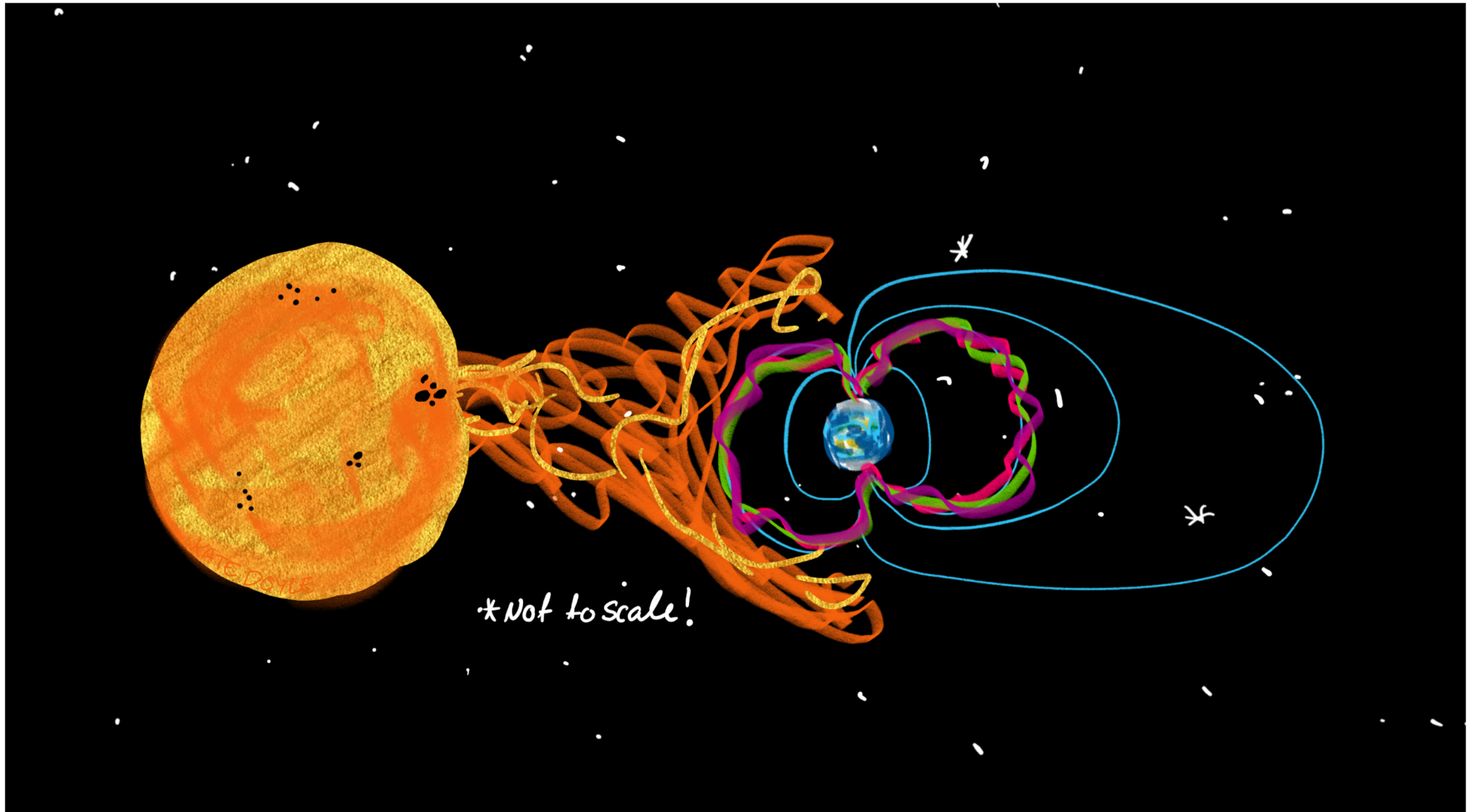
Great Storms Over the Centuries

Delores Knipp Smead Aerospace Engineering Sciences

HSS2020

Contributions by a Village of Space Weather Experts and Enthusiasts



Courtesy Australian Broadcast Corporation, Used with Permission

Outline and Themes

- **Great Storms and Space Weather**
- **Pre-Modern 'Space Weather' -- Auroral Storms**
- **Industrial Age 'Space Weather'**
- **Space Age Space Weather**
- **Throughout Storm Effects Not Previously Discussed**

- **Themes**
  - **We Live in the Atmosphere of a Magnetically Active Star**
  - **Societal Impacts of SWx are Linked to Engineered Systems**
  - **Space Weather Effects are Time Frame Dependent**
  - **More Complexity = More (& Surprising) Vulnerability**
  - **Indices can be Deceiving**

Aurora and Omens ~2600 Years Ago

First datable auroral record: Unusual "red glow" in the sky at night, 567 BCE

One of a series of carefully recorded astronomical observations

"Night of the 29th, red glow flared up in the west …"

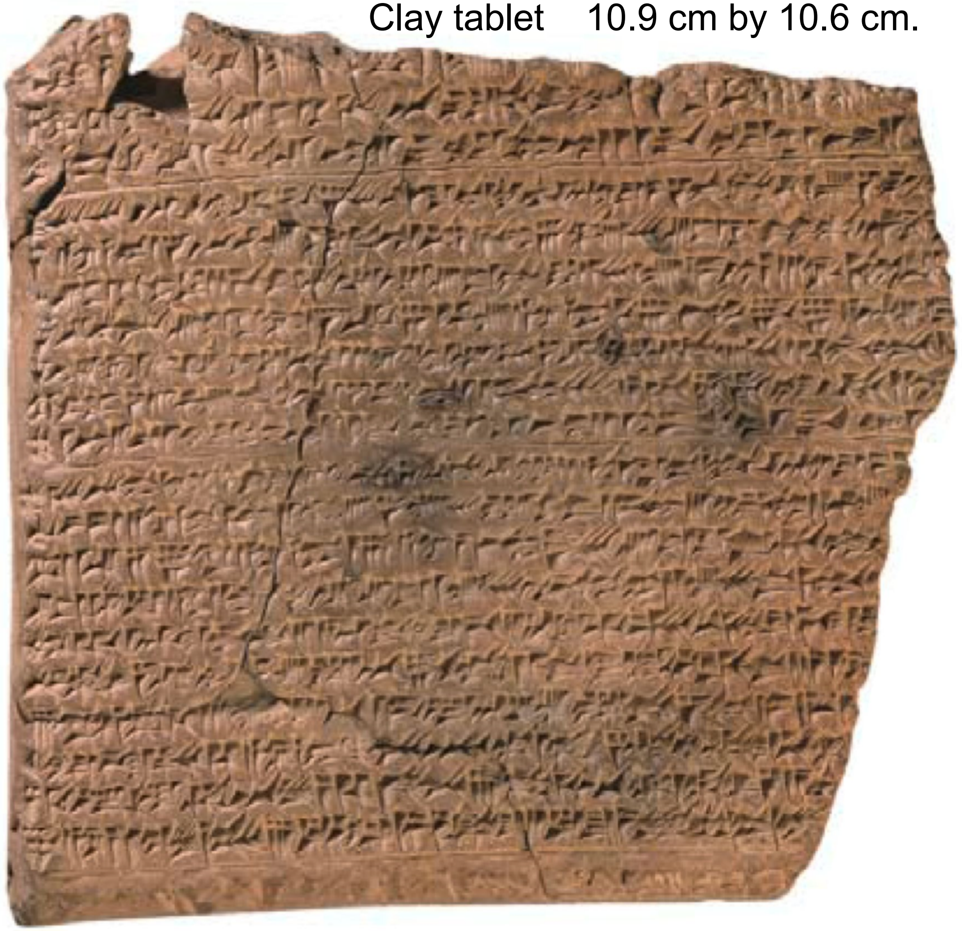
37th year of the reign of King Nebuchadnezzar II of Babylon

Babylon (~ 41 MLAT in that epoch)

In the modern calendar this is 12-13 March, 567 BCE

Annual frequency of visible aurora ~0.1/yr at that latitude

Clay tablet 10.9 cm by 10.6 cm.



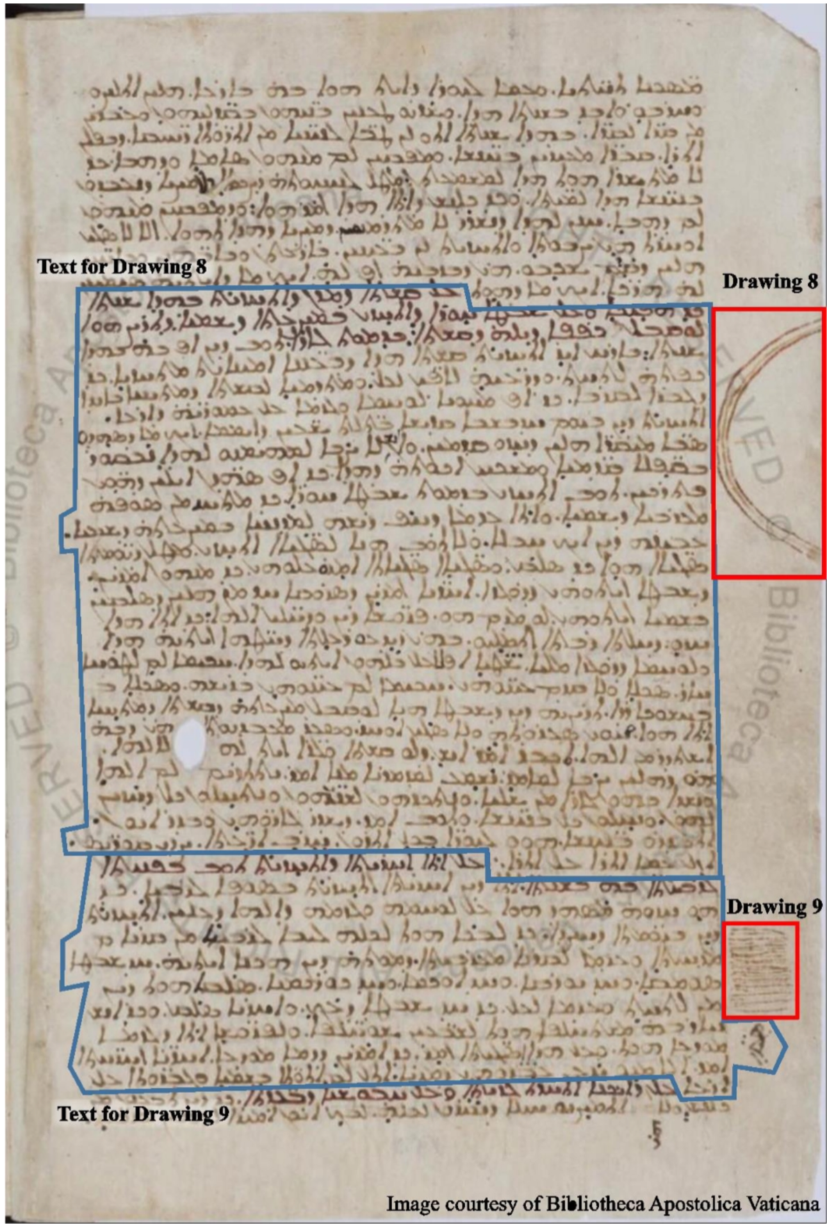
Stephenson et al. (2004), The earliest datable observation of the aurora borealis A&G. 2004;45(6):6.15-6.17. doi:10.1046/j 1468-4004.2003.45615.xA&G |

First datable auroral sketch : 771-772 CE

Blood-red scepter changing shapes

Margin sketches found in the Zūqnīn Chronicle,
a history of events from Creation to the late 8th century.
Attributed to a monk -- Joshua the Stylite, who lived in the monastery of Zūqnīn (now eastern Turkey). Circa 771-772

“It was seen at harvest time, occupying the entire northern side from the eastern corner to the western corner. Its form was as follows: a blood-red scepter, a green one, a black one, and a saffron-colored one. It was going from below to above. When one scepter was extinguished, another one went up. And when someone was looking at it, it was changed into seventy shapes.”



Hayakawa et al., (2017) **The earliest drawings of datable auroras and a two-tail comet from the Syriac Chronicle of Zūqnīn,** *Publications of the Astronomical Society of Japan*, 69, 2, 1 April 2017, 17, https://doi.org/10.1093/pasj/psw128

Aurora: Omens to Impacts on Local Society, 1204 CE

Documented space weather effect:
Pilgrimage delayed in Japan 1204 CE

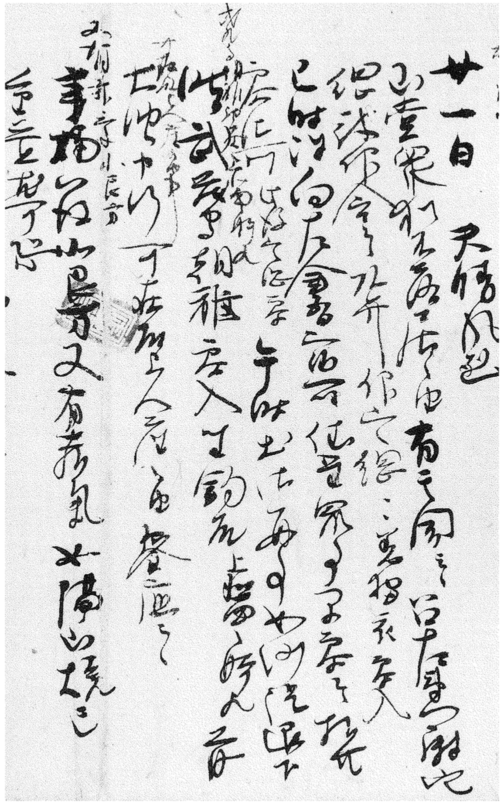
“red vapor” in the sky at night, 1204 CE, multi-night event

Historical Japanese record:

“On 1204/02/21, at 20:00, red vapor appeared with white cloud mixed and was seen from north-west to north-east. …. Takashige stated that these were very rare disaster. We put off the pilgrimage to Koyasan.”

“On 1204/02/23, it was sunny and quite windy. … In the time when to put a fire on the lamp, red vapor appeared in the north and north-east. It was like a distant mountain burning. It was very dreadful.”

Note: In 1619 Galileo coins the term ‘aurora borealis”



Aurora-like records on 21 and 23 February 1204 in Meigetsuki, p512.

Historical space weather monitoring of prolonged aurora activities in Japan and in China, Volume: 15, Issue: 2, Pages: 392-402, 28 January 2017, DOI: (10.1002/2016SW001493)

Aurora: Omens to Impacts on European Society
Middle Ages to Enlightenment

Wood-cuts, paintings and prints reveal awe and angst of auroral sightings

Red Sky at Night; Famine in Sight

Nuremberg, 5 October 1591, CE

Aurora 1770 CE: A Global Phenomena

First aurora recorded in both hemispheres:

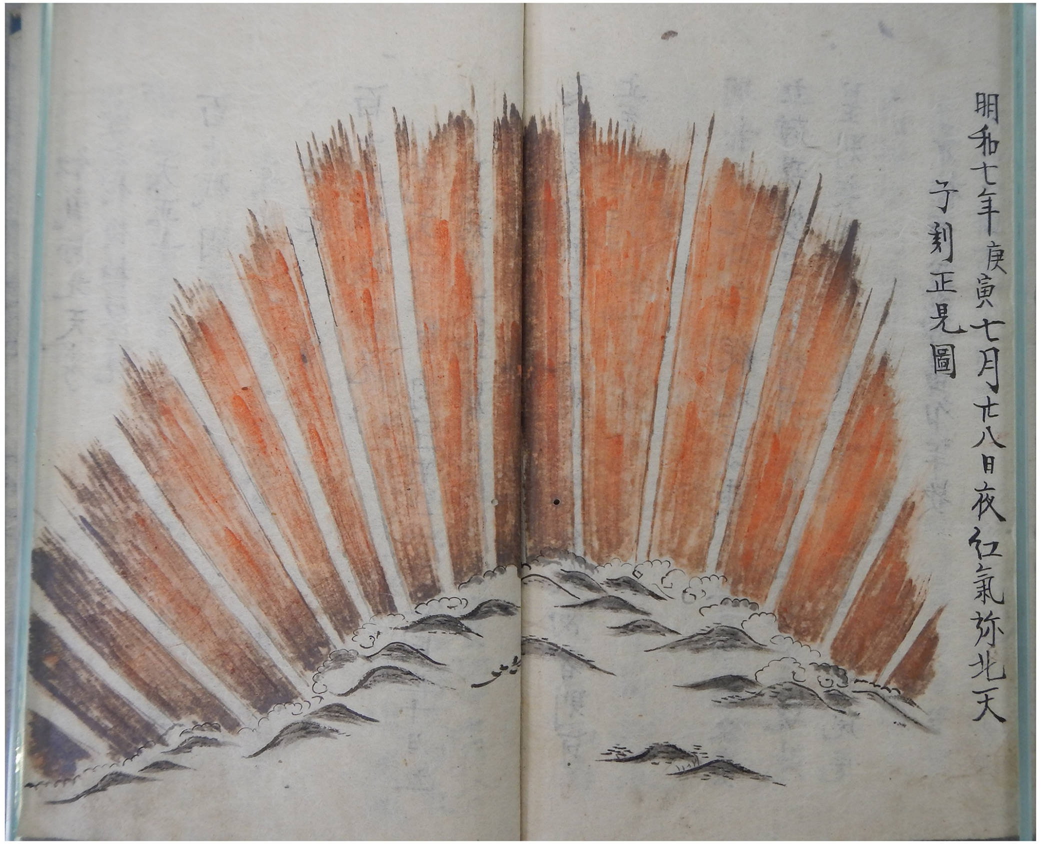
“red vapor” in the sky at night,

“*a fiery light like vermilion sand in the north with something with golden color rising up inside beyond the polar star*” in Toyoda, Japan

The painting of the red aurora of 17 September 1770 over Kyoto Japan, in the premodern Japanese text “Seikai,”

World-wide auroral event recorded in Europe and Asia.

Multi-day event



On 17 September 1770, at night, “..red vapor was active at northern sky. The figure was as it watched at midnight.”

Inclined Zenith Aurora over Kyoto on 17 September 1770: Graphical Evidence of Extreme Magnetic Storm, Volume: 15, Issue: 10, Pages: 1314-1320, First published: 18 September 2017, DOI: (10.1002/2017SW001690)

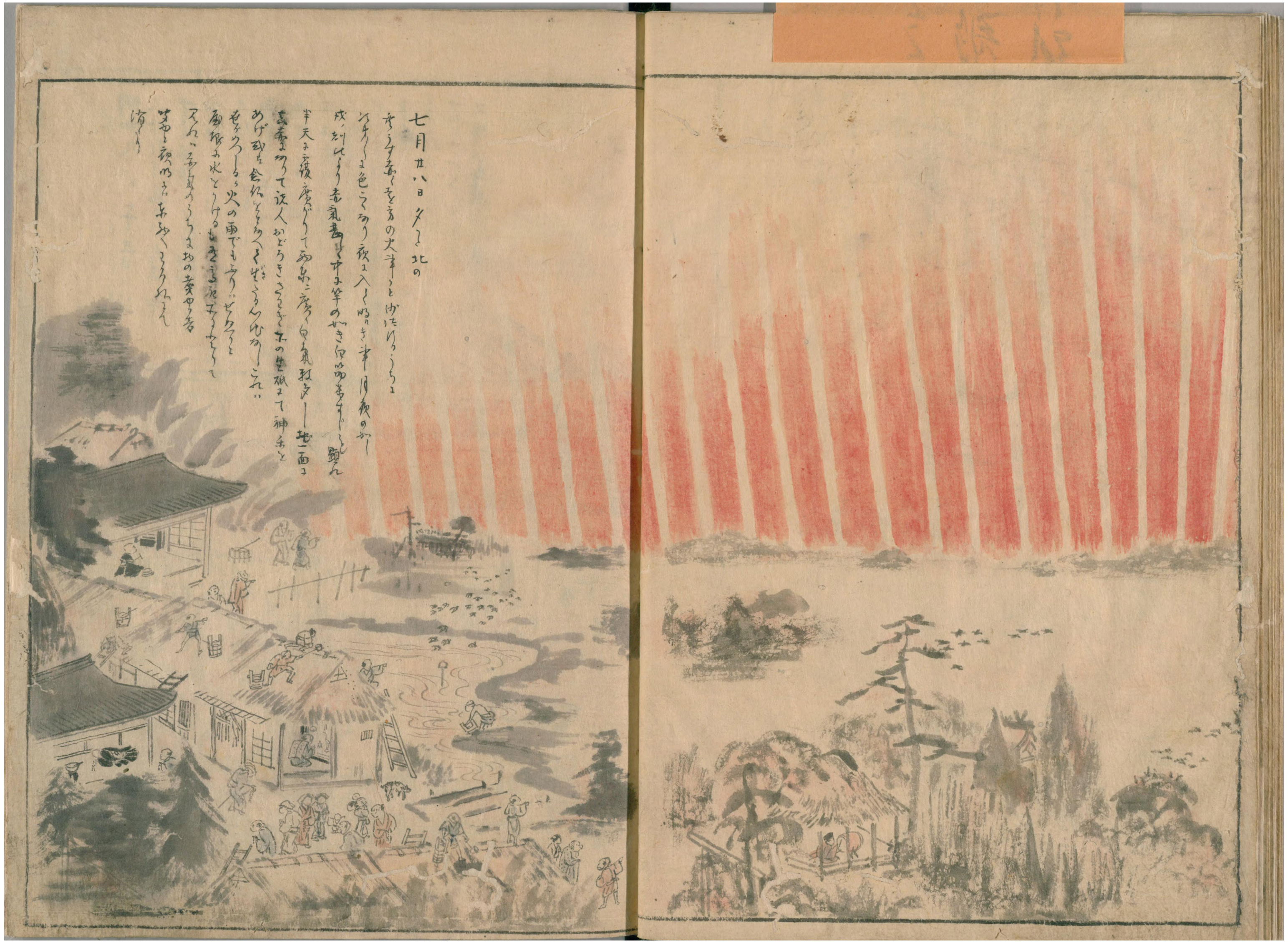
Hayakawa et al,, (2017) Long-lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents, Ap J Ltrs

Ebihara, Y., Hayakawa, H., Iwahashi, K., Tamazawa, H., Kawamura, A. D., & Isobe, H. (2017). Possible cause of extremely bright aurora witnessed in East Asia on 17 September 1770. *Space Weather*, 15, 1373–1382. https://doi.org/10.1002/2017SW001693

Aurora 1770 CE: A Global and Impactful Phenomena

Aurora recorded at low latitude in both hemispheres

Multi-day event



An extraordinary event 17 September 1770 Aurora recorded over southern Japan

Hayakawa et al,, (2017) Long-lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents, Ap J Ltrs

波の如し
すじ〳〵と顕れ
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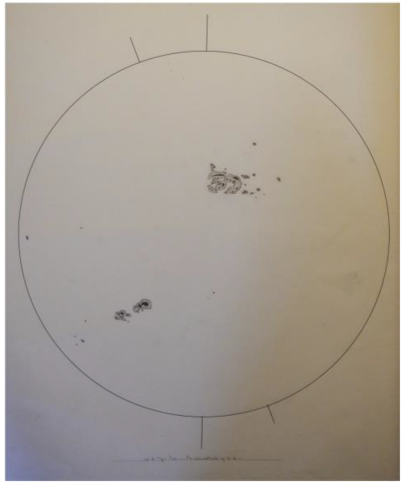
し 神楽と

1859 CE: Linking Aurora and Solar Storms

On the night of [September 1] we were high up on the Rocky Mountains sleeping in the open air. A little after midnight we were awakened by the auroral light, so bright that one could easily read common print. Some of the party insisted that it was daylight and began the preparation of breakfast. (Rocky Mountain News)

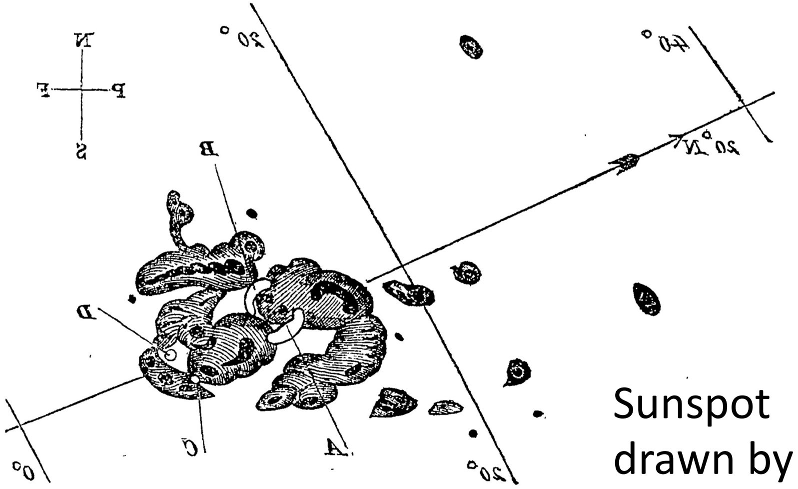


…Half-past eleven. The appearance now is positively awful. The red glare is over houses, streets, and fields, and the most dreadful of conflagrations could not cast a deeper hue abroad…[San Francisco Herald, September 5, 1859].

Multi-day event

Multiple eruptions

Second storm hit only 18 hr after flare was observed



Sunspot drawn by Carrington

Hayakawa et al,, (2017) Long-lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents, Ap J Ltrs

1859 CE: Linking the Aurora, Technology and Solar Storms

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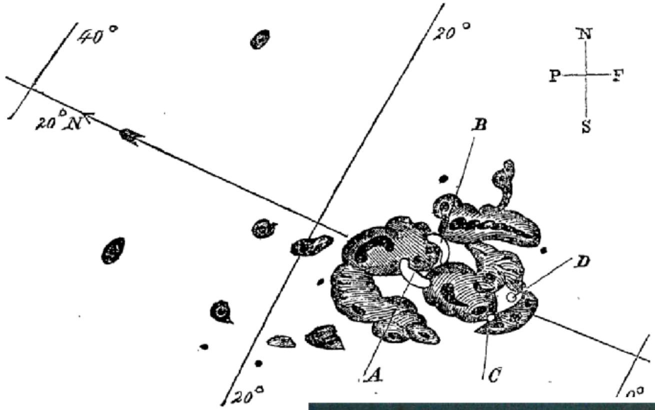
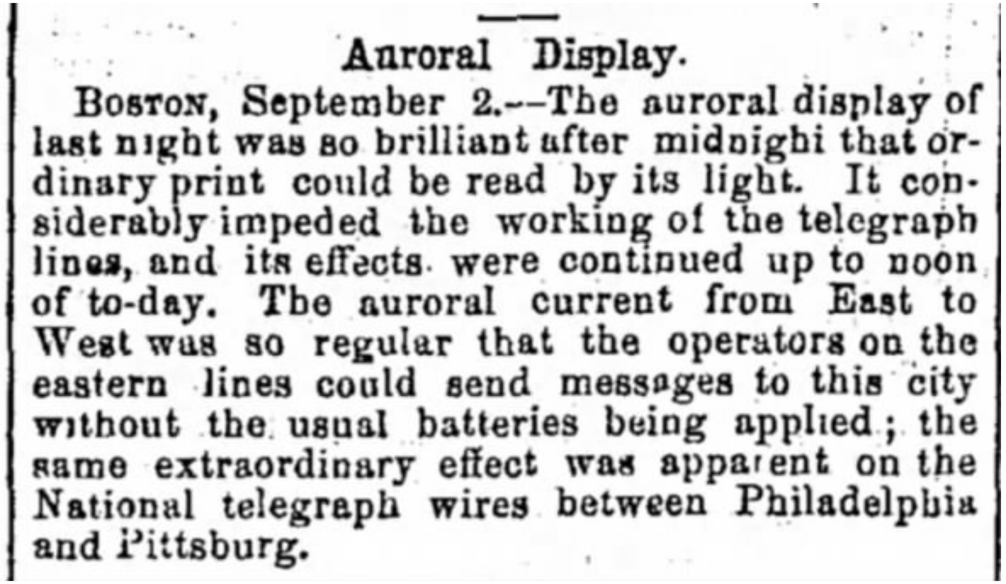
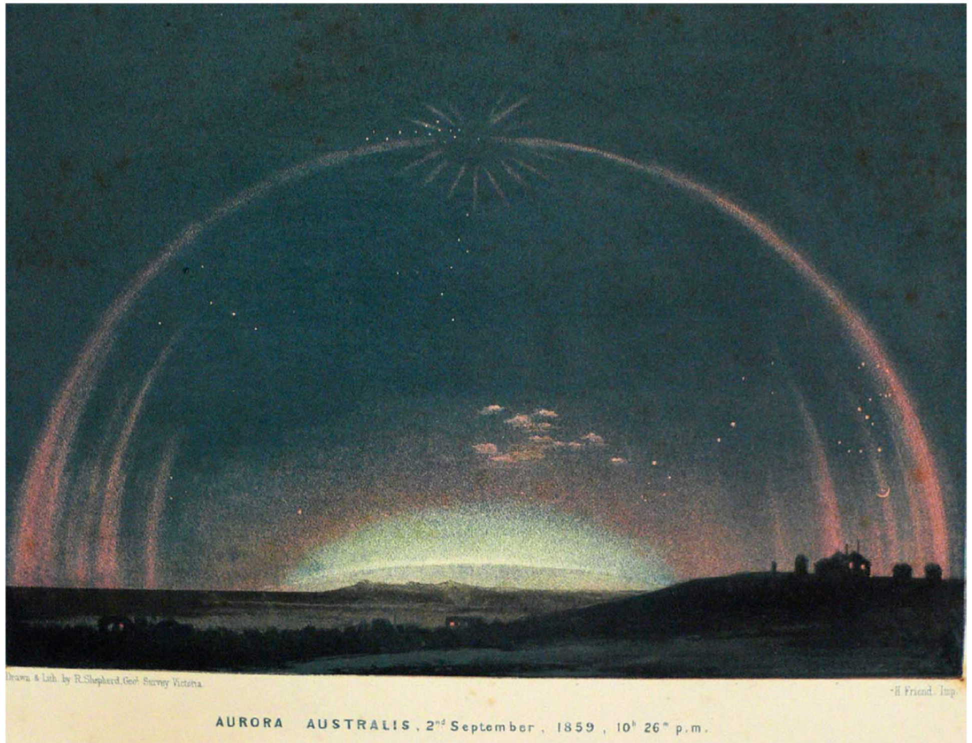




Auroral Display.

BOSTON, September 2.--The auroral display of last night was so brilliant after midnight that ordinary print could be read by its light. It considerably impeded the working of the telegraph lines, and its effects were continued up to noon of to-day. The auroral current from East to West was so regular that the operators on the eastern lines could send messages to this city without the usual batteries being applied; the same extraordinary effect was apparent on the National telegraph wires between Philadelphia and Pittsburg.

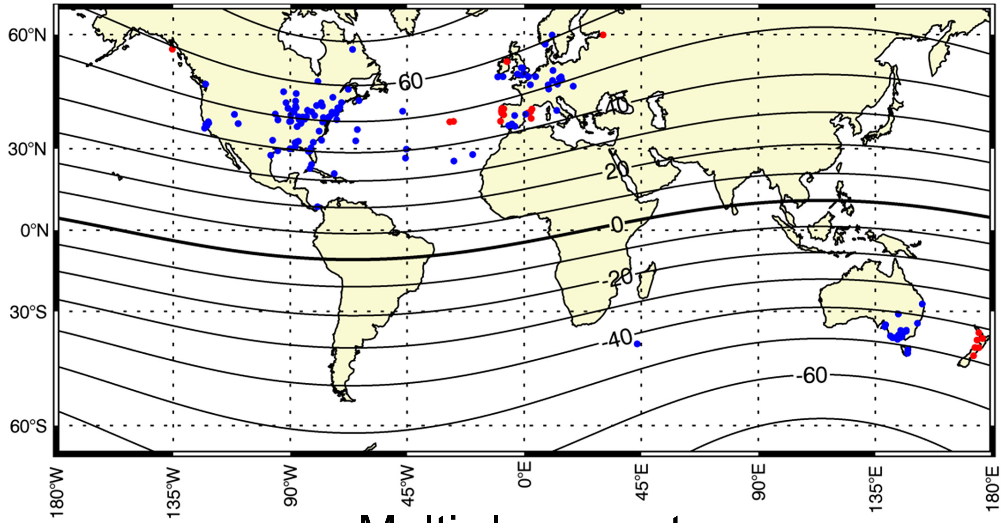


Hayakawa et al,, (2017) Long-lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents, Ap J Ltrs

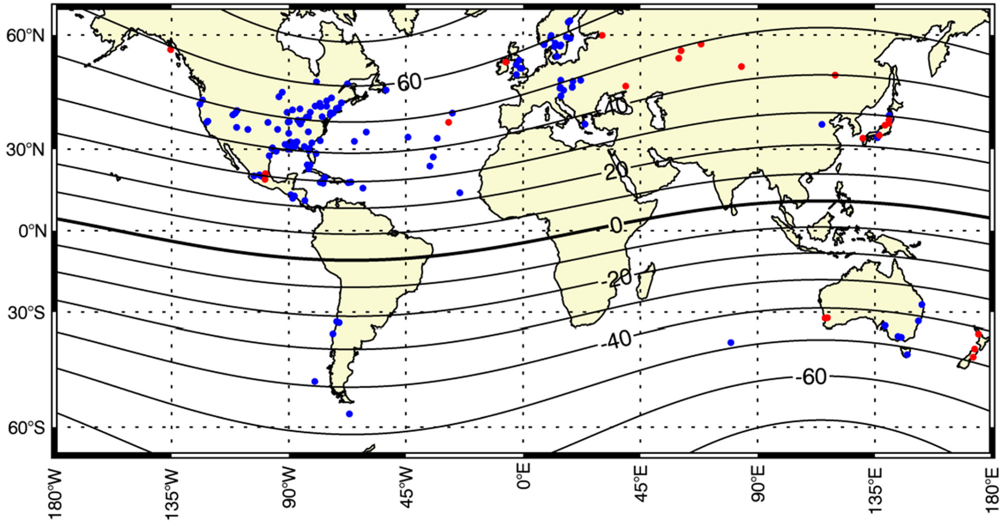
1859 CE: Linking the Aurora, Solar Storms and Technology

Worldwide reports of long lasting great aurora and telegraph disruption

At that time almost the whole southern heavens were in a livid red flame, brightest still in the southeast and southwest. Streamers of yellow and orange shot up and met and crossed each other, **like the bayonets upon a stack of guns,** in the open space between the constellations Aries, Taurus and the Head of Medusa – about 15 degrees south of the zenith.
…the magnificent auroral glory continued its grand and inexplicable movements until the light of morning overpowered to radiance and it was lost in the beams of the rising sun[New York Times, September 3, 1859].



Multi-day event



Hayakawa et al,, (2017) Long-lasting Extreme Magnetic Storm Activities in 1770 Found in Historical Documents, Ap J Ltrs

Industrial-Space Age: Technology and Solar Storms

1872 Telegraph outages/submarine cables

1882 Telegraph outages/submarine cables

1903 Telegraph/Telephone/ Street cars

1909 Telegraph

1921 Telegraph/ Railroad/Radio
(Buildings set afire)

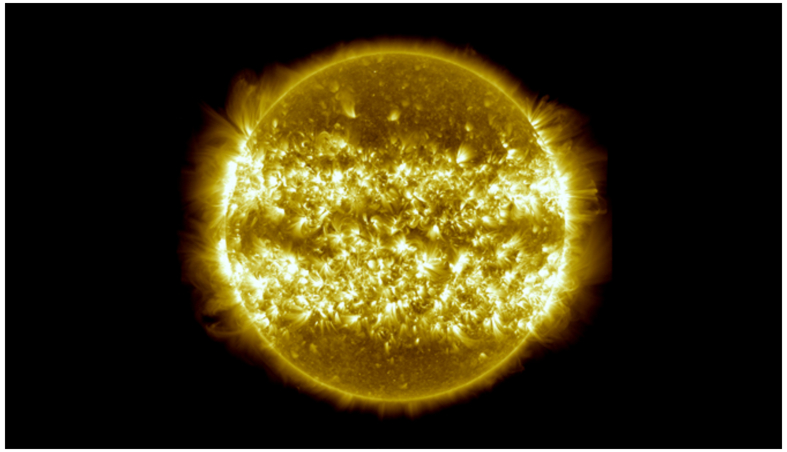
1938 Railroad/Radio

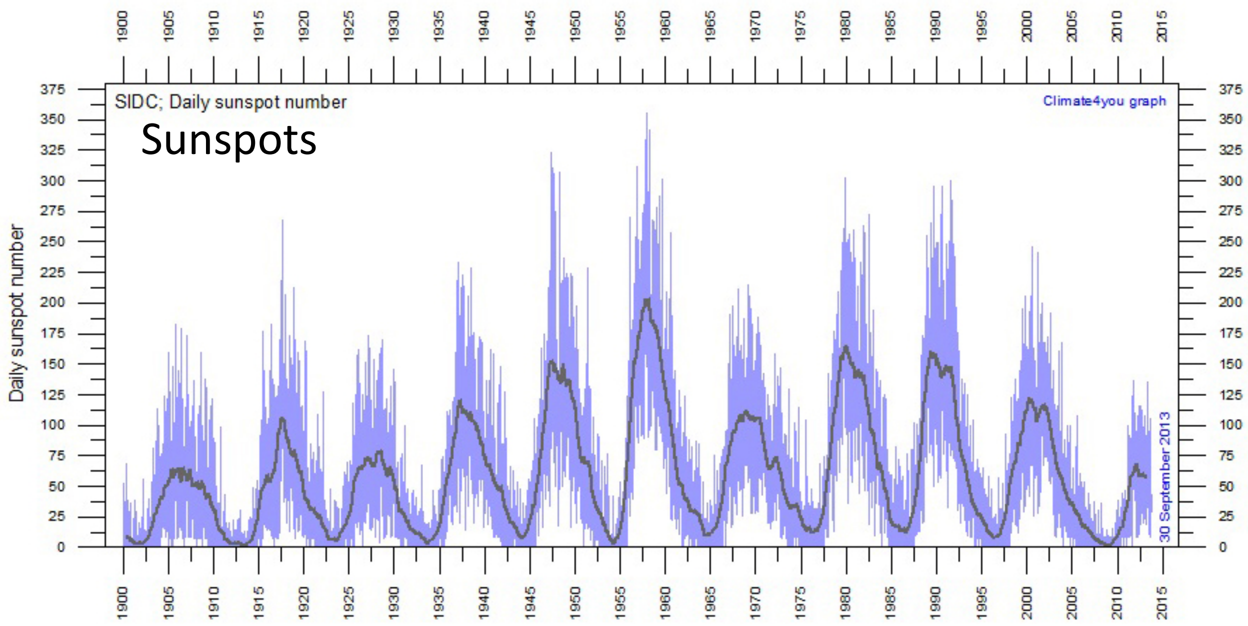
1940 Power Grid

1942-45 Radar/Radio/Military

1957-59 Submarine cables/Radio/Spacecraft

1960 Spacecraft/Military Command & Control

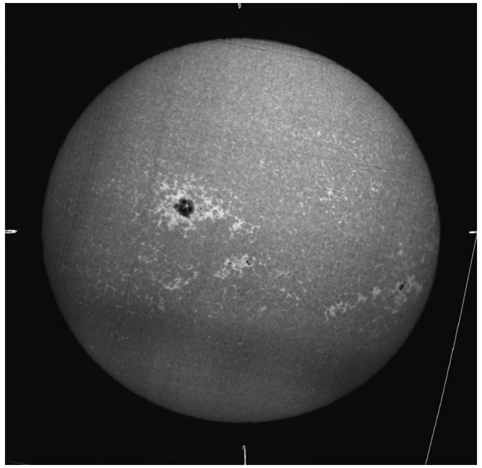




The Great August 1972 Heliospheric Disturbance

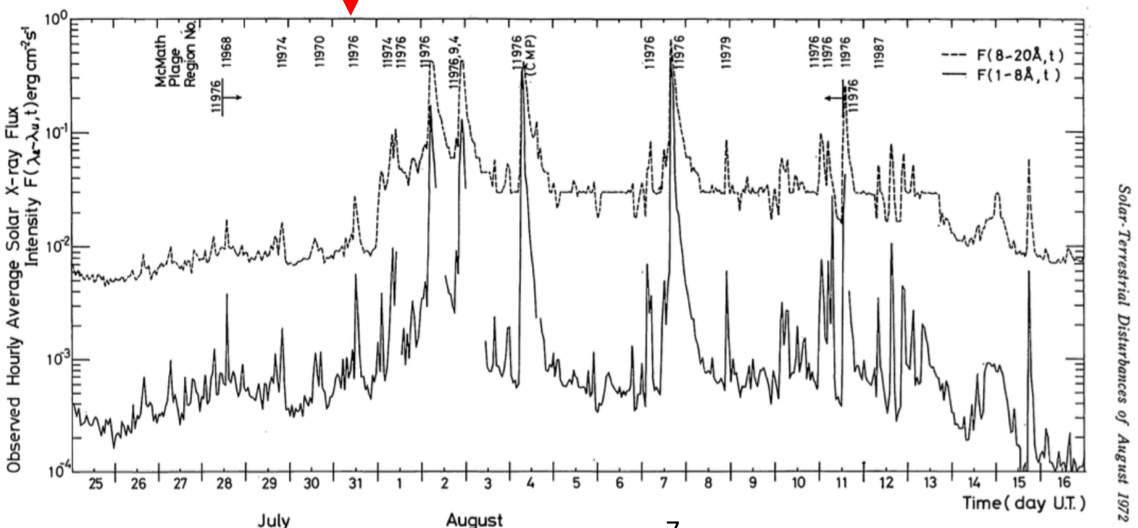
- Dozens of flares altered the dayside ionosphere

McMath Region, 11976, Ca-II



3 Aug
BASS2000, Paris Observatory, PSL

Hourly averaged X-ray Intensity for McMath Region, 11976, Aug 1972



Ohshio (1974)

•Knipp, D. J., et al. (2018), On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta:
•Facts, Commentary and Call to Action, Space Weather, 16. https://doi.org/10.1029/2018SW002024

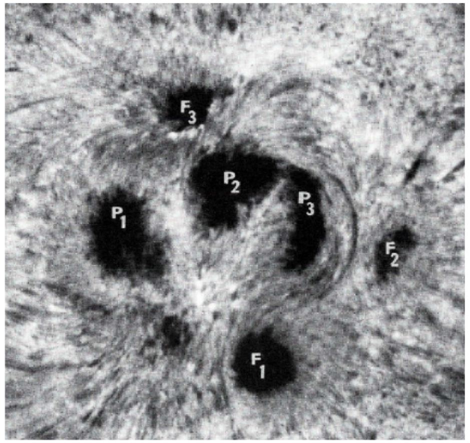
Overview August 1972

- One of the most intense intervals of solar/geospace activity during the space age

- Active Region
  - Single large penumbra;
  - Delta configuration
  - 1200 millionths of hemisphere
  - Light bridge

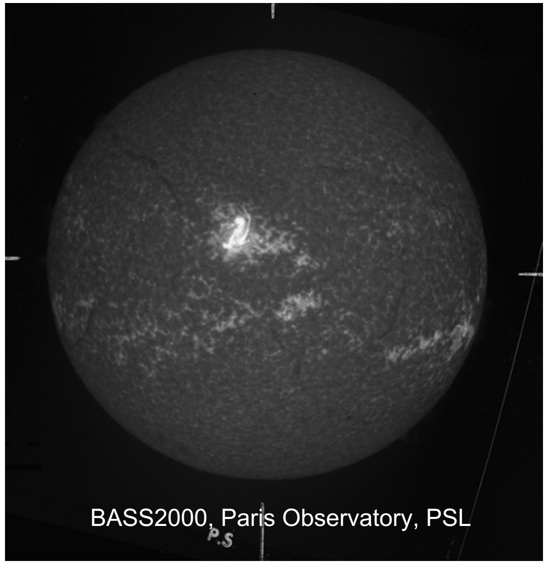
- Extraordinary solar flares
  - 2 Aug: (2), X class & WLF
  - 4 Aug: (1), X-20 + Gamma-rays
  - 7 Aug: (1) X class & WLF

- Flare level 4 Aug 0630 UT
  - 3B H-alpha
  - X-ray – LDE flare
  - Combined Flare Index = 17



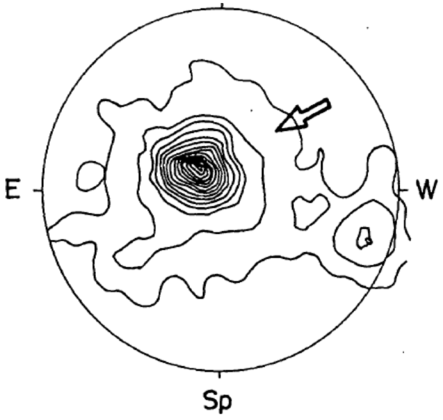
Zirin and Tanaka (1973) BBSO

Koyama(1972) Tokyo



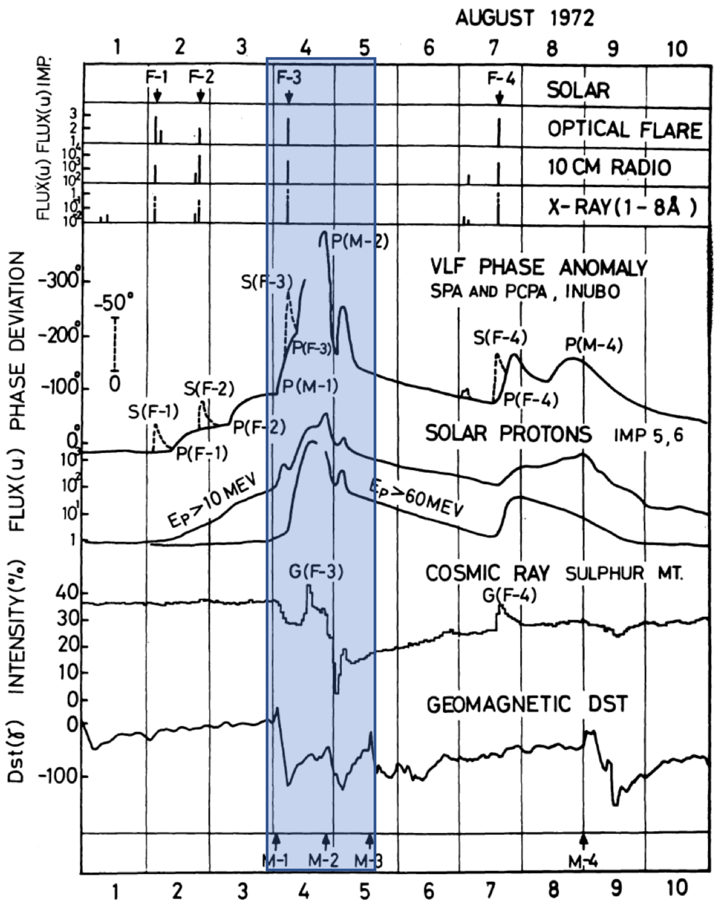
BASS2000, Paris Observatory, PSL

McMath Region 11976 4 Aug 1972
X-ray OSO 5
University College Leicester Univ



At Earth: 4 August 1972

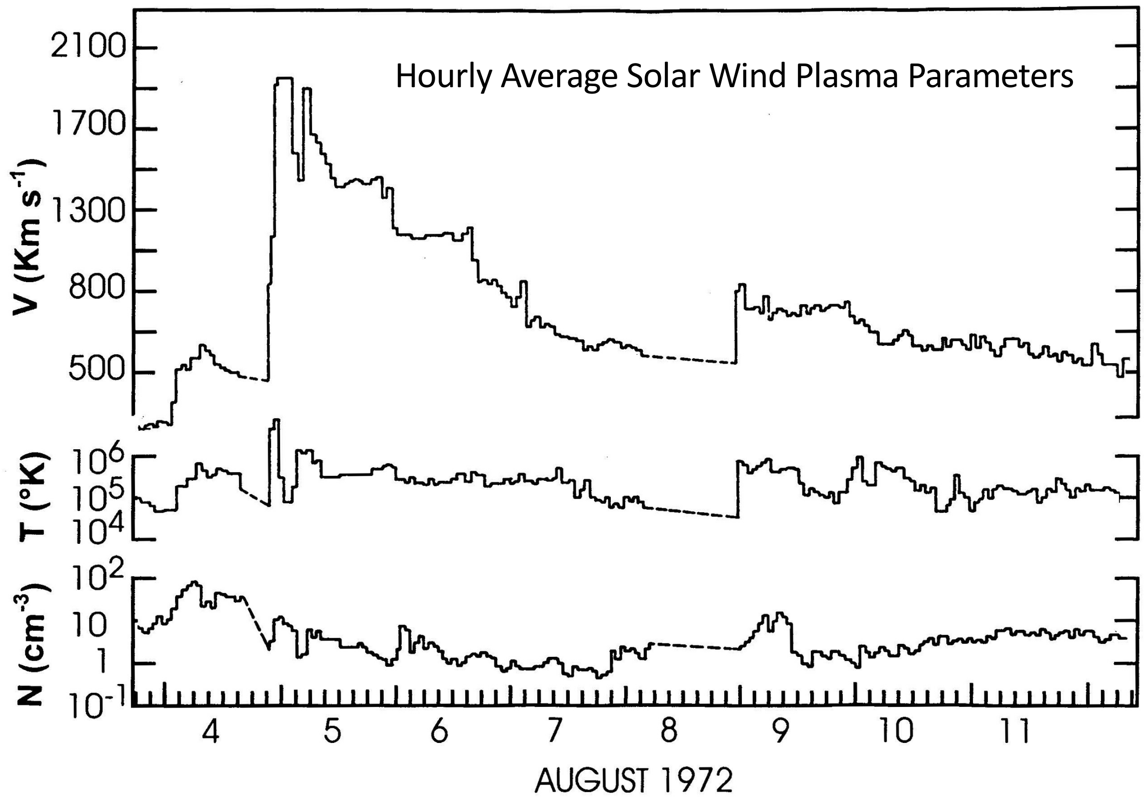
- Radio Propagation Disturbance & Blackout
  - Dayside & then Polar Cap then nightside
- Forbush Decrease
- Rapid Rise of SEPs
  - Then onset of Ground Level Event (GLE24)
  - Spacecraft solar panels deteriorated
  - Sensors overwhelmed with particles
  - Long-lasting ozone depletion
- Extreme Forbush Decrease
- Sudden Storm Commencements & Extraordinary Sudden Impulse



Hakura (1974)

Solar Wind (reconstructed) from Prognoz & Prognoz 2

- Significant solar wind density enhancements from previous CMEs
  - Preconditioning of geospace?
- Path-clearing events prior to shock arrival at 2054 UT
- Fastest CME on record—14.6 hrs to 1 AU
  - Average CME transit speed: 2850 km/s
- Shock & structures within sheath?

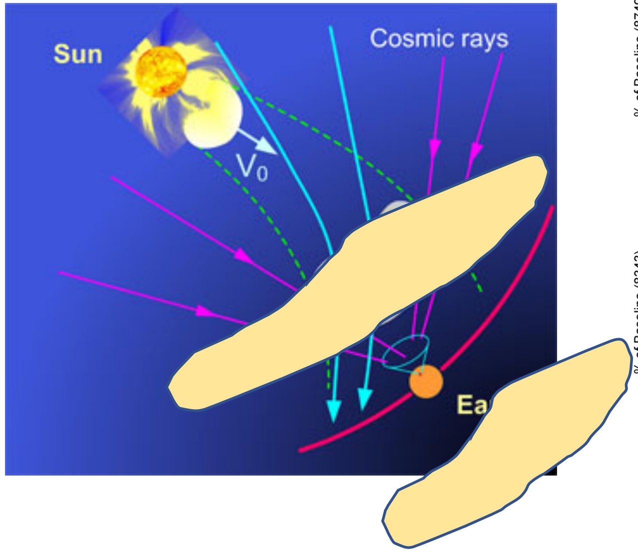


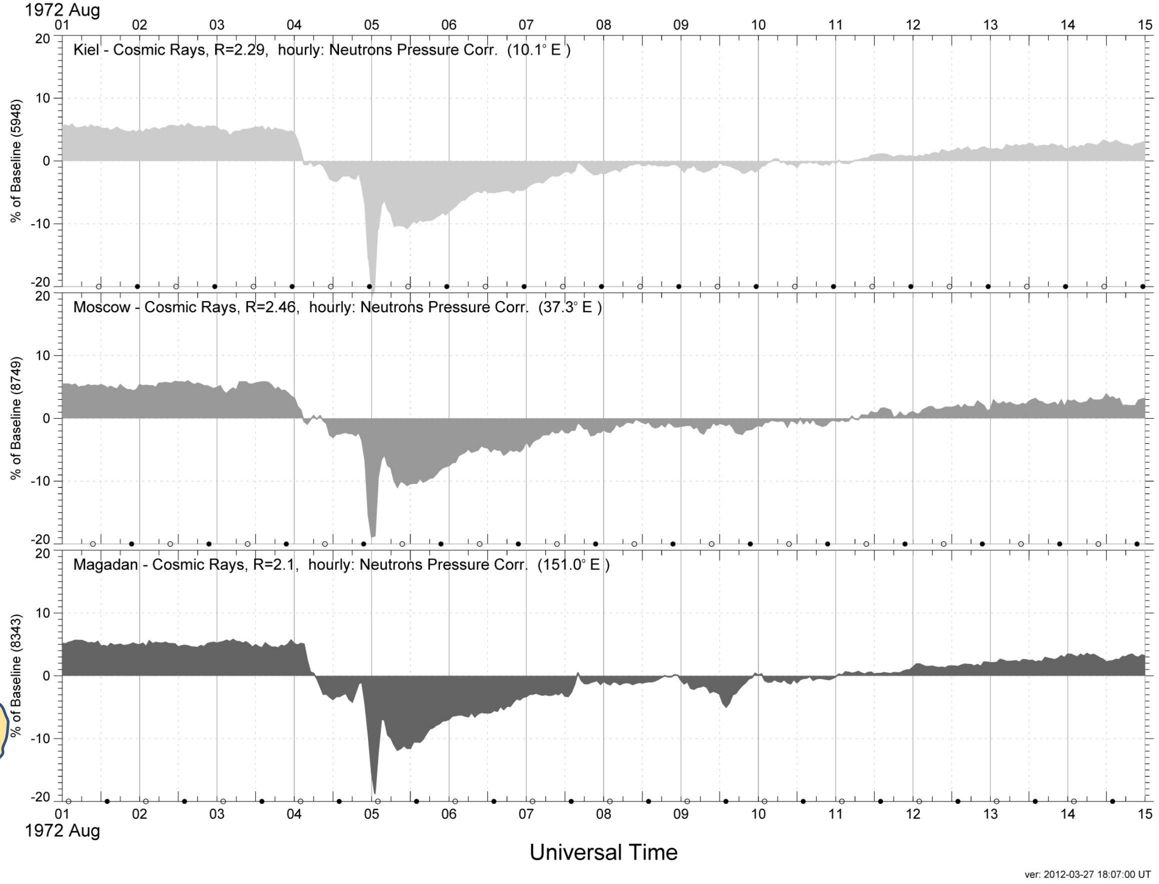
Vaisberg& Zastenker, (1976), Zastenker et al. (1978)

•Knipp, D. J., et al. (2018), Space Weather, 16. https://doi.org/10.1029/2018SW002024

Forbush Decrease

- Extreme temporal profile in neutron monitor record





NOAA NCEI

Solar Energetic Particles (reconstructed)

August 1972

The most intense flux of low and moderate energy SEPs in the space-age

Significant enhancements ahead of CMEs--Energetic Storm Particles

Solar Panels on spacecraft lose 5% of power generation capability in one day

One S/C mission lost within 90 days

Polar HF communications disappeared

Ionospheric E region appeared on the nightside as if it were daytime

P. Jiggens et al.: The magnitude and effects of extreme solor particle events

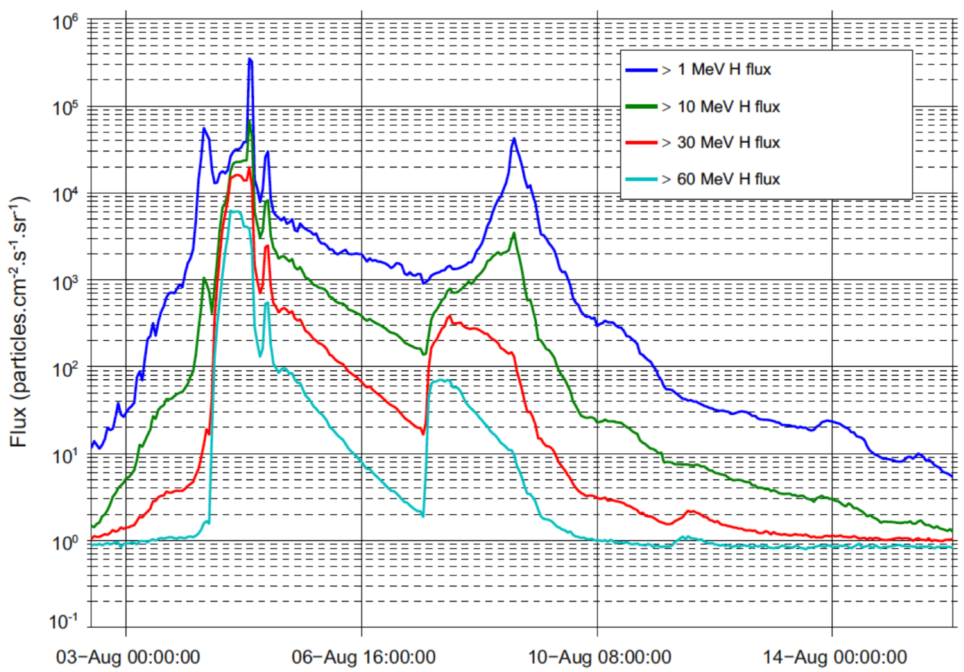
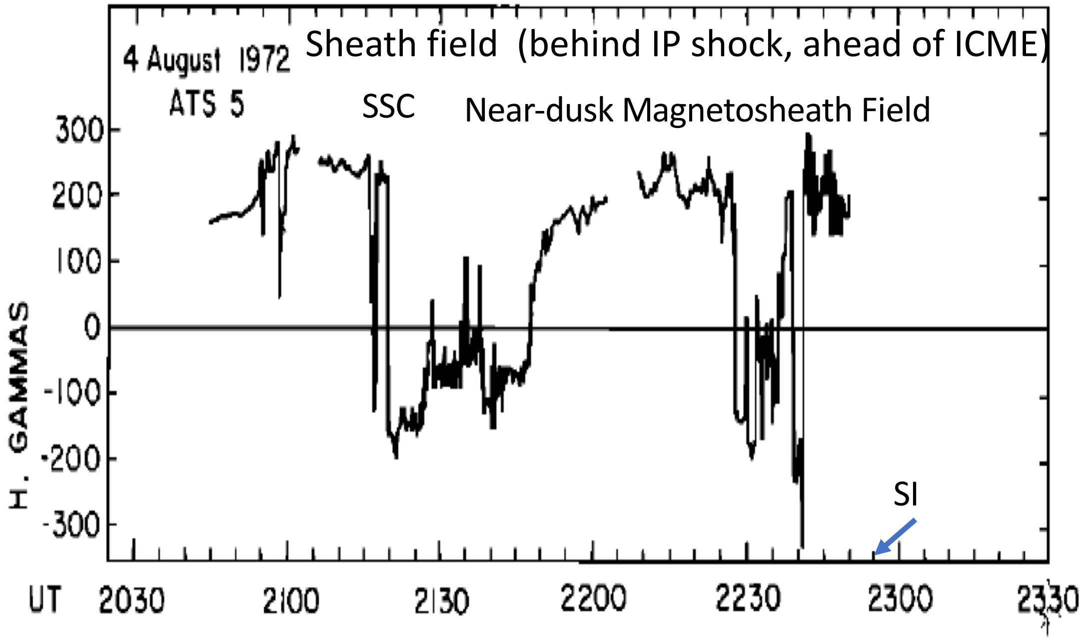


Fig. 1. Integral fluxes from the IMP-5 spacecraft measured during the large August 1972 SPE. These have been manually corrected for spikes and small data gaps have been filled using a 3rd-order polynomial.

Jiggens et al (2014)

Disturbance at Geosynchronous Orbit

- ATS 5 (GEO S/C) in the magnetosheath
  - Clear magnetopause compression
- Rapid solar wind fluctuations
  - In sheath ahead of ICME?
  - Extreme southward field
  - -300 nT in sheath
    - -75 – -100 nT in SW



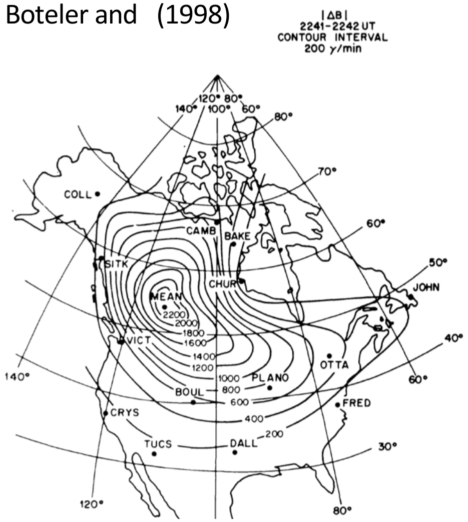
Cahill & Skillman (1977)

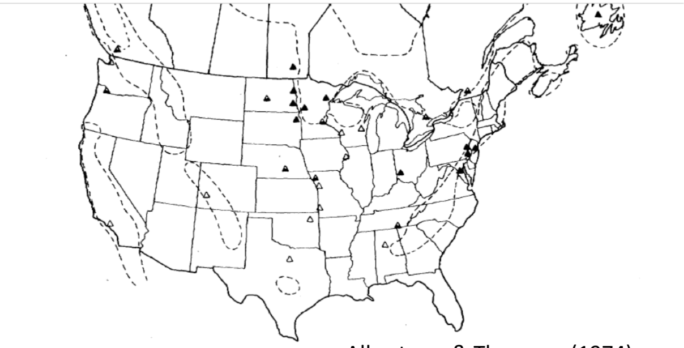
•Knipp, D. J., et al. (2018), Space Weather, 16. https://doi.org/10.1029/2018SW002024

High & Mid-latitude Ground Sudden Magnetic Impulse

- 2238-2242 UT Large voltage swings in northern tier US states.
- The Manitoba Hydro Company recorded 120 MW drops in power supplied to Minnesota in only a few minutes.
- Outage on the L4 (AT&T) cable in the US Midwest states
  - Induced electric field of 7.0 V/km, exceeded shutdown threshold for high current, accompanied magnetic field variations (dB/dt) of ~ 800 nT/min at 2240-2242 UT (the time of the L4 outage).
- dB/dT = 2000 nT/min in northern Canada
- Newfoundland, Canada, GICs activated protective relays many times on 4-5 August.
- Strong GIC effects reported in Ohio and Maryland

Boteler and   (1998)





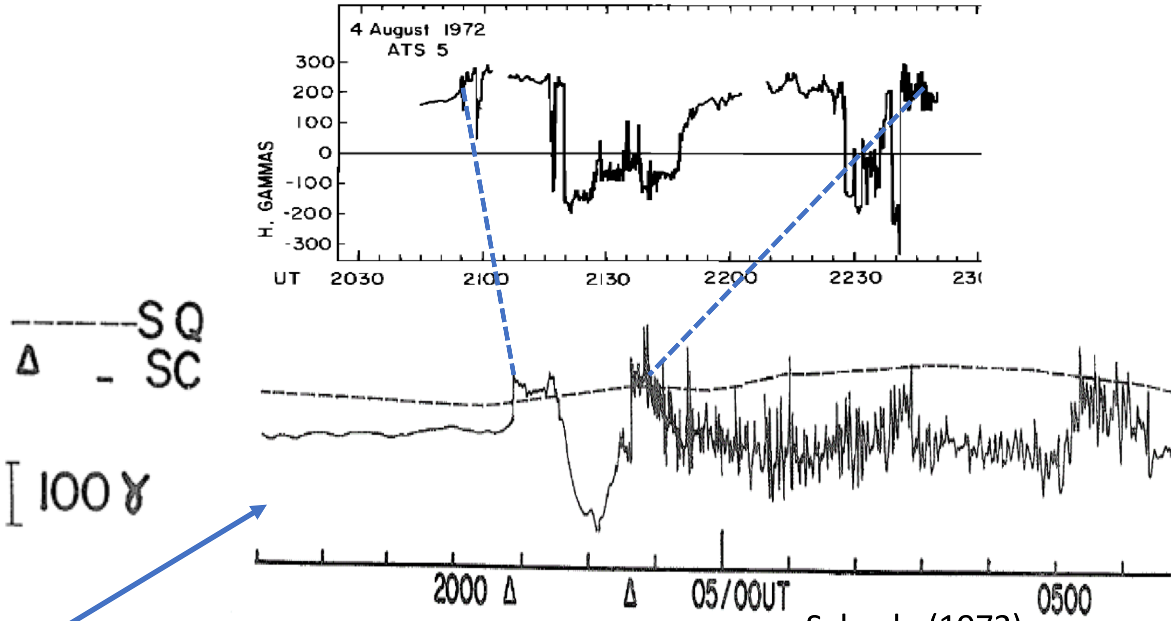
Albertson & Thorson, (1974),

Fig. 5. Reported Power System Disturbances or SIC August 4, 1972. ▲ = strong. ▲ = moderate. Δ = weak. Igneous Rock Areas outlined.

Shadow casting aurora in the southern UK

Low-Latitude Ground Magnetic Perturbations

- SSC 2054 UT
- SI 2038-2242 UT
- 168 nT/min Manila, Philippines
  - Near dawn Local Time
  - 7 deg MLAT
- Subsequent Giant Pulsations



Salcedo (1973)

•Knipp, D. J., et al. (2018), Space Weather, 16. https://doi.org/10.1029/2018SW002024

Hai Phong Mine Field ‘swept’ by a Solar Magnetic Storm on 4 August 1972

“… the HaiPhong Destructor (mine) Field was actually swept by a solar magnetic storm in August of 1972.” Hartmann & Truver (1991)

“During the first few weeks of August, a series of extremely strong solar flares caused a fluctuation of the magnetic fields, in and around, South East Asia. The resulting chain of events caused the premature detonation of over 4,000 magnetically sensitive DSTs (Destructor mines)”
Gonzales, https://www.angelo.edu/content/files/21974-a

Mine explosion
Haiphong Harbor 1973

By United States Navy photograph - Scanned from Melia, Tamara Moser, "Damn the Torpedoes": A Short History of U.S. Navy Mine Countermeasures, 1777-1991, Washington, D.C.: Naval Historical Center, 1991, ISBN 0-945274-07-6, p. 108., Public Domain, https://commons.wikimedia.org/w/index.php?curid=32761410

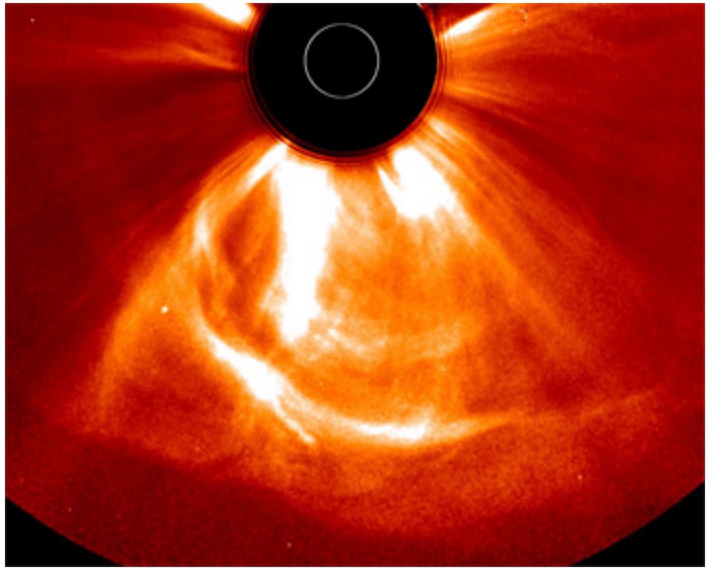
Extreme Storms: Last 50 years

Event	Solar Cycle	G-Scale	R-Scale	S-Scale	Kp	Ap*	X-ray	SEP
23 May -30 May 1967	20	G5	~R3[1]	S3[2]	9_o	241	X6[1]	~25,000[2]
01-Aug – 14-Aug 1972	20	G4	~R5	~S5	8_o	223	~X20	90000[4]
10-Mar – 15-Mar 1989	22	G5	R3	S3	9_o	285	X15	3,500
18-Oct – 31-Oct 1989	22	G4	R4	S4	8_+	162	X13	40,000
22 Mar – 28 Mar 1991	22	G5	~R4	S4	9_o	181	X9.4	43,000
14 Jul – 16 Jul 2000	23	G5	R3	S4	9_o	192	X5	24,000
26-Oct – 06-Nov 2003	23	G5	R5	S4	9_o	252	X28	29,500
05-Dec – 17-Dec 2006	23	G4	R3	S3	8_+	120	X9	1,980
08-Mar – 17-Mar 2012	24	G4	R3	S3	8_o	90	X5	6,530
06-Sep - 12 Sep 2017	24	G4	R5	S3	8_+	223	X9	20000(e)

Extension of a Chart Provided by Bill Dening, NOAA NCEI
Events from same active region, but may involve multiple flares SEPS and CMEs

Progress in Understanding Extreme Storms

- Gopalswamy (2001) Interacting CMEs
- Liu et al. (2014) Path-clearing CMEs permit even faster subsequent CMEs with strong shocks
- Lugaz et al (2015) Shocks inside CMEs
- Knipp et al. (2017) Shocks can drive the thermosphere into an nonlinear state



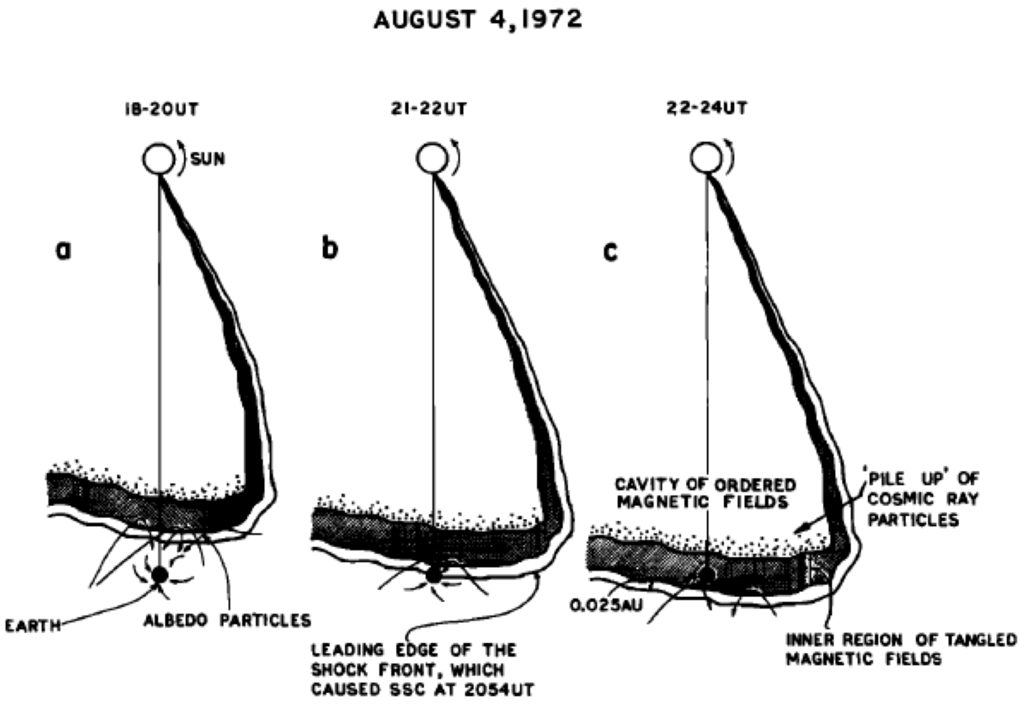
Liu et al (2014) Observations of an extreme storm in interplanetary space caused by successive coronal mass ejections, Nature Communications

Multiple interacting solar eruptions are likely responsible for the most extreme space weather events

Progress in Understanding Extreme Shocks & CMEs (1)

- Tousey (1973) Coronal Transients (CMEs) observed by OSO-7

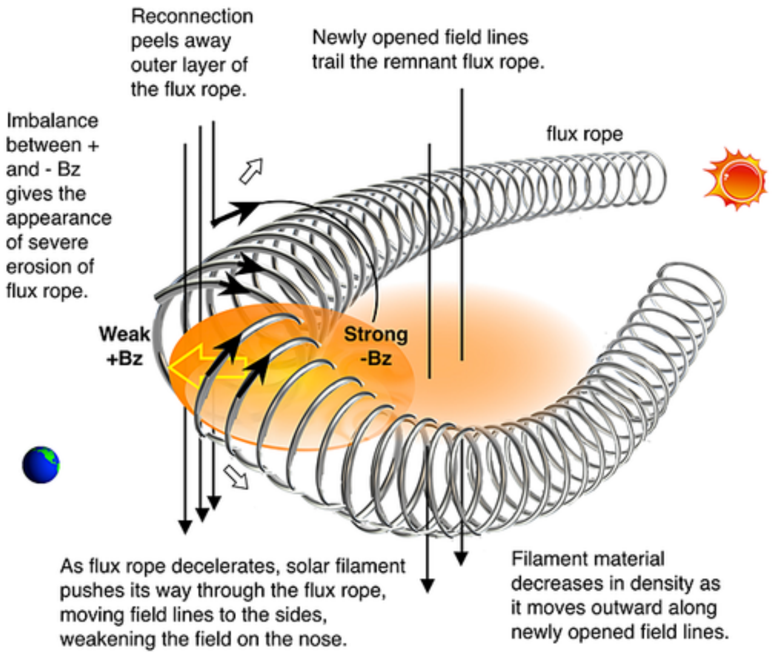
- Agrawal et al (1974) Shocks and CMEs 'organize' GCRs
  - Piles up and Depletions
- Early idea about 'path-clearing' by CMEs
- Developing ideas about Forbush Decreases



Agrawal, et al. (1974), High-energy cosmic ray intensity increase of nonsolar origin and the unusual Forbush decrease of August 1972, *J. Geophys. Res.*, 79(16), 2269–2280, doi: 10.1029/JA079i016p02269.

Progress in Understanding Extreme Shocks & CMEs (2)

- Kozyra et al (2013) Filament material originally behind CME moves through CME to interact with shock
  - Produces extreme effects on 21 Jan 2005
- Chatterjee (2018) demonstrate formation of a delta sunspot
  - From the collision of two or more young flux emerging regions developing in close vicinity.
  - Formation of dense filament in overlying region



Kozyra, J. U., W. B. Manchester IV, C. P. Escoubet, S. T. Lepri, M. W. Liemohn, W. D. Gonzalez,M. W. Thomsen, and B. T. Tsurutani (2013), Earth's collision with a solar filament on 21 January 2005: Overview, J. Geophys. Res. Space Physics, 118, 5967–5978, doi:10.1002/jgra.50567.

Progress in Understanding Extreme Shocks & CMEs Effects at Earth—Carrington-class storms

- Saiz et al. (2015) & Cid et al. (2105)
  - high solar wind pressure and abrupt reversals of the IMF appear as the interplanetary trigger of sharp geomagnetic field perturbations in extreme storms.
  - Possible roots of impulsive field-aligned current penetration to mid and low latitudes
- Consistent with SSC and SI late on 4 Aug

Fig. 5. Reported Power System Disturbances or SIC August 4, 1972. ▲ = *strong.* ▲ = *moderate.* △ = *weak. Igneous Rock Areas outlined.*

Albertson & Thorson, (1974),

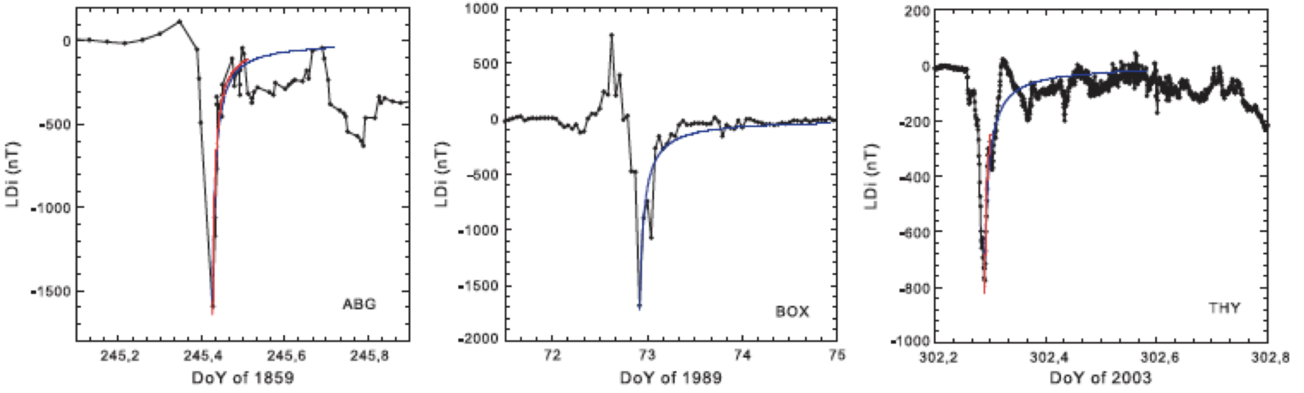


Fig. 5. Fitting results superposed to *LDi* for those analysed events (ABG, BOX, THY). Different colours indicate different time intervals in the fitting procedure: #1 (#2) results in Table 1 corresponds to red (blue) solid line.

Cid et al (2014)

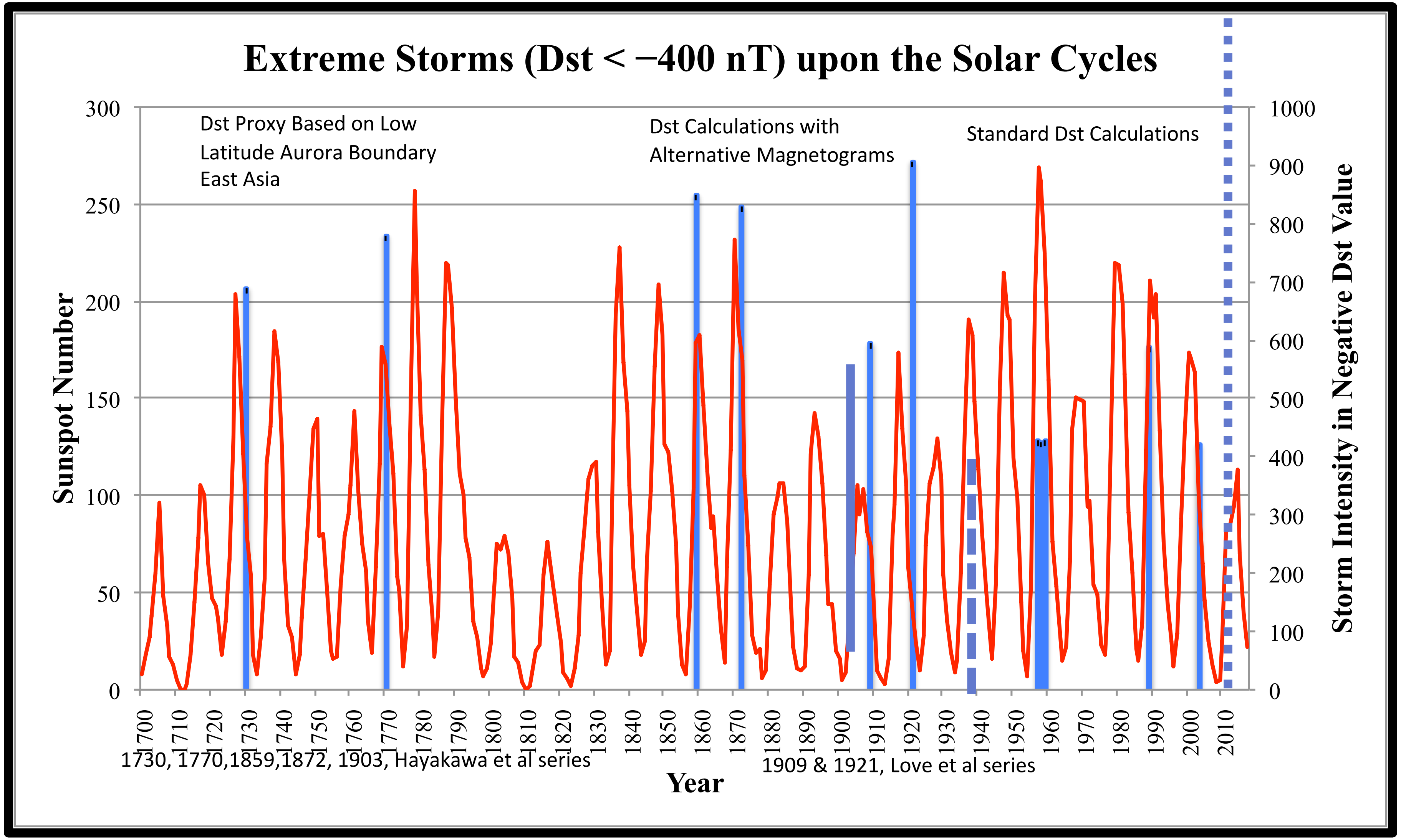
Why Did the Sea Mines Detonate?

- Apparently the SI magnetic signature mimicked that a of passing magnetized ship
- Magnetically (only) sensitive mines would trigger on
  - Rapid dB/dt, coupled with polarity change in B and magnitude of B
- Paraphrasing Saiz et al. "Searching for Carrington-like events and their signatures and triggers SWSC (2016):
  - FACs are the main magnetospheric current system involved in Carrington-like disturbances, (Cid et al. 2015) .
  - Rapid drops in Earth-field H-component occur when the IMF dBz/dt- are >10 nT/min under high dynamic pressure
  - The end of each drop in H is well correlated to a northward IMF turning.
  - IMF South/North abrupt reversals have been identified as the cause of prompt penetration electric field (PPEF) (Ohtani et al. 2013) and attendant FACs
  - PPEF is favored by high solar wind density pressure situations (Lopez et al. 2004 ; Fiori et al. 2014).
  - Large alternating IMFBz- and Bz+ contributed to extreme geomagnetic storms---4 August 1972, 15 July 2000 and 31 March 2001 (Skoug et al. 2004)
- Kozyra et al. (2013) suggest this event (as well as the Carrington event) triggered by solar filament material

Could Something Like This Happen Again?

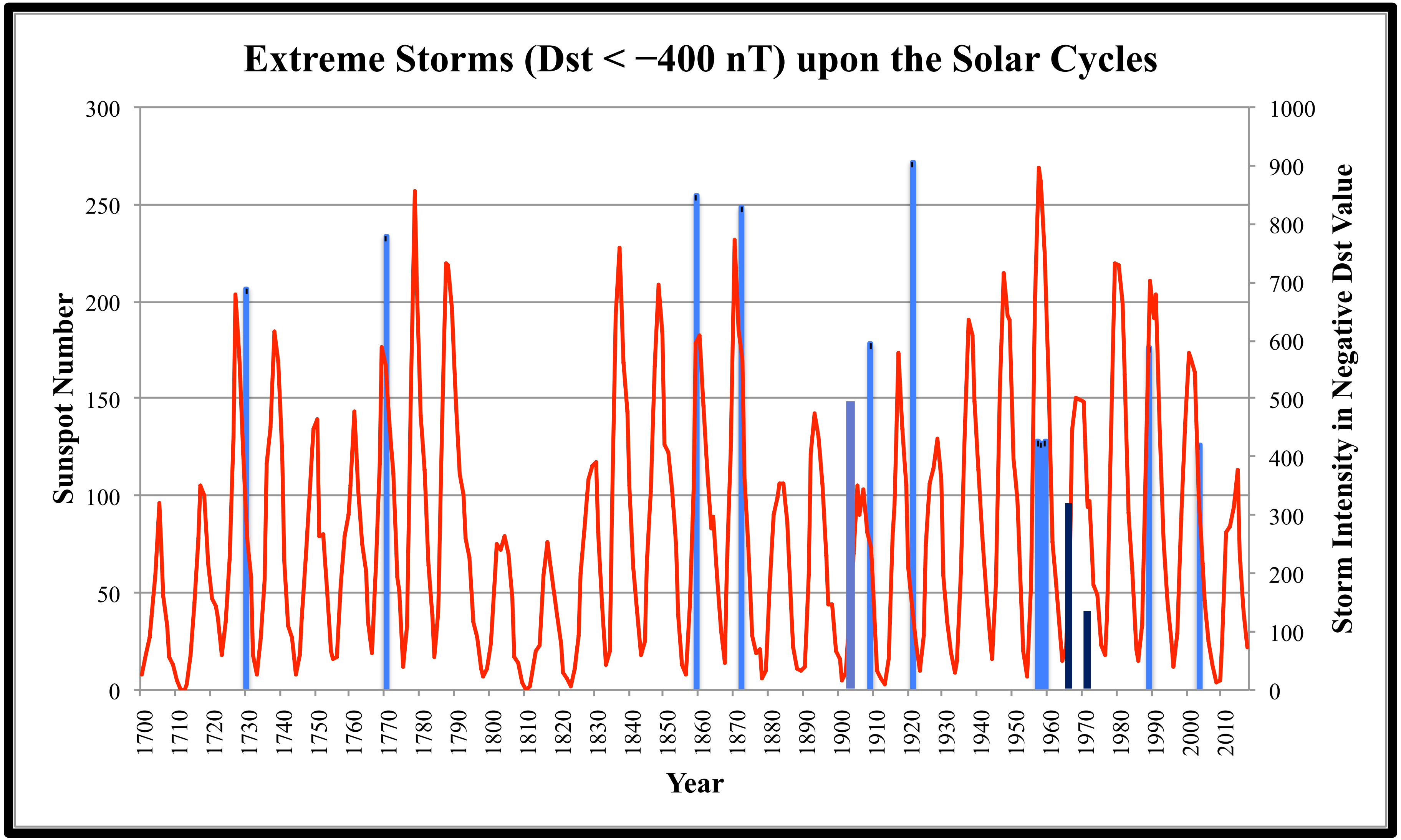
- It Depends on What "This" is
- Solar Driver of this Proportion
  - This event appears to be of Carrington-class with Bz+ at leading edge of ICME
  - Carrington class events in 1859, 1921, 1972, & 2012 (at STEREO A)
- Mine Technology?
  - US Navy rapidly upgraded/replaced mines with more robust triggers
- Power Grid Effects?
  - Already observed multiple times since 1972
- Other Technologies at Risk?

Extreme Space Weather Based on the Dst Index



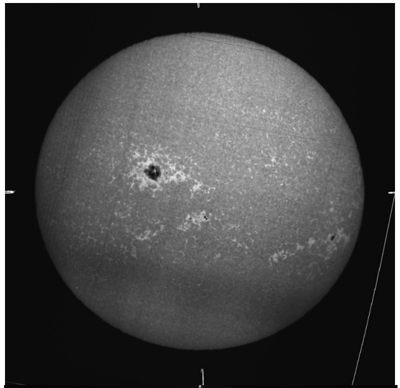
Weak storms: Dst ~-50 nT; Intense Storms Dst < -100 nT (Top 1%); Extreme Storm 400 nT???

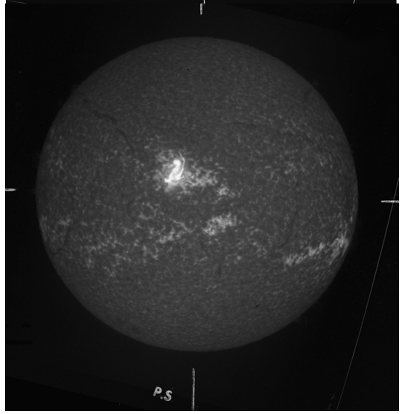
Extreme Space Weather:
Why are Some Events not Well Characterized by an Index?



Updated from Hayakawa (2019) Ph. D. Dissertation

Summary: From Sun to Mud August 1972



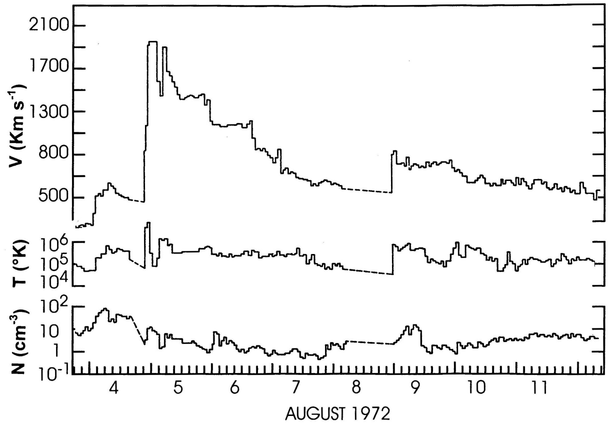


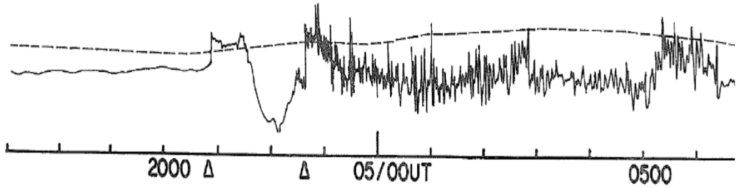
A Extreme Event Struck Earth 4 Aug 72

- SEP s disrupted spacecraft/missions
- Destabilized some of the North American Power Grid
- dB/dt detonated Sea Mines in Southeast Asia
- Long lasting radio disruption

- Rooted in reverse polarity delta spot
- Eruption
  - moved through clear-path
  - Carried solar filament matieral
  - produced GLE and Forbush Decrease
  - Impulsive magnetopause compression and FACs
- We are on the verge of understanding these extreme events

•Knipp, D. J., et al. (2018), On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary and Call to Action, Space Weather,
16. https://doi.org/10.1029/2018SW002024





Backup

Great Red Aurora

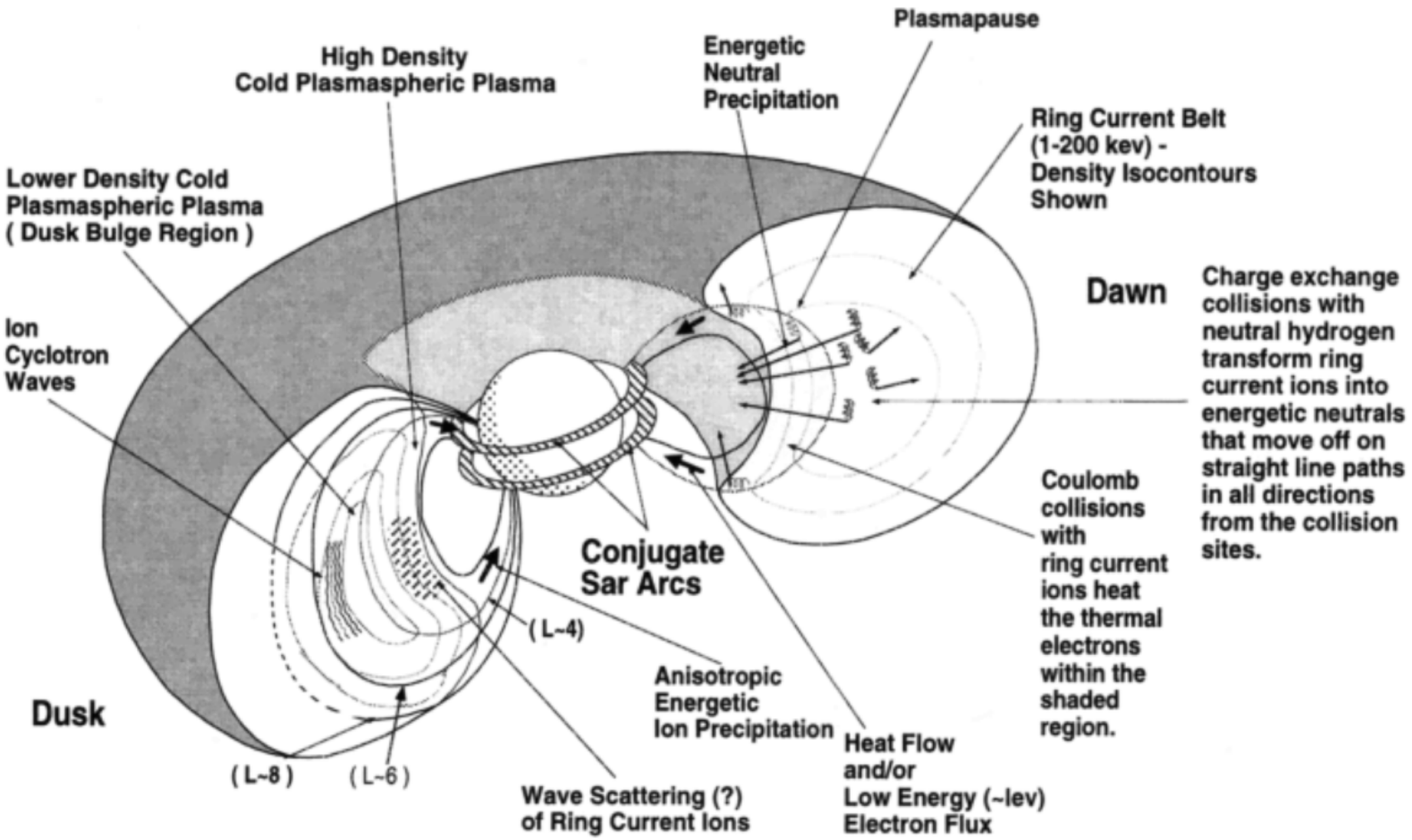


Figure 5. Blowup of the inner magnetosphere showing the overlap between the ring current and plasmasphere and the position of conjugate SAR arc emissions. Major ring current loss processes are summarized.

Historical Geopolitical Context

- Early 1972:   US-Vietnam War
  - The US Navy mined Hai Phong harbor (approved by former President Nixon)
  - Slow/stem flow of war materials
  - All international ships had 72 hours to depart the harbor
  - Other coastal regions of North Vietnam similarly mined in subsequent days

- Mine fields were monitored by aircraft and ship
  - Mines were either magnetically sensitive or multi-factor sensitive
  - Mines (self-sterilized in ~ 6 months)
  - Could be “swept” with appropriate technology