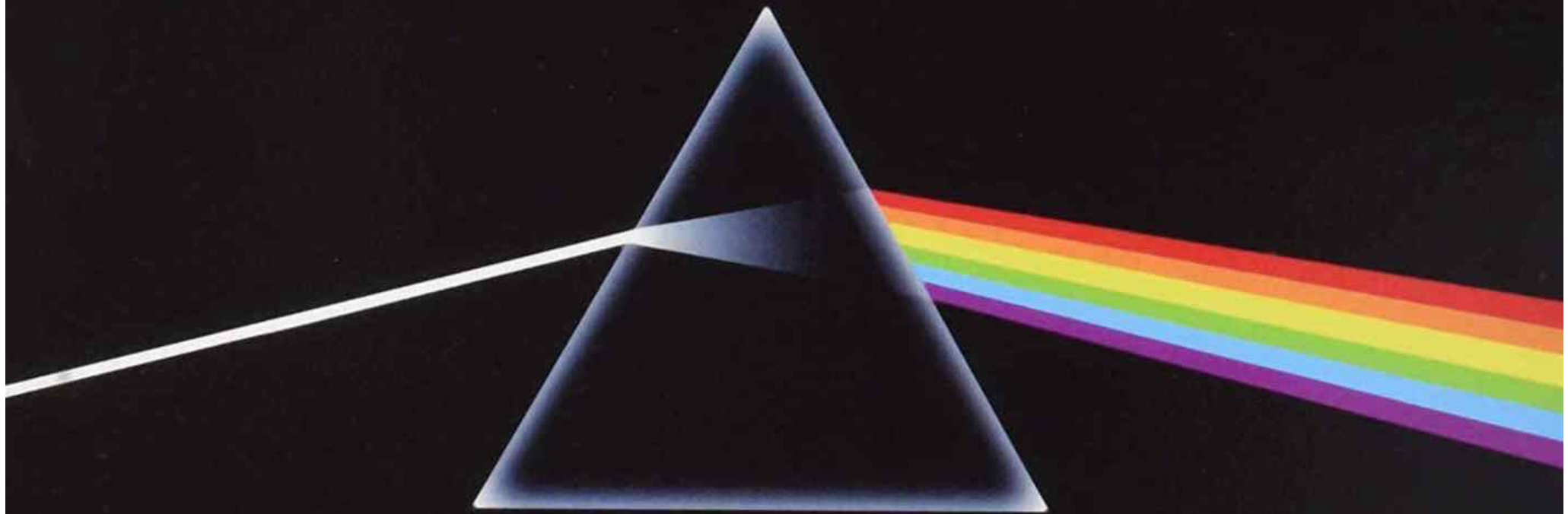


# The Dark Side of the Sun



F. M. Walter

Physics & Astronomy Colloquium

31 March 2026

**1 September 1859**

**A Solar Flare**

(the first ever recorded)

Brighter than the  
surrounding  
photosphere

Motion: AB to CD

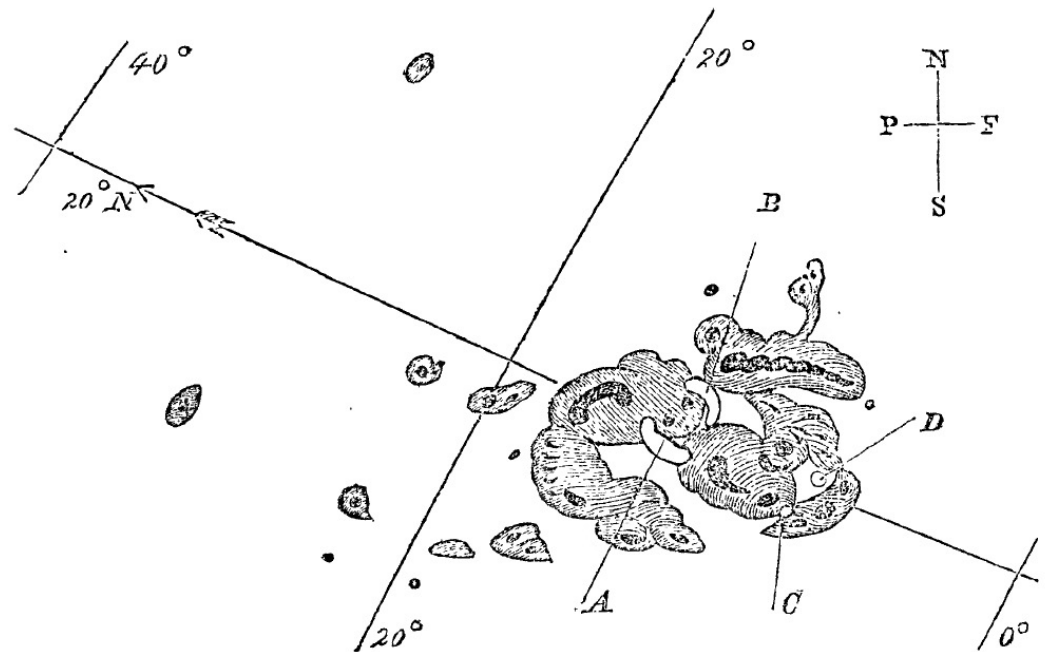
Duration: <5 minutes

Reference:

**MNRAS 20, 13 (1859)**

*Description of a Singular Appearance seen in the Sun on  
September 1, 1859. By R. C. Carrington, Esq.*

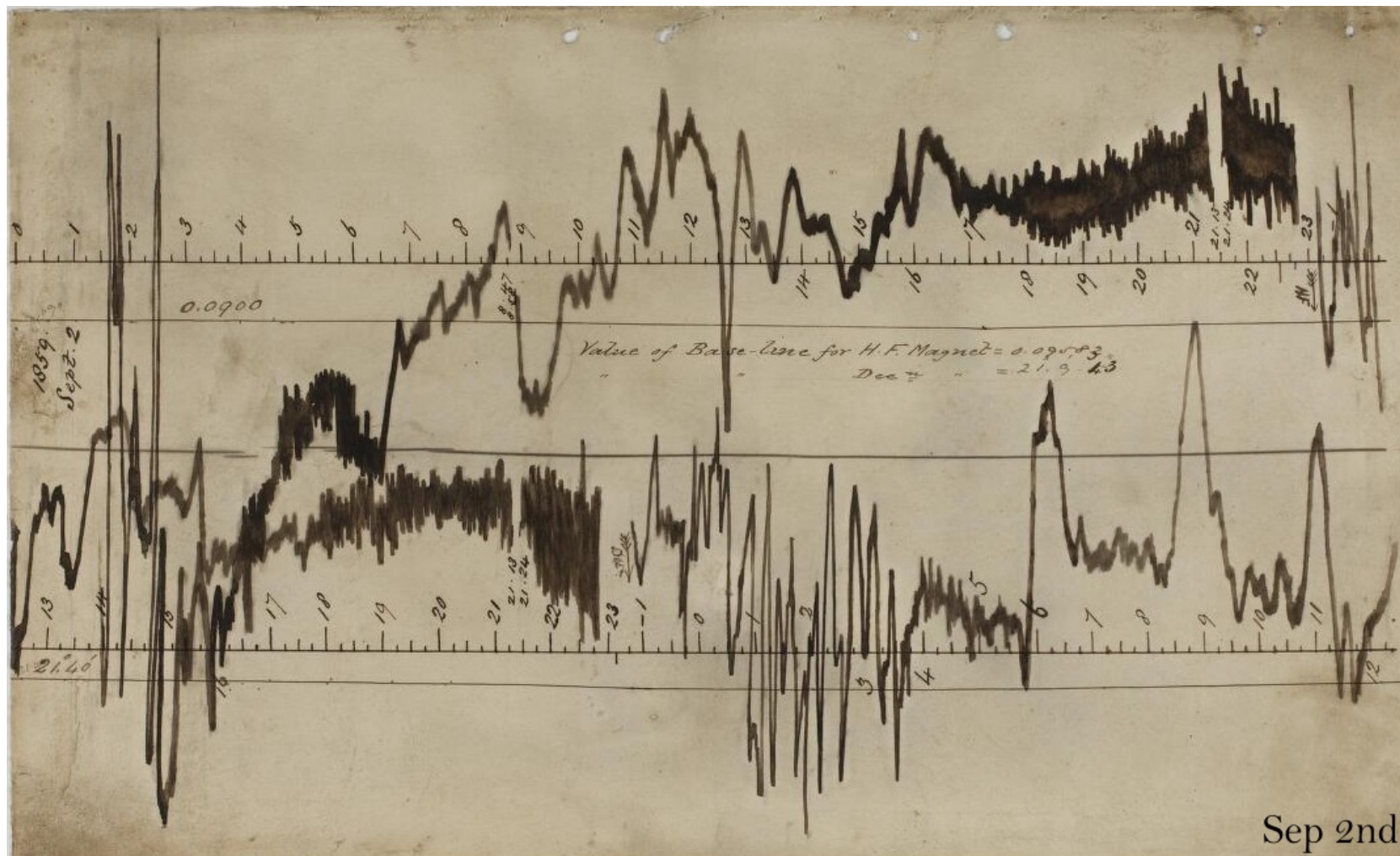
While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

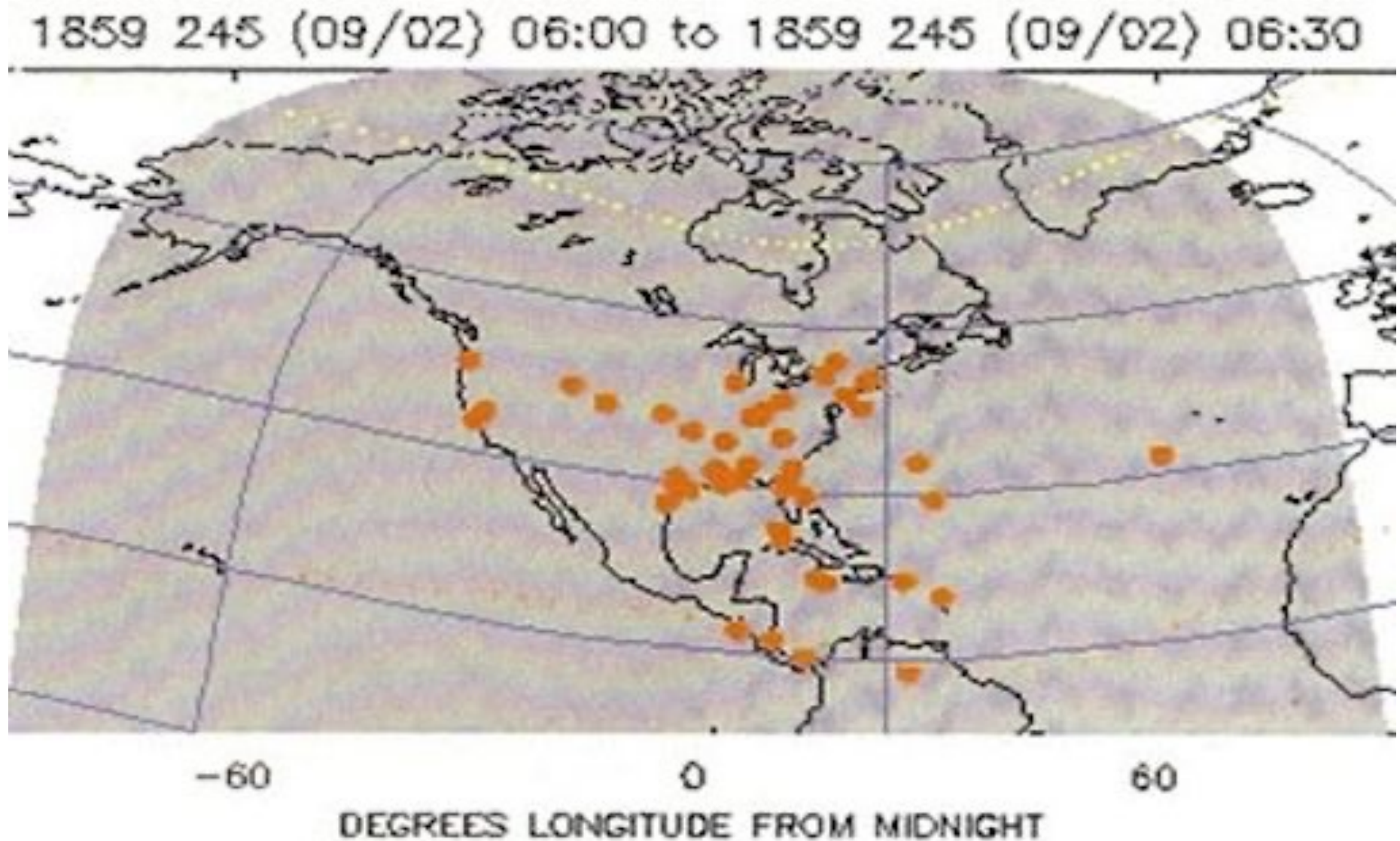
## 2 September 1859: The Aftermath

Earth's magnetic dipole strength depressed -950 nT  
(from a typical 30  $\mu$ T, or by about 3%)



## 2 September 1859: The Aftermath

### Worldwide Aurorae



## 2 September 1859: The Aftermath

Induced currents in telegraph lines

- Telegraphs operated without batteries
- Operators shocked
- Telegraph offices caught fire

### ***The Auroral Display in Boston.***

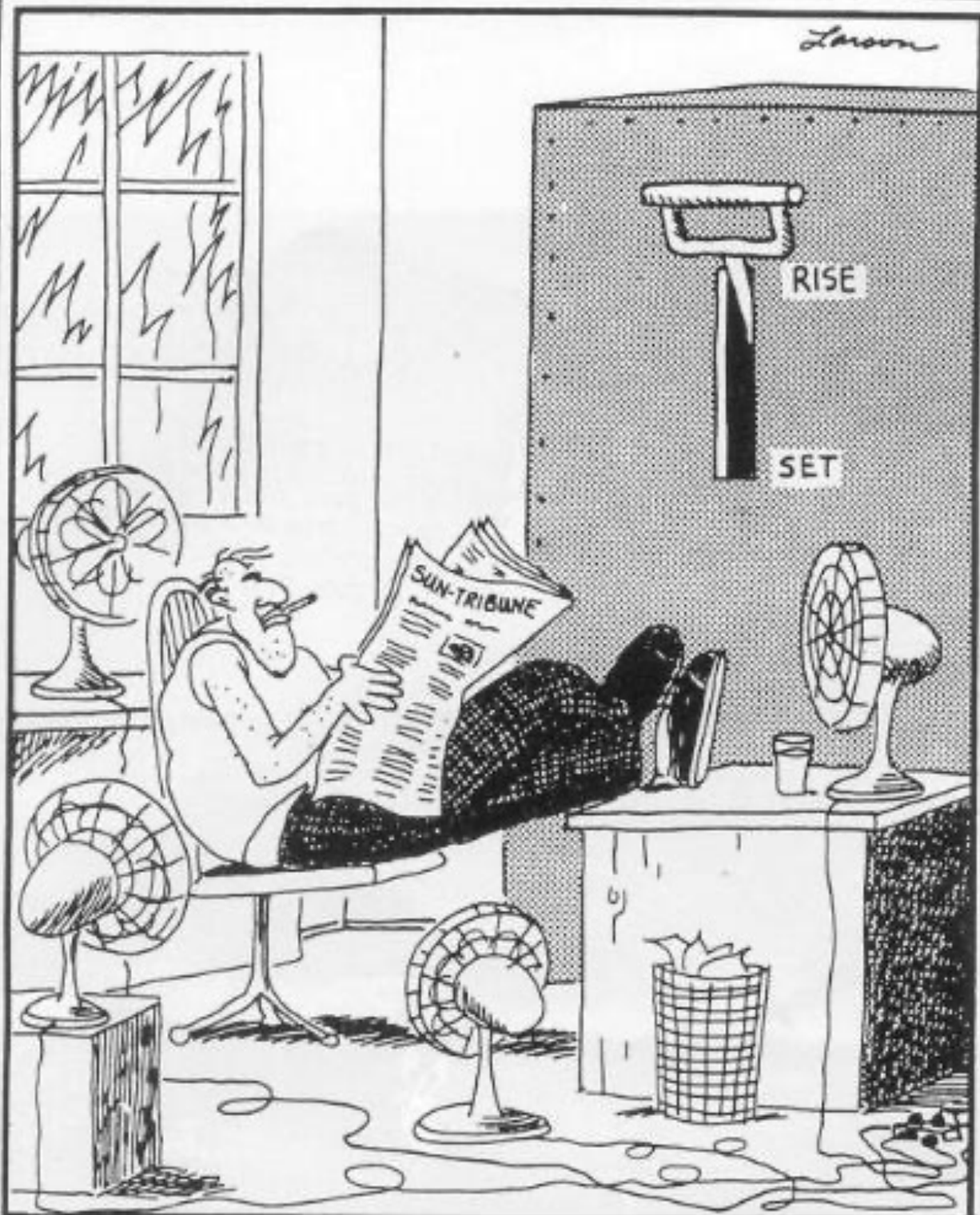
Boston, Friday, Sept. 2.

There was another display of the Aurora last night, so brilliant that at about one o'clock ordinary print could be read by the light. The effect continued through this forenoon, considerably affecting the working of the telegraph lines. The auroral currents from east to west were so regular that the operators on the Eastern lines were able to hold communication and transmit messages over the line between this city and Portland, the usual batteries being discontinued from the wire. The same effects were exhibited upon the Cape Cod and other lines.

**The New York Times**

Published: September 3, 1859

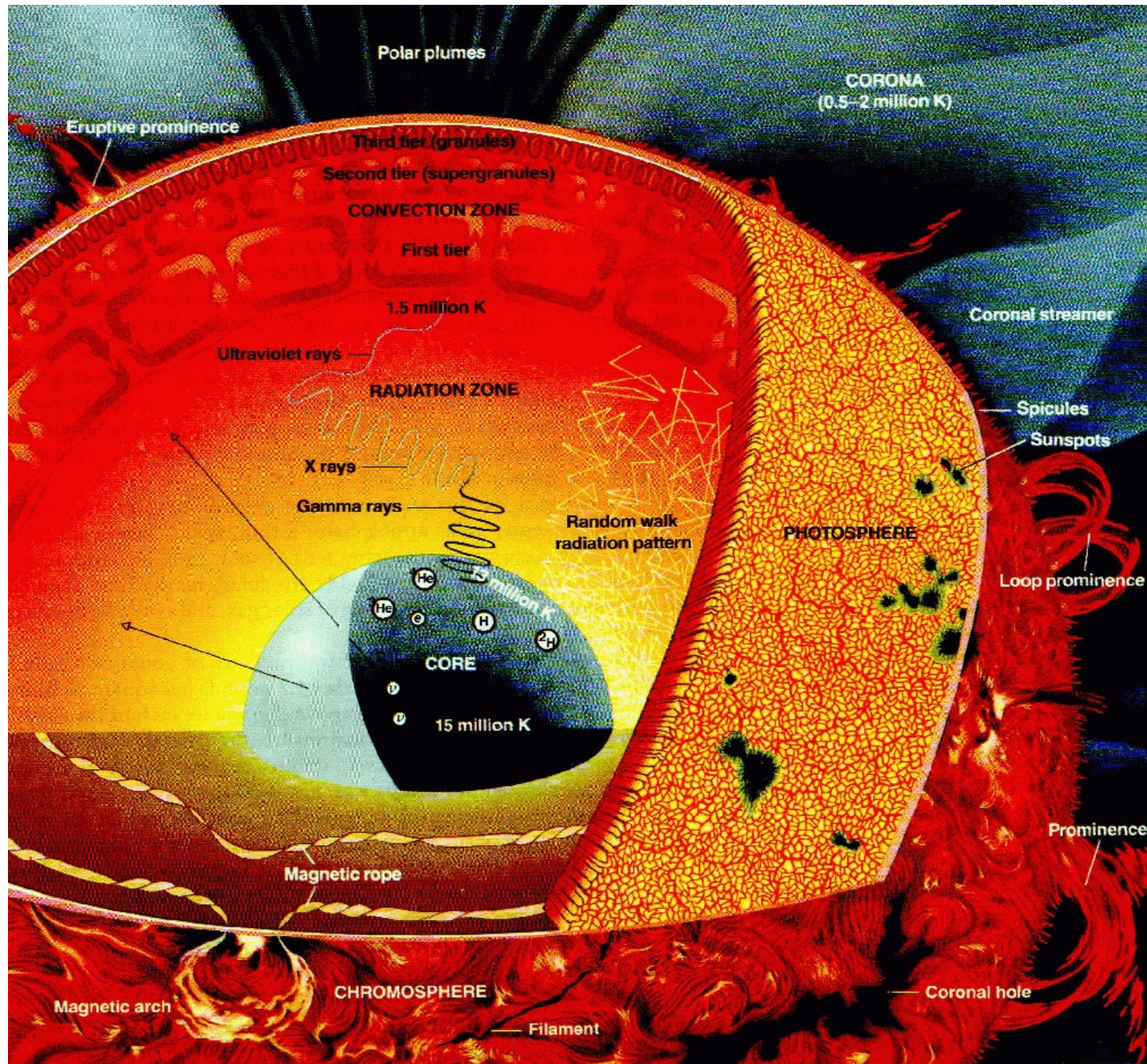
Copyright © The New York Times



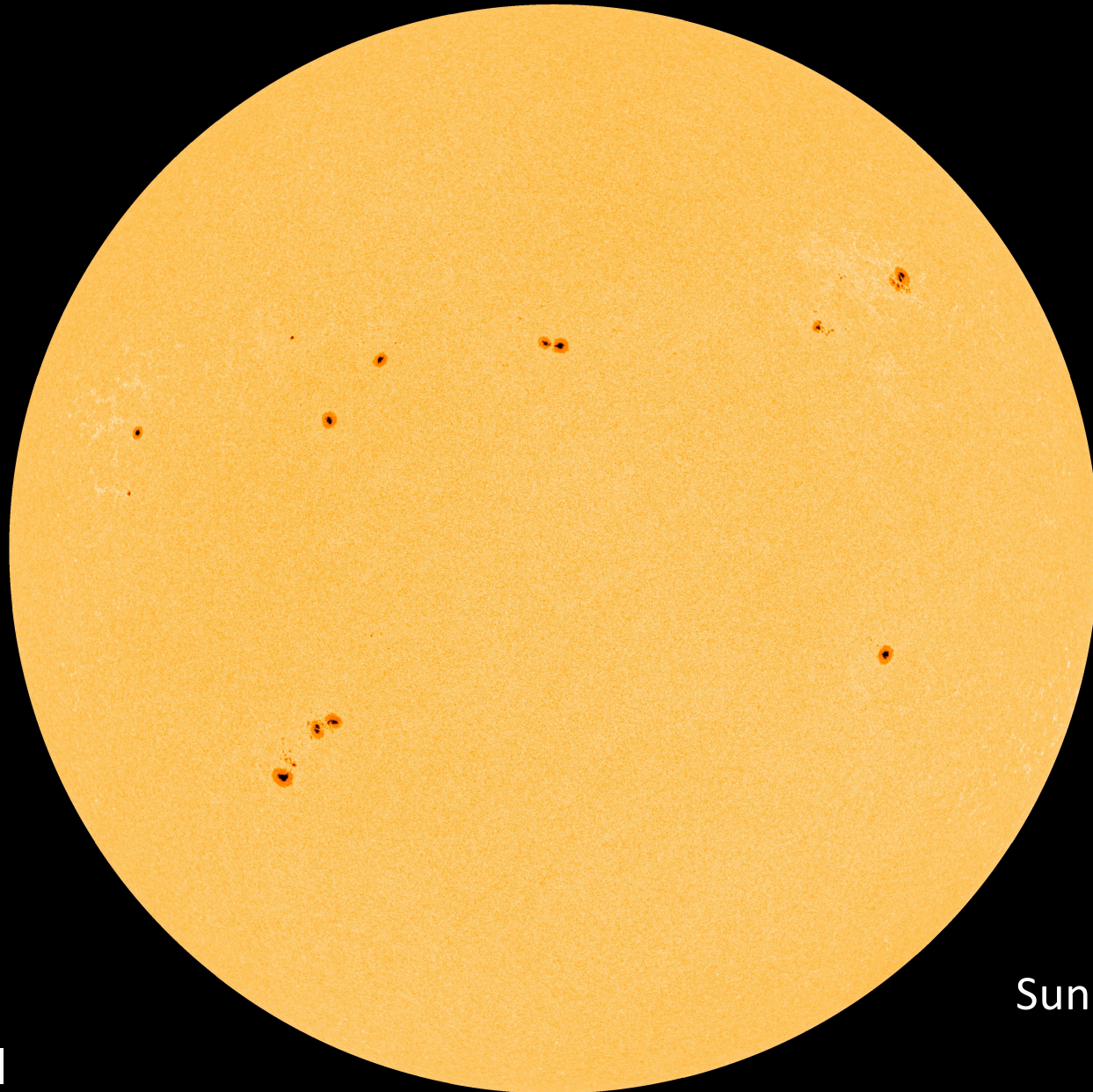
**Inside the  
Sun**

*Far Side*  
Gary Larson

# Anatomy of a Star



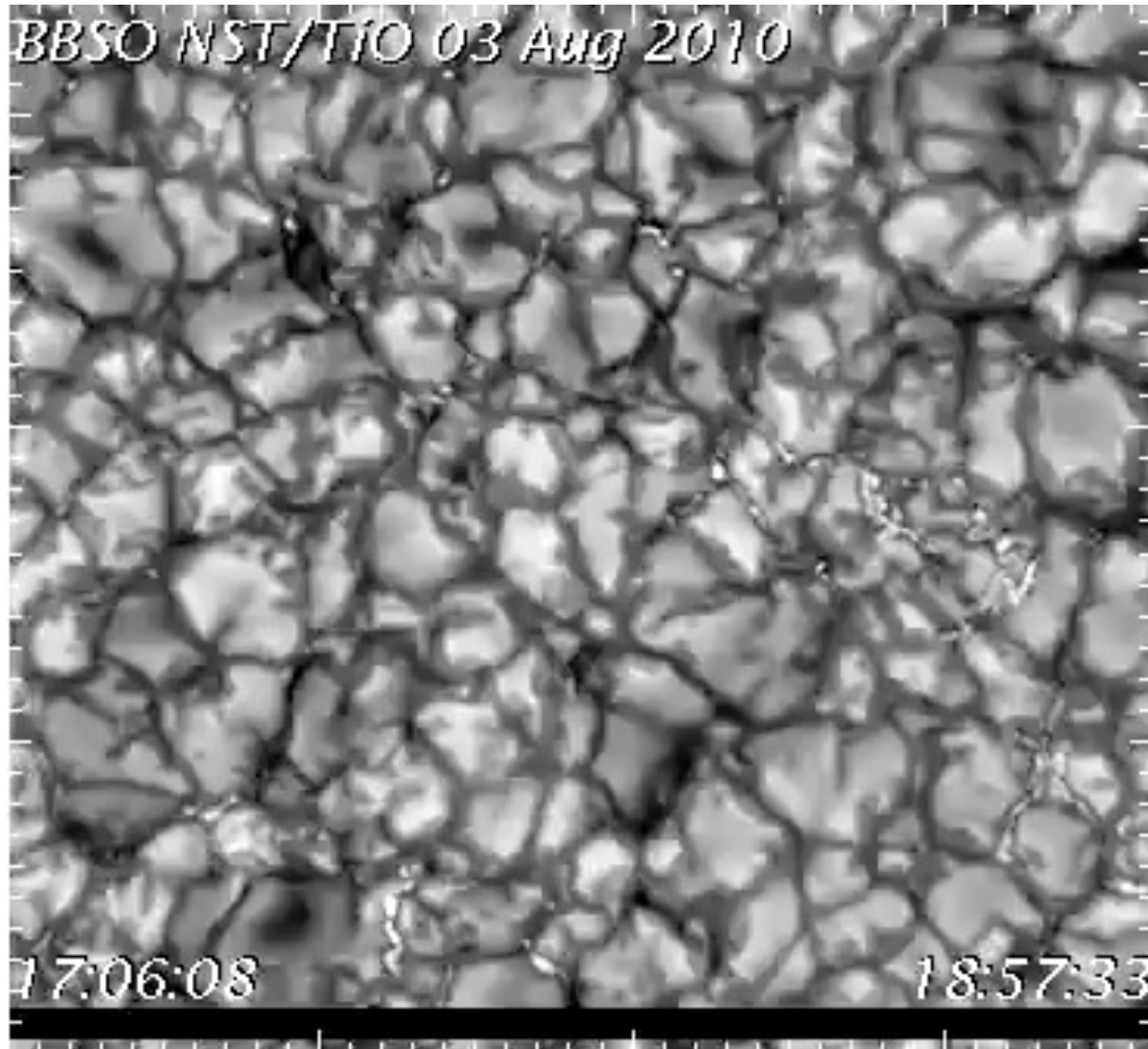
# The Sun Today



260331  
SDO HMI

Sunspot Number:  
143

# Solar Granulation



Real time: 100 minutes

Size: 20,500 x 19,000 km

# Sunspots

## Pressure balance:

Gas pressure + magnetic  
pressure

in spot

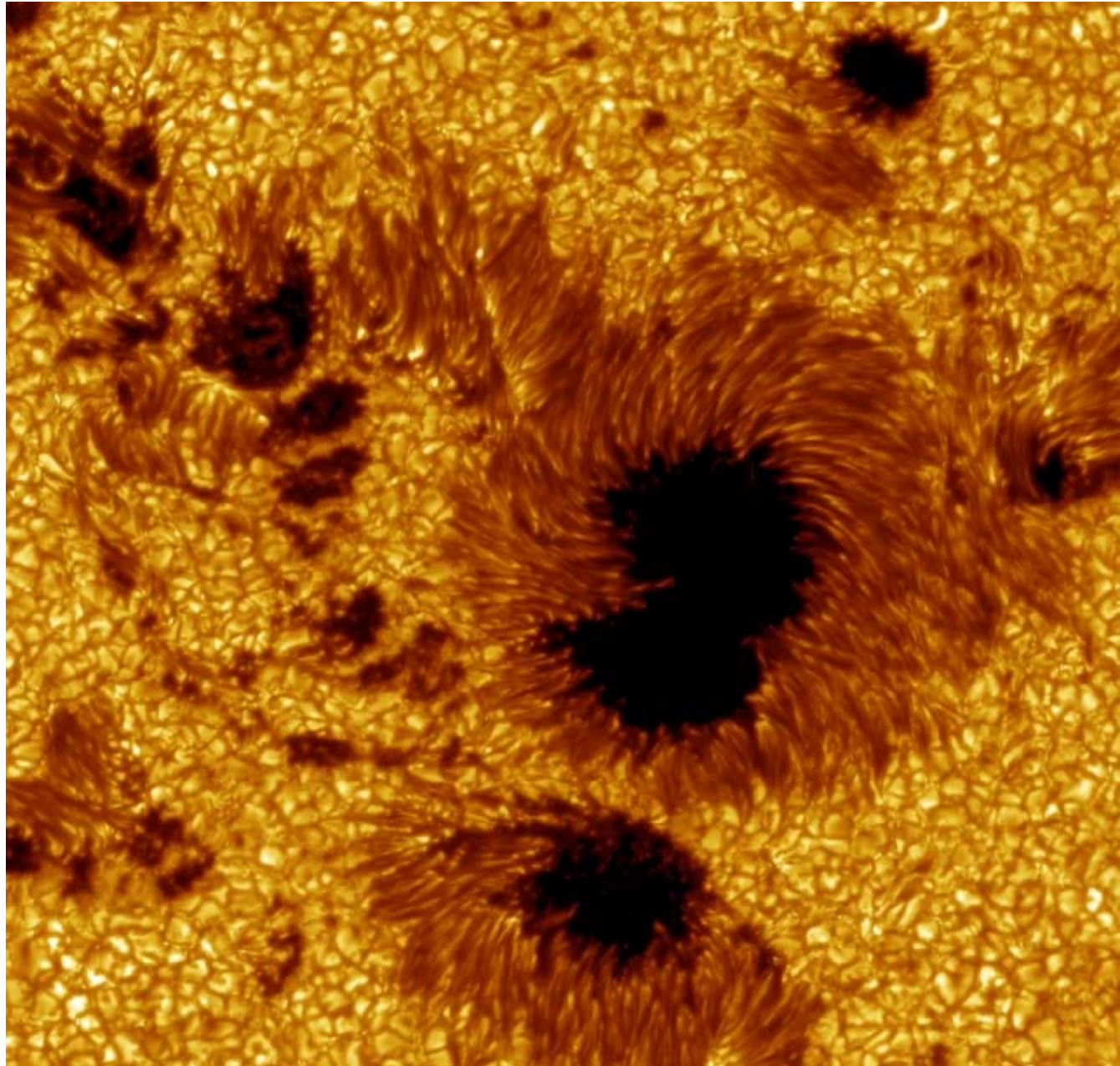
=

gas pressure  
outside spot

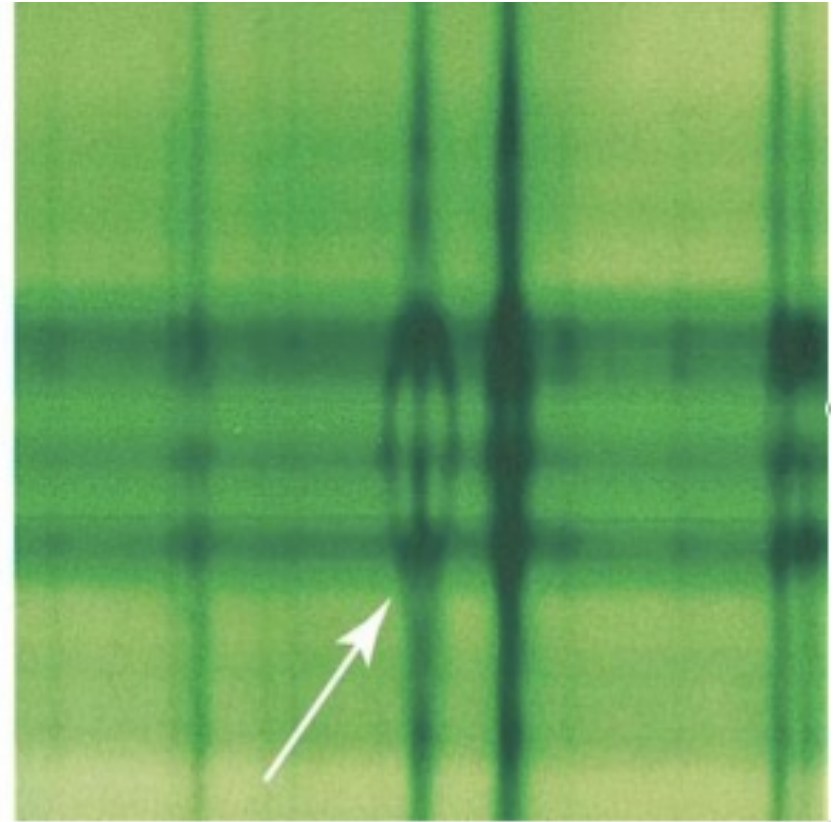
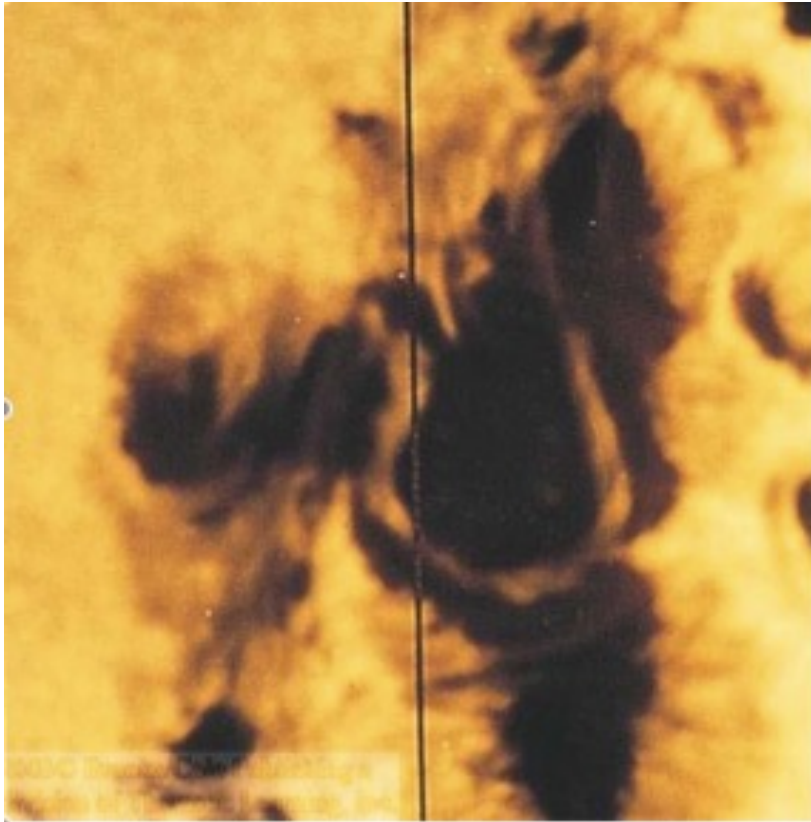
$$nk_B T_s + B^2/8\pi = nk_B T_\odot$$

$$B_s \sim 2\text{kG}$$

$$T_s \sim 4500\text{K}$$



# Photospheric Magnetic Fields



## Zeeman Effect

Line splitting  $\Delta\lambda \propto g'B\lambda^2$

$g'$ : Landé g factor

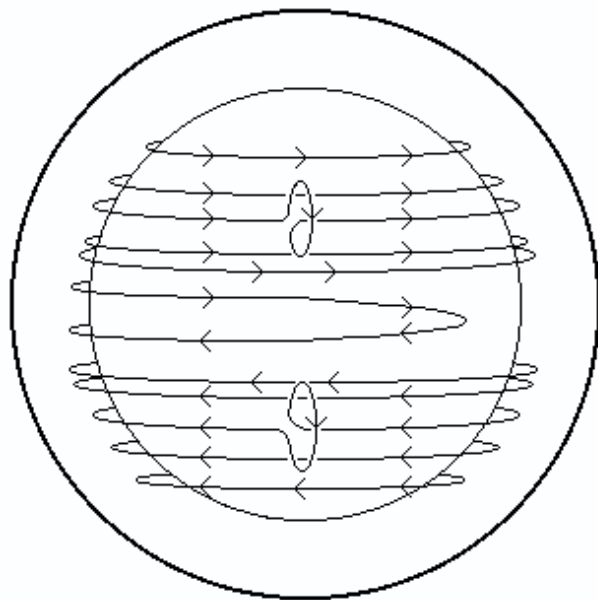
Fe I 6173.3Å

$^5P_1 - ^5D_0$

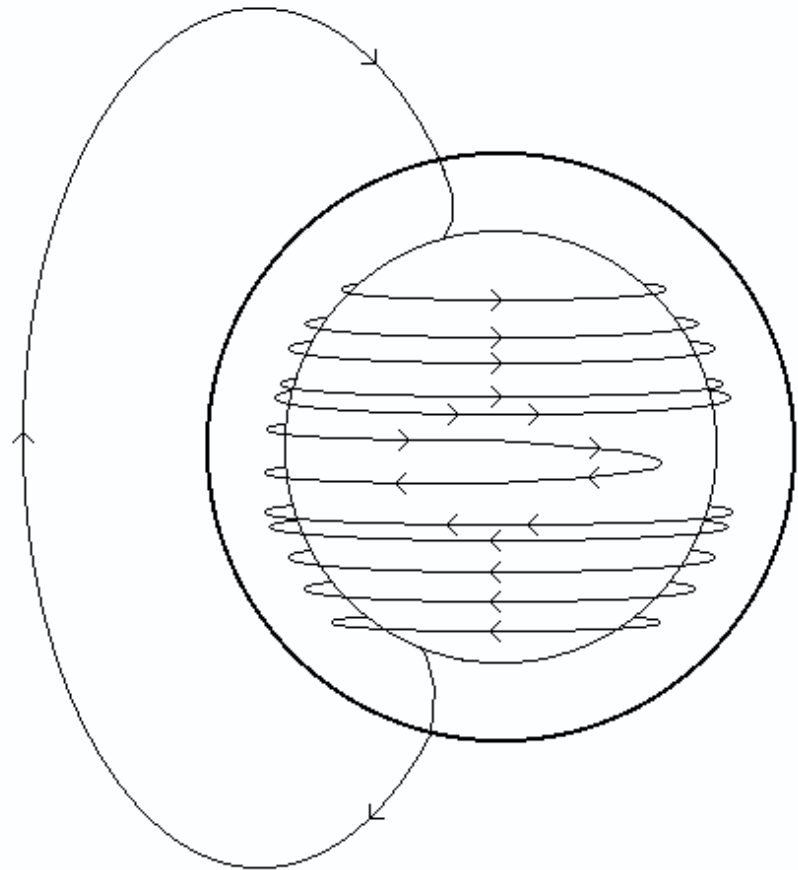
$g'=2.5$

# The Solar Magnetic Field

- Generated in the tachocline
  - The shear layer at the base of the convective zone
- Carried by convecting plasma
- Amplified by  $\alpha$  effect

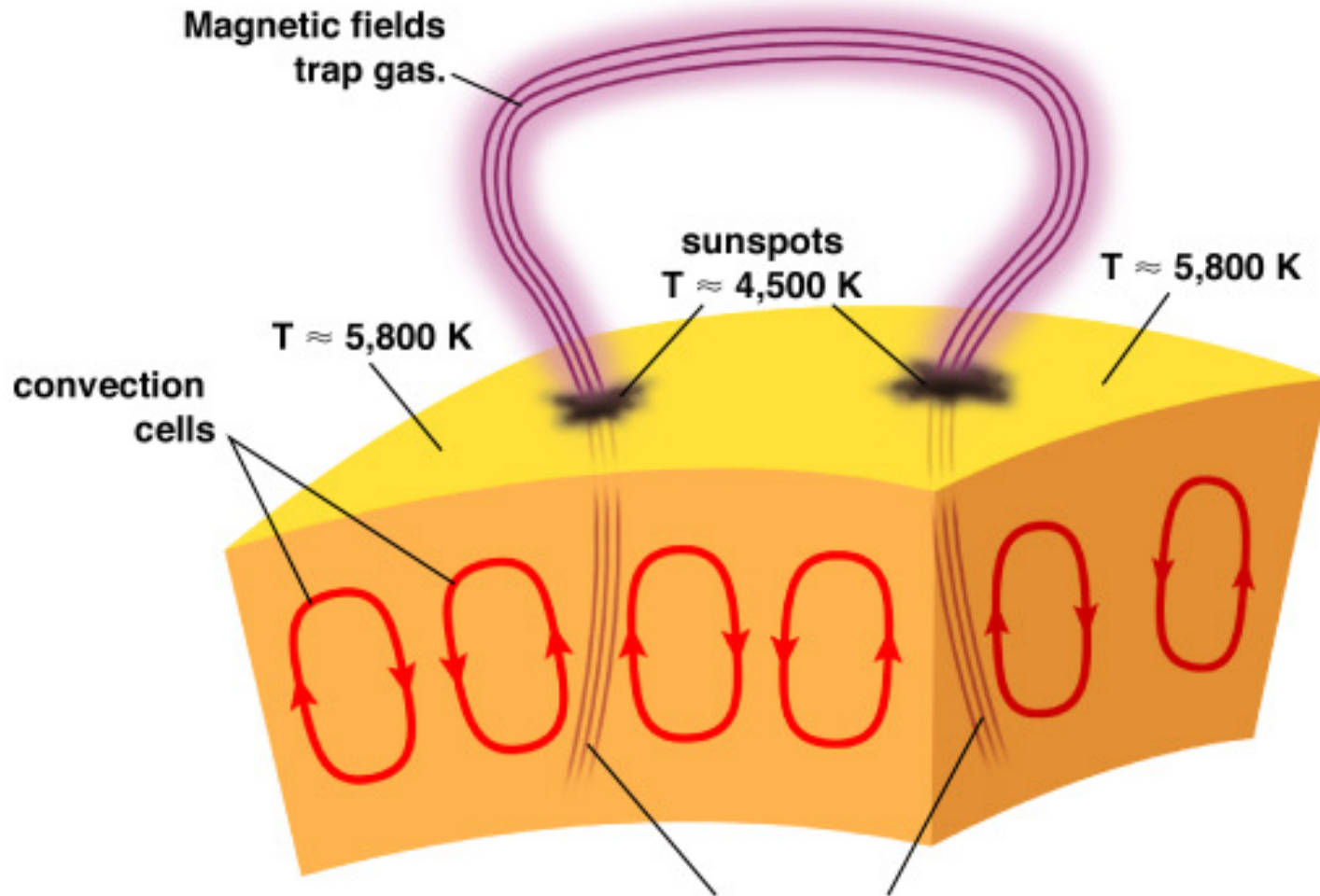


The  $\alpha$ -effect



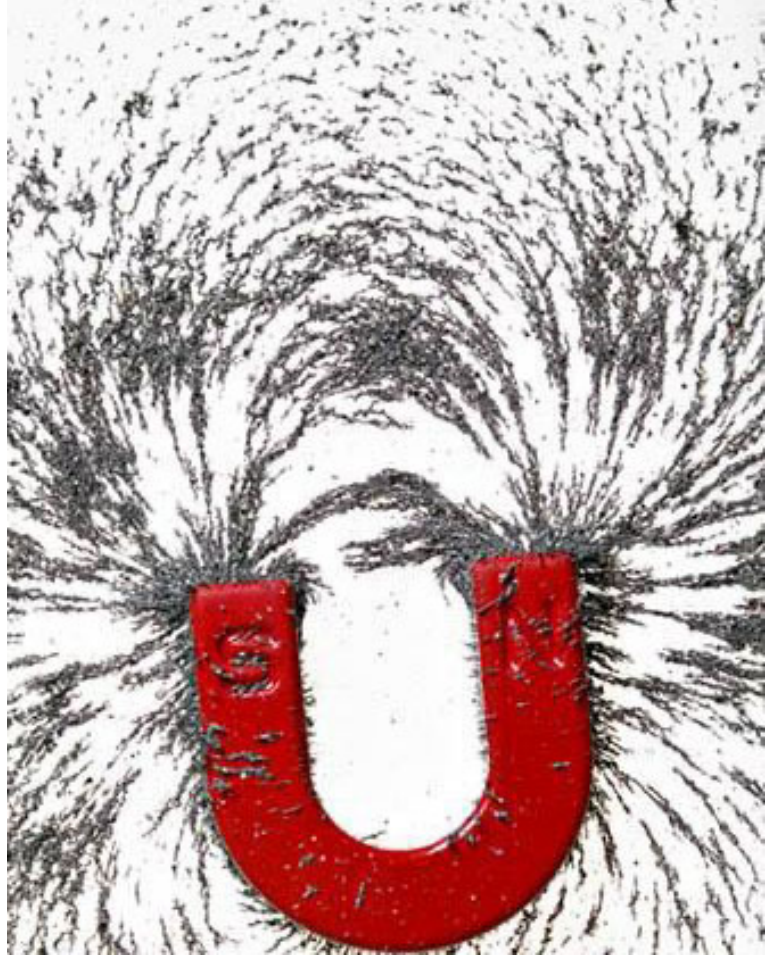
The  $\omega$ -effect

# The Solar Magnetic Field



(b)

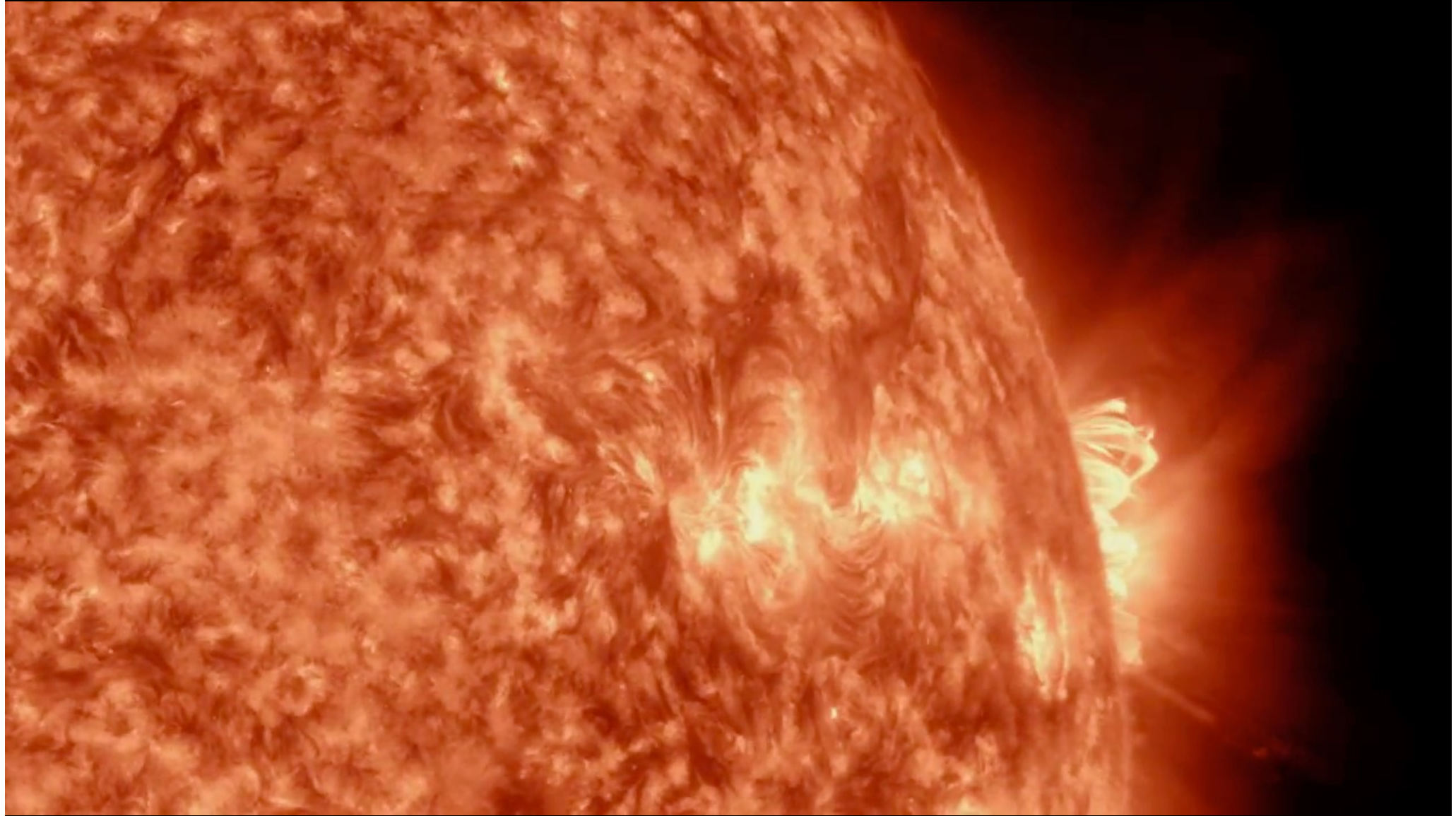
Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.



# Coronal Arcs

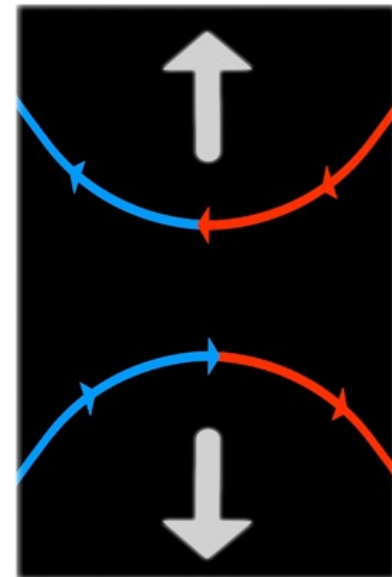
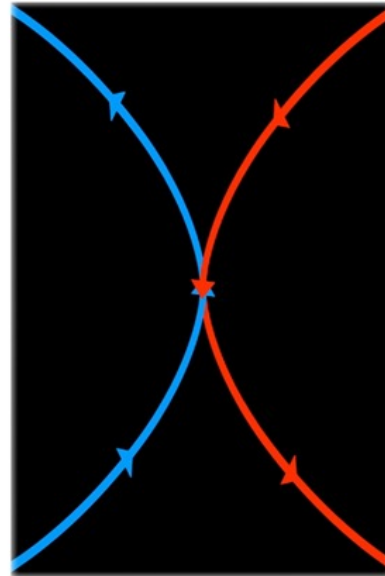
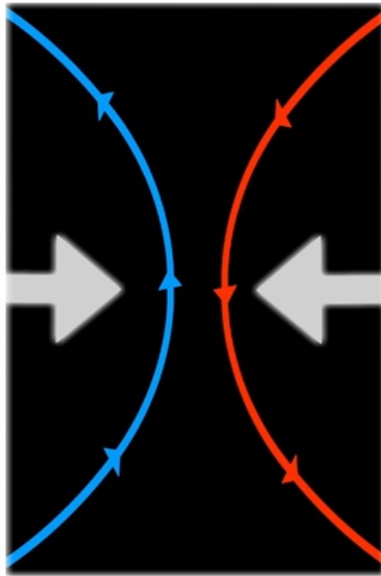


Imaged by TRACE  
Light of Fe IX (173 Å)



AR 2192, October 14-30 2014 He II  $\lambda 304\text{\AA}$

# Magnetic Reconnection

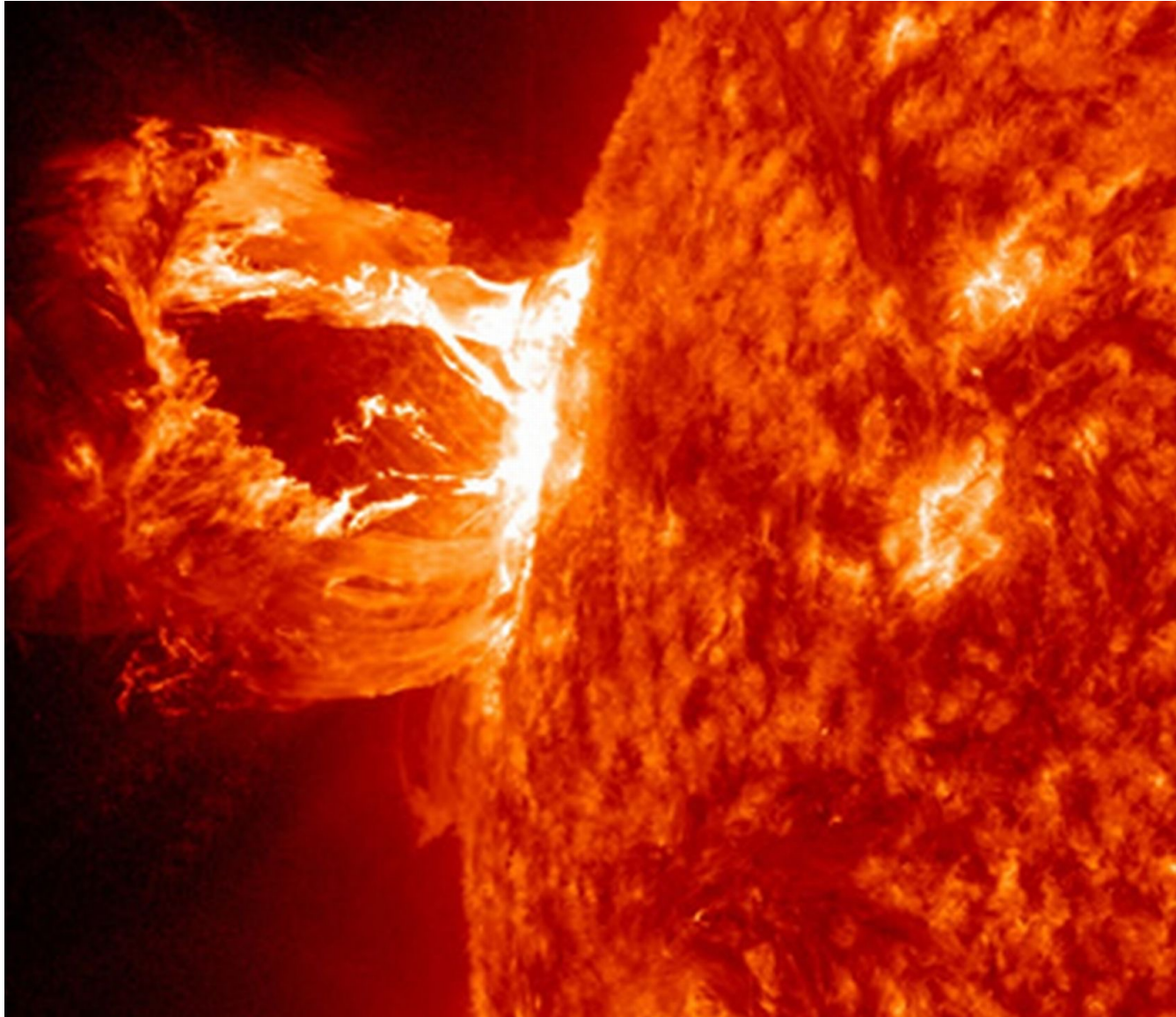


31 Aug 2012 CME

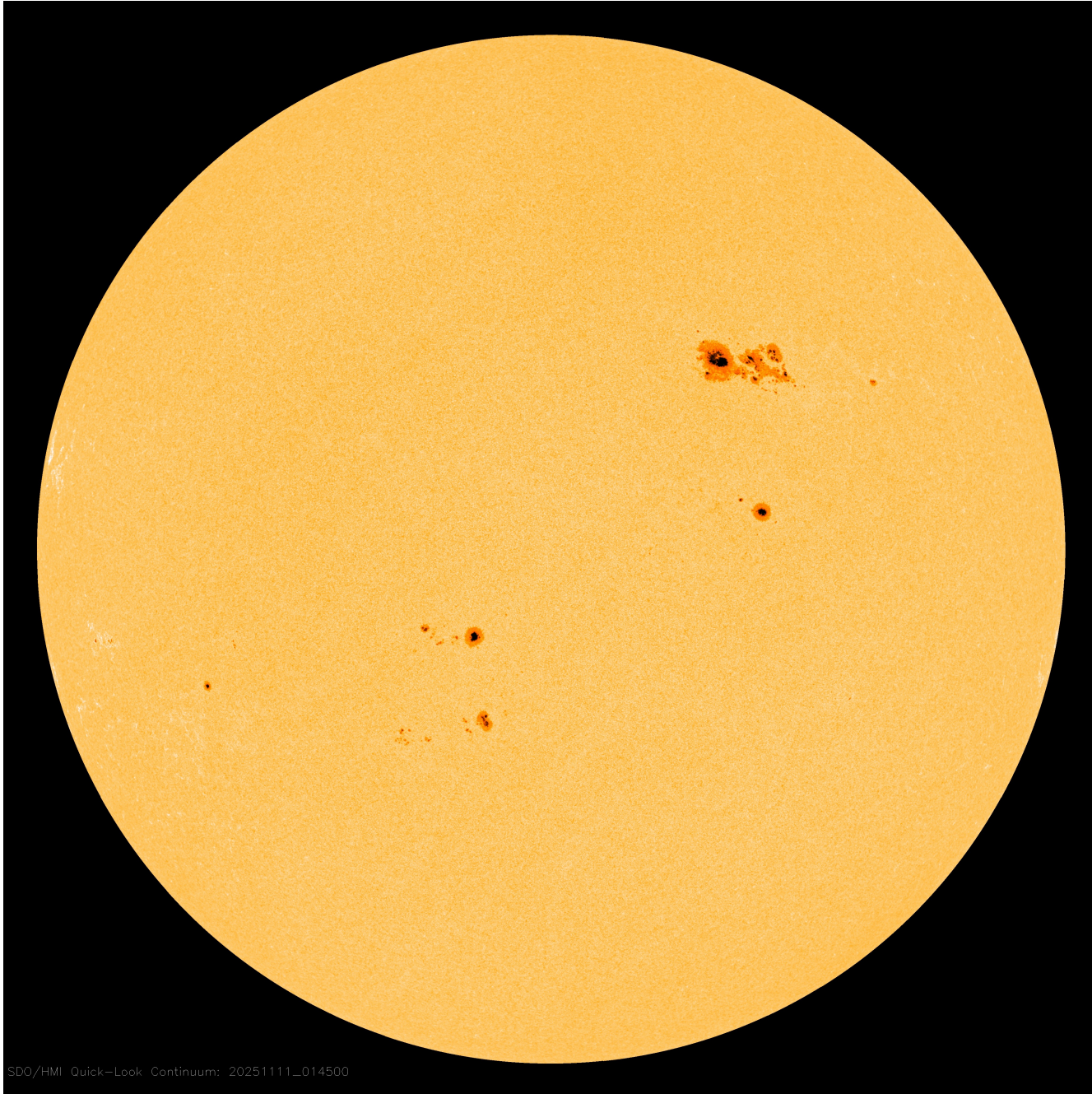
31 Aug 2012 CME

# Coronal Mass Ejections (CME)

- Mass:  
~  $10^{12}$  kg
- Velocity:  
500 km/s  
Up to 3200 km/s

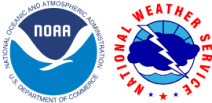


# The 11 November 2025 flare



AR 4274  
SDO HMI

# The 11 November 2025 X5 flare



SPACE WEATHER PREDICTION CENTER  
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Wednesday, November 12, 2025 12:58:43 UTC

[HOME](#) [ABOUT SPACE WEATHER](#) [PRODUCTS AND DATA](#) [DASHBOARDS](#) [MEDIA AND RESOURCES](#) [TESTBED](#) [SUBSCRIBE](#) [WORKSHOP](#) [FEEDBACK](#)

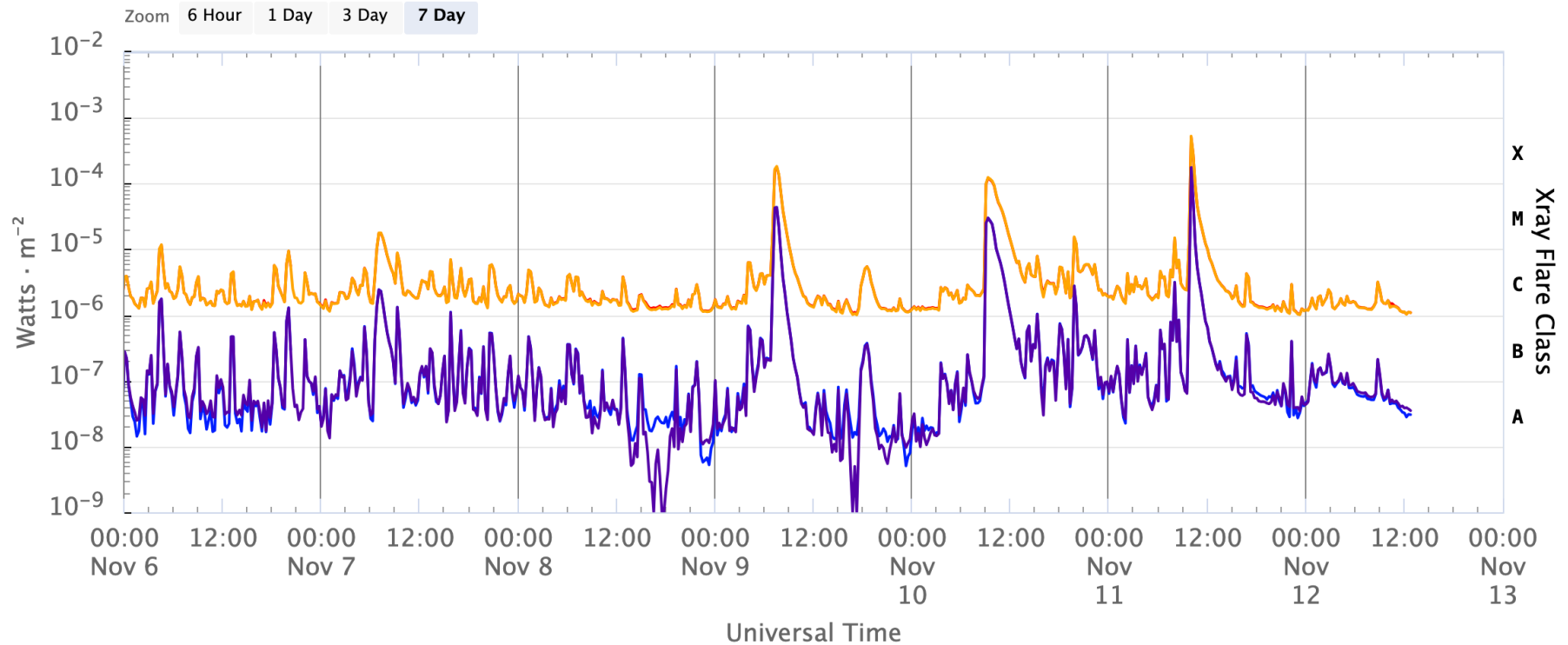
Home > Products and Data > Observations > GOES X-ray Flux

CURRENT SPACE WEATHER CONDITIONS on NOAA Scales

R	S2	G1
none	moderate	minor

## GOES X-RAY FLUX

GOES X-Ray Flux (1-minute data)



# Flare Classification

Flare Class	Peak Flux
A	$10^{-8} \text{ W/m}^2$
B	$10^{-7} \text{ W/m}^2$
C	$10^{-6} \text{ W/m}^2$
M	$10^{-5} \text{ W/m}^2$
X	$10^{-4} \text{ W/m}^2$

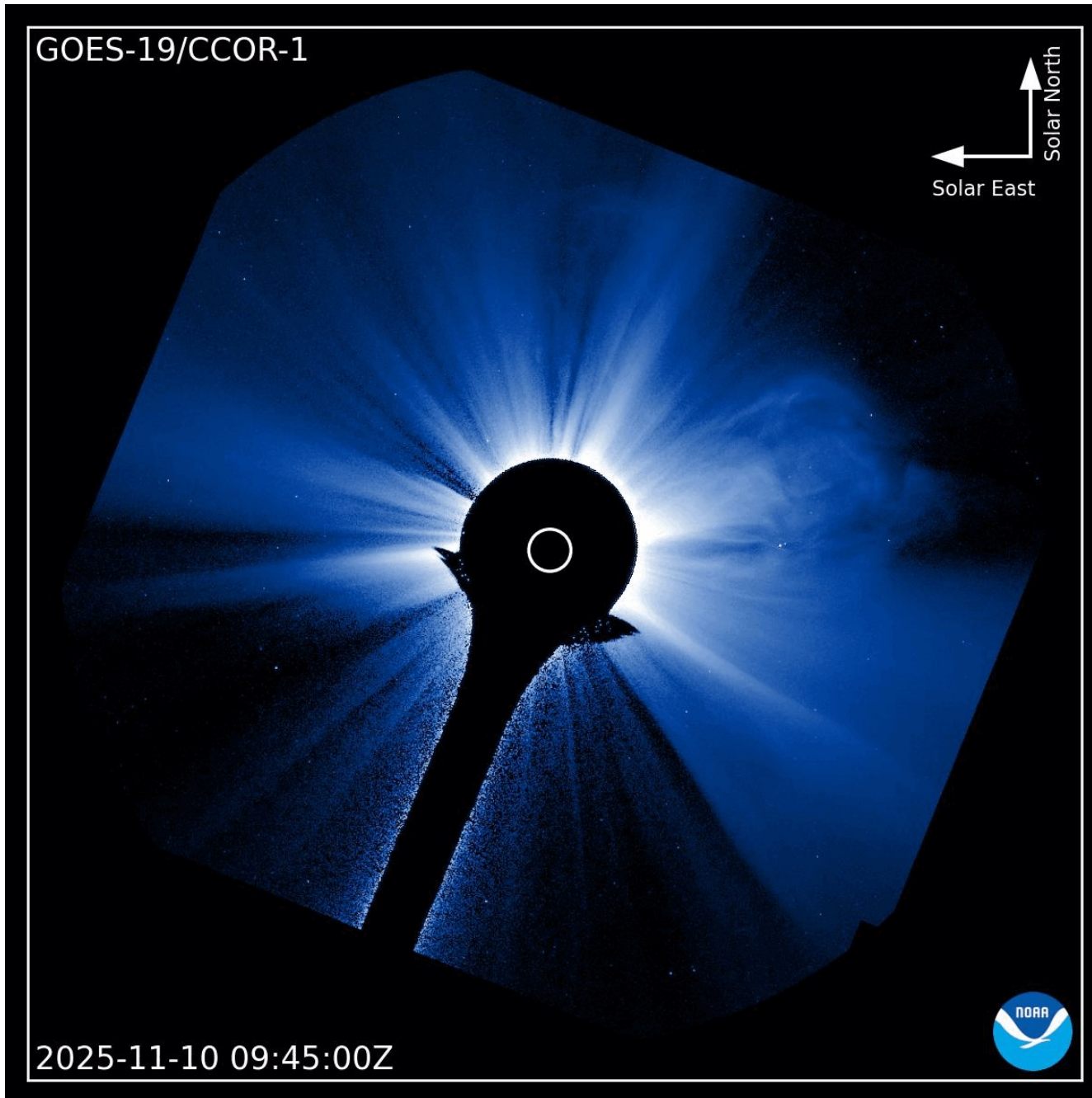
Subclasses 1.0-9.9 are linear

X subclasses are unlimited

X1 corresponds to  $2.8 \times 10^{26} \text{ erg/s}$ , or  $7 \times 10^{-8} L_{\odot}$  (about  $3 \times 10^4 \text{ MT/s}$ )

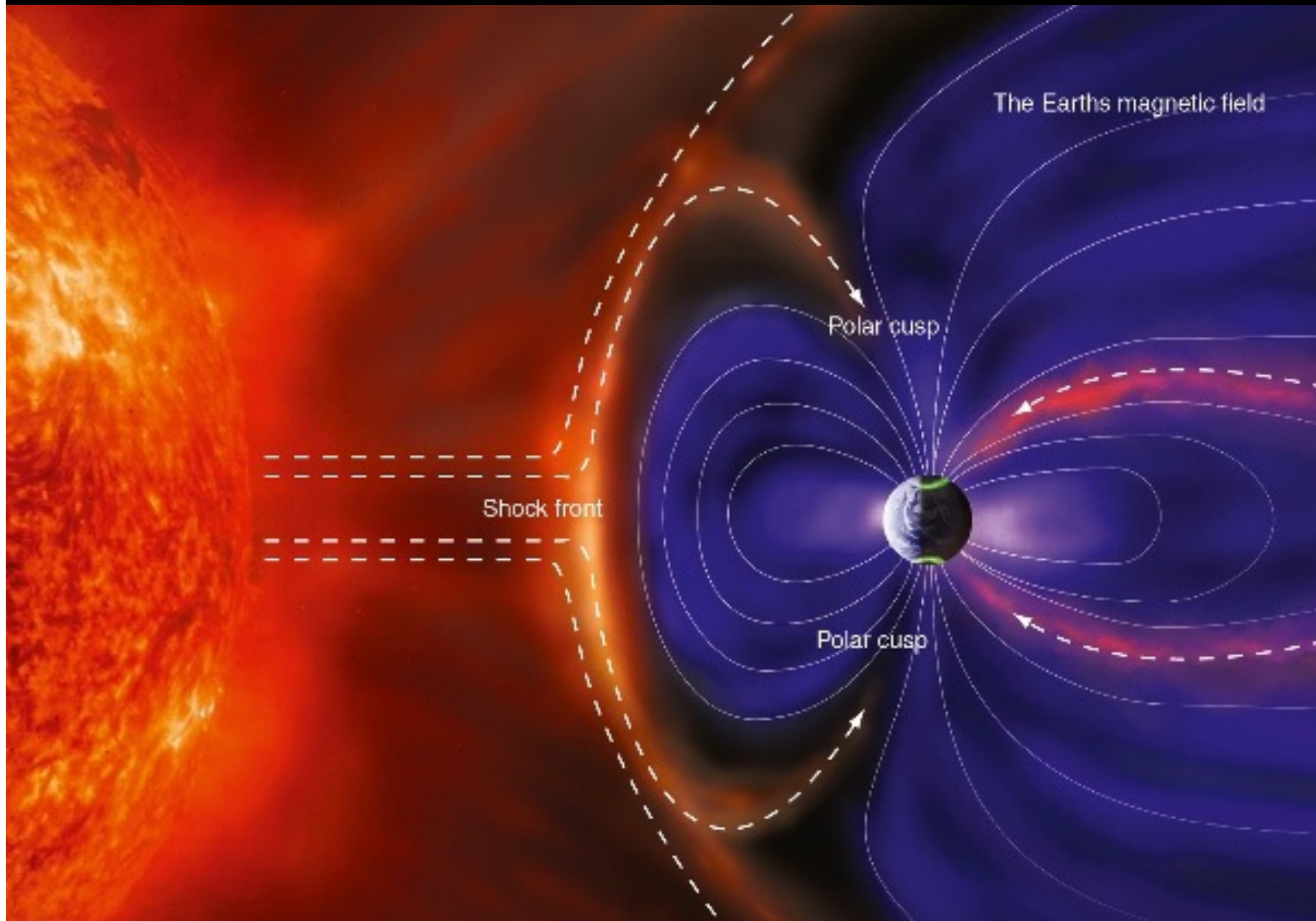
About 30% of flare radiation is radiated in 1-8 keV X-rays

# The 11 November 2025 flare

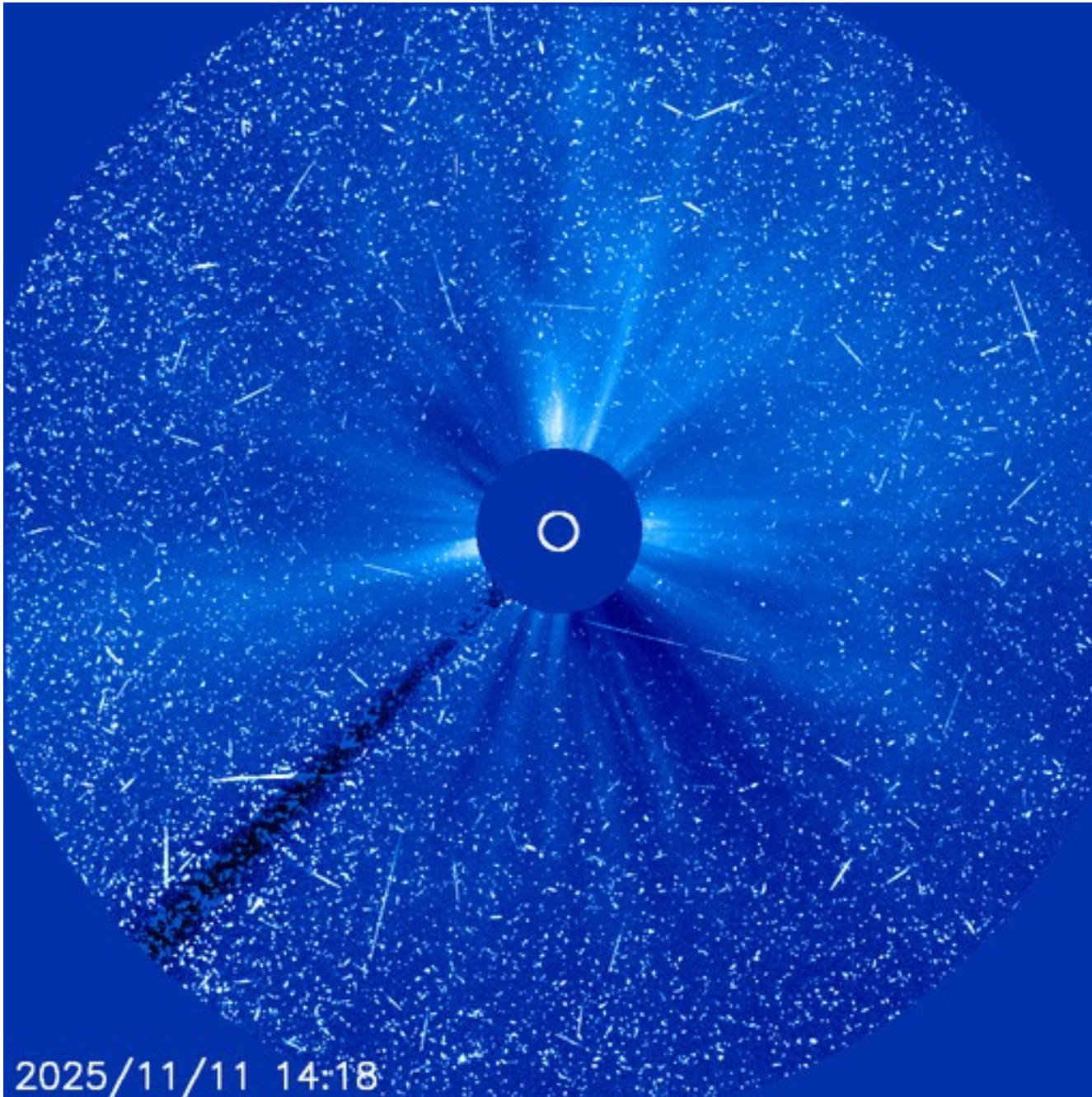


Halo CME

# When a CME Reaches Earth



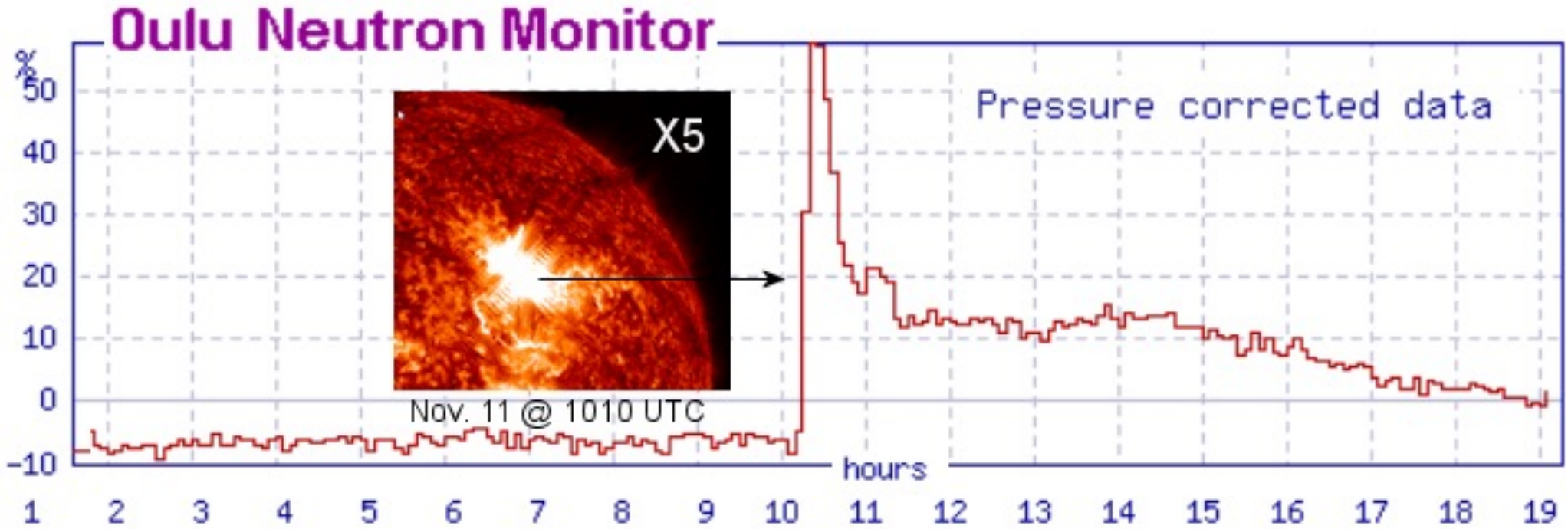
# The 11 November 2025 flare



Solar  
energetic  
protons  
(SPE)

SOHO  
L1

# The 11 November 2025 flare



Primary source of atmospheric  $^{14}\text{C}$ :  $^{14}\text{N}$  (n,p)  $^{14}\text{C}$

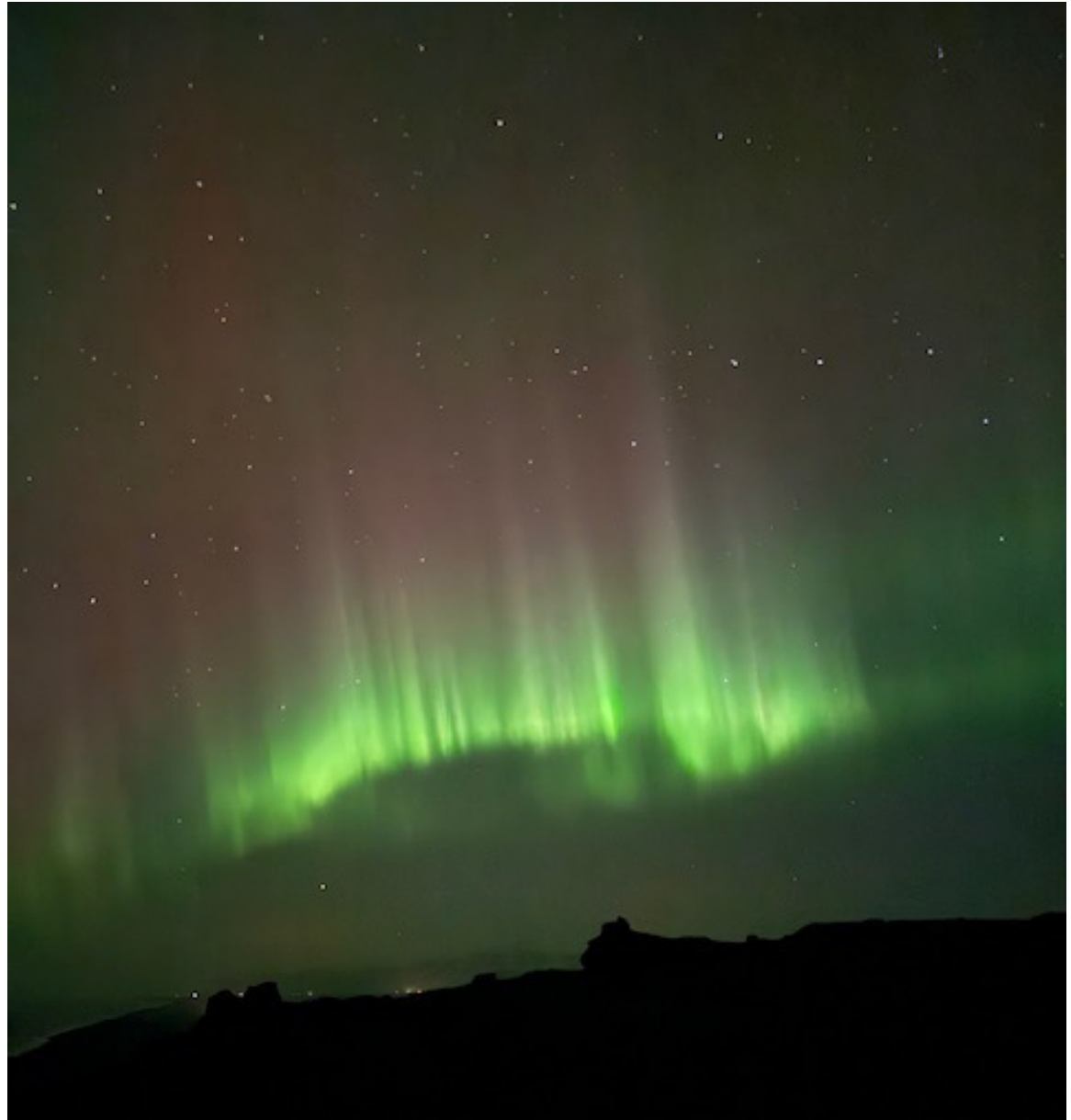
# The 11 November 2025 flare

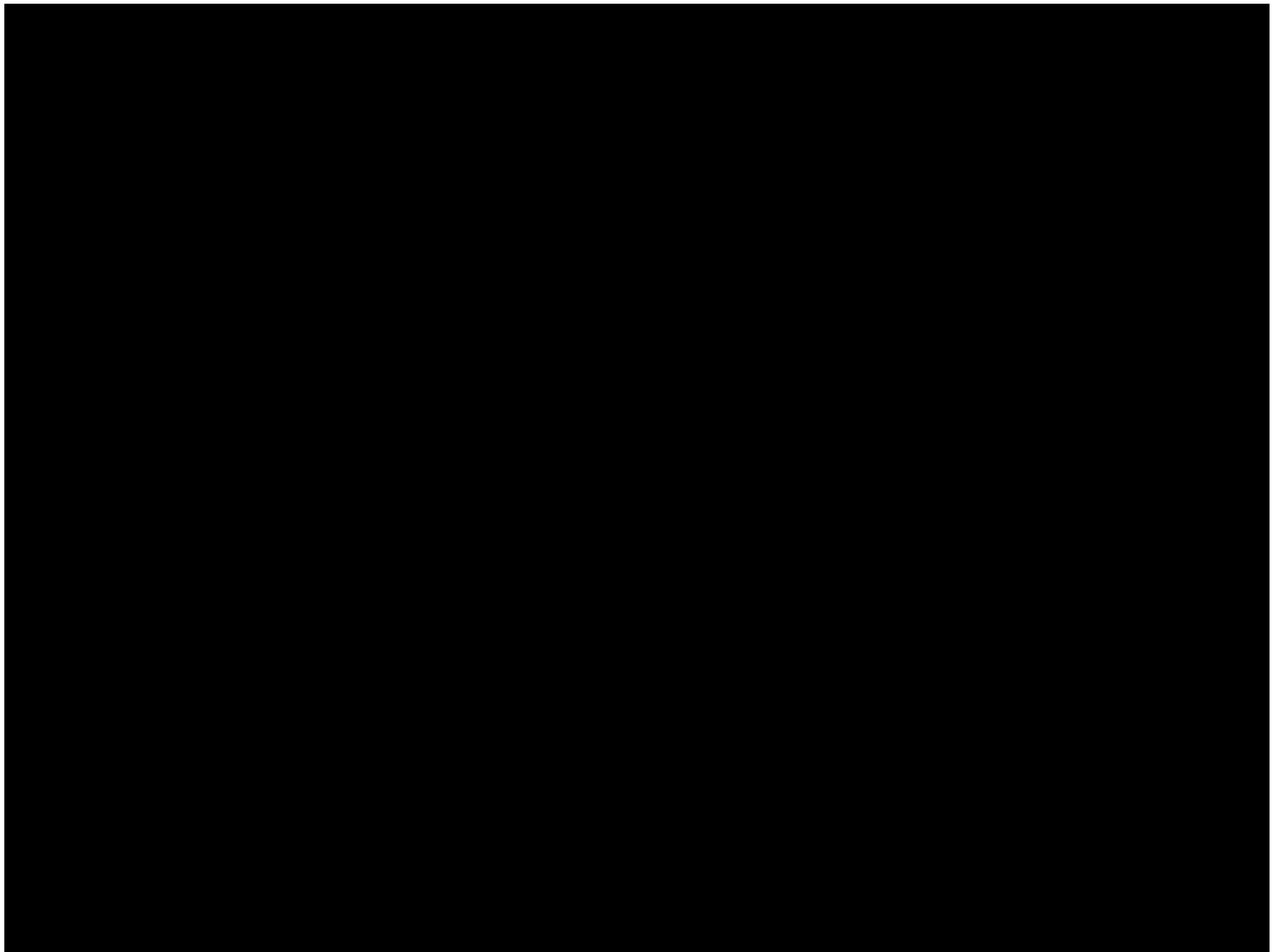


Aurora Borealis 11/12/25; ESS; Timothy Glotch

# Consequences of a CME

- Aurora
  - [O I] 6300 (red)
  - [O I] 5577 (green)

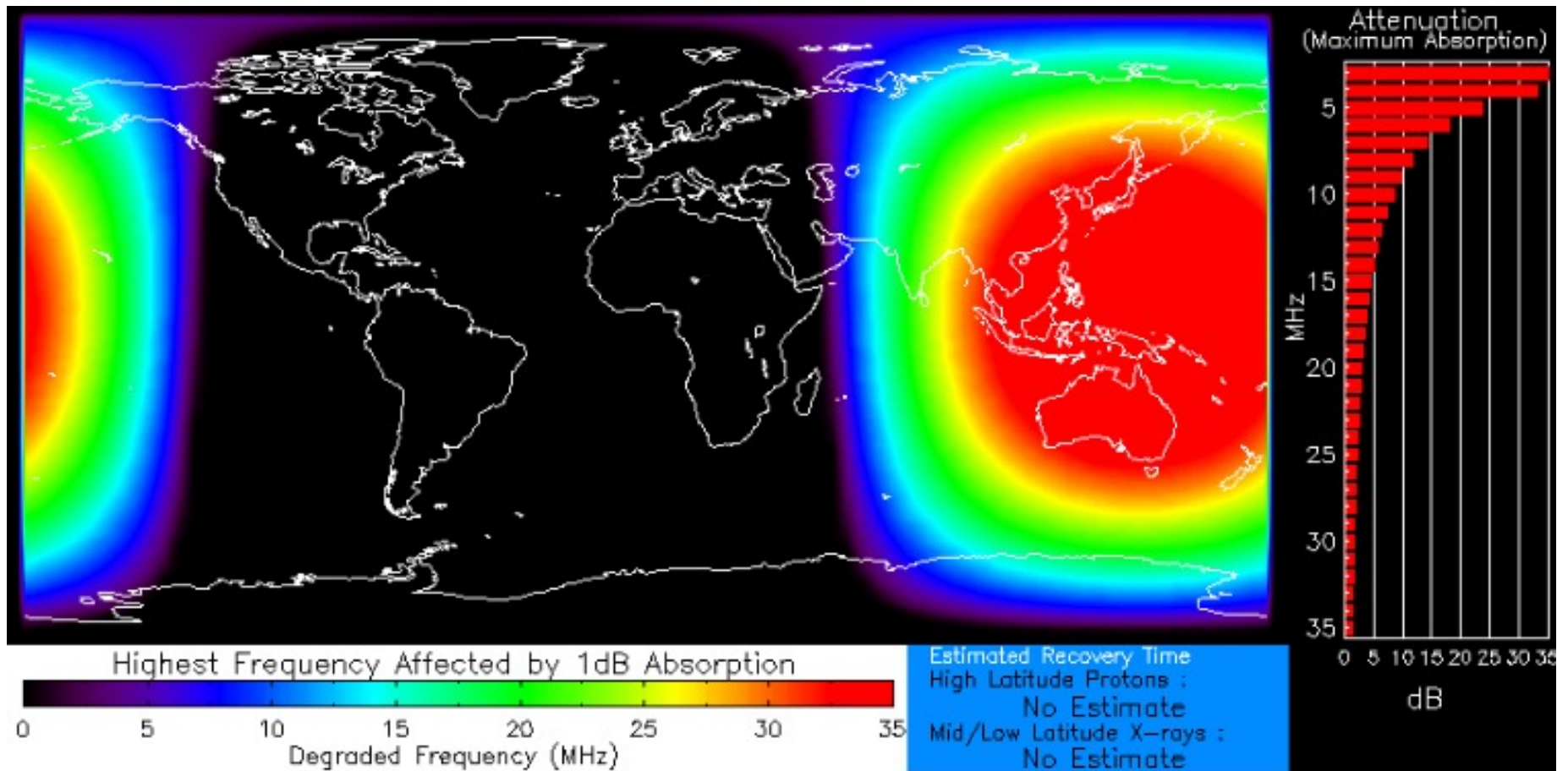






# Consequences of a CME

- Aurora
- Radio blackouts



Strong X-ray flux  
Product Valid At : 2023-03-29 02:34 UTC

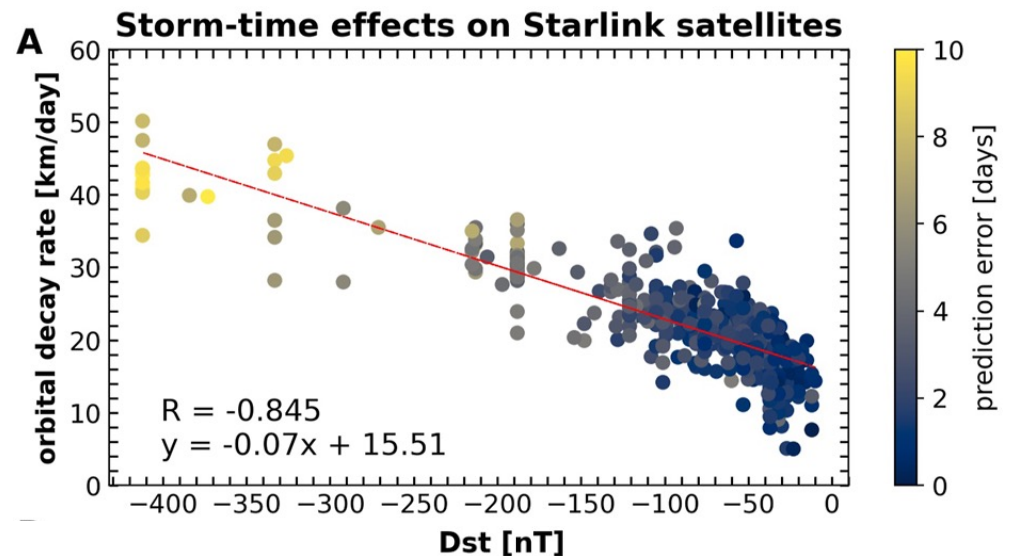
Normal Proton Background  
NOAA/SWPC Boulder, CO USA

# Consequences of a CME

- Aurora
- Radio blackouts
- Exospheric heating
  - Enhanced drag
  - 2/22/22 example:  
38/49 Starlinks re-entered within days of launch during a geomagnetic storm.  
Dst=-100 nT.  
Cost ~ \$100 million  
Guarnieri , F.L. *et al.* 2025, NPG **32**, 75–88.  
<https://doi.org/10.5194/npg-32-75-2025>

When tens of thousands of Starlink satellites get lost:

Beware the Kessler effect



Olivera, D.M., Zesta, E. & Garcia-Sage, K., 2025, *Front. Astron. Space Sci.* **12**  
<https://doi.org/10.3389/fspas.2025.1572313>

*Tracking reentries of Starlink satellites during the rising phase of solar cycle 25*

# Consequences of a CME

- Aurora
- Radio blackouts
- Exospheric heating
- Enhanced radiation exposure
  - Astronauts
  - Aircraft on polar routes

# Consequences of a CME

- Aurora
- Radio blackouts
- Exospheric heating
- Enhanced radiation exposure
  - Astronauts
  - Aircraft on polar routes
- **GPS anomalies**
  - Positional errors of 50-100m for aircraft **on ground** during May 2024 storm; Schmölter & Berdermann, 2025, *Space Weather* **23**, e2025SW004718
  - “SOLAR STORMS ARE DRIVING FARMERS CRAZY”  
*spaceweather.com*, 12/9/24

# Induced Currents

Charged particles generate electric and magnetic fields

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

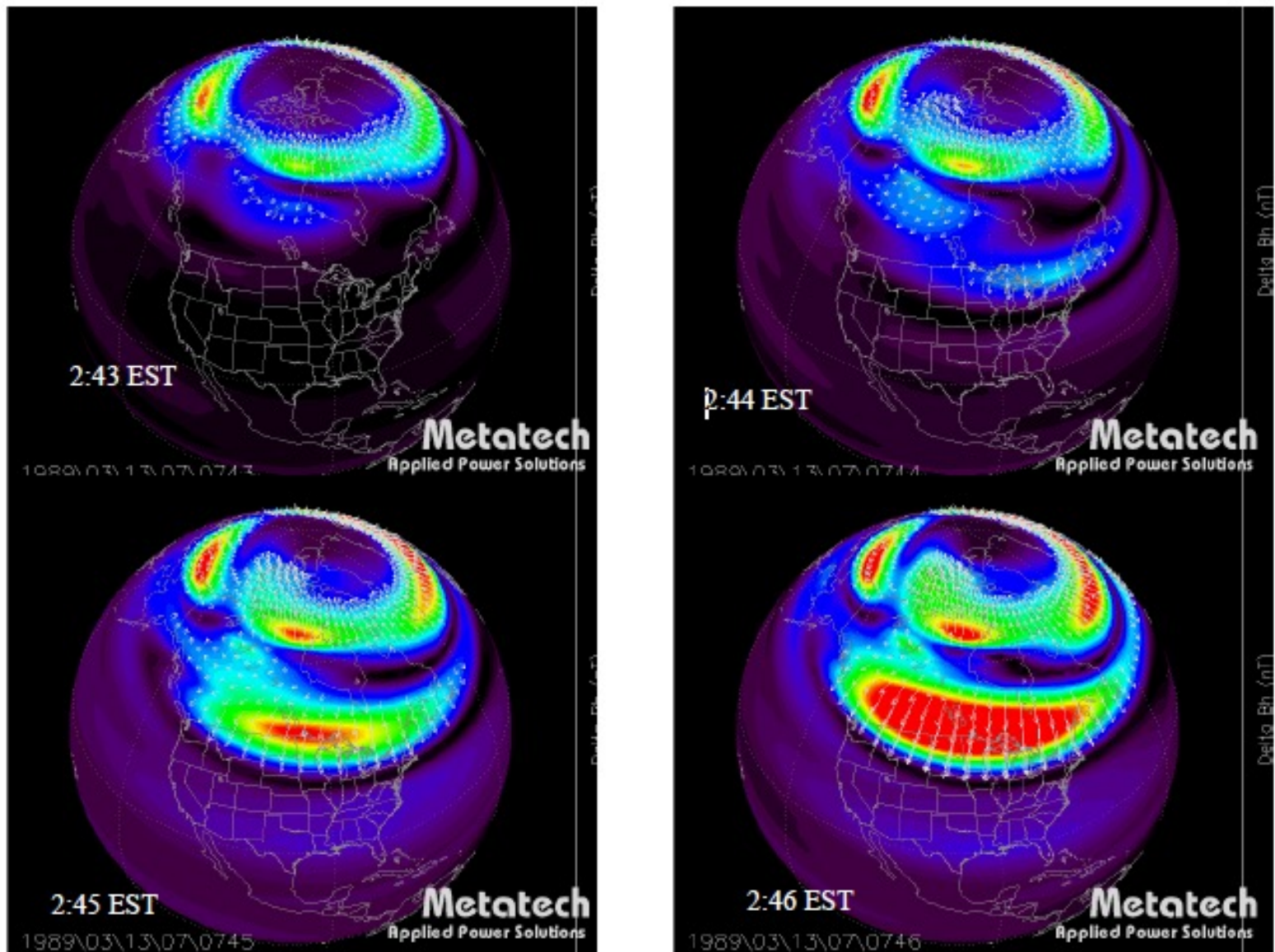


Figure 2-1. Rapid development of electrojet conditions over North America and principally along U.S./Canada border lead to Hydro Quebec collapse and other reported problems in Minnesota, Manitoba and Ontario at these times. These images depict the ground level geomagnetic intensification for over 4 minutes from 2:43 – 2:46 EST.

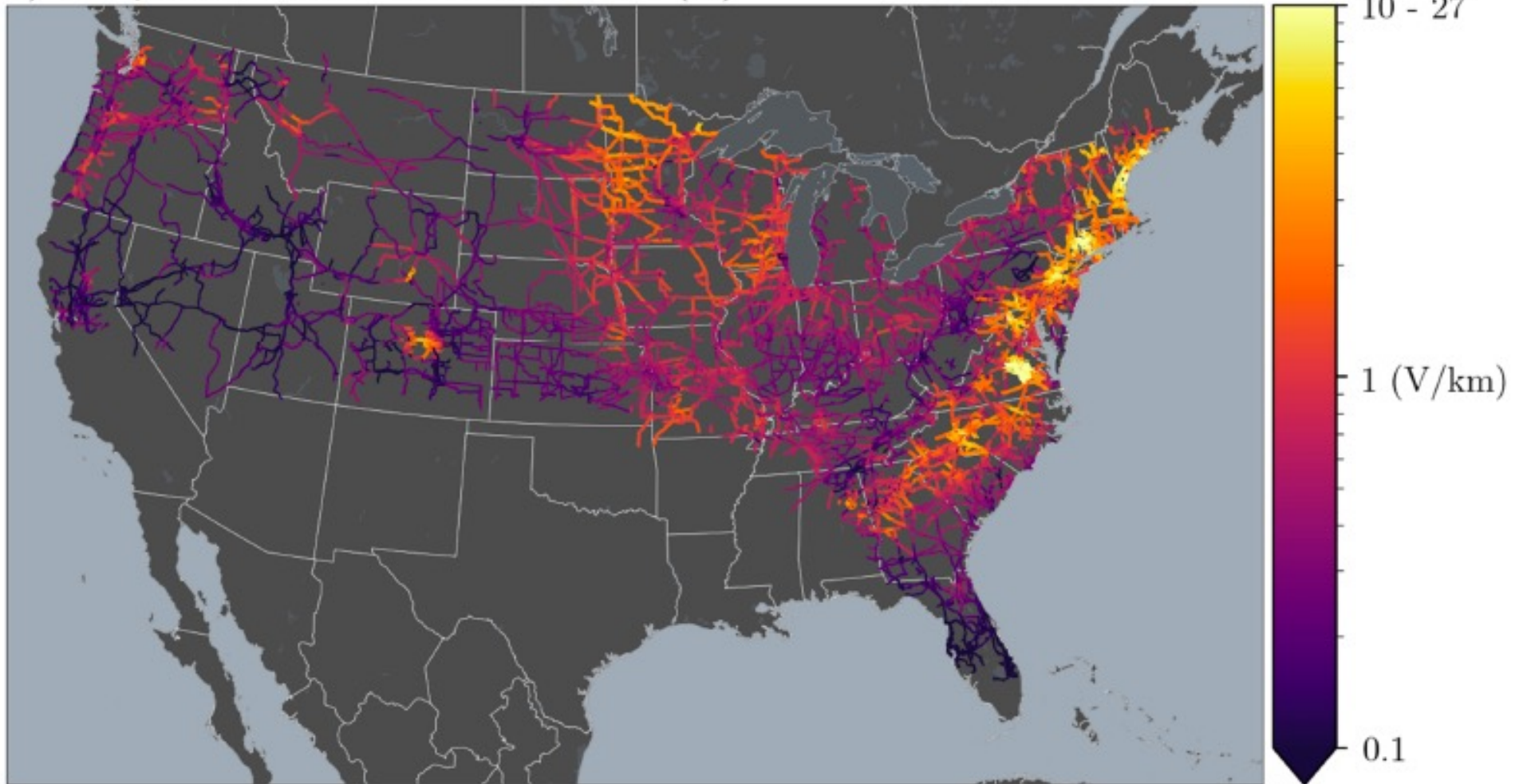
# How Solar Storms Affect Earth

## **Geomagnetically Induced Currents (GIC)**

- Charged particles in upper atmosphere cause varying magnetic fields
- Ampere's law: changing B induces electric fields
- Electric potentials (20V/km) drive currents in ground
  - Current strength depends on conductivity
- Current flow in power lines can overload the grid.

# Geological Considerations

b) 100-year Maximum Electric Field ( $E$ )



High tension power lines

High impedance  $\rightarrow$  high voltages and GICs

# This is a New York Issue

- Close to north geomagnetic pole
- Granite is conductive
- High population density

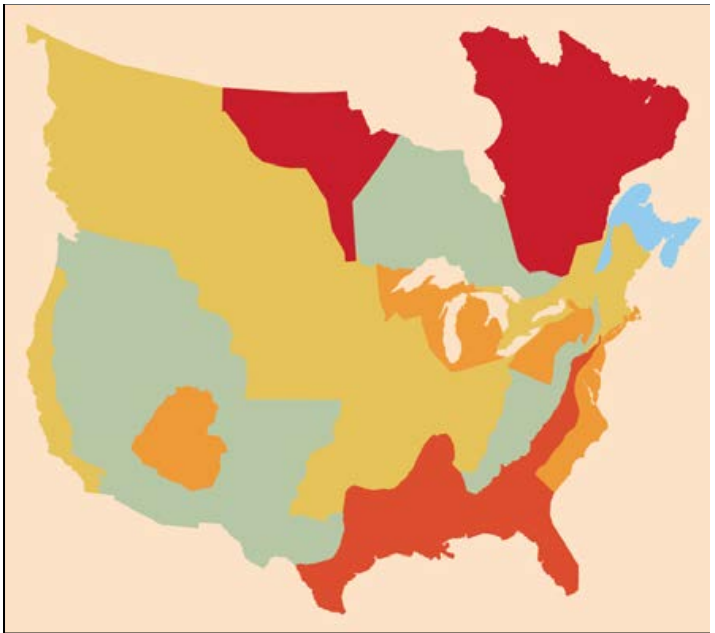


Figure 3: Relative risk from strong electric field fluctuations in the US and Canada based on ground conductivity models. Red and blue represents the highest and lowest risk regions, respectively.

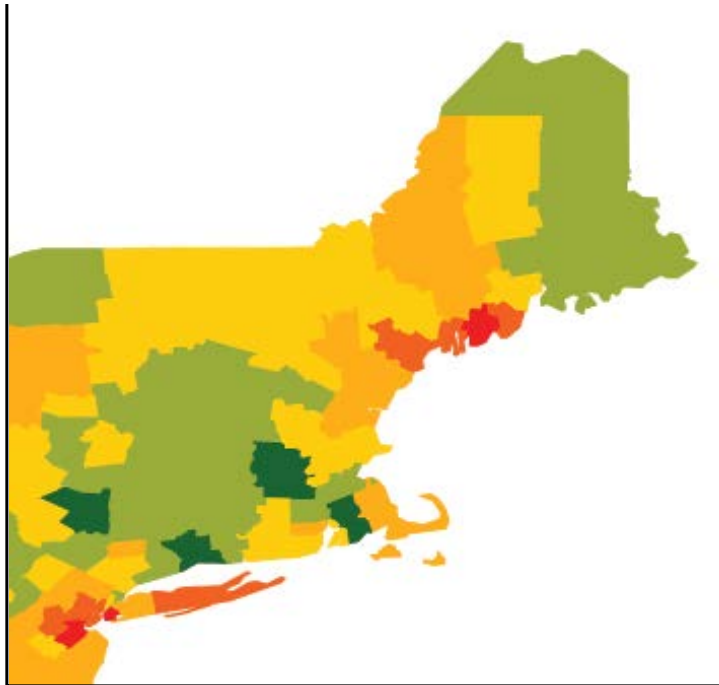


Figure 4: Relative risk of power outage by county in New England.

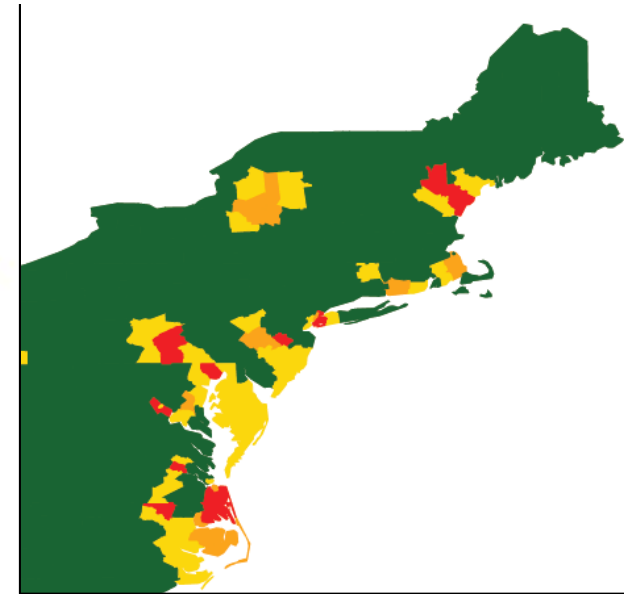


Figure 9: Fraction of EHV transformers damaged by county during an extreme geomagnetic storm scenario. Red and orange are likely to be without power. Yellow is uncertain. Green would be very likely to have power.

Figures: Lloyds *"Solar storm risk to the north American electric grid"* (2013)

# Known Solar Super Storms. I.

- **660 BCE:** large proton event
- **567 BCE:** intense red aurora (Babylon; 32°N)
- **774/5 CE:**  $^{14}\text{C}$ ,  $^{10}\text{Be}$ ,  $^{36}\text{Cl}$  enhancements. **X285**±140
- **993/4 CE:**  $^{14}\text{C}$ ,  $^{10}\text{Be}$ ,  $^{36}\text{Cl}$  enhancements
- **1582, 1730, 1770, 1872:** strong equatorial aurorae
- **Sept 1859:** Carrington event. **X45** (estimated)
  - 17.1 hours travel time from Sun to Earth (2500 km/s)
  - Dst ~ -950 nT
- **May 1921:** New York Railroad Superstorm
  - Maximum Dst: -901 ± 132 nT
- **March 1940:** daytime event
  - Geopotentials > 800V
  - Affected communications and power lines on East Coast

# Known Solar Super Storms. II.

- **May 1967:** Geomagnetic storms coincident with 7 Day War spur DoD investment in Space Weather
- **August 1972:** Geomagnetic storm sets off >4000 mines in Haiphong harbor ( $dH/dt=150$  nT/s)
  - Fast CME: 14.6 hours to Earth (2800 km/s)
  - NORAD loses track of ~1000 satellites
- **March 1989: X15+.** Hydro Quebec collapse
  - strongest storm since IGY
  - Maximum Dst -589 nT ; red aurorae in Mexico City
  - Magnetosphere within GEO for 7 hours
  - TDRS anomalies; effects still classified by DoD
- **October 2003: X35±5.** Halloween storm.
  - >2000 km/s CME
  - Dst: -400 nT
  - 4<sup>th</sup> largest known proton storm
  - NORAD loses track of half of satellites
  - Solar storms recognized as national security concern

# The 13 March 1989 Hydro Quebec Collapse

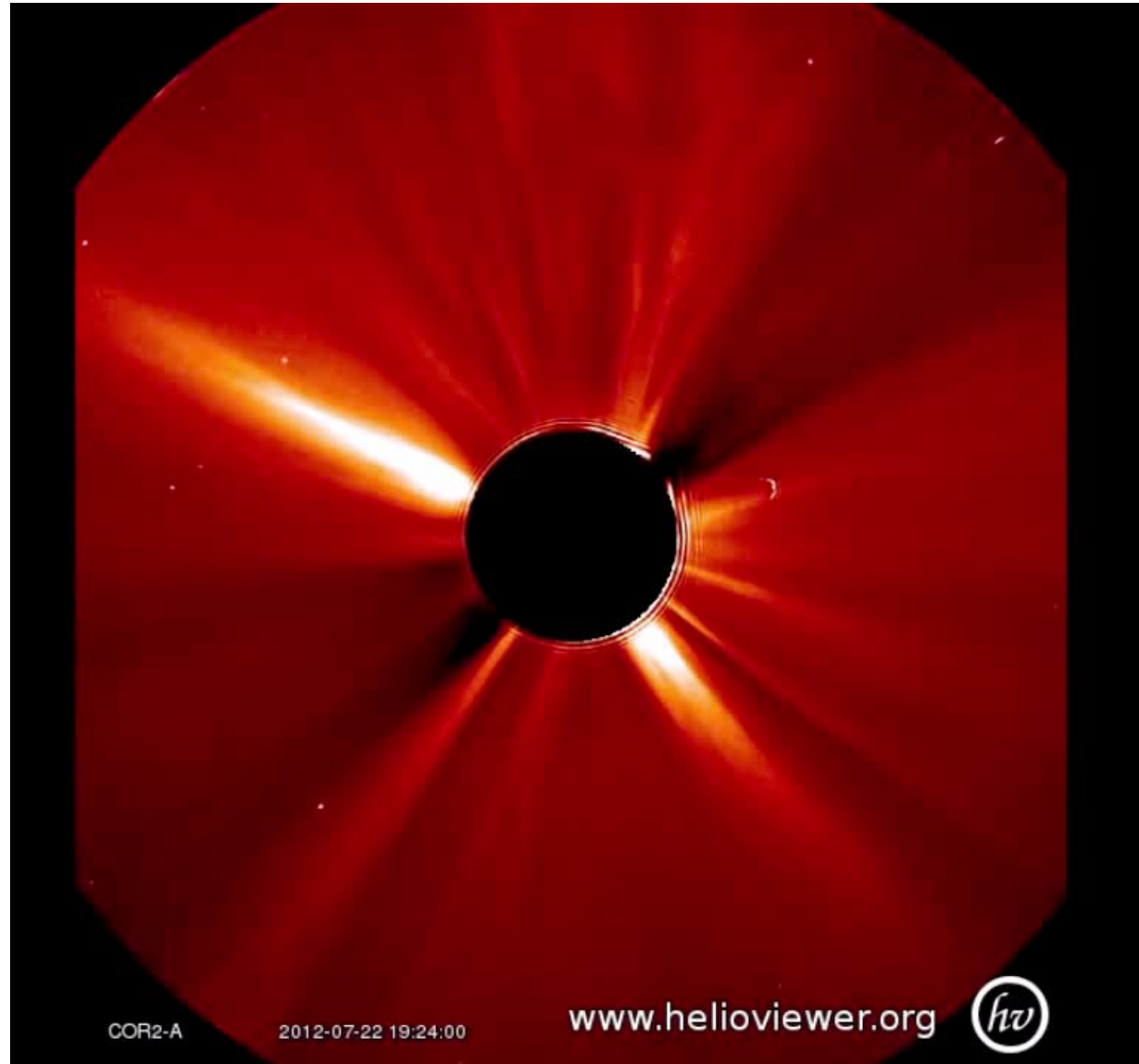
Strongest geo-magnetic storm since 1932  
( $\sim -500$  nT/min; Dst =  $-589$  nT)

- Hydro-Quebec grid down for 9 hours
- Affected 6 million people
- Three transformers damaged (1 in NJ)
- Cost: CDN \$ 13.2 million

Nearly brought down North American grid  
( $\sim 200$  “anomalies”)

# The 23 July 2012 Flare

- At least as energetic as the 1859 Carrington event
- 2 CMEs recorded
  - Cannibal CME
- Missed Earth by about 1 week



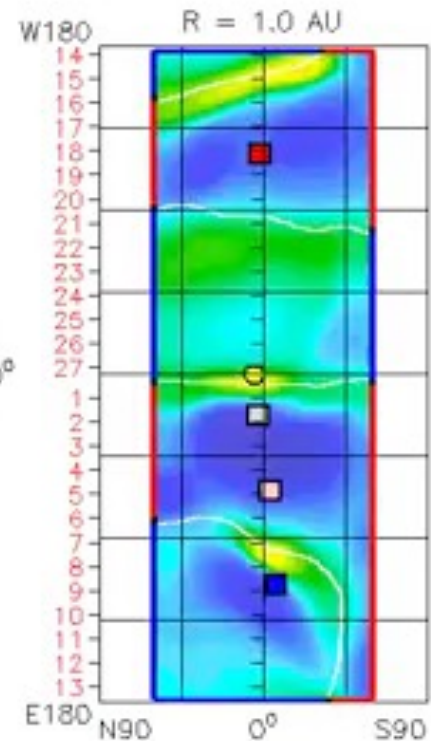
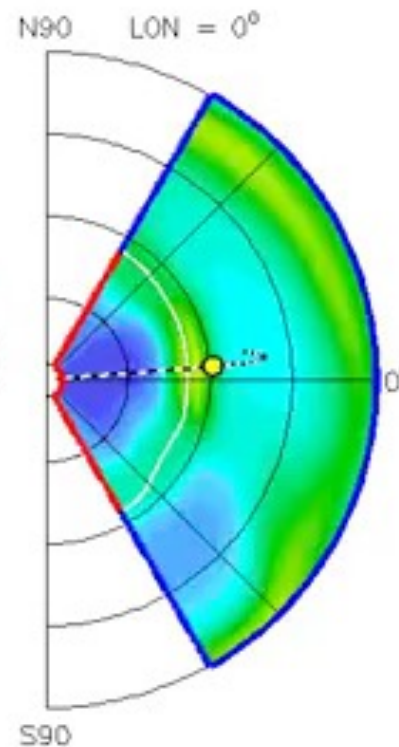
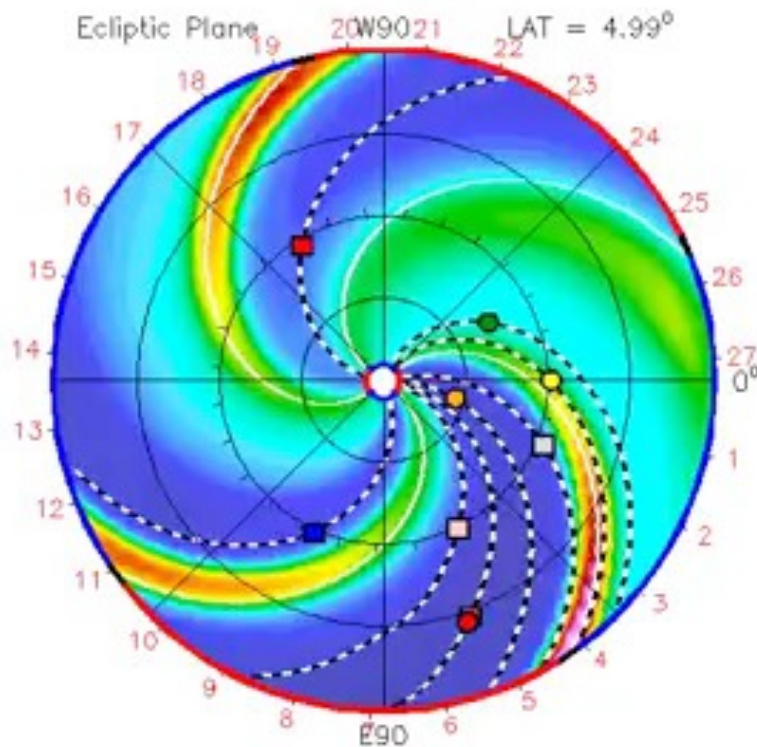
# The 23 July 2012 Flare

- At least as energetic as the 1859 Carrington event
- Missed by about 1 week

2012-07-22T00:00

2012-07-22T00 +0.00 day

● Earth    ● Mars    ● Mercury    ● Venus     Kepler     MSL     Spitzer     Stereo\_A  
 Stereo\_B



$R^2 N$  ( $\text{cm}^{-3}$ )

0 10 20 30 40 50 60

IMF polarity

- ■ ■ +

Current sheath

==

3D IMF line

- - -

# Estimated Economic Impact of a 23 July 2012 Strength Flare

- Over 130 million in North America lose power
- Over 350 million heavy-duty transformers threatened
- \$2 trillion to recover – 20 x greater than hurricane Katrina
- Full recovery: 4-10 years



See:  
[http://science.nasa.gov/science-news/science-at-nasa/2014/23jul\\_supers\\_torm/](http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_supers_torm/)

Transformer damage  
13 March 1989 storm  
Salem NJ nuclear plant

# The Odds

**12% per decade** (Carrington-level)

Riley, P. 2012, Space Weather **10**, s0212

**Carrington event ( $D_{ST} \sim -850$ ):** 0.7% /yr

**Extreme storm ( $D_{ST} > -500$ ) :** 4% /yr

**Severe storm ( $D_{ST} > -250$ ) :** 28% /yr

Chapman, S.C. *et al.* 2020, GRL **4**, 3. doi: 10.1029GRL086524  
based on 14 cycle averages of aa indices

**Carrington-level event:** 100-200 years

**Quebec 1989 event:** 35-70 years

Lloyd's/AER report (2013). Methodology: historical auroral records

# Insurers are Concerned

- From Lloyds *“Solar storm risk to the north American electric grid”* (2013)
- **The total U.S. population at risk of extended power outage from a Carrington-level storm is between 20-40 million, with durations of 16 days to 1-2 years.** The duration of outages will depend largely on the availability of spare replacement transformers. If new transformers need to be ordered, the lead-time is likely to be a minimum of five months. The total economic cost for such a scenario is estimated at \$0.6-2.6 trillion USD.
- **Storms weaker than Carrington-level could result in a small number of damaged transformers (around 10-20), but the potential damage to densely populated regions along the Atlantic coast is significant.** The total number of damaged transformers is less relevant for prolonged power outage than their concentration. The failure of a small number of transformers serving a highly populated area is enough to create a situation of prolonged outage.

# National Security Issue

- 5 times since 1967 NORAD has lost track of satellites due to Solar events
  - Cause:
    - increased drag due to exospheric expansion
  - Affects:
    - Communications
    - Navigation (GPS)
    - Military readiness
  - As number of LEO satellites increases, so do risks of collisions



# NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

*Product of the*  
SPACE WEATHER OPERATIONS, RESEARCH, and MITIGATION  
WORKING GROUP  
SPACE WEATHER, SECURITY, and HAZARDS SUBCOMMITTEE  
COMMITTEE ON HOMELAND and NATIONAL SECURITY  
*of the*  
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

March 2019

- **Objectives:**
- **I.** Enhance the Protection of National Security, Homeland Security, and Commercial Assets and Operations against the Effects of Space Weather
- **II.** Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts
- **III.** Establish Plans and Procedures for Responding to and Recovering from Space Weather Events
- **Conclusion:** Space weather poses a constant threat to the Nation's critical infrastructure, our satellites in orbit, and our crewed and uncrewed space activities. *Extreme space weather events can cause substantial harm to our Nation's security and economic vitality.*

# Cost of Protecting Against EMP & CME Events

- EMP Commission (2017) estimated cost to harden 2000 critical nodes (large and medium sized transformers) against EMP and CME: ~ \$2 Billion

## Resilient Societies Cost Projections

<b>Electric Generation Plants</b>	\$23,000M
<b>Electricity Transmission &amp; Distribution</b>	\$2,300M
<b>Electric Grid Control Centers</b>	\$1,390.M
<b>Telecommunications</b>	\$1,480M
<b>Natural Gas System</b>	\$640M
<b>Railroads</b>	\$1,380M
<b>Blackstart Plant Resiliency</b>	\$80M
	\$30,270M

# Cost of Not Protecting Against EMP & CME Events

- EMP Commission estimated loss of life from EMP event that would drop electrical grid for 1 year:

60 to 90% of US population

Note: CMEs can have a similar effect, but won't affect the entire country

*“The Congressional EMP Commission on which I served calculated that within a year of a blackout that knocks out the national grid, we would probably lose up to 9 out of 10 Americans through starvation, disease, and societal collapse... The only reason we can sustain a population of 326 million Americans is technology. If you take that away, we don't have any way of feeding, providing water or even providing communications and government for an orderly society that is going to sustain 326 million Americans.” – Dr. Peter Pry, Executive Director for Task Force on National and Homeland Security, 2017.*

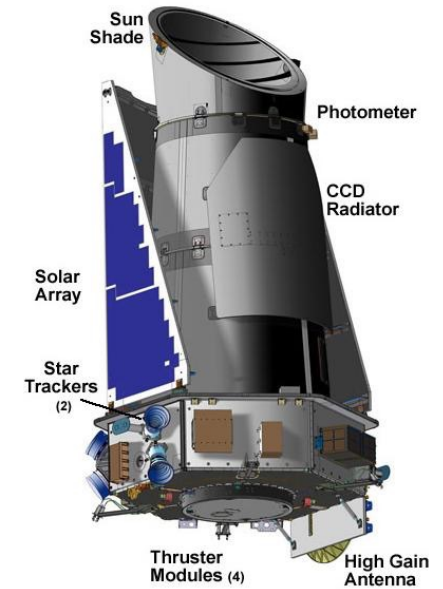
# What do the stars tell us?

*Not from the stars do I my judgement pluck,  
And yet methinks I have astronomy –  
But not to tell of good or evil luck,  
Of plagues, of dearths, or seasons' quality;  
...*

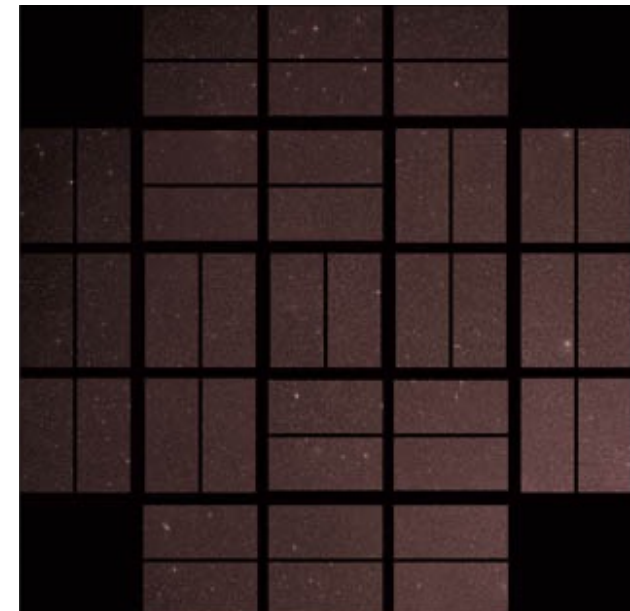
Wm. Shakespeare, Sonnet 14

# Superflares

Okamoto *et al.* (2021) *ApJ* **906**, 72

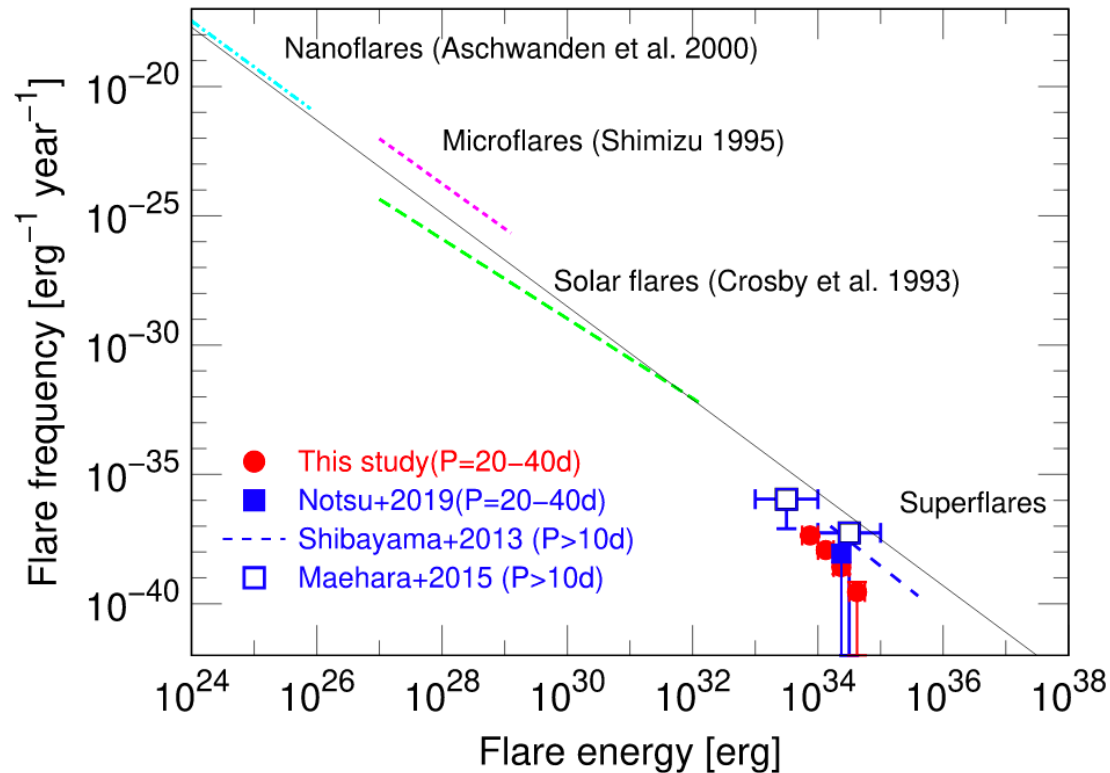


- Analysis of Kepler primary mission data
  - 3.5 years of continuous observations of 100 deg<sup>2</sup>
- **2341 superflares** on 265 Solar-like stars
  - 5600-6000K;  $5^d < P_{\text{rot}} < 20^d$
  - Energies to  $10^{36}$  erg
- **26 superflares** on 15 Sun-like stars
  - 5600-6000K;  $P_{\text{rot}} > 20^d$ ;  $\langle \text{age} \rangle \sim 4.6$  Gyr
  - Energies to  $4 \times 10^{34}$  erg



# Upshot

THE ASTROPHYSICAL JOURNAL, 906:72 (28pp), 2021 January 10

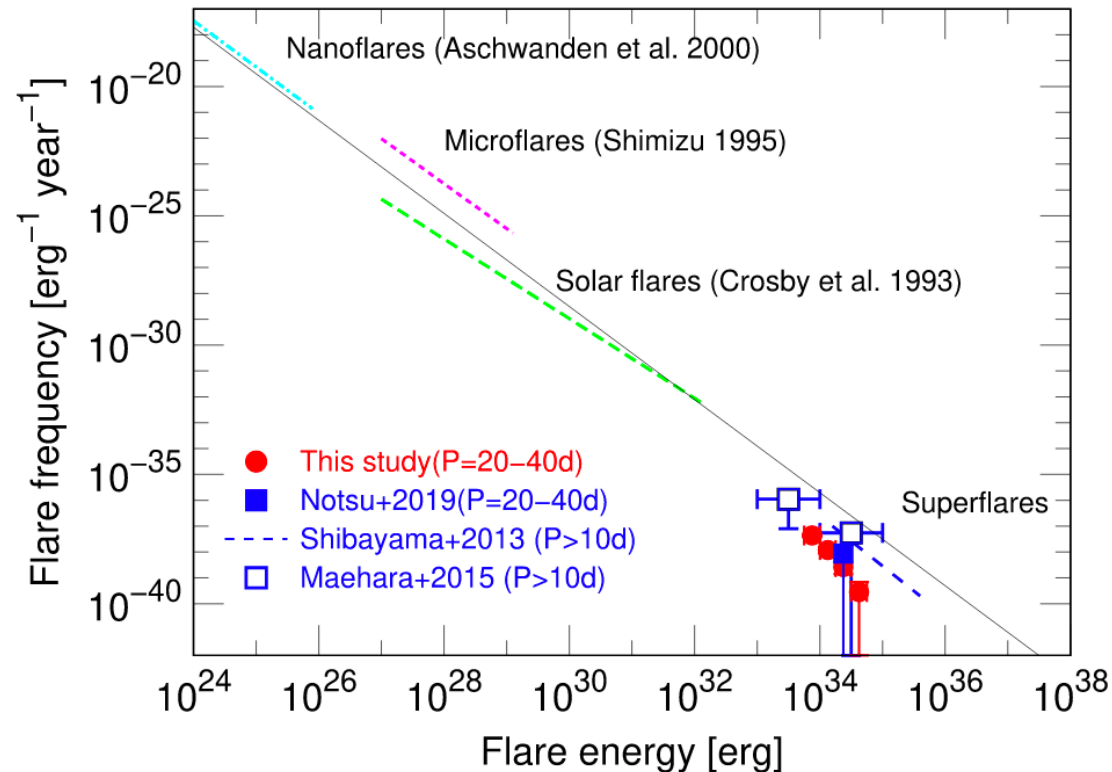


A slowly-rotating Sun-like star will produce a

- $4 \times 10^{33}$  erg flare every 3000 years
- $4 \times 10^{34}$  erg flare every 80,000 years

# Upshot

THE ASTROPHYSICAL JOURNAL, 906:72 (28pp), 2021 January 10



A slowly-rotating Sun-like star will produce a

- $4 \times 10^{33}$  erg flare every 3000 years
- $4 \times 10^{34}$  erg flare every 80,000 years

Carrington flare ( $\sim 6 \times 10^{32}$  erg) expected every 175 years

# Characterizing Stellar Flares

Light curves from

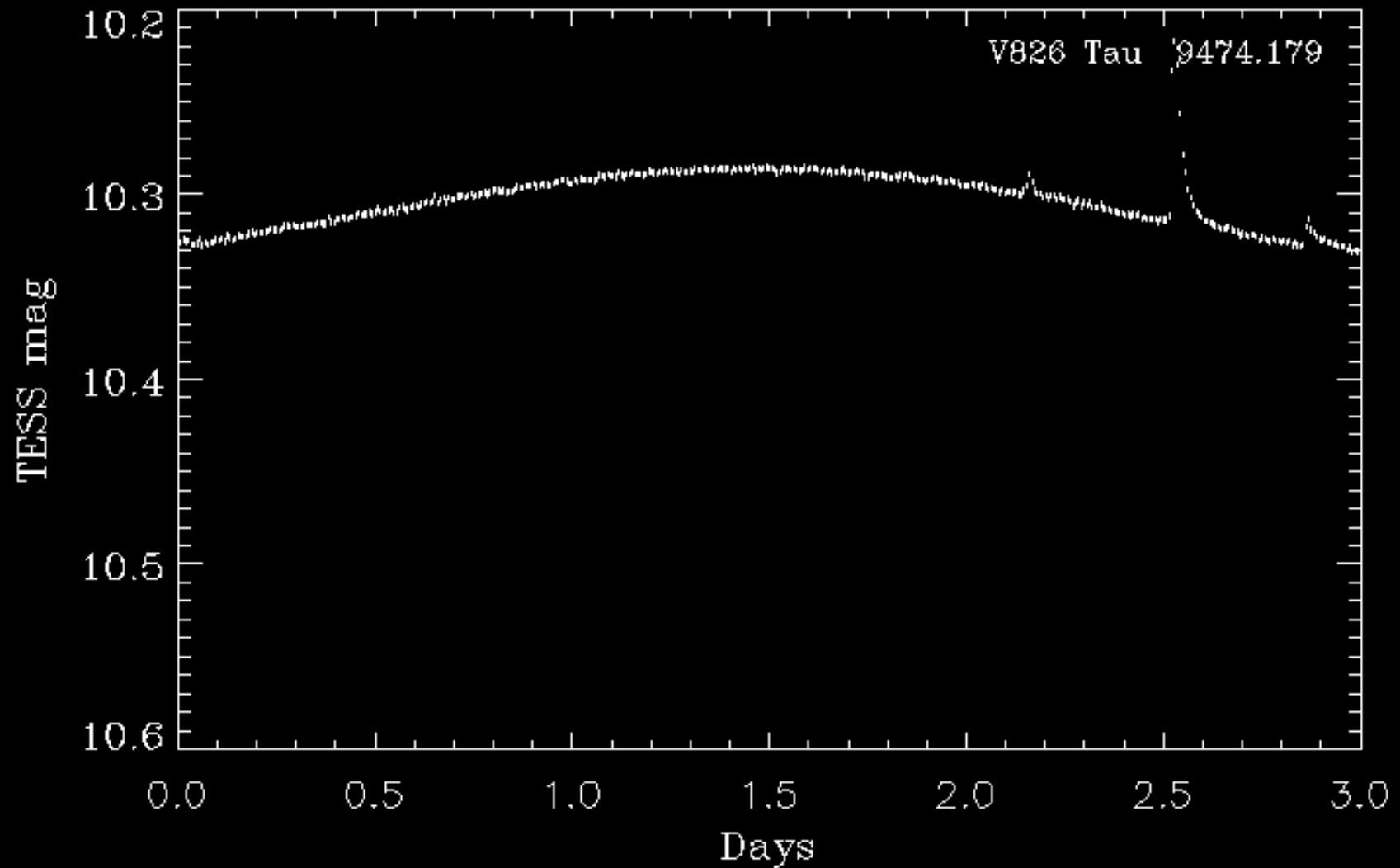
**TESS**, the *Transiting Exoplanet Survey Satellite*



Assisted by

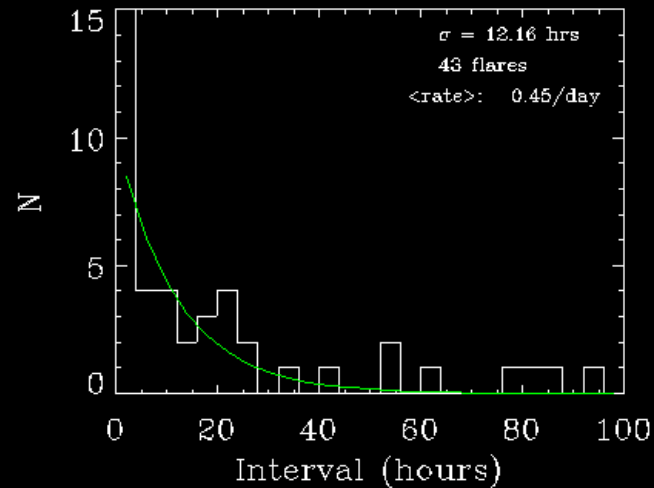
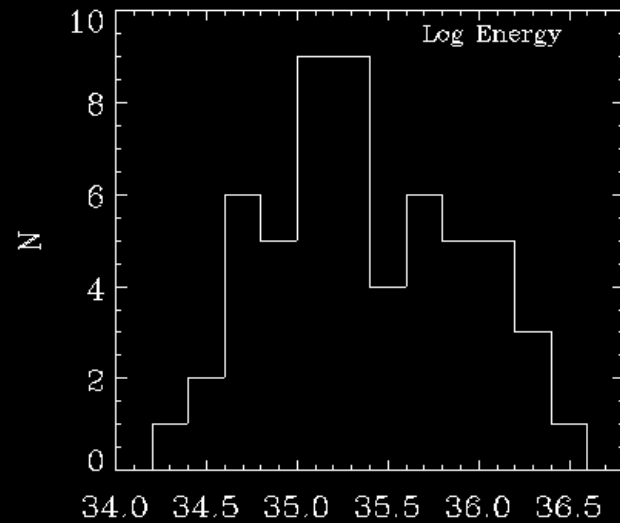
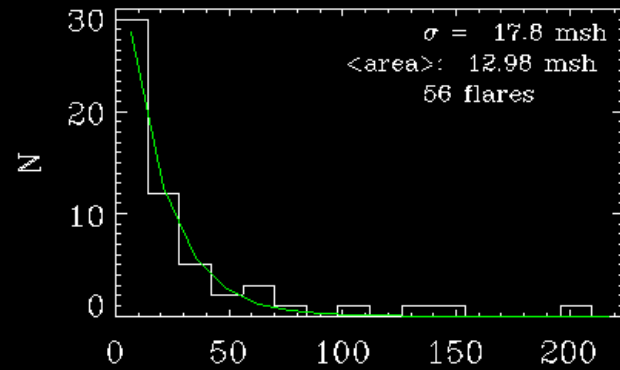
- Melinda Mercedes (BS Astronomy 2023)
- Jackson Proothi (Ward Melville High School)

# V826 Tau (PMS star; $\sim 10^6$ years)

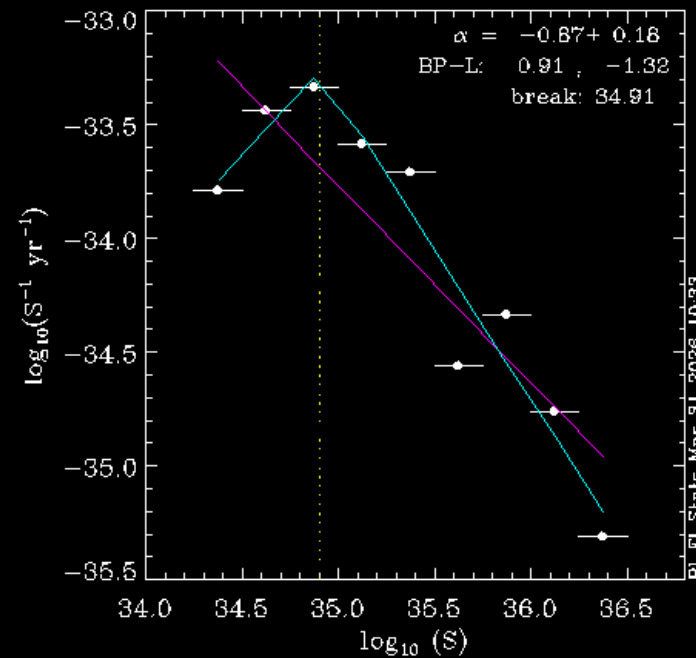
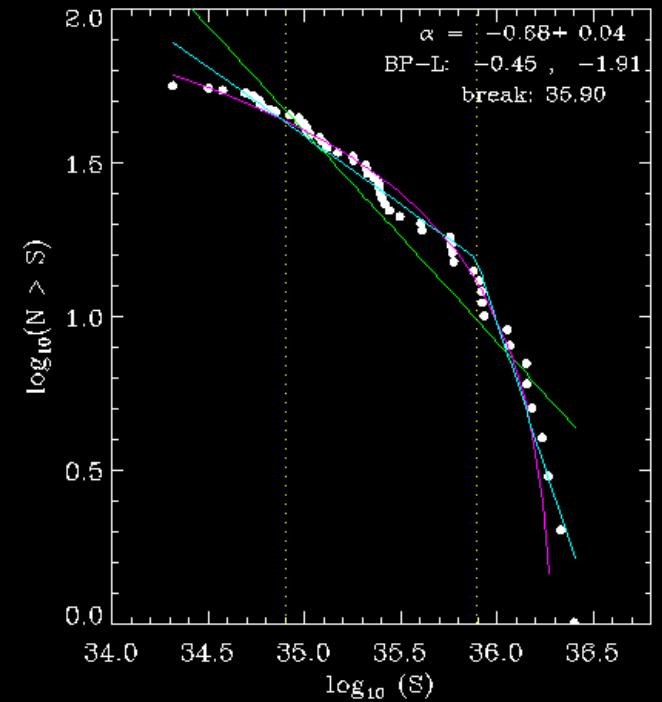


# Flare Statistics

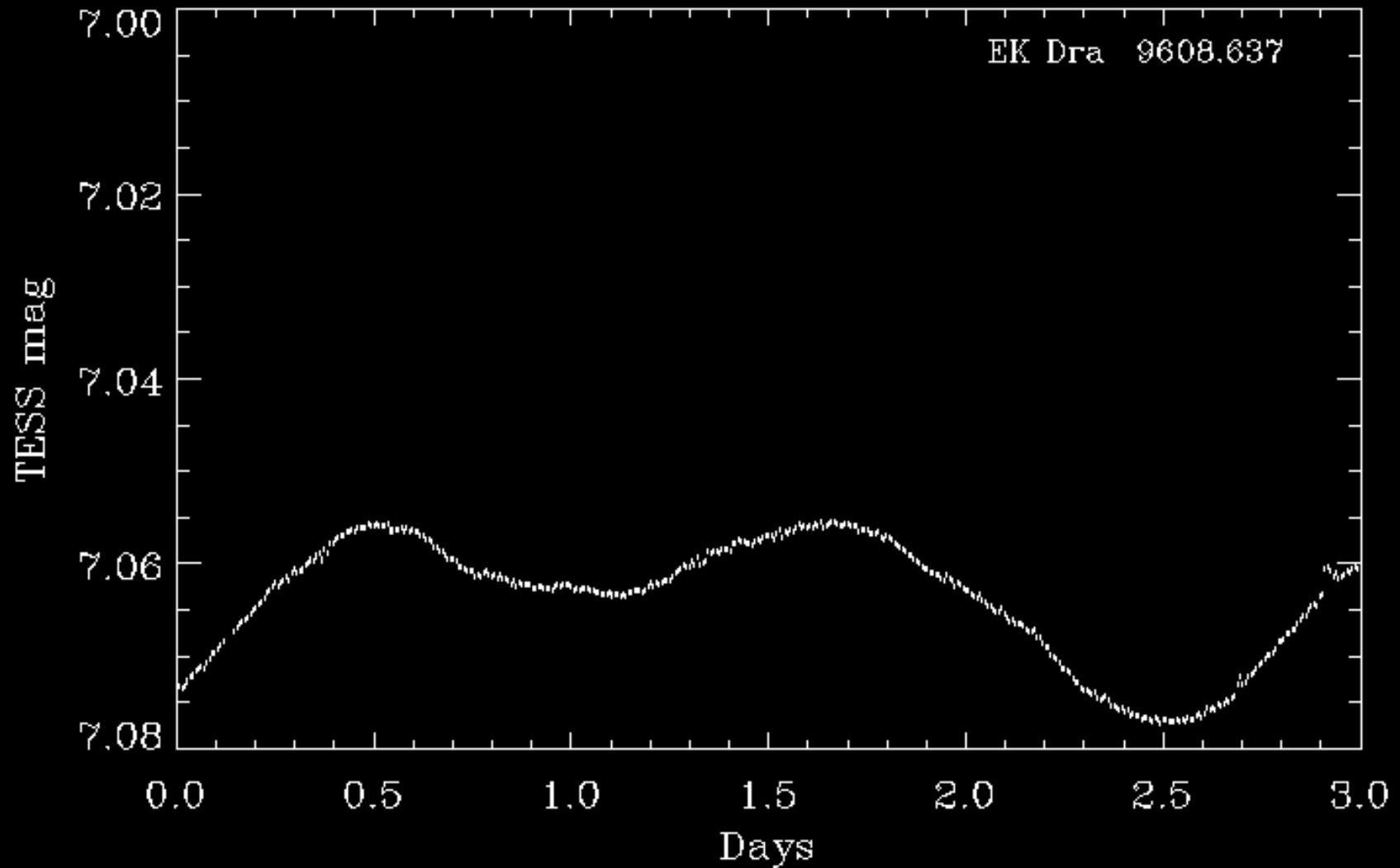
## V826 Tau



## V826 Tau

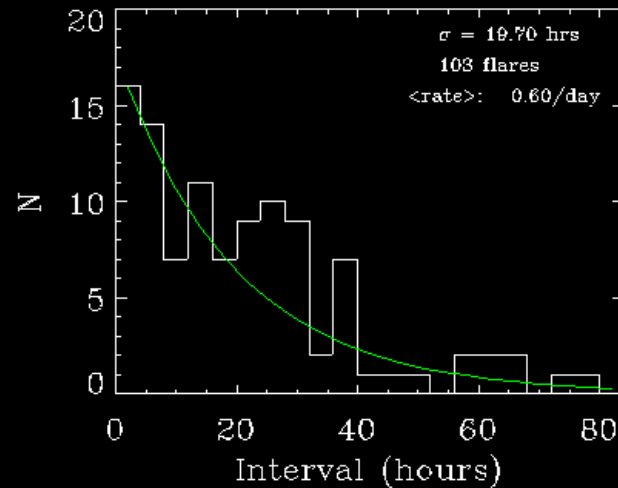
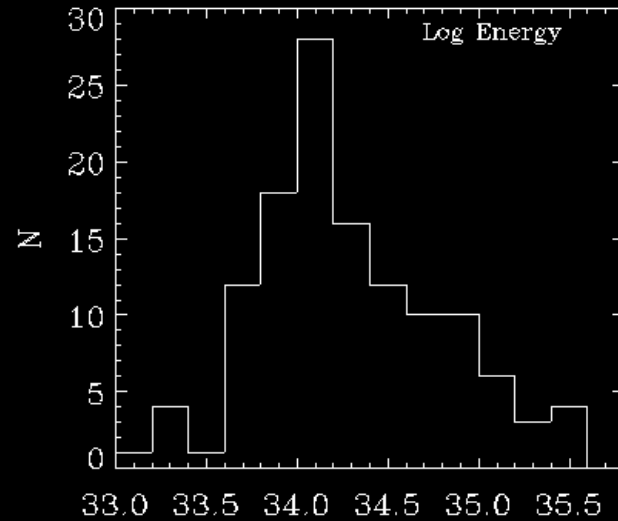
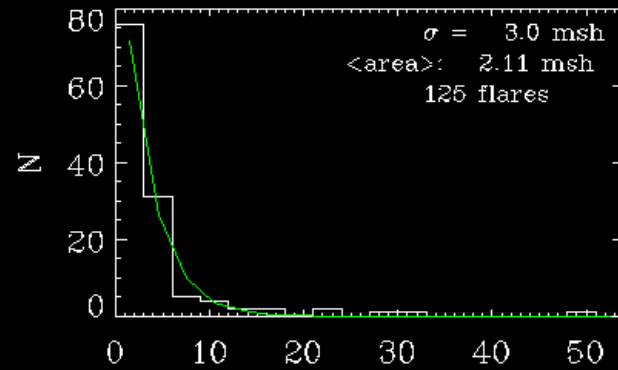


# EK Dra (ZAMS star; $\sim 10^8$ years)

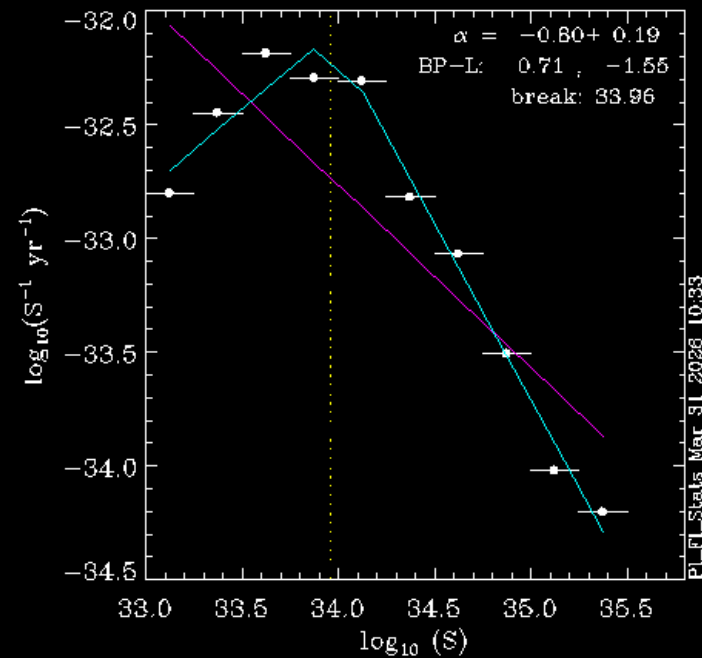
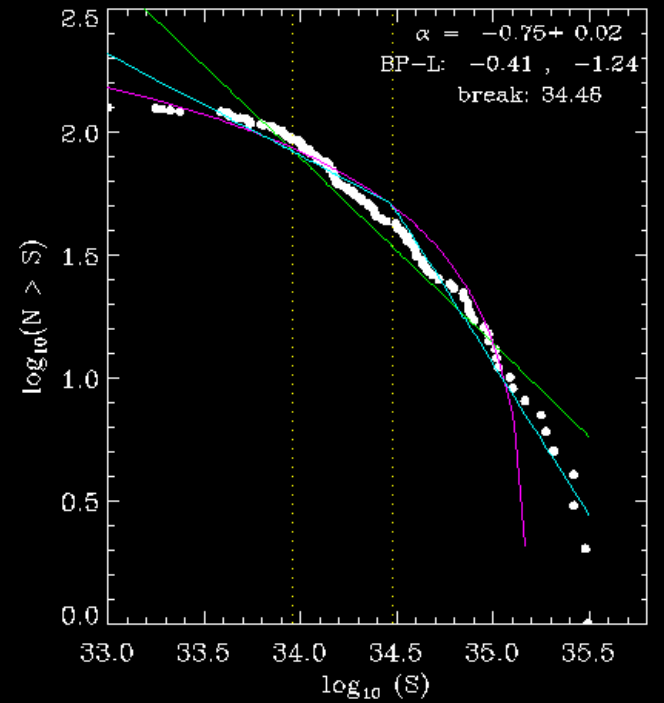


# Flare Statistics

## EK Dra



## EK Dra



# TESS Flare Comparison

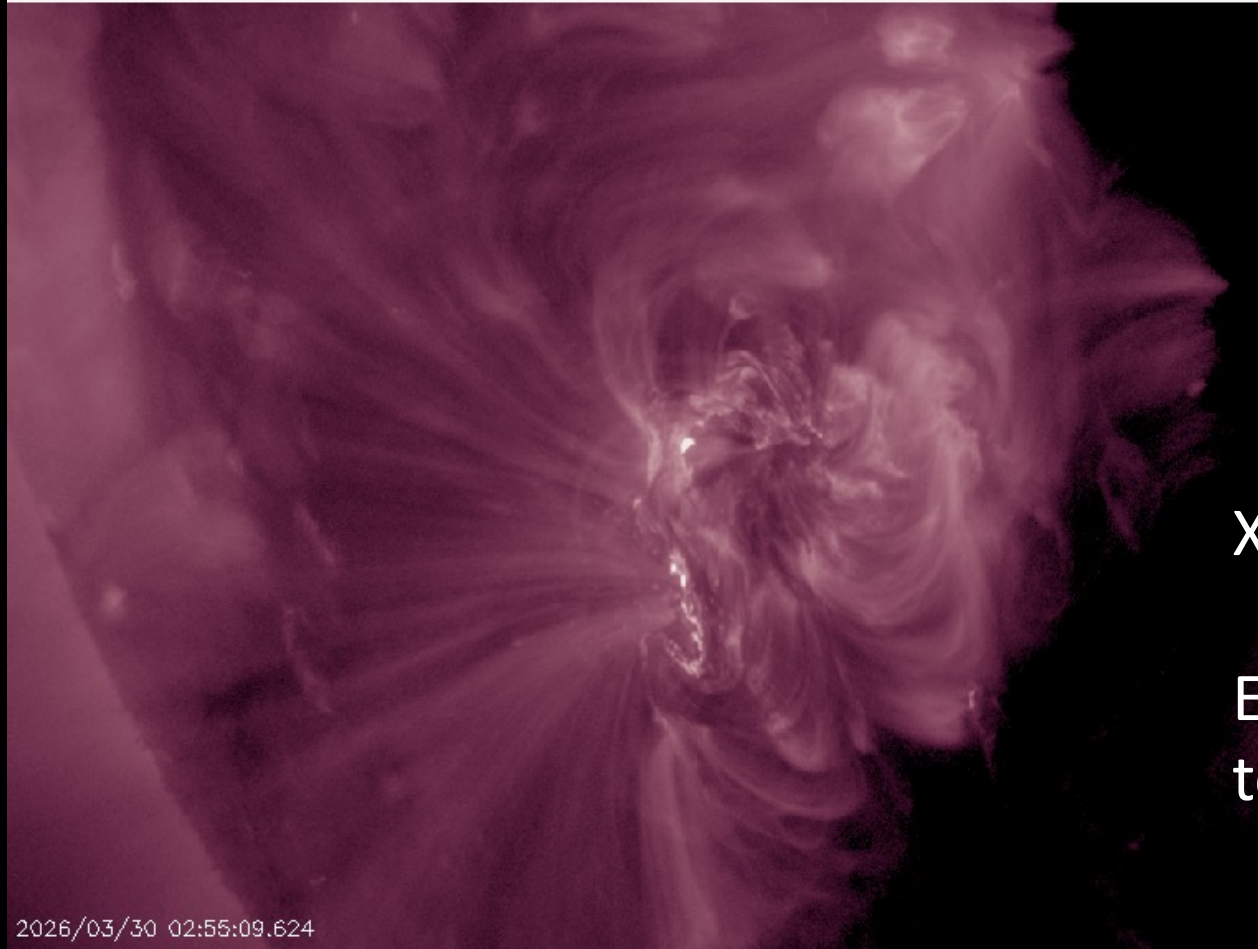
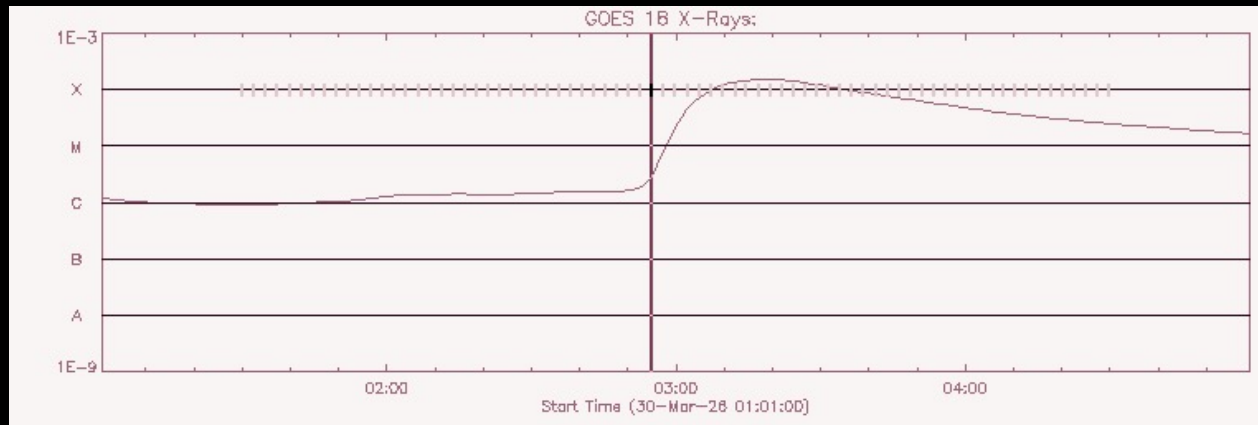
	V826 Tau	EK Dra	EK Dra (cutoff)
Age (years)	$3 \times 10^6$	$10^8$	$10^8$
Distance (pc)	144	34.4	34.4
Number of flares	56	125	13
Flare rate ( $\text{day}^{-1}$ )	0.59	0.72	0.06
Completeness (erg/s)	$10^{35}$	$10^{34}$	$10^{35}$
Slope ( $S^{-1}\text{yr}^{-1}/S$ )	-1.32 (0.21)	-1.55 (0.12)	
<Flare area> (msh)	13	2.1	16

## Carrington Flare:

Luminosity:  $\sim 6 \times 10^{32}$  erg/s

Area:  $\sim 6$  msh

# The Sun Yesterday



X1.5 flare

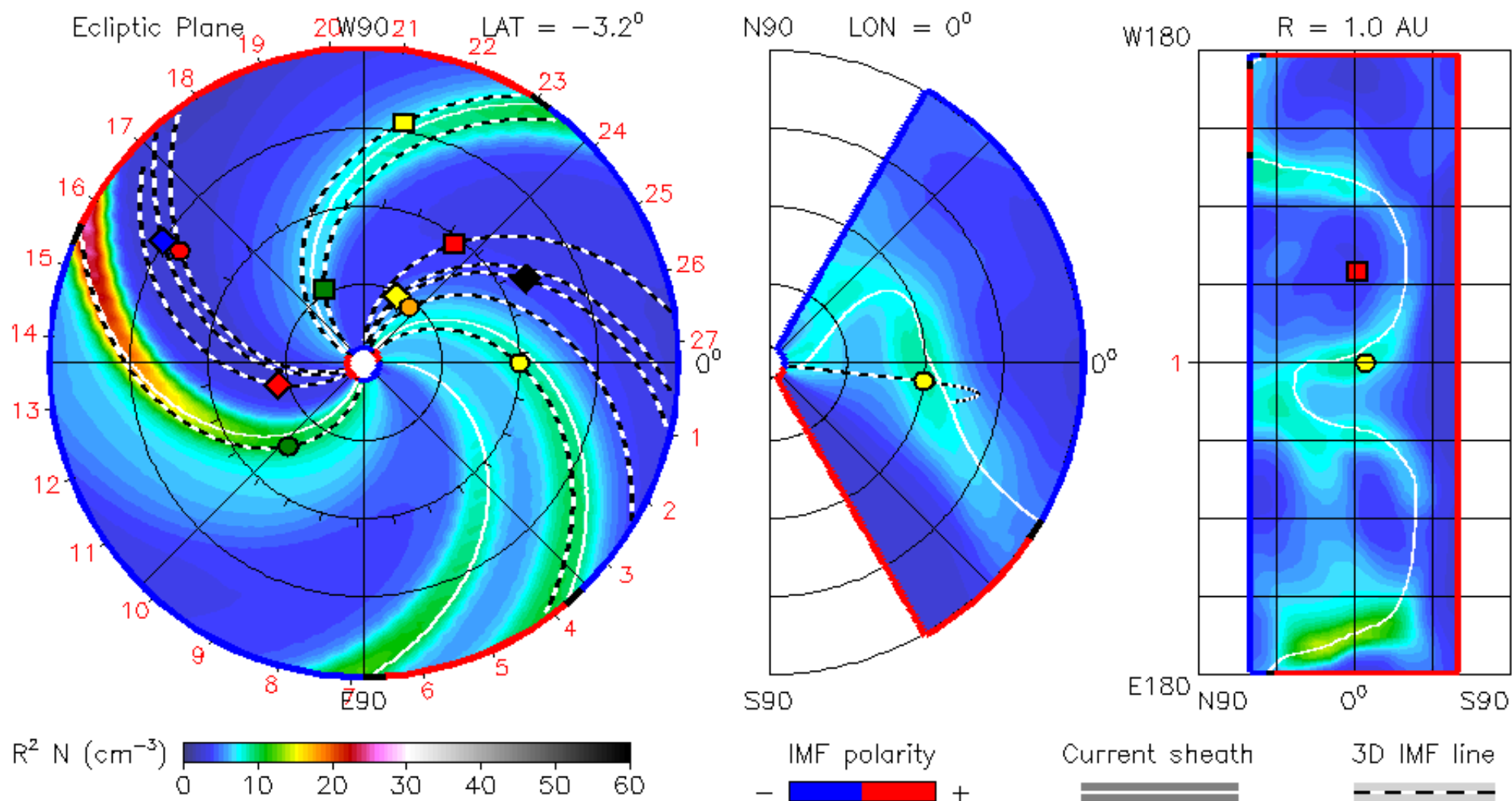
Expect a CME  
tonight

# 260331 CME model

2026-03-29T00:00

2026-03-29T00 +0.00 day

- Earth
- Mars
- Mercury
- Venus
- ◆ Bepi
- Juice
- ◆ OSIRIS-APEX
- ParkerSP
- ◆ Psyche
- ◆ SolO
- Stereo\_A



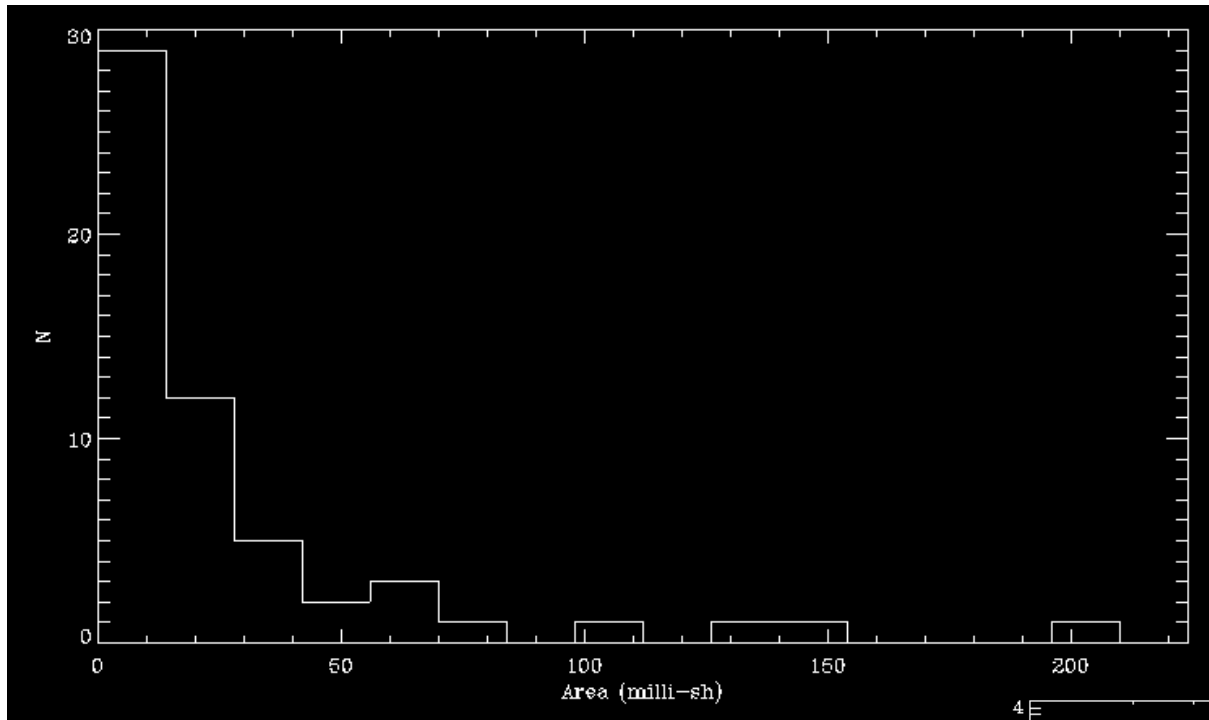
Be Afraid.  
Be Very Afraid.

# General References

- Cliver, E.W. *et al.* 2022. “*Extreme Solar Events*”. *Living Reviews in Solar Physics* **192**  
doi:10.1007/s41116-022-00033-8
- Hudson, H.S. 2021. “*Carrington Events*”. *Ann Rev Astron Astroph* **59**, 445
- “*Solar Storm Risk to the North American Electrical Grid*” [https://www.lloyds.com/Solar Storm Risk to the North American Electric Grid.pdf](https://www.lloyds.com/Solar%20Storm%20Risk%20to%20the%20North%20American%20Electric%20Grid.pdf)

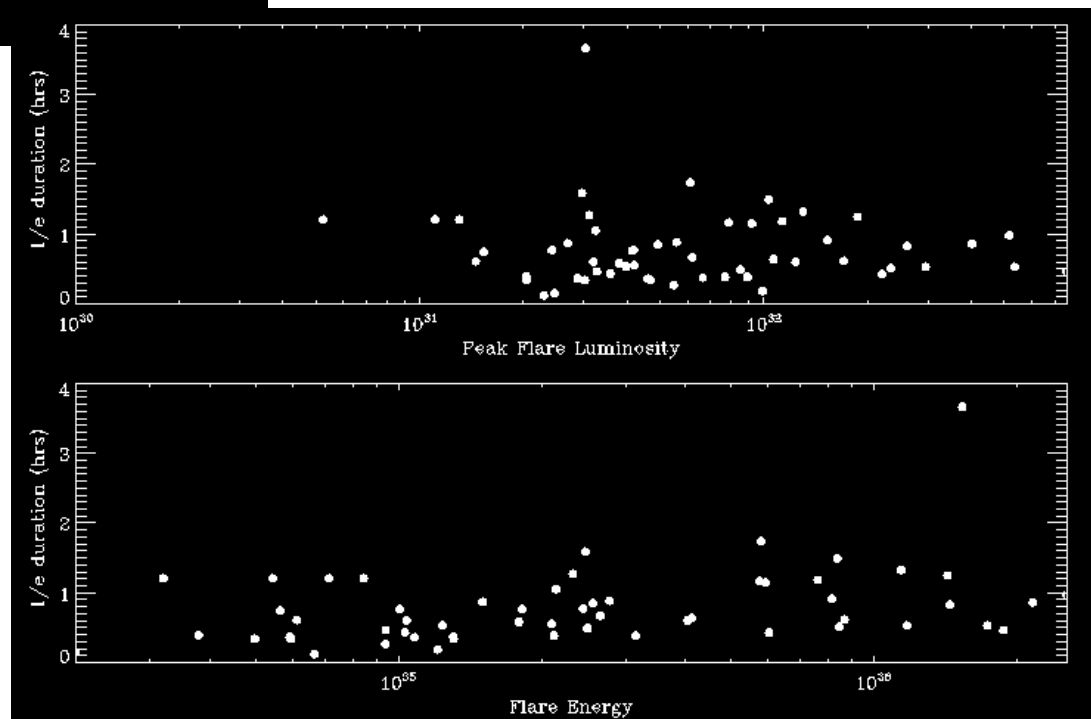
Spares

# Flares on Young Stars: V826 Tau



Area of visible flare  
msh =  $10^{-3}$  stellar hemispheres

Flare Durations



# Current Economic Impact

Based on insurance claims, 2000-2010

- Claims **increase** with geomagnetic activity
- ~4% of US power grid disturbances due to geomagnetic storms and GICs
  - 59% caused by “electrical surges”
  - Implies about 500 disturbances/year
- Estimated losses **\$118-188 Billion/year**

Reference: Schrijver, C.J. *et al.*, *Space Weather*, **12**, 487 (2014)

# Revisited Economic Impact

## Costs of a full blackout:

- Economic cost in North America \$20B-\$40B/day
- Cost to New York economy >\$3B/day
- Time to recover >6 months

Reference: Oughton, E.J. *et al.*, *Space Weather*, **15**, 65 (2017)

# Extremes

- **Flare:**

- Largest observed: X35 (2003)
- Inferred: X45 (1859)
- Extrapolated: >X140 (774)
- Theoretical: X180 (-100,+300)

- **CME:**

- Largest observed:  $4 \times 10^{33}$  erg (2005)
- Inferred:  $10^{34}$  erg (774)
- Theoretical:  $9 \times 10^{33}$  erg

Theory based on largest observed spot group area: 6132  $\mu$ sh (1947)

1  $\mu$ sh =  $10^{-6}$  solar hemispheres ( $3 \times 10^6$  km<sup>2</sup>)

# Mitigation Strategies

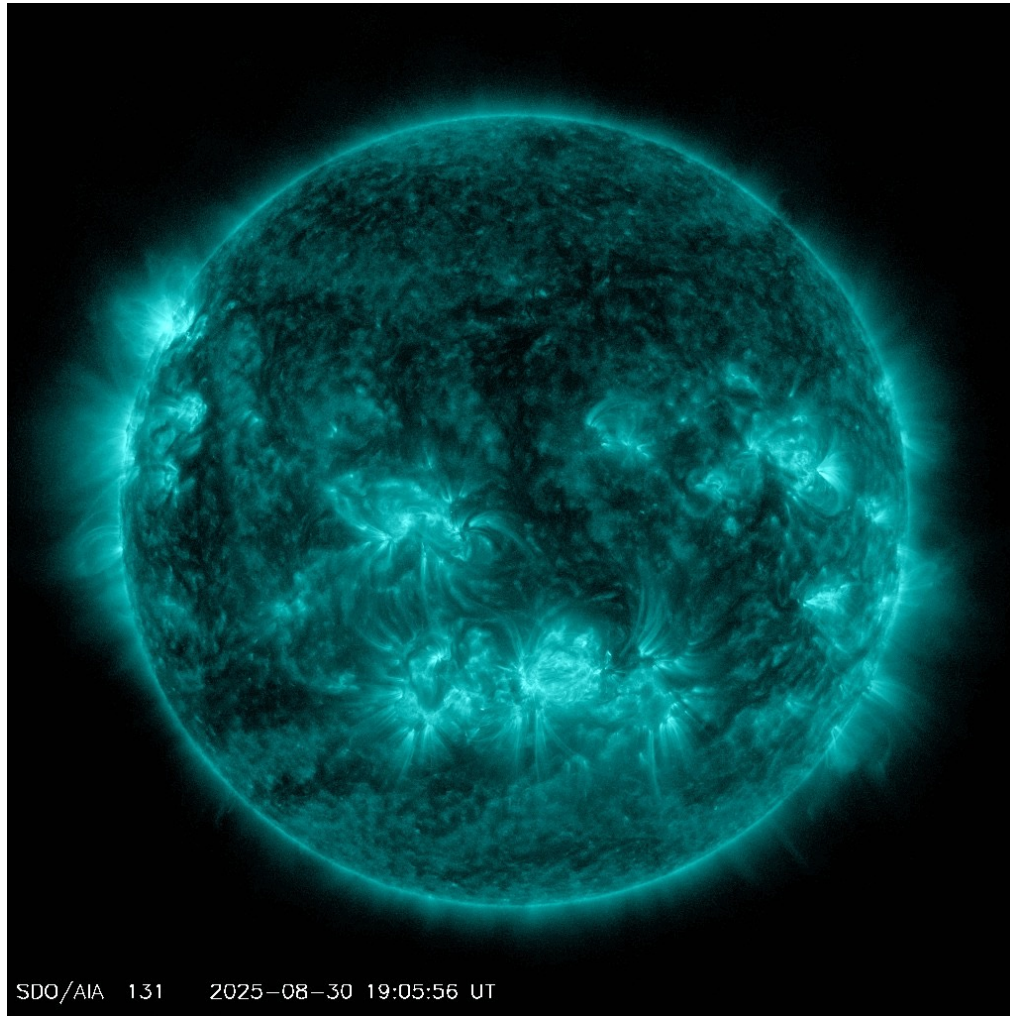
- Education
  - Raise awareness of vulnerability to solar events
- Science
  - Develop better predictive ability
  - Better understanding of large event rates
- Engineering
  - Better grounding/isolation from possible GICs
  - Locating transformers in areas less prone to GICs
  - Rapid sensing of saturated transformers

# Current Conditions

- [spaceweather.com](http://spaceweather.com) The Sun and NEOs
- [www.swpc.noaa.gov](http://www.swpc.noaa.gov) NOAA Space Weather Prediction Center
- [solarcyclescience.com](http://solarcyclescience.com) Cycles and long term predictions

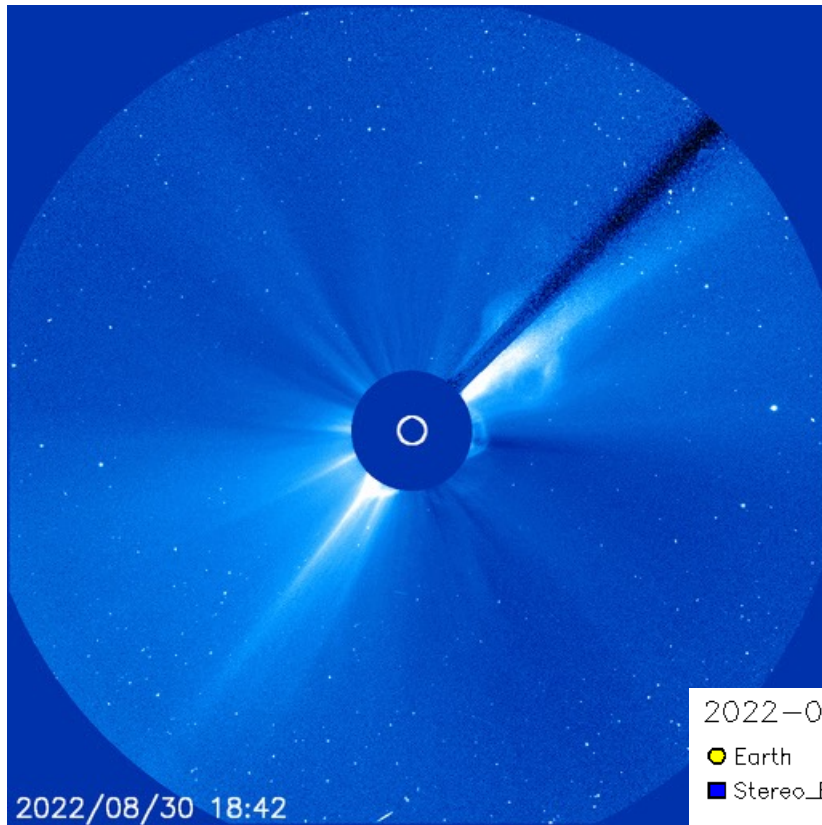
# Other References

- “The 23<sup>rd</sup> Cycle”, Odenwald, S.F. 2001, Columbia University Press
- “Solar Storm Risk to the North American Electrical Grid” [https://www.lloyds.com/Solar Storm Risk to the North American Electric Grid.pdf](https://www.lloyds.com/Solar%20Storm%20Risk%20to%20the%20North%20American%20Electric%20Grid.pdf)
- “Geomagnetic Storms and their Impacts on the U.S. Power Grid” <https://fas.org/irp/eprint/geomag.pdf>
- “Solar Storm Threat Analysis” [http://www.breadandbutter-science.com/Solar\\_Storm\\_Threat\\_Analysis.pdf](http://www.breadandbutter-science.com/Solar_Storm_Threat_Analysis.pdf)



SDO/AIA 131 2025-08-30 19:05:56 UT

# September 2022 Venus in the crosshairs

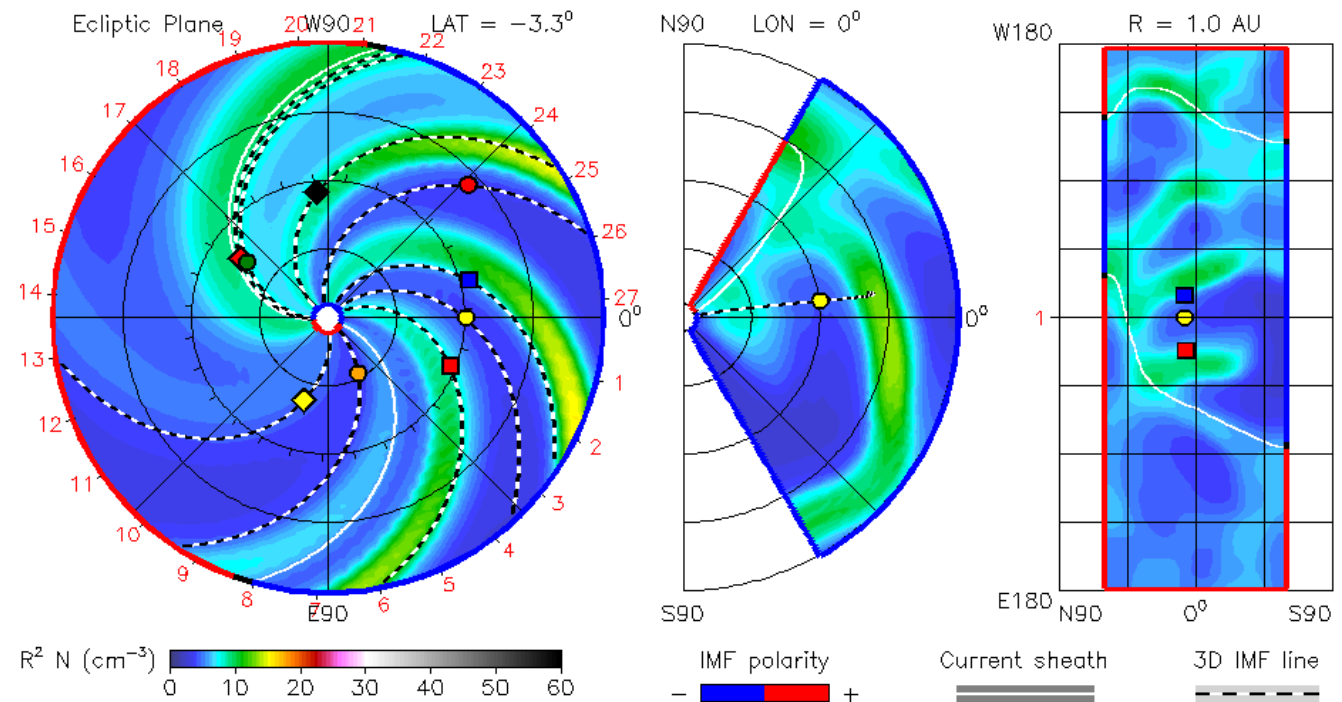


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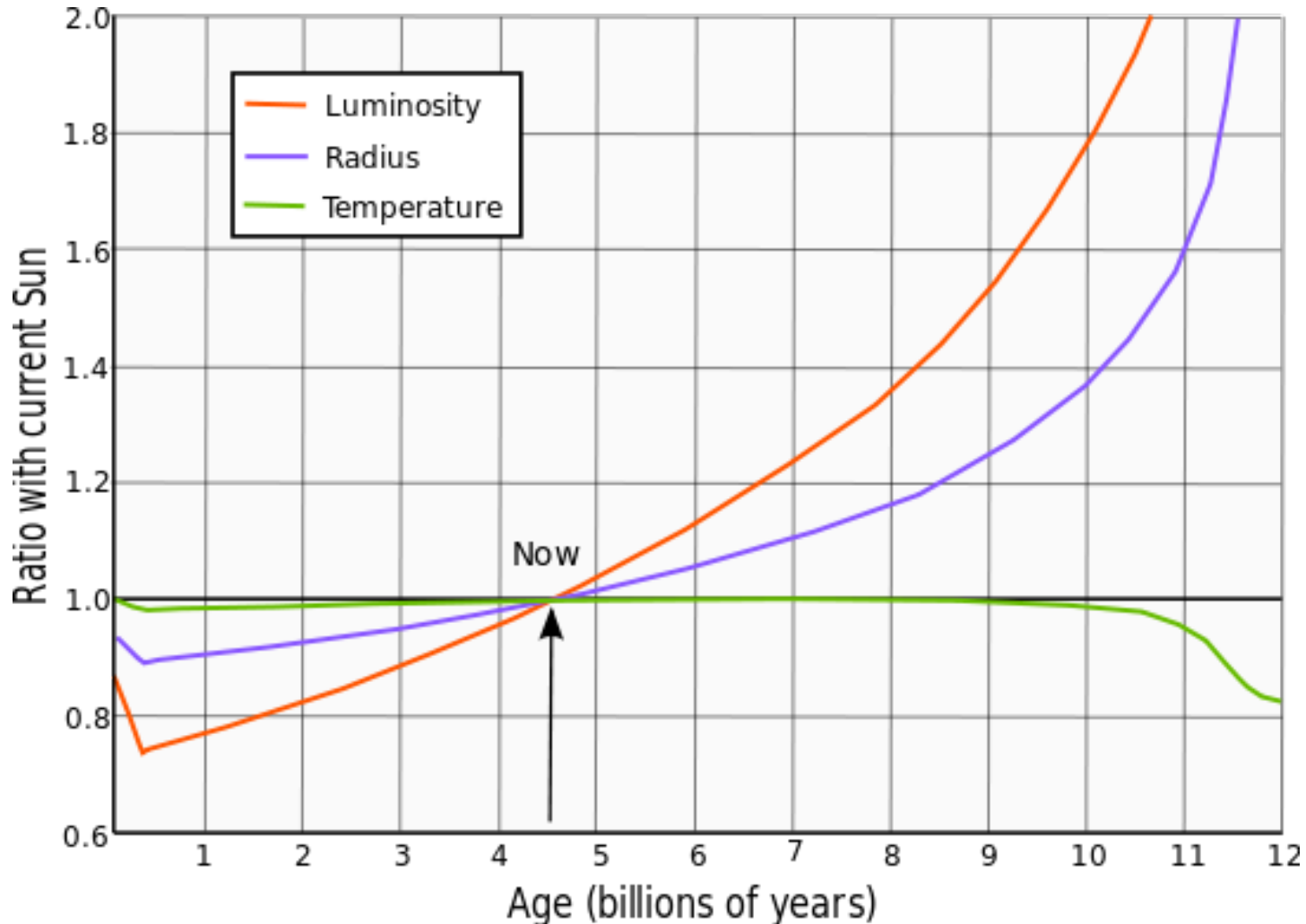
2022-08-29T00:00

2022-08-29T00 +0.00 day

- Earth
- Mars
- Mercury
- Venus
- ◆ Bepi
- ◆ OSIRIS-REx
- ◆ SolO
- Stereo\_A
- Stereo\_B

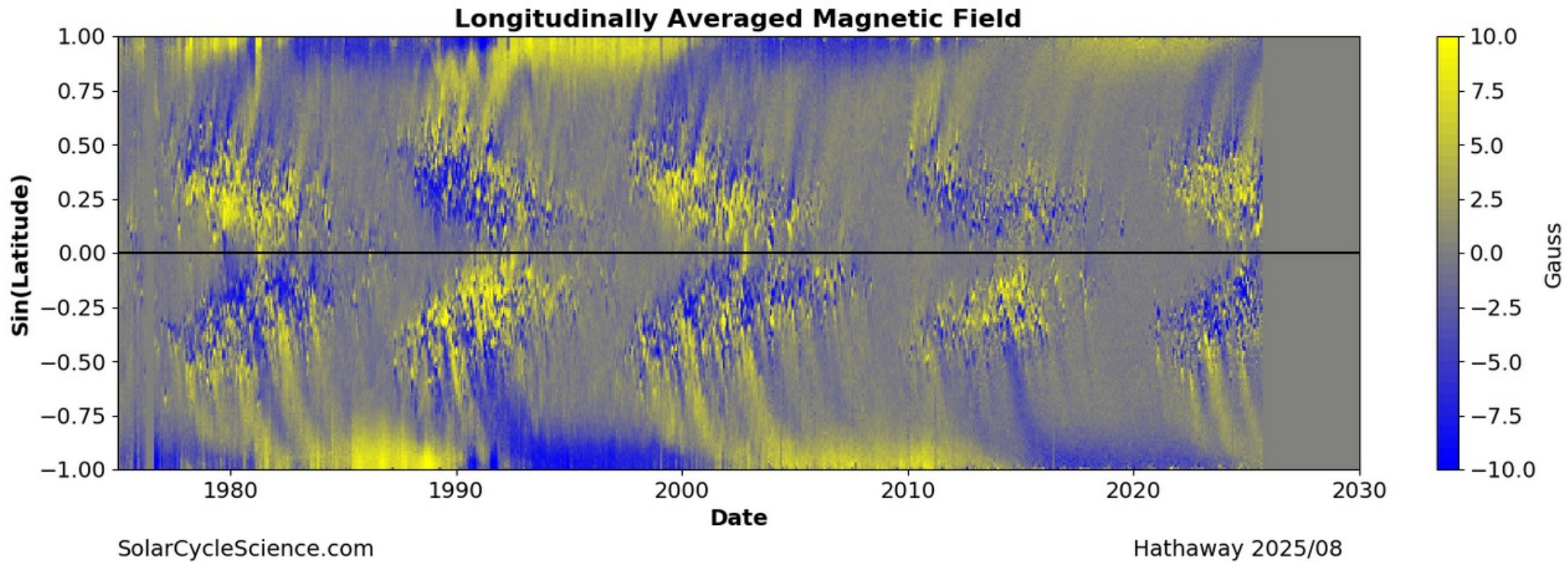


# Practical Solar Evolution

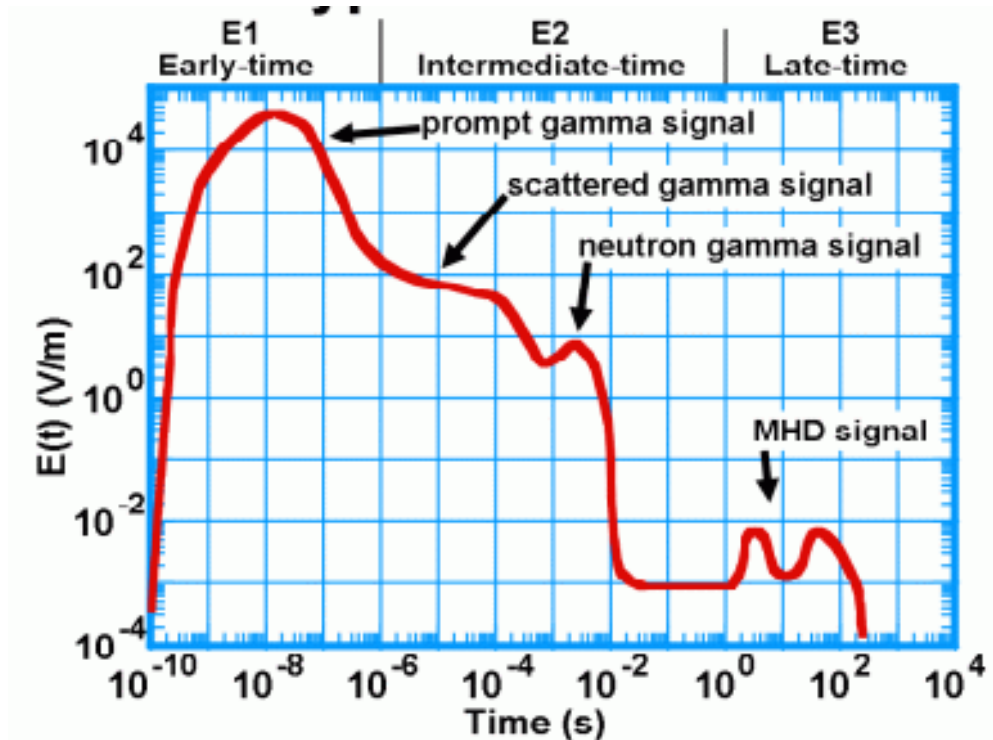


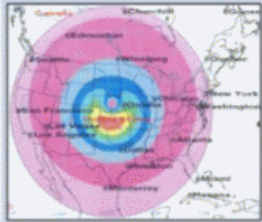
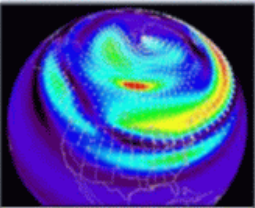
Driven by pressure balance:  $4 \text{ } ^1\text{H} \rightarrow \text{}^4\text{He}$

# Magnetic Butterfly Diagram



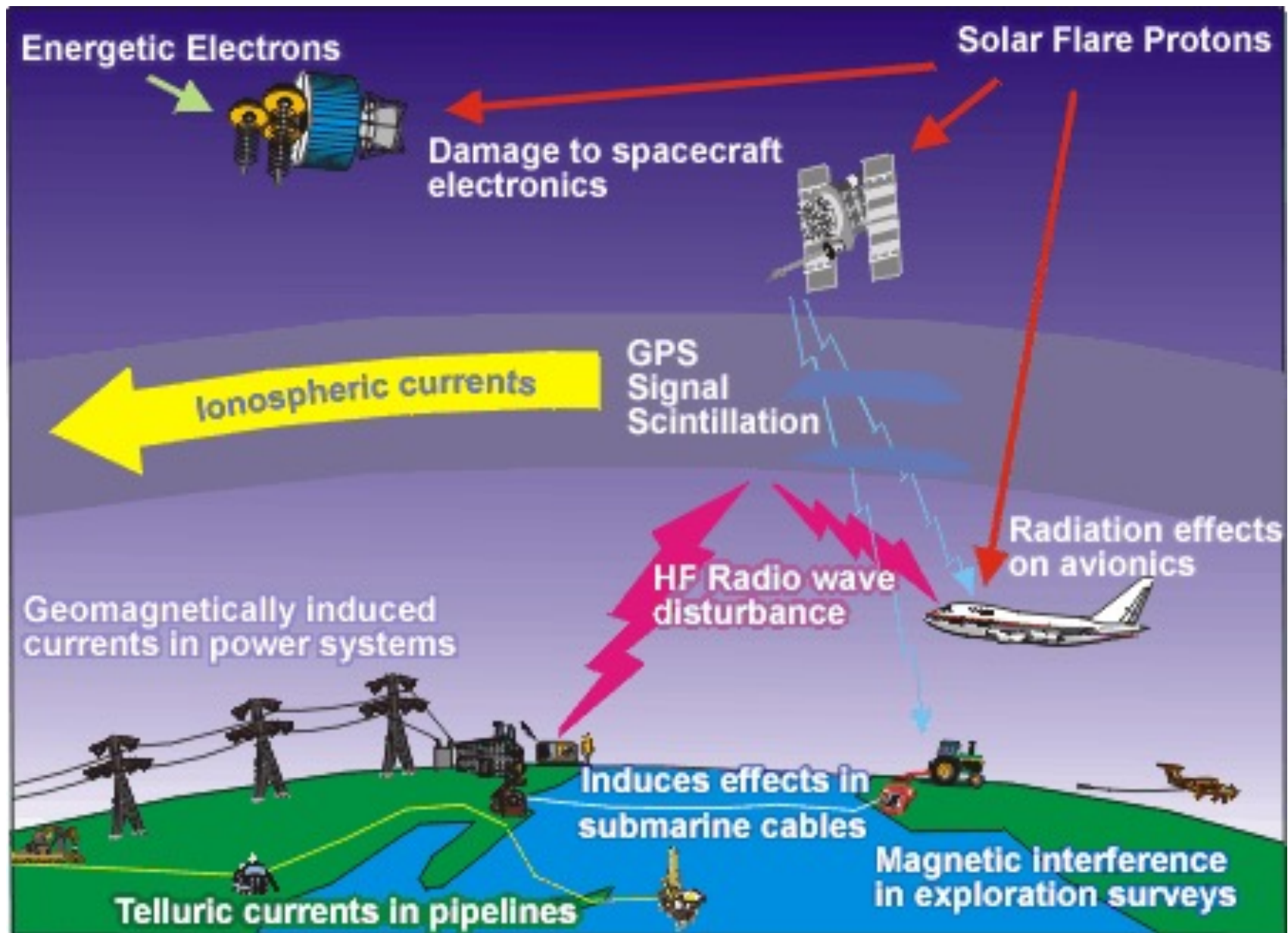
# Aside: CME vs EMP



	THREAT	Environments	Susceptible Systems
	High Altitude EMP	Fast Pulse E1	Long-line and short-line electrical and electronic systems
		Slow Pulse E3	Long-line network systems incl. electric power grid, terrestrial and undersea comm. lines, pipelines
	Solar Super Storms	Geomagnetic Disturbance	Long-line network systems incl. electric power grid, terrestrial and undersea comm. lines, pipelines



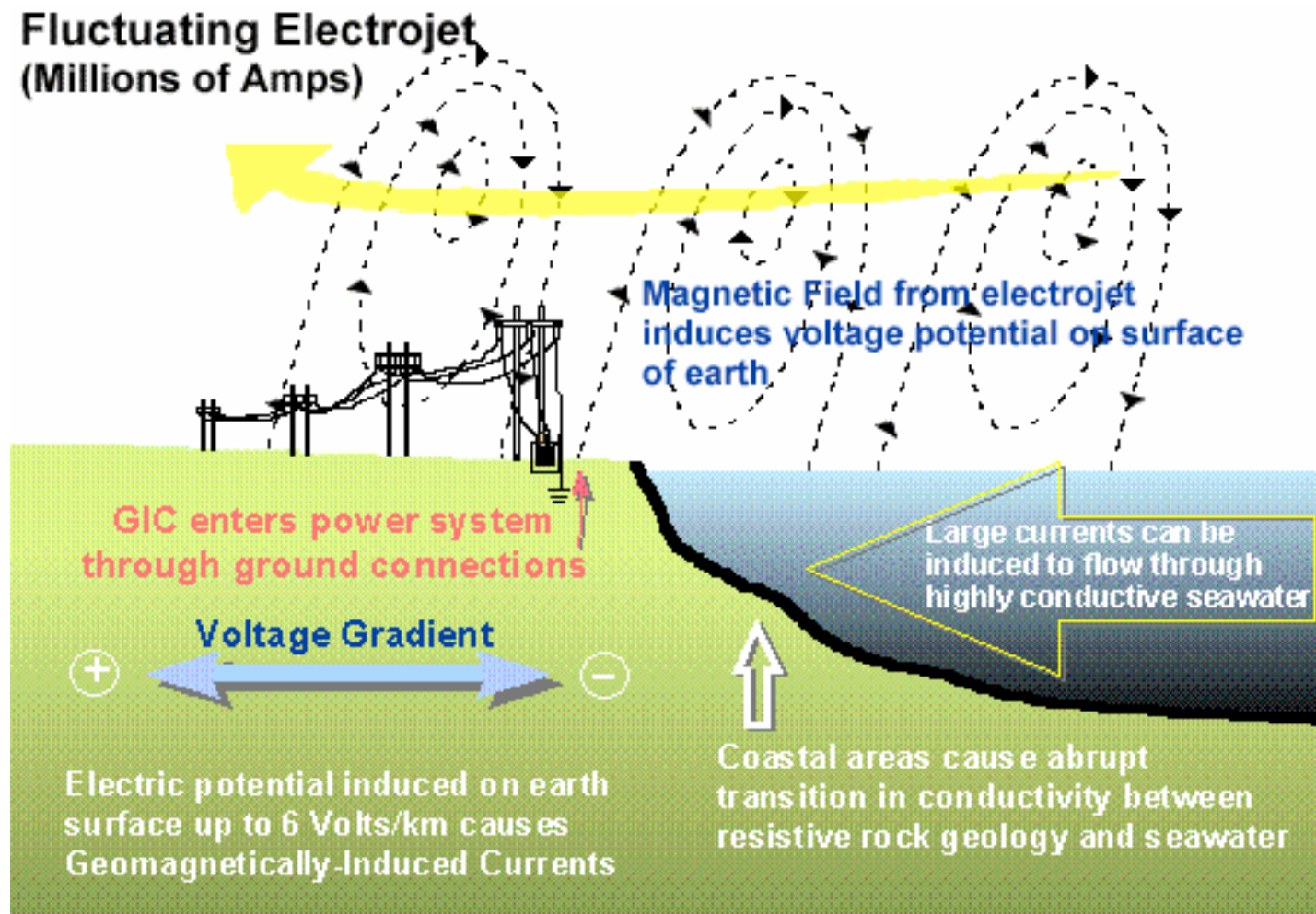
# When it hits



# When it hits

Geomagnetically-induced currents (GIC):

- Drive DC currents in power lines
  - Potentials up to 20V/km; Currents  $>10^6$  amperes



# The 13 March 1989 Hydro Quebec Collapse

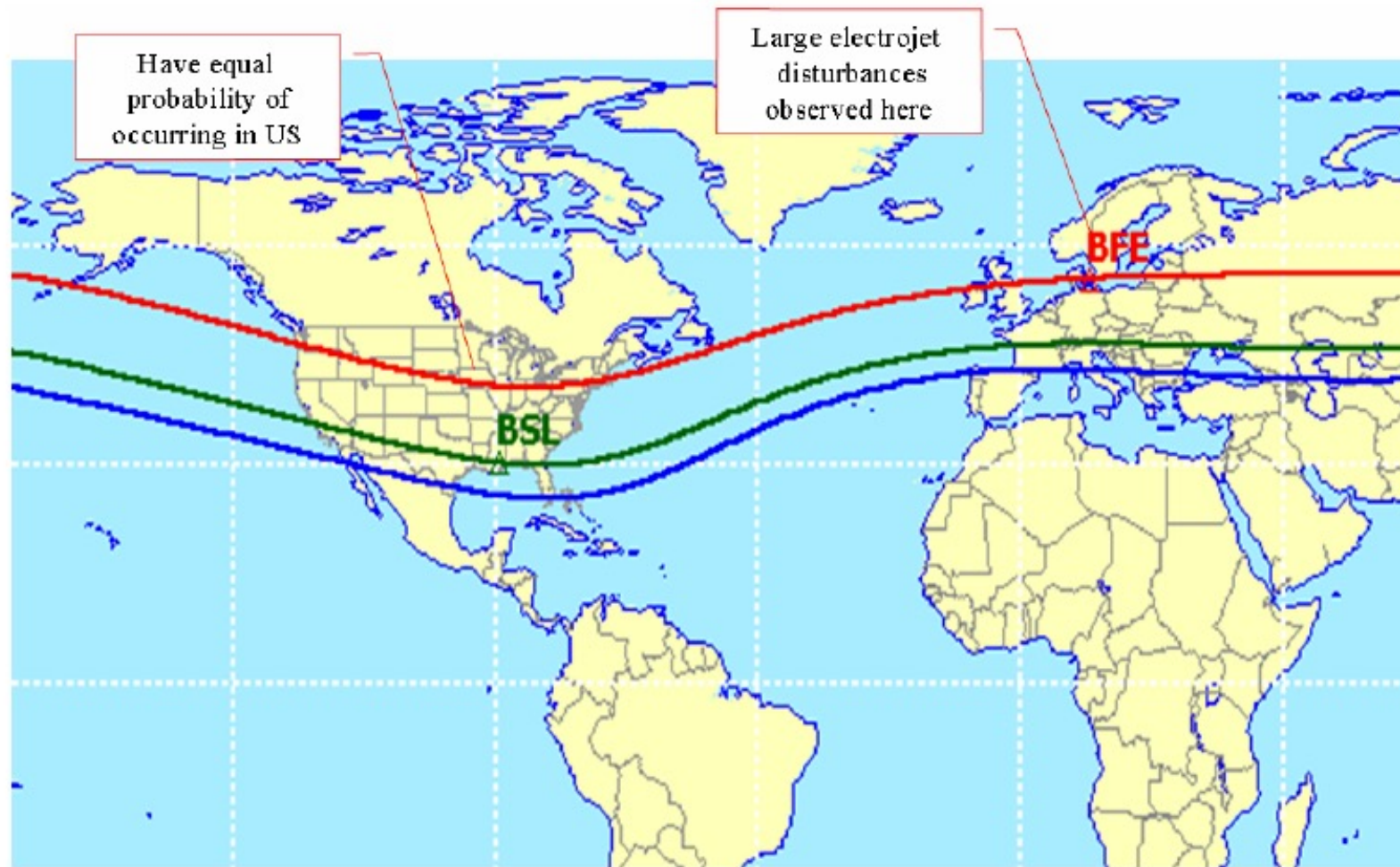


Figure 3-3. World climatology and developing great storm scenarios.

See <http://www.spaceweather.gc.ca/tech/se-pow-en.php>

# Dst: Disturbance Storm Time

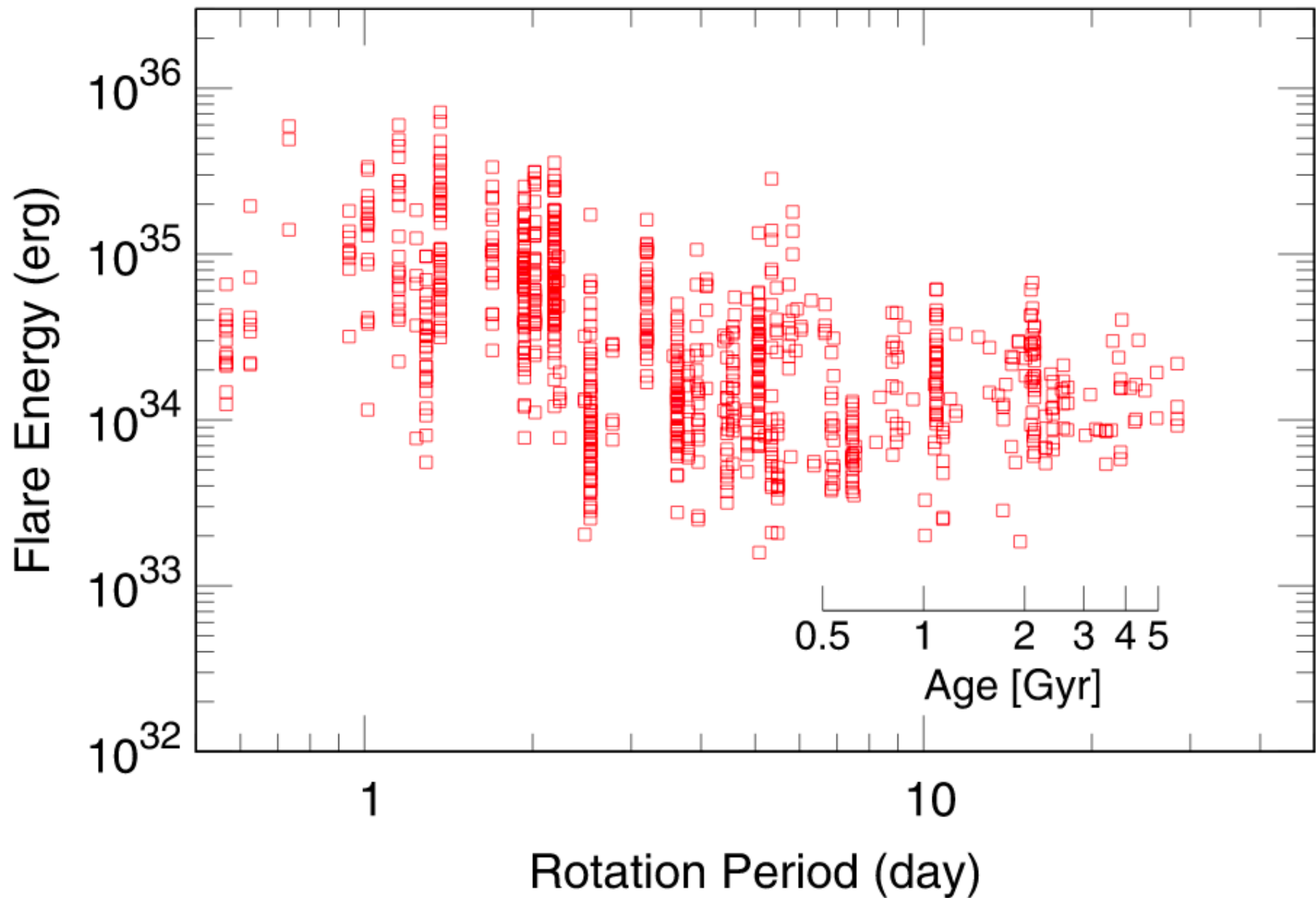
- Measures strength of Earth's magnetic field
- Surface B field strength normally about  $30 \mu\text{T}$
- SEPs drive polar ring current
- Polar ring current opposes terrestrial B field
- Dst is measured in nT
- Largest Dst recorded is  $\sim -900$  nT
  
- Dst records are kept at Kyoto University,  
<https://wdc.kugi.kyoto-u.ac.jp/dstdir/>

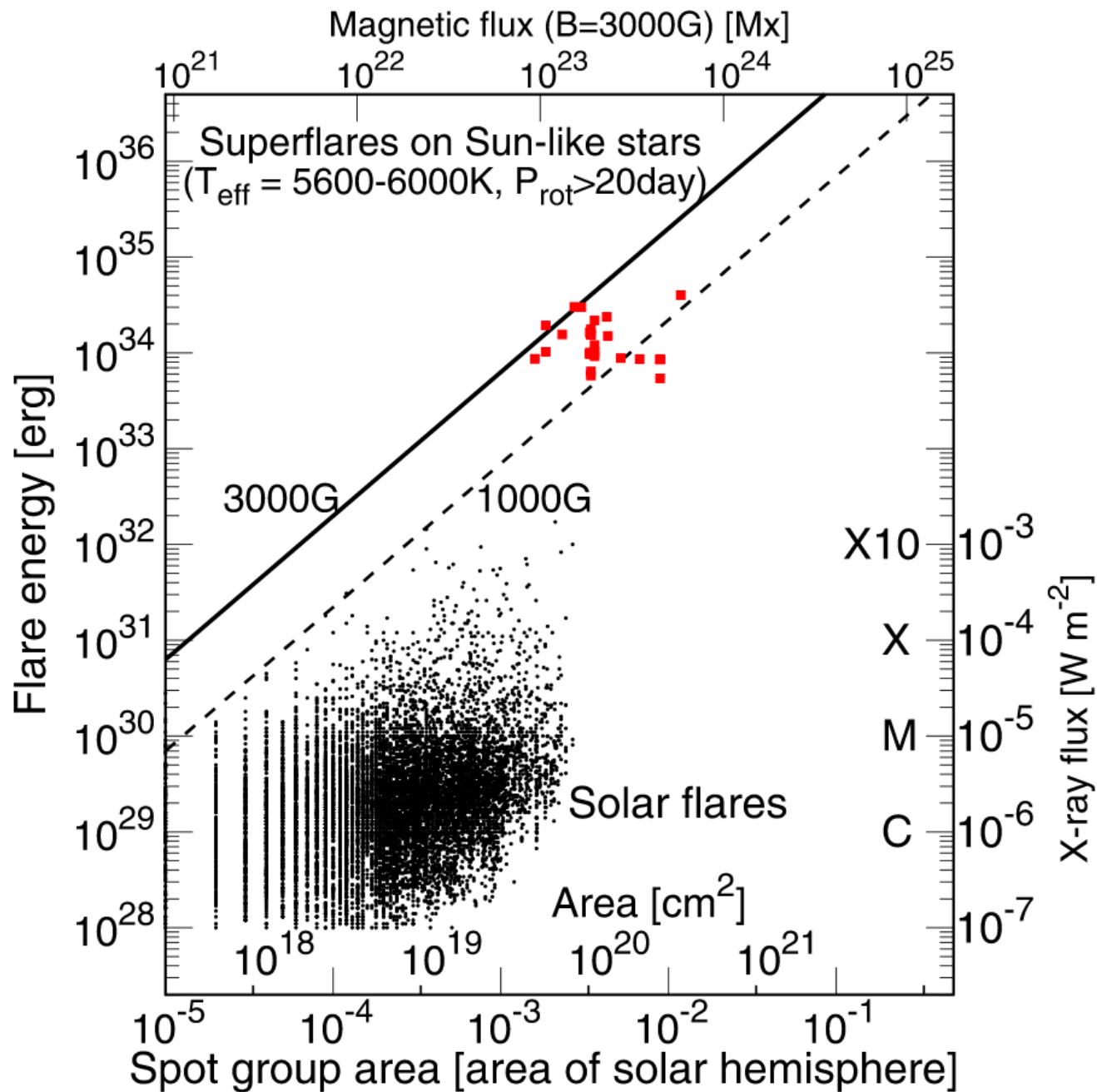
# Superflares. I.

Brightest ☉ flare observed ~  $10^{32}$  erg

- Maehara *et al.* (2012) analyzed Kepler database for superflares ( $E > 10^{33}$  erg). They found:
  - $dN/dE = E^{-2.3 \pm 0.3}$
  - 365 superflares on 148 solar-like stars
  - 14 superflares on 10 old or inactive stars
- Conclusion:
  - A  $10^{35}$  erg solar flare can be expected about **every 5000 years**

$T_{\text{eff}}=5600\text{-}6000\text{K}$





**Figure 5.** Same as Figure 4, but for Sun-like stars.

# Interpretation

A slowly-rotating Sun-like star will produce a

- $4 \times 10^{33}$  erg flare every 3000 years
- $4 \times 10^{34}$  erg flare every 80,000 years

Carrington flare estimate:  $\sim 6 \times 10^{32}$  erg

