Solar origin of severe space weather

Nat Gopalswamy

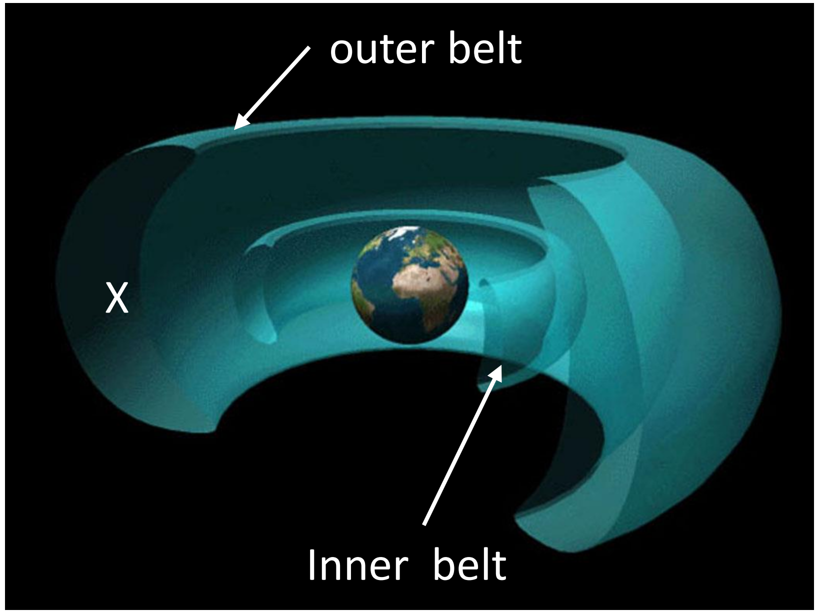
NASA Goddard Space Flight Center

Greenbelt, MD 20771, USA

Applications and Experts Seminar: Space Weather Effects on GNSS
Fifteenth Meeting of the International Committee on Global Navigation Satellite Systems
27 September – 1 October 2021, Vienna International Center & Online

Space Weather & GNSS

- The term space weather generally refers to conditions on the Sun, in the solar wind, and within Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.
- GNSS satellites can be affected by the variable radiation environment in the outer radiation belt; GNSS applications can be affected by Ionospheric space weather; signals can be drowned by solar microwave flares
- The underlying cause of these impacts is the Sun



X GNSS satellites are in the outer Van Allen belt

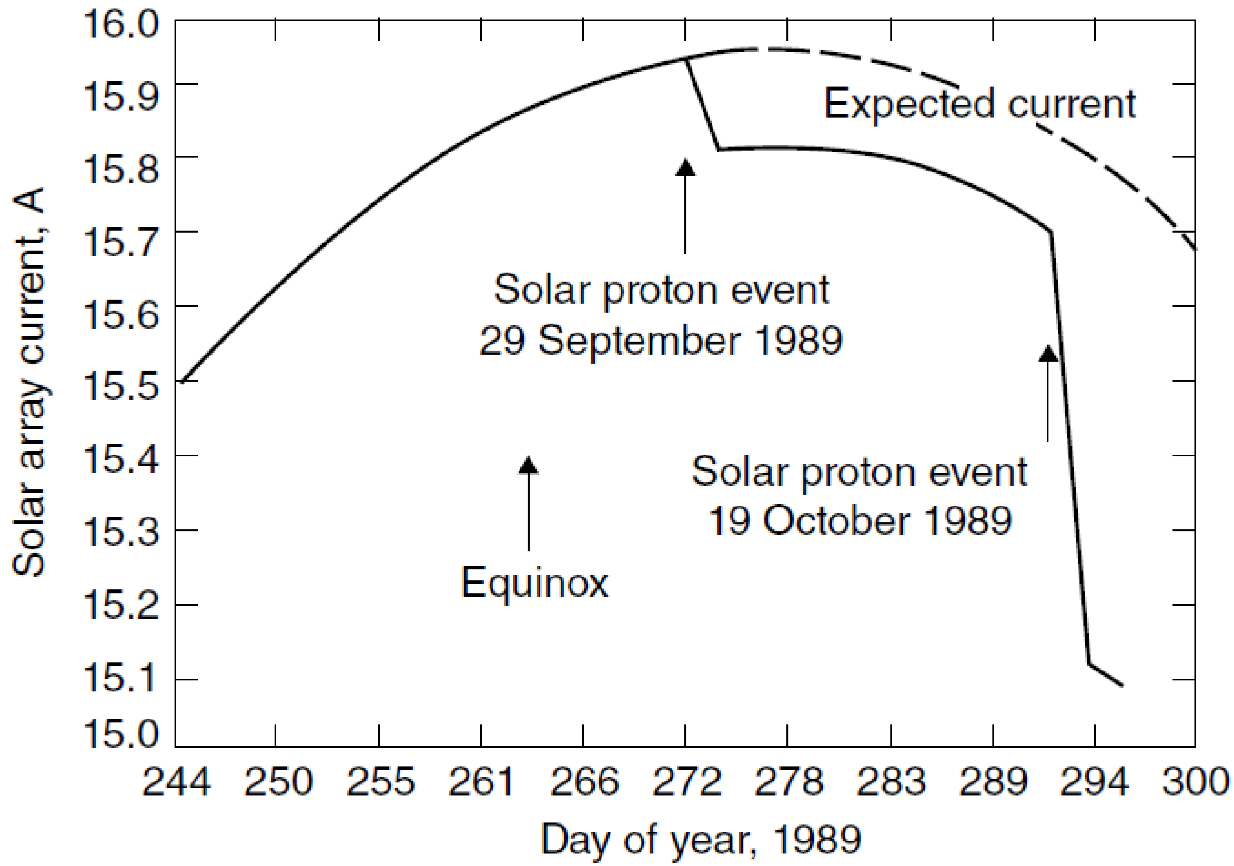
Hazards from Radiation Environment

Particles	Effects	Sources
Electrons 10-100 keV	S/C charging	Trapped particles
Electrons > 100 keV	Deep dielectric charging, solar cell damage	Trapped particles
Electrons > 1 MeV	Radiation damage (ionization)	Trapped/quasi trapped
Protons 0.1-1 MeV	Surface damage to materials	Trapped particles
Protons 1-10 MeV	Displacement damage in solar cells	Trapped particles, IP shocks*
Protons >10 MeV	Ionization, disp. damage; sensor background	Rad belt, SEPs, GCRs
Protons > 30 MeV	Damage to biological systems	Rad belt, SEPs, GCRs
Protons > 50 MeV	Single event effects	Rad belt, SEPs, GCRs
Ions >10 MeV/nuc	Single event effects	SEPs, GCRs
GeV particles (GLEs**)	Single event effects, hazard to humans in polar flights and in deep space	SEPs, GCRs

**Ground Level Enhancement (GLE) in SEPs; *ESP events

Feynman and Gabriel 2000

Radiation related damages to S/C



Marvin & Gorney, 1991

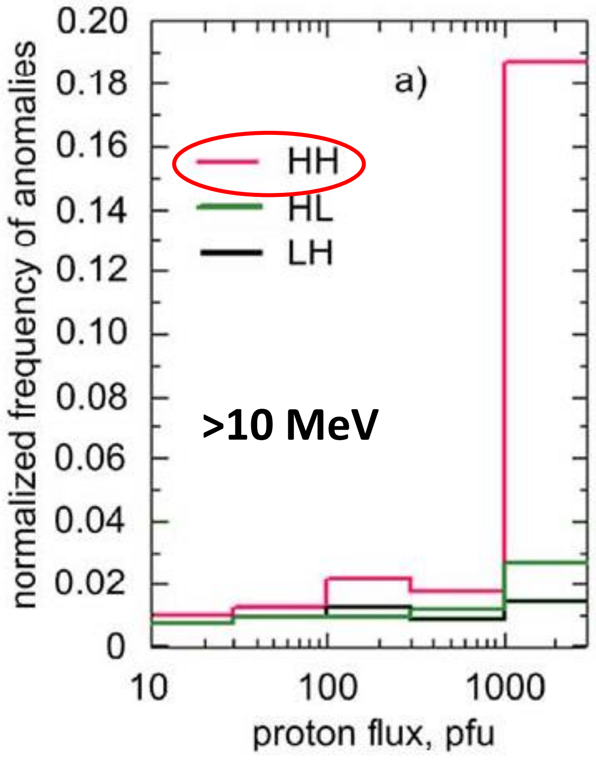
Recent estimates show that relativistic electrons in the magnetosphere following extreme geomagnetic storms can be equally dangerous in cumulative radiation damages in MEO orbits:

- total ionizing dose (TID) leading to leads to charge trapping and device performance degradation
- dielectric displacement dose (DDD) resulting in increased dark currents, solar cell degradation, and loss of gain in bipolar transistors

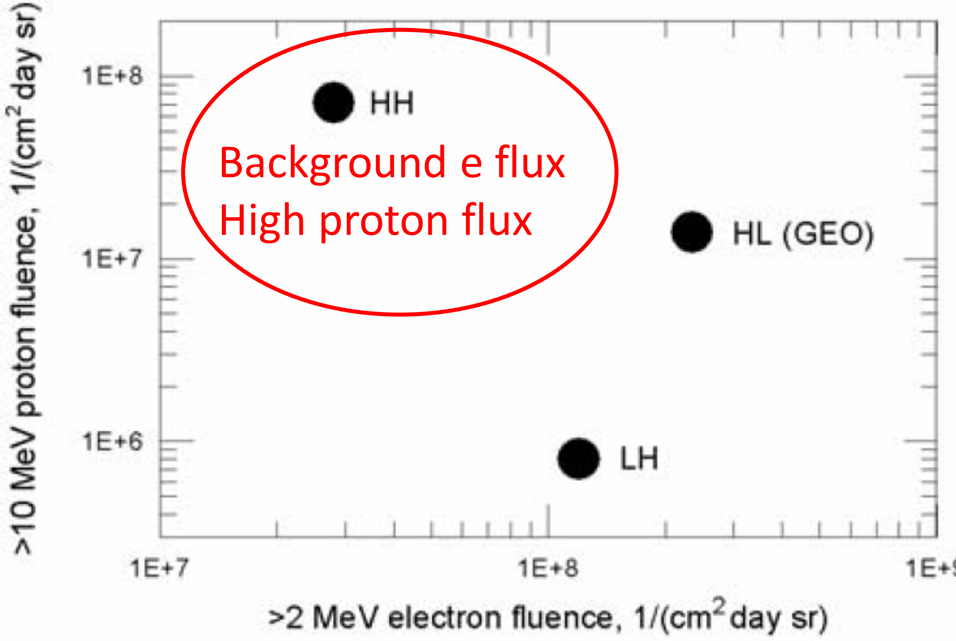
(Hands et al. 2018)

S/C anomalies due to SEPs

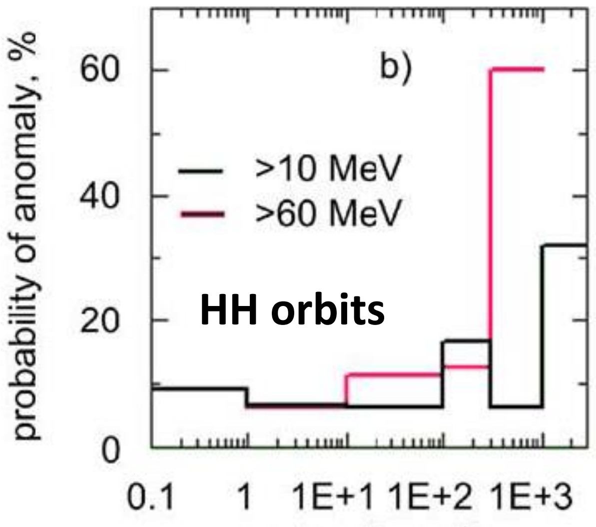
- Anomaly frequency averaged over the first 2 days of proton enhancements: the highest for HH (GNSS) orbits (0.19 vs. 0.01 for LH) – more than an order of magnitude higher
- The anomaly frequency rapidly increases with proton flux
- The probability of an anomaly for HH orbit is significantly higher for high proton flux



5700 anomalies: 1036 in HH from 13 S/C



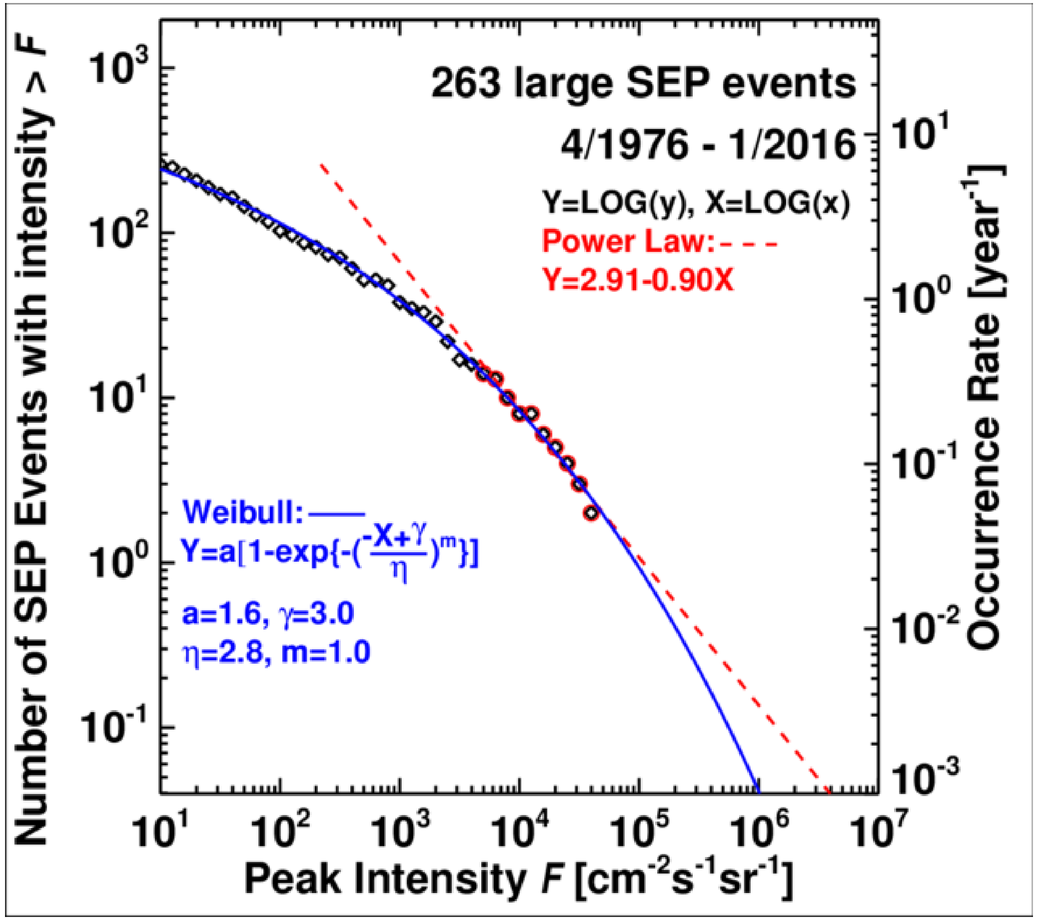
HH: High altitude (>15000 km), high inclination (>55°)
Relevant to GNSS

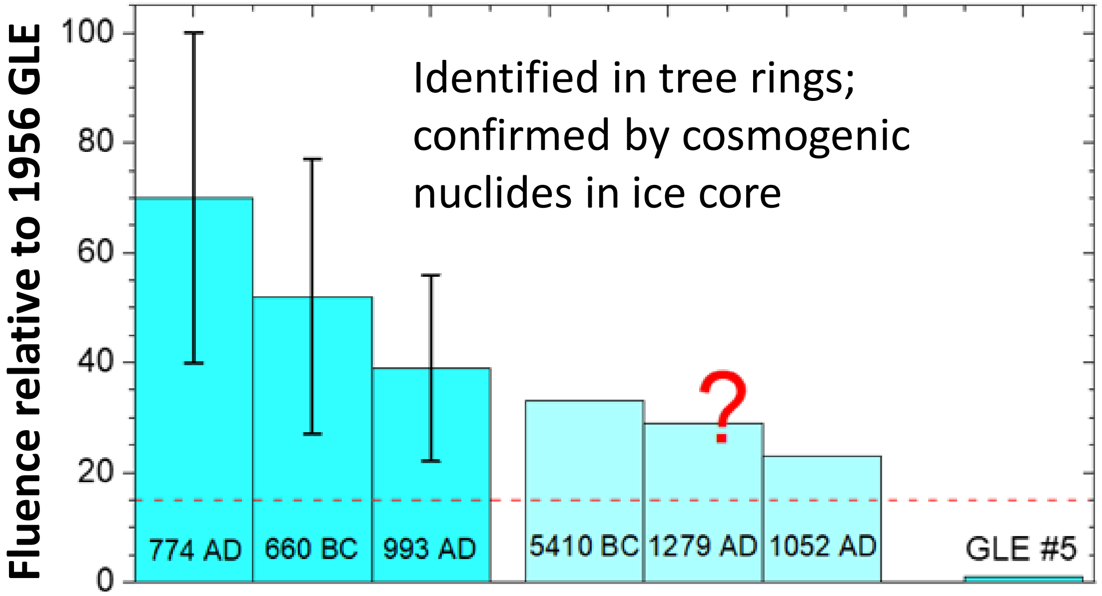


Iucci et al. 2005

proton flux (pfu)

SEP peak flux (>10 MeV) can be much higher





SEP event hypothesis bolstered by recent identification of five new candidate historical events, including two 774-class events (5259 BC, 7176 BC; Brehm et al., 2021)

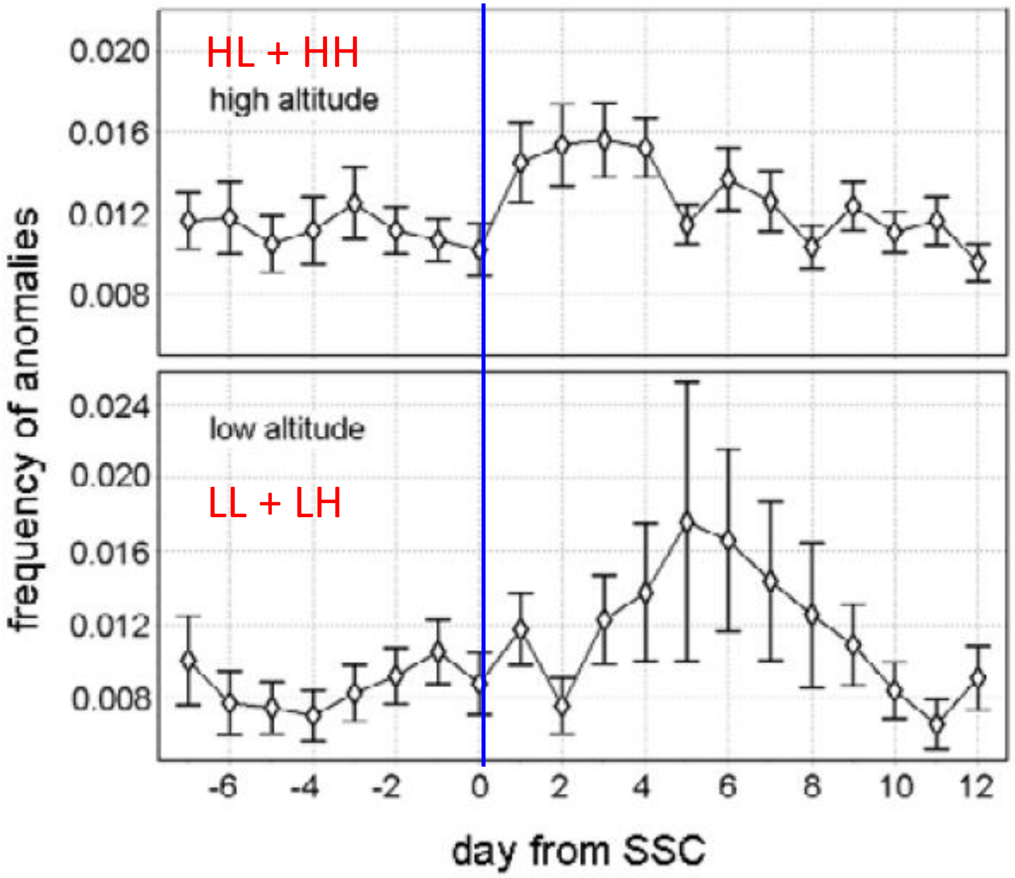
100-year 2.04×10^5 pfu
1000-year 1.02×10^6 pfu

23 March 1991 SEP:
4.3×10^4 cm^{-2} s^{-1} sr^{-1}.

Cliver 2021
Miyake et al. 2012
Mekhaldi et al. 2015

Satellite Anomalies Following Storm Sudden Commencement

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



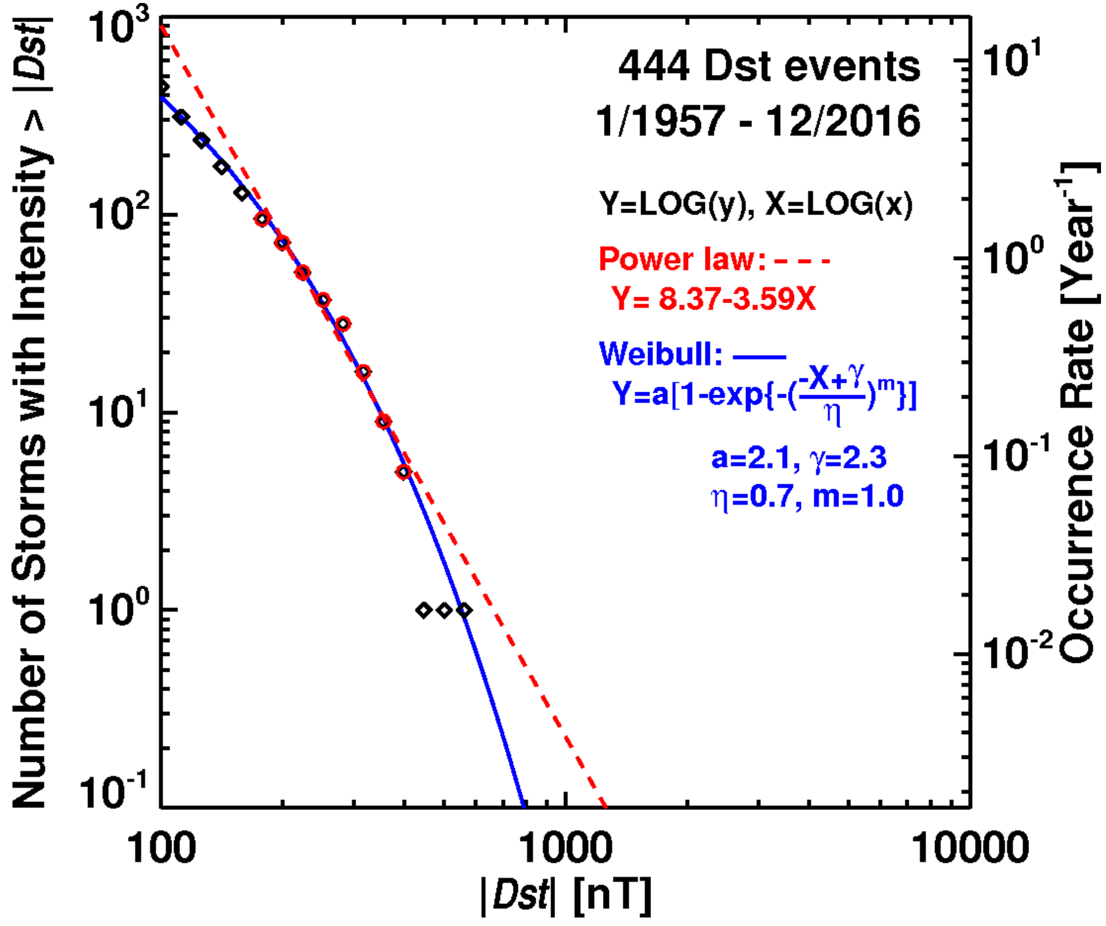
Iucci et al. 2005

Geomagnetic Storms

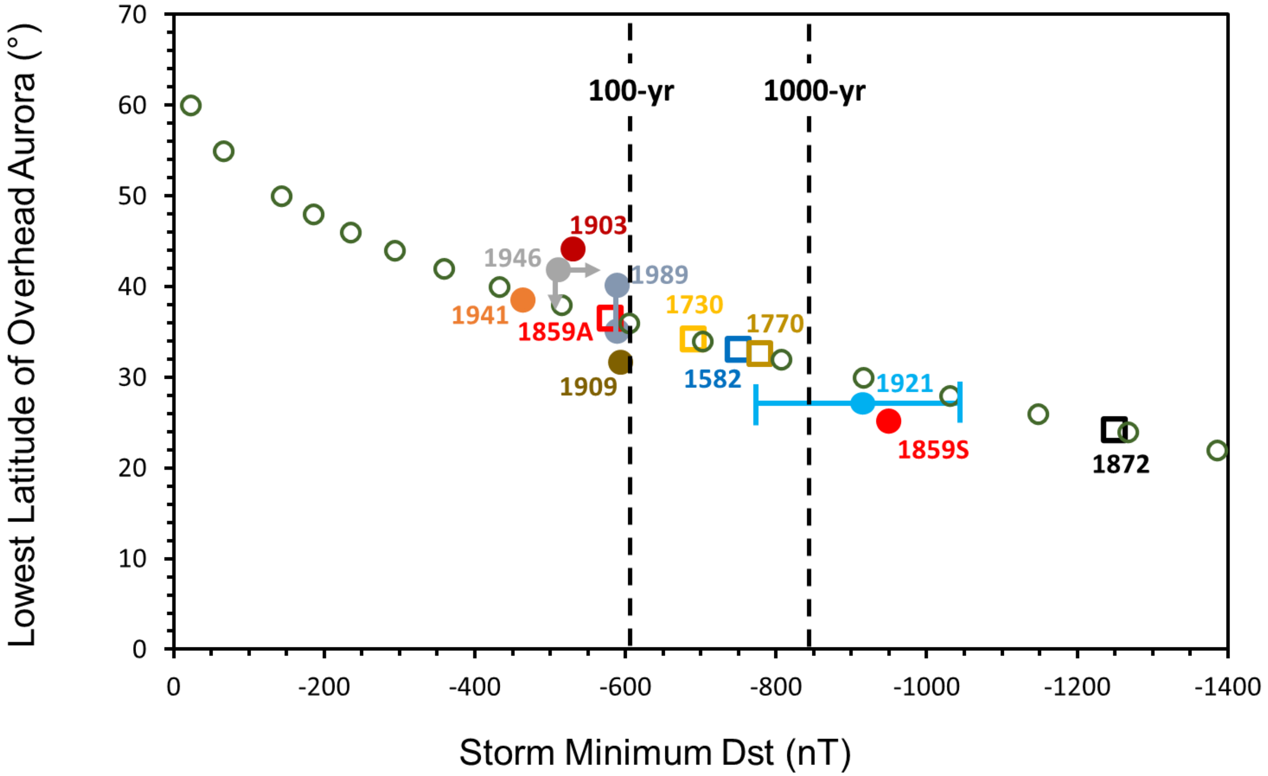
Six 100-yr storms (Dst ≤ -600 nT) in ~450 years (1582, 1730, 1770, 1859S, 1872, 1921)

Three 1000-yr storms (Dst ≤ -845 nT) in ~450 years (1859S, 1872, 1921)

Potential storms of -1200 nT (July 2012; Li et al., 2013) and -1400 nT (August 1972; Gonzales et al., 2011)



Gopalswamy 2018

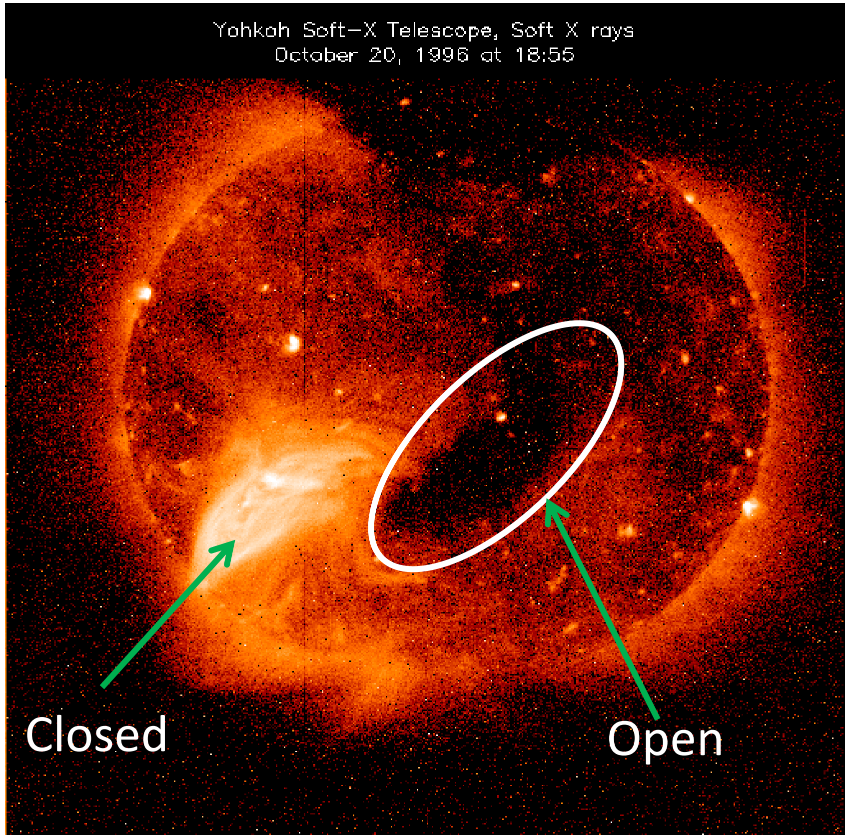


Cliver 2021

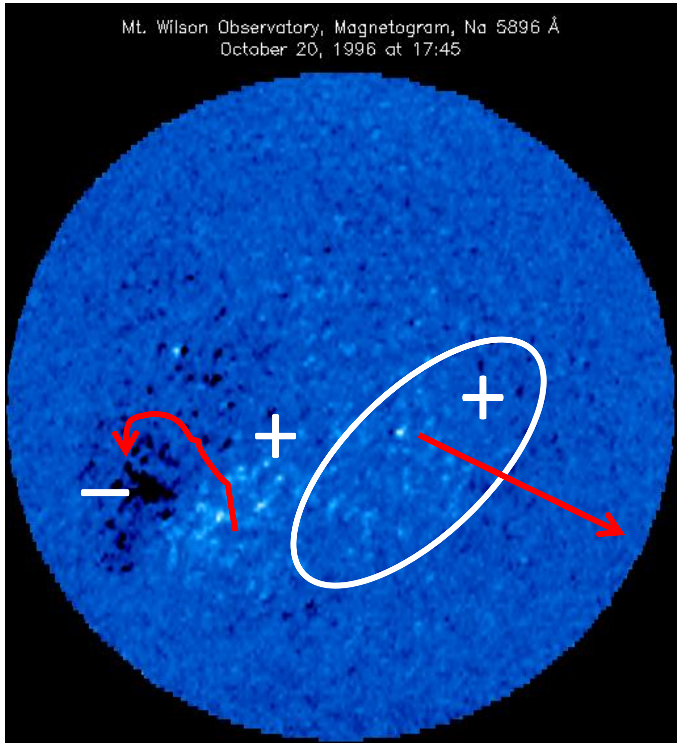
Two Types of Magnetic Topologies on the Sun

Closed magnetic field regions: source of coronal mass ejections (CMEs) and flares

Open magnetic field regions: source of high speed solar wind (HSS) that result in corotating interaction regions (CIRs)

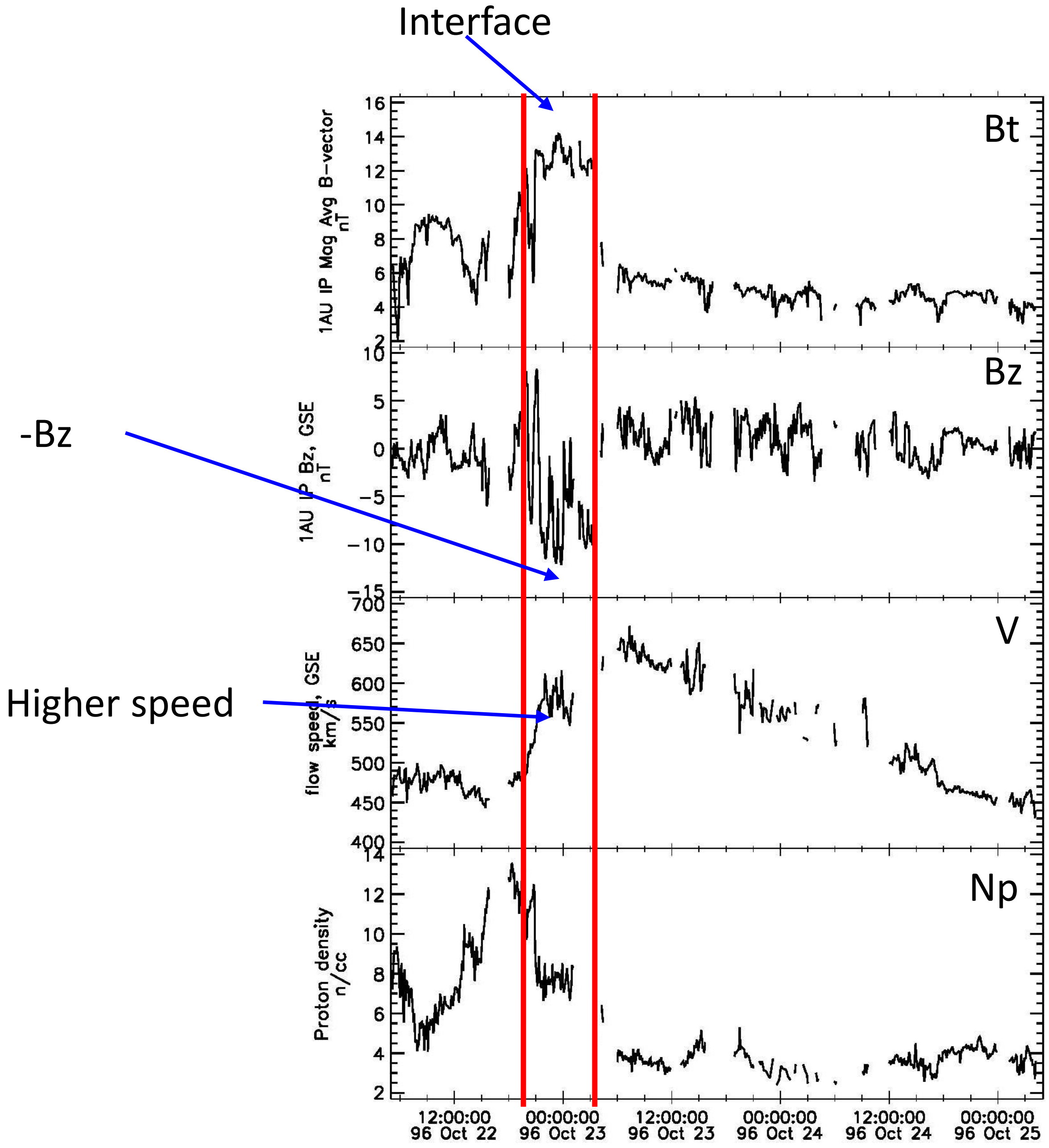


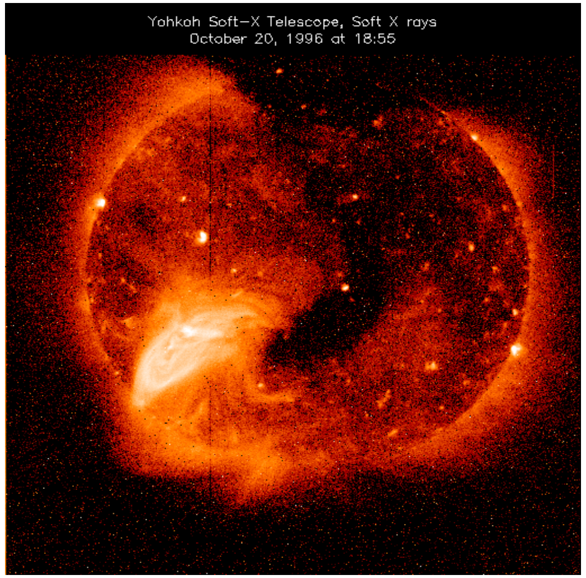
Soft X-ray Image of the Sun showing hot active region and cool coronal hole

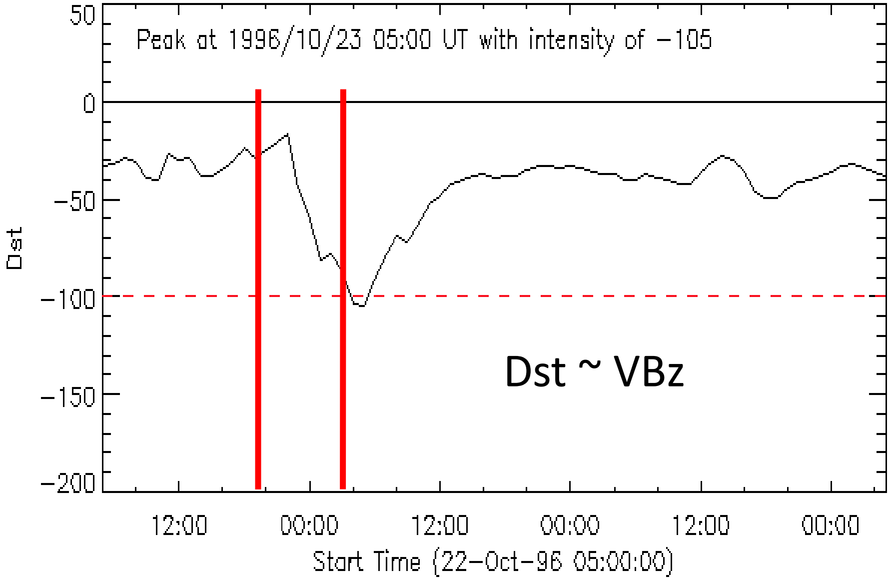


Magnetogram showing a bipolar region (+, –), and a unipolar region (+)

Unipolar, enhanced B, lower temperature, dark in X-ray and EUV, bright in microwave, 27-day recurrence, polar & equatorial





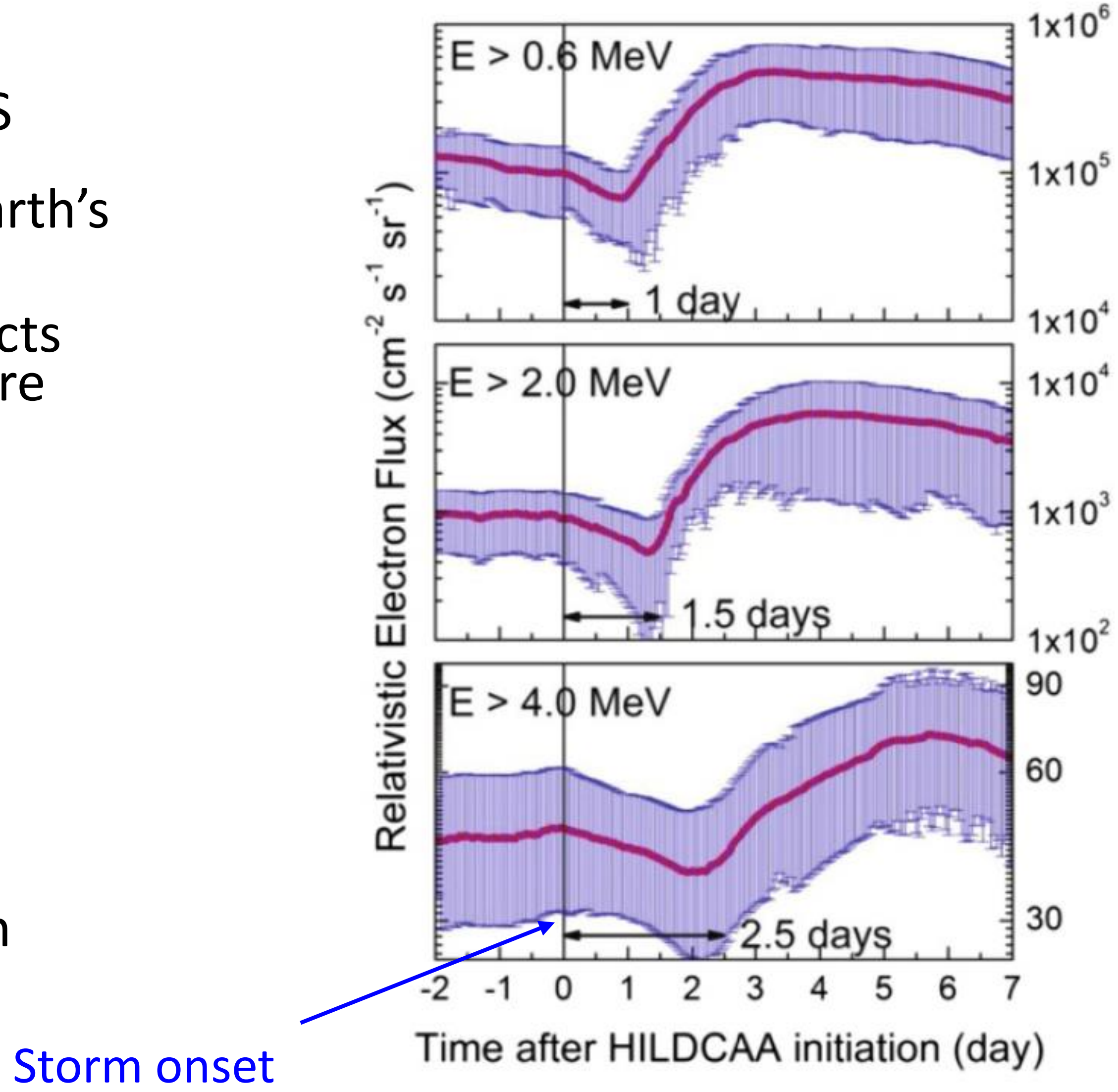


Gopalswamy, 2008

How the Sun is responsible for the relativistic electron flux?

- Solar structures such as CMEs, CIRs, and HSS carrying southward component of the interplanetary magnetic field couple with Earth's magnetic field via dayside reconnection
- The subsequent nightside reconnection injects 10-100 keV electrons into the magnetosphere via substorm events
- These electrons excite low frequency waves such as chorus waves
- 100 keV electrons are further energized by interacting with the chorus waves
- Bootstrap mechanism energizes electrons progressively to relativistic energies
- Initial compression of the magnetosphere causes a decrease in the flux, followed by an increase over many days

Hajra et al. (2014)

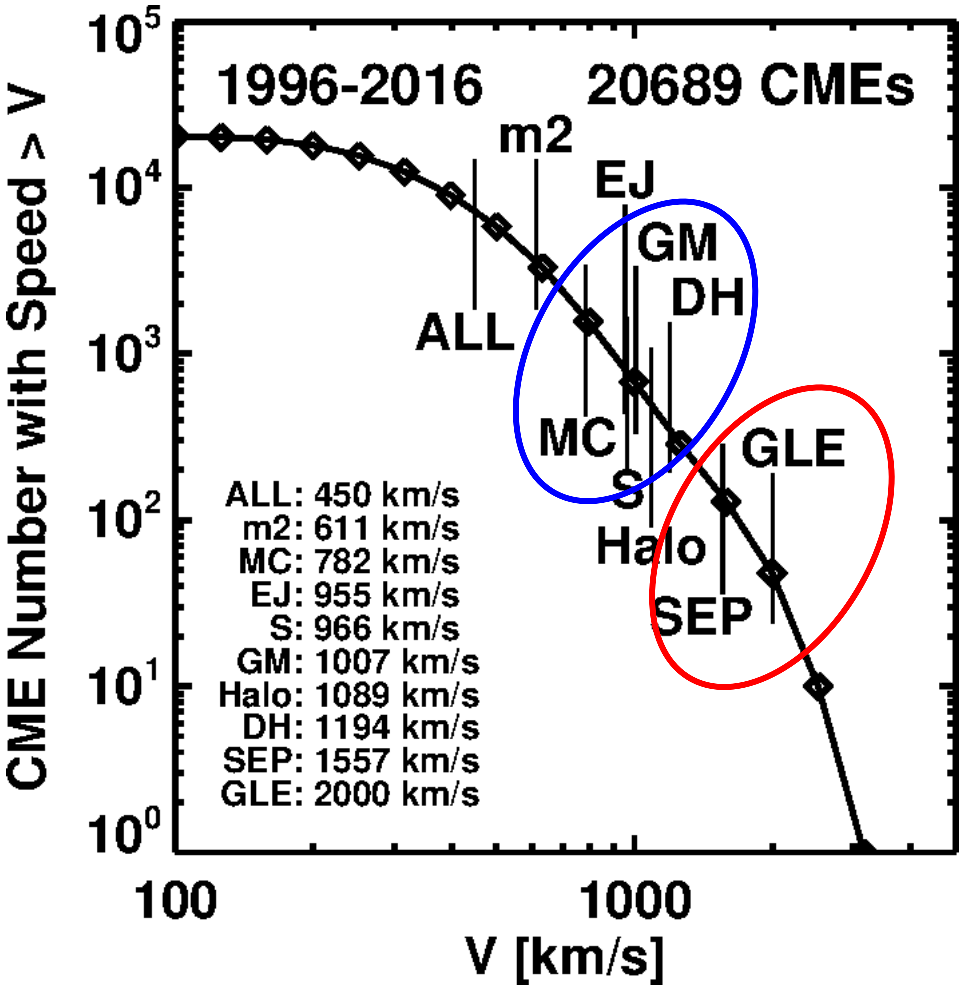


Significant CMEs & their Consequences

Cycle 23 – 24 CMEs from SOHO/LASCO

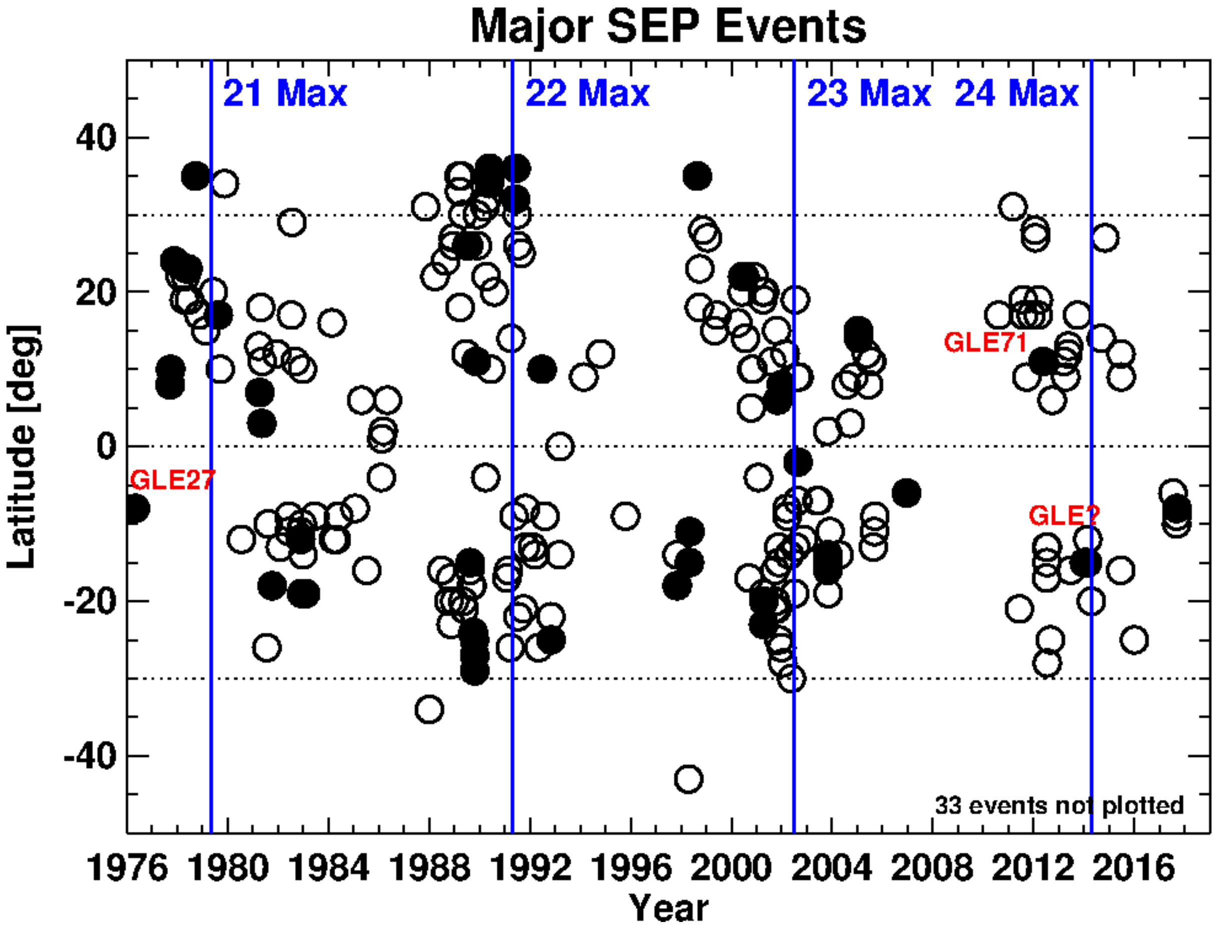
m2 – Metric type II
MC – Magnetic Cloud
EJ – Ejecta
S – Interplanetary shock
GM – Geomagnetic storm ↙
Halo – Halo CMEs
DH – Type II at λ 10-100 meters
SEP – Solar Energetic Particles ↙
GLE – Ground Level Enhancement

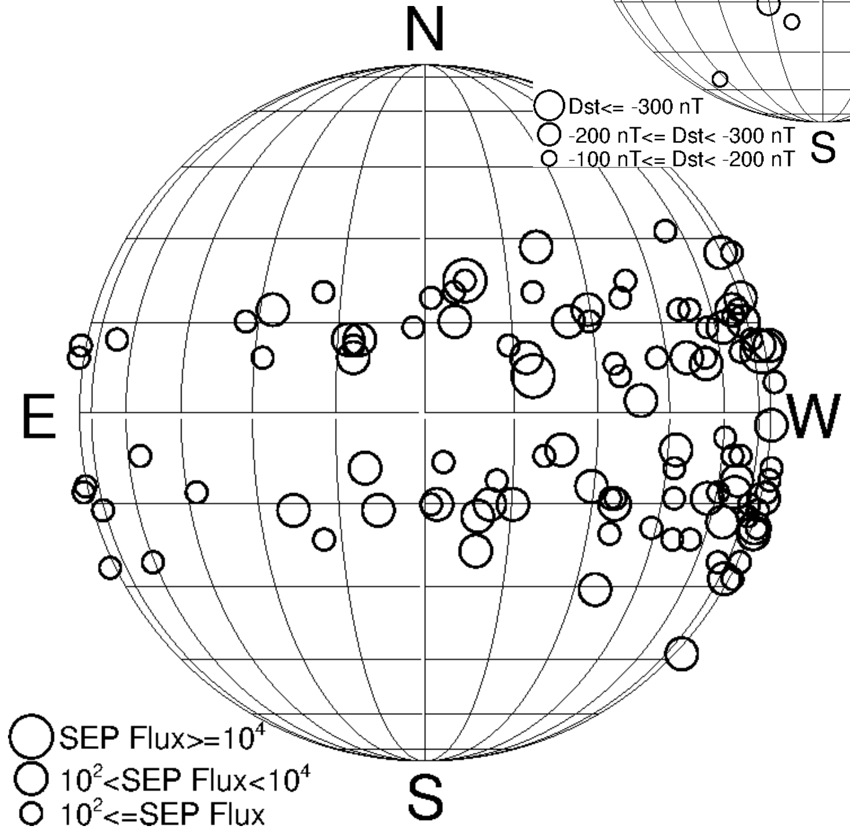
Gopalswamy, 2006; 2010

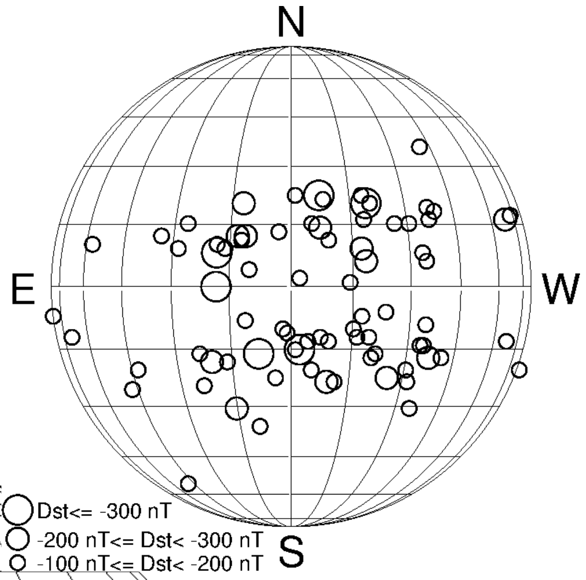


CME speeds: 1000 km/s (Dst <-100), 1500 km/s (>10 MeV), 2000 km/s (GeV)

SEP Source Regions on the Sun





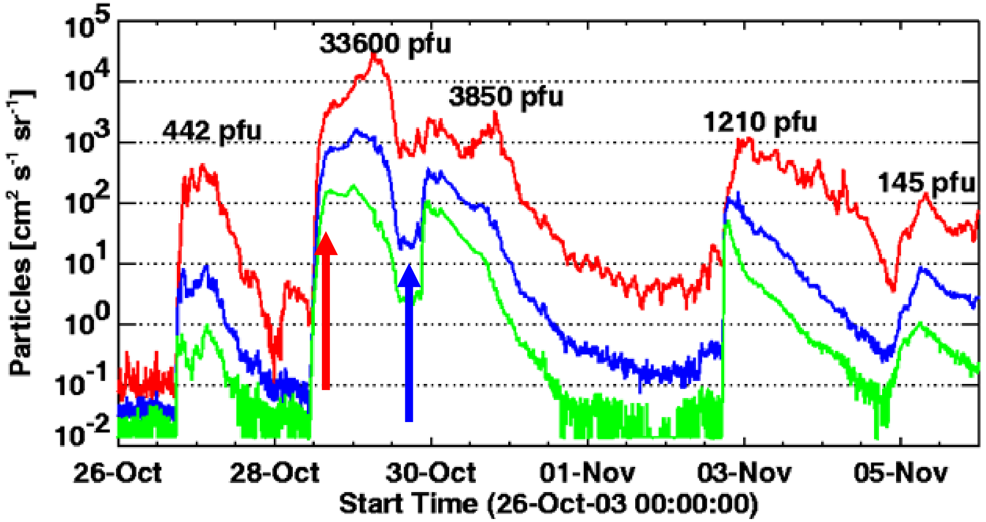


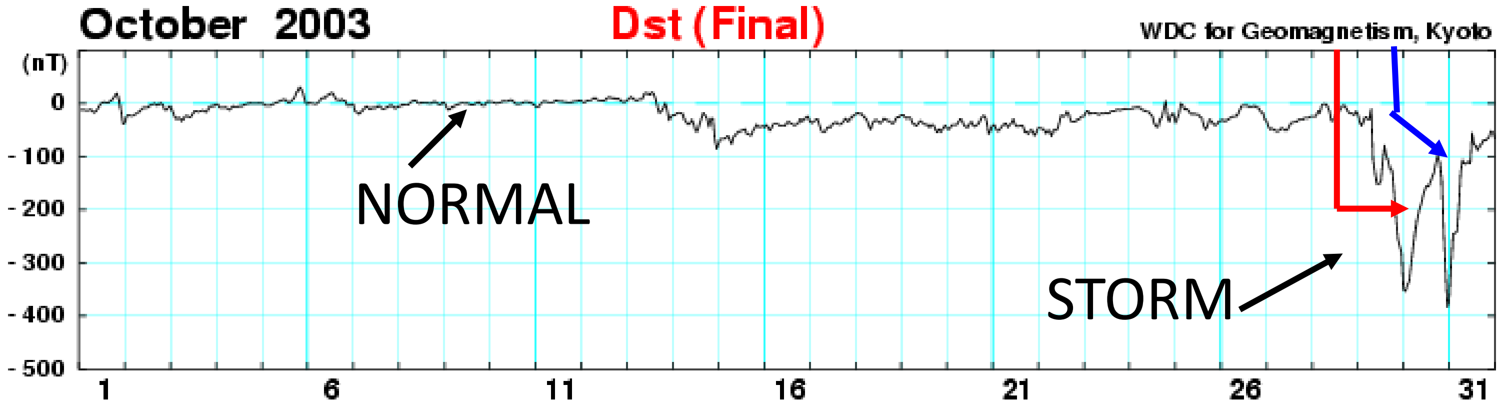
Confined to active region belt

Western hemispheric preference

Solar Sources of Space Weather: Particles and Magnetic Field

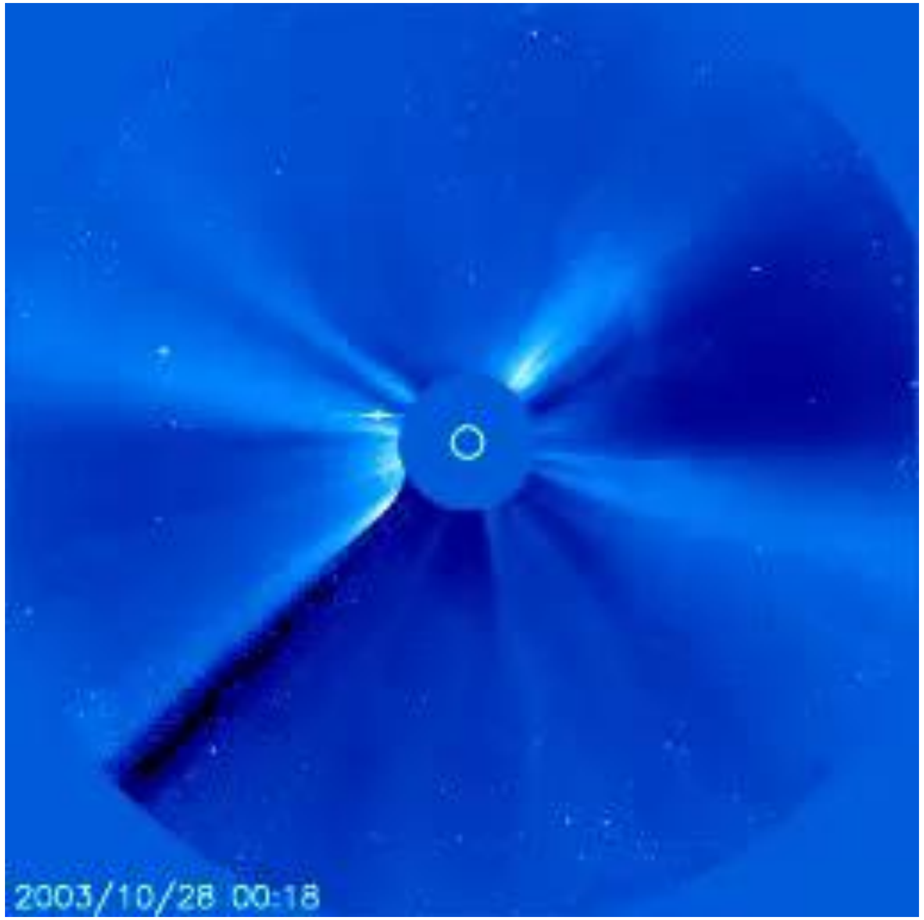
Some times eruptions occur in quick succession maintaining elevated level of particle radiation
Gopalswamy et al. 2005





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

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

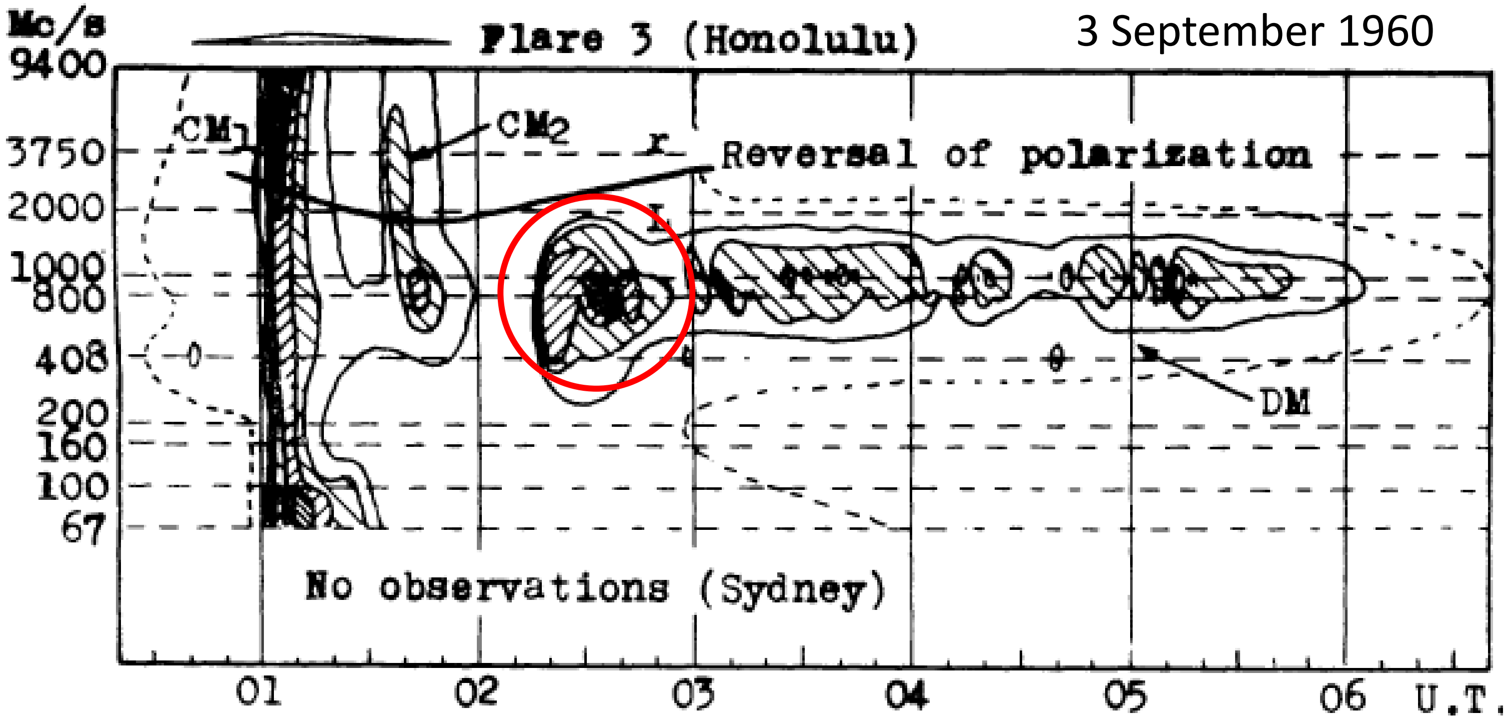


SOHO/LASCO

Signal Drowning

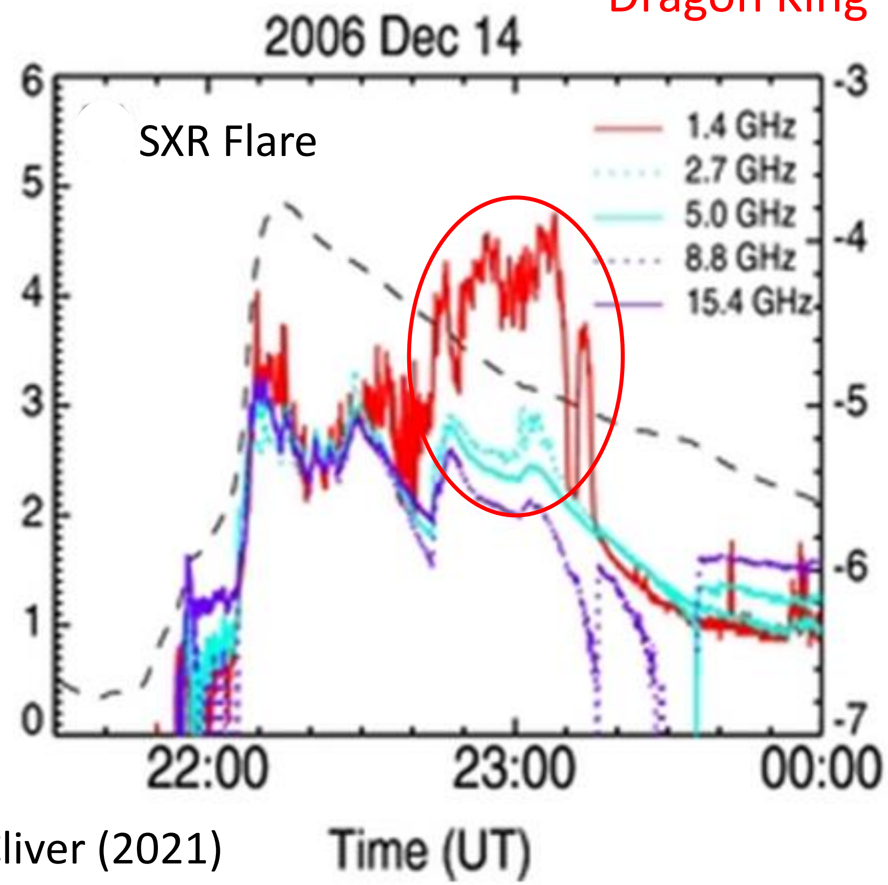
The flare-related solar radio flux in the 1-1.5 GHz range is unusually high resulting in elevated background so GNSS signals can be drowned

Dynamic spectrum showing emission peaking below 2000 MHz



Tanaka & Kakinuma (1962)

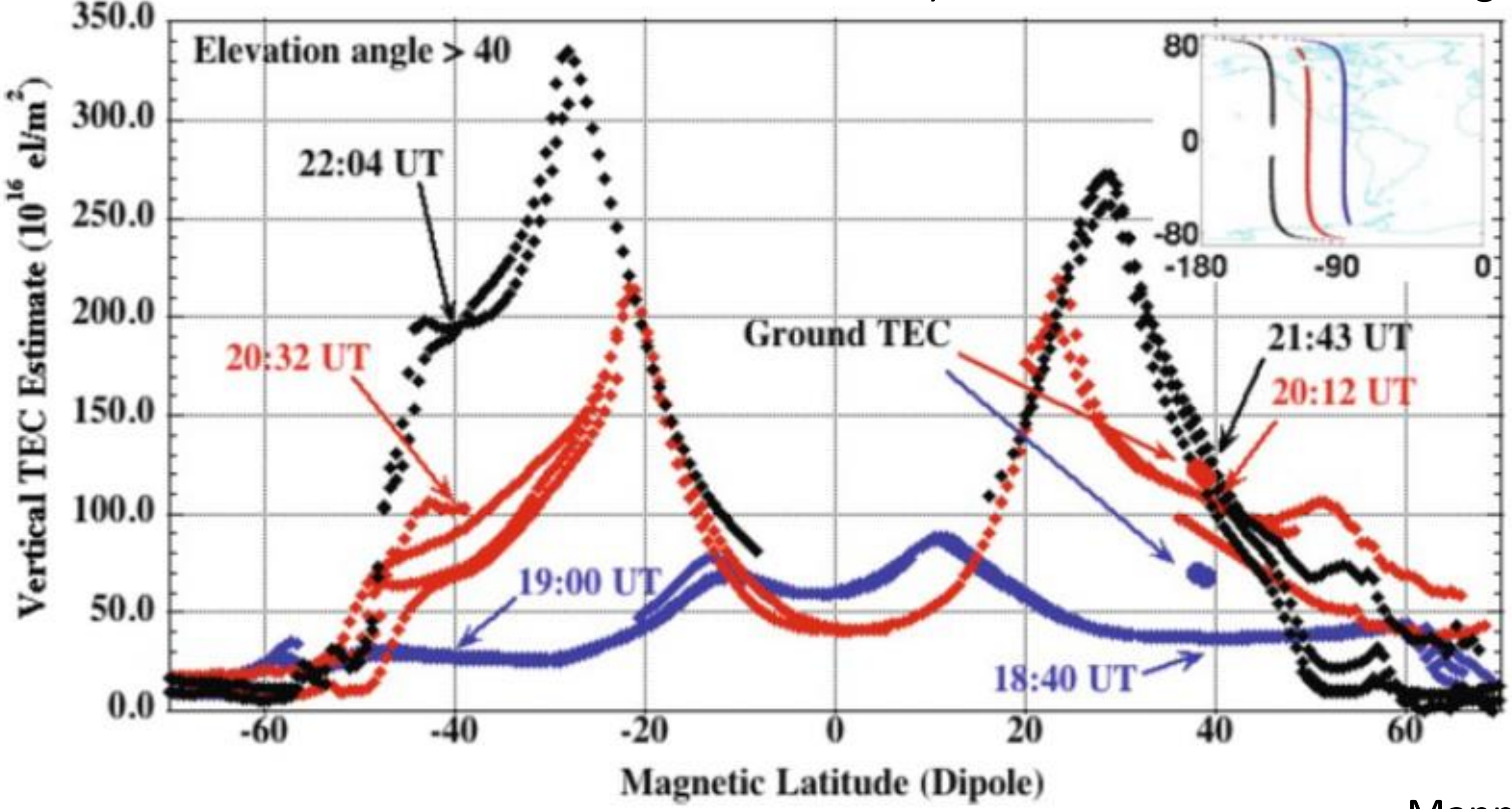
Dragon King



Cliver (2021)

CME Impact on the Ionosphere: Super-fountain Effect

The vertical TEC above the CHAMP satellite (approximately 400-km altitude) for the 30 October 2003 magnetic storm



Mannucci et al. 2015

- TEC enhances by a factor of 5
- The enhancement spreads to mid latitudes (up to ~50 deg from <20 deg)

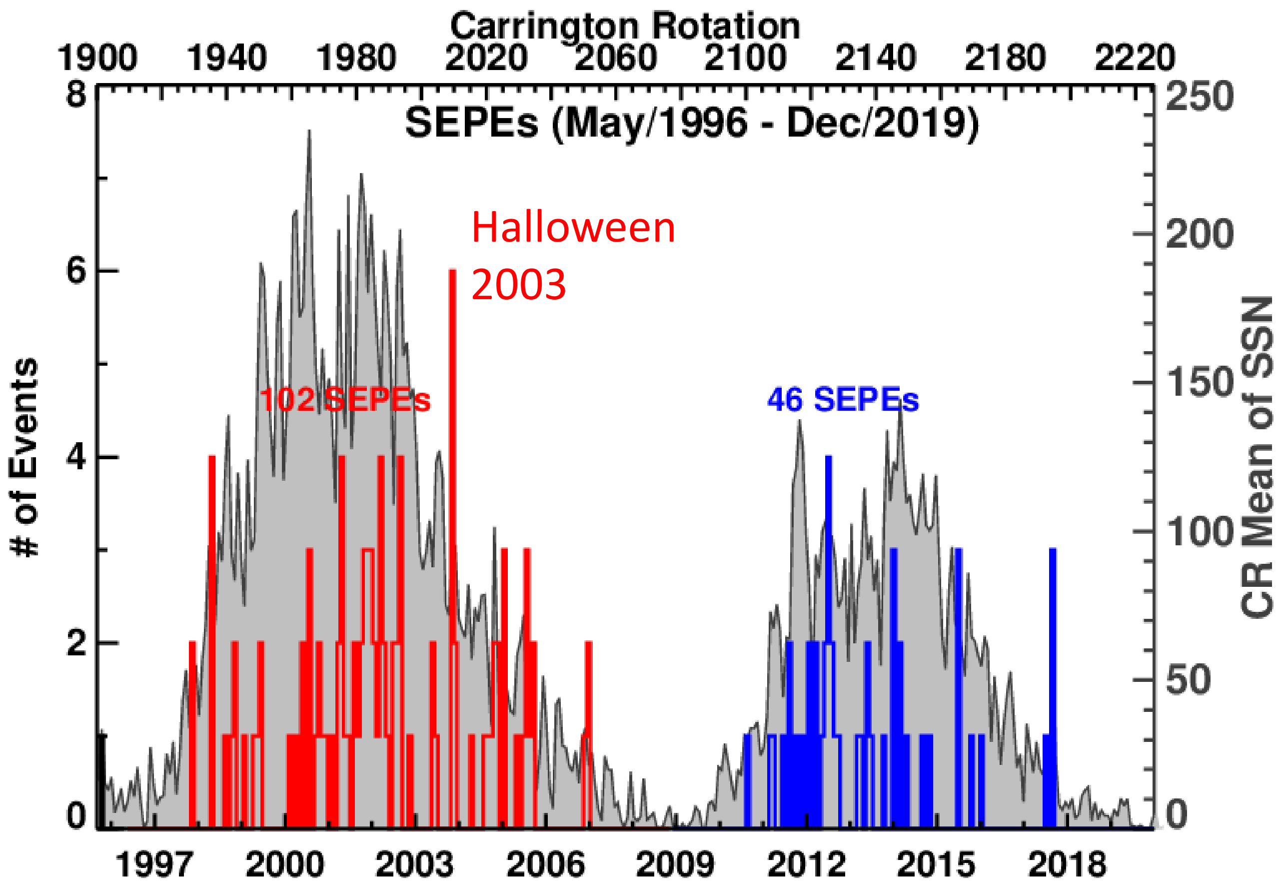
Talk by Keith Groves

Summary

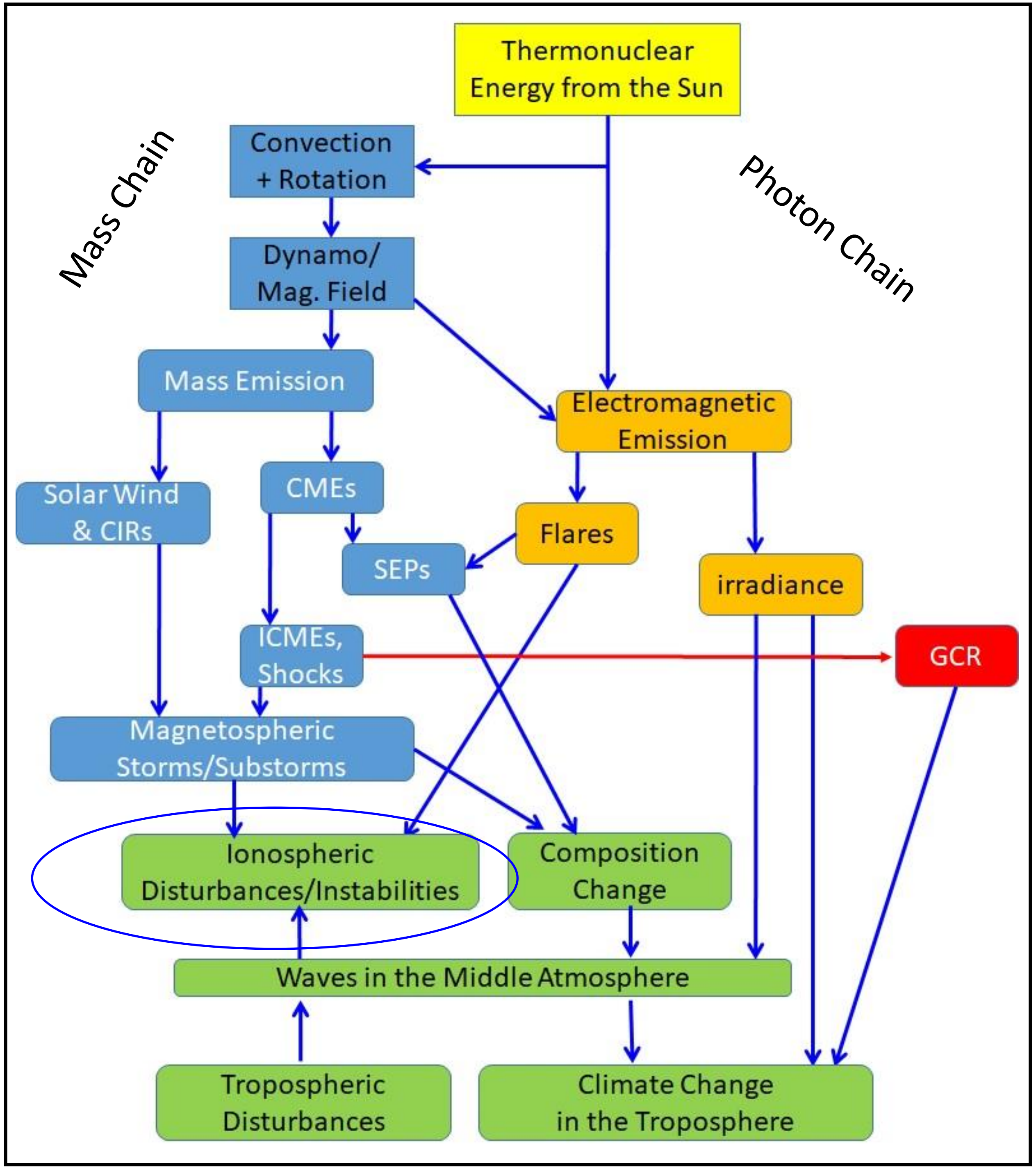
- Severe space weather events are coronal mass ejections (CMEs), which are responsible for solar energetic particle events and geomagnetic storms, which contribute to the radiation environment of GNSS satellite orbits.
- Corotating interaction regions and High speed streams (HSS) cause intense relativistic electron fluxes
- CMEs originate from closed field regions such as sunspot regions
- CIRs and HSS originate from open field regions (coronal holes)
- Signal drowning is a serious effect for GNSS applications
- Both CMEs and CIRs can cause ionospheric disturbances that affect GNSS signal propagation

Back-up slides

Intracycle & Inter-cycle variability of SEP events



- Large SEP events contribution to the hazardous radiation environment occur mostly during solar maximum phase with significant numbers occurring also in the rise and declining phases
- Occasionally large active regions can result in large number of events. E.g., the Halloween 2003 period in solar cycle 23
- Cycle-to-cycle variability in the number of SEP events follows the activity cycle. E.g., the smaller cycle 24 has less than half of the number of events in cycle 23



Mass Chain:

Coronal Mass ejections (CMEs, CIRs)
Corotating interaction regions
Magnetic field transported with plasma
Energetic particles from CME-driven shocks

EM Chain:

Flares

Galactic Cosmic Rays (GCRs):

Contribute to Inner Van Allen Belt

Upward chain:

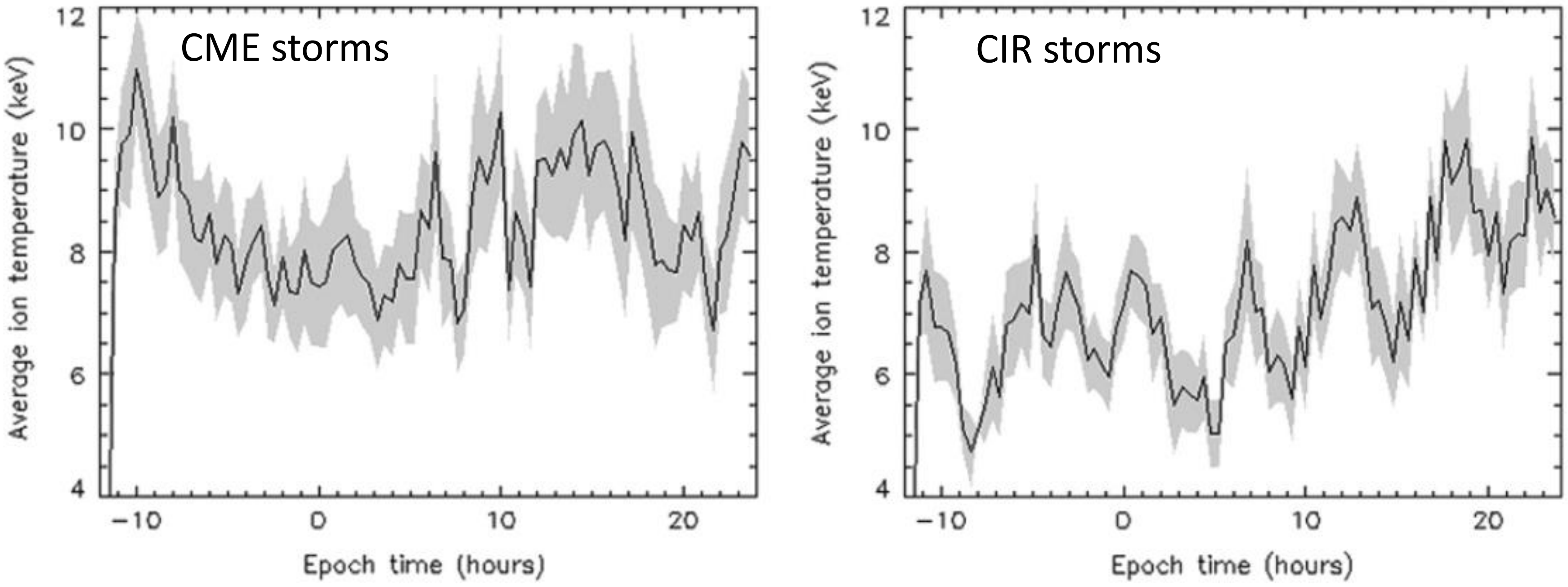
Ionospheric disturbances/irregularities
Contributions from flares & CMEs

Geomagnetic Storms due to CMEs and CIRs

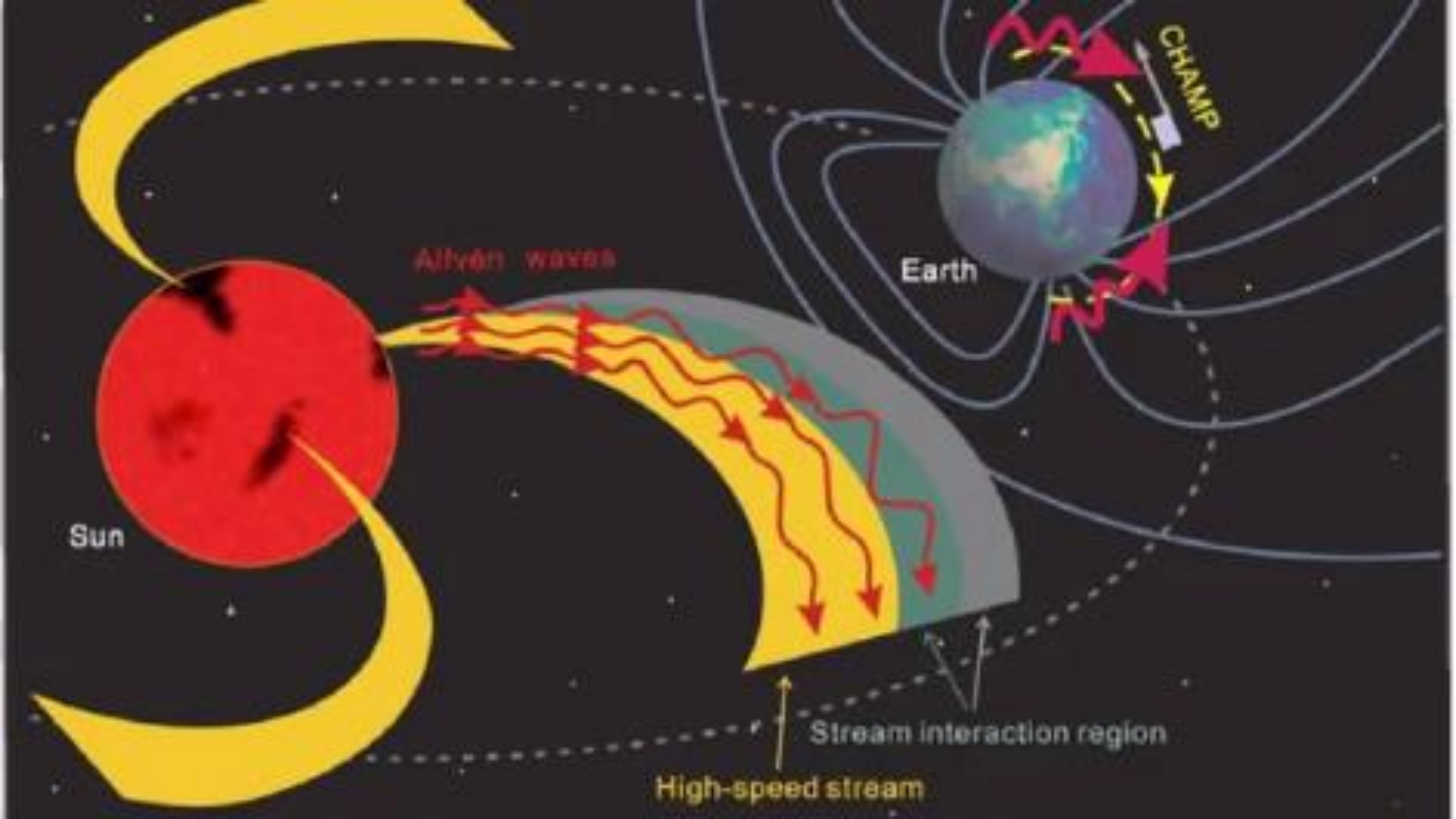
- Geomagnetic storms caused by CMEs and CIRs (plus the following HSSs) differ in some important ways

Hot Ions in the Magnetosphere

Keesee et al. 2014



- Characteristics of the injection of hot ions differ between the two storm drivers, yielding differing ring current structure
- Ion temperatures in the $3R_E$ - $20R_E$ region of the magnetosphere for 48 storms that occurred between June 2008 and April 2012.

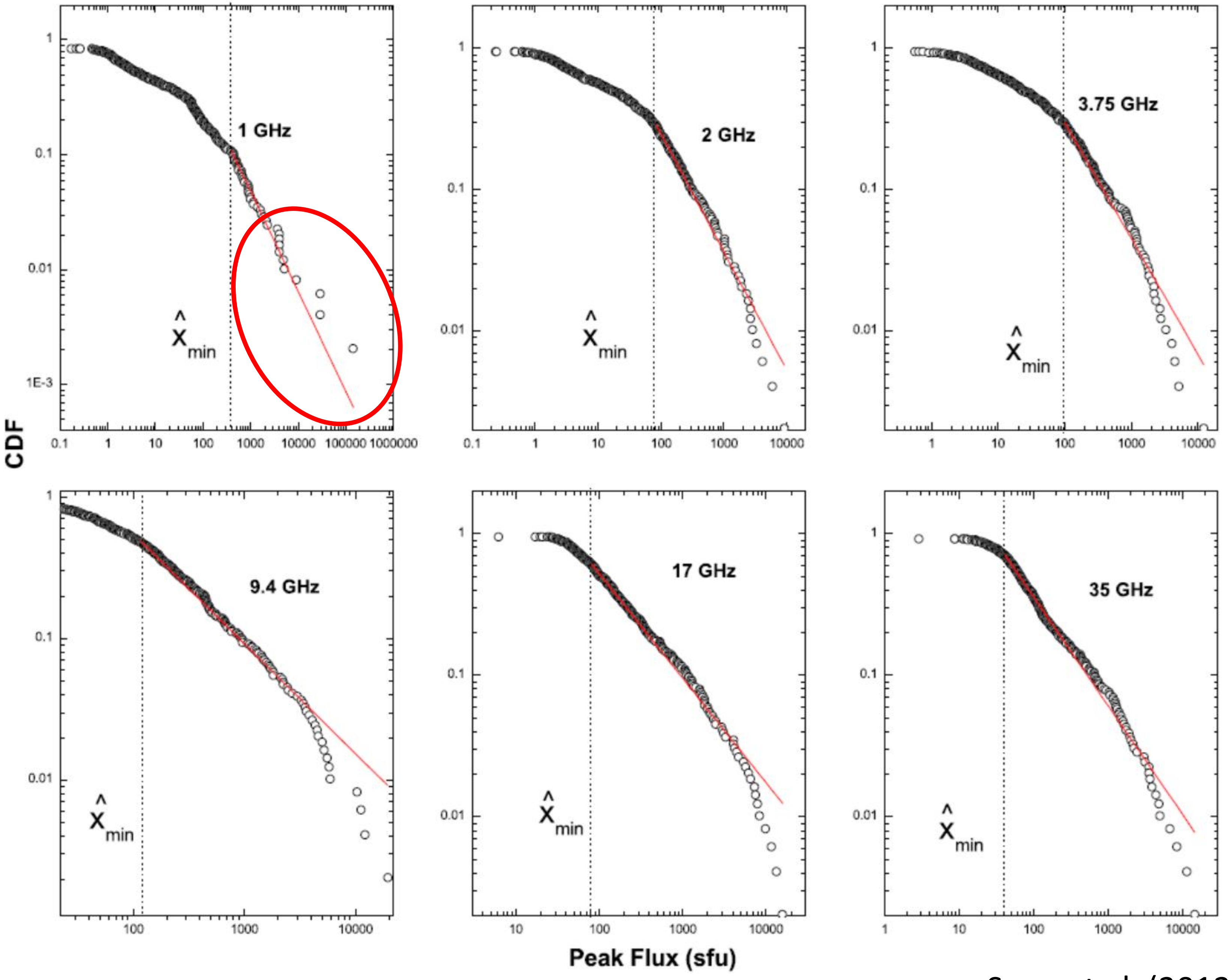

CHAMP
Alfvén waves
Earth
Sun
Stream interaction region
High-speed stream

Van Allen Belts

- Inner belt: L: 1-3
- 10-100 MeV protons (due to the CRAND mechanism)
- 100 KeV electrons
- Outer Belt: L: 3-7
- >100 keV electrons and 30–300 keV protons that are injected into the nightside magnetosphere by substorms and magnetic storms
- Highly variable >1 MeV relativistic electrons

Galactic Cosmic Rays

- 2% electrons and positrons
- 87% protons
- 12% alpha particles
- 1% heavies
- Kinetic energies ranging up to and exceeding 10s of GeV/nucleon



- Cliver (2021) points to the 1 GHz spectrum different from others
- There seems to be an additional mechanism different from the one that produces spectra at other frequencies (dragon king events)
- One possibility is that conditions for an electron cyclotron maser exists for frequencies around 1 GHz

Song et al. (2012)