ASTR-6000 Seminar

COLLAGE: Coronal Heating, Solar Wind, & Space Weather

April 7, 2022
Space Weather
Terrestrial Responses and Technological Impacts (continued): Extreme Events

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Outline

1. Major space weather events at Earth
    - CME and SEP impacts at Earth
2. Extreme Events
    - The 1859 “Carrington Event”
    - 1921 Extreme geomagnetic storm
    - 1972 Extreme SEP event
    - 1989 Quebec Blackout Event
    - 2003 Halloween storms

Review: Solar Magnetic Eruptions

Solar magnetic eruptions are the result of explosive release of magnetic "free energy" stored in magnetic flux ropes in the corona.

Magnetic flux ropes can form in active regions (largest eruptions) or in quiet Sun regions (slower filament eruptions).

Solar magnetic eruptions (may) cause

1. **Flares: photonic output from gamma rays to radio waves**
2. **Coronal Mass Ejections (CMEs): magnetic plasma clouds that (usually) escape to interplanetary space.**
3. **Solar Energetic Particles (SEPs): relativistic electrons and protons that (mostly) that travel along the Parker spiral**

Review: Solar Magnetic Eruption – Impacts

1. Flares – time scales: 10 min to several hours
    - Sudden ionospheric TEC increase
    - HF (3—30 MHz) radio absorption – "D-region absorption"
    - Radio bursts – direct radio noise into radar systems
    - GNSS scintillation

2. **CMEs – time scales: hours to days**
    - **Geomagnetic storms: minor to extreme depending on CME impact parameters**
        - **Geomagnetically Induced Currents in long-line conductors (power lines, pipelines)**
        - **Surface charging of satellites via "dipolarization events", "bursty bulk flows", "substorms"**
        - **Thermospheric expansion due to Joule heating – satellite drag increase**
        - **GNSS scintillation and radio interference – polar particle precipitation "Polar Cap Absorption"**
        - **Radiation belt enhancement – satellite avionics upsets/damage**
        - **Precision magnetic navigation disruption**

Review: Solar Magnetic Eruption – Impacts

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Review: Solar Magnetic Eruption – Impacts

2. CMEs – time scales: hours to days
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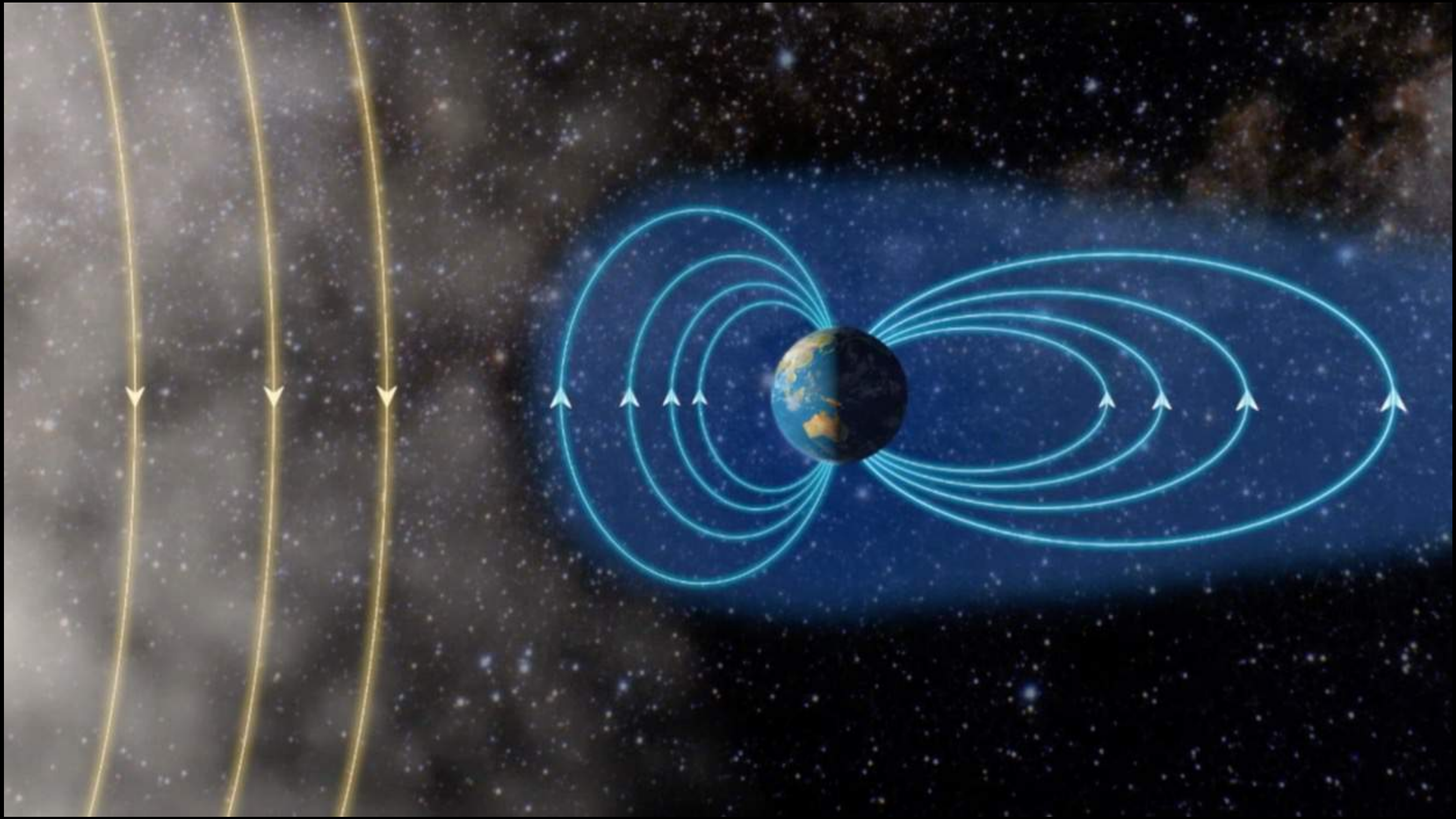
3. **SEPs – time scales: hours to days**
    - Satellite and (possibly) airline avionics upsets/damage
    - Satellite solar panel degradation
    - Health risks to astronauts and increased exposure to airline passengers & Crew

The Phenomena of Geomagnetic Storms

Geomagnetic storms are the result of reconnection of the geomagnetic field with solar magnetic fields

- Ring current – magnetosphere/plasmasphere equatorial current
- "Equatorial electrojet" – ionospheric equatorial current
- "Auroral electrojet" – ionospheric high latitude (>70°) current
- Joule heating from electrojet currents → thermospheric expansion
  - Satellite drag in LEO
  - GNSS scintillation
- "Substorms" – reconnection in the magnetotail = "bursty bulk flows" = "dipolarization"
  - Aurora
  - Upper atmospheric chemistry (O_3 and NOx creation/destruction)
- NOx IR radiation and thermospheric *cooling – storm recovery mechanism*

Geomagnetic Storms: Solar-Geo Magnetic Reconnection



Classifying geomagnetic storm intensity

NOAA/SWPC G-scale

Based on Kp

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Based on SCs 20 – 23.

Number in SC24 = 0

Problem: Kp and G-scale saturate at 9 and 5

Historical storms have saturated and demonstrated the need to have an unbounded measure

Classification	NOAA G-scale	Kp Threshold	Ap Threshold	Dst Minimum, nT
Minor	G1	5	40	< -30
Moderate	G2	6	65	< -60
Strong	G3	7	110	< -100
Severe	G4	8 to 9-	180	<-200
Extreme	G5	9 to 9+	400	< -300
SuperStorm	Above scale	Above scale	Above scale	< -500

***Suggested* classification based on Dst Index**

Follows NOAA terminology up to “extreme” class and extends it to “SuperStorm” class following Lakhina & Tsurutani (2016).

Lakhina, G.S. and Tsurutani, B.T. (2016) ‘Geomagnetic storms: historical perspective to modern view’, *Geoscience Letters*, 3(1), p. 5. doi:10.1186/s40562-016-0037-4.

Quantifying geomagnetic storm intensity

Ring Current energization is due to rate of IMF $-B_z$ ("B_z south") reconnection on dayside magnetopause

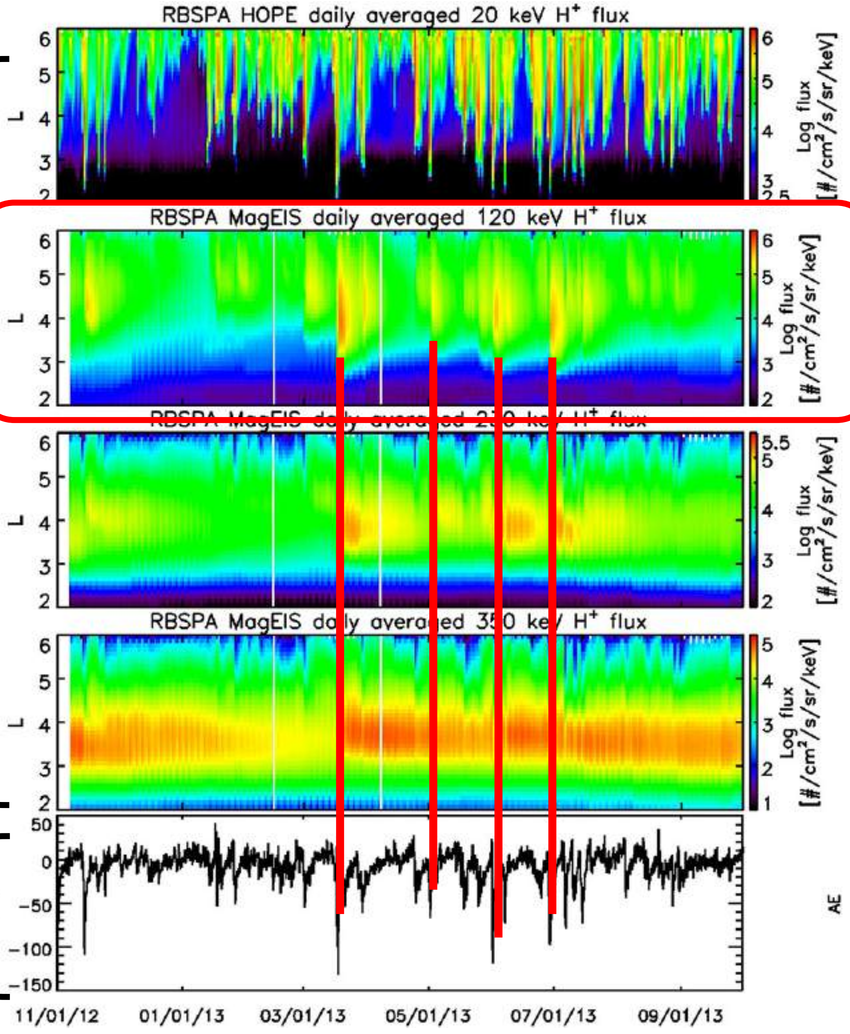
Van Allen Probes A satellite measurements during 2013

HOPE and MagEIS instrument proton (H^+) flux from 20 keV (top) to 350 keV (bottom).

Ring current:

- H+, He+, and O+ ions
- $2 \leq L \leq 4$
- Energies ~100 keV

Dst: geomagnetic field disturbance



Dessler-Parker-Sckopke relationship:

$\Delta B(\mathrm{nT}) = -W_{ring}/2.8\times10^{13}$ J

W_{ring} = total energy of ring current plasma

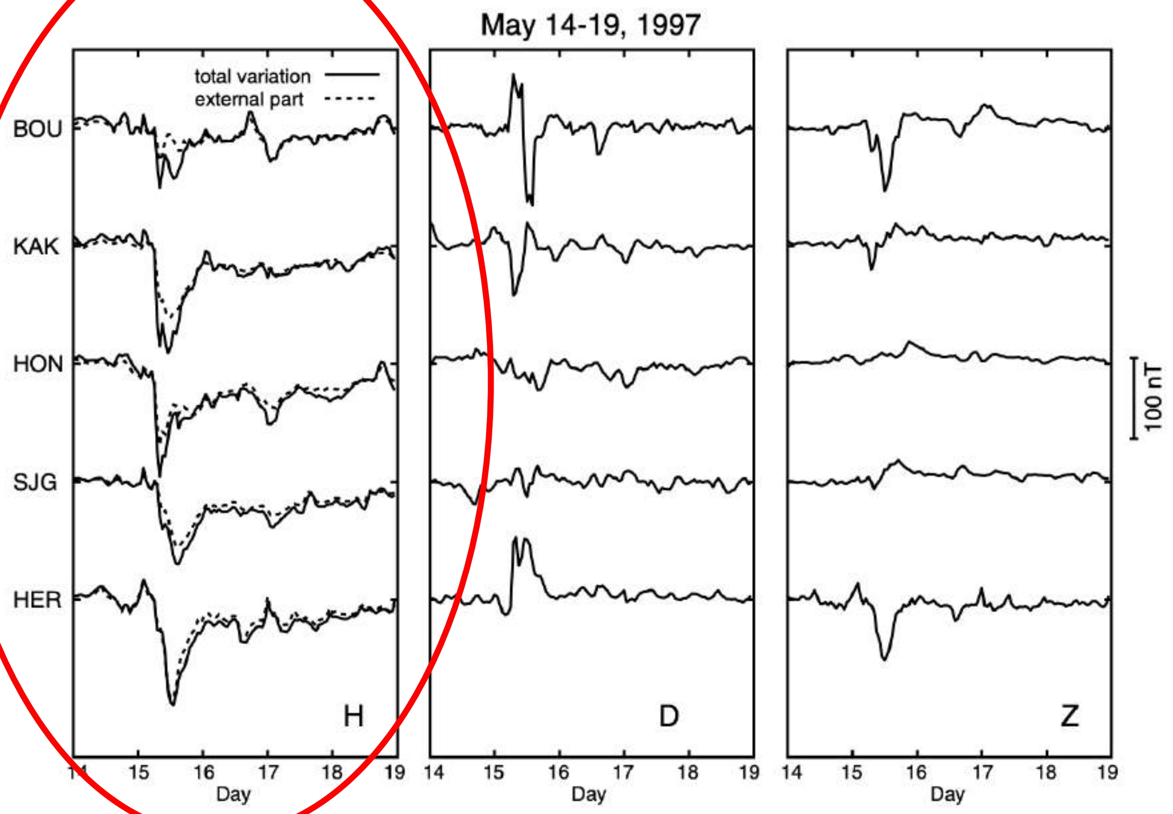
Dst = -100 nT → $W_{ring} \sim 3\times10^{15}$ J

Williams, D.J. (1987) 'Ring current and radiation belts', *Reviews of Geophysics*, 25(3), p. 570. doi:10.1029/RG025i003p00570.

Dst measurement for geomagnetic storms

Disturbance Storm Time index *quantifies* the intensity of the magnetospheric “**Ring Current**”

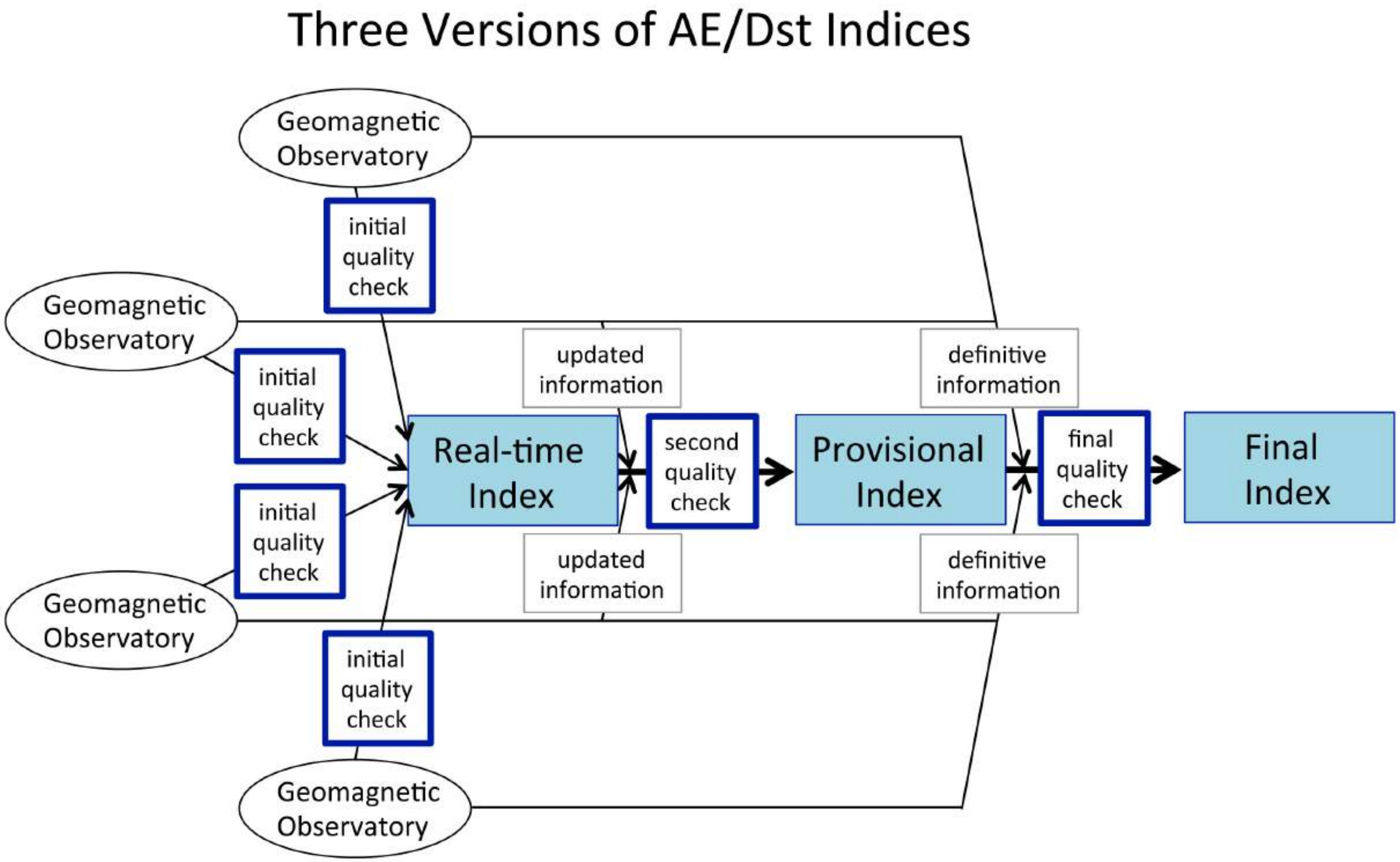
Dst = the average depression of the horizontal magnetic field component, B_H, at four low-latitude stations.



Storm-time response of all three B components (H, D, Z) at the four Dst stations vs. Boulder (BOU) at mid-latitude for comparison.

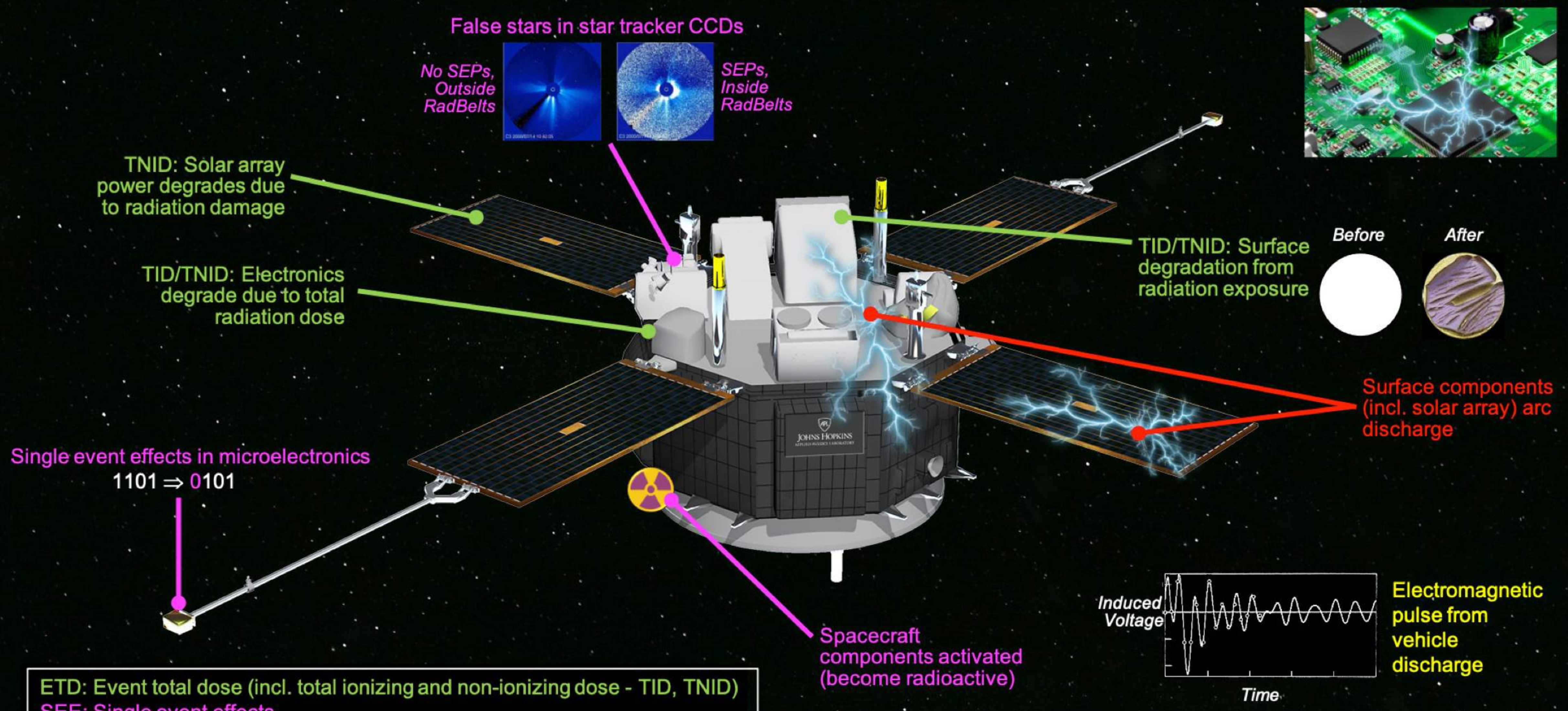
Häkkinen, L.V.T. (2002) *Journal of Geophysical Research*, 107(A1), p. 1014. doi:10.1029/2001JA900130.

Review: Dst index for geomagnetic storms



https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html

Space Radiation Hazards on Spacecraft



ETD: Event total dose (incl. total ionizing and non-ionizing dose - TID, TNID)
SEE: Single event effects
IC: Internal charging/discharge
EHC: External/hybrid charging/discharge

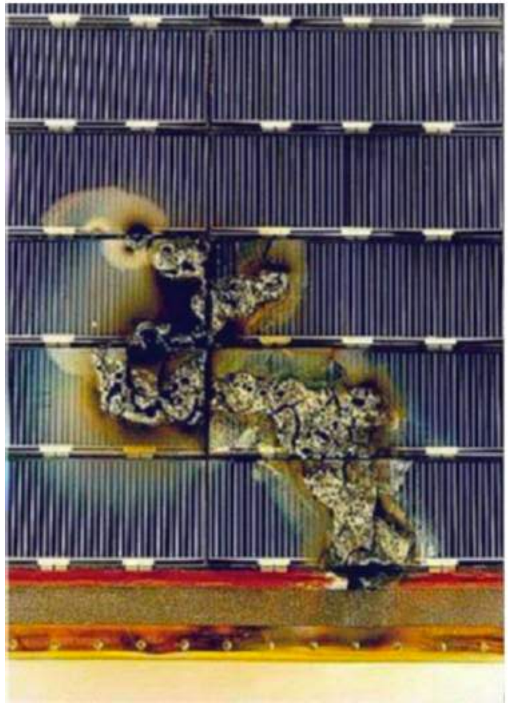
“Killer Electrons” (and protons and ions)

- **Surface Charging & Arcing**: primarily 100 eV–100 keV electrons (Ferguson, 2018)
- **Deep Di-electric Charging**: MeV electrons and ions (Lai, 2018)
- **Single Event Upsets**: > 10 MeV protons and ions. (Also called Single Event Effects)

	space hazard	spacecraft charging:		single event effects			total radiation dose		surface degradation		plasma interference with spacecraft communication	
	specific cause	surface	internal	galactic cosmic rays	trapped radia-tion	solar particle	trapped radia-tion	solar particle	ion sputter-ing	O+ erosion	scintilla-tion	wave refract-ion
orbit	LEO i<60	1	1	not applic-able	2	not applic-able	2	1	1	2	2	2
	LEO i>60	1	1	2	2	2	2	1	1	2	2	2
	MEO	2	2	2	2	2	2	2	1	2	2	2
	GPS i~55	2	2	2	not applic-able	2	2	2	1	2	2	2
	GTO	2	2	2	2	2	2	2	1	1	2	2
	GEO	2	2	2	not applic-able	2	2	2	1	1	2	2
	HEO	2	2	2	2	2	2	2	1	1	2	2
	Inter-planet-ary	not applic-able	not applic-able	2	not applic-able	2	not applic-able	2	1	not applic-able	1	1

2 Important
1 Relevant

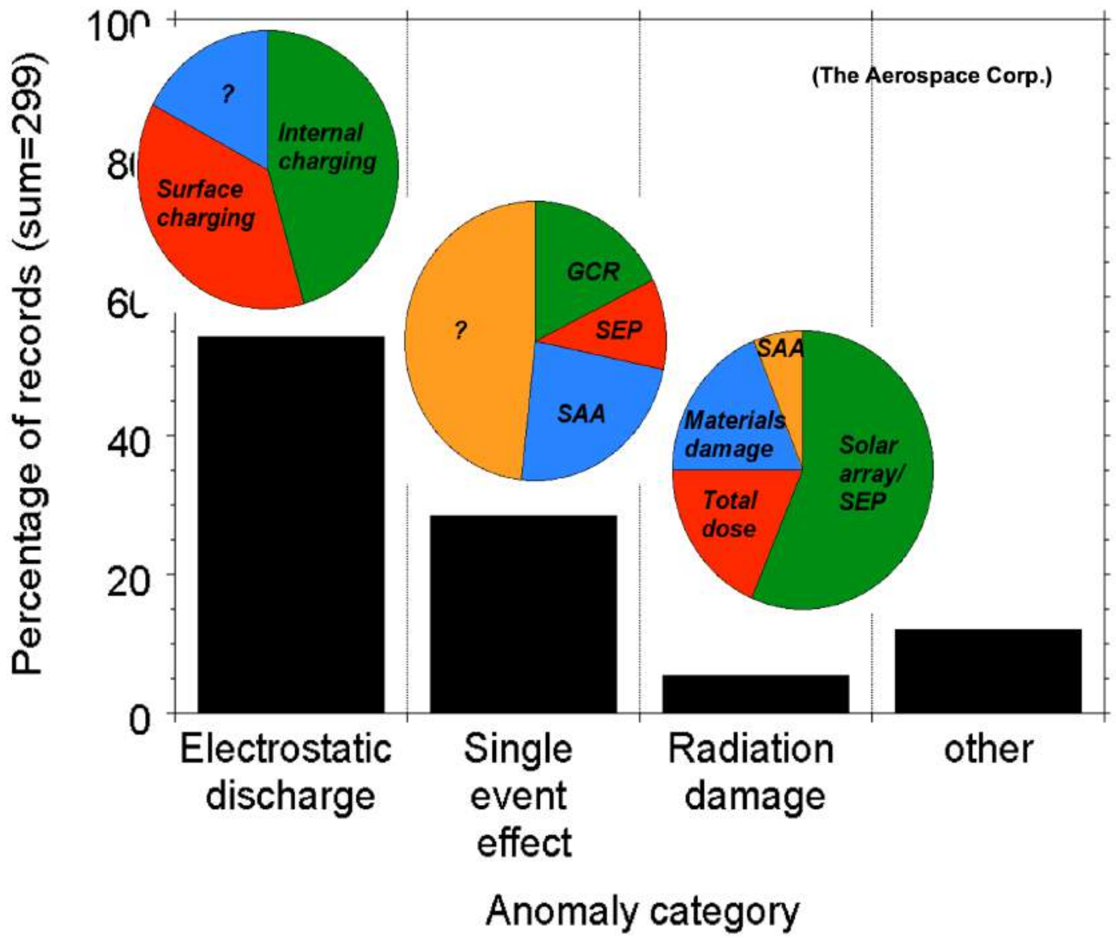
Mazur et al., 2007



Surface discharge damage to a solar array
Ferguson, 2018

"Killer Electrons" (and protons and ions)

~300 Anomalies analyzed for root cause and environmental origin.



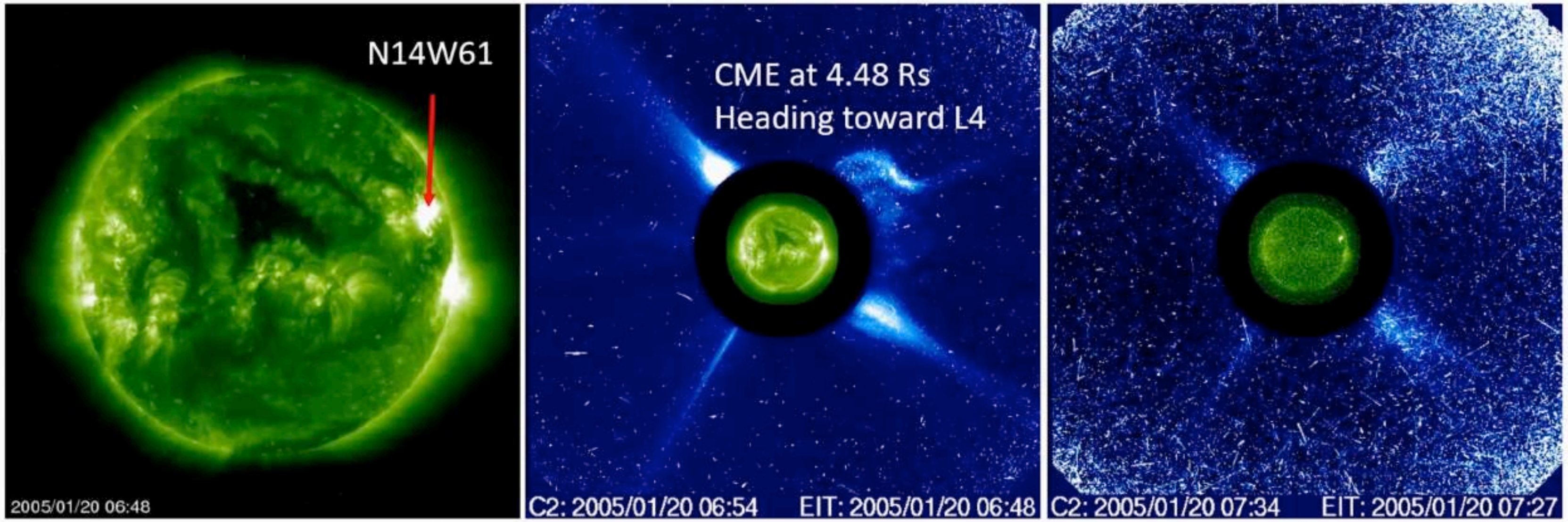
Mazur et al., 2007

Solar Energetic Particle (SEP) events cause imaging system interference

Deep space instruments are most vulnerable, but large SEP events can impact orbital instruments as well.

Star trackers, cameras, spectrographs can be “snowed out” by relativistic protons.

Single Event Upsets can cause loss of S/C, as in ADEOS mission in 2003.



Estimated speed ~3500 km/s from
Flare onset: 06:39 UT (~2 km s^{-2})
LASCO/C2: 4.48 Rs at 06:54

The GLE was the largest in cycle 23 with intensity 277% above background

Example: major solar eruption and radiation storm on 20-January-2005

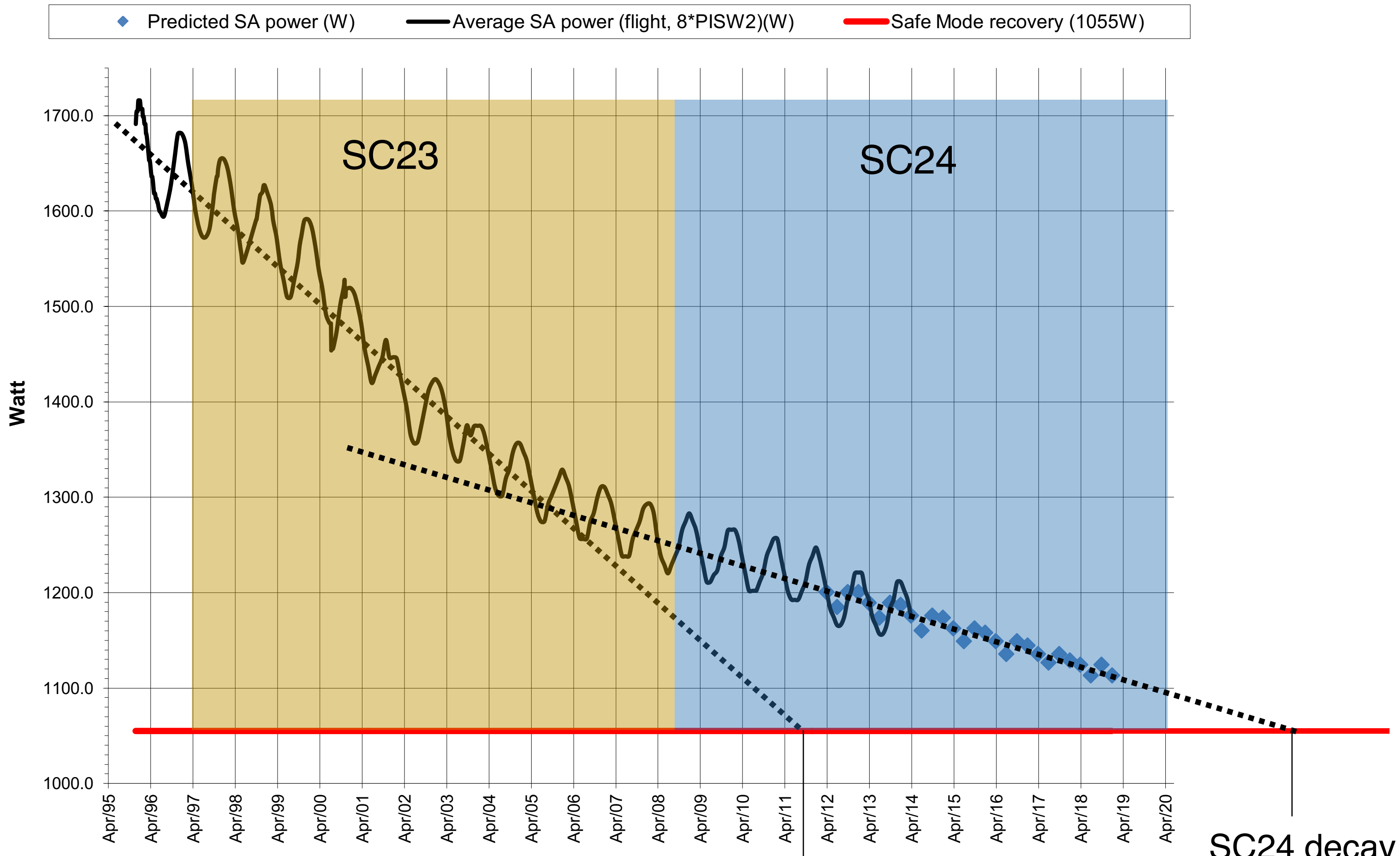
SOHO/LASCO coronagraph at L1 Sun-Earth Lagrangian point cannot properly characterize the associated CME due to SEP “snowstorm” disabling detector.

Initial speed estimates indicate a possible “Carrington Event” geomagnetic storm if CME hits Earth.

In the end, CME did not impact Earth, but radiation storm was strongest of Solar Cycle 23 and caused major neutron Ground-Level Event.

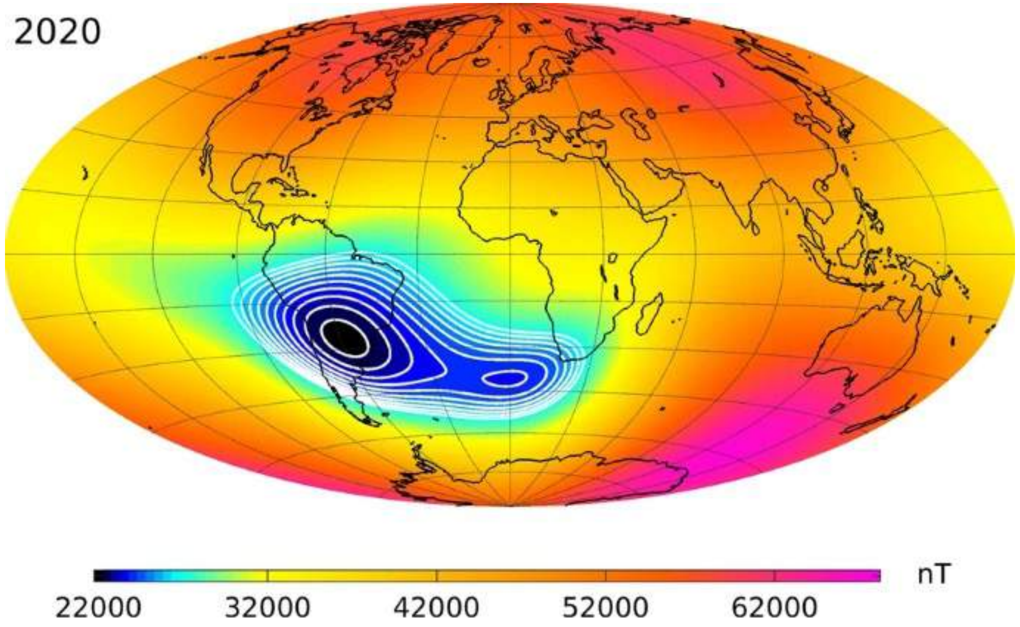
Sometimes the Sun helps!

Solar array degradation of SOHO satellite decreased significantly due to weak Solar Cycle 24.

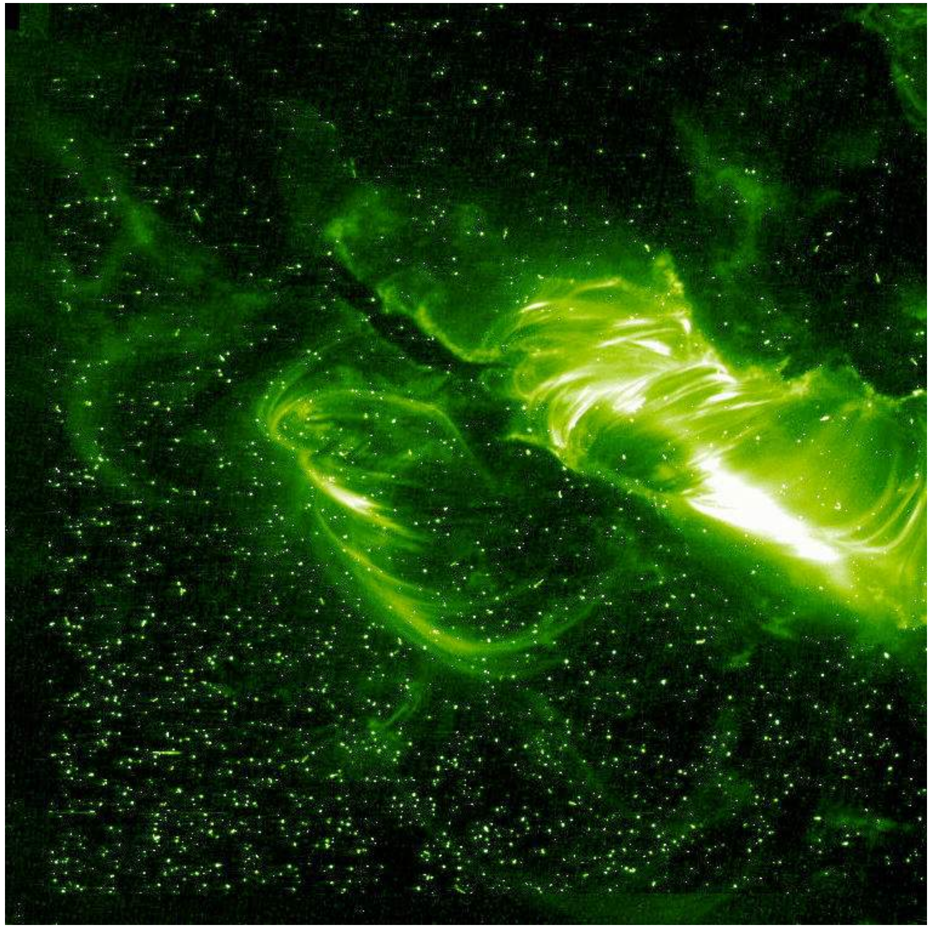


SA Degradation.xls

The South Atlantic Anomaly: Penetration Point for ECPs



Finlay et al., 2020

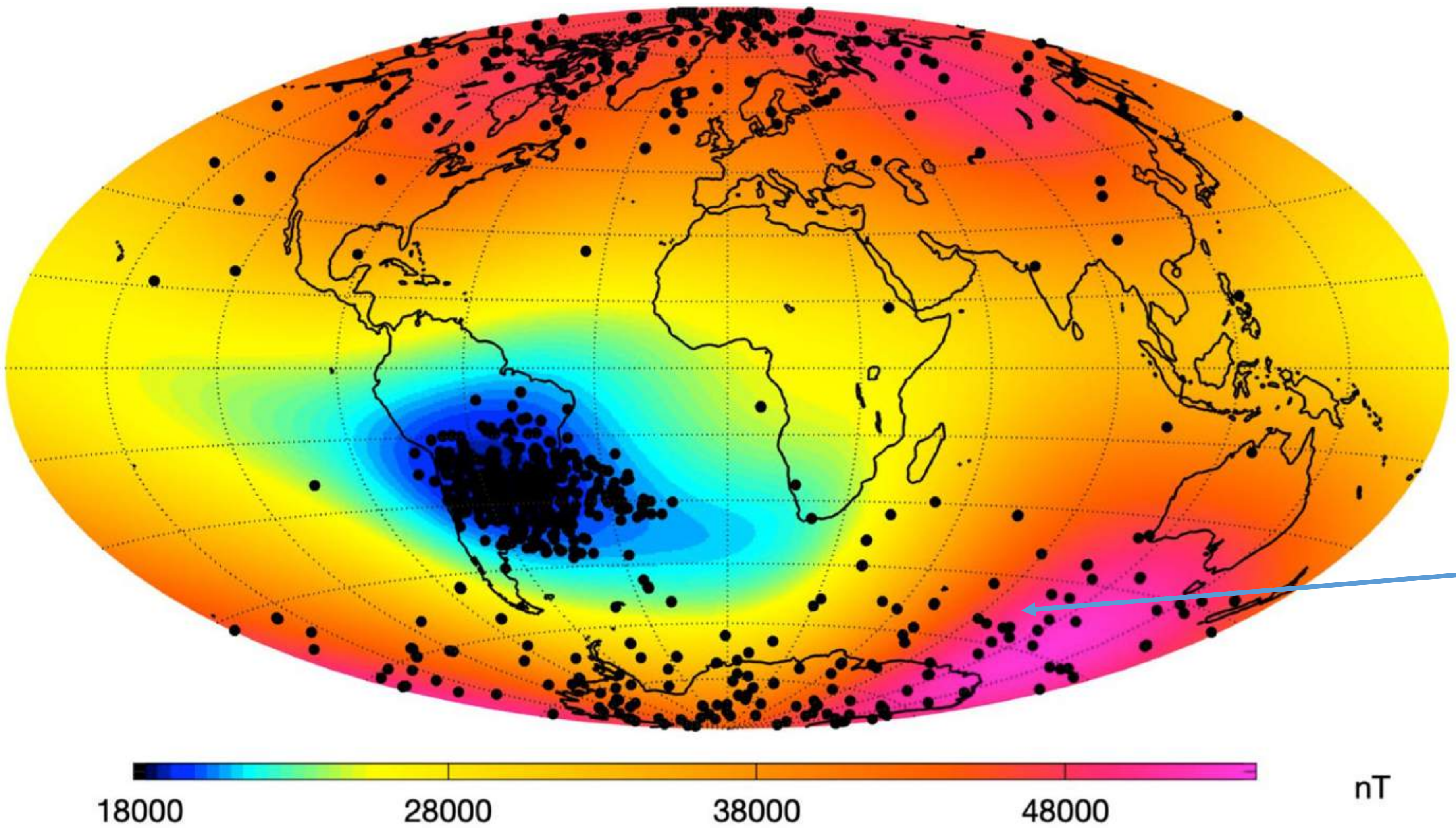


28-October-2003 X18 Flare
TRACE 195Å channel

NASA TRACE mission
20 cm UV/EUV telescope

518x555 km Sun-Synch orbit
P = 95 min
i = 97.53°

Single Event Upsets of the SWARM satellites 2013—2019



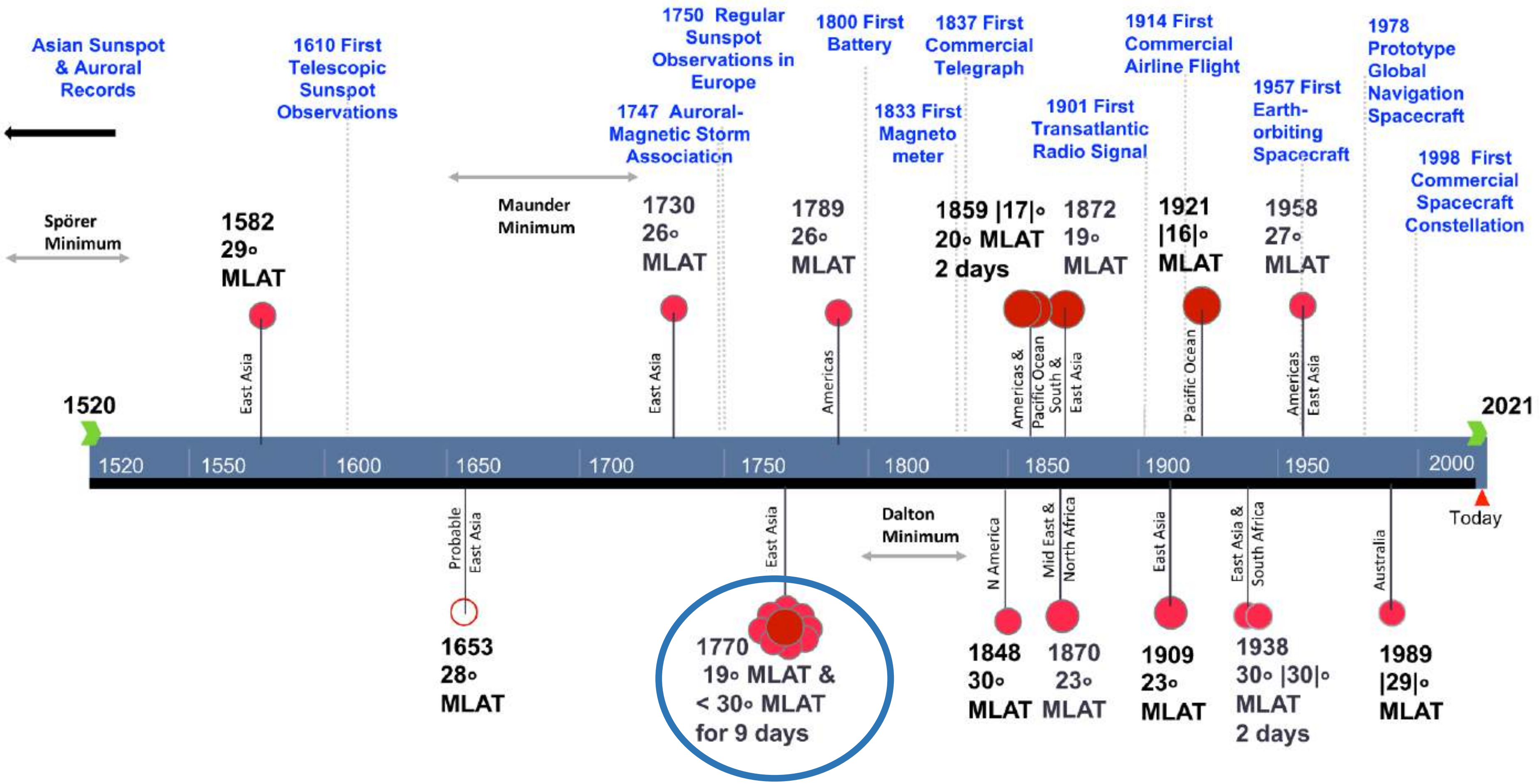
Locations of single-event upsets (**SEU**s) registered onboard the *Swarm* satellites between November 2013 and August 2019 (black dots) plotted on top of the field intensity at **450-km altitude** in August 2017 according to the CHAOS-7 model.

Note the prevalence of high-latitude SEUs as well:

- Auroral zone precipitation.

Finlay et al., 2020

2. Extreme Events



Extreme events defined by aurora visibility below 30° magnetic latitude

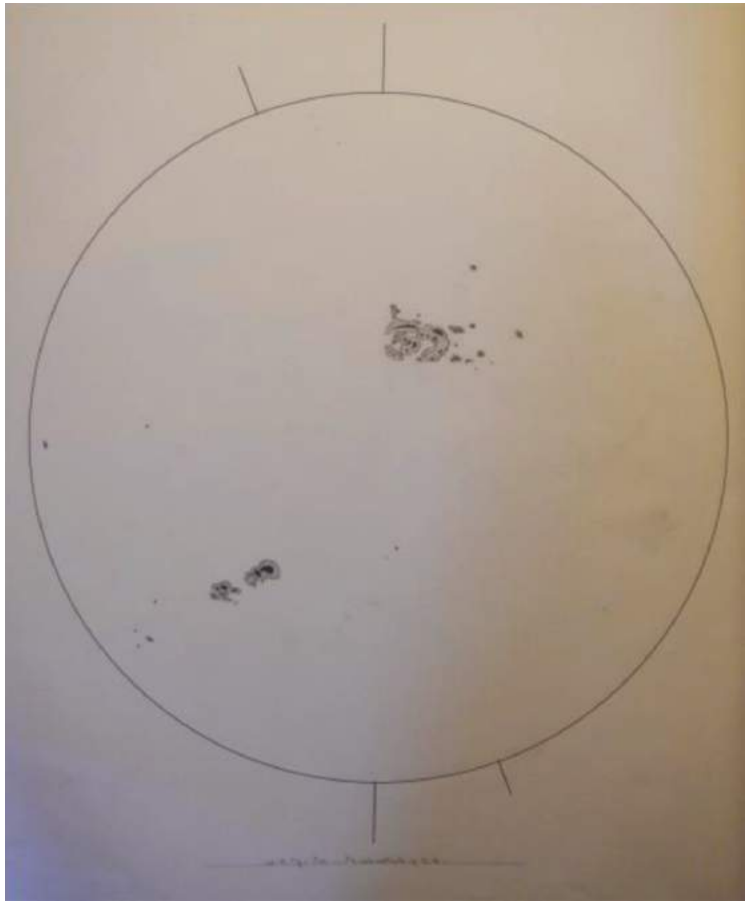
Knipp, D.J. *et al.* (2021) *Journal of Space Weather and Space Climate*, 11, p. 29. doi:10.1051/swsc/2021011.

The 1859 Carrington Event: 28 Aug – 2 Sep

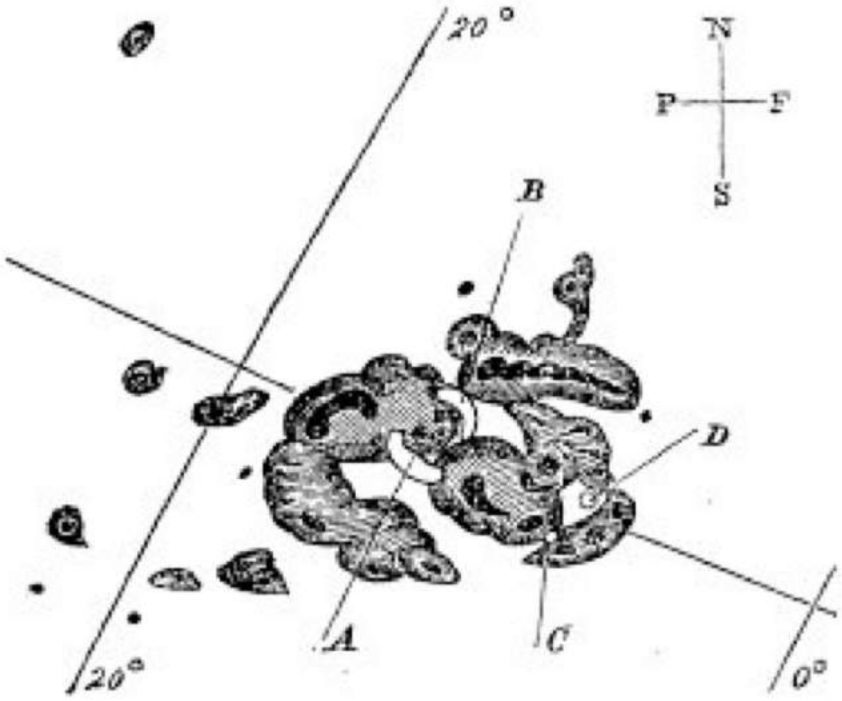
Dst min estimated from Colaba, India, magnetometer trace to be **-1600 nT**: all-time record in the magnetometer era.

Or was it? Other estimates are Dst min ~ -850 nT (see Baker et al., 2008 for references).

In any case, Classification = SuperStorm.



Obviously very complex magnetic topology



Flare class estimated at X5—X20

Hayakawa, H., Ebihara, Y., Hand, D. P., Hayakawa, S., Kumar, S., Mukherjee, S., and Veenadhari, B. "Low-Latitude Aurorae during the Extreme Space Weather Events in 1859." *The Astrophysical Journal*, Vol. 869, No. 1, 2018, p. 57. https://doi.org/10.3847/1538-4357/aae47c.

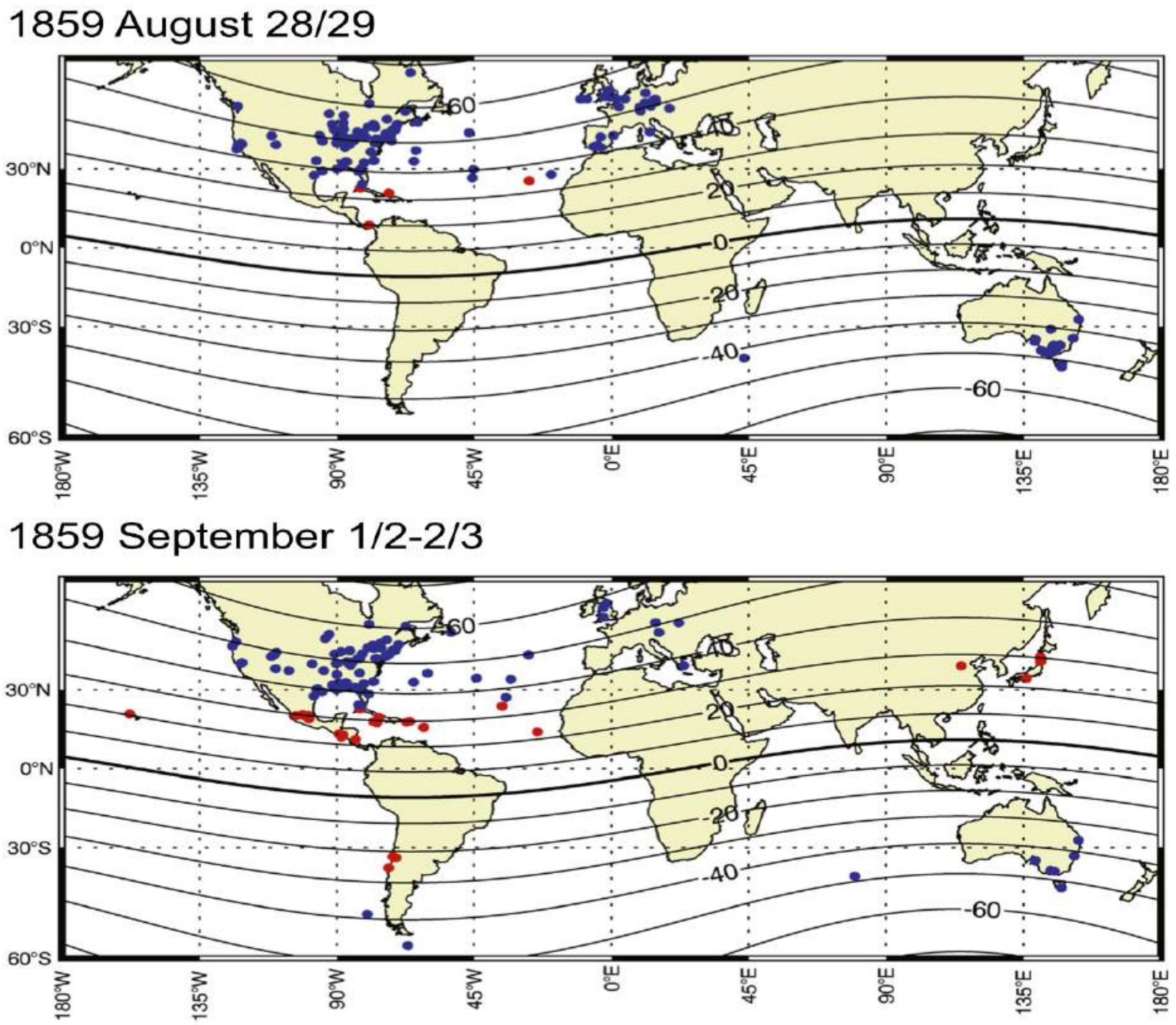
See also

Adv. Space Res., Vol. 38, 2006, for an entire issue devoted to the Carrington Event. https://doi.org/10.1016/j.asr.2005.02.100

The 1859 Carrington Event: 28 Aug – 2 Sep

Multiple CME impacts/geomagnetic storms, starting on 28 August.

Total duration = 7 days



Red aurora sightings down to MLAT 17—20°

Hayakawa, H., Ebihara, Y., Hand, D. P., Hayakawa, S., Kumar, S., Mukherjee, S., and Veenadhari, B. “Low-Latitude Aurorae during the Extreme Space Weather Events in 1859.” *The Astrophysical Journal*, Vol. 869, No. 1, 2018, p. 57. https://doi.org/10.3847/1538-4357/aae47c.

See also

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The 1859 Carrington Event: 28 Aug – 2 Sep

By far the largest nitrate signal in ice cores in the last 450 years.

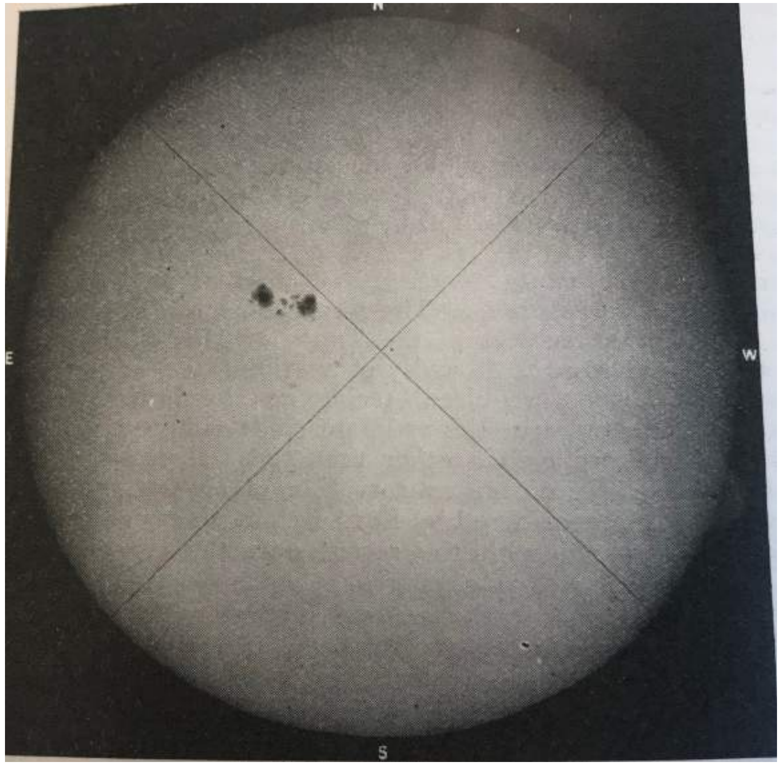
Table 2
Solar proton events between 1570 and 1950 as identified from impulsive nitrate enhancements in Polar ice

Solar cycle	Cycle start	Event date	Rank	>30 MeV fluence	G Mag storm	Mid-lat aurora	Sequence of activity
		1603.6	18	5.2×10^9		Kr	
		1605.7	8	7.1×10^9		Kr	
−11	1619.0	1619.6	5	8.0×10^9			
−10	1634.0	1637.7	12	6.1×10^9		Kr	P
−9	1645.0	1647.9	17	5.2×10^9			
−4	1698.0	1700.8	14	5.8×10^9			
−3	1712.0	1719.5	7	7.4×10^9		Kr	P
−2	1723.5	1727.9	11	6.3×10^9		Kr, Yau	P
1	1755.2	1756.0	16	5.4×10^9			
4	1784.7	1793.6	15	5.5×10^9		Kr	
6	1810.6	1813.2	10	6.4×10^9		Kr	
9	1843.5	1851.8	3	9.3×10^9	G, CM	Kr	P
10	1856.0	1859.8	1	18.8×10^9	G, CM	Kr	Yes
10	1856.0	1864.8	9	7.0×10^9	G	Kr	
11	1867.2	1878.6	19	5.0×10^9	G, CM	Kr	P
13	1889.6	1894.9	6	7.7×10^9	G, CM	Kr	Yes
13	1889.6	1895.7	2	11.1×10^9	G, CM	Kr	P
13	1889.6	1896.7	4	8.0×10^9	G, CM	Kr	Yes
18	1944.2	1946.5	13	6.0×10^9	G, CM	Sil	

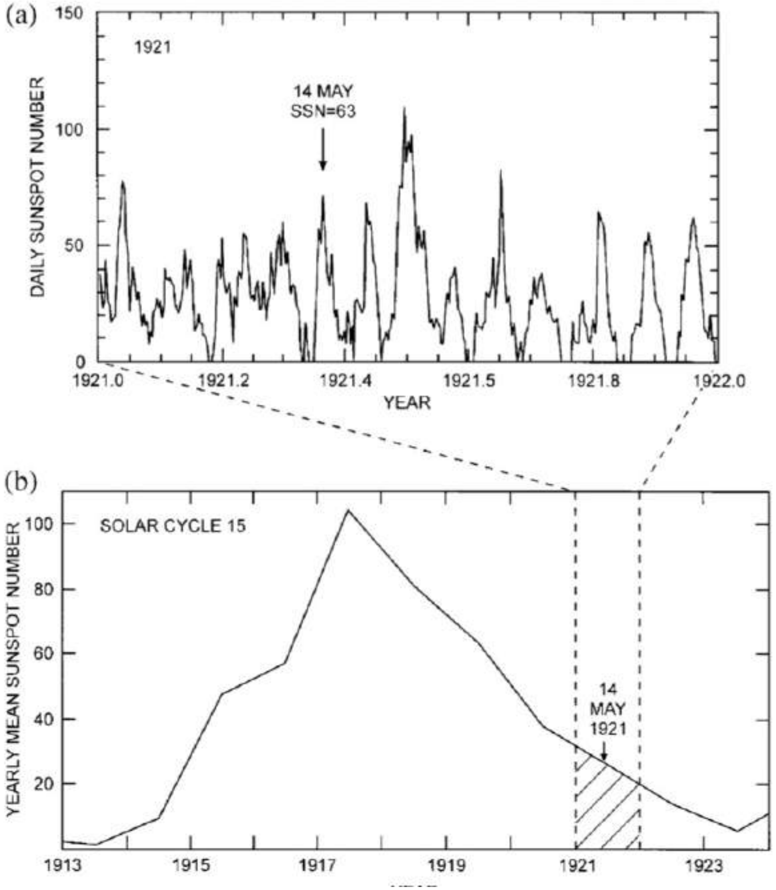
Shea, M. A., Smart, D. F., McCracken, K. G., Dreschhoff, G. A. M., and Spence, H. E. "Solar Proton Events for 450 Years: The Carrington Event in Perspective." *Advances in Space Research*, Vol. 38, No. 2, 2006, pp. 232–238. https://doi.org/10.1016/j.asr.2005.02.100.

The 1921 New York Railway Storm: 13—16 May

- Dst min estimated to be -907 nT
- Largest storm by far of last 150 years. May rival Carrington Event in geomagnetic severity.
- First major impact of space weather on transportation systems.
- Classification: SuperStorm



Surprisingly simple McIntosh Fhi AR produced at least 4 Earth-directed CMEs in 2 days

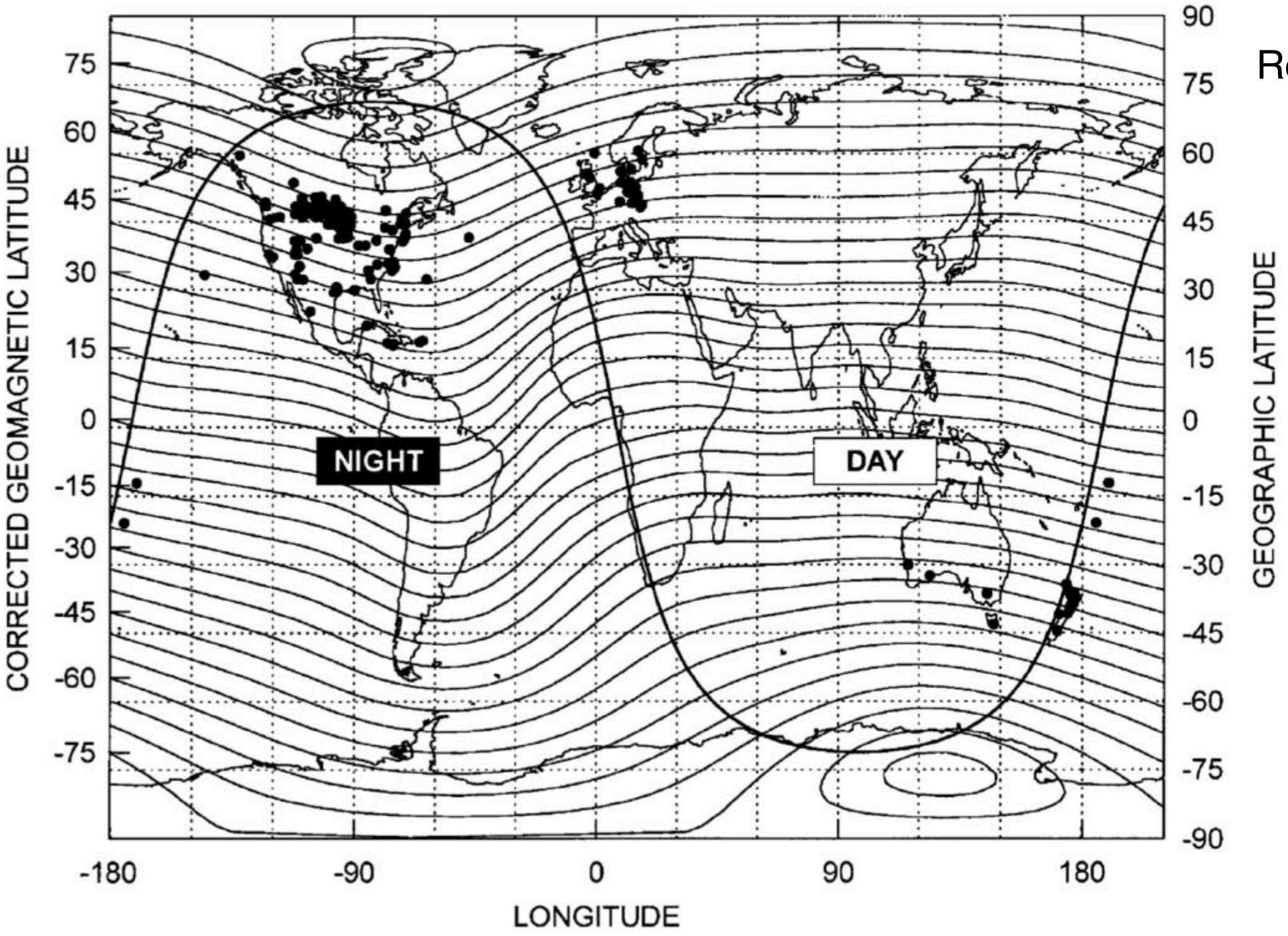


Like the Carrington Event, occurred during declining phase of solar cycle

Silverman, S. M., and Cliver, E. W. *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 63, No. 5, 2001, pp. 523–535. https://doi.org/10.1016/S1364-6826(00)00174-7.

The 1921 New York Railway Storm: 13—16 May

Aurora visibility equal to Carrington Event for southern MLAT extent.

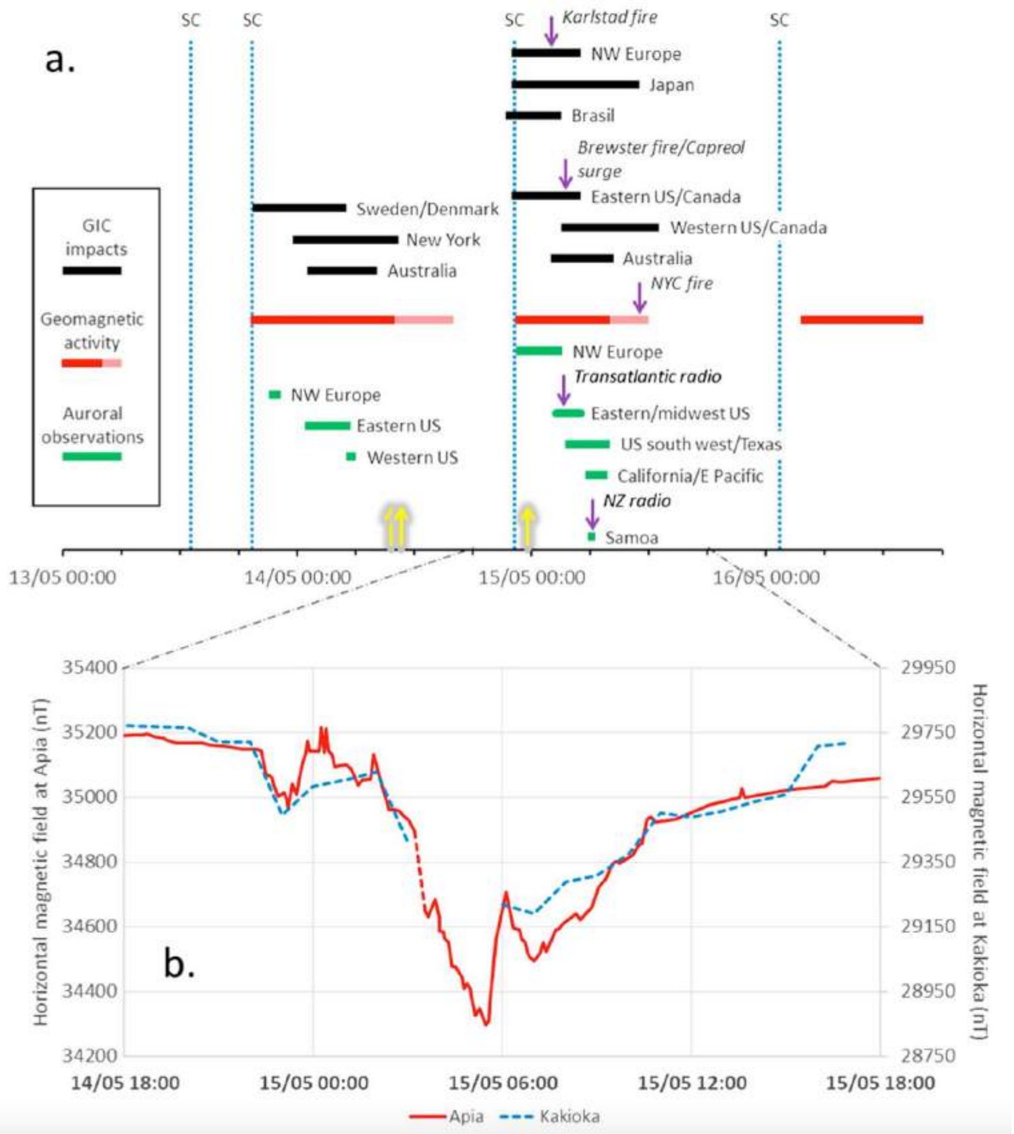


Red aurora sightings down to MLAT 16°

Silverman, S. M., and Cliver, E. W. *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 63, No. 5, 2001, pp. 523–535. https://doi.org/10.1016/S1364-6826(00)00174-7.

The 1921 New York Railway Storm: 13—16 May

- The storm drove strong “Earth currents” (GICs) around the world.
- In Karlstad, Sweden, a telephone exchange burned down. Estimated geoelectric induced field of **10 V/km! 10km line = 1,000 V!**
- In the US, a switchboard of the Central New England Railway in Brewster, New York, caught fire and burned the building down.



Hapgood, M. “The Great Storm of May 1921: An Exemplar of a Dangerous Space Weather Event.” *Space Weather*, 2019, p. 2019SW002195. https://doi.org/10.1029/2019SW002195.

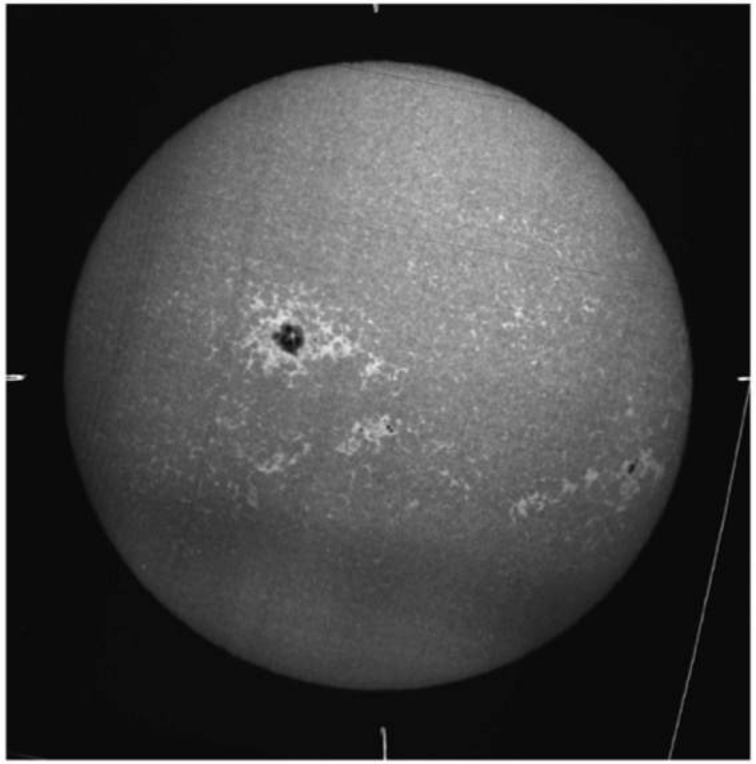
The 1972 Extreme SEP Event: 4—5 August

Solar flares from McMath region 11976 among strongest recorded to that date.

Associated CME arrival at Earth 14.6 hours after flare: 2850 km s^{-1}. Carrington Event: 17 hours arrival time.

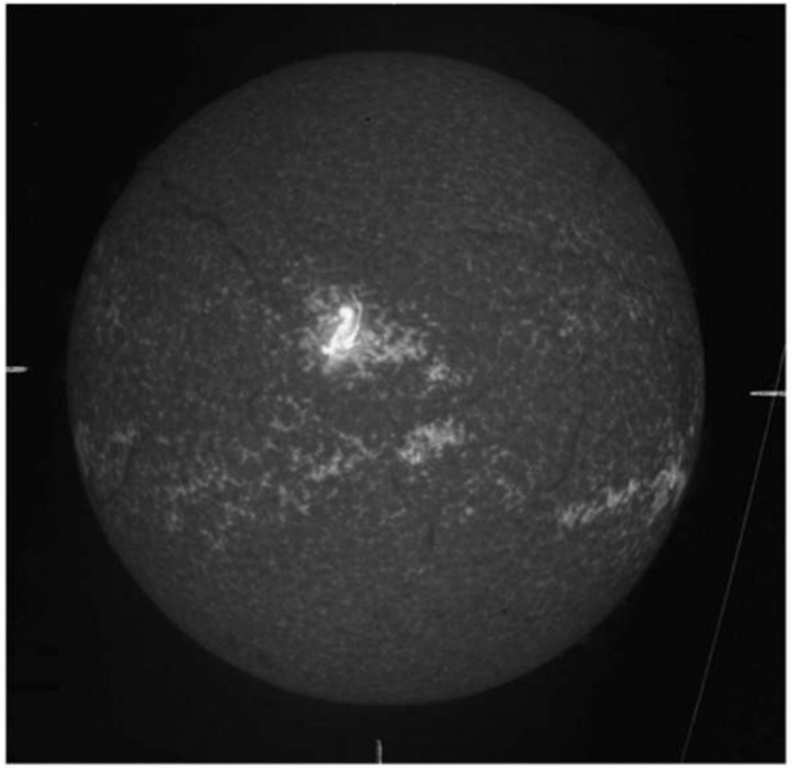
Dst min ~ -125 nT (estimated) – only a “Strong” geomagnetic storm associated with fastest CME on record. Why?

a) Calcium Emission, 3 August 1972



Ca K-line

b) Hydrogen-α Emission, 4 August 1972



Hα Line

Hα importance = 3B

Estimated GOES X20 flare

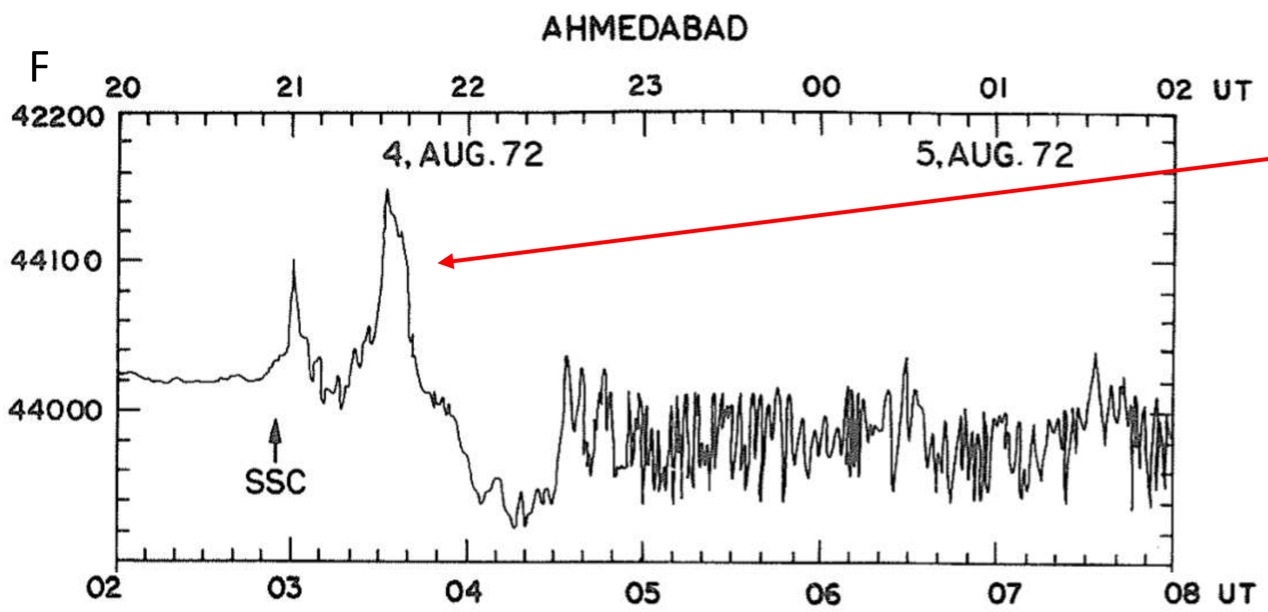
R5 on the SWPC scale

First detection of γ-rays from solar flare

Knipp, D.J. *et al.* (2018) *Space Weather*, 16(11), pp. 1635–1643. doi:10.1029/2018SW002024.

The 1972 Extreme SEP Event: 4—5 August

CME arrival on 4 August pushed plasmapause to 2 Re. Normal location is ~ 7 Re.



Very large and double-peaked “**Storm Sudden Commencement**” (SSC) signal indicates CME shockwave followed by sheath/filament plasma impact to magnetosphere.

Subsequent minor decrease in F with rapid recovery to slightly disturbed conditions indicates surprisingly mild geomagnetic storming following CME driver.

Tsurutani et al. 2003 cite 1992 study of Pioneer 10 data indicating that IMF Bz was *Northward* for entire CME passage.

The 1972 Extreme SEP Event: 4—5 August

Strong geomagnetic storm, but Radiation SuperStorm

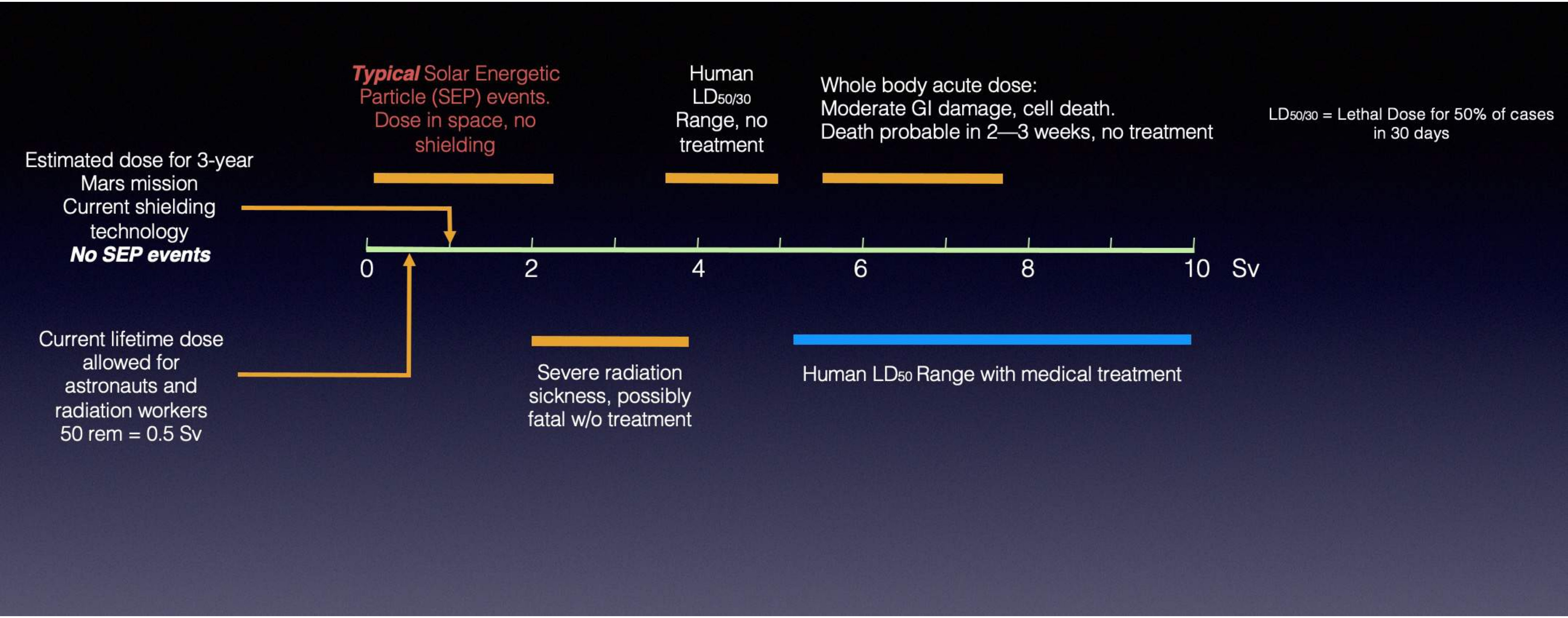
- Nitrate compounds in ice cores along with GOES proton measurements indicate > 30 MeV omni-directional proton fluence above 5×10^9 cm^{-2}.
- 12 Nov 1960 had fluence of 9×10^9 cm^{-2}.
- These two events are the largest SEP events in the space age.
- Estimated equivalent dose to Apollo astronauts outside magnetosphere or on the Moon at the time: **10 Sv** (Lockwood& Hapgood 2007)

M.A. Shea et al., “Solar proton events for 450 years: The Carrington event in perspective”, Advances in Space Research 38 (2006) 232–238

Lockwood, M. and Hapgood, M. (2007) *Astronomy & Geophysics*, 48(6), p. 6.11-6.17. doi:10.1111/j.1468-4004.2007.48611.x.

Interlude: radiation dose scales

SV = Sievert, SI unit of equivalent energy delivered by radiation in Joules/kg of body absorption



The 1972 Extreme SEP Event: 4—5 August

Recently declassified data from Viet Nam conflict: over two-dozen magnetically triggered sea mines in Haiphong Harbor simultaneously detonated due to the magnetic Sudden Impulse of the CME impact.

The mines were set to very low thresholds that were below the SI magnitude.

The 1972 Extreme SEP Event: 4—5 August

- Strength of CME "**Sudden Impulse**" (SI) caused very large GICs, even though the subsequent geomagnetic storm achieved only "Strong" levels that would not be expected to cause this level of current.

Louis (Lou) Lanzerotti

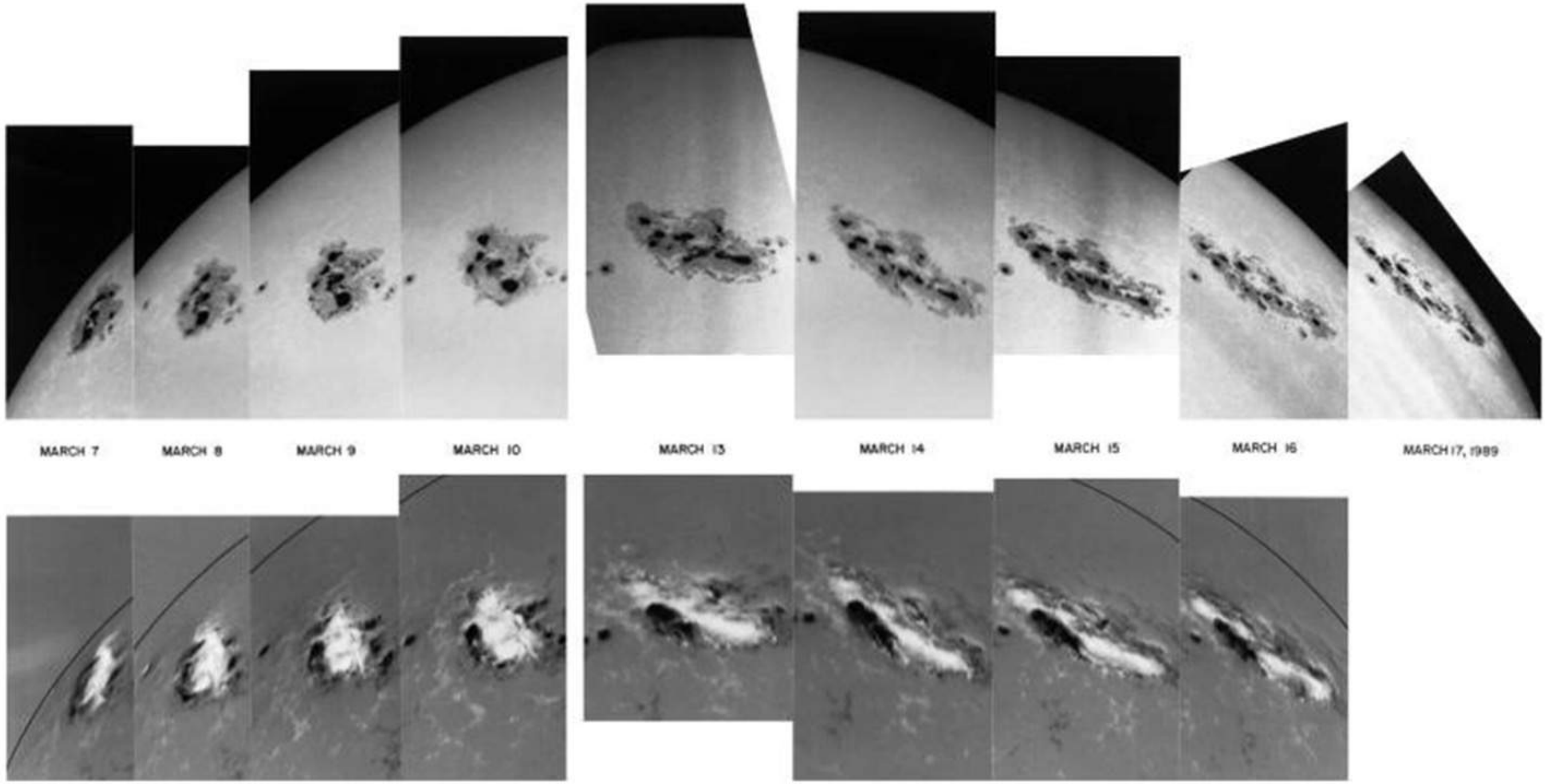
Final word on this storm: even though the geomagnetic storm was relatively minor for the CME ferocity, the SI caused very high GICs which triggered the outage of the AT&T L4 telephone cable between Illinois and Iowa. Geoelectric field estimated at **7 V/km**.

A young AT&T physicist named Louis (Lou) Lanzerotti investigated the failure. Lou had worked on the Telstar satellites and their vulnerability to orbital radiation, but this was his first assignment to investigate ground-based space weather impacts, before the term "space weather" was even in use.

Lou went on to be one of the founders of the fields of space weather research, founding editor of the Space Weather Journal, a Co-Investigator on NASA's Van Allen Probes mission, and remains active in the field today.

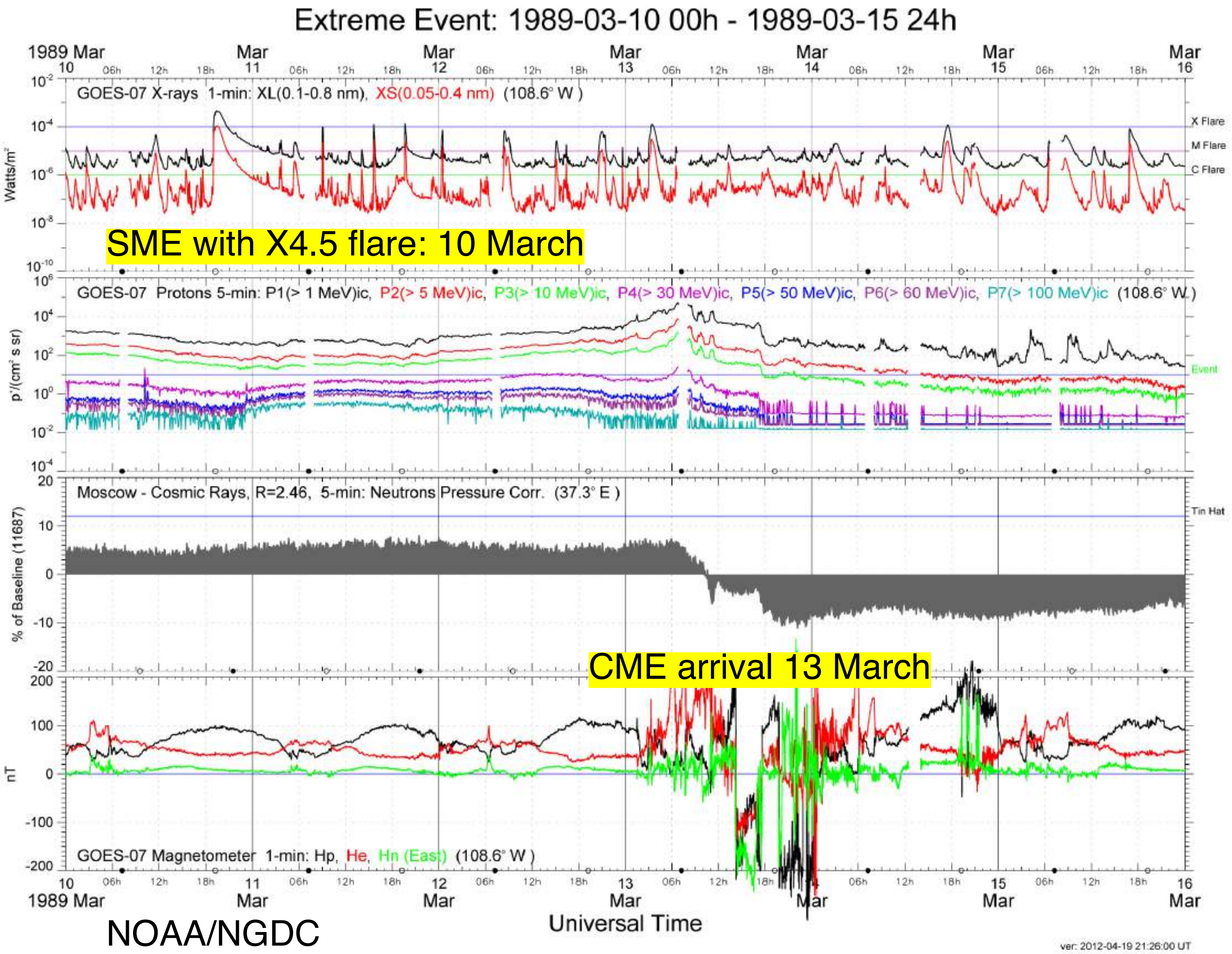
The 1989 Quebec Blackout Storm: 13—14 March

Largest storm in the modern space age.
First major power grid failure from space weather.



Boteler, D. H. “A 21st Century View of the March 1989 Magnetic Storm.” *Space Weather*, Vol. 17, No. 10, 2019, pp. 1427–1441. https://doi.org/10.1029/2019SW002278.

The 1989 Quebec Blackout Storm: 13—14



NOAA/NGDC

- Dst min estimated to be **-589 nT**
- First major power grid failure caused by space weather.
- First major impact on orbital space catalog from space weather.
- Classification: SuperStorm

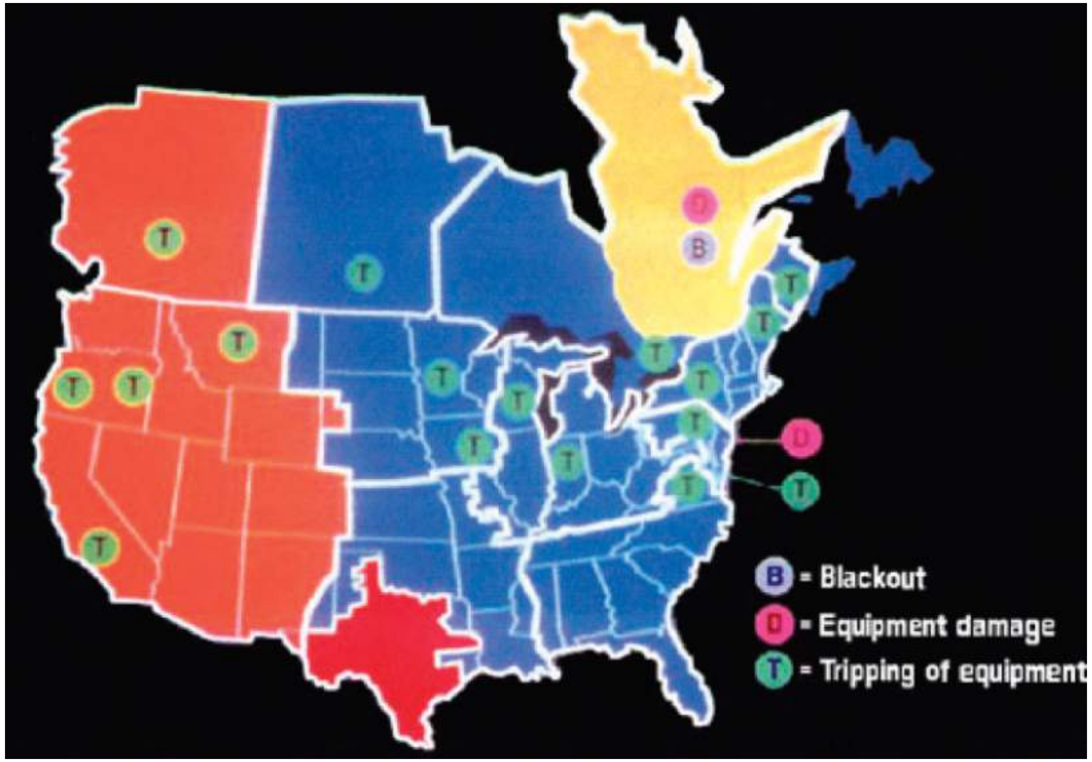
CME transit time = **54 hours**! Velocity ~ 770km/s

Evidence of second CME and pileup from M7.3 flare on 12 March (Boeteler, 2019).

Strong double-dip Forbush decrease.

The 1989 Quebec Blackout Storm: 13—14 March

GICs in Quebec province destabilized the power grid in 90 seconds leading to a 9-hour blackout.
6 Million people impacted.



GIC Impacts across N. America

Damage to EHV transformer in New Jersey, USA.

Kappenman, J., *Geomagnetic Storms and Their Impacts on the U.S. Power Grid*. Publication Meta-R-319. MetaTech, 2010.

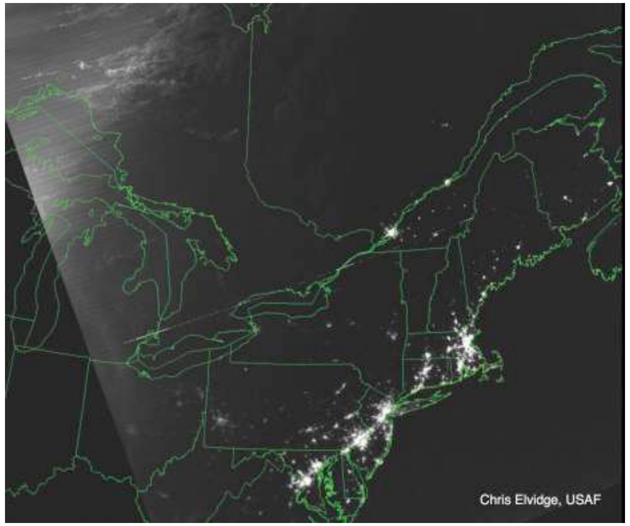
Impact of March 1989 Geomagnetic Storm

- Hydro-Québec La Grande power network destabilized by GICs at 0245 ET on 13 March
  - 9,500 MW of generation lost within seconds
  - 9-hour blackout of entire province, 6 million people impacted
  - Equipment damage prevented earlier re-start
  - Outside temperature at the time = -15°C (5°F)

- PJM transmission grid in NE US narrowly escaped collapse
  - EHV transformer destroyed by DC overheating in New Jersey

- Epidemiological study of 2003 NYC blackout: for every 24 hours the power is out in a metropolitan area ~100 people die.
  - Main causes: falls, traffic accidents, home medical equipment failure.

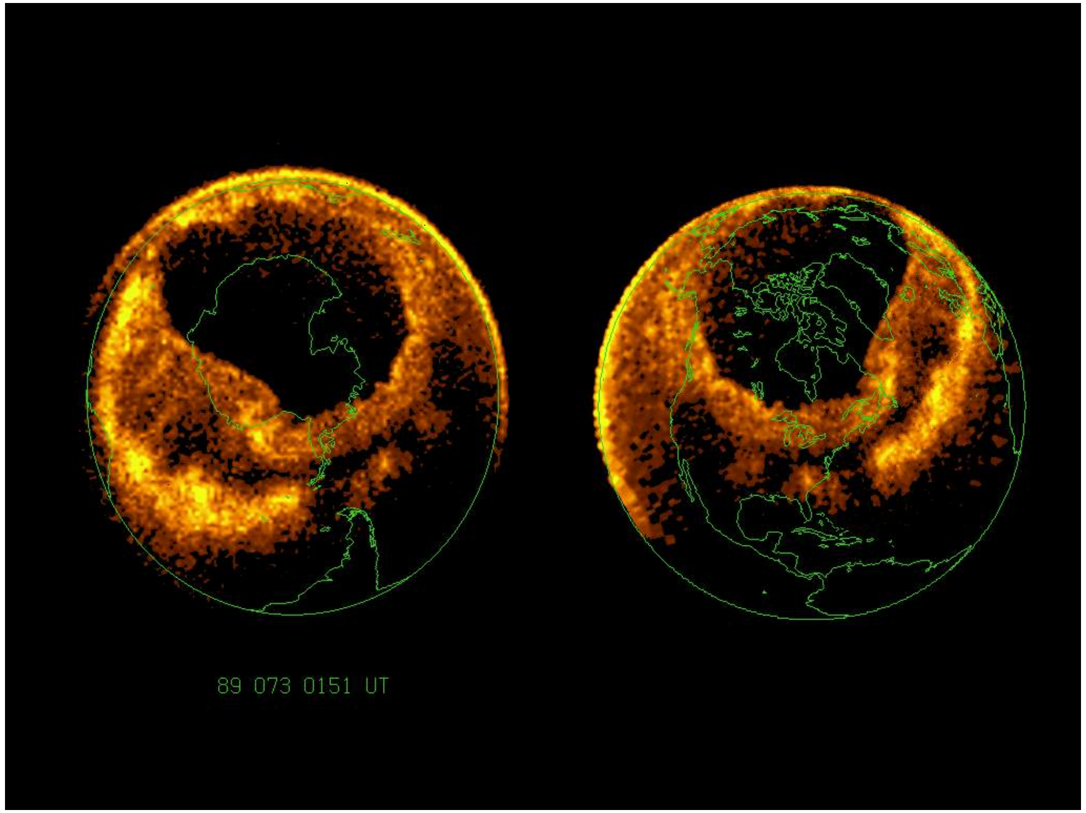
- Orbital impacts: ~2500 objects lost from LEO catalog due to satellite drag trajectory changes (Burke, 2018).



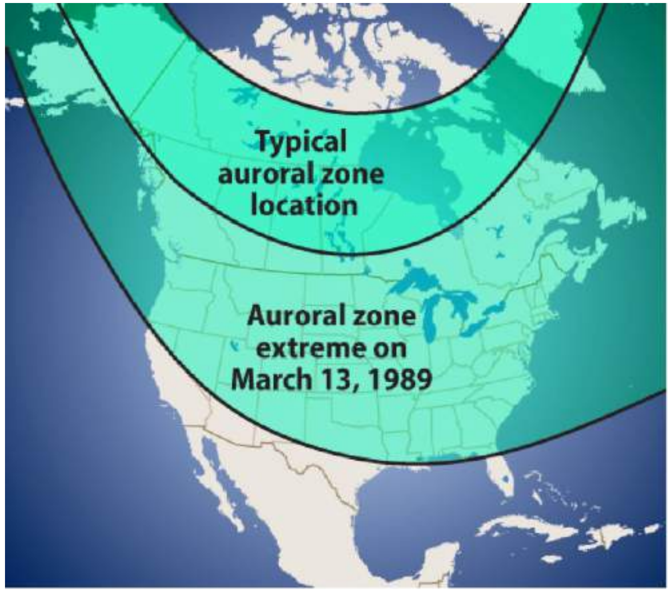
DMSP satellite image

The 1989 Quebec Blackout Storm: 13—14 March

Aurora visible down to S. Texas and Florida in the US. MLAT southerly extent ~29°.



NASA Dynamics Explorer
FUV Aurora over Southern (left) and Northern (right) hemispheres



Aurora over London
Mike Hapgood

The 2003 Halloween Storms

Dst min = **-421 nT** Classification = Extreme
Most recent space weather event to have major impacts to technological systems (18 years ago).
Best studied extreme geomagnetic storm in history.

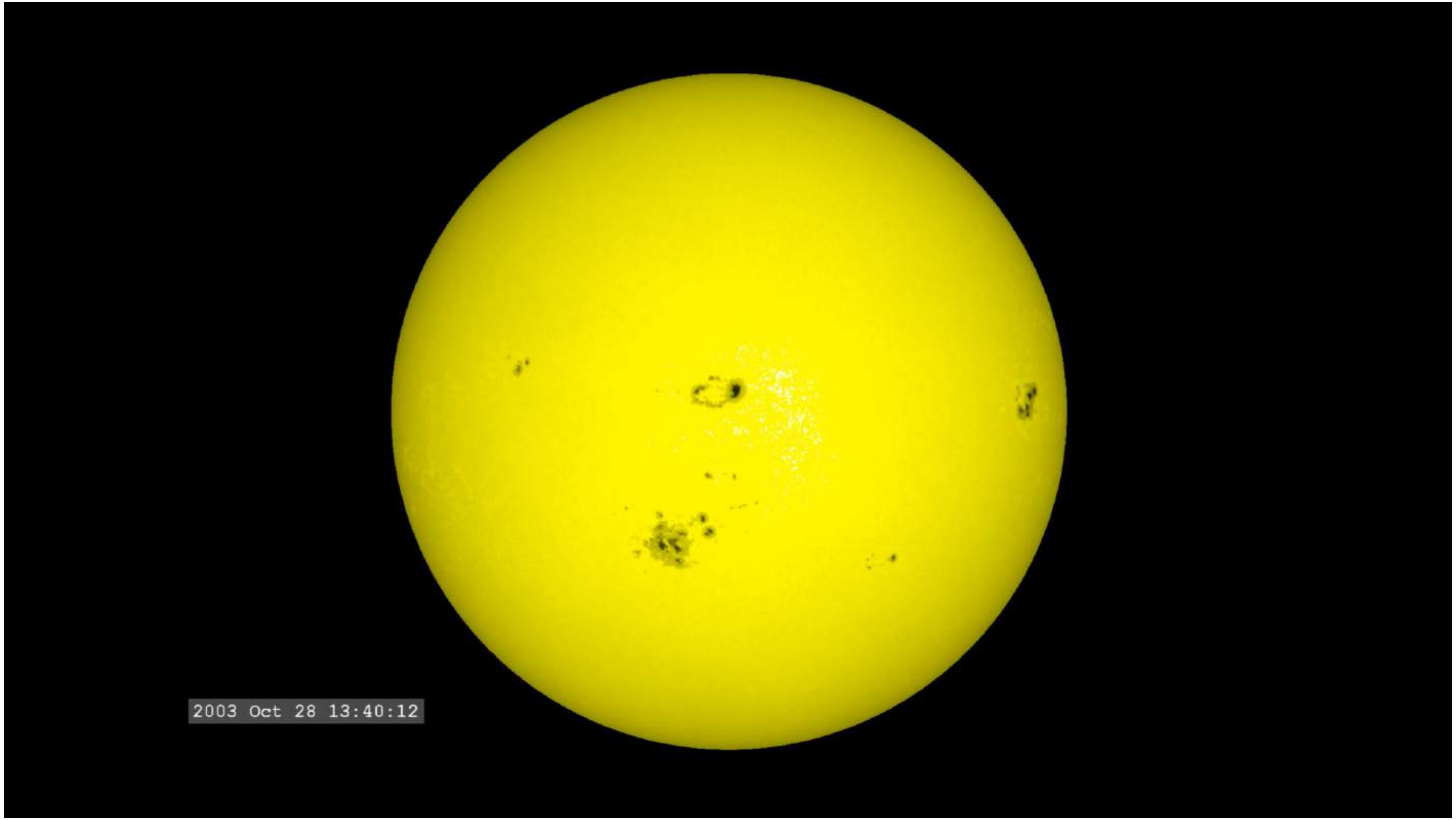
N. Texas, USA: MLAT ~33° N

Athens, Greece: MLAT ~36°N

Red aurora visible in North Texas (left) and Athens, Greece (right) indicate major plasmasphere compression consistent with superstorms of the past, but Dst min > -500 nT.

The 2003 Halloween Storms

Solar AR progenitor (NOAA 10486) was among the most complex ARs seen on the Sun in the last 2 Solar Cycles. Fkc McIntosh classification. 2120 mhs.

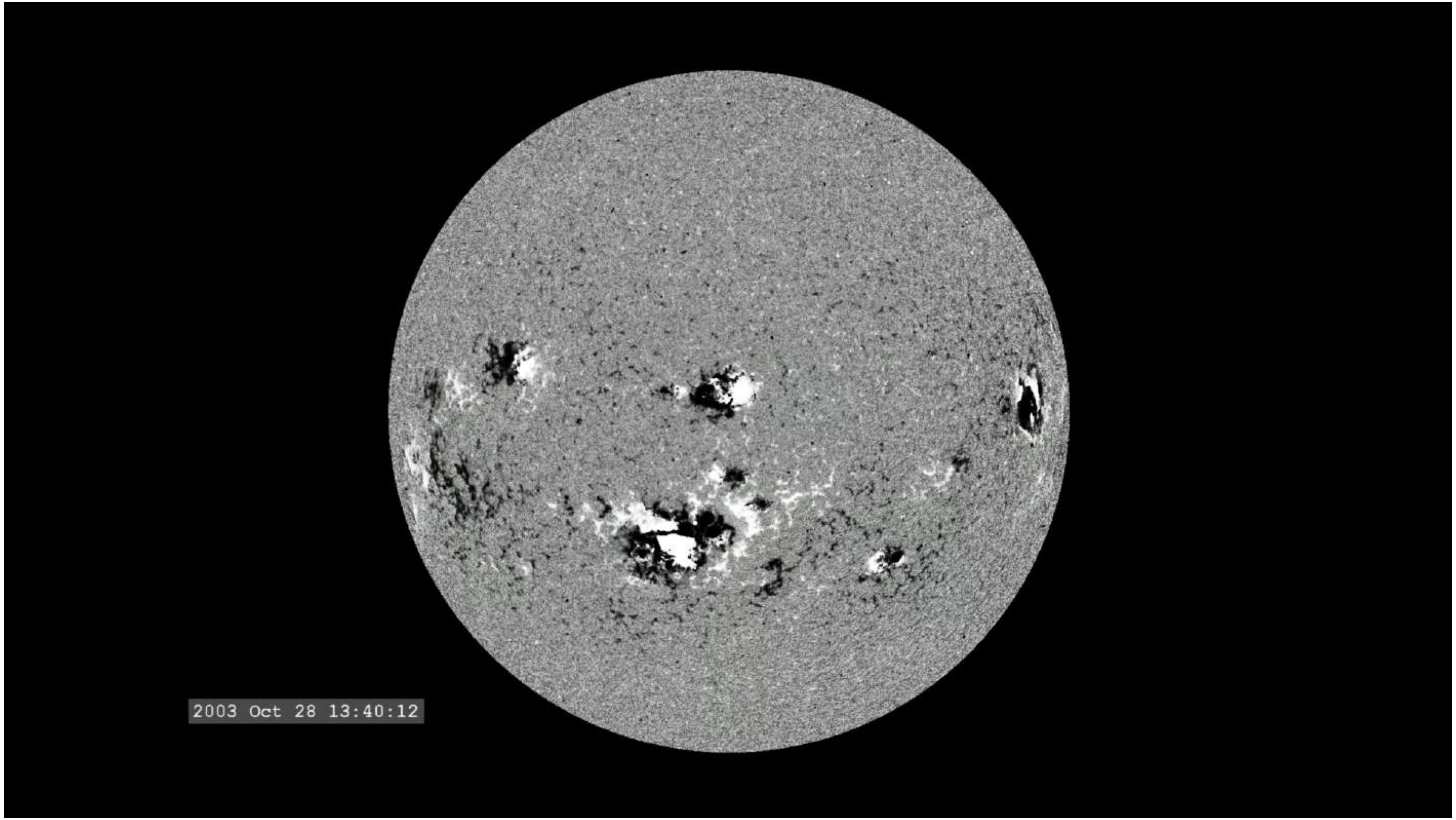


ESA/NASA SOHO Michelson Doppler Imager (MDI)

Continuum Channel

The 2003 Halloween Storms

Solar AR progenitor (NOAA 10486) was among the most complex ARs seen on the Sun in the last 2 Solar Cycles. $\beta\gamma\delta$ Mt. Wilson classification.

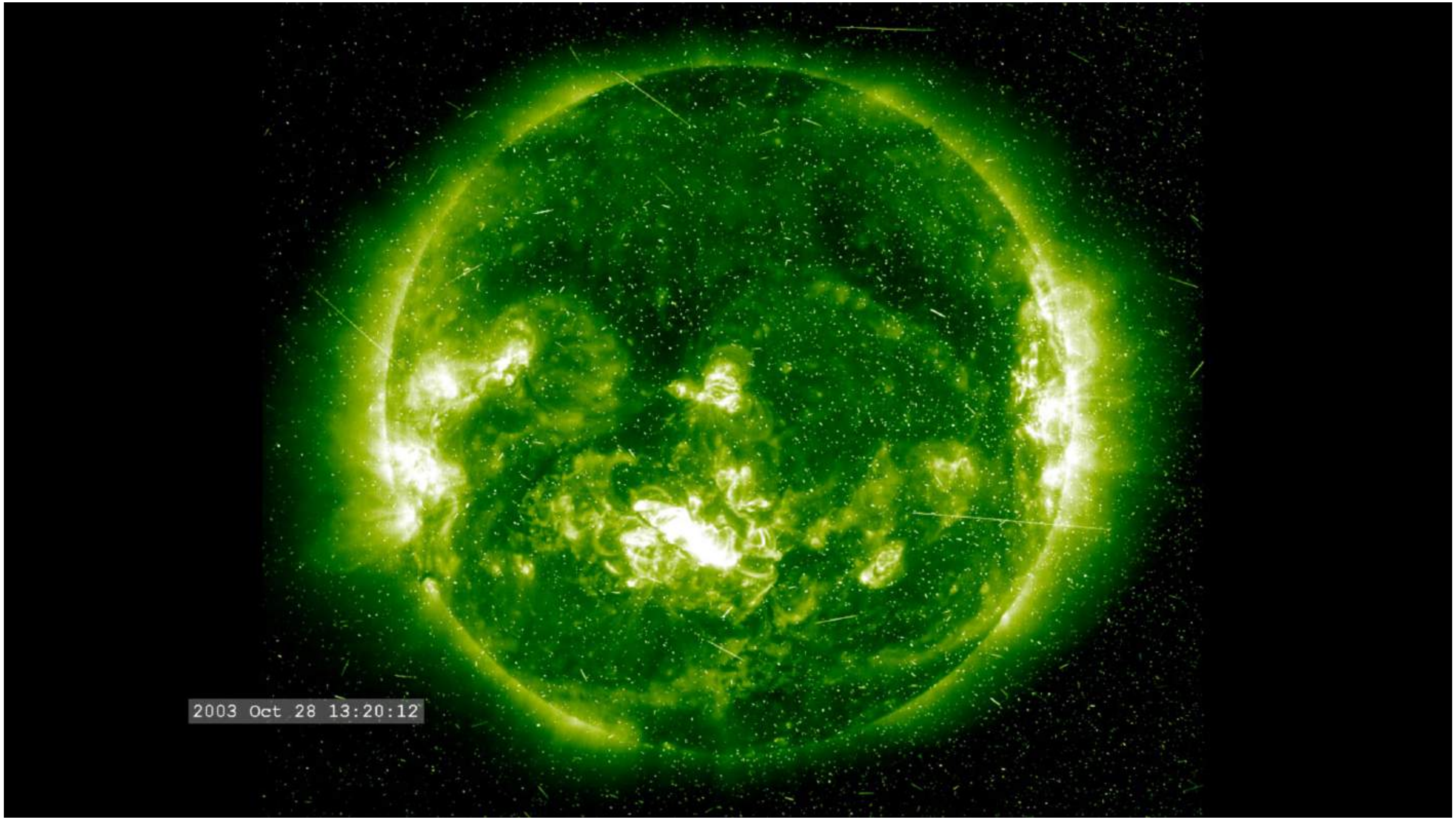


ESA/NASA SOHO Michelson Doppler Imager (MDI)

Magnetogram Channel

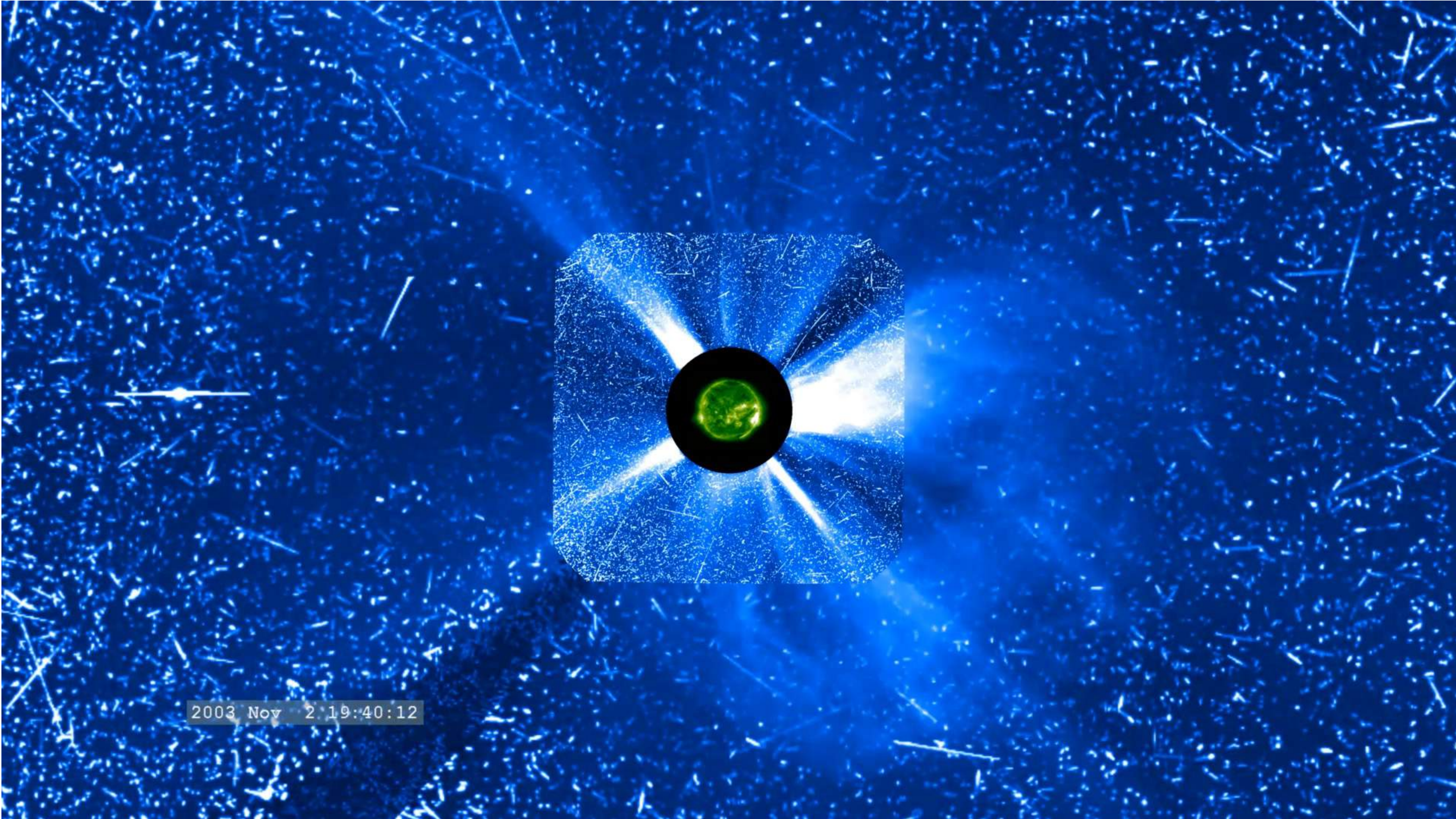
The 2003 Halloween Storms

Solar AR progenitor (NOAA 10486) was among the most complex ARs seen on the Sun in the last 2 Solar Cycles. $\beta\gamma\delta$ Mt. Wilson classification.



ESA/NASA SOHO Extreme ultraviolet Imaging Telescope (EIT)

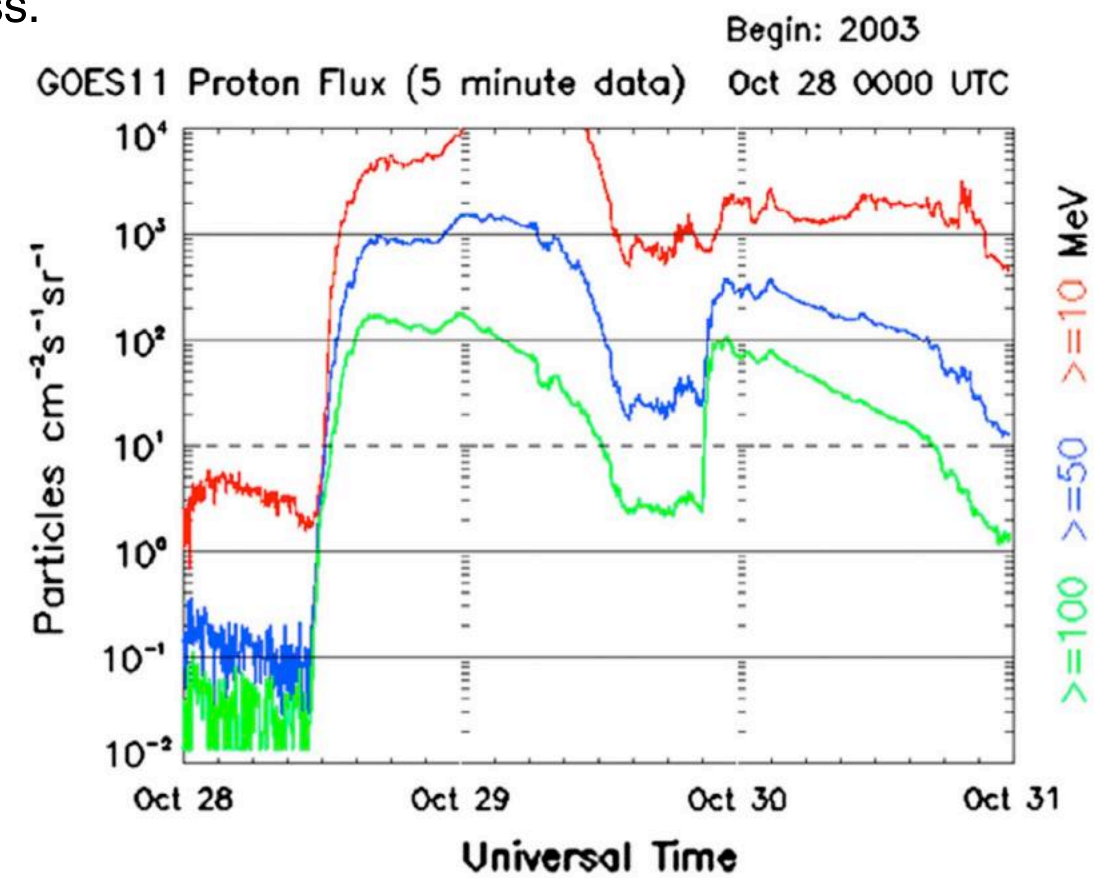
195 Å Coronal Channel


2003 Nov 2 19:40:12

The 2003 Halloween Storms

GOES proton flux at S4 levels for 12 hours on 29-Oct-2003.

Above S3 levels for 3 days. EVAs in LEO would be hazardous. Unsheltered activity on Moon would cause radiation sickness.



NOAA S-scale: >10MeV protons

S4

S3

S2

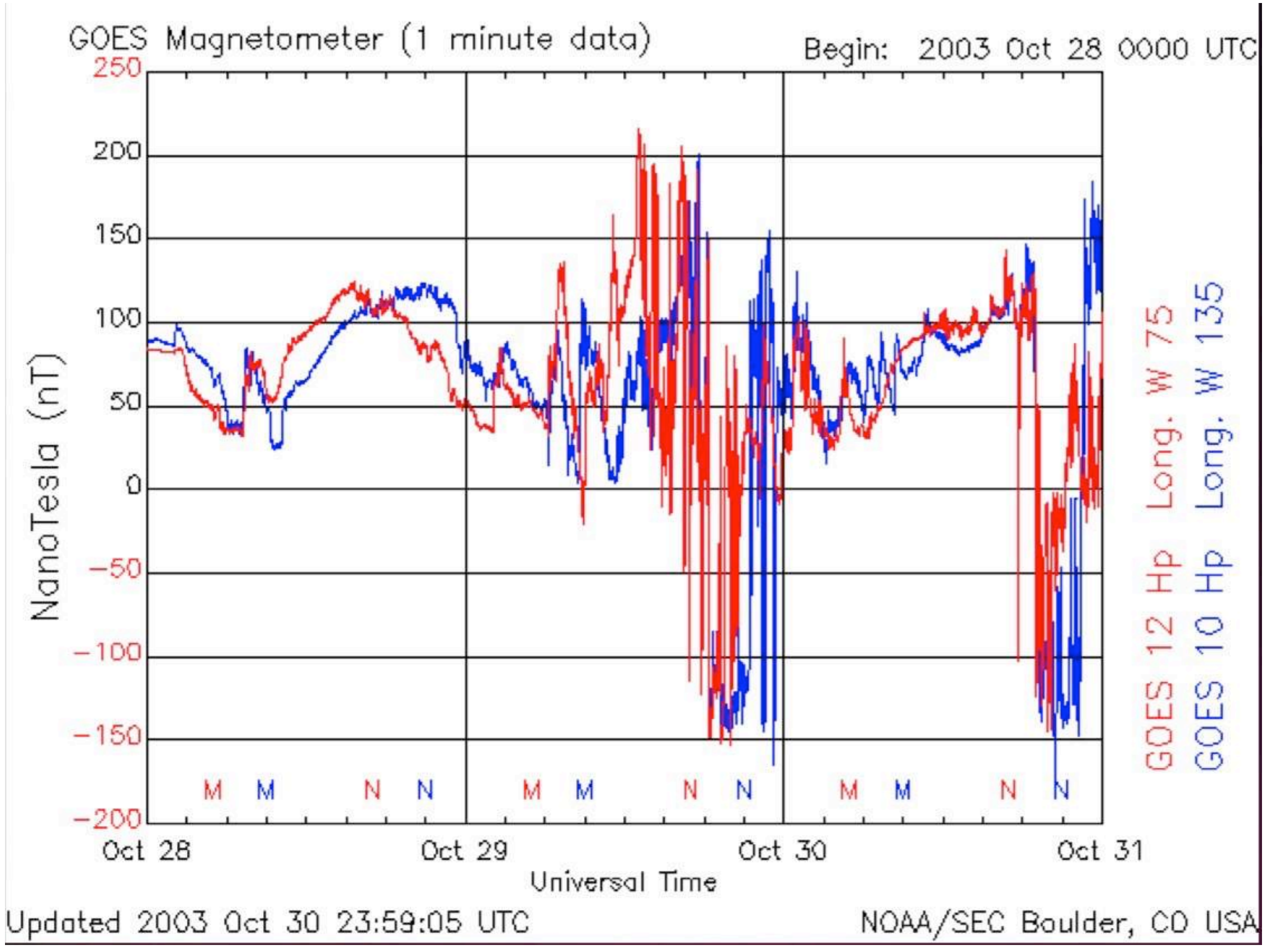
S1

- No astronauts in deep space in 2003.
- Astronauts left the ISS on 28 Oct!

Expedition 7		*Yuri Malenchenko* Ed Lu	26 April 2003 03:53 UTC	Soyuz TMA-2	28 October 2003 02:40 UTC	Soyuz TMA-2	184.93

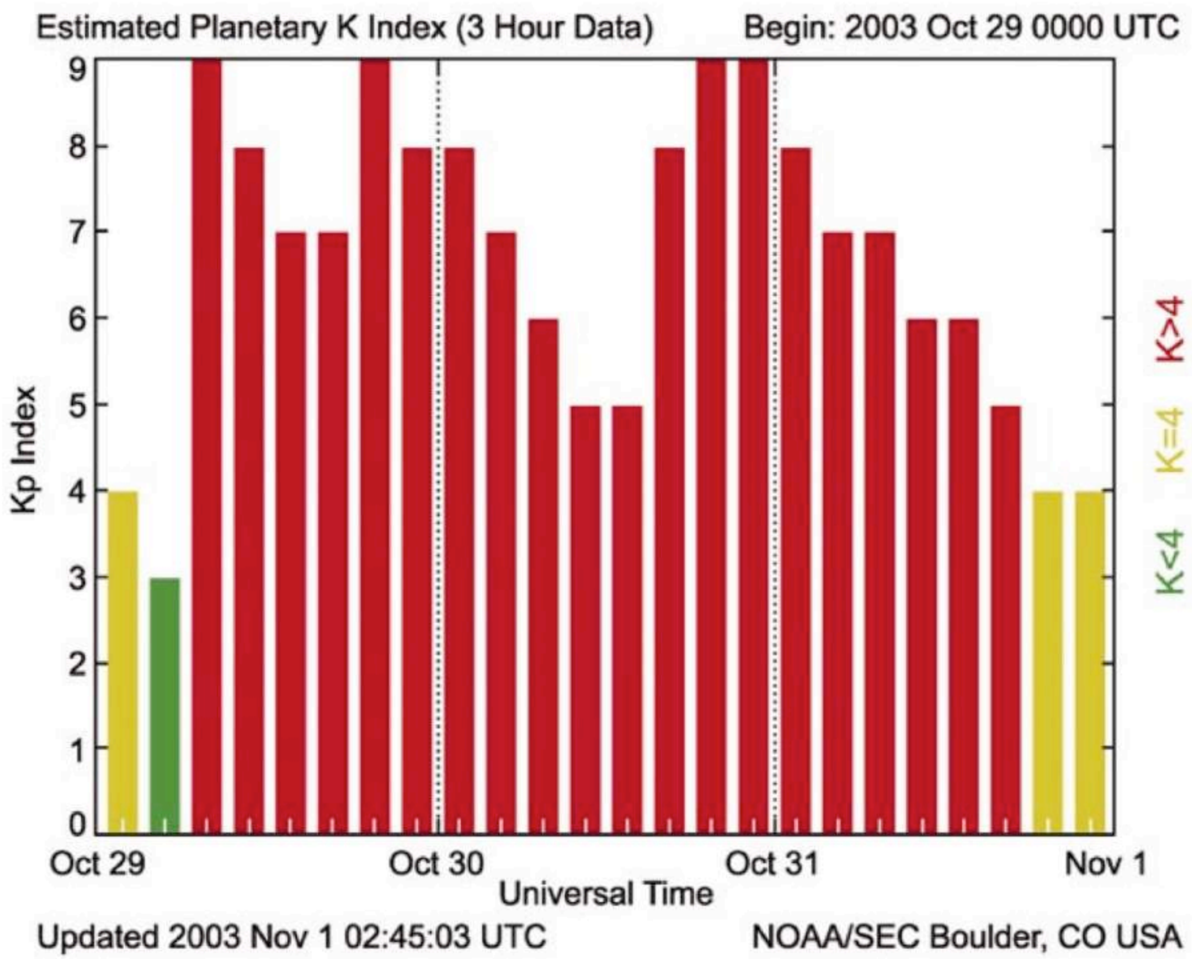
The 2003 Halloween Storms

- GOES magnetometer shows sustained Bz South for 9 hours on 29 Oct 2003. Peak levels < -150 nT.



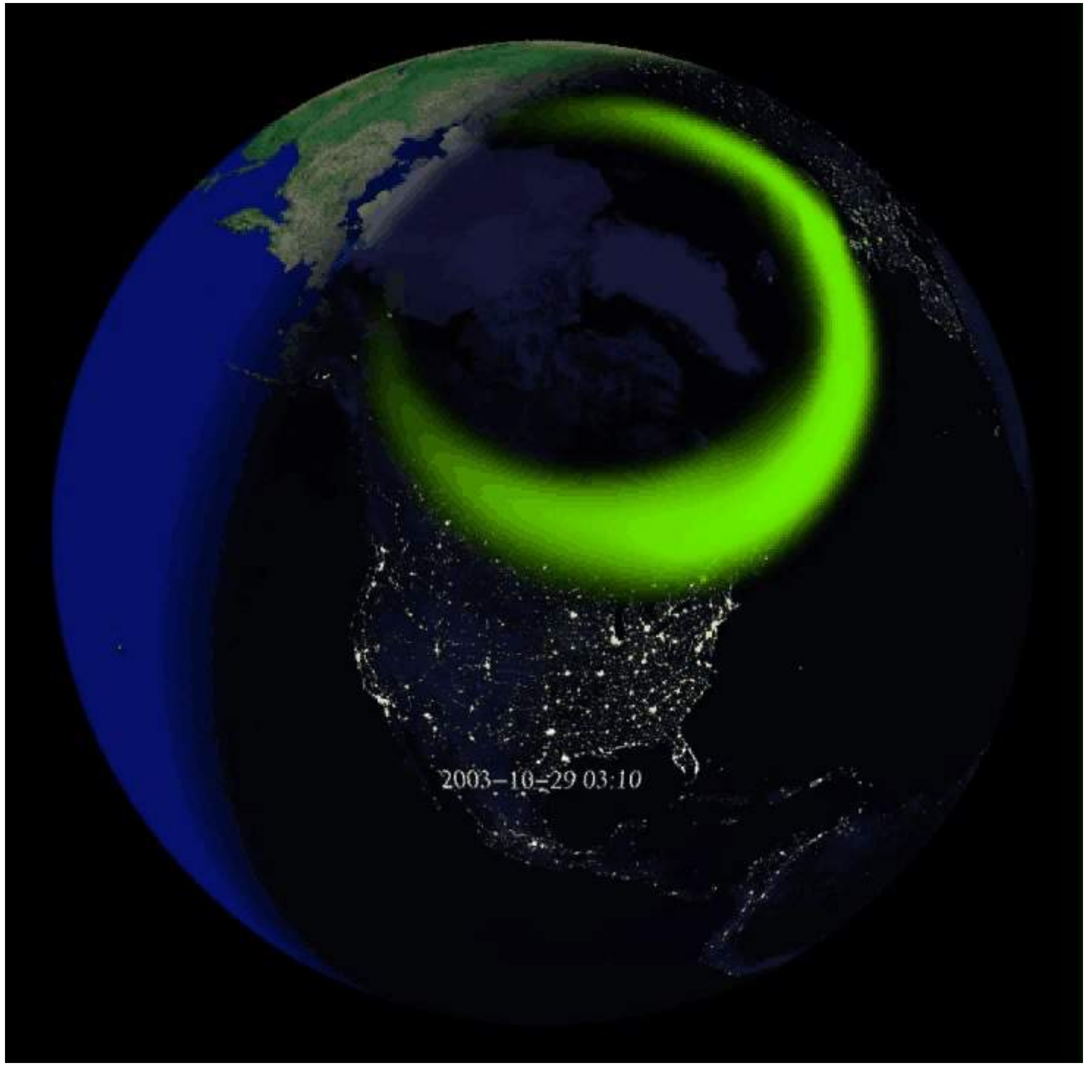
The 2003 Halloween Storms

- Geomagnetic storm at Extreme levels for 2 days and Severe levels for 3 days.



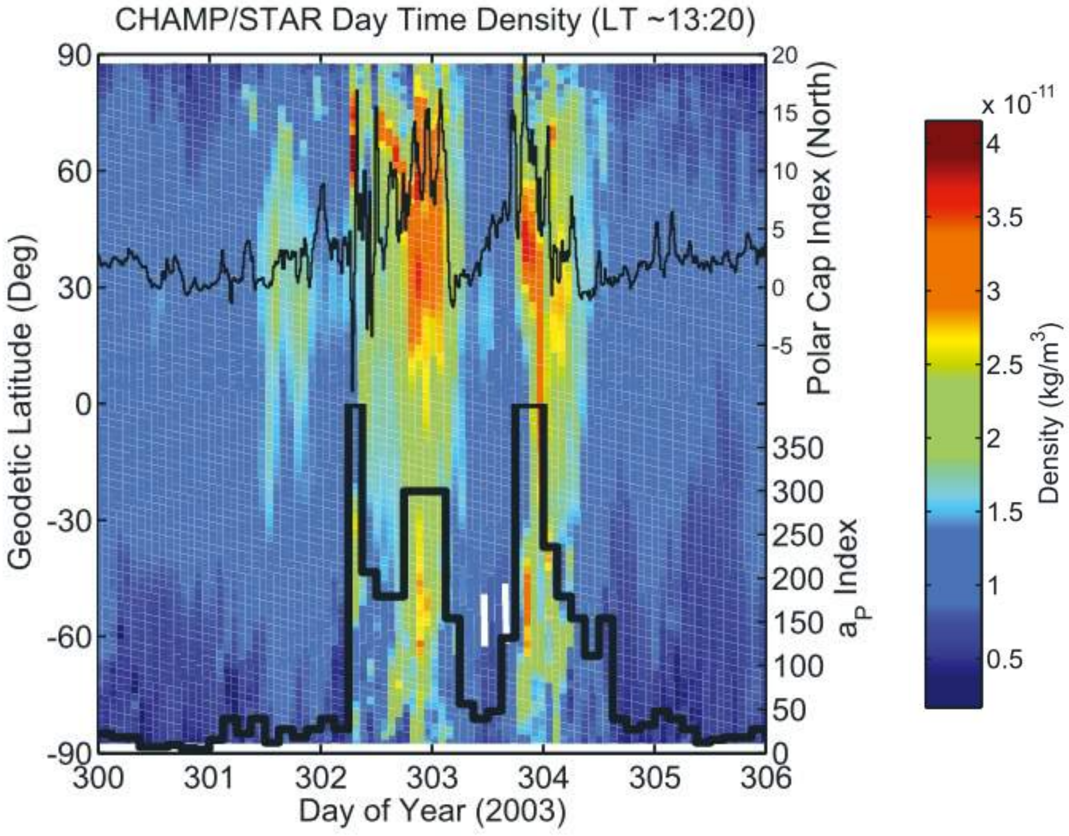
The 2003 Halloween Storms

- Aurora visible to ~33° Magnetic Latitude (MLAT)

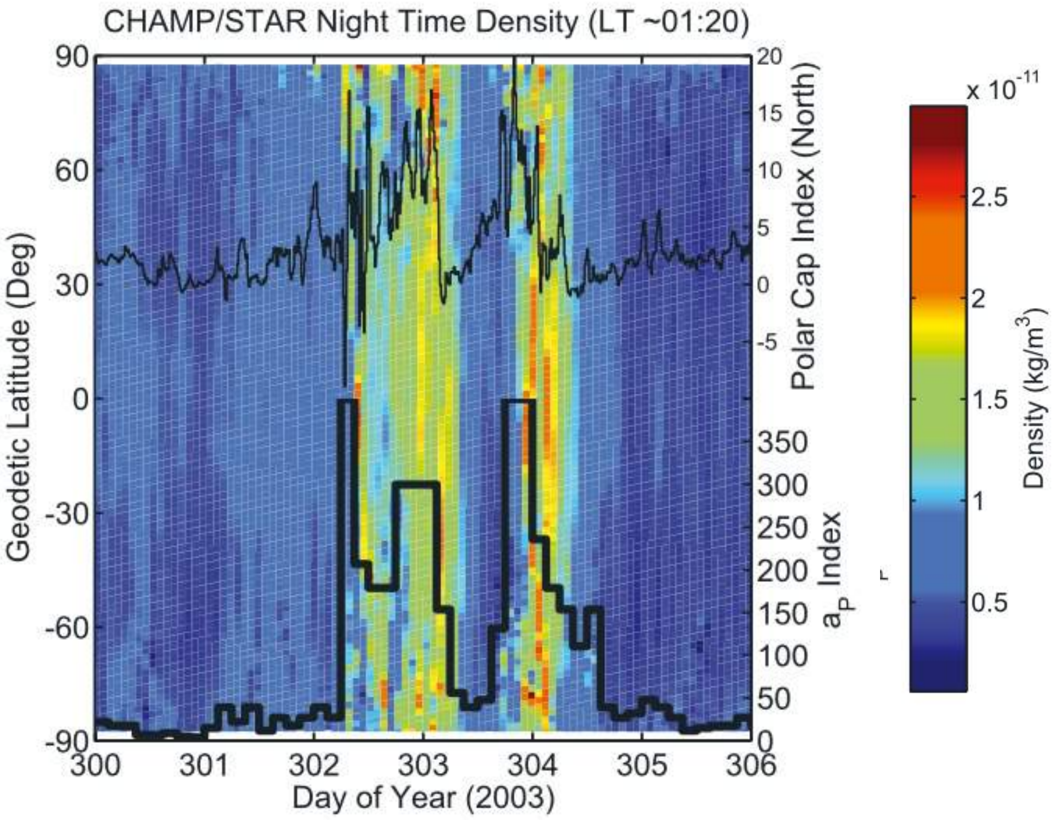


The 2003 Halloween Storms

- Rapid thermospheric density changes up to factor of 8 on day side at 410 km.
- CHAMP satellite accelerometer measurements.



Day side Density

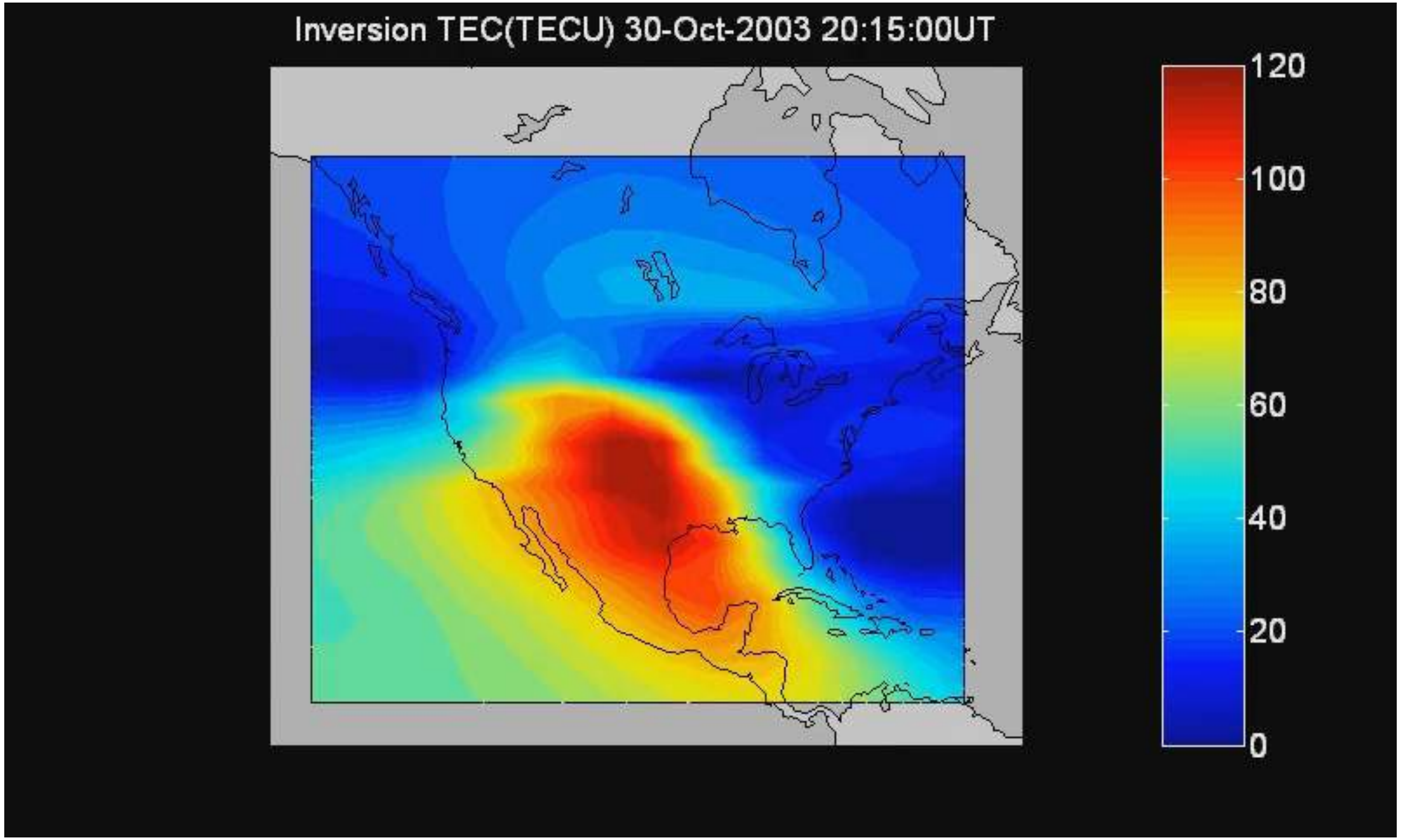


Night side Density

Sutton et al., 2005

The 2003 Halloween Storms

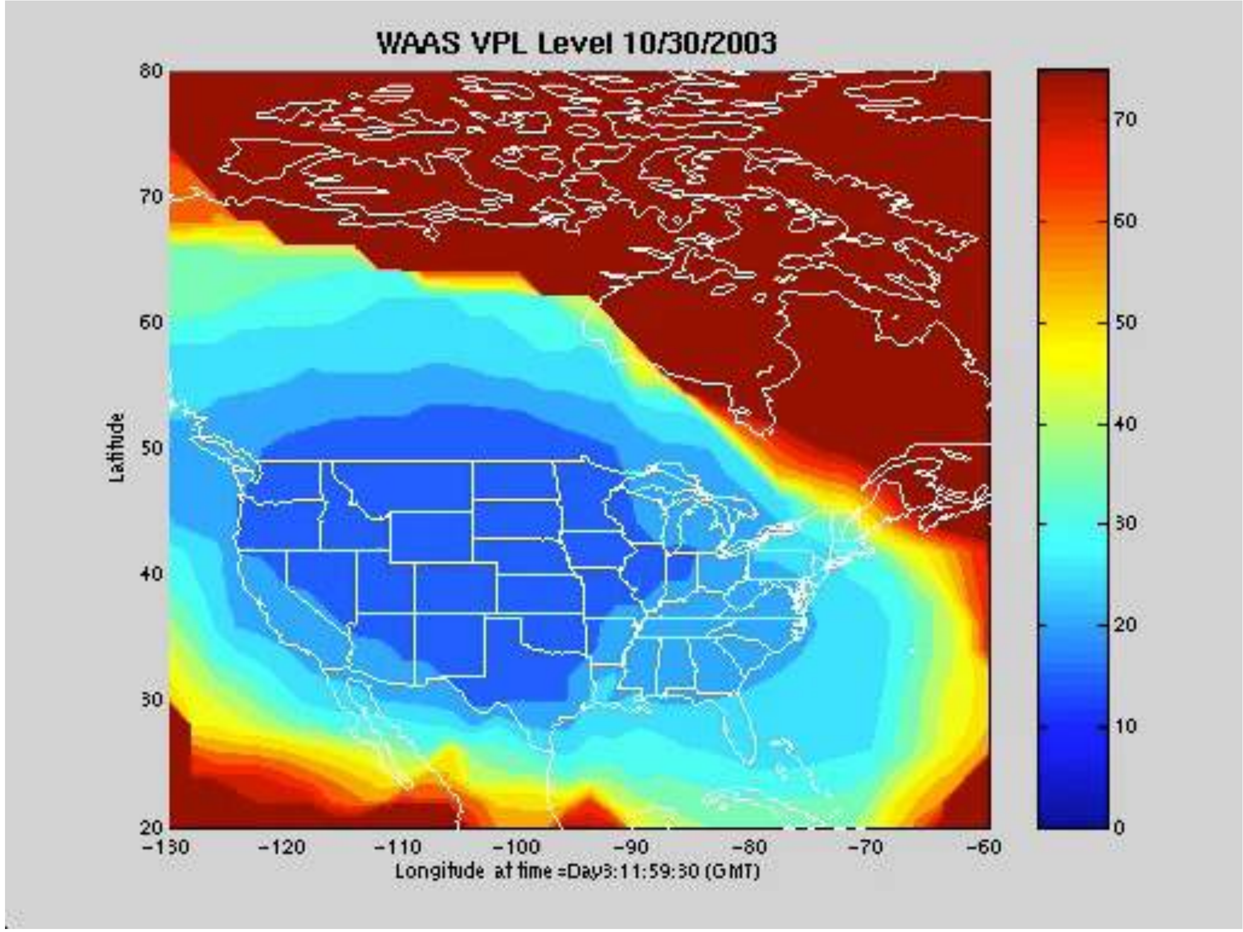
Ionospheric TEC disturbance among the largest ever measured over mid-latitudes.
Plasma gradient effects may have extended to LEO altitudes: GPS reception by satellites compromised.



2003 Halloween Storms: GPS impacts

The FAA's Wide Area Augmentation System (WAAS) for precision GPS landing of aircraft L1-band (1575 MHz) correction signals to aircraft from satellites in GEO.

VPL = Vertical Protection Level, m. The lowest altitude that the system will safely guide a plane to.



30-October-2003:

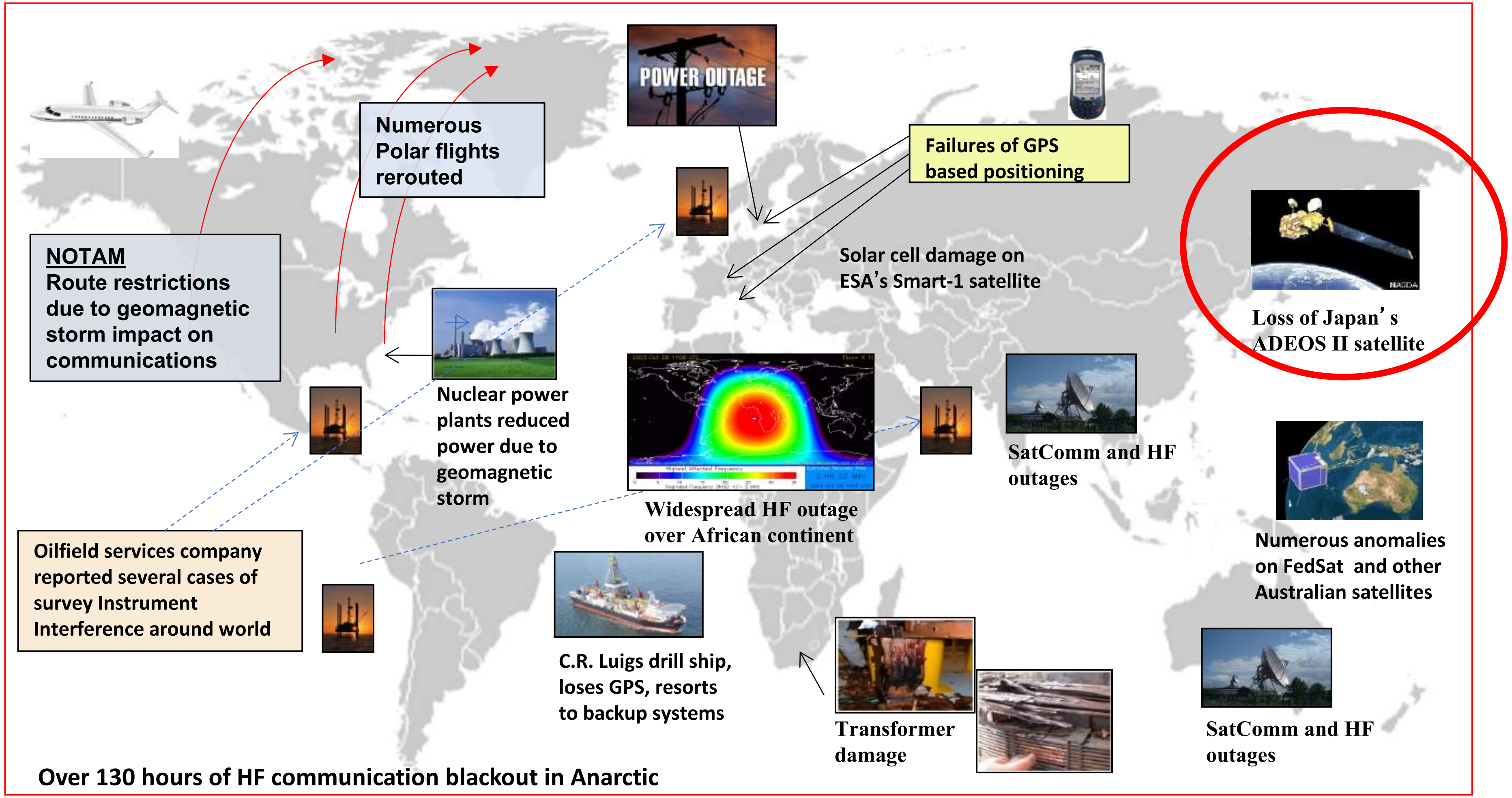
- M1.5 flare at 15:15 UT
- **X10** flare at 20:37 UT

This followed several days of eruptions and geomagnetic storming due to NOAA AR 10486 – thus the polar region problems right from the start.

Note: **this is not L-band radio burst noise from the flares** – it is degradation of the signals to/from the WAAS relay satellites in GEO due to ionospheric TEC disturbances traveling from polar regions.

The 2003 Halloween Storms: Technological Impacts

2003 Halloween storms had the most documented impacts of any modern event.



Other reports:

- Entire LEO orbital catalog was invalidated. 72 hours of emergency ops at JSpOC to find active satellites.
- Magnetopause pushed inside of GEO orbit. All GEO satellites exposed to direct solar wind proton and SEP flux.
- WAAS system above 70m limit for over 8 hours on 30-Oct-2003.

Reading for Lecture 4

Crown, M.D. (2012) ‘Validation of the NOAA Space Weather Prediction Center’s solar flare forecasting look-up table and forecaster-issued probabilities: VALIDATION OF SWPC FLARE PROBABILITIES’, *Space Weather*, 10(6)

doi:10.1029/2011SW000760.