The Role of Sun in Space Weather

- Flares
- Coronal Mass Ejections (CMEs)
- Shocks
- Solar energetic particles
- Coronal holes
- High speed streams of solar wind
- Stream interaction regions

- Particle radiation
- Geomagnetic storms
- Ionospheric and atmospheric disturbances

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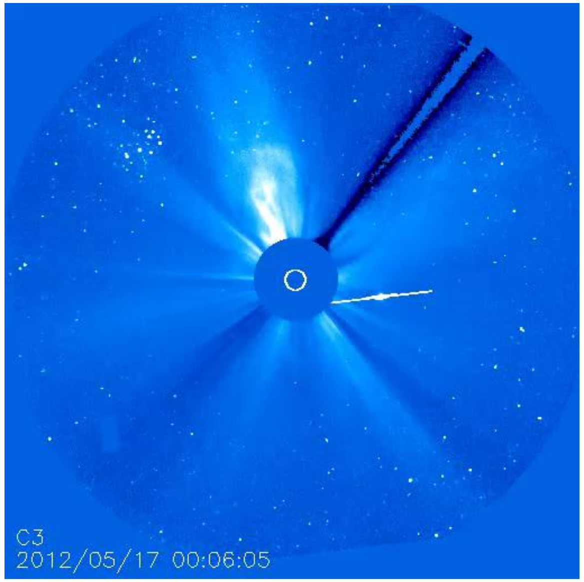
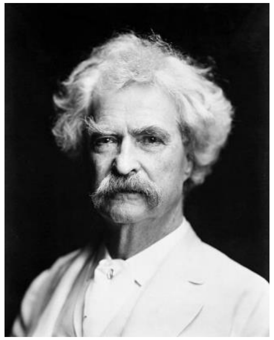


ESA/NASA/SOHO

International Workshop on Machine Learning for Space Weather: Fundamentals, Tools and Future Prospects Nov 7, 2022

Climate & Weather



Mark Twain
1835 - 1910

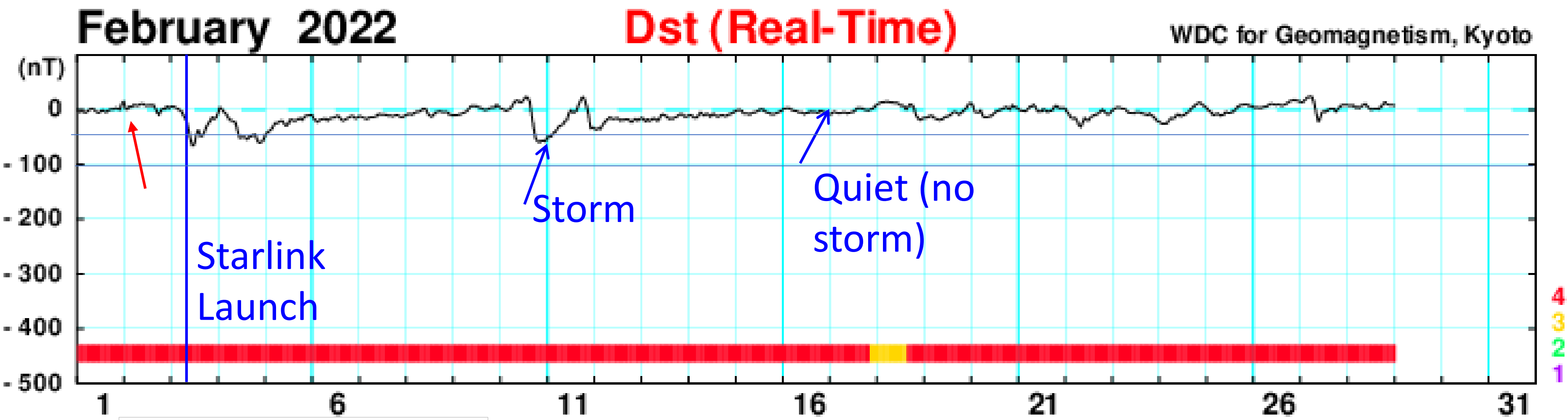
"Climate is what we expect, weather is what we get."

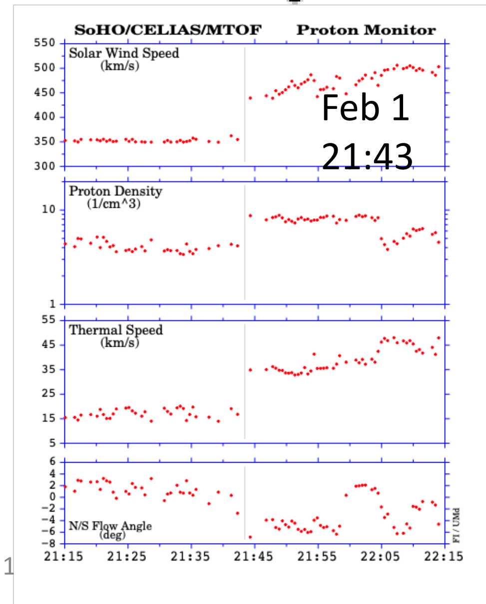
Terrestrial Weather:
Conditions in the atmosphere and on the ground
High winds, hail, excessive precipitation, and wildfires

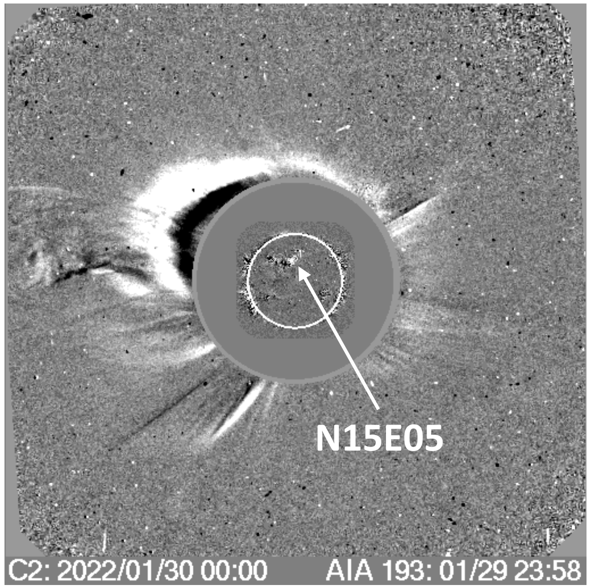
Space weather:
conditions in space: ground, atmosphere, ionosphere, magnetosphere, interplanetary space and the Sun
Density, temperature, magnetic field, energetic particles: solar storms, particle storms

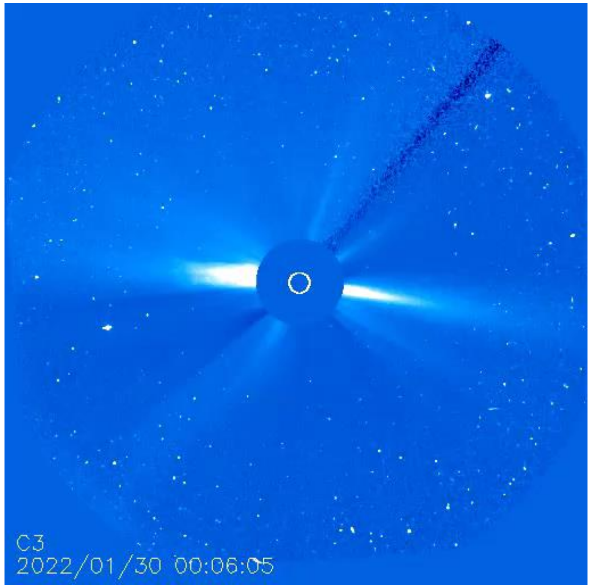
Normal, inconvenient, dangerous (as severity increases)

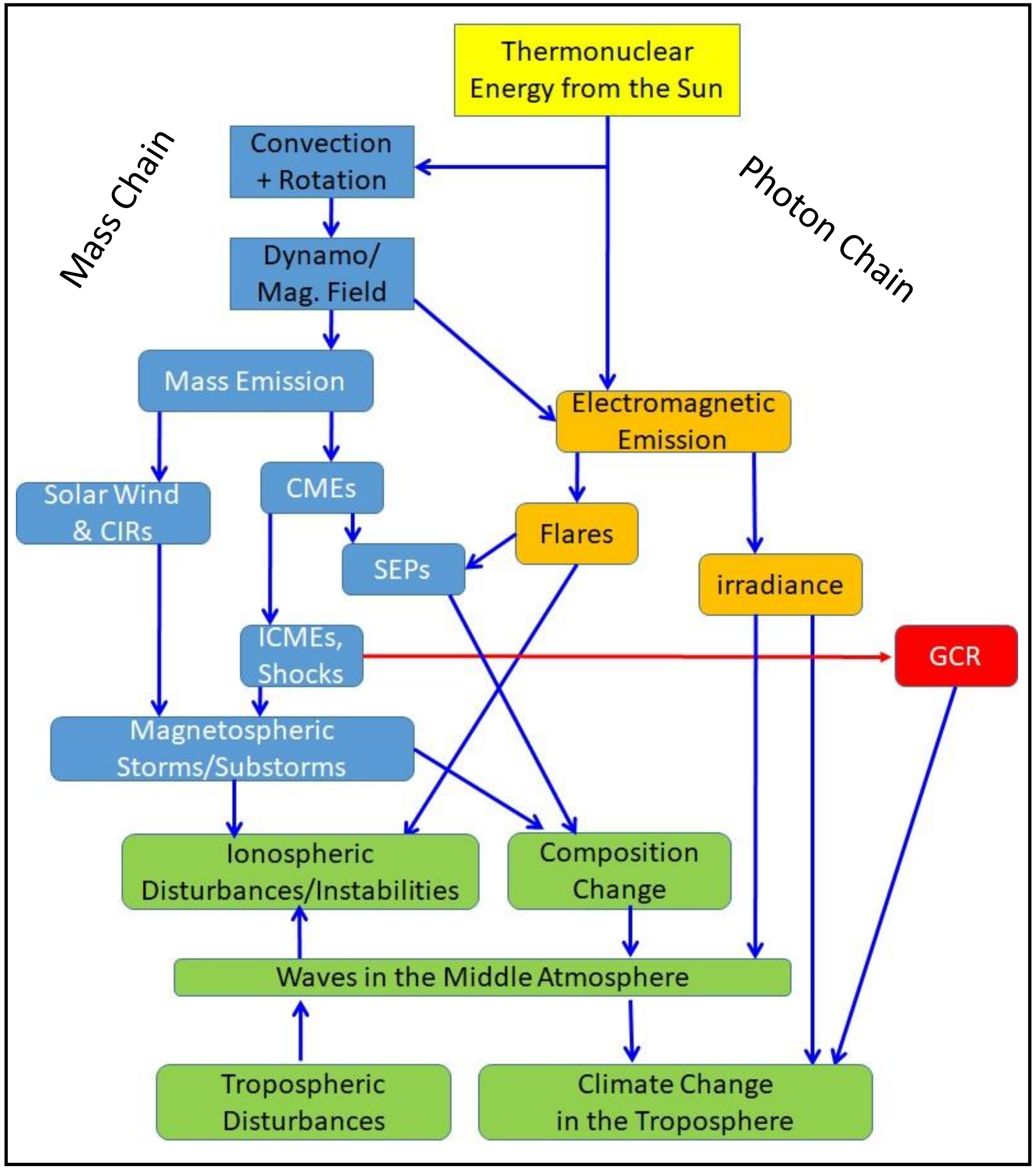
Mitigation, Prediction


February 2022
Dst (Real-Time)
WDC for Geomagnetism, Kyoto
(nT)
0
-100
-200
-300
-400
-500
1
6
11
16
21
26
31
Starlink Launch
Storm
Quiet (no storm)
4
3
2
1


SoHO/CELIAS/MTOF Proton Monitor
Solar Wind Speed (km/s)
Proton Density (1/cm^3)
Thermal Speed (km/s)
N/S Flow Angle (deg)
Feb 1 21:43
21:15
21:25
21:35
21:45
21:55
22:05
22:15


N15E05
C2: 2022/01/30 00:00
AIA 193: 01/29 23:58


C3
2022/01/30 00:06:05



Source of Energy

Nuclear fusion: 600 million tons of H burns to yield 596 million tons of He every second

Missing 4 million tons of 4 billion kg becomes energy

$E = mc^2$ (c^2 joules per kg = 9×10^{16} J/kg)

4 billion kg → 3.6×10^{26} J per second (W)

Mass Chain:

Consequence of solar dynamo (convection + rotation)

Release of magnetic energy

Coronal Mass ejections (CMEs) closed field regions

High speed streams (CIRs) open field regions → Corotating interaction regions

Magnetic field transported with plasma: magnetic storms

Energetic particles from CME-driven shocks, flares

EM Chain:

Flares superposed on steady EM radiation

Galactic Cosmic Rays (GCRs):

Modulated by CME, CIR magnetic fields

Contribute to Inner Van Allen Belt

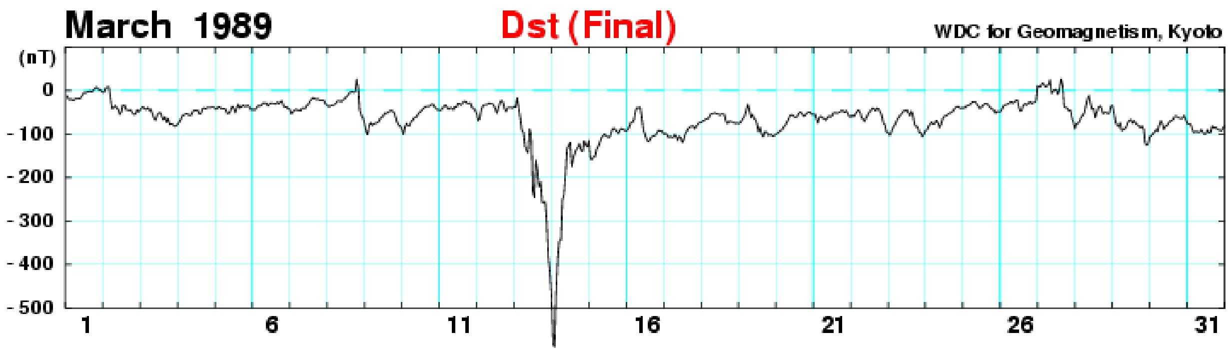
Upward chain:

Ionospheric disturbances/irregularities

Contributions from flares & CMEs

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



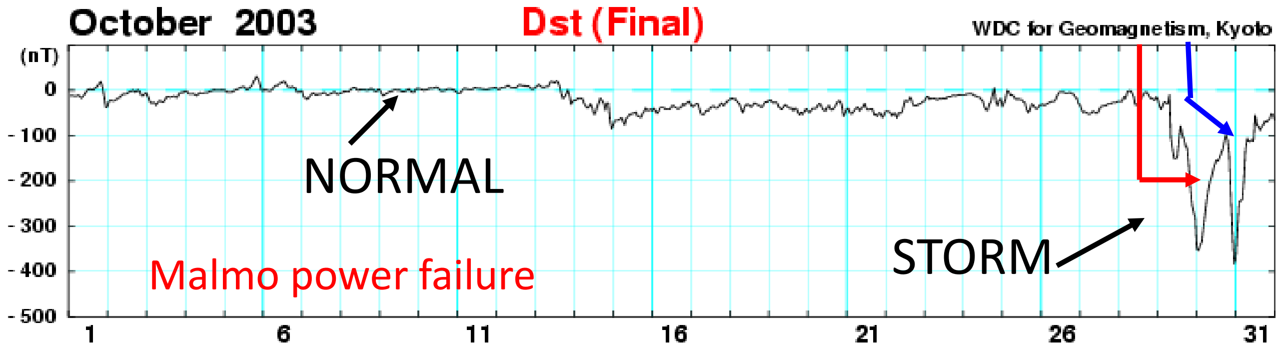
March 12 00:16 UT Eruption (1300 km/s)
Shock arrival: March 13 07:47 UT → 31.5 hrs

- 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

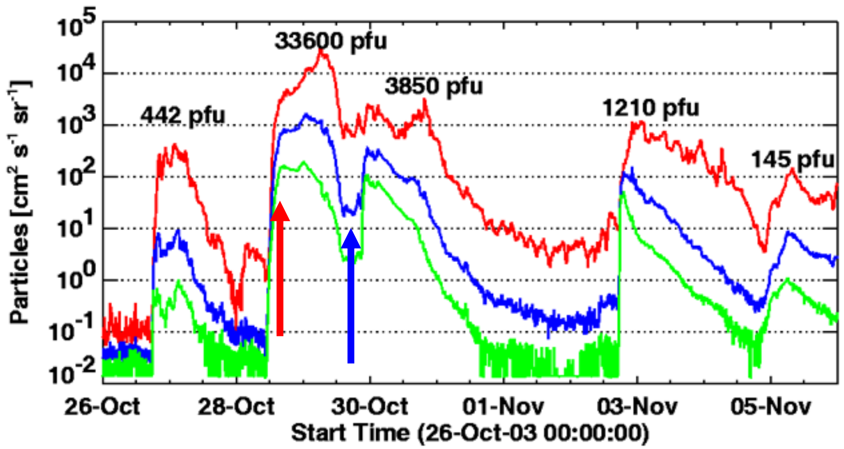


http://wdc.kugi.kyoto-u.ac.jp/dstdir/

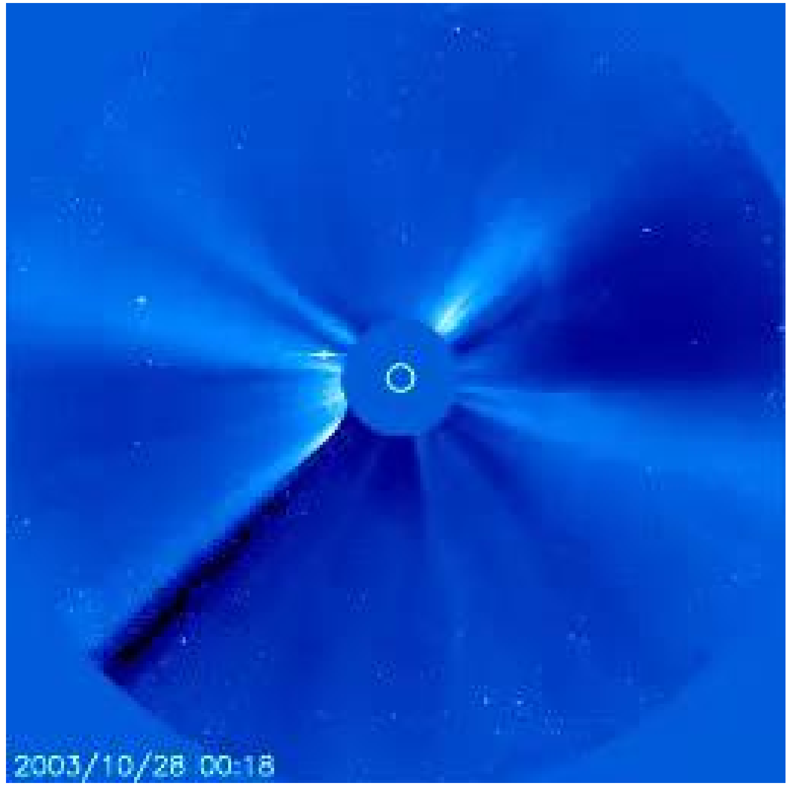
Transit under 19 hours

Particle radiation another huge hazard to human technology in space
Mars mission affected
Gopalswamy et al. 2005

Double Whammy Events

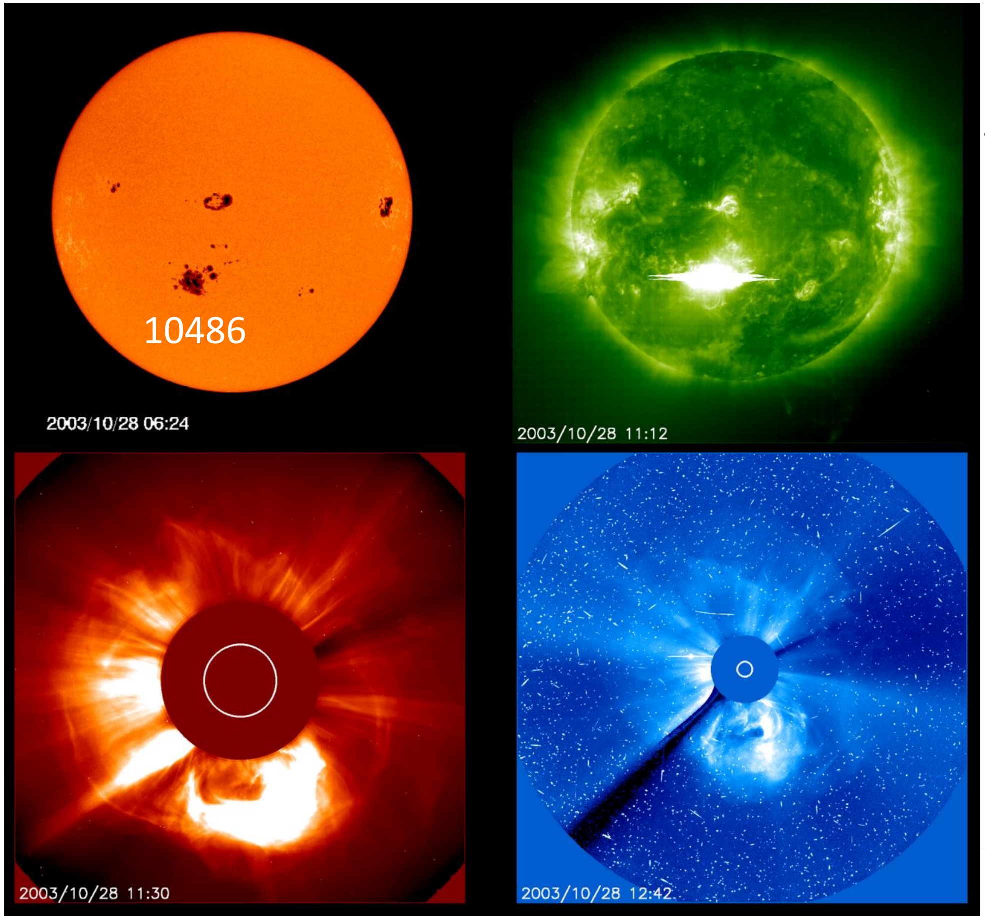


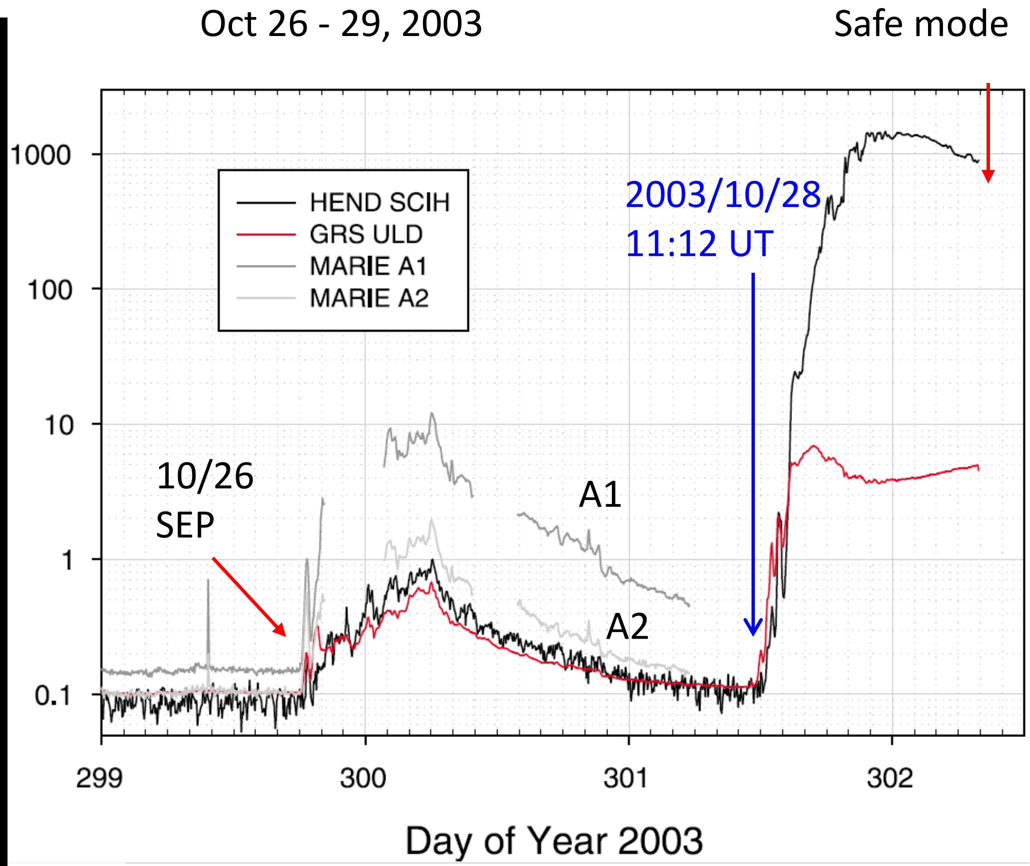
Two halo CMEs: 10/28 and 10/29 2003



SOHO/LASCO

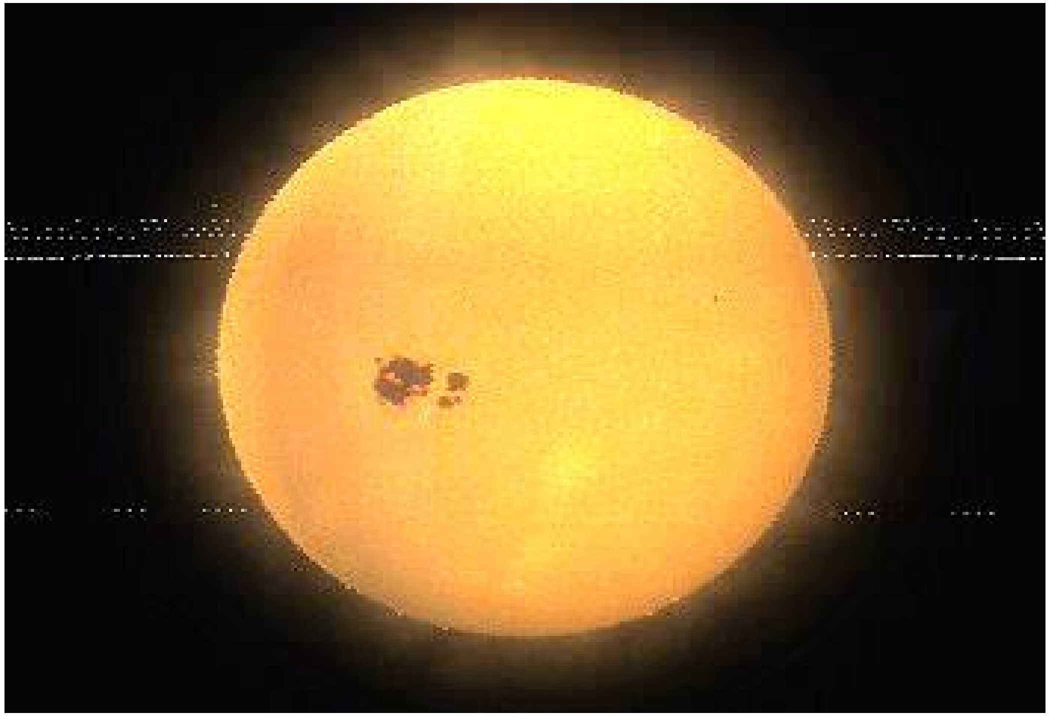
The MARIE Slayer: 2003 Oct 28 Halloween Storm





Zeitlin+2010

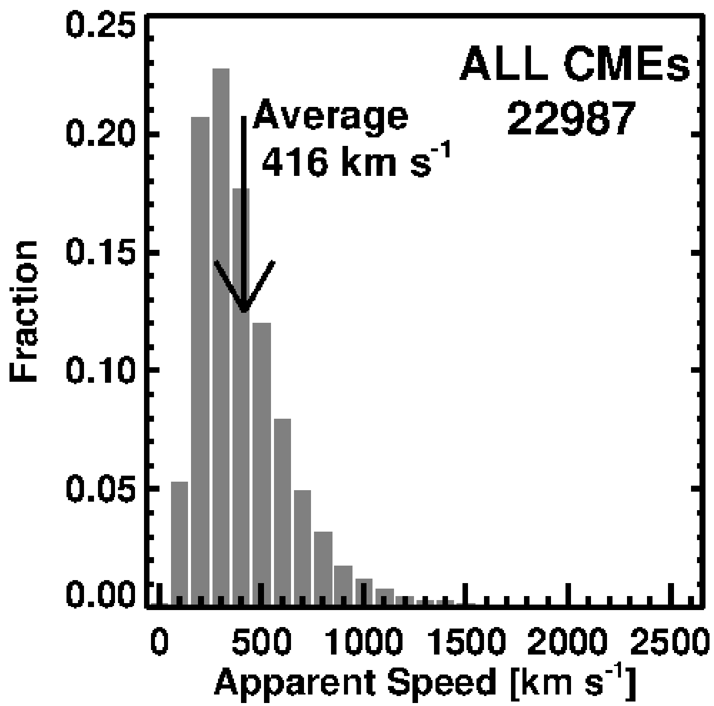
Animation of Halloween 2003 CMEs

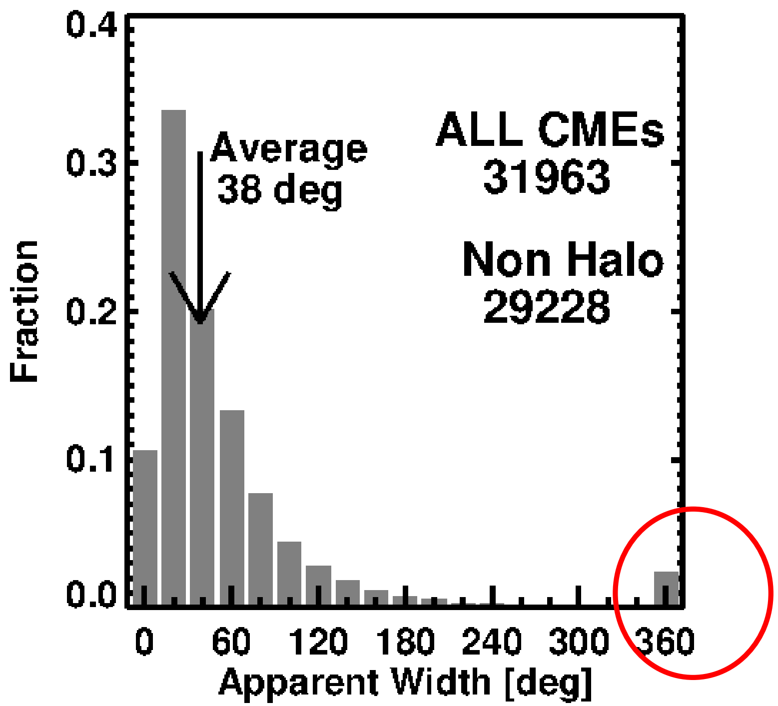


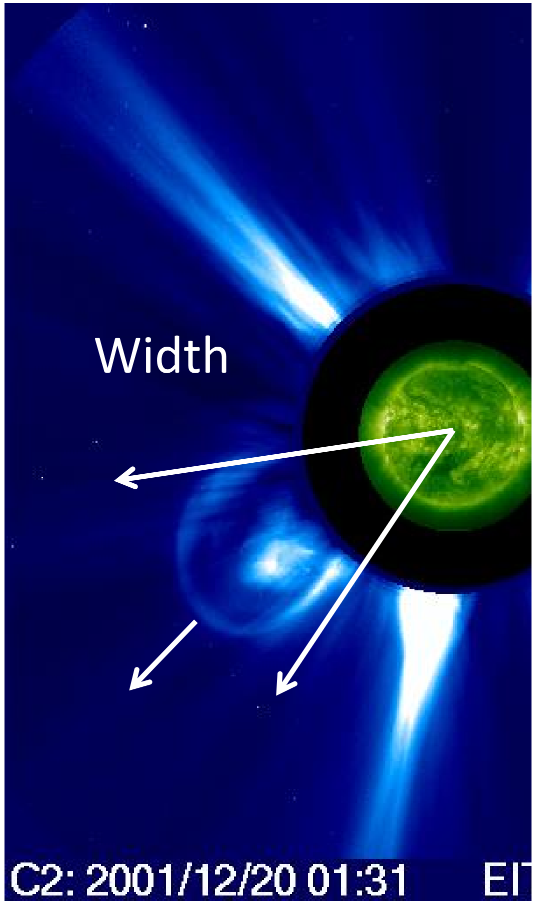
Consequences of the CMEs were observed at Earth, Jupiter, Saturn and even at the edge of the solar system where the Voyagers were located. The CMEs took 6 months to reach the termination shock.

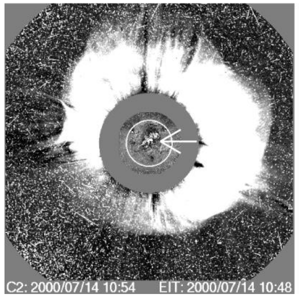
CMEs represent the most energetic phenomenon in the heliosphere

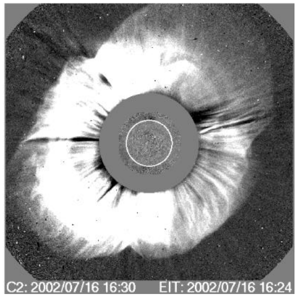
CME Kinematic Properties



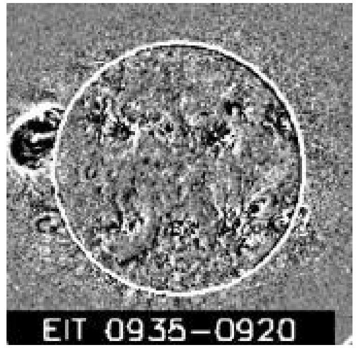




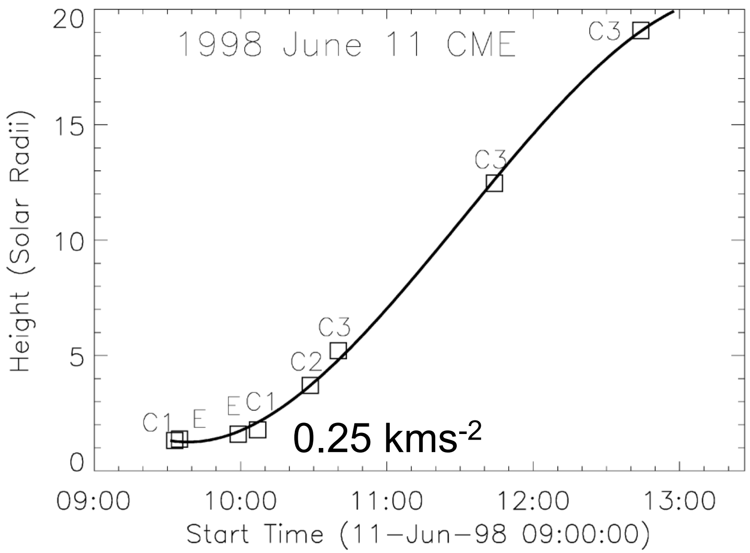


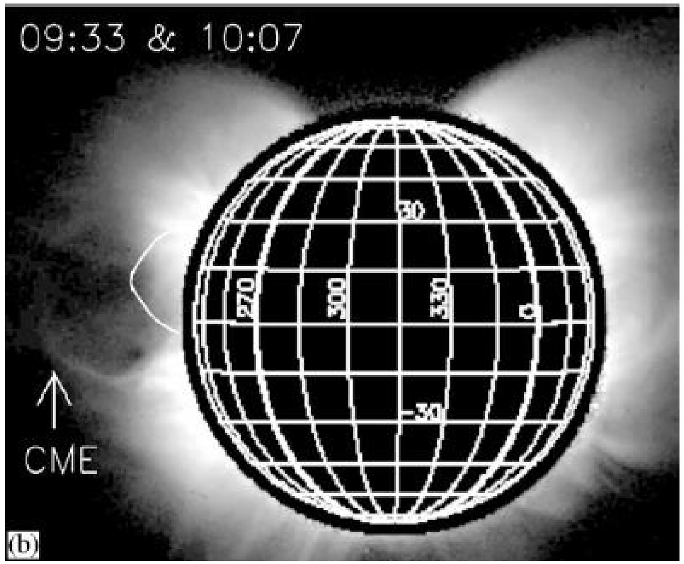


Acceleration from LASCO C1, EIT



Gopalswamy & Thompson 2000

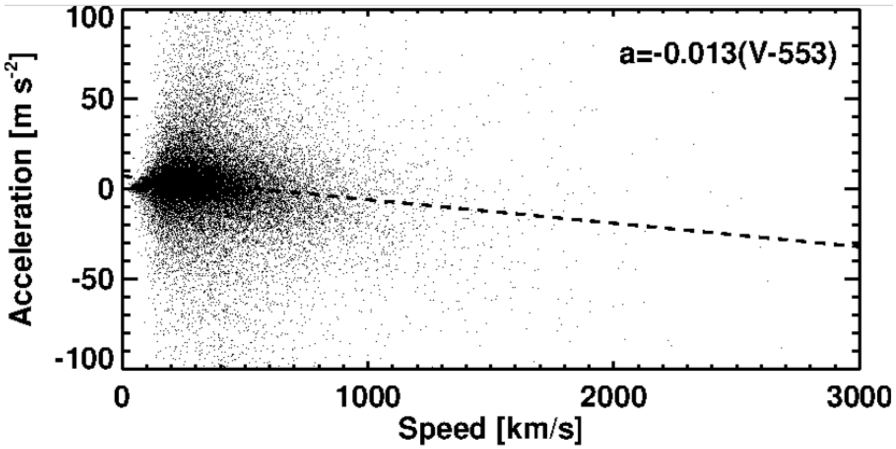


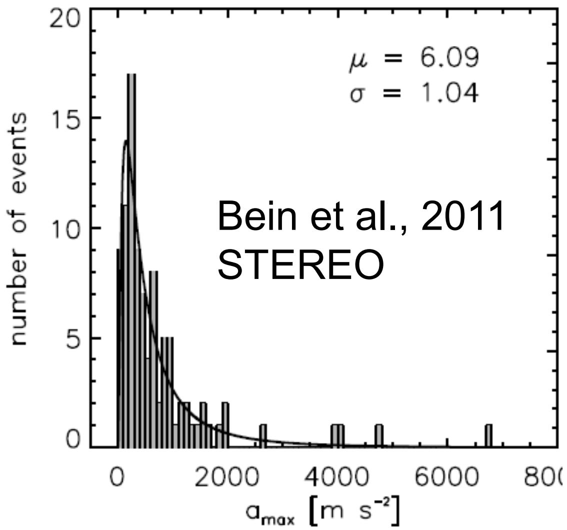


$$h = 3.1 - 0.1t + 1.5\times10^{-3}t^2 - 3.4\times10^{-6}t^3$$

Before June 1998, SOHO had inner coronagraph that measured CMEs close to the surface. The height-time measurement can be fit to a 3rd order polynomial indicating early acceleration and later deceleration (a_p = 0.25 kms^{-2} and residual acceleration = -36 ms^{-2})

Acceleration in LASCO C2/C3 FOV





The measured acceleration is a combination of accelerations due to the propelling force, gravity, and aerodynamic drag.

$a = a_p - a_g - a_d$

In the SOHO coronagraph, the measurements are made beyond 2.5 solar radii

By this distance a_p and a_g are weakened significantly

So, the measured acceleration is mostly due to aerodynamic drag:

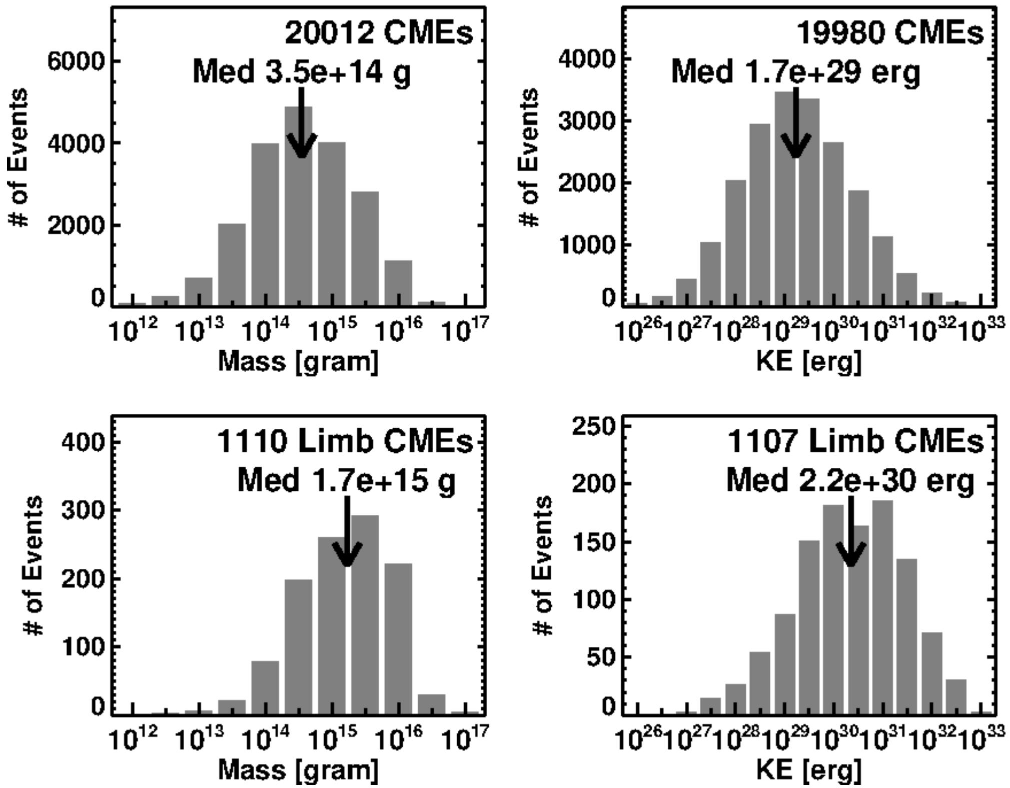
$a = -a_d$

and is referred to as residual acceleration

a_p can be 2-3 orders of magnitude higher than the residual acceleration (0.1 – 10 km s^{-2}).

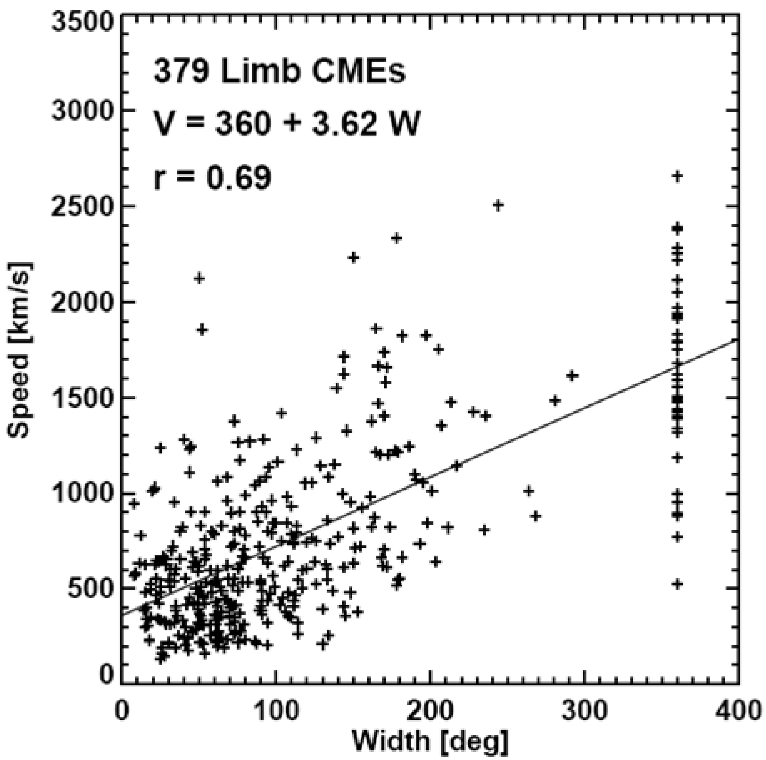
Mass and Kinetic Energy

- The CME mass determined from the excess brightness due to the CME and how many electrons are needed to produce this brightness.
- CME kinetic energy from mass and speed.
- Limb CMEs give the true distribution because they are not subject to projection effects

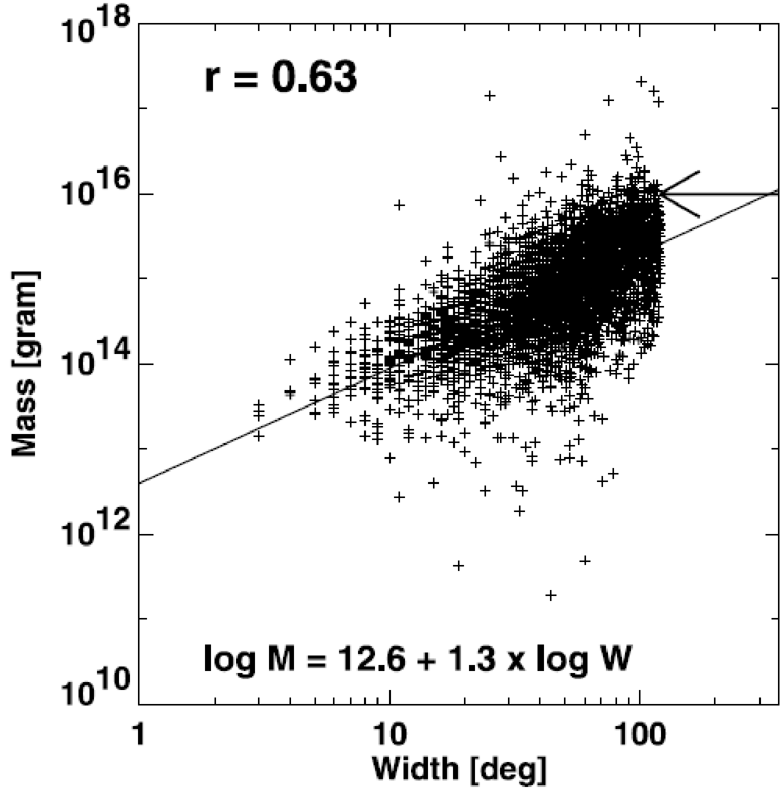


Faster and Wider CMEs are More Energetic

Wider CMEs are faster



Wider CMEs are more massive



Halo CMEs are more energetic

Fraction of halos is a measure of the energy of a CME population

Solar Cycle Variation

- CMEs come from closed field regions on the Sun (e.g. Sunspot regions).
- CME speed and rate in phase with sunspot number (CME rate SSN are well correlated)
- There are exceptions especially during solar maximum phase
- Cycle 23 and 24 (when good CME observations are available) give details of this correlation

CME Rate & Speed (Rotation Averaged)

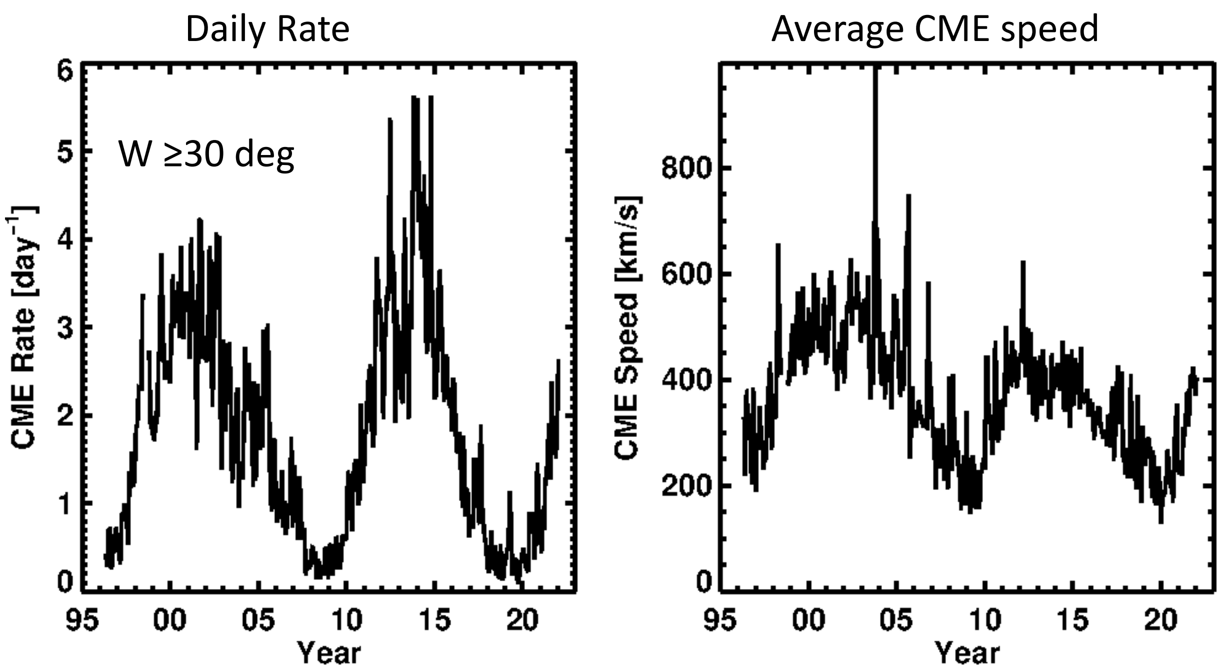
#CMEs per year ~10^3

Mass per CME ~4×10^{14} g

Mass loss due to CMEs
~4×10^{14} kg.yr^{-1}
= 2×10^{-16} Ms. yr^{-1}

Solar wind mass loss:
~2×10^{-14} Ms. yr^{-1}

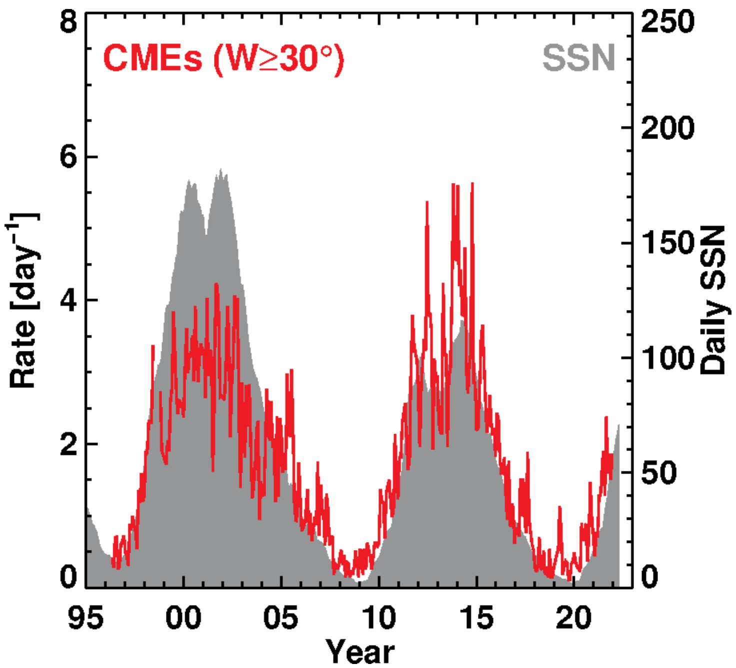
During solar max, mass loss up to 10% of solar wind flux



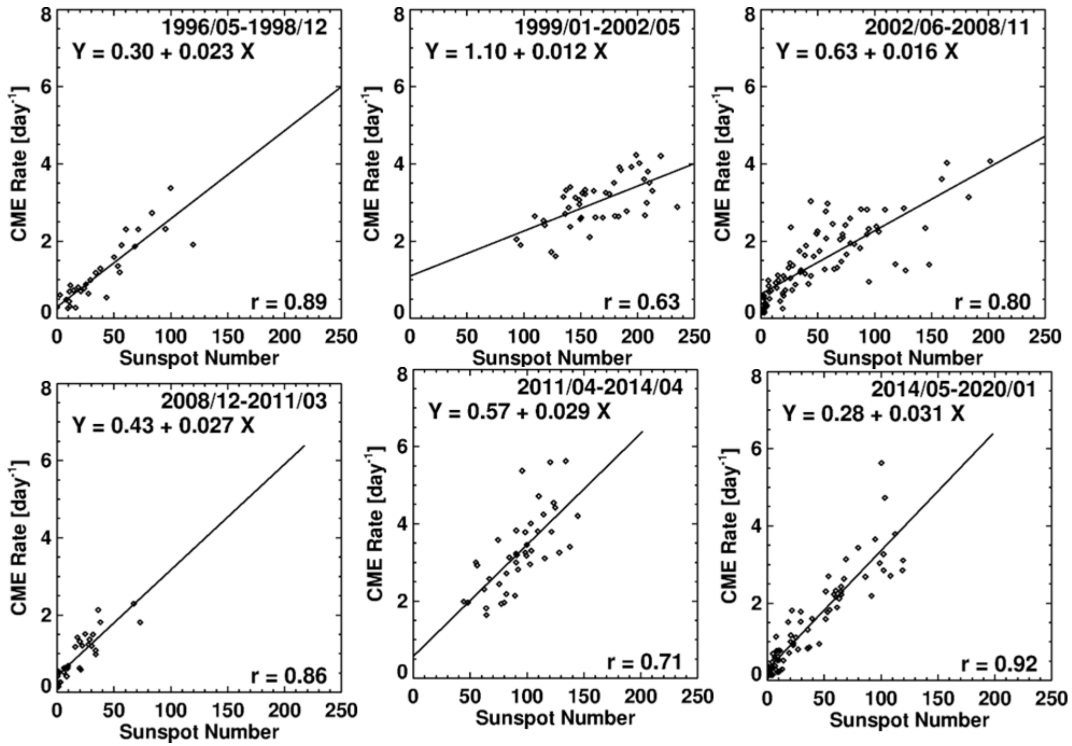
The rate is ~0.5 per day during solar min and exceed ~4 per day during maximum

The CME speed also varies with solar cycle: CMEs are generally faster during solar maxima

CME Occurrence Rate and Sunspot Number



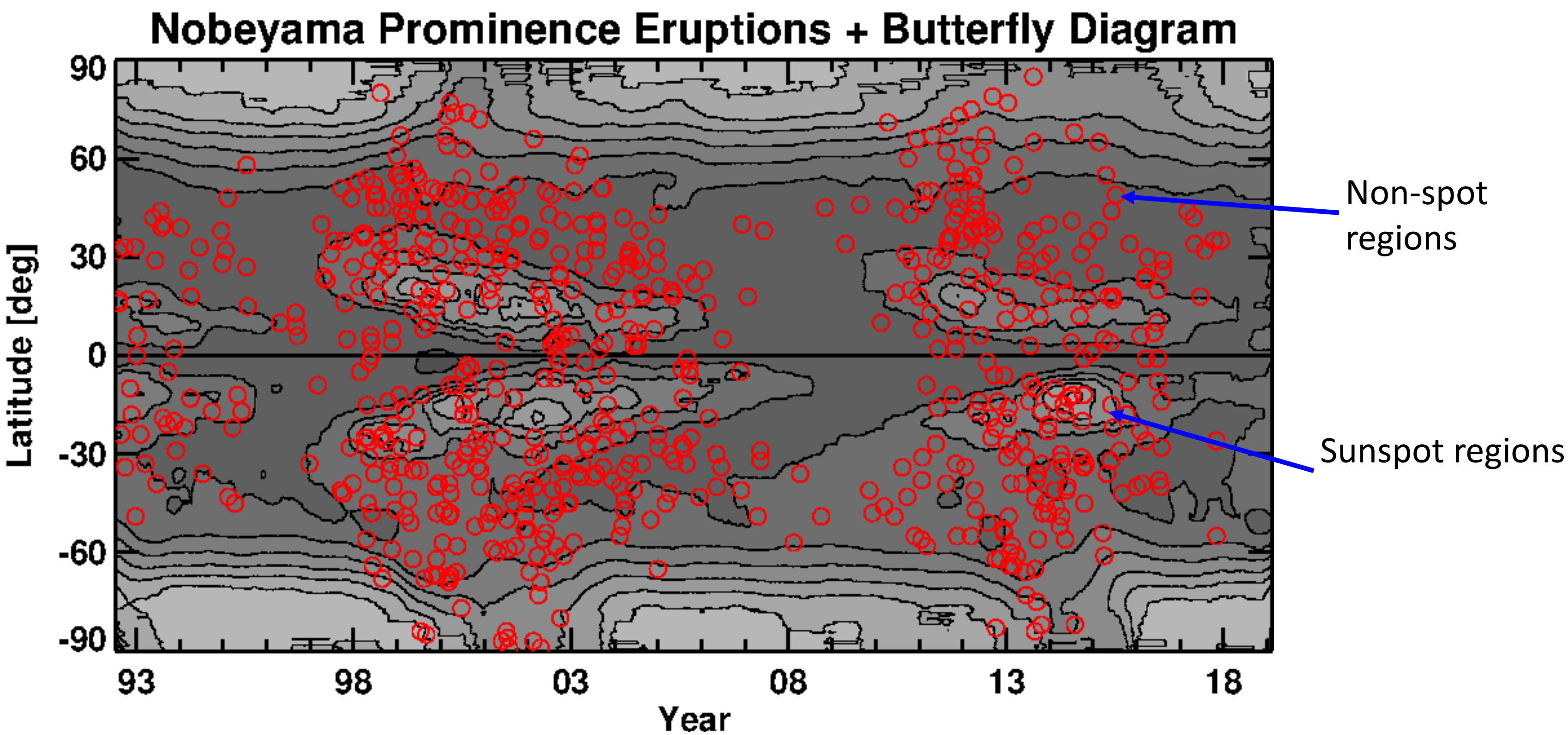
Weaker correlation during max phase: CMEs from outside sunspots – filament regions



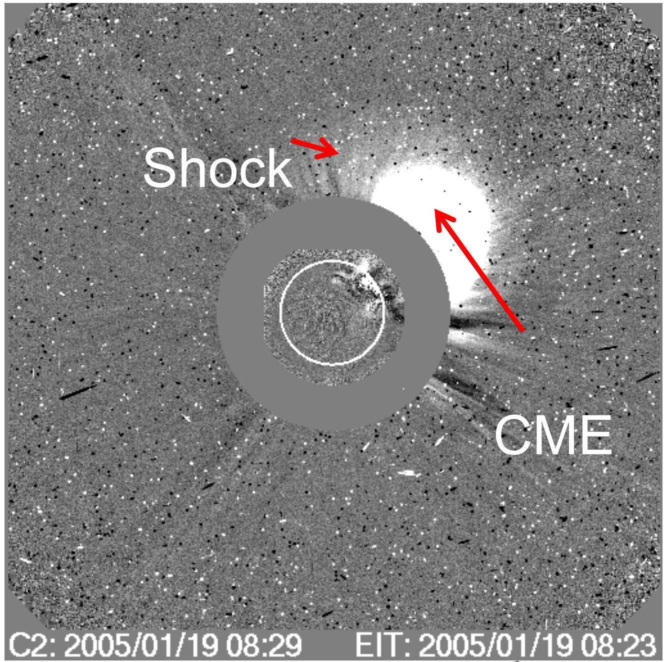
Overall good correlation between CME rate and sunspot number

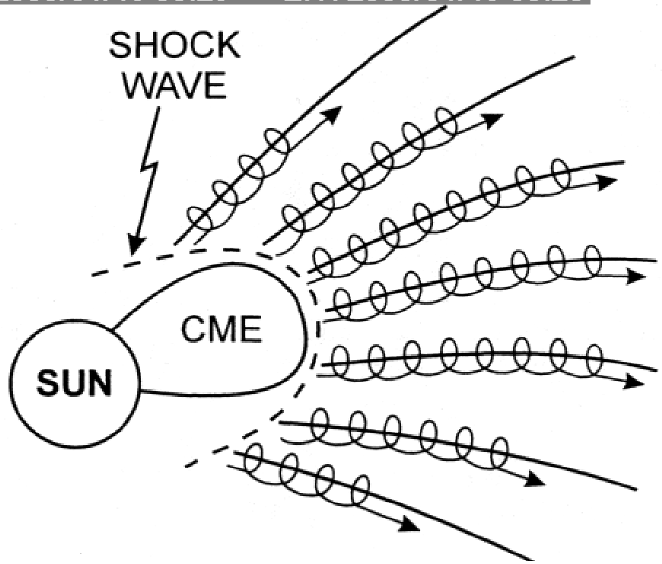
CME rate - sunspot number correlation is lowest in the maximum phase

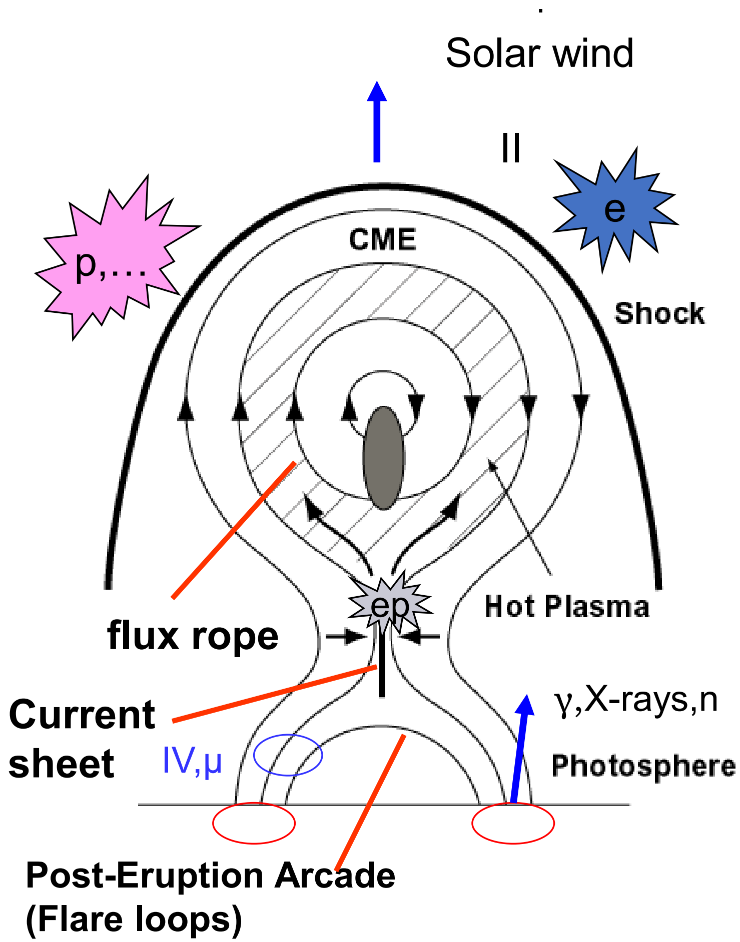
CME source regions



Locations of prominence eruptions (PEs) automatically detected from Nobeyama Radioheliograph images

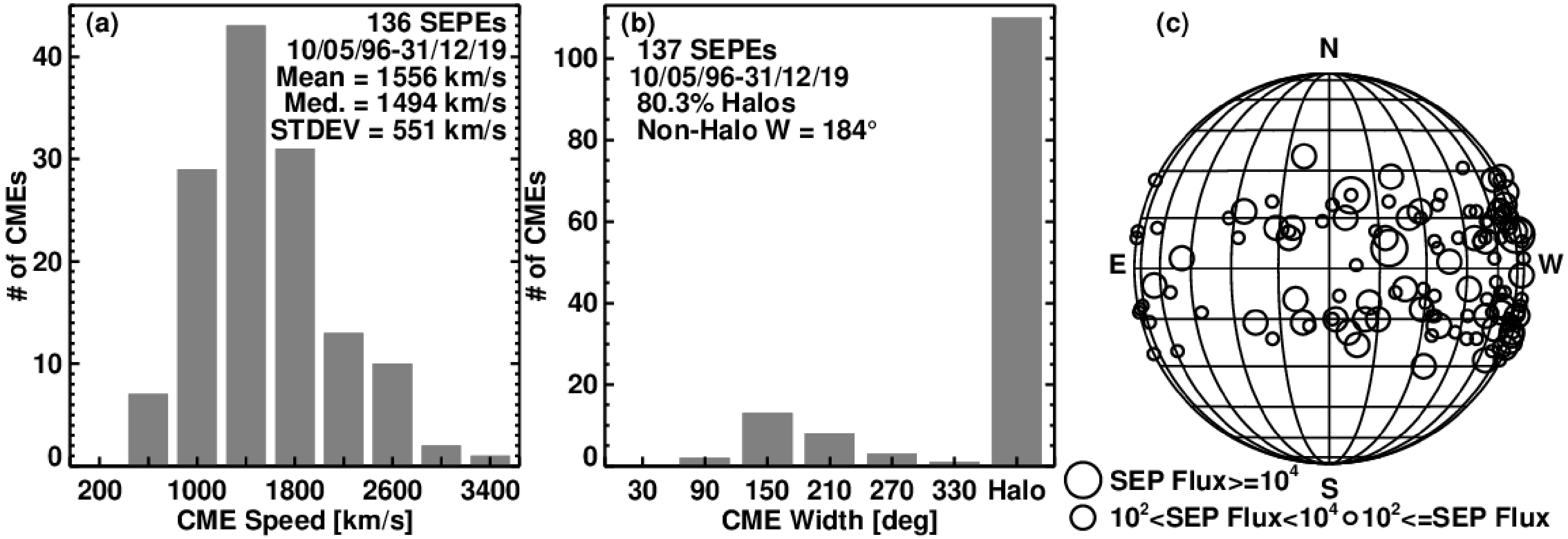






Kahler, Hildner, & Van Hollebeke (1978)

Properties of CMEs Producing Large SEP Events

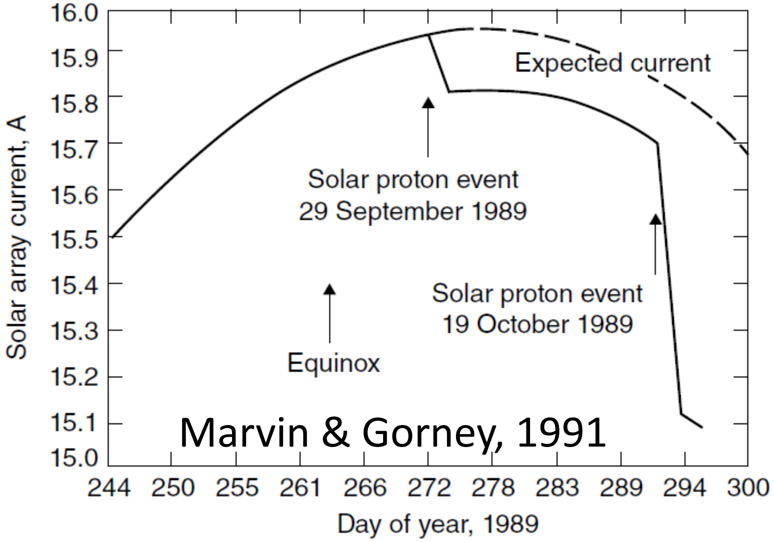


- SEP Events are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Shock-driving capability of CMEs key for SEPs

Typical speed: 400 km/s
Typical width 40 deg

SEPs and S/C Anomalies

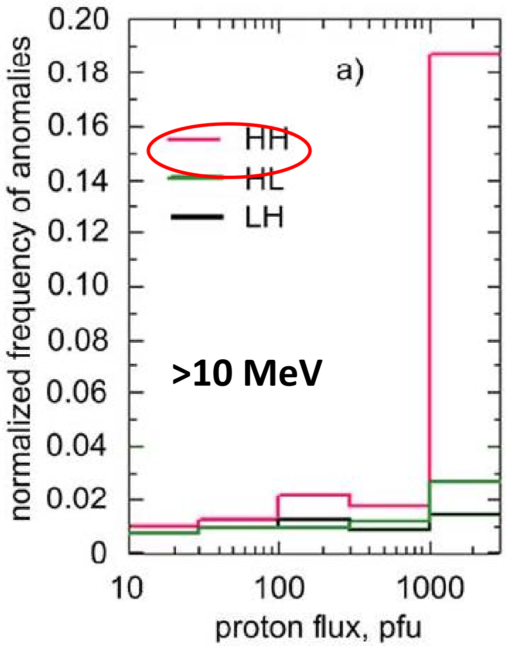
GOES-7 current drop by ~5 – 10%.

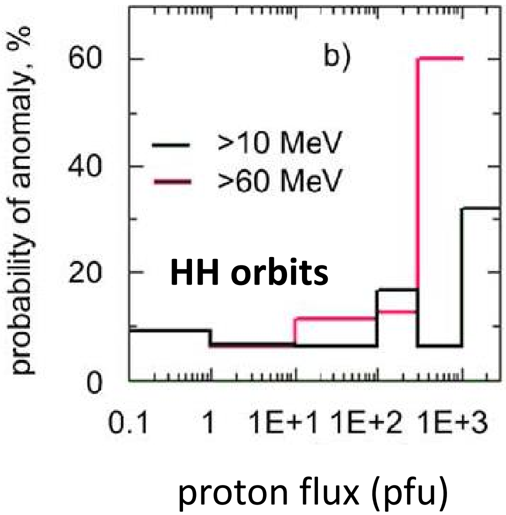


Major impact on solar arrays

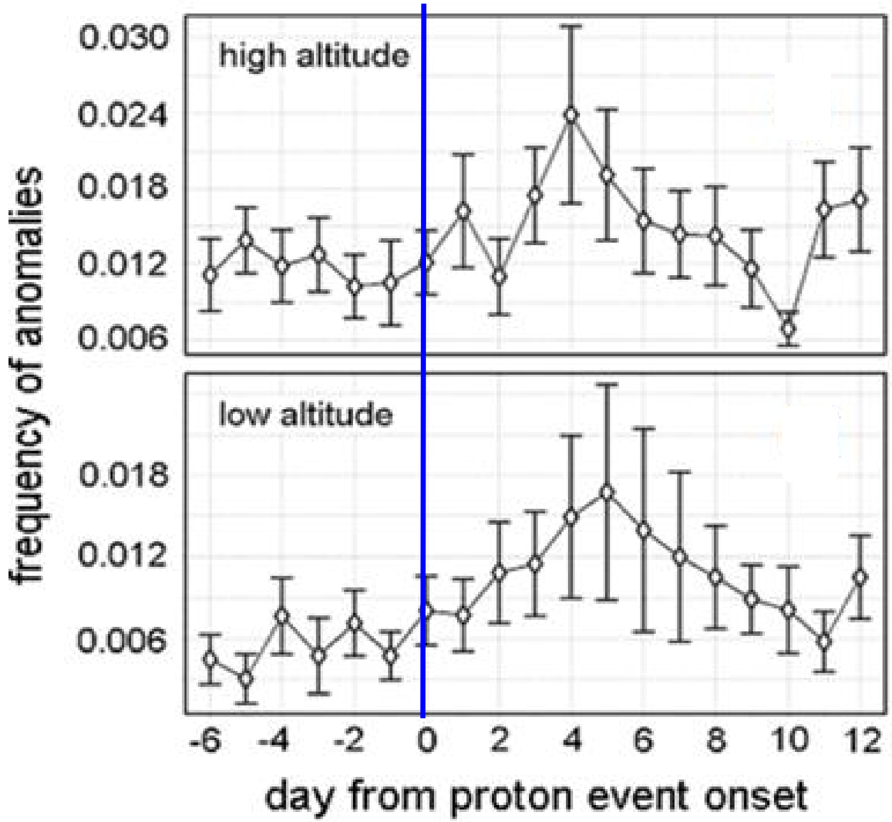
- Anomaly frequency highest for HH (GNSS) orbits (0.19 vs. 0.01 for LH)
- The anomaly frequency rapidly increases with proton flux
- The probability of an anomaly for HH orbit is significantly higher for high proton flux and proton energy

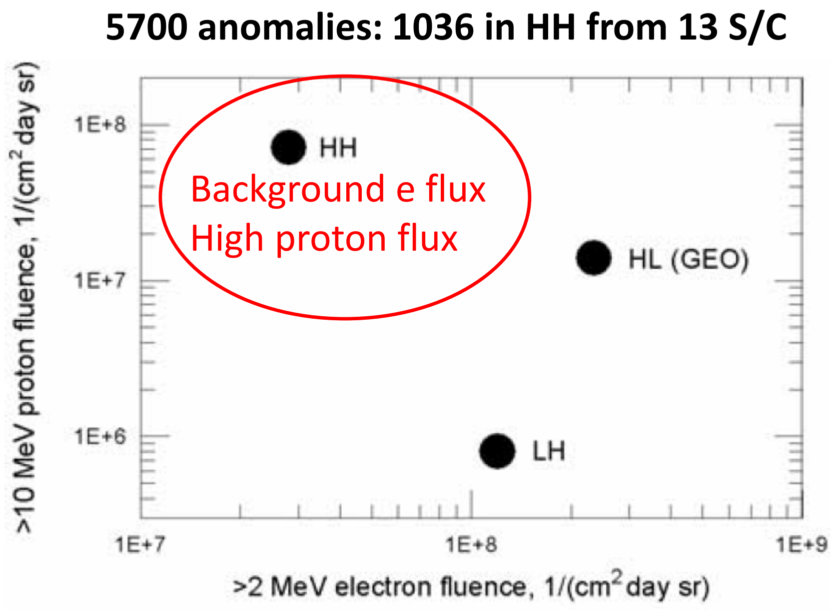
Iucci+ 2005





S/C anomalies due to protons and electrons

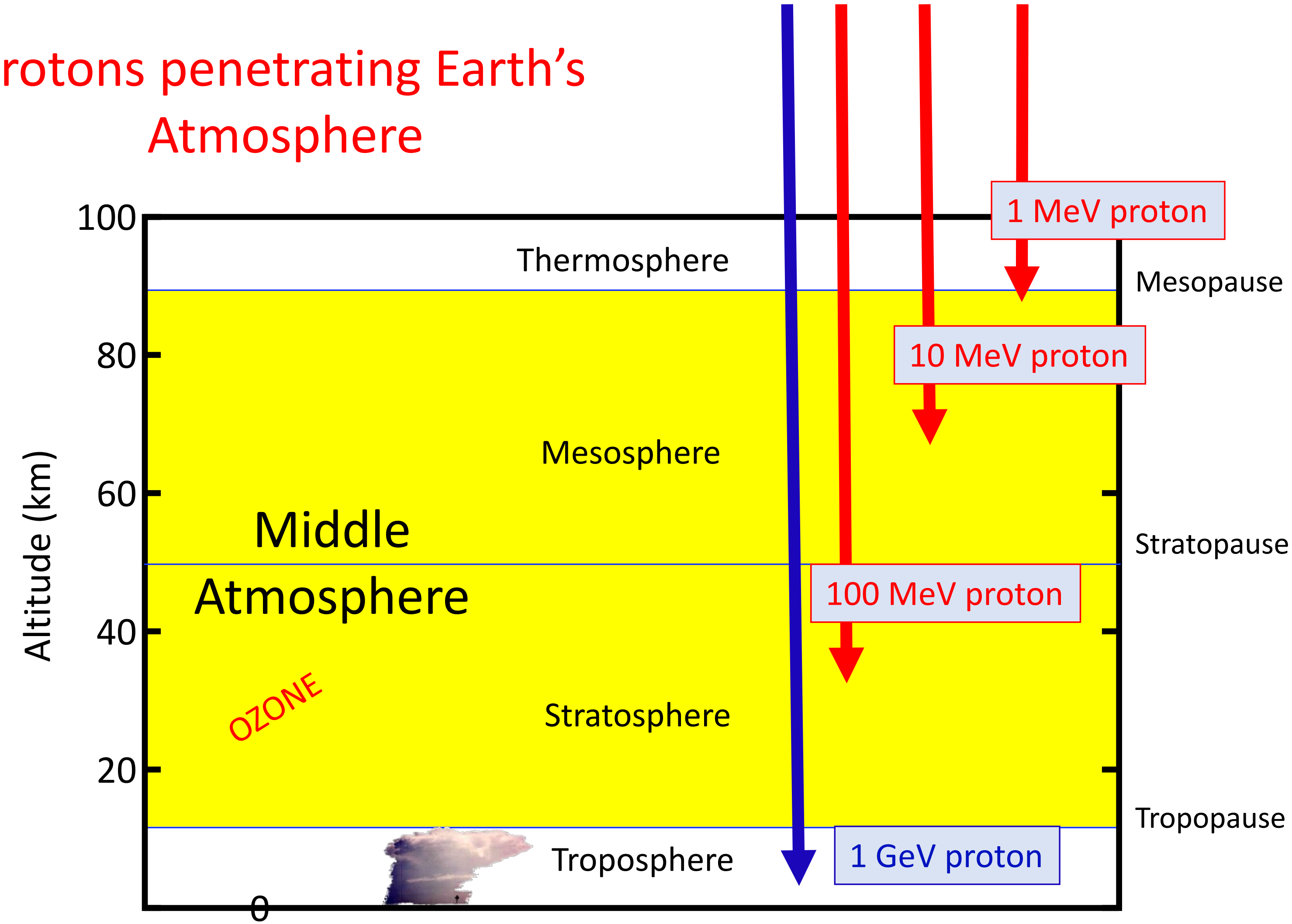


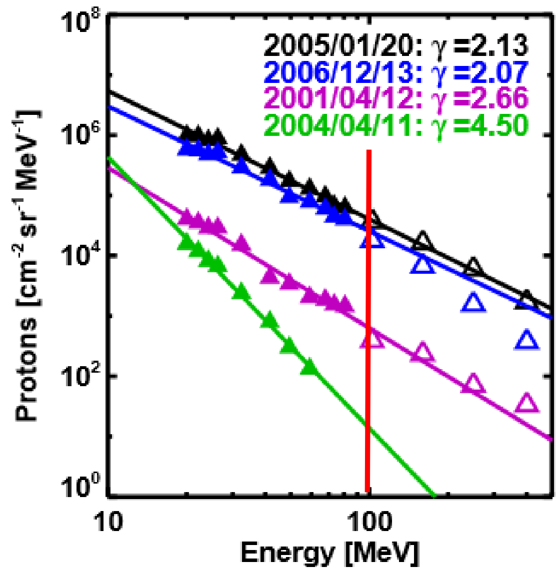


HH: High altitude (>15000 km), high inclination (>55°)
Relevant to GNSS

Iucci et al. 2005

Protons penetrating Earth's Atmosphere



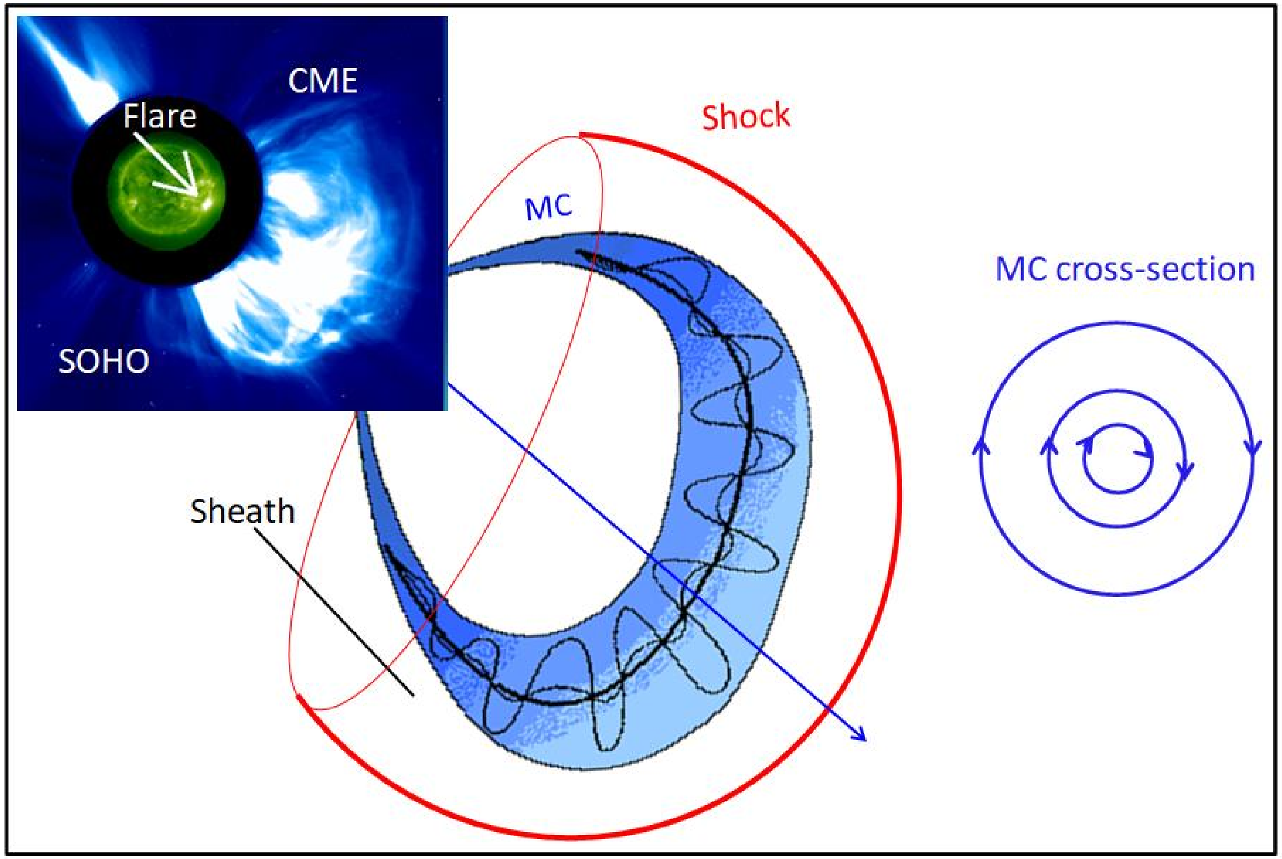


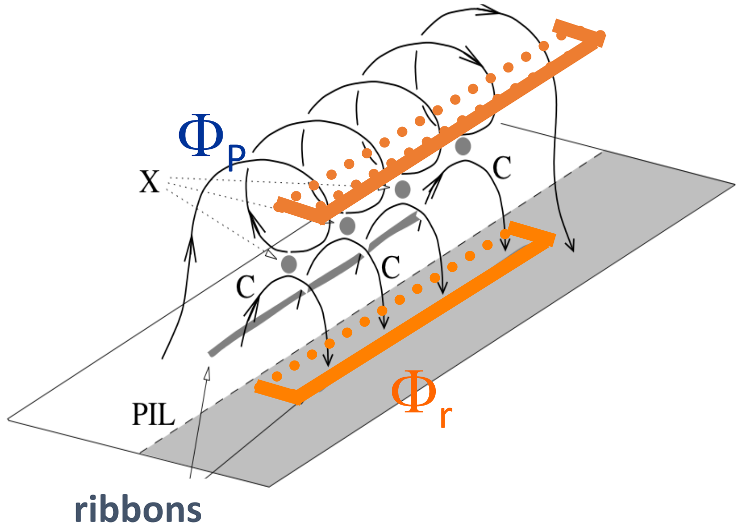
The spectrum of energetic particles decides the space weather impact

100 MeV protons penetrate to the stratosphere and can destroy ozone.

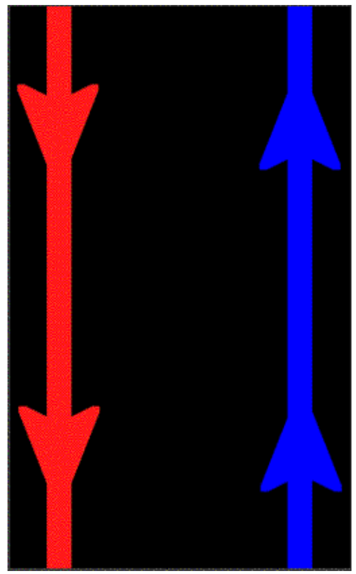
GeV particles can affect airplane crew/passengers in polar routes

Courtesy: C. Jackman





Magnetic flux rope and the shock sheath



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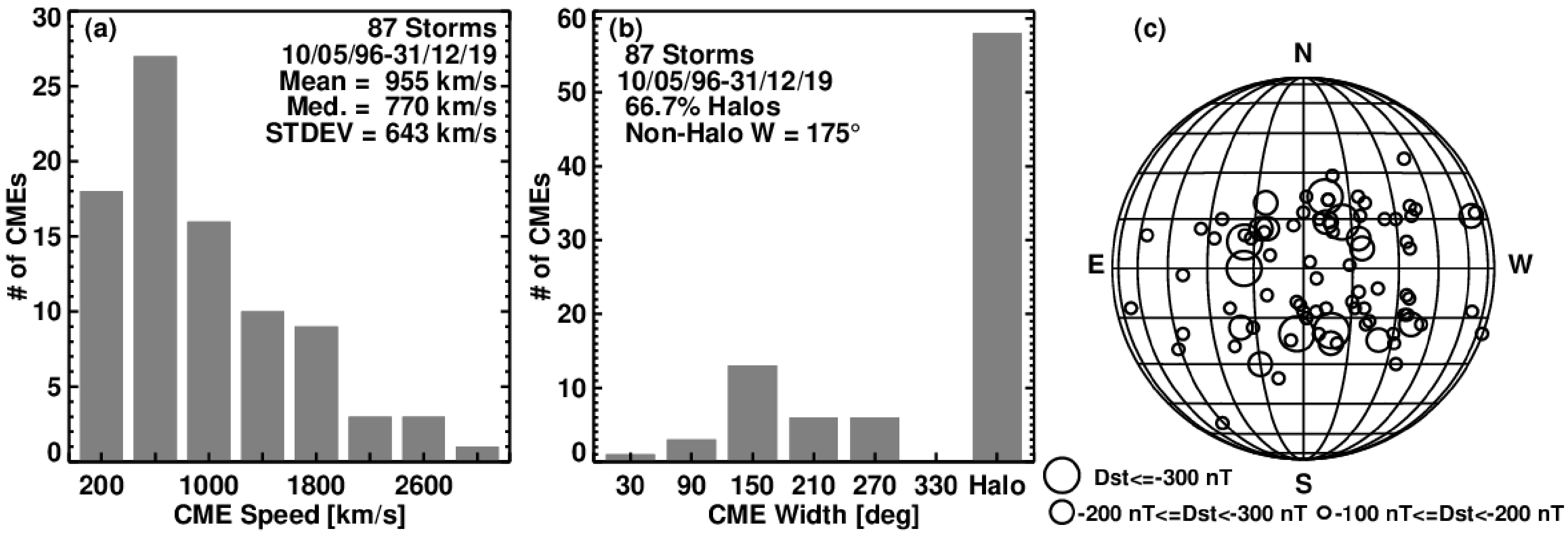


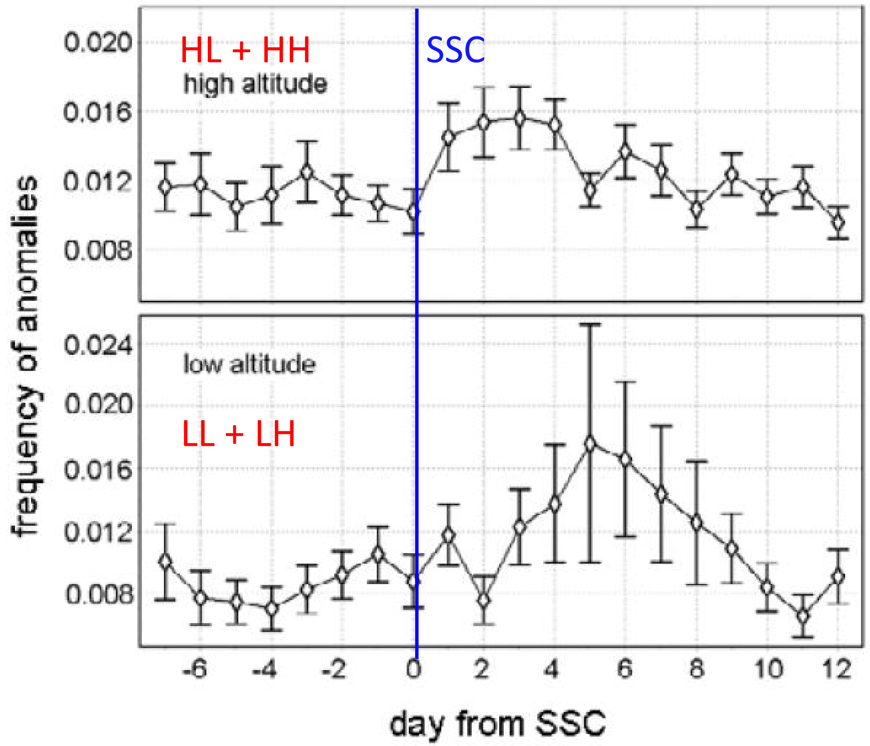
- Magnetic storms are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs ~10^{32} erg
- Southward IMF in CMEs key for magnetic storms

Typical speed: 400 km/s
Typical width 40 deg

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

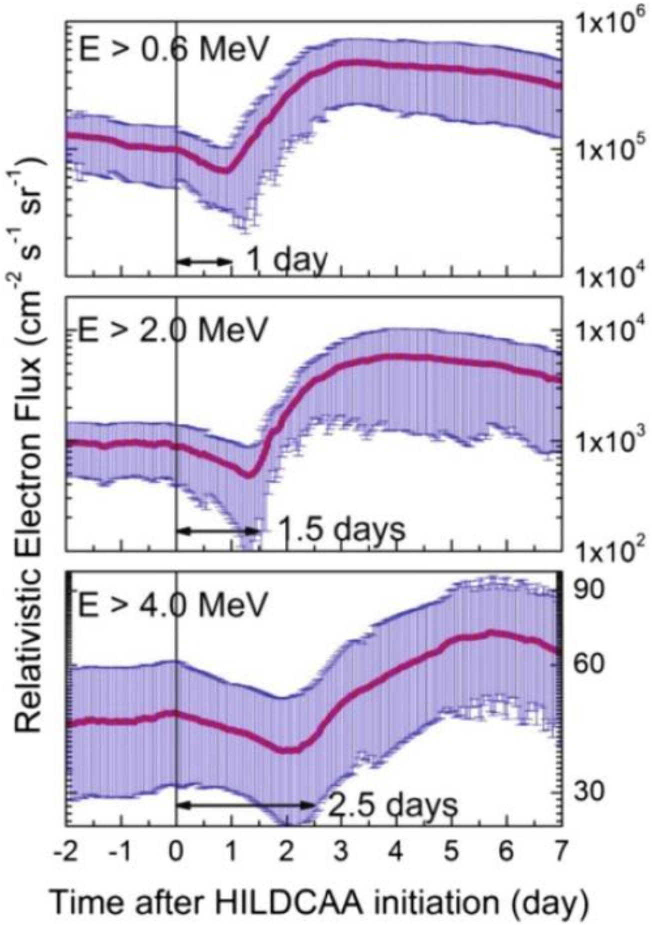
Number of anomalies per day per spacecraft



Iucci et al. 2005

Electron energization following geomagnetic storms

Hajra et al. (2014)



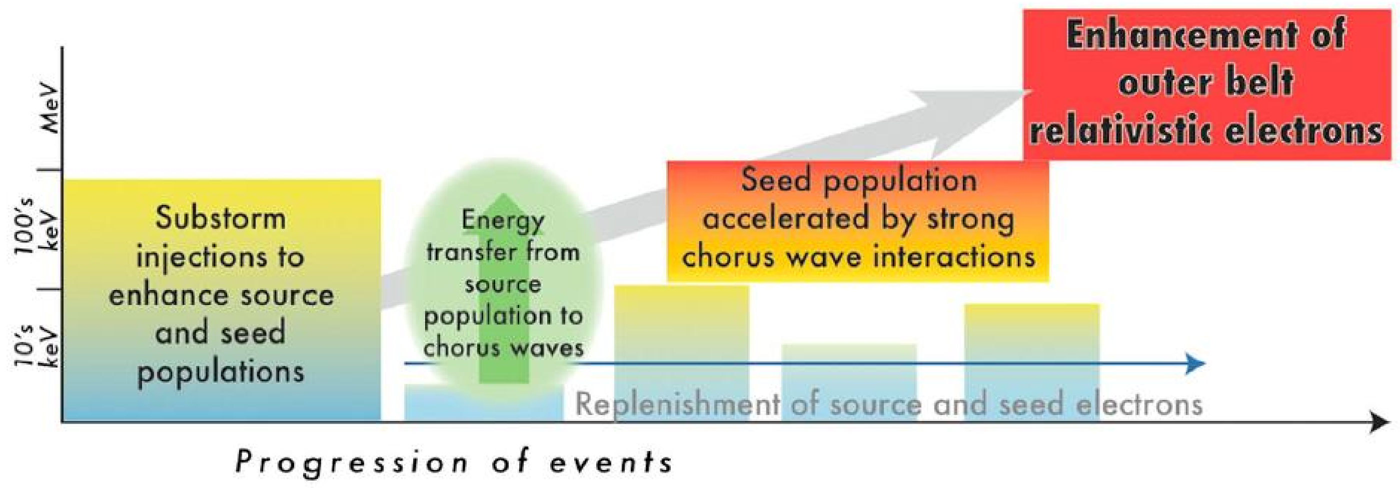
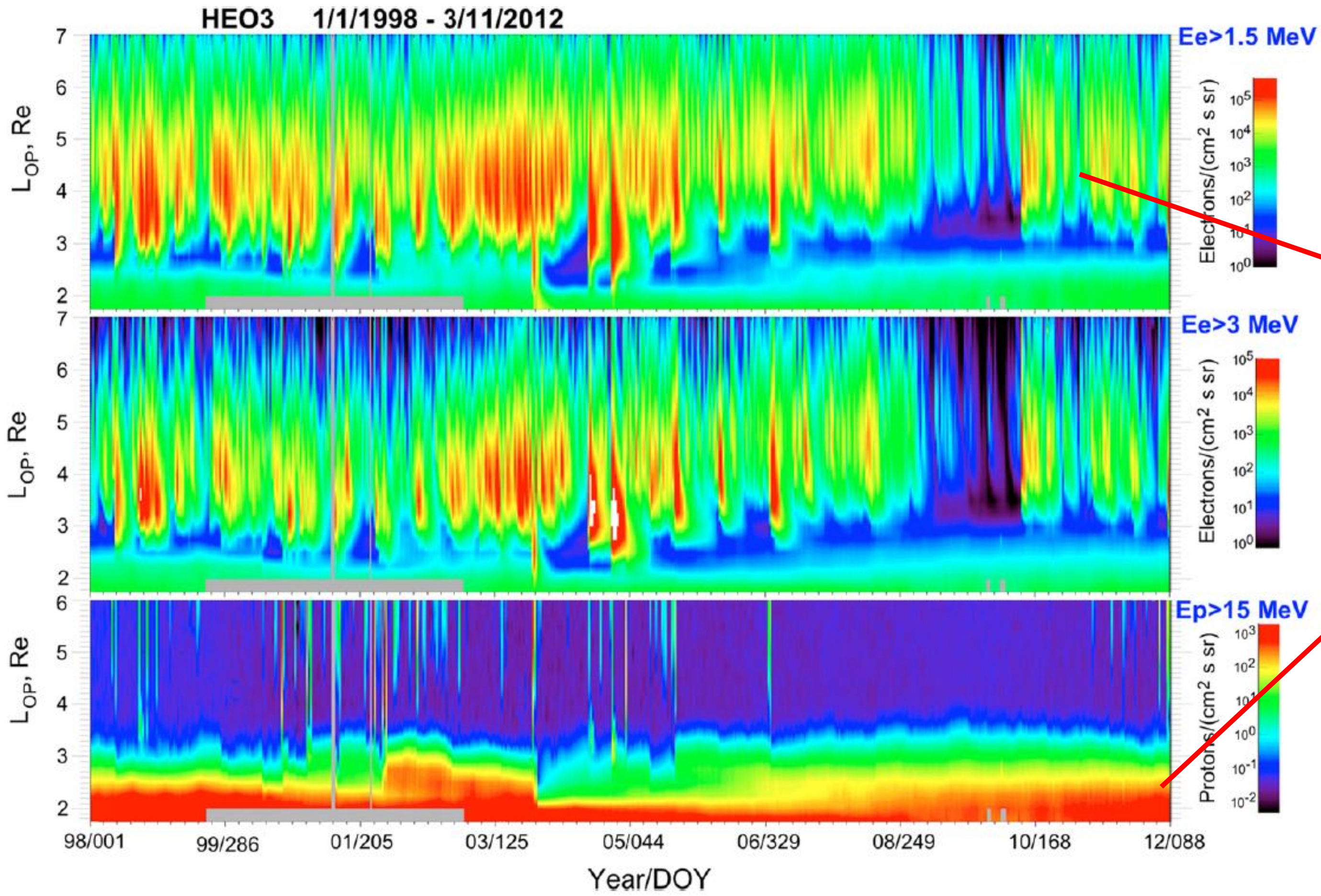


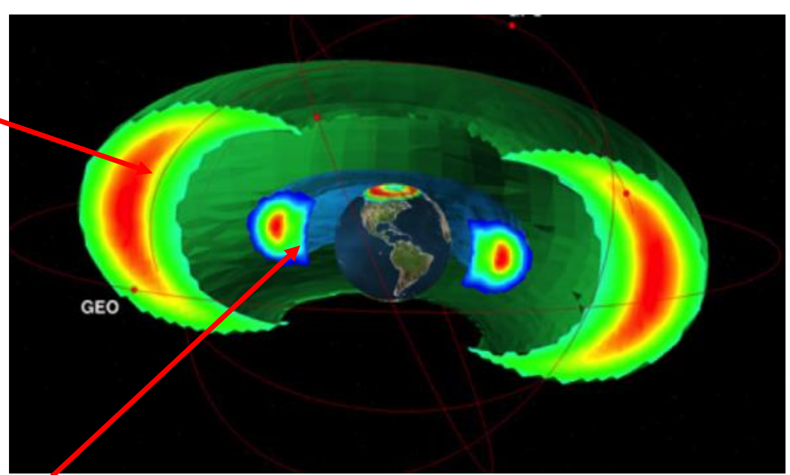
Figure 1. Schematic of the ideal setup and sequence for strong enhancement of outer belt electrons >1 MeV.

Jaynes et al. 2015

Van Allen belts

- The outer belt consists mainly of high energy (0.1–10 MeV) electrons (3-10 R_E)
- It is more variable than the inner belt as it is more easily influenced by solar activity.



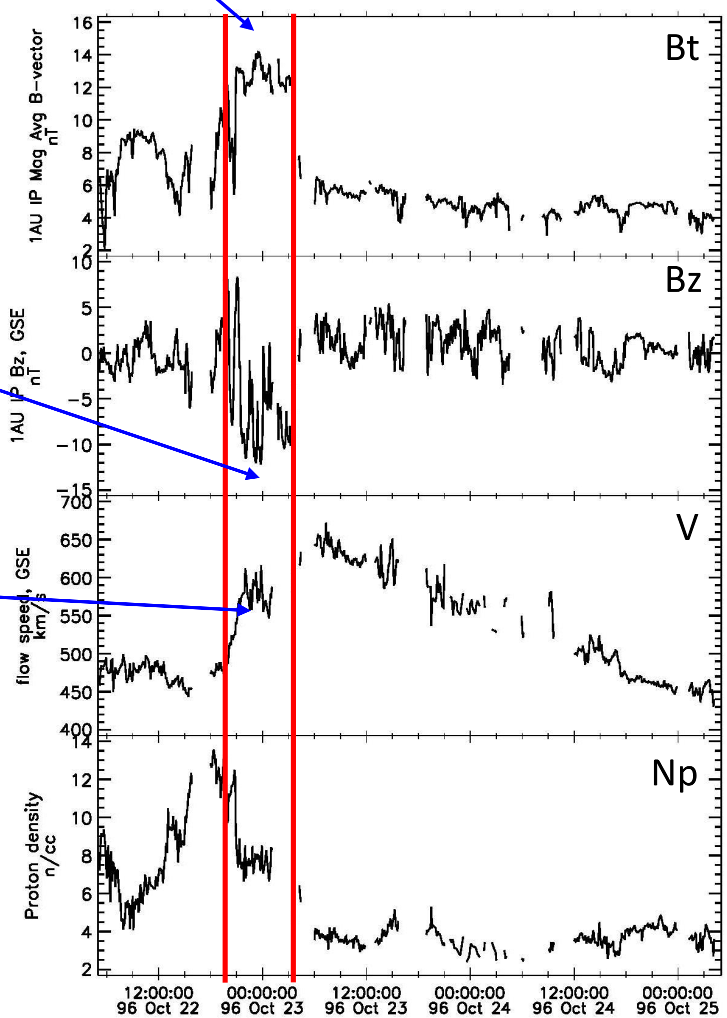


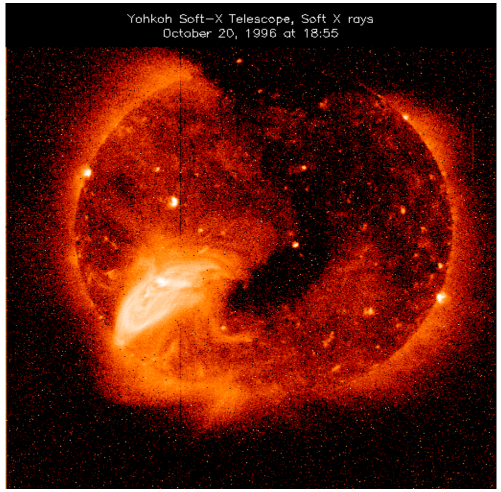
Innerbelt: Mostly protons produced by the CRAND mechanism. Modulated by SEPs

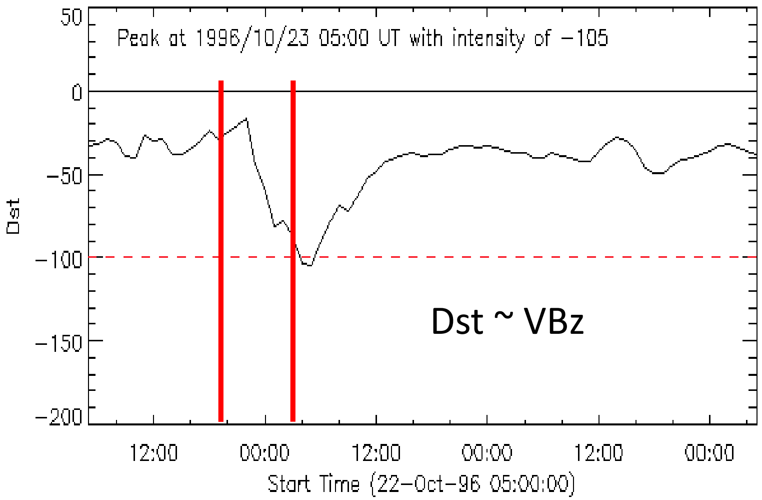
Interface

-Bz

Higher speed





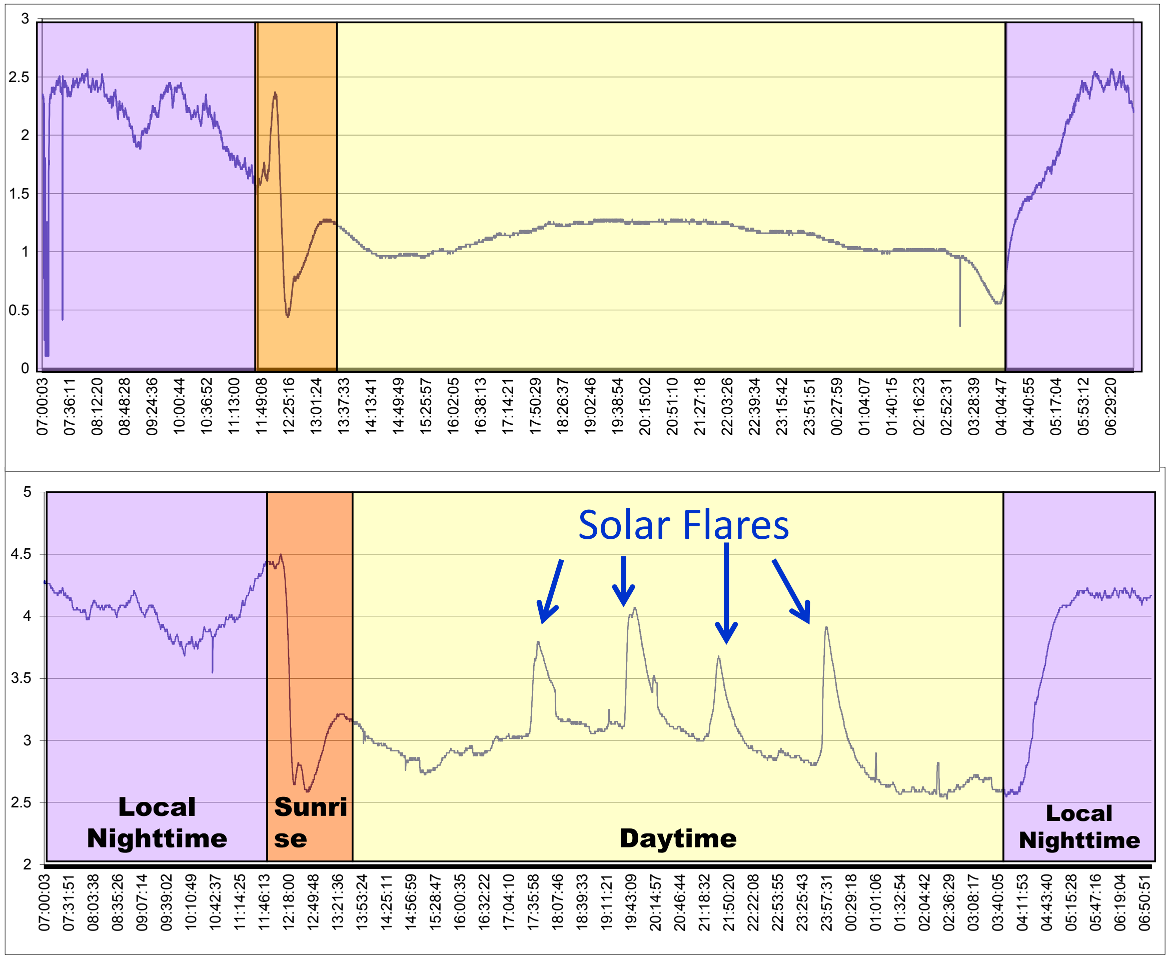


Gopalswamy, 2008

Sudden Ionospheric Disturbance (SID) Event

Quiet Day

Active Day

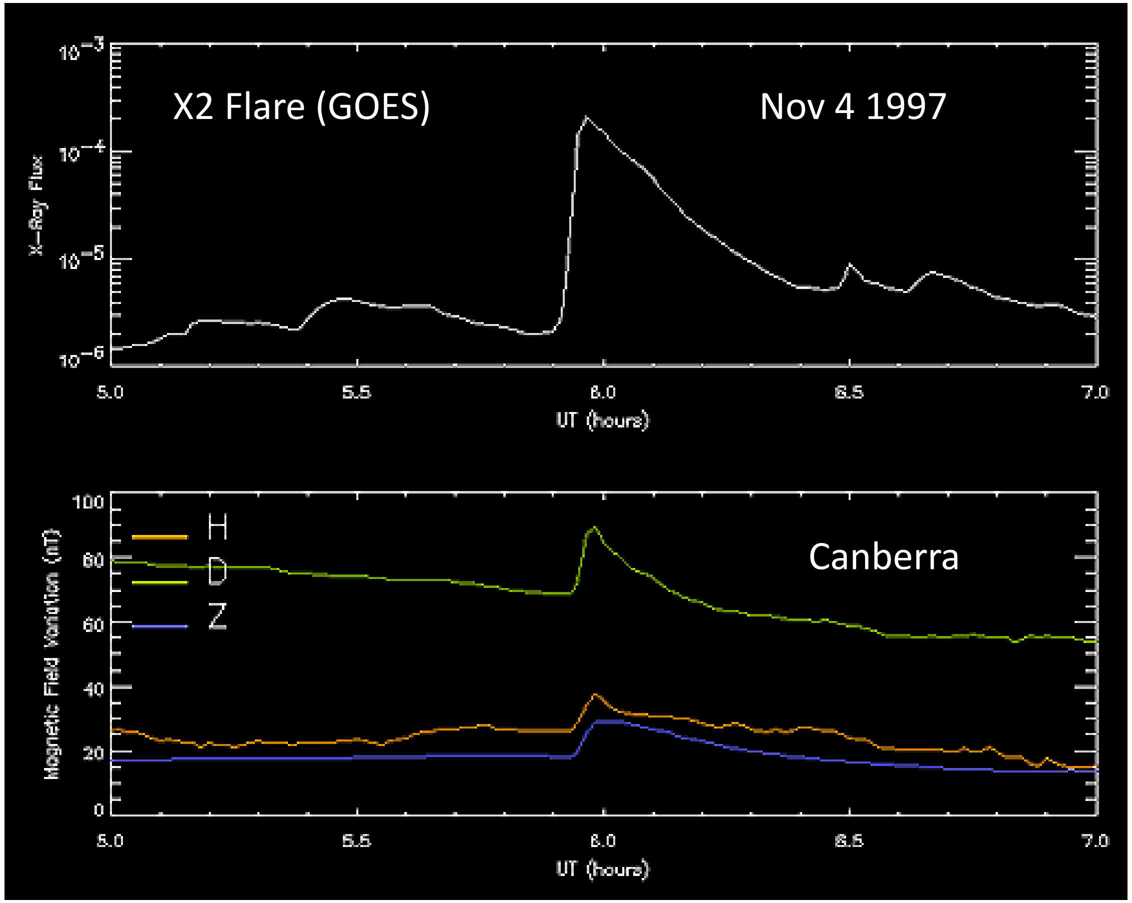


NLK
24.8 kHz

Courtesy
Ray
Mitchell

The VLF signal amplitude and phase are modified when flare photons modify the ionosphere
GNSS signals pass through the ionosphere, so disturbed conditions affect the performance of devices using GPS signal

Magnetic Crochet



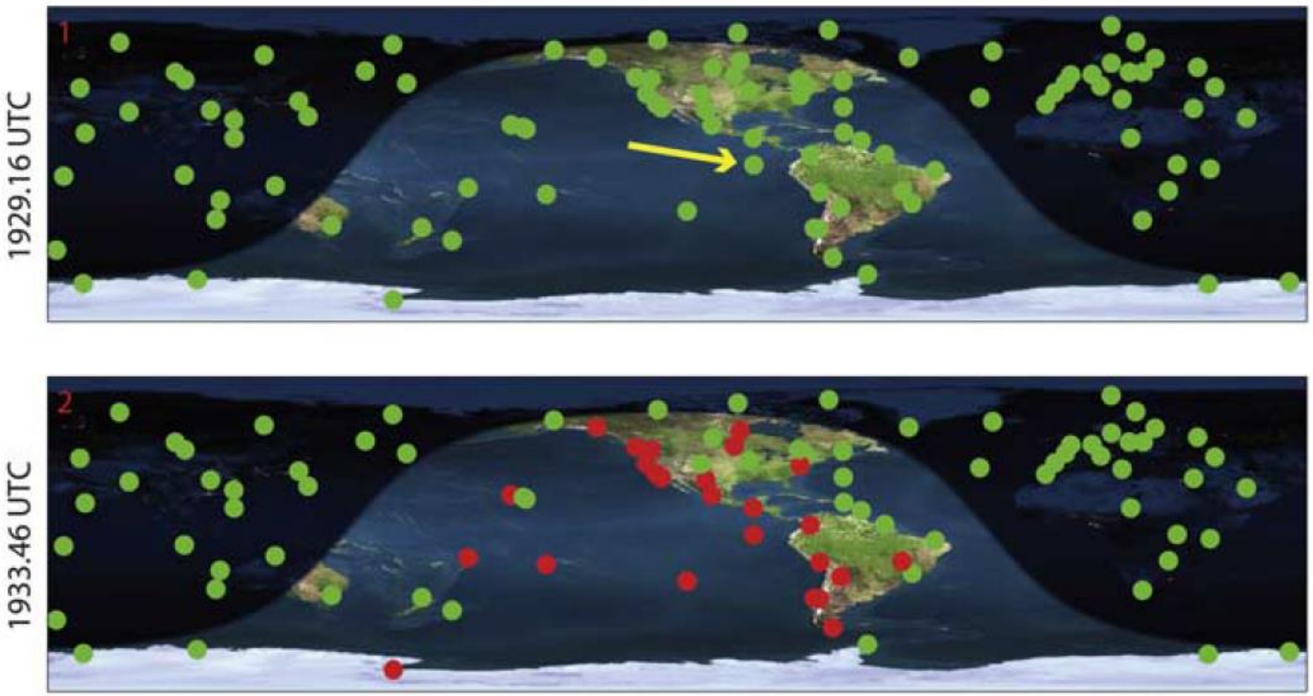
- Flares: increased ionization in the D and E layers
- Enhanced conductivity → enhanced current resulting in the new magnetic field
- Only observed during large flares, especially when the rise time is short

R. Thompson, IPS

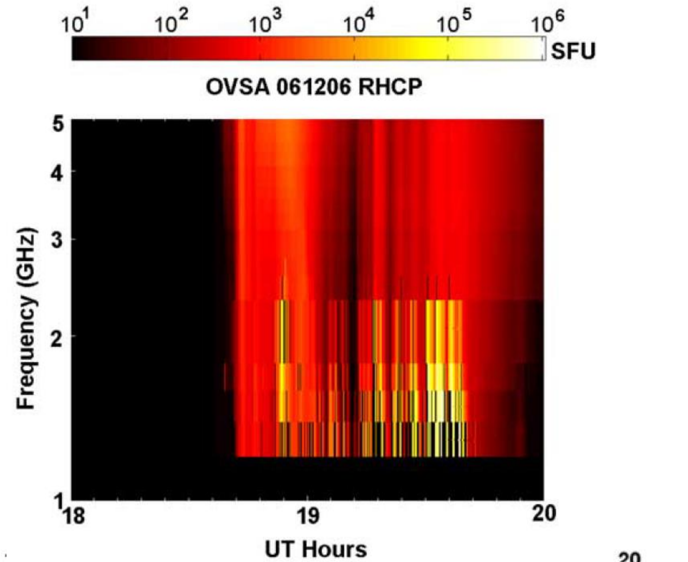
Solar Radio Burst Affecting GPS

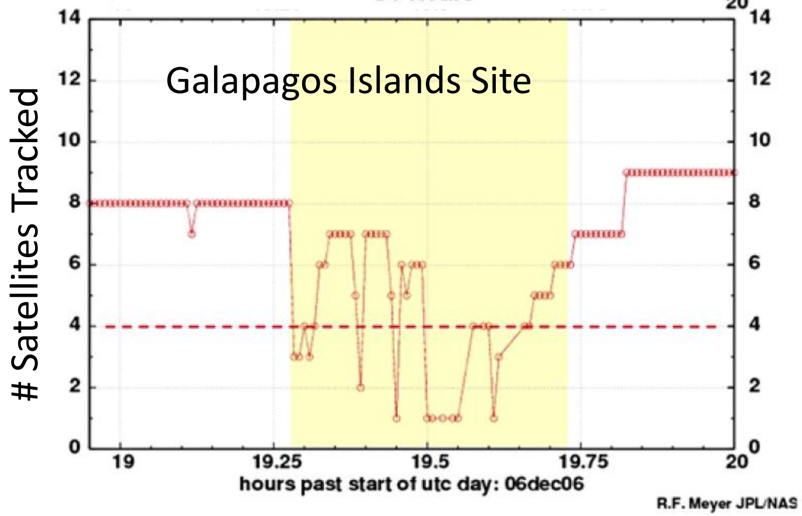
Microwave bursts are due to electrons accelerated in flaring regions

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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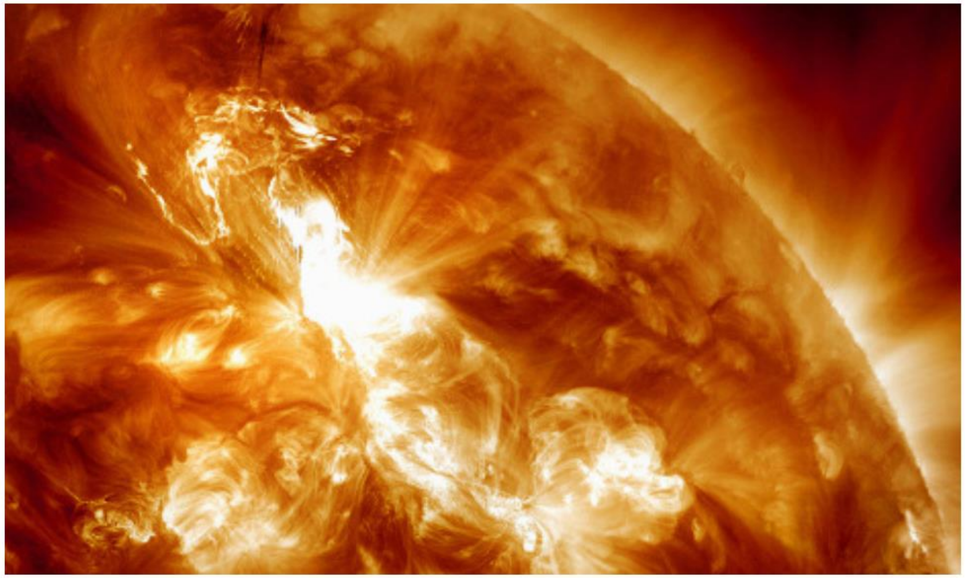
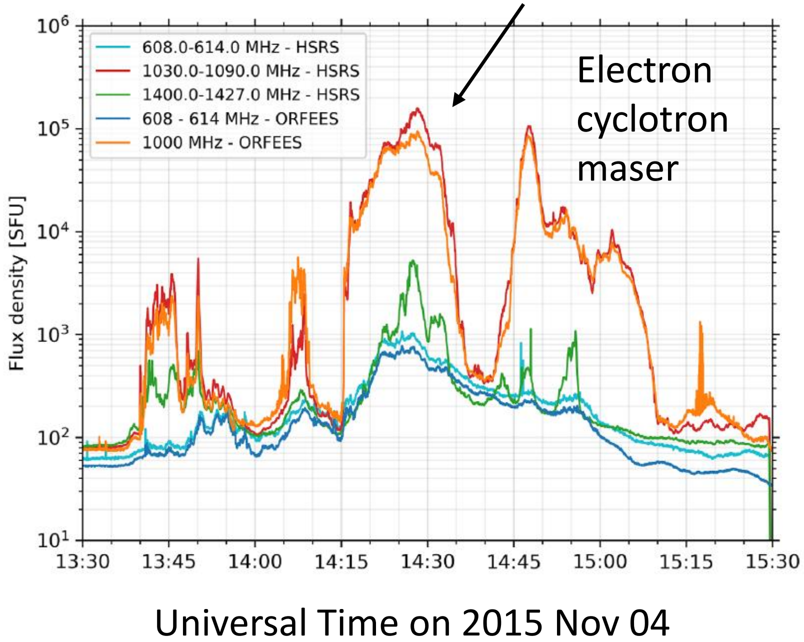


A solar flare erupting from the sun. Photo: AP Photo/NASA

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



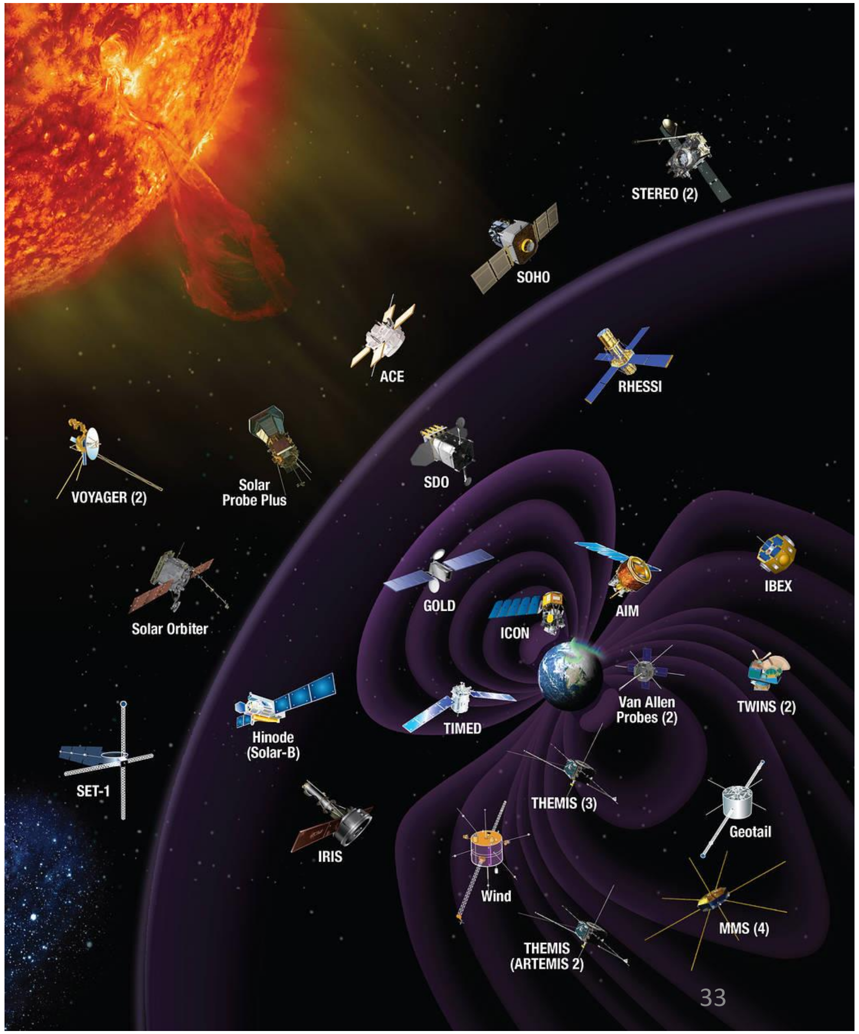
- Radar disturbances in Belgium, Sweden and Norway: false echoes when the airport antennas looked sunwards (2-12^{o})
- Temporal association between periods of strongest disturbances and solar microwave bursts

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