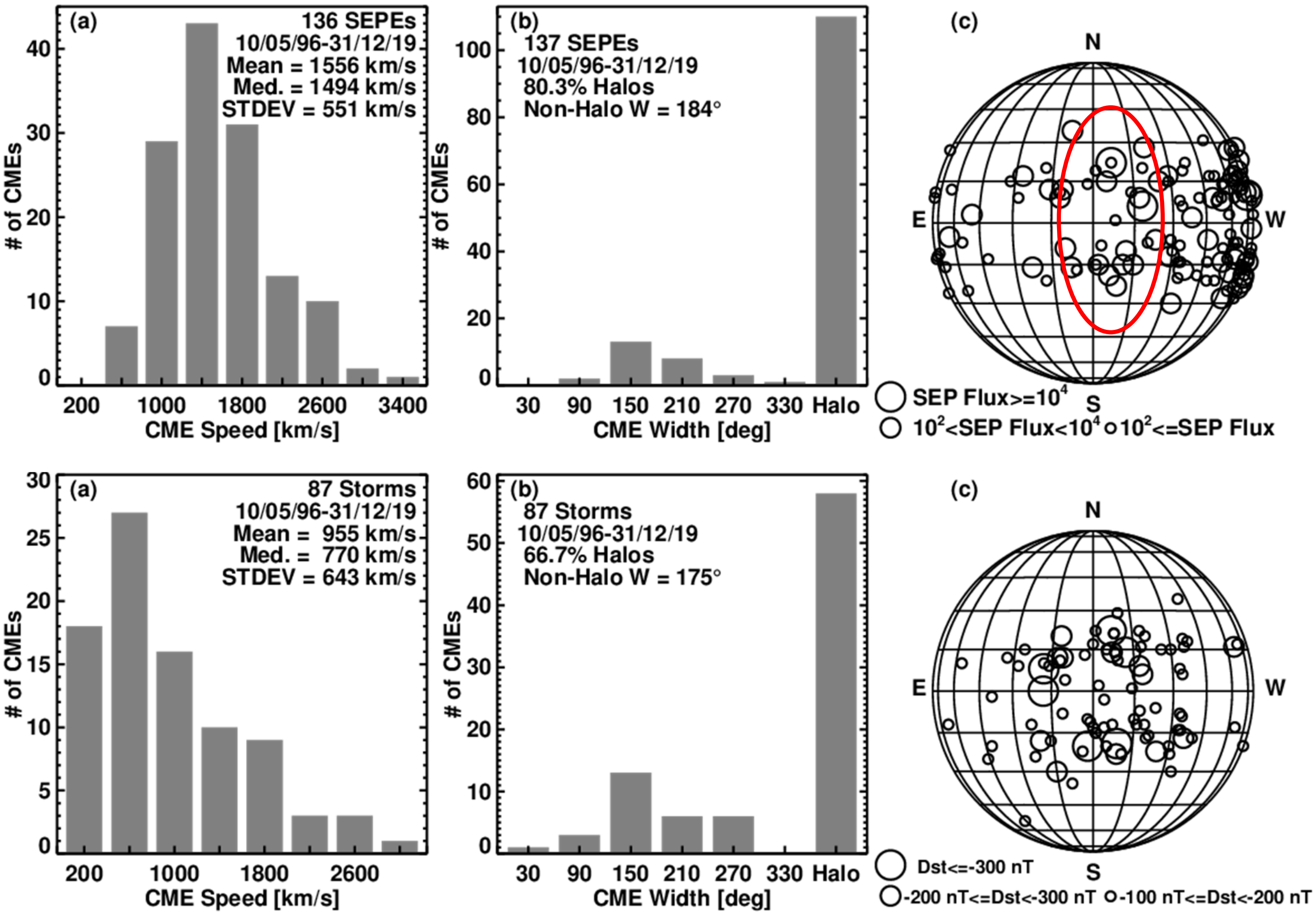


GM Storms

CMEs with Bz <0 in Flux Rope &/ Sheath

SEP Events

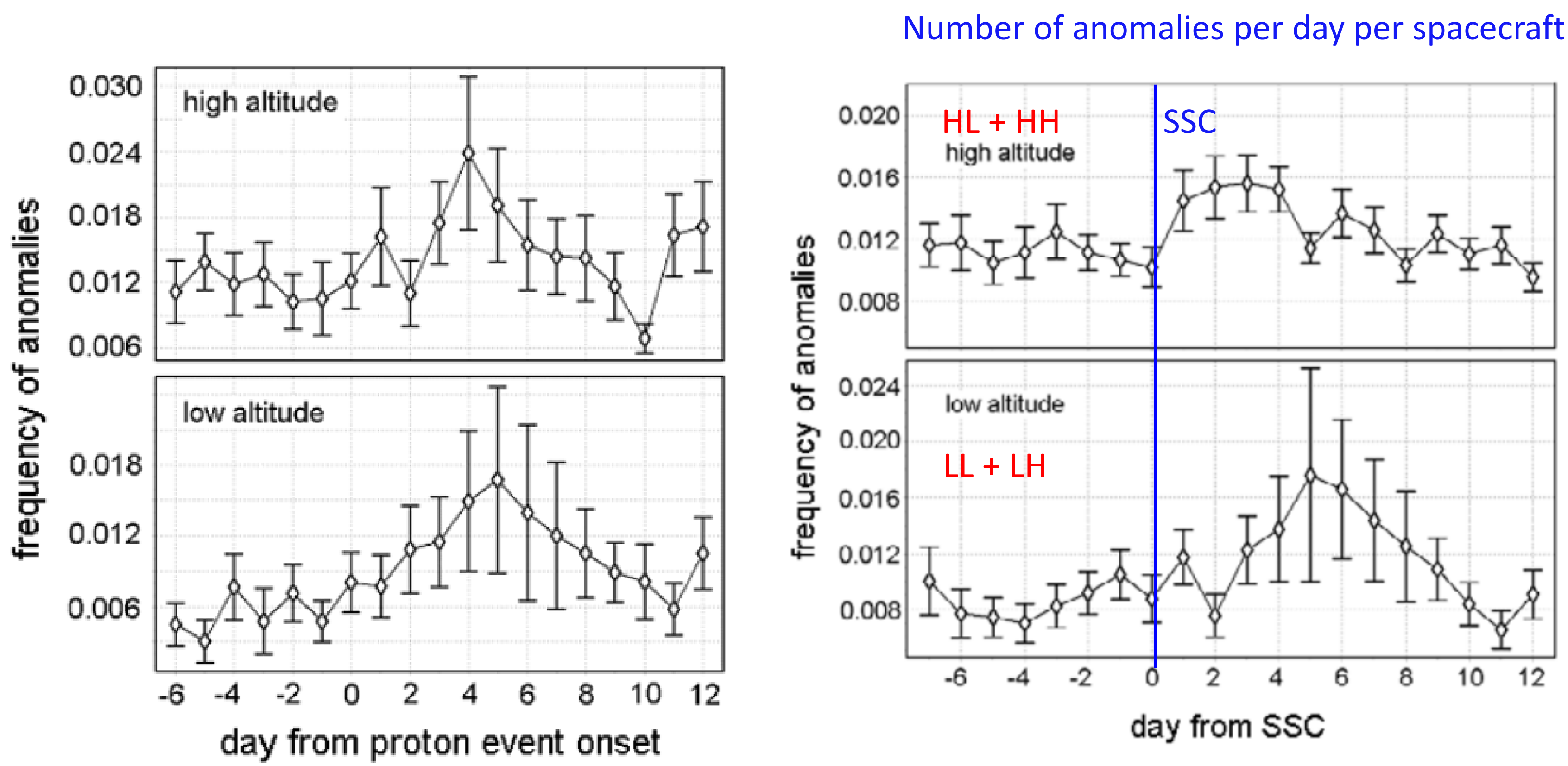
Shock-driving CMEs



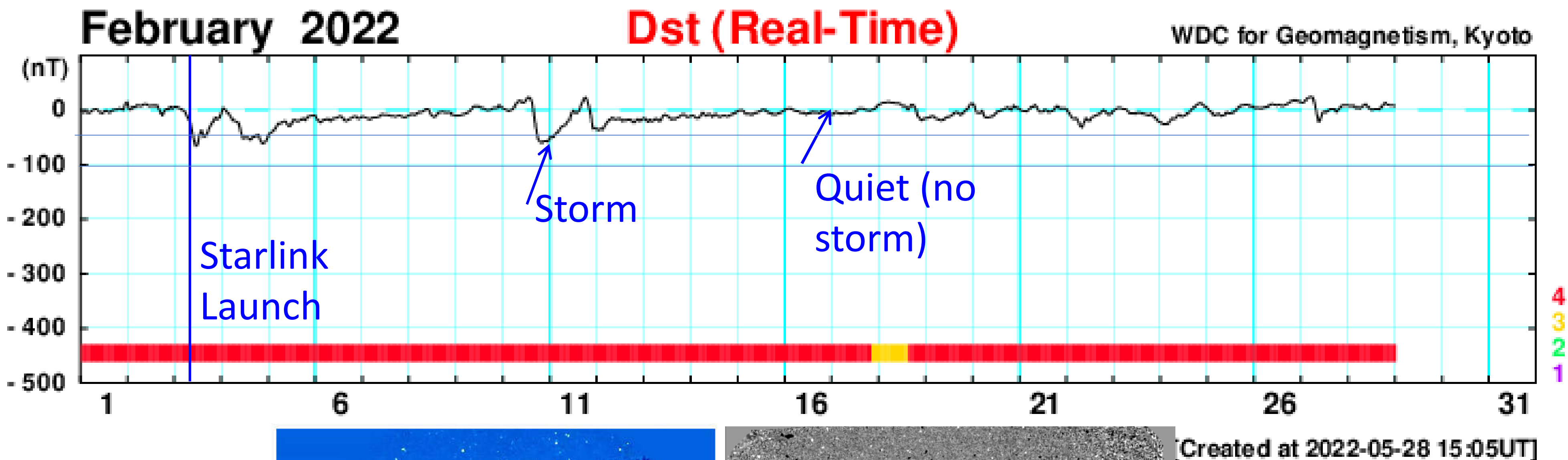
GM Storms

CMEs with Bz <0 in Flux Rope &/ Sheath

Geomagnetic Storms and Satellite Anomalies



Iucci et al. 2005



February 2022
Dst (Real-Time)
WDC for Geomagnetism, Kyoto
(nT)
0
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- 300
- 400
- 500
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16
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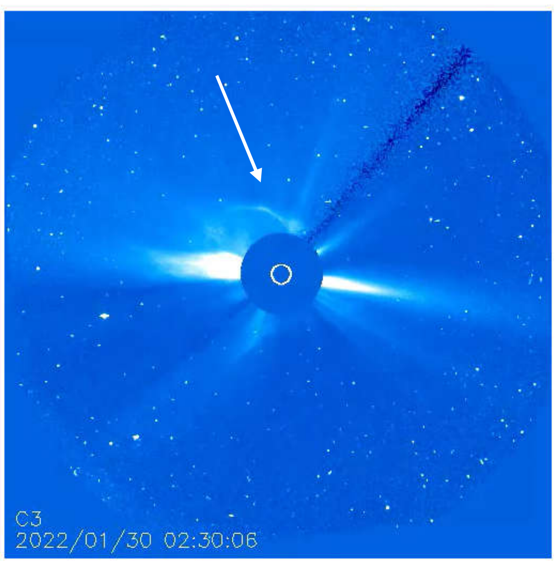
Starlink
Launch
Storm
Quiet (no
storm)
[Created at 2022-05-28 15:05UT]



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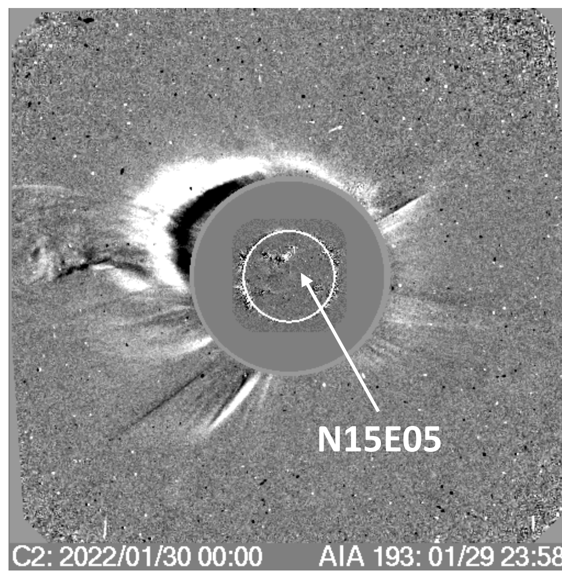

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