AI & Space Weather

AI Revolution in Space Weather
a new era of Prediction Forecasting

Ammar Sakaji

The Regional Center for Space Science and Technology Education for Western Asia, RCSSTEWA-JORDAN,

President of the Jordanian Astronomical Society JAS

The 3rd International Conference on the Artificial Intelligence in Sustainable Development in Jordan

RAISD 2025

November 19-20, 2025

Amman- Jordan

Outline

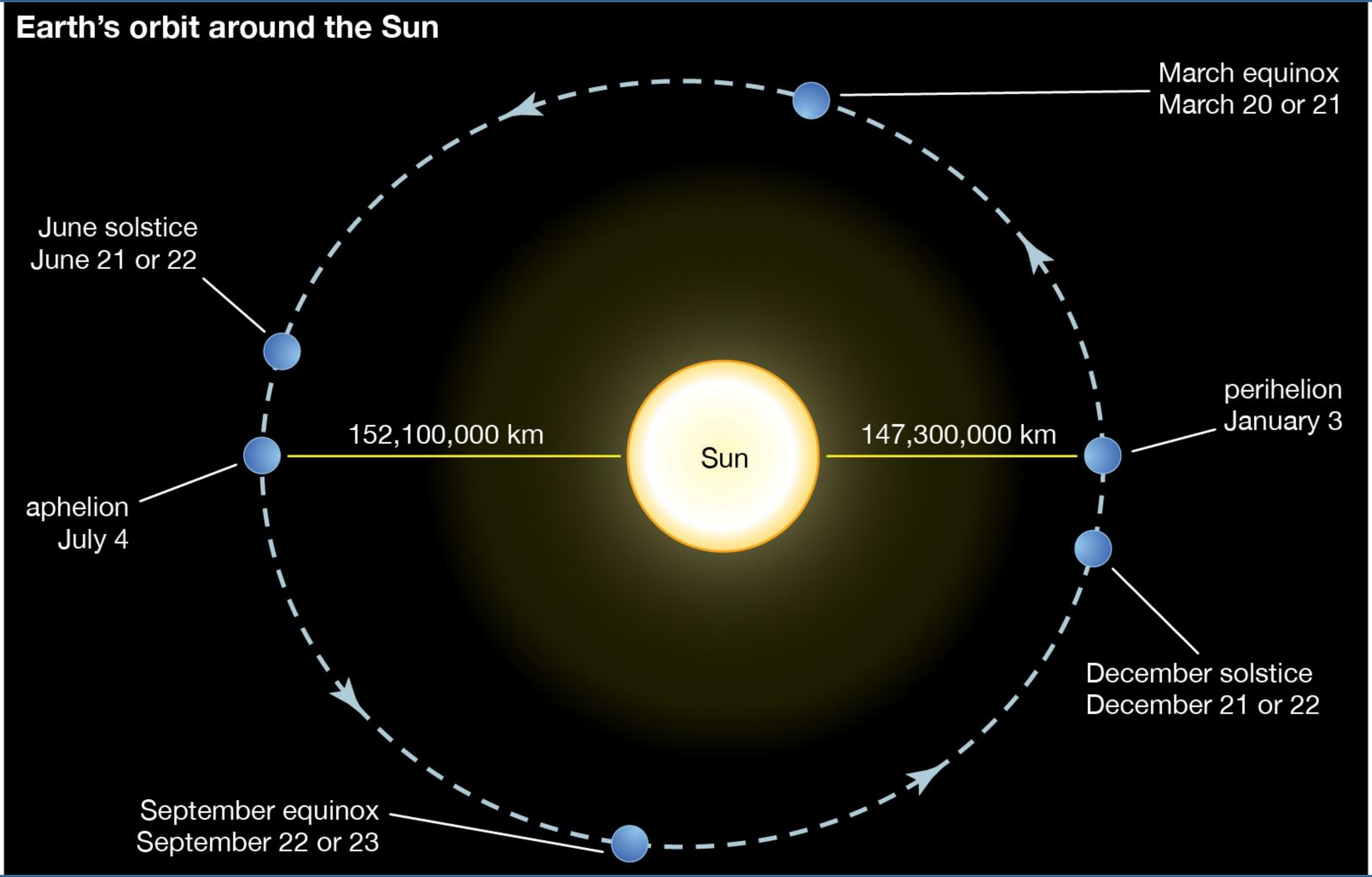
- Space Weather: Solar Flares, Sunspots, Coronal Mass Ejections **CME, Solar wind & Geomagnetic storm**
- **Space Weather Effects on** GNSS Satellite Charging & Anomalies, Solar Radio Burst Interference, communication, transformers, electric grids……
- Sunspots from Jordan
- AI is revolutionizing the Space Weather science

Space Weather

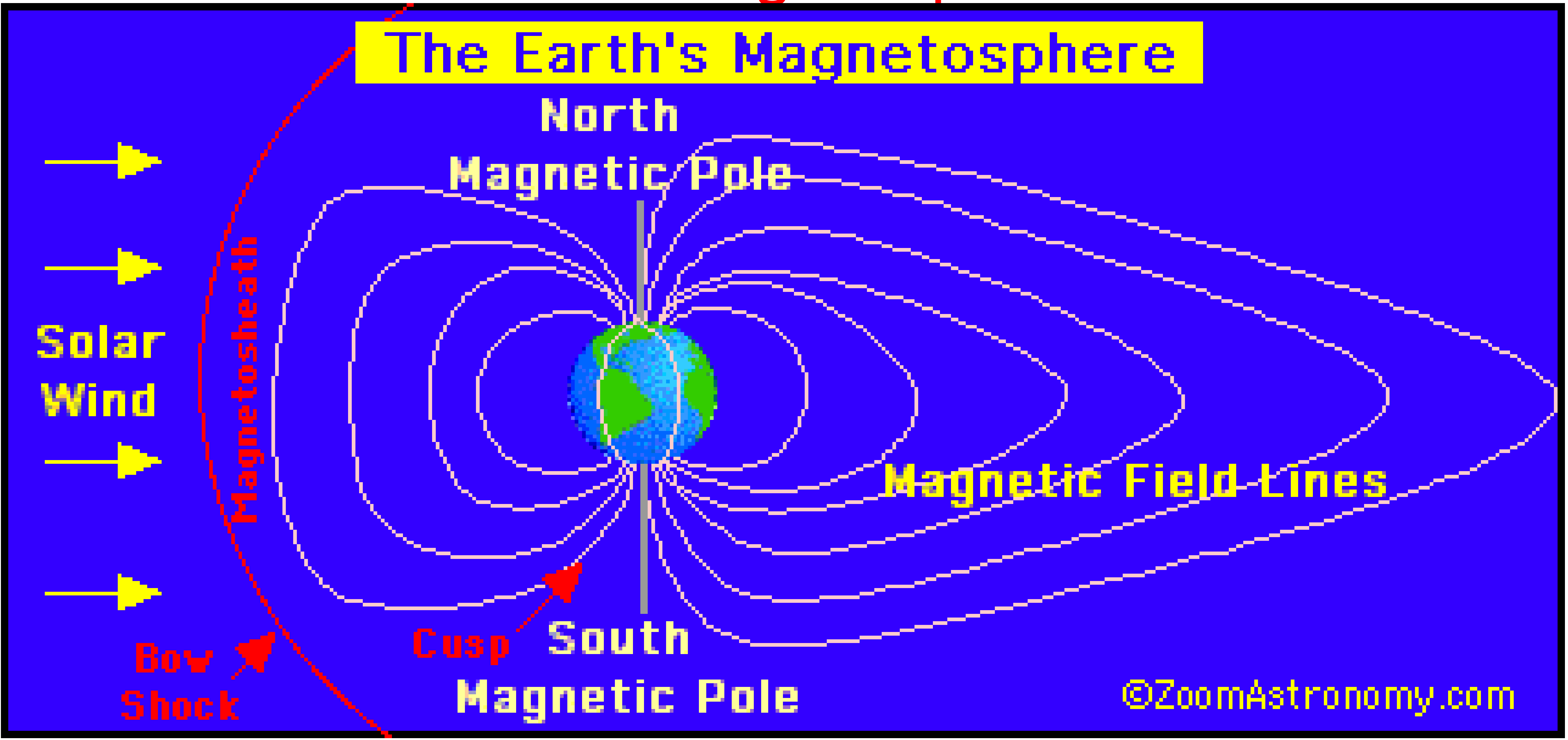
Space weather refers to the changing conditions in space caused mainly by the Solar activities—such as solar flares, radiation bursts, and streams of charged particles—that interact with Earth's magnetic field and atmosphere, sometimes affecting communications, satellites, power grids, and causing auroras.

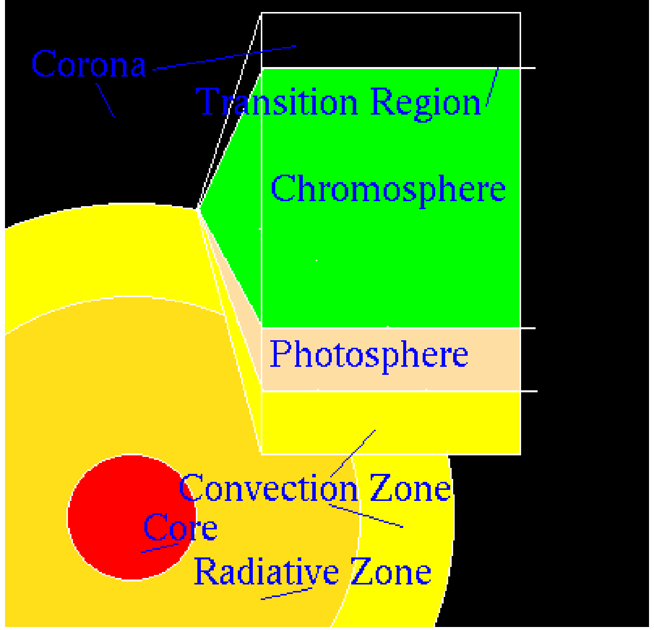
Solar Wind: A continuous stream of charged particles (mainly electrons and protons) flowing outward from the Sun in all directions, carrying magnetic fields through space and interacting with planets.

Geomagnetic Storm: A major disturbance in Earth's magnetic field that occurs when **strong solar wind or a coronal mass ejection hits the magnetosphere**, causing auroras and potential disruptions to satellites, communications, and power systems.

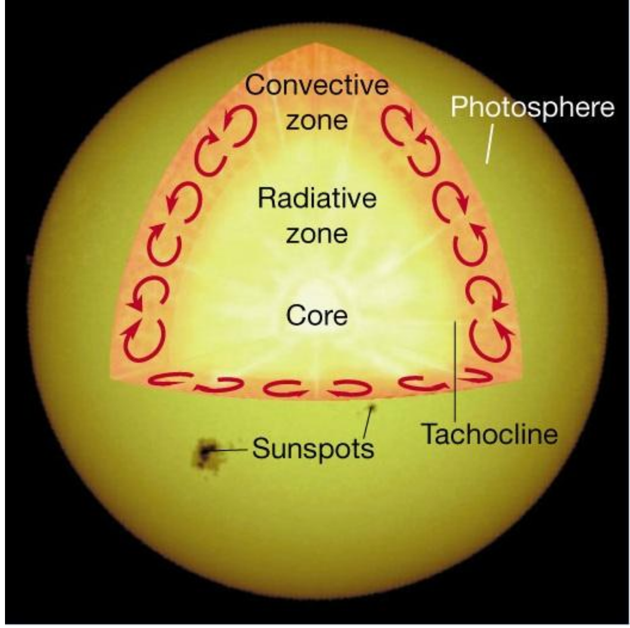

Earth's orbit around the Sun
March equinox
March 20 or 21
June solstice
June 21 or 22
perihelion
January 3
152,100,000 km
Sun
147,300,000 km
aphelion
July 4
December solstice
December 21 or 22
September equinox
September 22 or 23

Earth’s magnetosphere





Solar Interior



- **Core**

  $R < 0.1\ R_o$ $M \approx 1/3\ M_o$

  (the site of nuclear reactions)

- **Radiative zone**

  $(0.1 \div 0.7)\ R_o$ $M \approx 2/3\ M_o$

- **Convective zone**

  $(0.7 \div 1)\ R_o$ $M \approx 2\%\ M_o$

  (As temperature drops, opacity increases and radiation is not efficient for energy transport)

- **Photosphere**

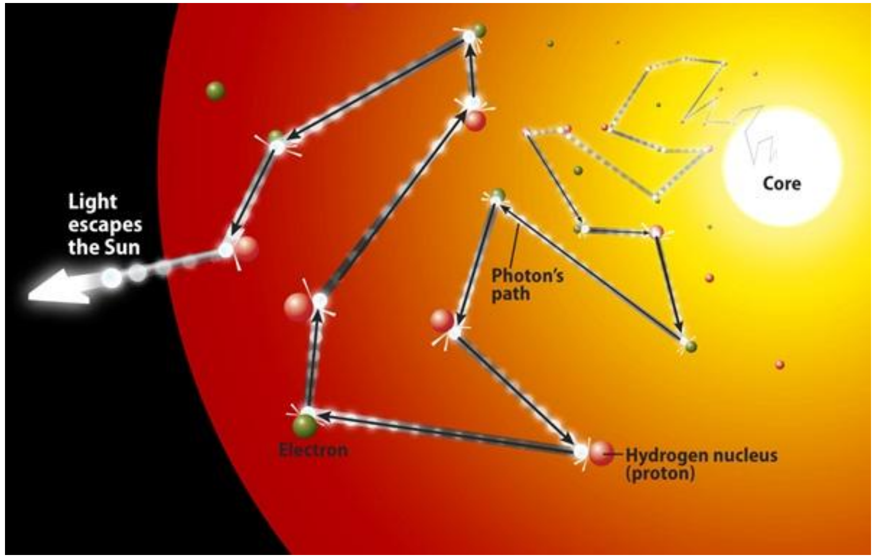
  the very tiny layer of the Sun that we can observe directly

The **core is the energy source**, where hydrogen fuses into helium (Nuclear Fusion).

Heat from the core spreads out through the **radiative** and **convective** zones.

Photon Journey from the core of the sun to earth

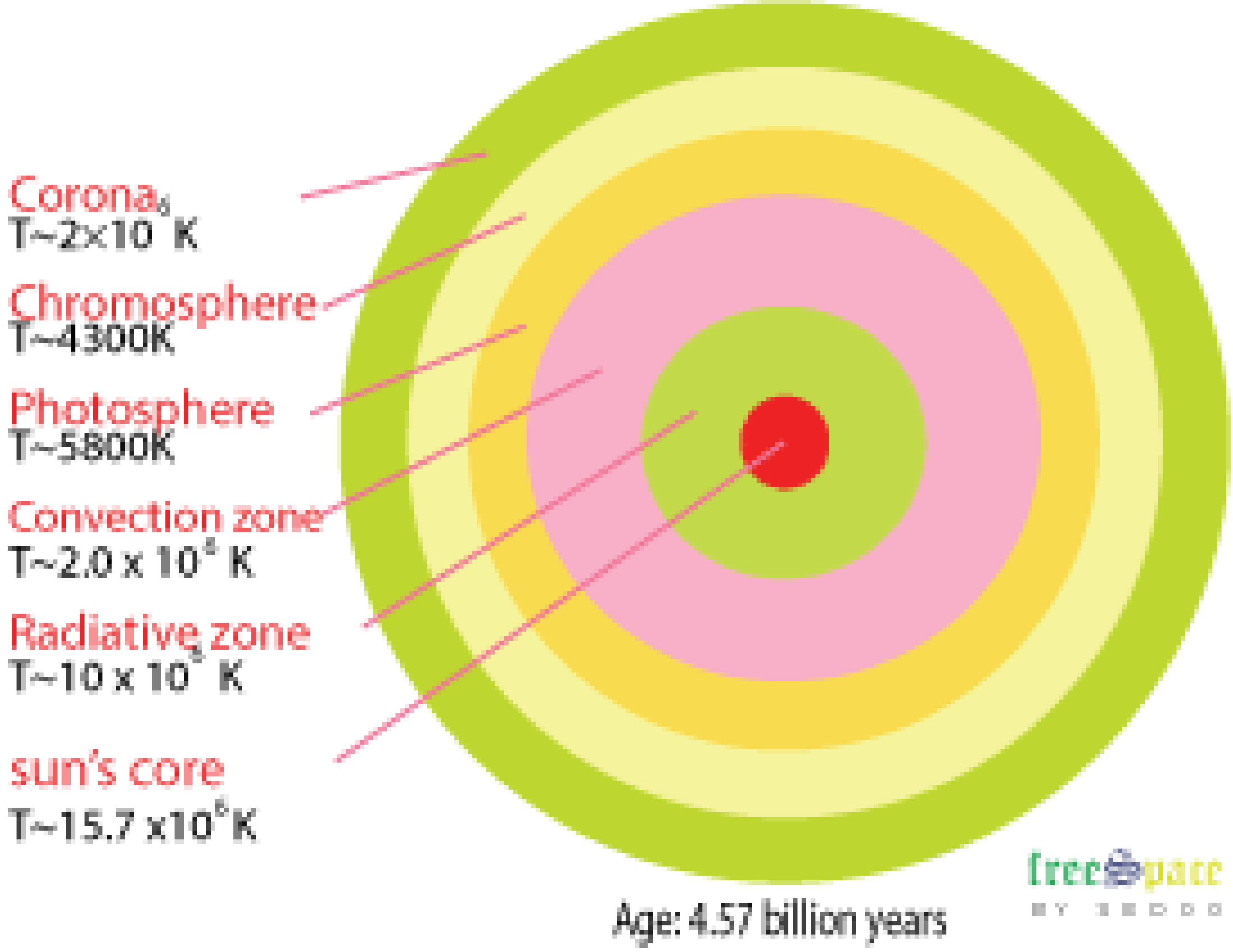
- A photon generated in the Sun's core undertakes a "**random walk**" through the radiative zone by being absorbed and re-emitted by dense solar plasma, a process that can take tens of thousands to over a million years.
- **Sun's core to surface**
- Time: few thousands, to 100,000–200,000 years or more
- **Sun's surface to Earth**
- Time: 8 minutes and 20 seconds



- **Interactions**
- As photons leave the Sun's core, they scatter off electrons and atomic nuclei, which causes them to take a long time to travel.
- **Density**
- The Sun's core is 150 times denser than water, so the gamma rays generated by nuclear burning are absorbed and re-radiated as they move up from the core.
- **Zigzagging**
- Photons travel in a "drunken walk" pattern, zigzagging from atom to atom as they move toward the surface.

Sun Temperatures

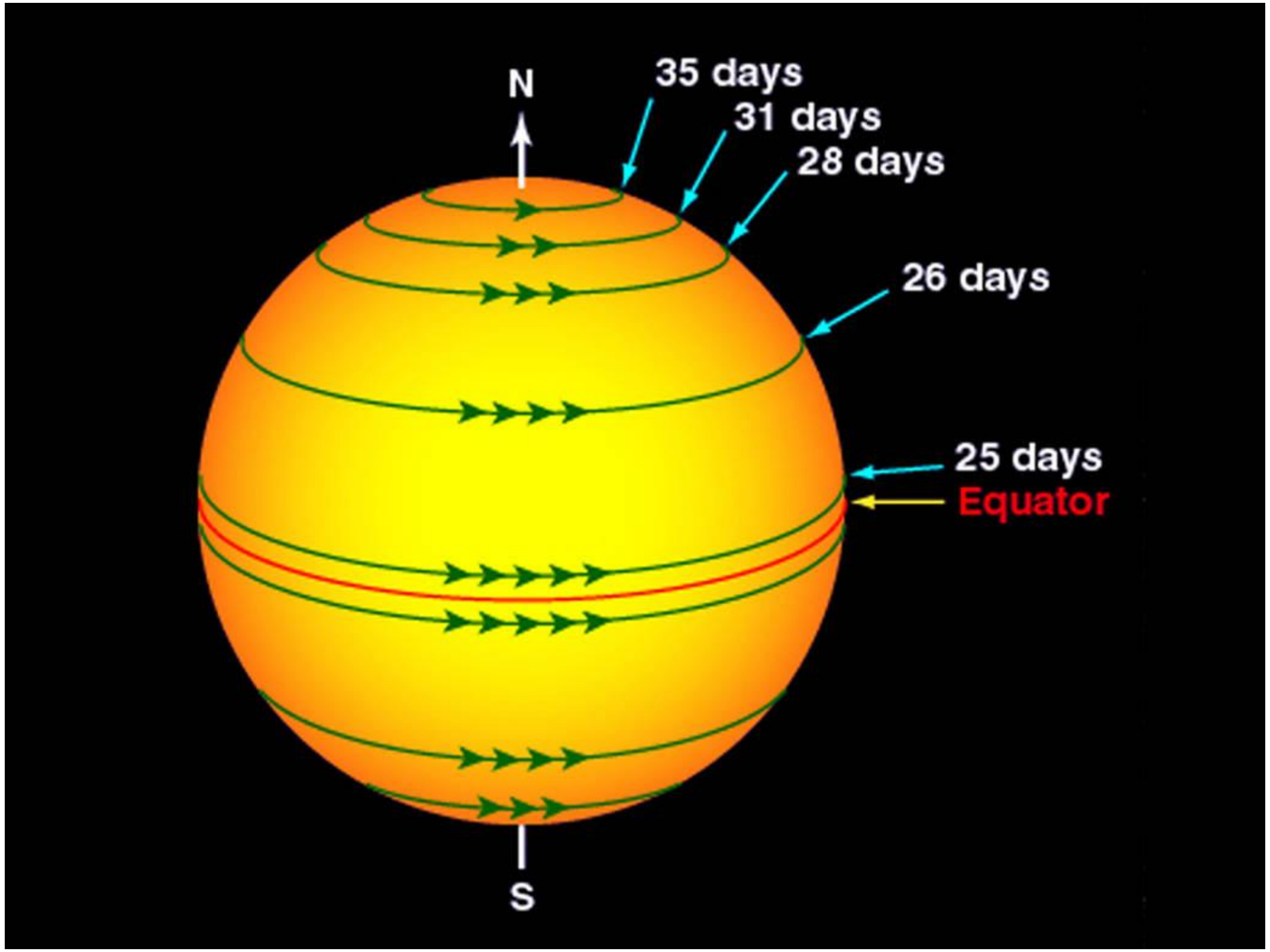
The sun is a spherical star located in the center of the system solar



Solar rotation

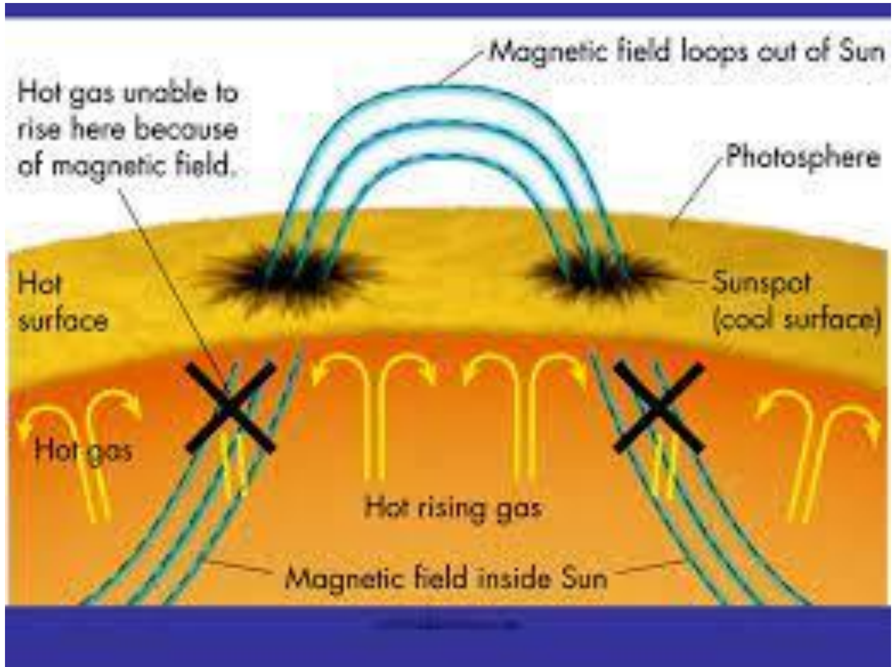
Solar surface does not rotate uniformely:

Differntial rotation:**T=24 days at equator** & **30 days at the poles**.



What are Sunspots?

- Strong magnetic fields coming up from the solar interior.
- The field is strong enough to inhibit convection, so the surface cools & darkens.
- They last from **days to weeks**, then fragment and spread out.



Coronal Mass Ejections (CMEs)

The Equivalent of a Hurricane

- Massive bubbles of plasma
- Disrupt the flow of solar wind
- Few per week at peak solar activity
- Occasionally causes geomagnetic storm on Earth
- Arrives in 1-5 days
- The most threatening of solar events

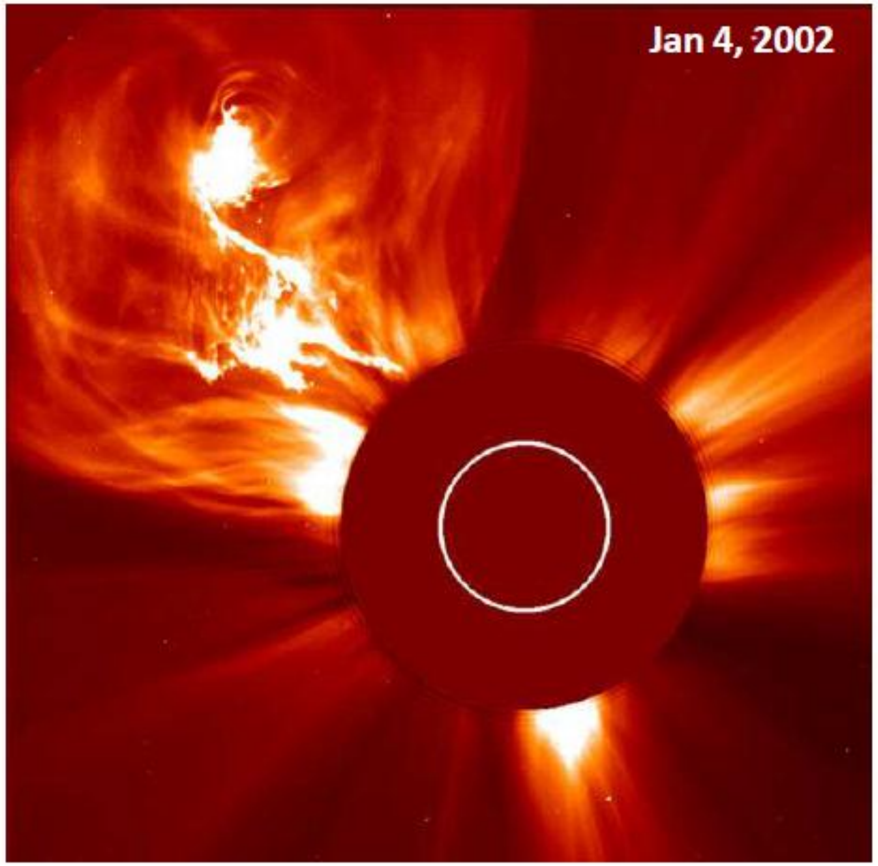
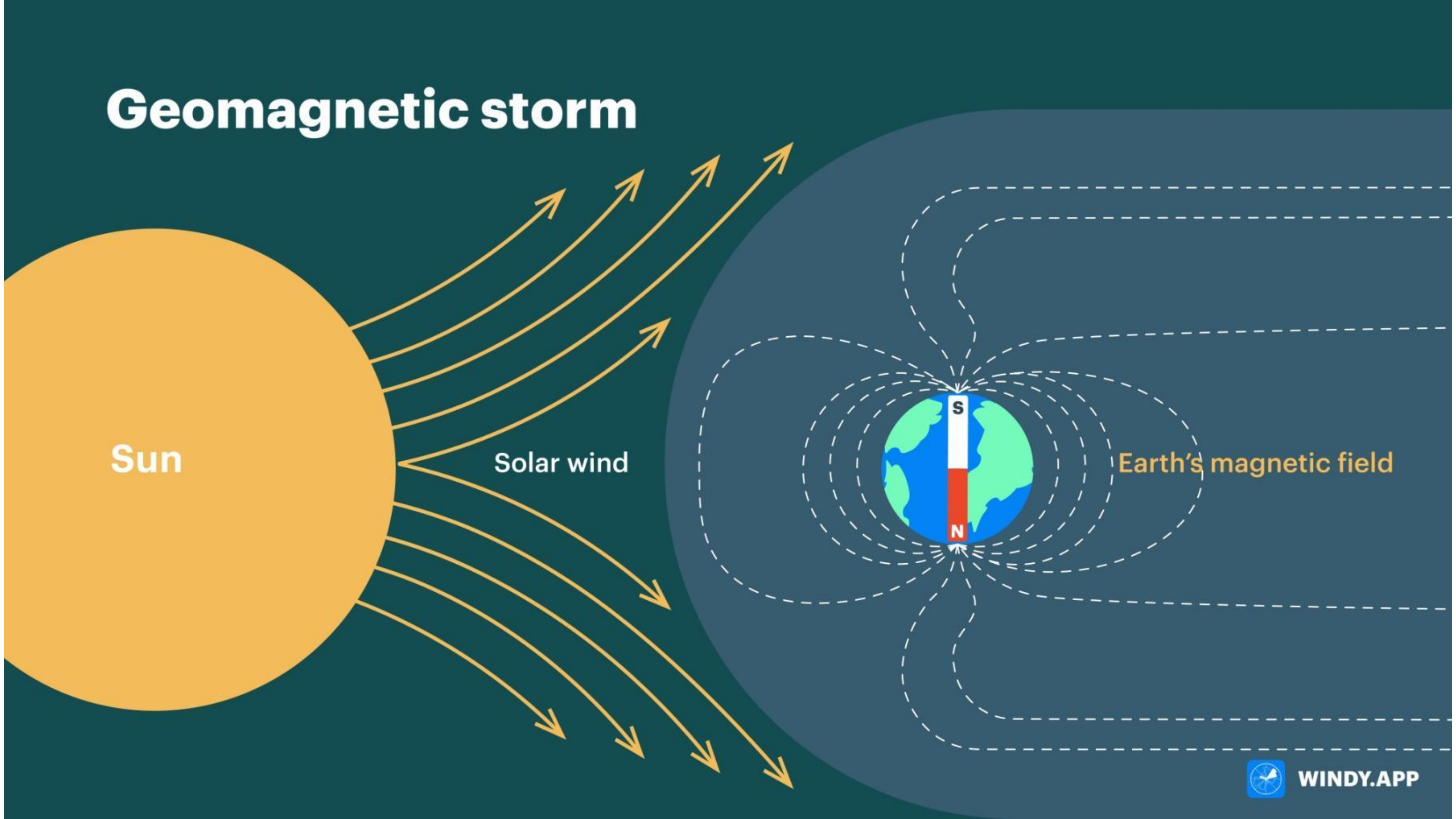
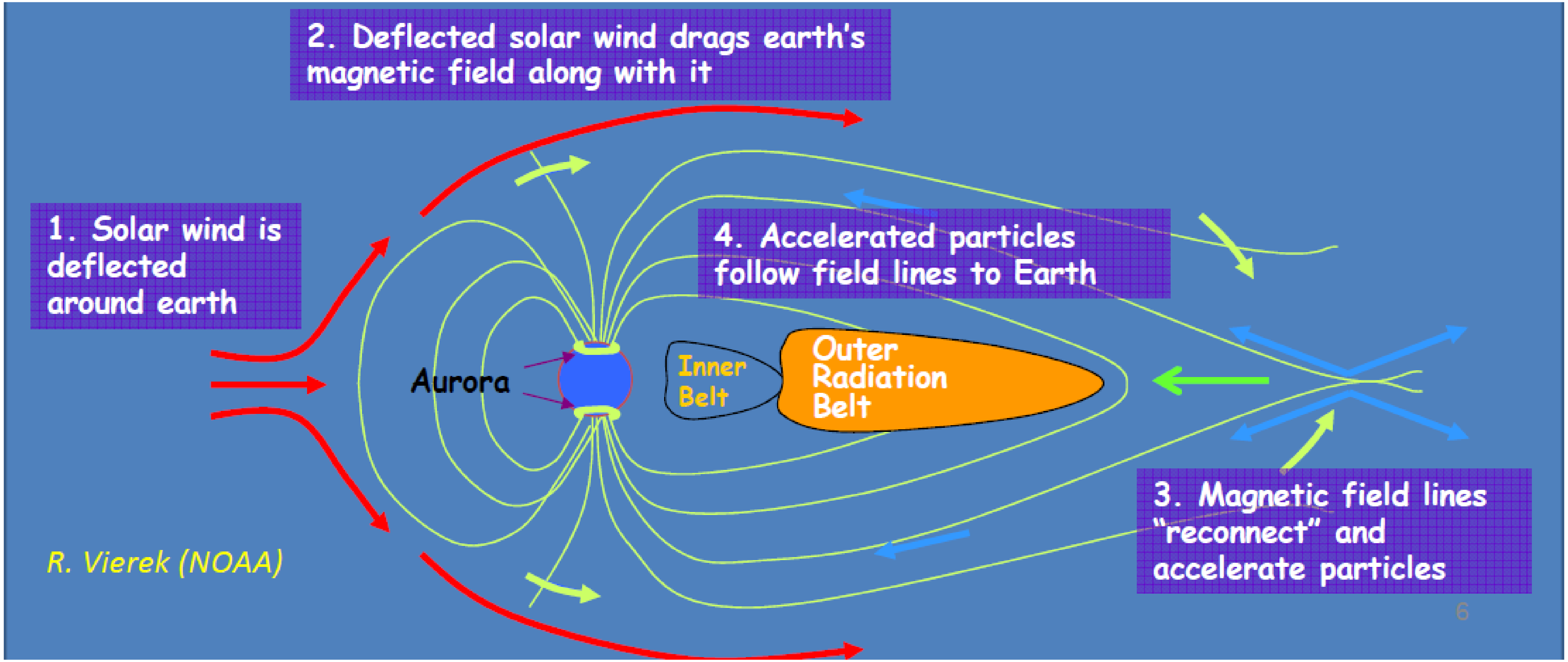


Image from SOHO

Coronal loops

Filamentary structure traces the magnetic field (plasma)
Closed & open loops


Geomagnetic storm
Sun
Solar wind
S
N
Earth's magnetic field
WINDY.APP

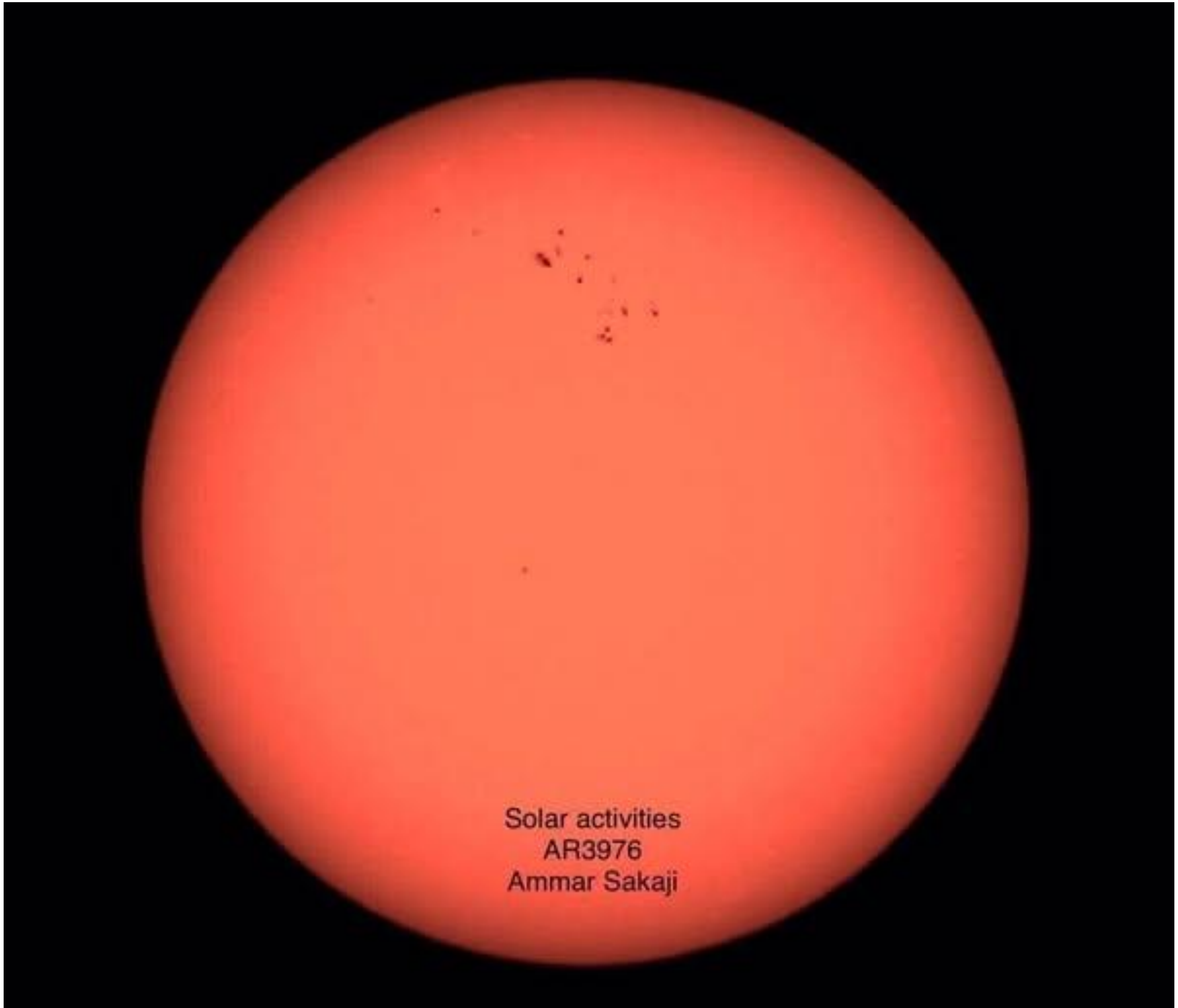

2. Deflected solar wind drags earth's magnetic field along with it
1. Solar wind is deflected around earth
4. Accelerated particles follow field lines to Earth
Aurora
Inner Belt
Outer Radiation Belt
3. Magnetic field lines "reconnect" and accelerate particles
R. Vierek (NOAA)
6

Geomagnetic Storms

G Level	Kp Index	Description	Typical Effects
G1 — Minor	5	Weak geomagnetic storm	Small power-grid fluctuations; minor satellite effects; aurora at high latitudes
G2 — Moderate	6	Moderate disturbance	Voltage alarms possible; satellite issues; aurora reaches mid–high latitudes
G3 — Strong	7	Strong storm	Grid corrections needed; increased satellite drag; aurora at mid-latitudes
G4 — Severe	8	Severe geomagnetic storm	Widespread voltage issues; radio disruptions; aurora at low latitudes
G5 — Extreme	9	Extreme storm	Possible power-system failures; satellite problems; aurora at very low latitudes

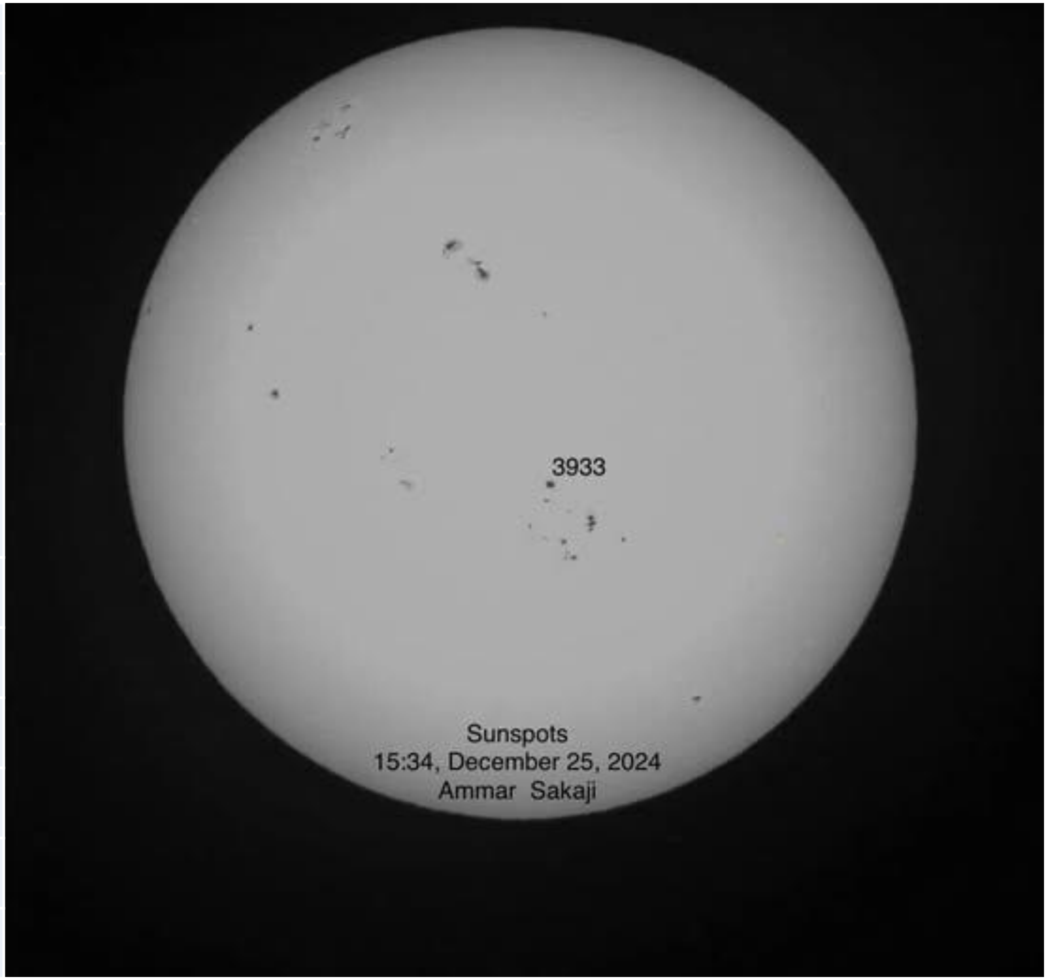
Kp	G-scale	Geomagnetic latitude	Auroral activity	Average frequency
0	G0	66° or higher	Quiet	
1	G0	64.5°	Quiet	
2	G0	62.4°	Quiet	
3	G0	60.4°	Unsettled	
4	G0	58.3°	Active	
5	G1	56.3°	Minor storm	1700 per cycle (900 days per cycle)
6	G2	54.2°	Moderate storm	600 per cycle (360 days per cycle)
7	G3	52.2°	Strong storm	200 per cycle (130 days per cycle)
8	G4	50.1°	Severe storm	100 per cycle (60 days per cycle)
9	G5	48° or lower	Extreme storm	4 per cycle (4 days per cycle)

Sunspot Activity Seen from Jordan

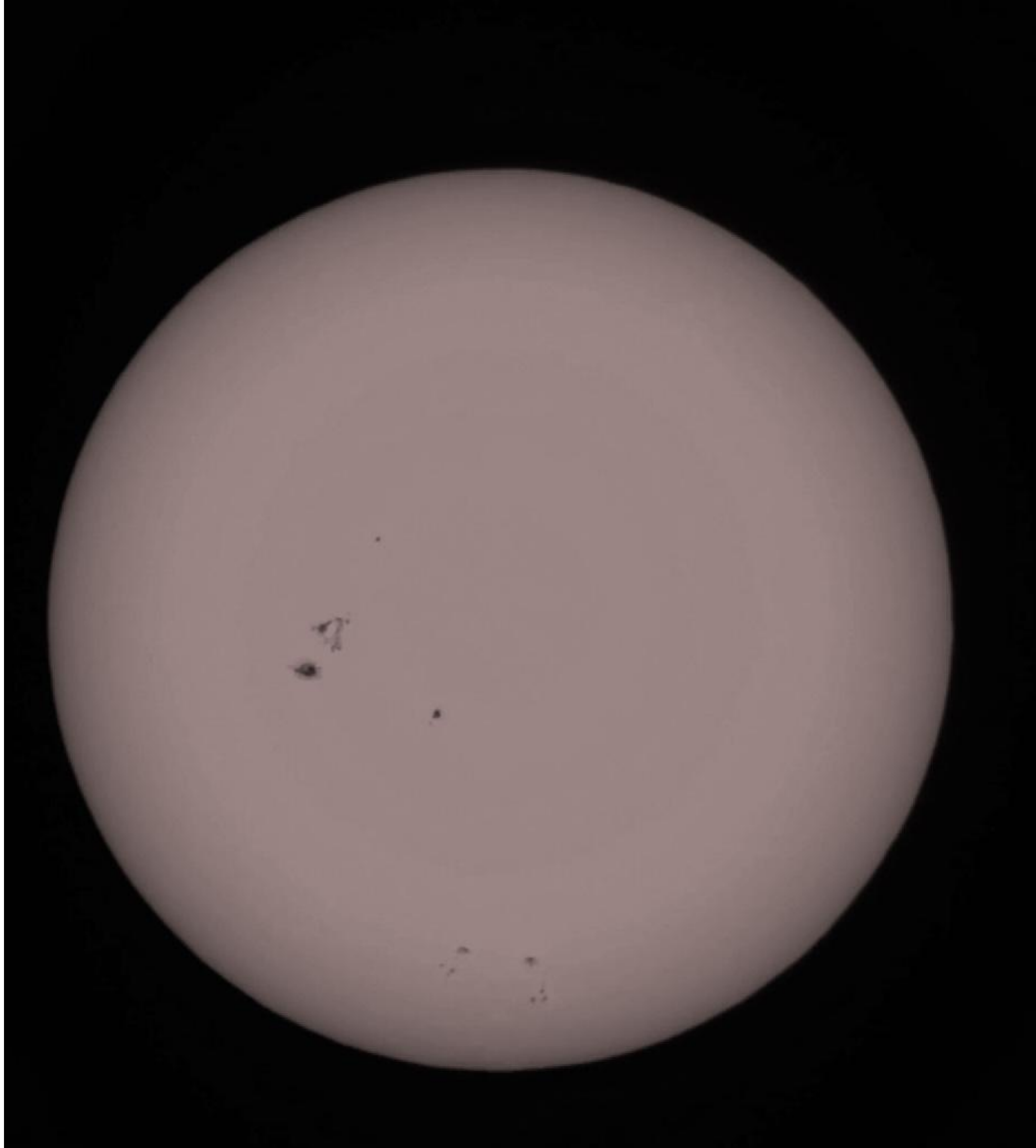

Solar activities
AR3976
Ammar Sakaji

Sunspots (December 25, 2024): G1
Alook-Jordan

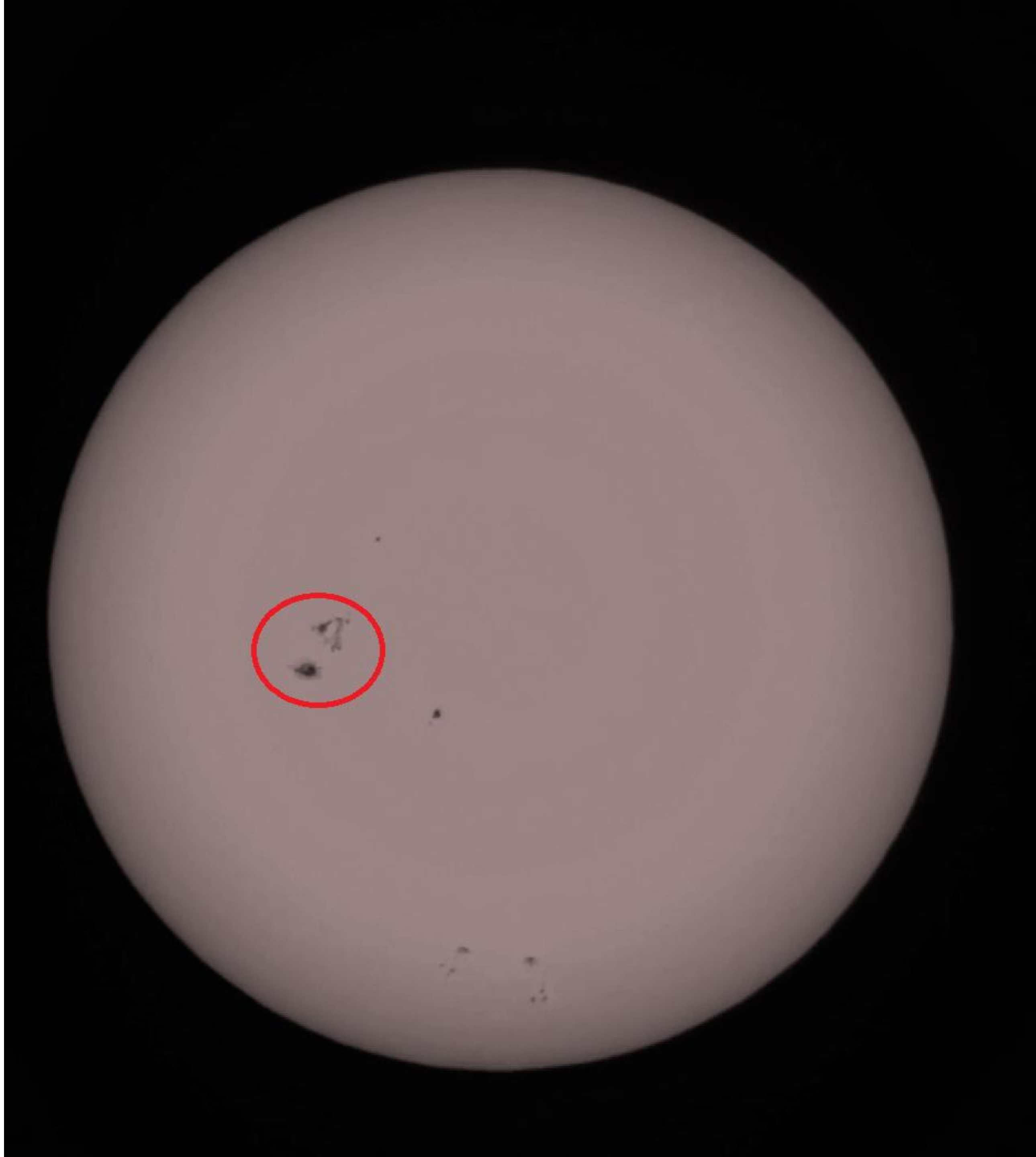
Sunspot	Number	Class
3926	1	alpha
3927	2	alpha
3928	26	beta-gamma
3930	6	beta
3932	34	beta-gamma
3933	18	beta-gamma-delta (1.5 surface area of Earth)
3934	1	alpha
3935	2	beta
3936	9	beta
3937	1	alpha
3938	12	beta-gamma
3939	2	beta



Sunspot AR4274, (4 x Earth Surface)
at 8:29 am Nov 8, 2025,
Alook-Jordan



Sunspot Ar4274,
at 8:29 am Nov 8,
2025, Alook-Jordan



Key dates for its appearance and activity

- Sunspot region AR4274 first appeared on the Sun's Earth-facing disk around **November 4, 2025**, emerging over the eastern limb (edge).
- **November 4, 2025:** The sunspot was first observed as it rotated into view on the northeast limb of the Sun and produced an initial X1.8-class flare.
- **November 8, 2025:** Observed and photographed in Jordan's sky
- **November 9-11, 2025:** The region rotated to a near Earth-facing position and produced several powerful flares, including an X1.8, X1.2, and an X5.2 flare (the **strongest of 2025 at the time**).
- **November 14, 2025:** AR4274, while approaching the western limb and rotating out of view, fired another powerful **X4.0 flare**.
- **November 15, 2025:** The region rotated out of Earth's view, heading to the Sun's far side.

AR4274 Sunspot

When it first reappeared on the northeast limb, AR4274 raised big expectations.

Over this transit, it produced four powerful **X flares, X1.8, X1.2, X5.2, X4**, plus a steady stream of M- and C-class flares.

Last week, AR4274's X flares launched a series of coronal mass ejections (CMEs) that slammed into Earth's magnetic field between **November 10–11**.

These impacts drove geomagnetic storms as strong as G3–G4, pushing bright auroras deep into the mid-northern latitudes.

Skywatchers across the continental U.S., southern Canada, northern Europe, and even parts of northern Mexico (including Sonora, Zacatecas and Icamole near Monterrey) reported vivid curtains, arcs, and pillars of red and green light.

For many skywatchers, these storms produced the most vivid auroral displays since the May 2024 "once-in-a-generation" and October 2024 events.

- **Solar Activity:** The sunspot region, which re-emerged on the visible side of the Sun, was incredibly active, producing multiple flares, including an **X5.1-class flare on November 11, 2025**. This flare was the most intense since October 2024 and was accompanied by several powerful coronal mass ejections (CMEs).
- **Impact on Earth:** The energy from these flares caused radio blackouts, particularly R3-level disruptions in parts of Africa and Europe. The CMEs that followed could lead to a severe G4-level geomagnetic storm, which can affect power grids, GPS systems, and satellite operations.
- **"Cannibal CME":** The third and fastest CME from this event was predicted to merge with earlier ones, creating a "Cannibal CME" that could amplify the geomagnetic storm's impact on Earth.
- **Solar Cycle 25:** The intense activity from AR4274 is a key indicator that the Sun is nearing the peak of Solar Cycle 25, a period of heightened solar activity.

The Sunspot AR4274…cont

- The sunspot AR4274 (whose area has expanded to nearly **seven times** the surface area of Earth) has launched a powerful X5.1-class coronal mass ejection, the strongest of the year so far.
- Severe G4 geomagnetic storm on Wednesday, **November 12**.
- This level could allow auroras to appear at mid-latitudes around the world and may cause temporary disruptions in radio communications and navigation systems.
- However, the expected impacts remain within non-alarming limits, with no danger to daily life.

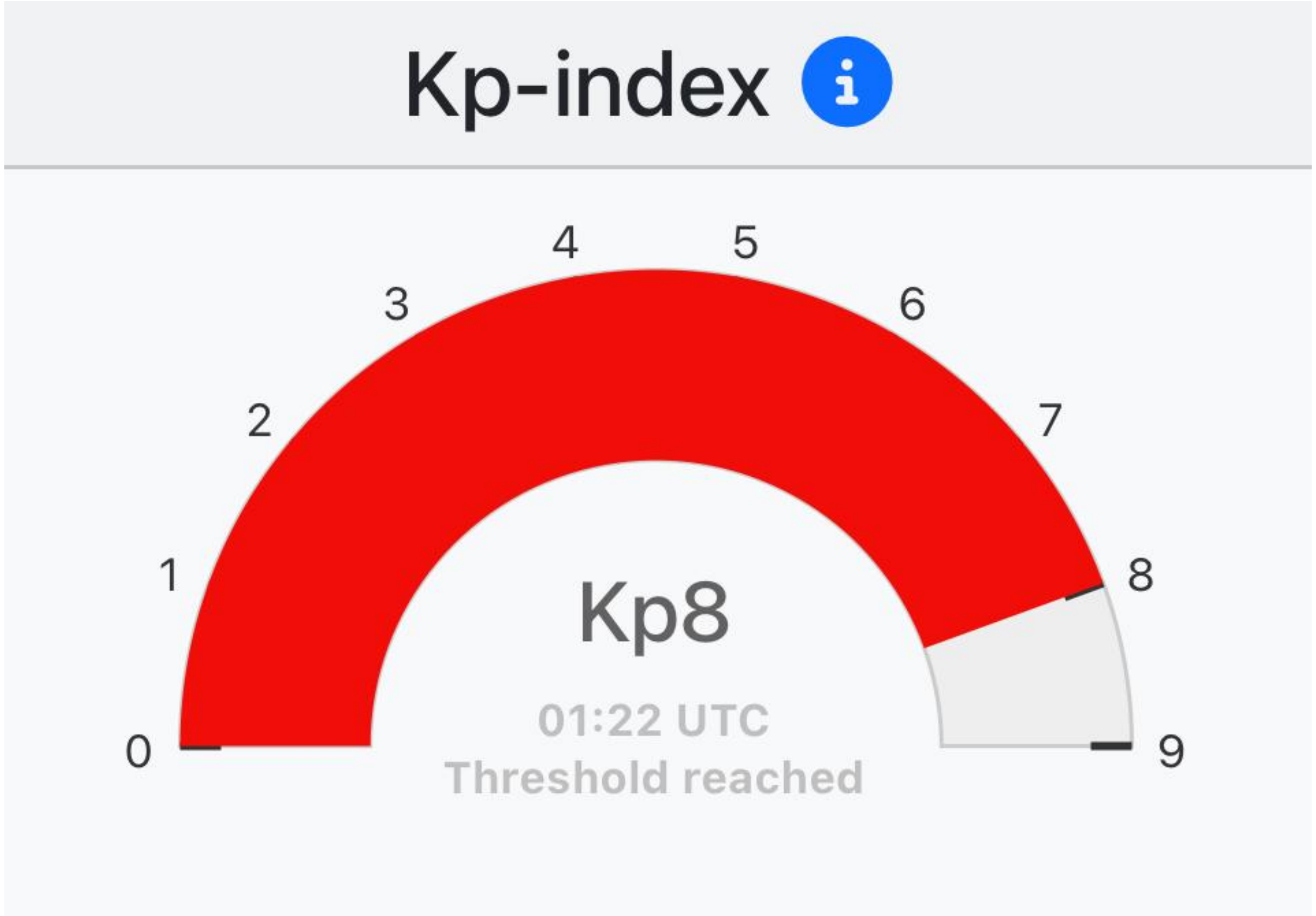
Strong R3-level radio blackout due to AR4272

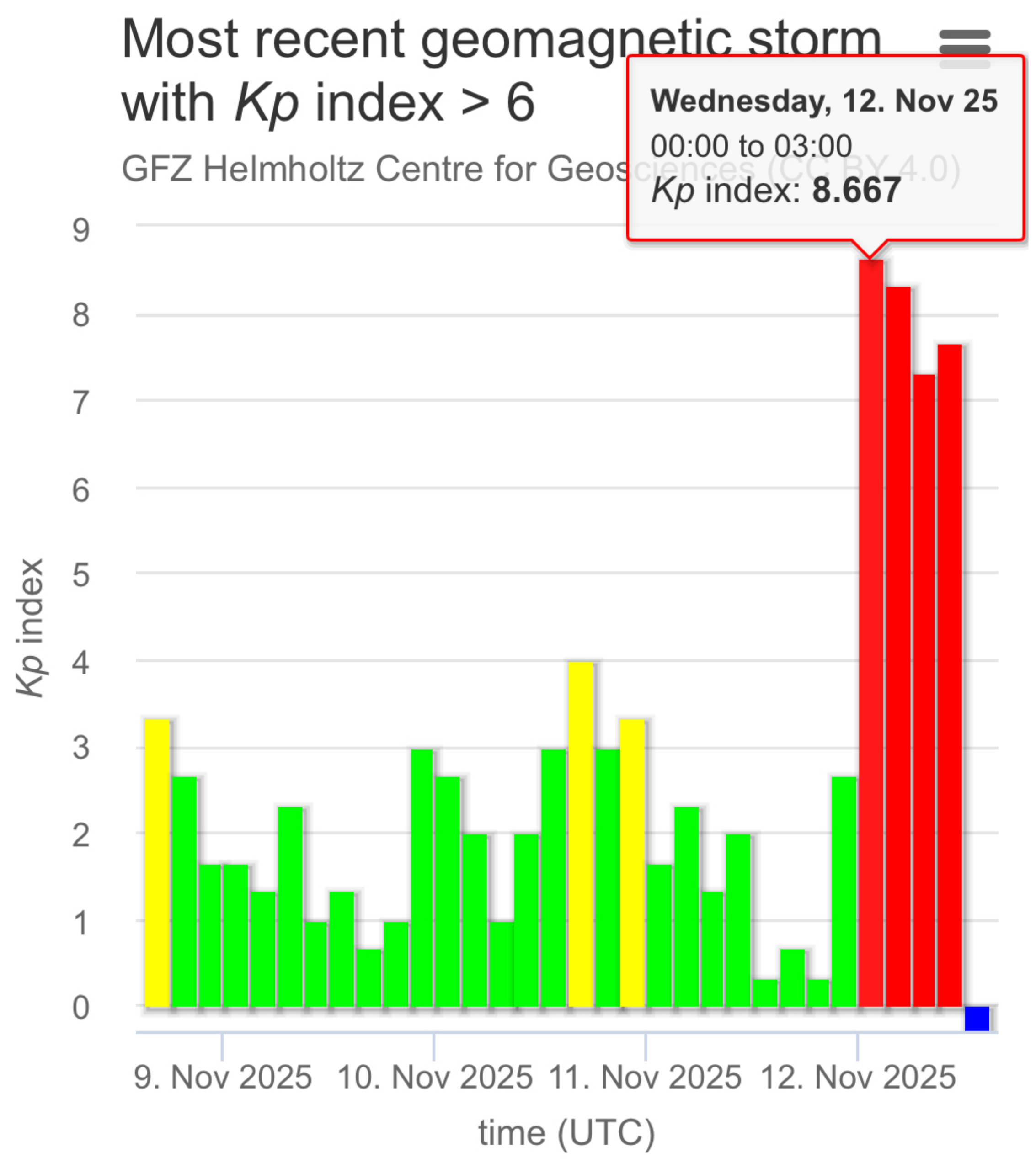
- (14 November), the Sun released another major eruption, generating a powerful **X4-class flare** — the second most intense solar flare of 2025 so far — from the same hyperactive sunspot AR4274, which only days ago produced this year's record-setting X5 flare.
- According to NOAA's Space Weather Prediction Center (SWPC), Earth experienced a **strong R3-level radio blackout** peaking on 14 November 2025 at 08:30 UTC.
- This blackout resulted from repeated flares emitted by the active region AR4274, currently the primary source of ionospheric disturbances.

- NOAA forecasts a 70% daily chance of R1–R2 (minor to moderate) radio blackouts, and a 30% chance of another **strong R3 event through 16 November**, based on the region's highly active record and its ongoing capability to produce major flares.
- At the peak moment (08:30 UTC), the Sun-lit portion of Earth included **eastern and central Africa, extending over the Arabian Peninsula, the Levant, and Iraq**.
- Thus, the following **Arab countries** were within the R3 radio blackout zone, with varying intensities.
- For reference, R5 is the highest level on this scale.

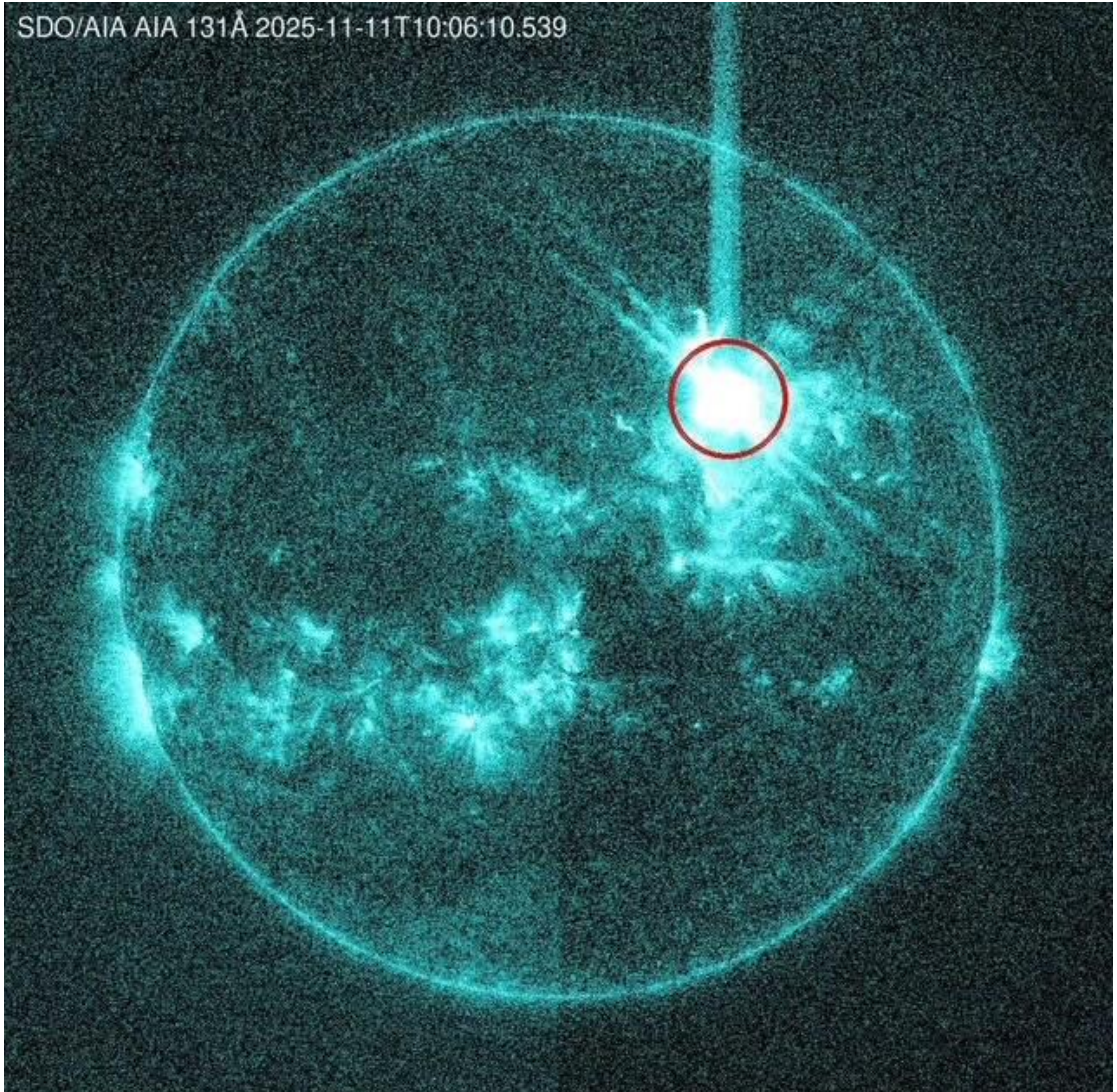

X4.05
With CME
GOES-19 SUVI Composite 131 Angstroms 2025-11-14 08:32:36

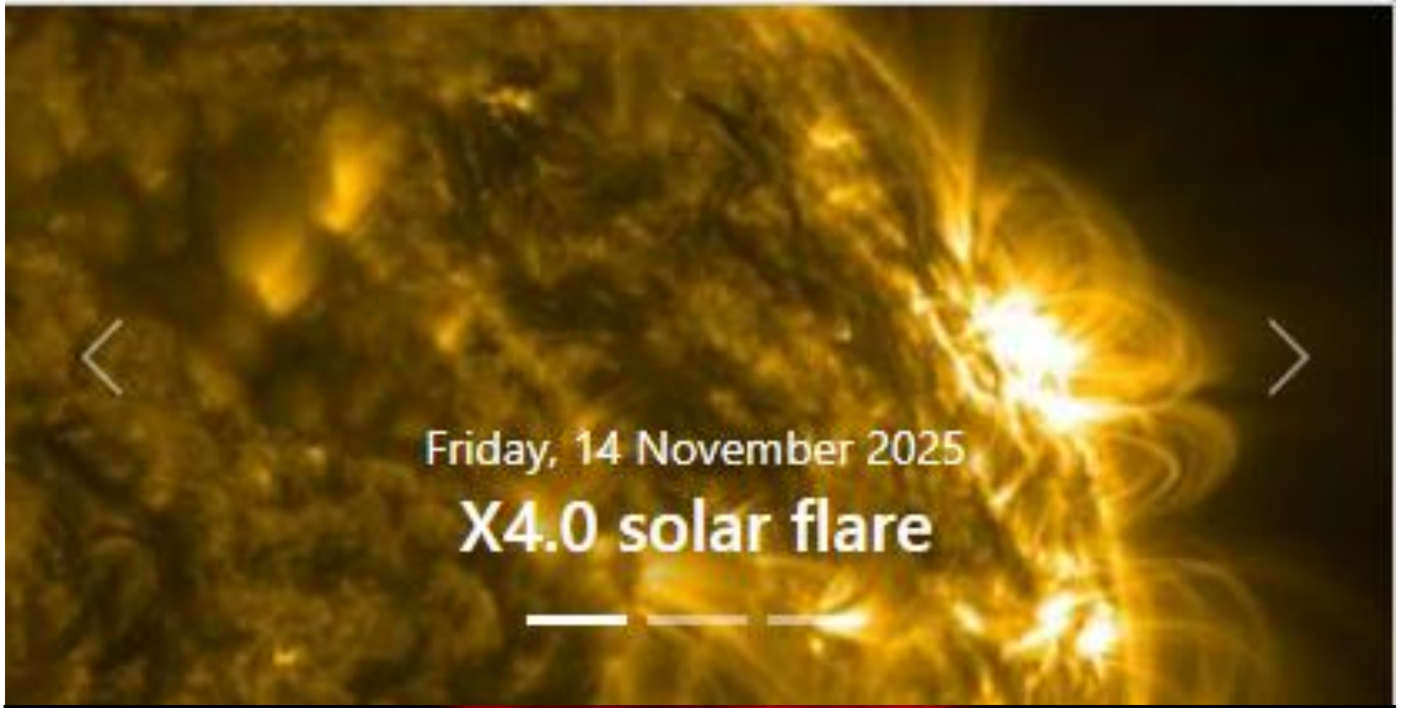
Geomagnetic Storm Kp
12 Nov, 2025





Most recent geomagnetic storm with Kp index > 6
GFZ Helmholtz Centre for Geosciences (CC BY 4.0)
Wednesday, 12. Nov 25
00:00 to 03:00
Kp index: 8.667
Kp index
0
1
2
3
4
5
6
7
8
9
9. Nov 2025
10. Nov 2025
11. Nov 2025
12. Nov 2025
time (UTC)


SDO/AIA AIA 131Å 2025-11-11T10:06:10.539


Friday, 14 November 2025
X4.0 solar flare

Tuesday, 11 November 2025
X5.1 solar flare, G4
geomagnetic storm watch

Severe (G4)
Geomagnetic Storm Watch

- Beginning middle to late day on November 12th (UTC)

- Visible aurora possible at middle latitudes.

3 Day Geomagnetic Forecast

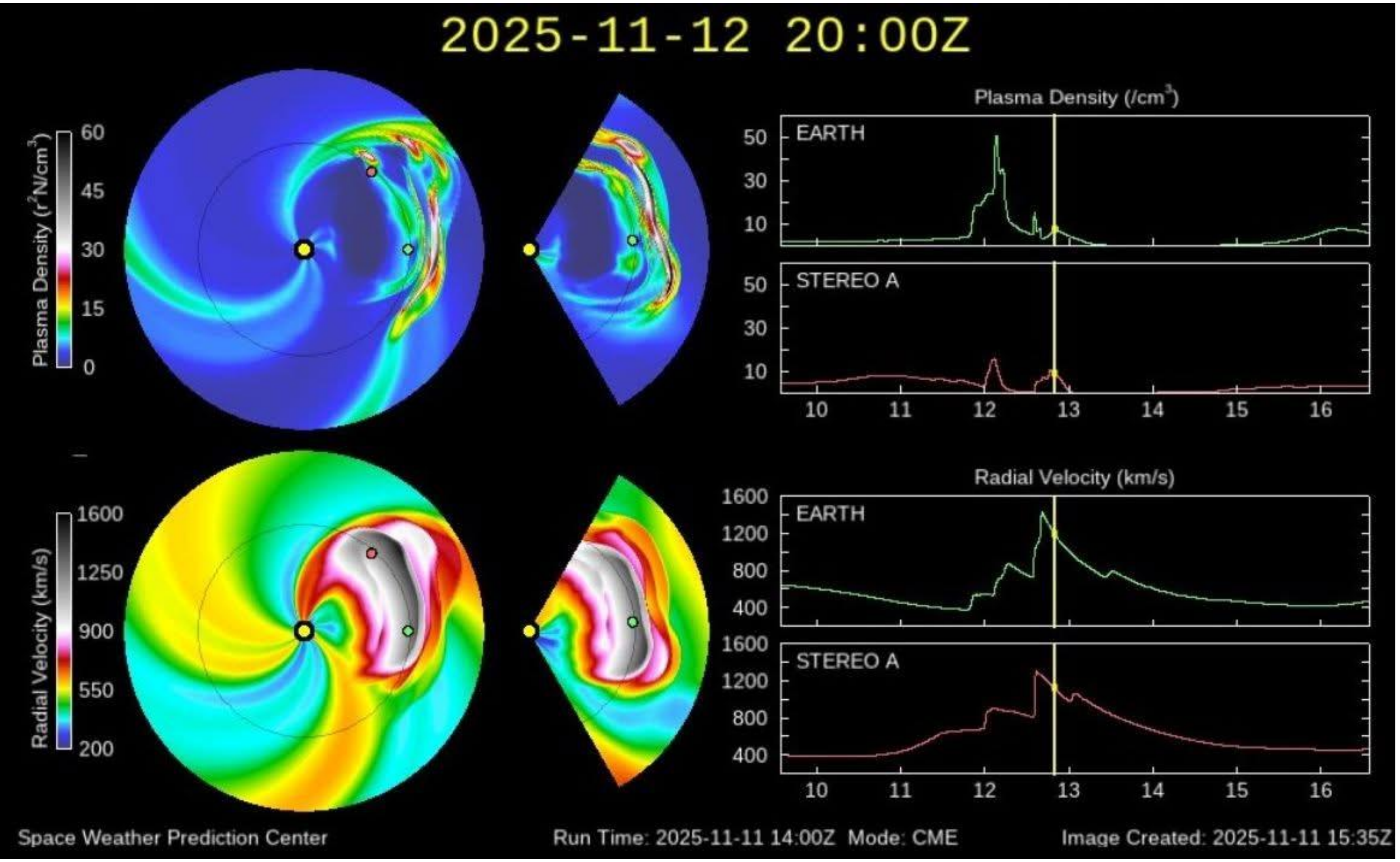
Nov. 11	Nov. 12	Nov. 13
5-6 (G2)	8 (G4)	6-7 (G3)

Max Kp

Nov. 11	Nov. 12	Nov. 13
M-Lat 40%	M-Lat 45%	M-Lat 40%
H-Lat 80%	H-Lat 85%	H-Lat 80%

Probabilities

Latest SWPC Forecast (@ 00:30 + 12:30 UTC)

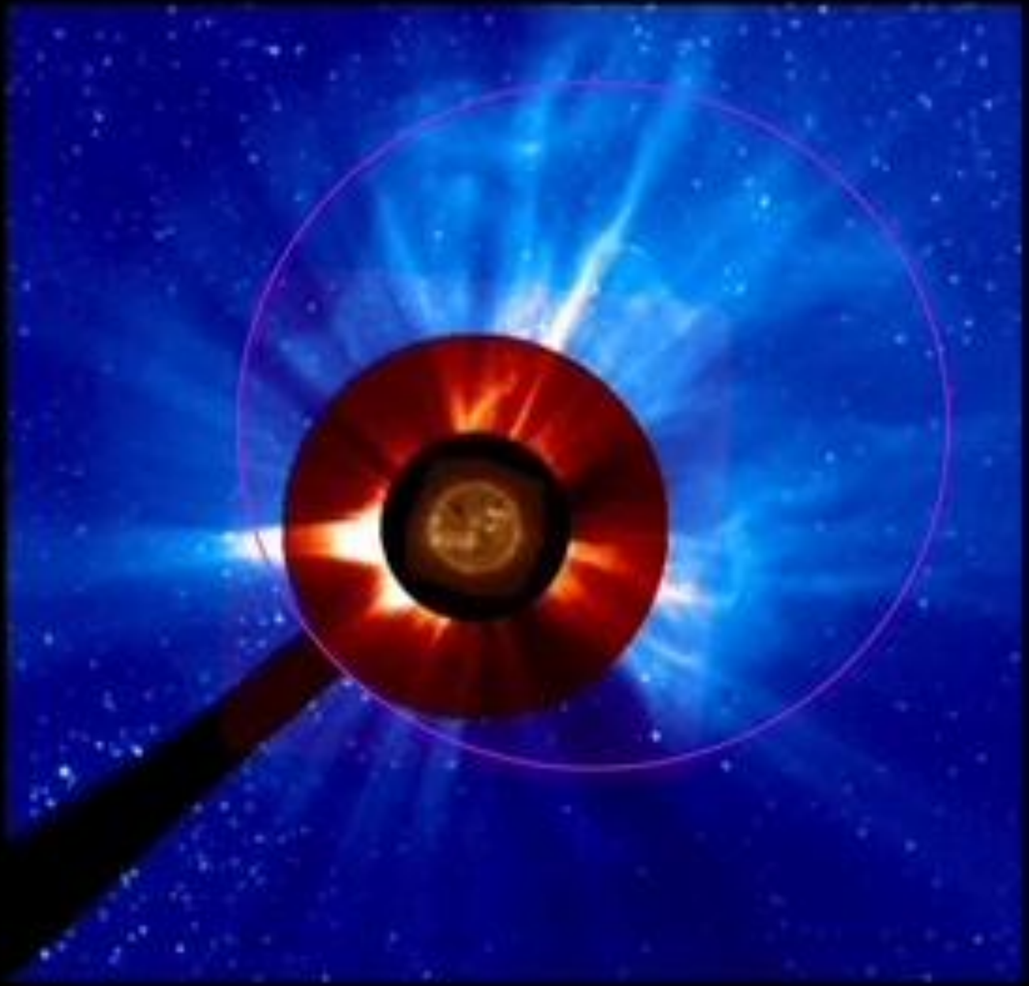


Severe Geomagnetic Storm WATCH for Nov 12 UTC-day

G4

Updated:
Tue, 11 Nov, 2025
17:15 UTC

WHAT: A CME will likely arrive at Earth and lead to highly elevated geomagnetic activity



EVENT:

A coronal mass ejection (CME) is an eruption of solar material and magnetic fields. When they arrive at Earth, a geomagnetic storm can result. Watches at this level are very rare; still, this is the fourth G4 Watch issued so far this solar cycle.

EXPECTATION:

A CME is anticipated to arrive at and partially impact Earth around mid-day, 12 Nov; with the potential for elevated geomagnetic response and dependent upon the orientation of the embedded magnetic field, potential exists for Severe Storm levels.

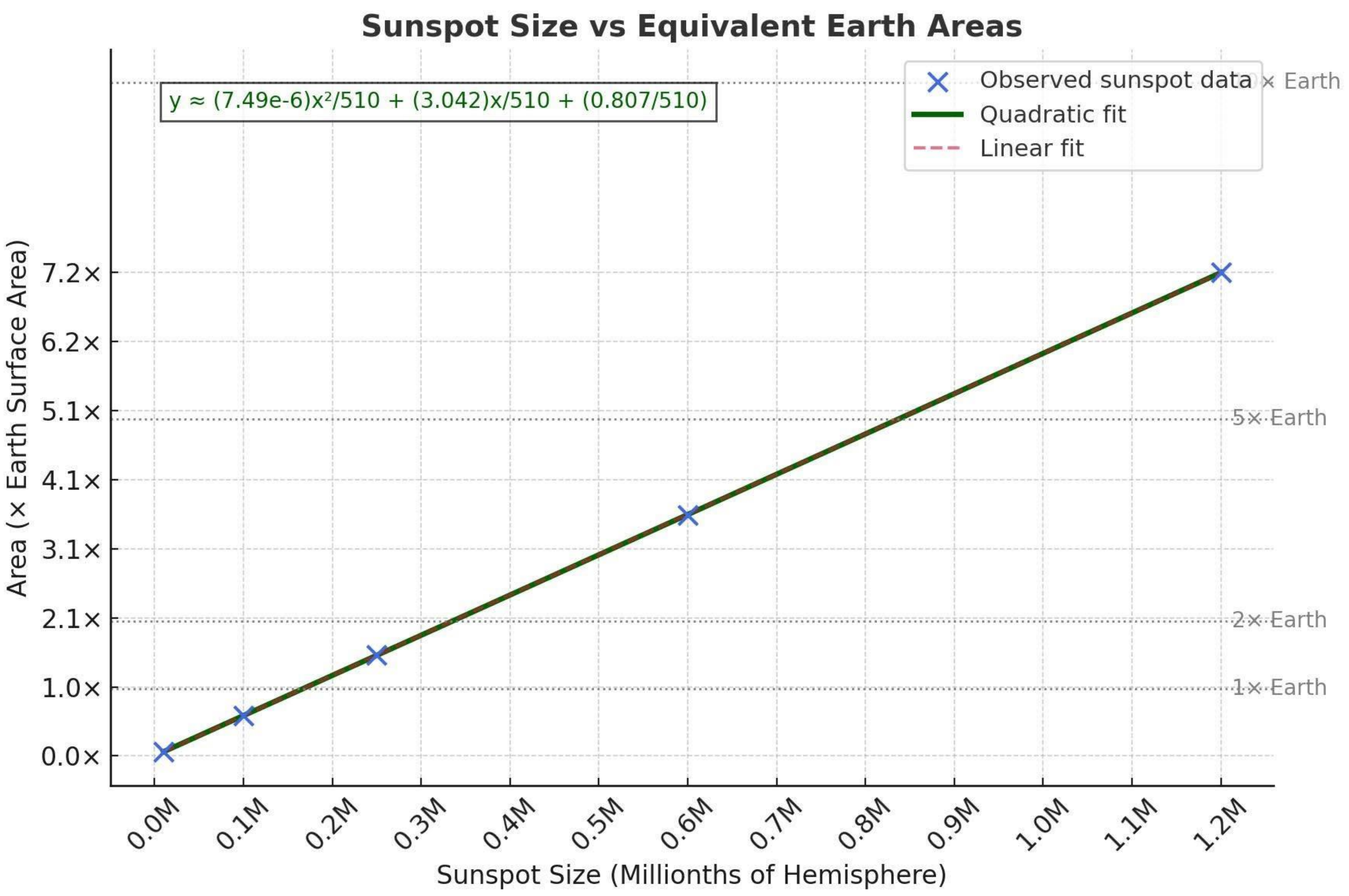
EFFECTS:

Detrimental impacts to some of our critical infrastructure technology are possible, but mitigation is possible. The general public should visit our webpage to keep properly informed. The aurora may become visible over much of the northern half of the country, and maybe as far south as Alabama to northern California.

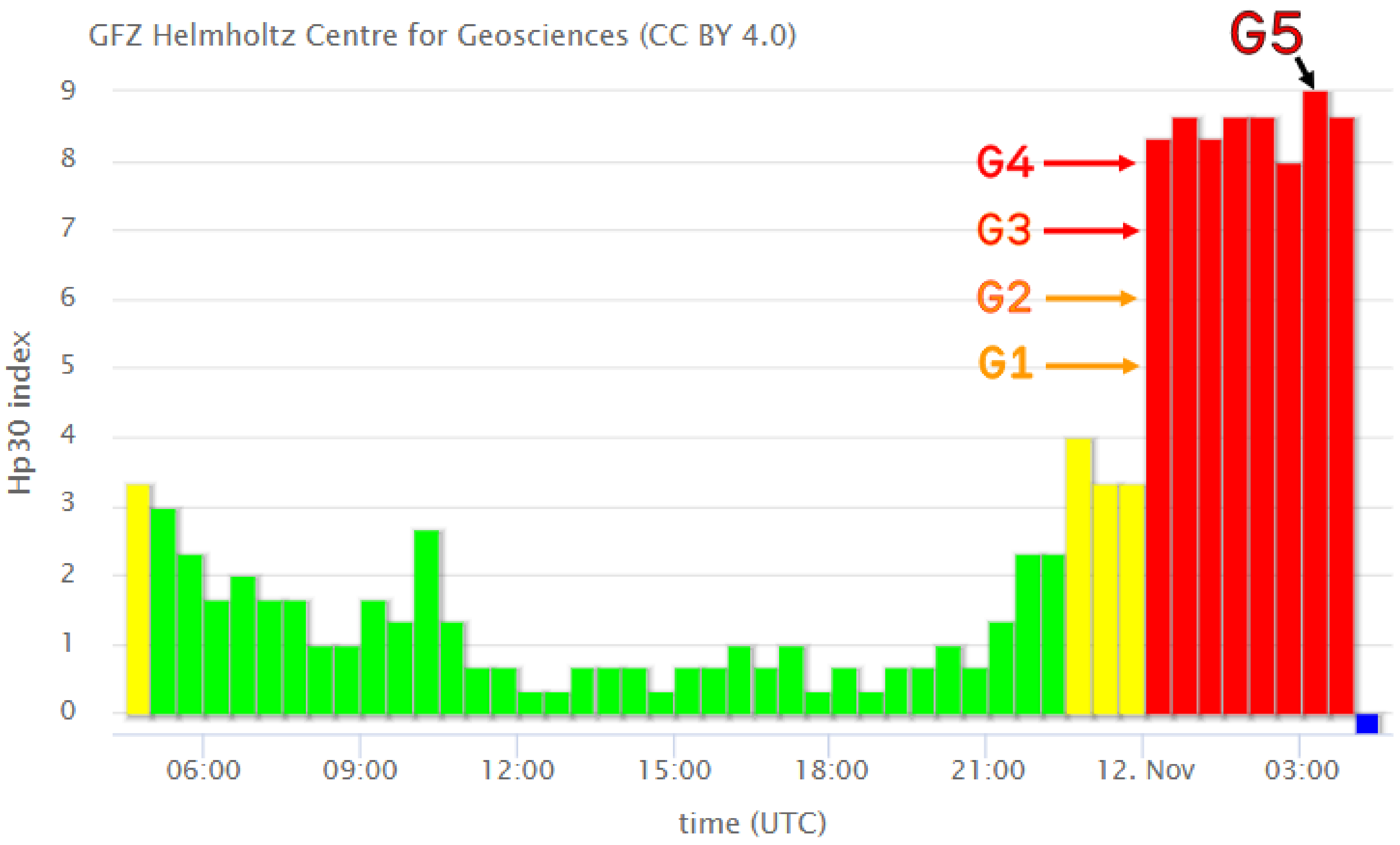
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

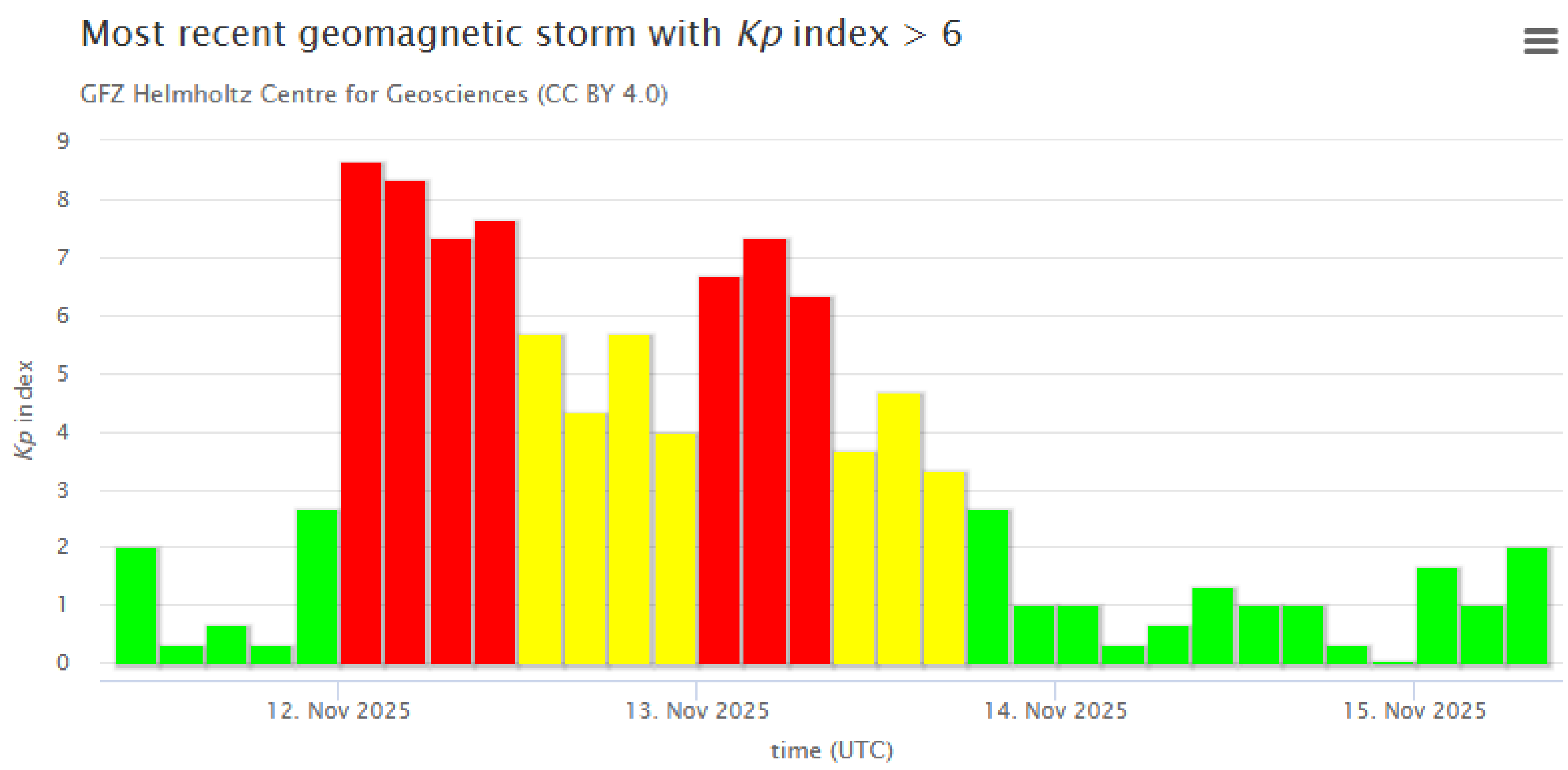
Safeguarding Society with Actionable Space Weather Information

Space Weather Prediction Center
Boulder, CO

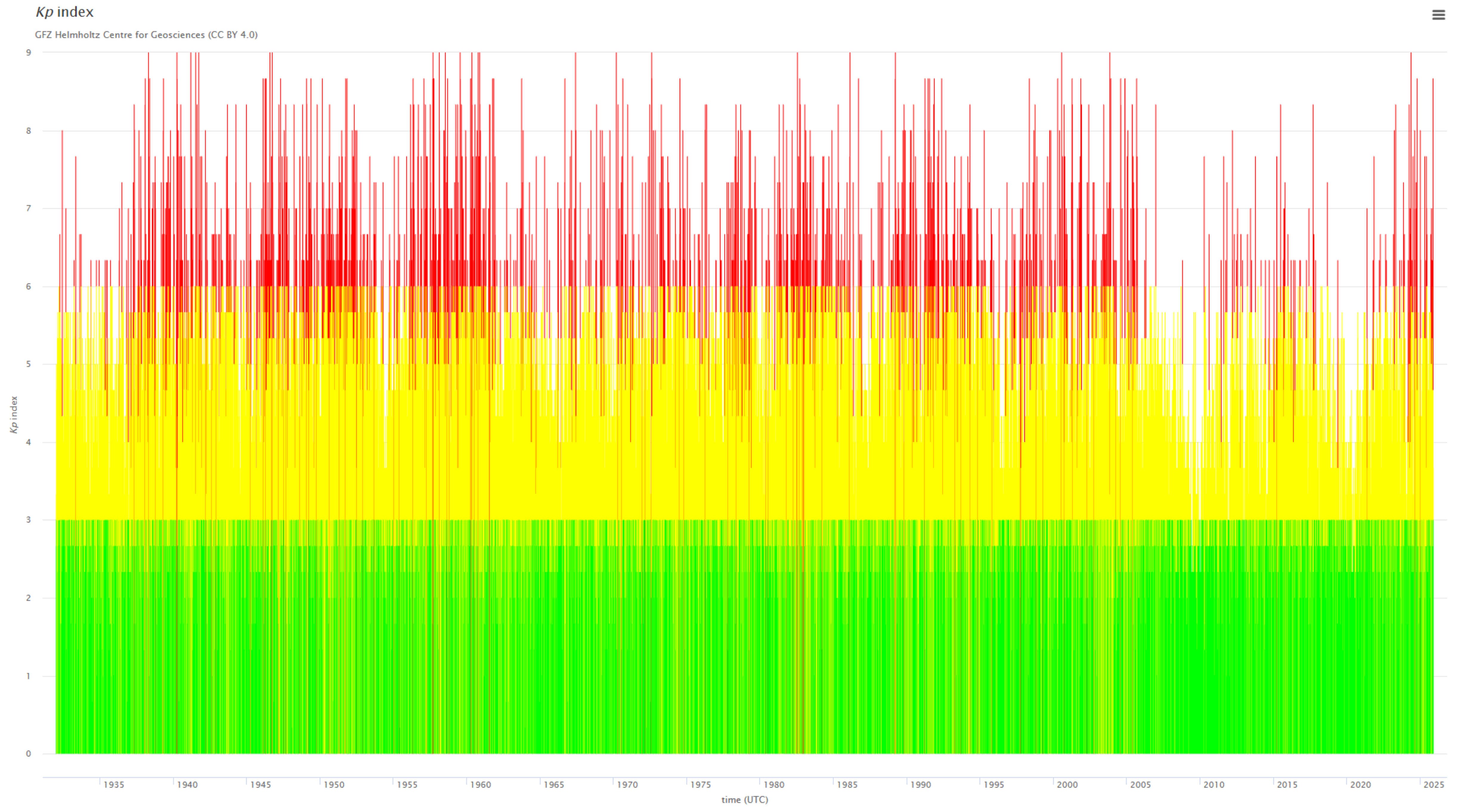


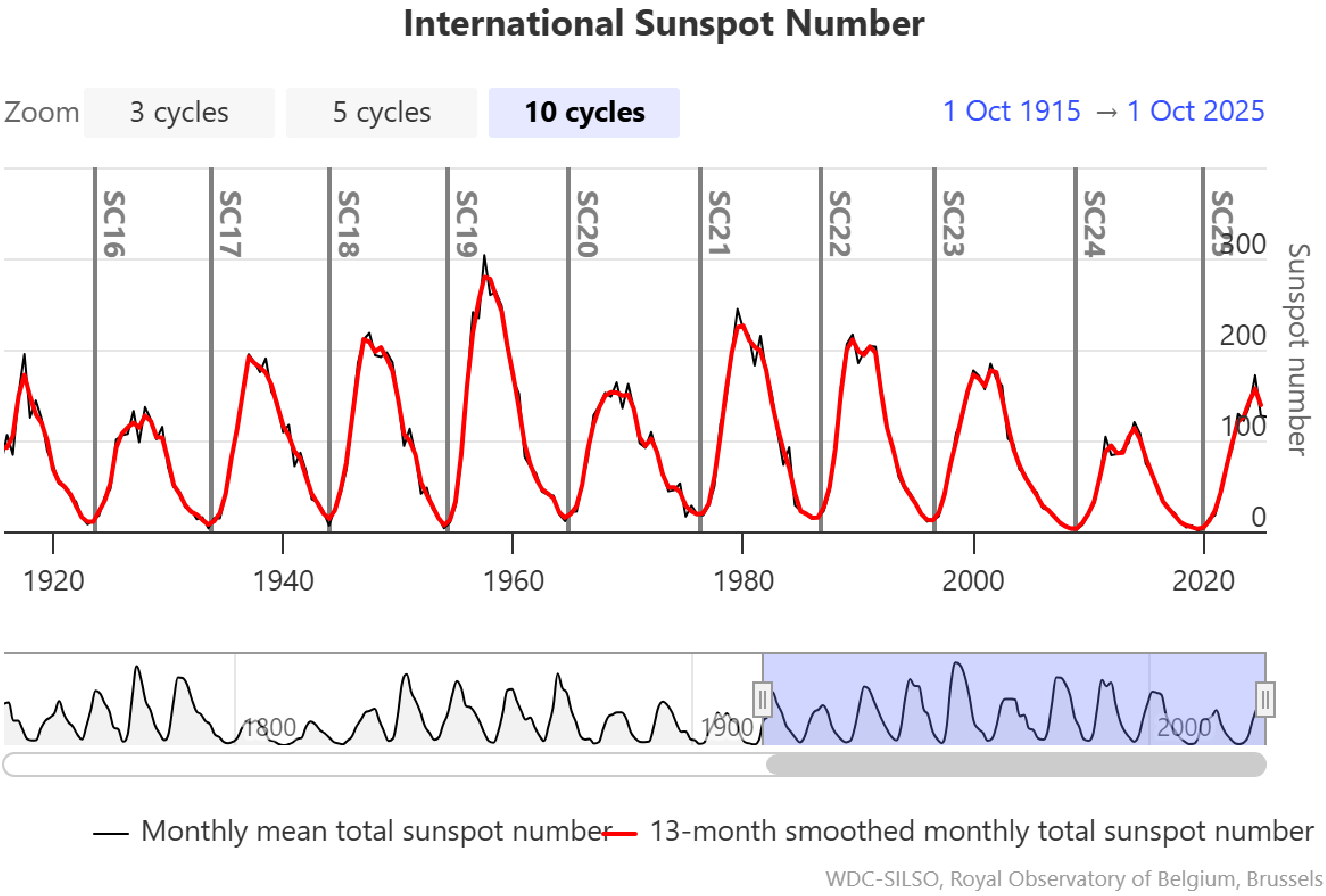
Sunspot Size vs Equivalent Earth Areas
y ≈ (7.49e-6)x²/510 + (3.042)x/510 + (0.807/510)
Observed sunspot data
Quadratic fit
Linear fit
× Earth
5× Earth
2× Earth
1× Earth
Area (× Earth Surface Area)
7.2×
6.2×
5.1×
4.1×
3.1×
2.1×
1.0×
0.0×
0.0M
0.1M
0.2M
0.3M
0.4M
0.5M
0.6M
0.7M
0.8M
0.9M
1.0M
1.1M
1.2M
Sunspot Size (Millionths of Hemisphere)

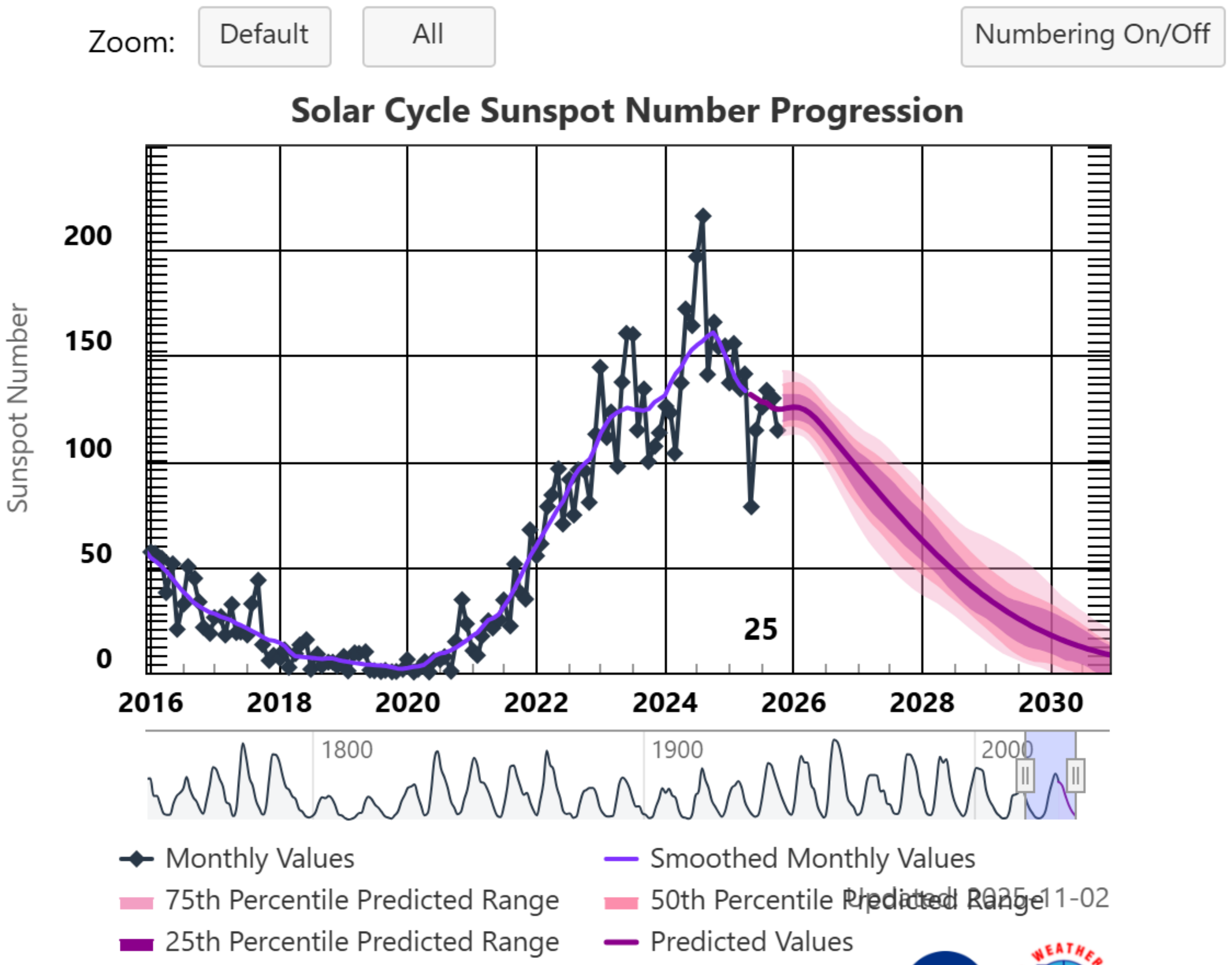

GFZ Helmholtz Centre for Geosciences (CC BY 4.0)
G5
G4
G3
G2
G1
Hp30 index
0
1
2
3
4
5
6
7
8
9
06:00
09:00
12:00
15:00
18:00
21:00
12. Nov
03:00
time (UTC)

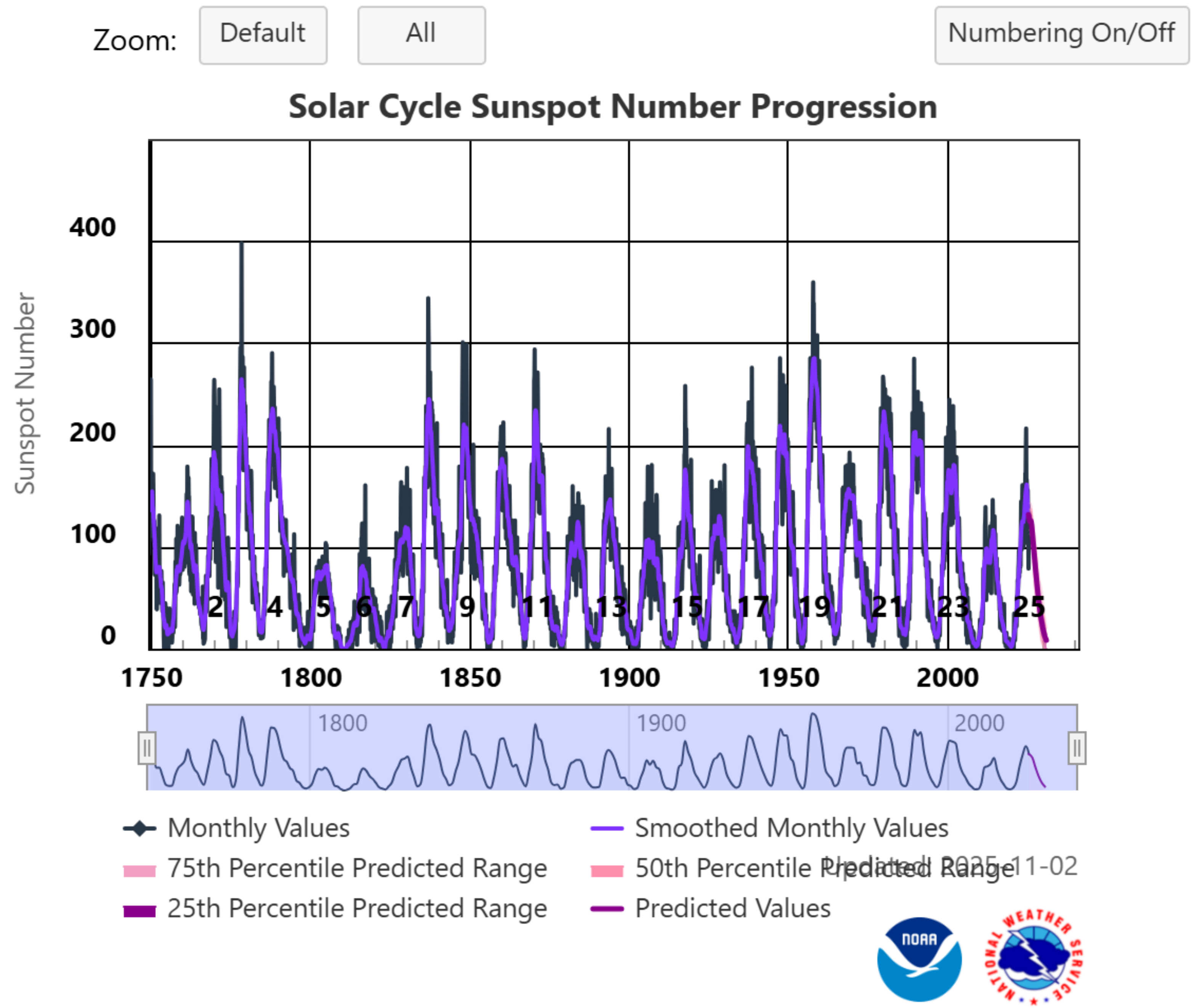


Most recent geomagnetic storm with Kp index > 6
GFZ Helmholtz Centre for Geosciences (CC BY 4.0)
Kp index
9
8
7
6
5
4
3
2
1
0
12. Nov 2025
13. Nov 2025
14. Nov 2025
15. Nov 2025
time (UTC)


Kp index
GFZ Helmholtz Centre for Geosciences (CC BY 4.0)
Kp index
0
1
2
3
4
5
6
7
8
9
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
time (UTC)

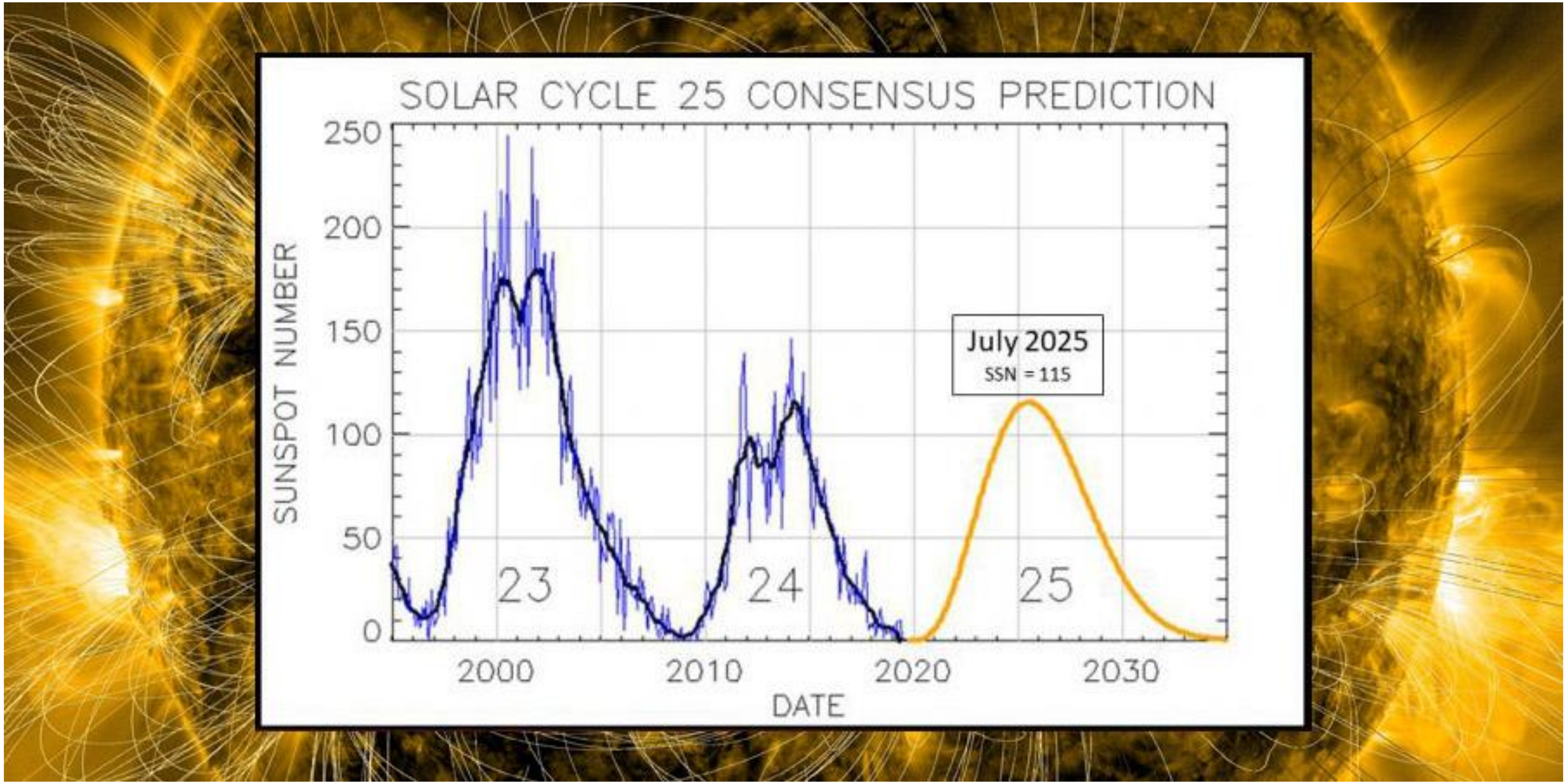

International Sunspot Number
Zoom
3 cycles
5 cycles
10 cycles
1 Oct 1915 → 1 Oct 2025
SC16
SC17
SC18
SC19
SC20
SC21
SC22
SC23
SC24
SC25
300
200
100
0
Sunspot number
1920
1940
1960
1980
2000
2020
1800
1900
2000
Monthly mean total sunspot number
13-month smoothed monthly total sunspot number
WDC-SILSO, Royal Observatory of Belgium, Brussels


Zoom:
Default
All
Numbering On/Off
Solar Cycle Sunspot Number Progression
Sunspot Number
200
150
100
50
0
25
2016
2018
2020
2022
2024
2026
2028
2030
1800
1900
2000
Monthly Values
Smoothed Monthly Values
75th Percentile Predicted Range
50th Percentile Predicted Range
Updated: 2025-11-02
25th Percentile Predicted Range
Predicted Values

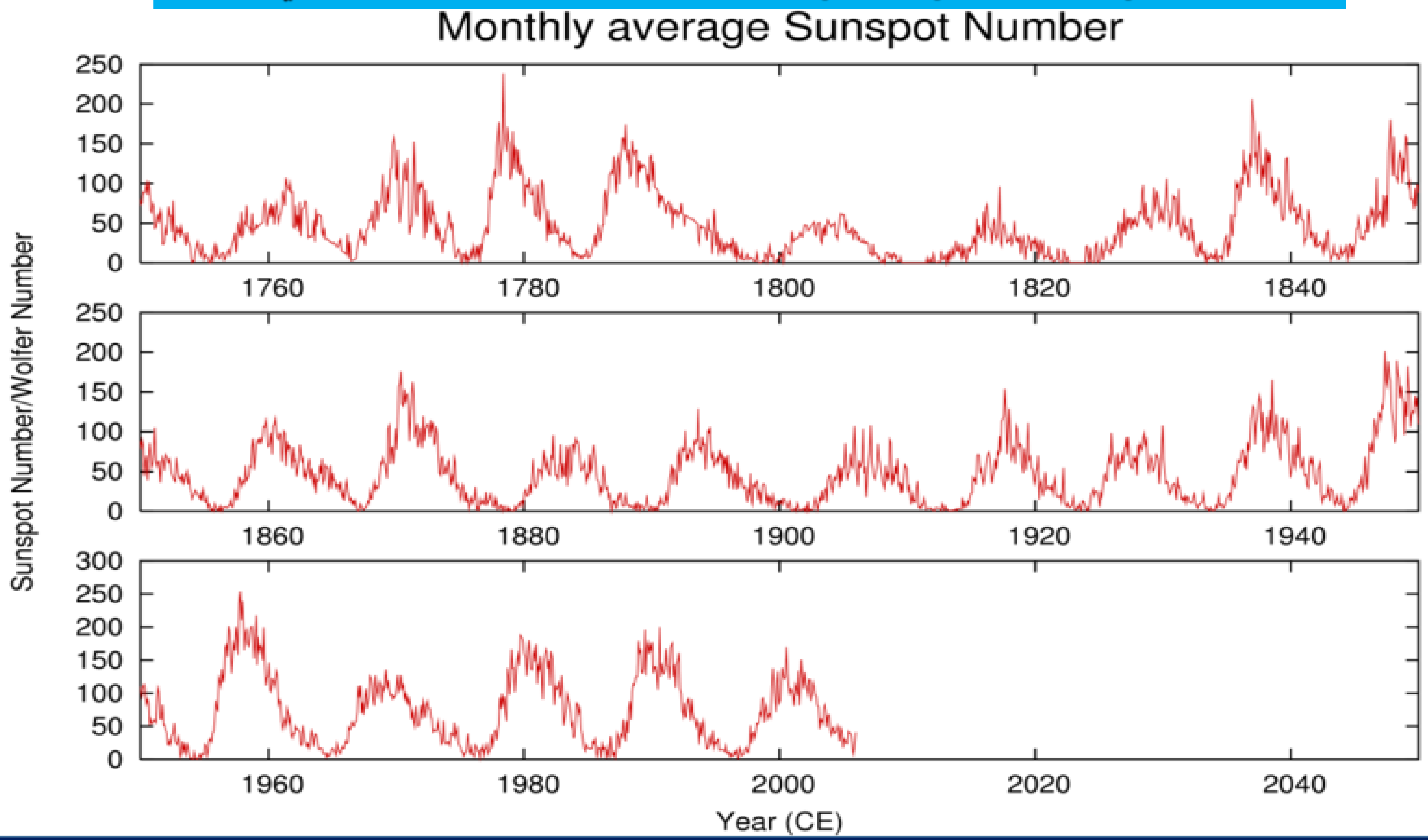

Zoom:
Default
All
Numbering On/Off
Solar Cycle Sunspot Number Progression
Sunspot Number
400
300
200
100
0
1750
1800
1850
1900
1950
2000
2
4
5
6
7
9
11
13
15
17
19
21
23
25
1800
1900
2000
Monthly Values
Smoothed Monthly Values
75th Percentile Predicted Range
50th Percentile Predicted Range
25th Percentile Predicted Range
Predicted Values
Updated: 2025-11-02

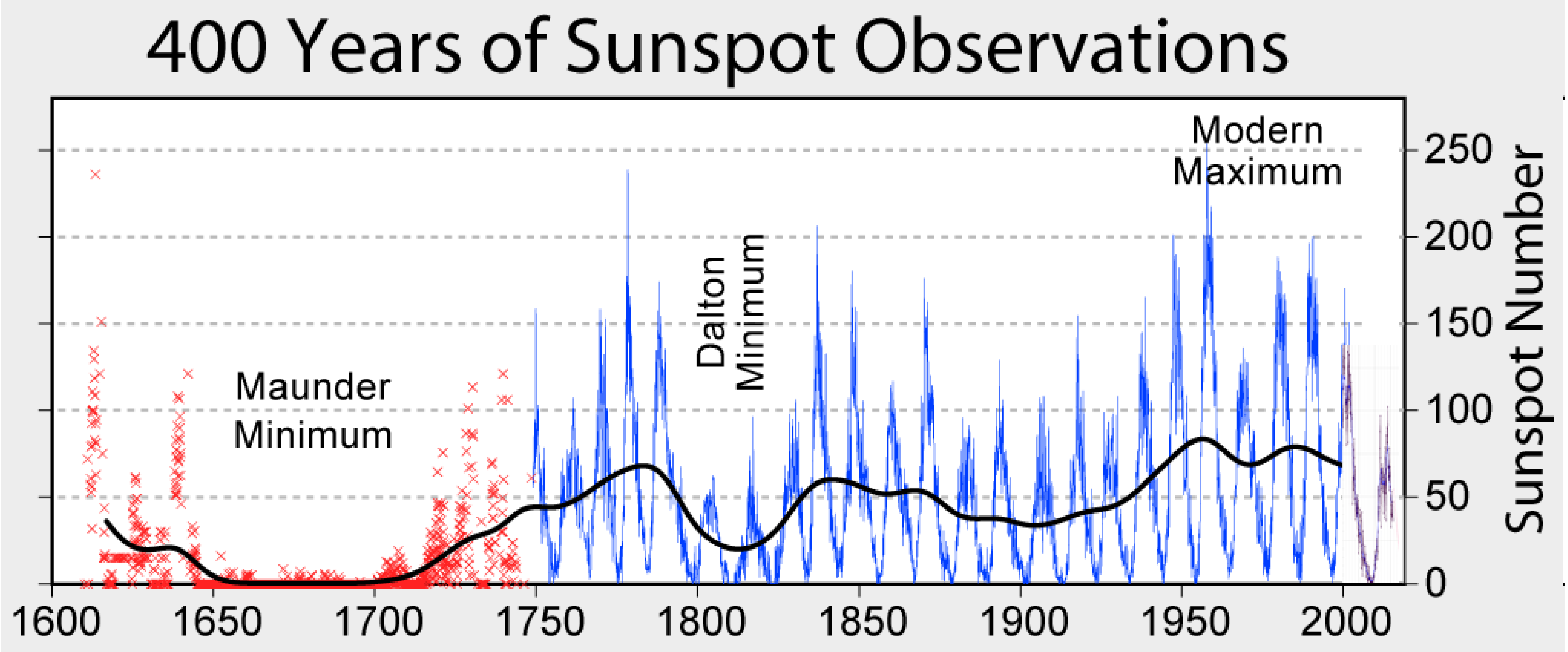
Solar Cycle

- Magnetic activity comes and goes on an 11-year cycle



دورة النشاط الشمسي The Sunspot Cycle = 11 years

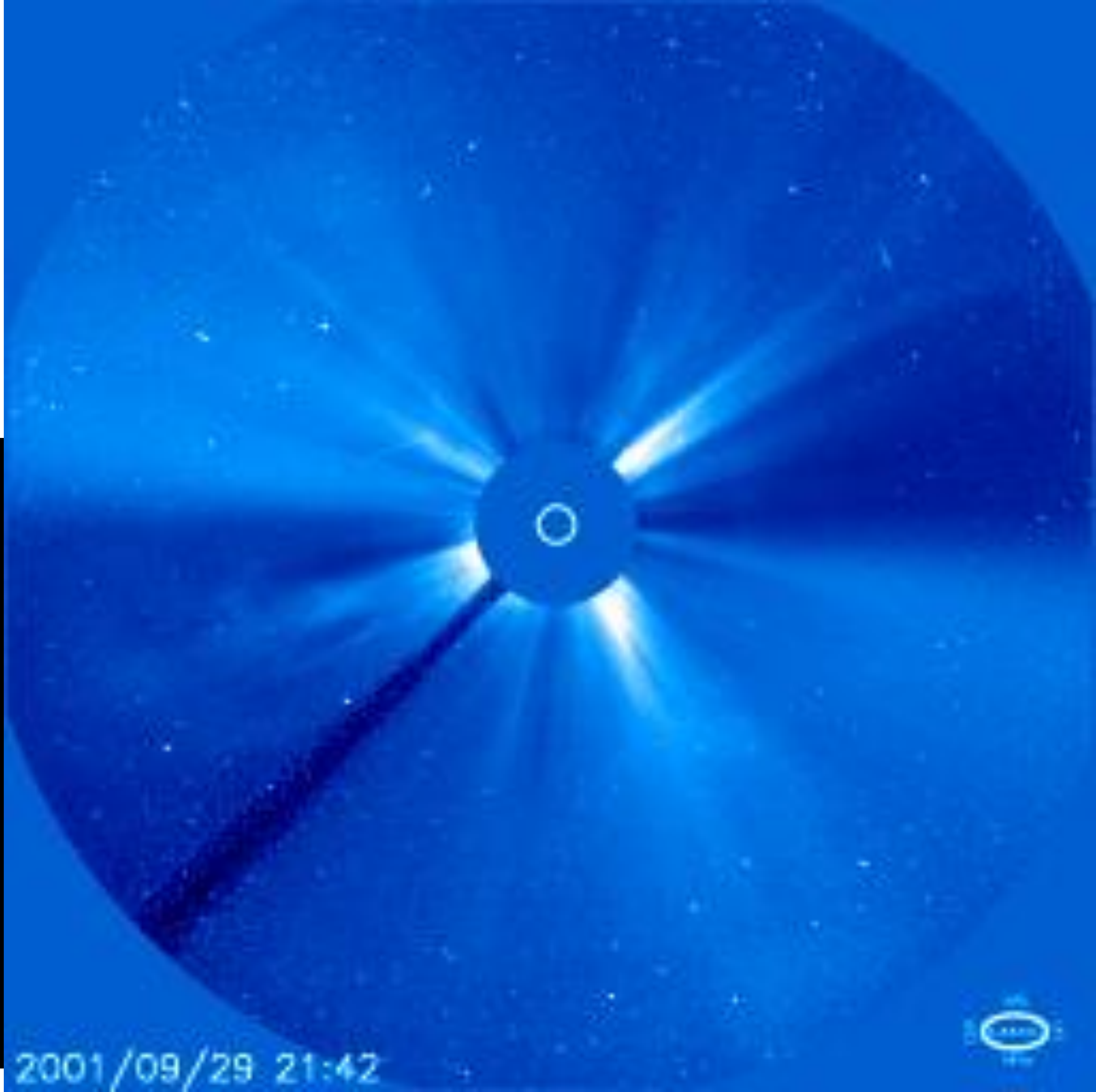




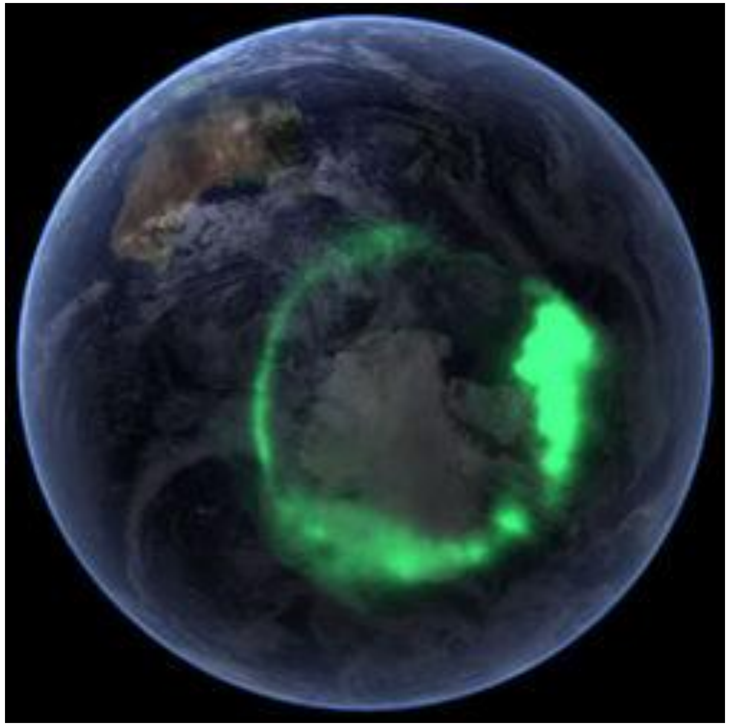
400 Years of Sunspot Observations
Modern Maximum
Dalton Minimum
Maunder Minimum
Sunspot Number
0
50
100
150
200
250
1600
1650
1700
1750
1800
1850
1900
1950
2000

High activity Elements

- Many sunspots (size)
- Coronal mass ejections
- Flares



Aurora Australis and Borealis

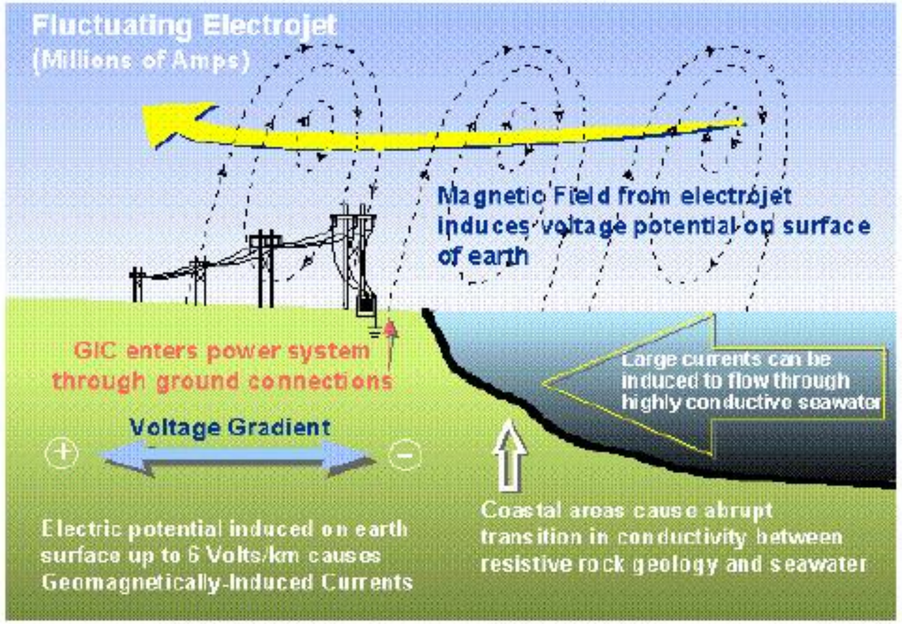


Space weather effects on Humans

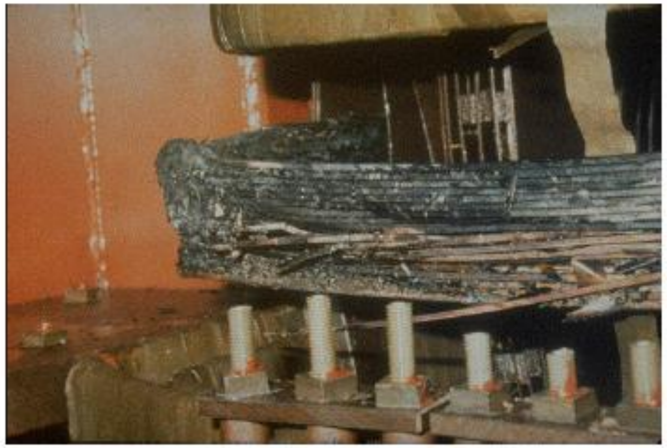
- Humans in space
  - Space Shuttle
  - International Space Station
  - Missions to Mars
- Crew/Passengers in high-flying jets
  - Trans-polar routes
  - Passengers may receive radiation doses equivalent to several chest X rays

Geomagnetic Induced Currents

- Currents leak into long conductors:
  - Power grids
  - Oil and gas pipelines
- Train light signals can be affected
-
  - Eg. Multiple documented events in Sweden.

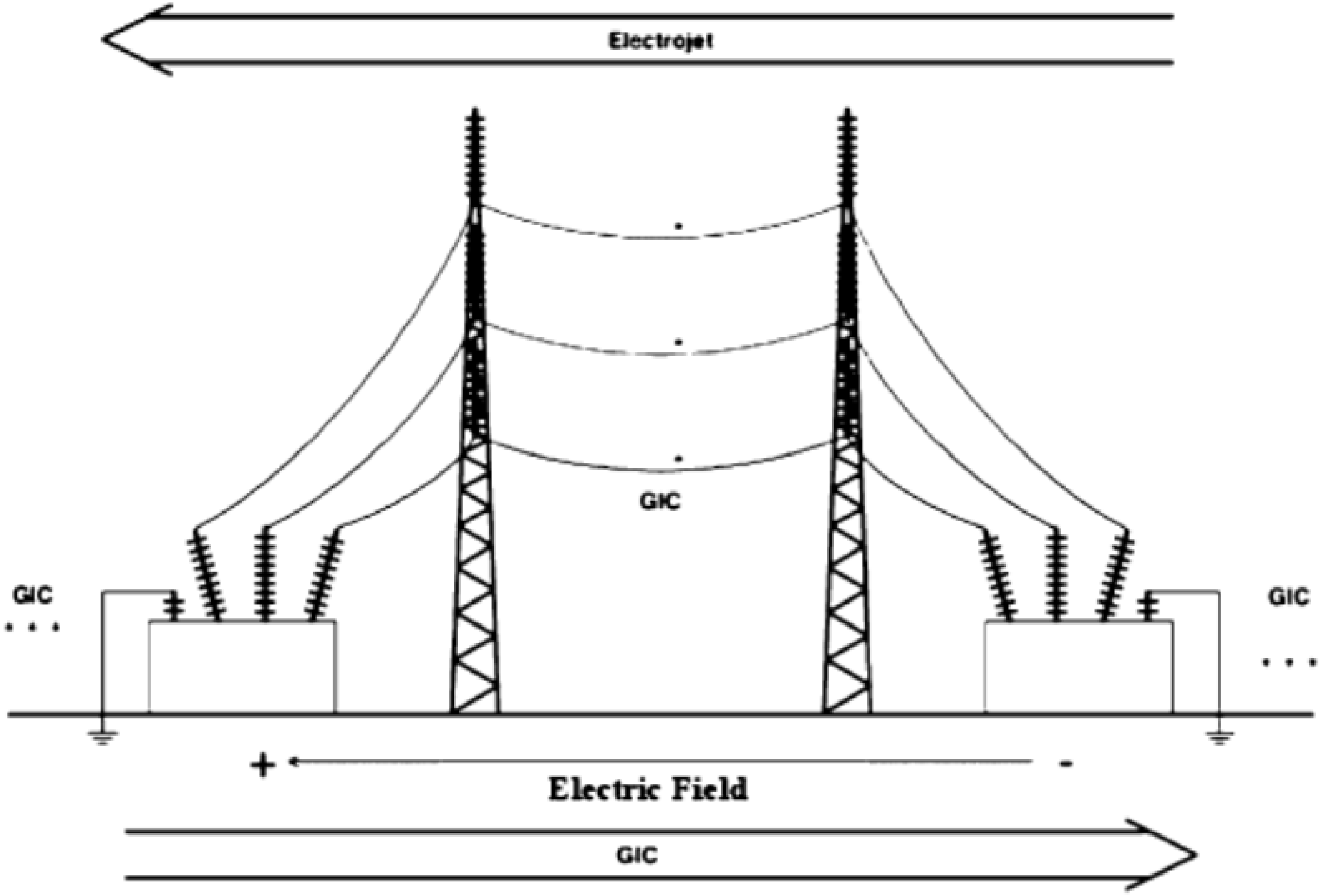


Damage to Transformers



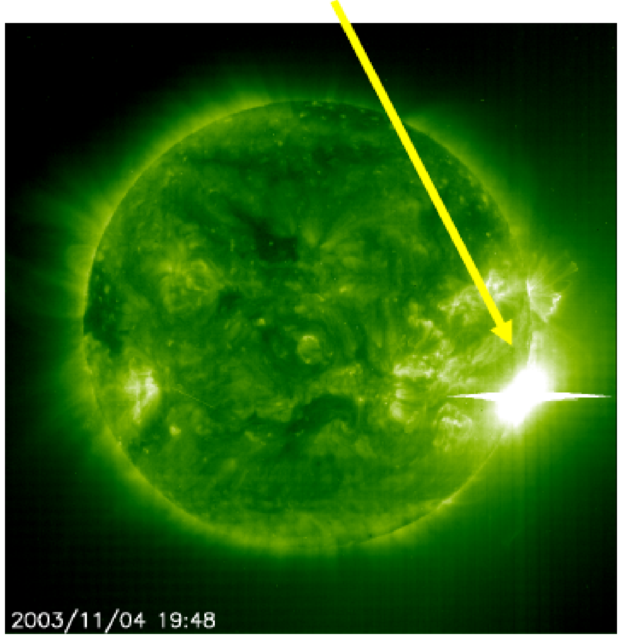
- Damage to a transformer in New Jersey in March 1989
  - Cost $10 million and took 6 weeks to restore
- Sweden: simultaneous power loss in six 130 kV power distribution lines
- Chicago: 5 transformers in the Chicago area failed due to elevated geomagnetic activity in April 94
- Recent failures in South Africa and New Zeeland.

Space Weather and Power Systems



Oct – Nov 2003 Storms
Actual System Impacts

Extreme X-ray / Optical Flare
4 November 2003
X-28 Flare



NASA/ESA

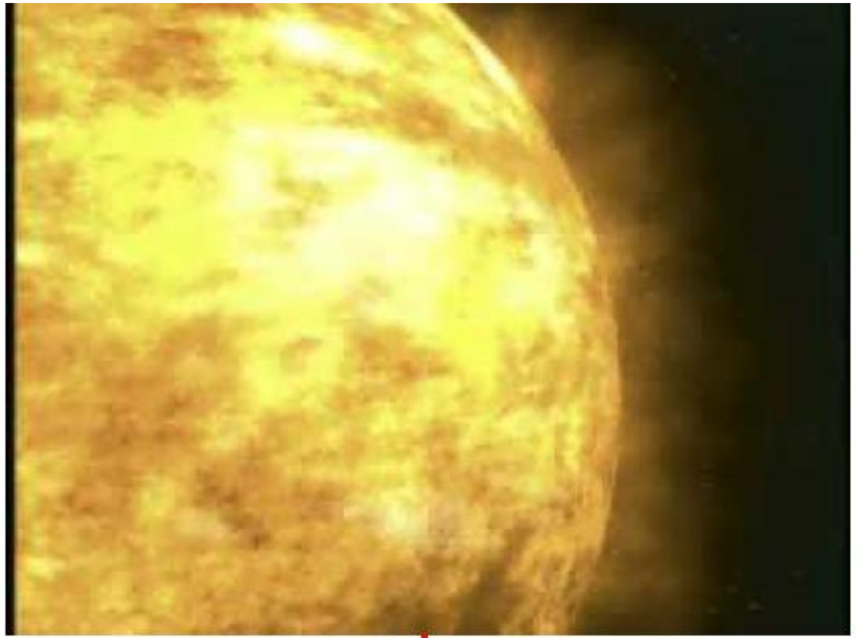
Largest Flare Ever Recorded

Numerous satellite, aircraft & ground anomalies, including:

- Loss of Japan's Midori satellite
- Anomalies on ~30 satellites
- Effects felt on 2/3 of NASA satellites
- FAA issued first-ever passenger alert
- FAA WAAS system: >100m errors
- Satellite communications interrupted
- Electric power service failure in Sweden

Classic Case: Magnetic Storms

Driven by Solar flares and coronal mass ejections (CMEs) on the sun



Animation courtesy of NASA

Iono Storm Physics

Buonsanto, M. Space Science Reviews (1999) 88: 563. doi:10.1023/A:1005107532631

Phenomena & Effects

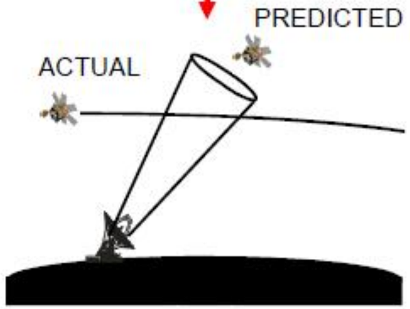
http://www.swpc.noaa.gov/phenomena

Effects

Degrades Satellite Instruments

Dangerous Particles to Electronics and People

Disrupts GNSS and Satellite Comms



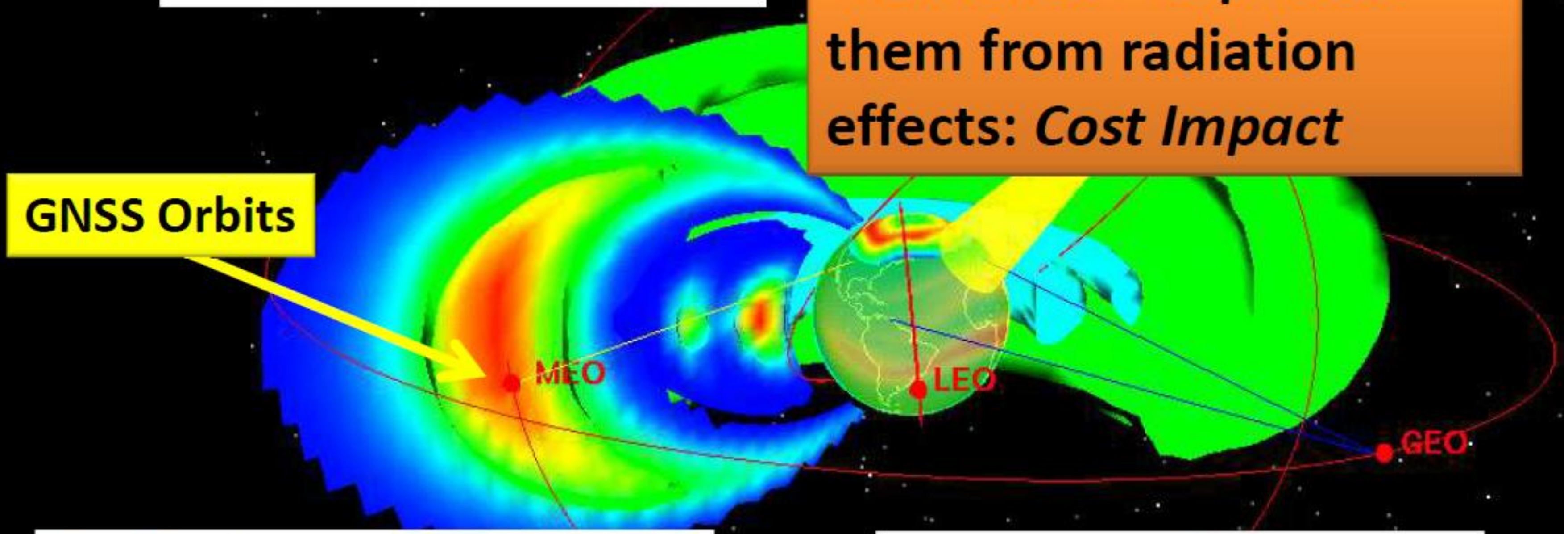
Possible Collisions in Space

Space Weather Effects on Systems

Direct Solar Processes

- Radio, optical and X-ray interference
- Solar energetic particle degradation and clutter

GNSS satellites must be "hardened" to protect them from radiation effects: *Cost Impact*



Space Particle Hazards

- Radiation degradation and electronics upsets
- Surface and internal charging / discharging
- Increased hazard for humans at high altitudes (space/aviation)

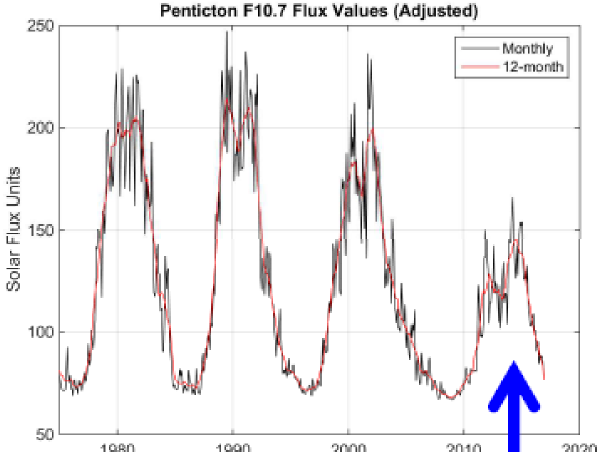
Ionosphere/Neutral Effects

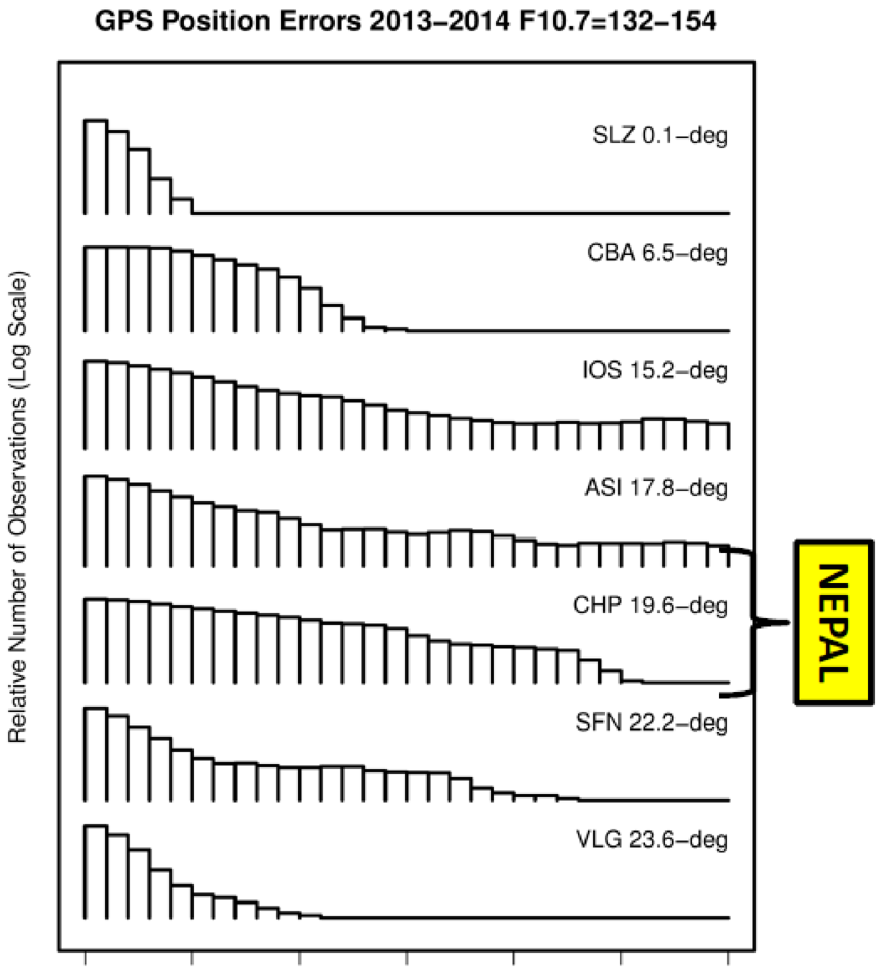
- Comm/Nav link degradation and outage
- Satellite Drag
- Variations in HF communications (black-outs and modified channels)

GPS Positioning Errors from Space Weather Magnetic Latitude Dependence

- Night time positioning errors from 2013-2014 in South America
- Largest errors occur 15-20 degrees from magnetic equator (Nepal)

Solar Cycle Intensity



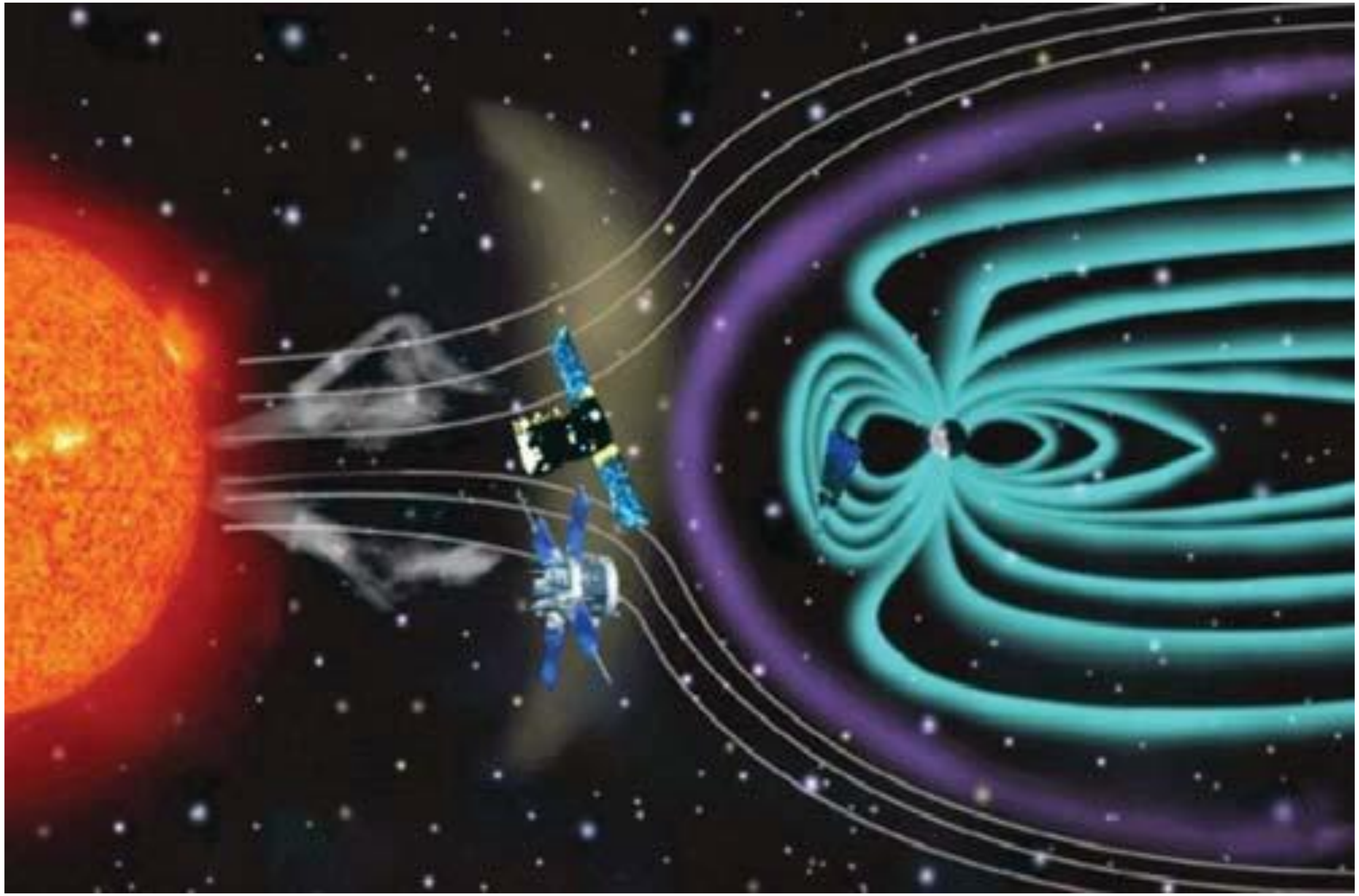


The Sweden Case: Airplanes disappear from radars due to "solar storm"

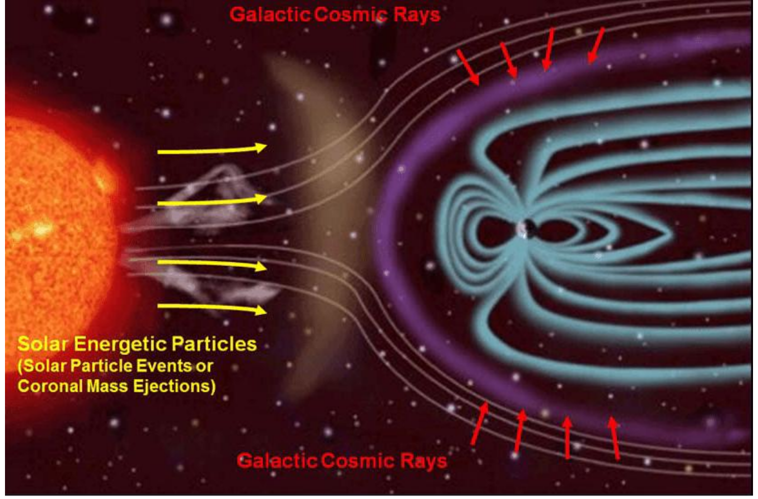
Posted by Adonai on November 05, 2015 in categories Featured articles, Geomagnetic storms, Solar activity

Follow @TheWatchers_

The **2015 Nov. 4th** there is a radio burst **[15.30 to 16.30 LT]** exceeding everything before. It was so strong that neither GPS nor radar nor communication nor instrument landing system did work properly. All these receivers were completely saturated by the radio radiation, instruments went blind",



Satellite in front of the magnetosphere



Galactic cosmic radiation

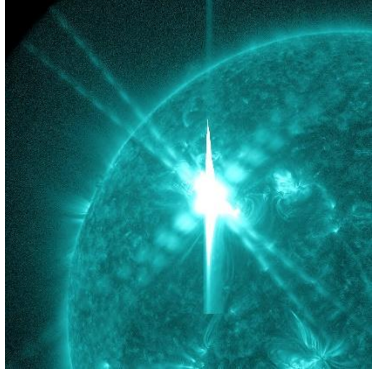
- Galactic cosmic radiations (GCR) are not directly connected to our Sun. They originate from outside the solar system.
- **GCR consists of ionized atoms ranging from a single proton up to a uranium nucleus.** The flux level of these particles is very low. Notwithstanding, they produce intense ionization as they pass through matter because they travel at a speed that is very close to that of light, and because some of them are composed of very heavy elements such as iron. The energy of cosmic rays is usually measured in units of mega electron volt (MeV), or the giga electron volt (GeV).
- Most GCRs have energies between 100 MeV and 10 GeV. Cosmic rays include essentially all of the elements in the periodic table; about 85% protons, 14% alpha particles, and 1% heavy nuclei [16]. The Earth's magnetic field provides natural shielding from both cosmic and solar particles depending primarily on the inclination and secondarily on the altitude. As inclination reaches auroral to polar regions, a satellite is outside the protection of the geomagnetic field lines. At polar orbits intense fluxes of energetic electrons, known as precipitating electrons, propagate down along magnetic field lines (and create the aurora), and as altitude increases, the exposure to these particles gradually increases.

AI Revolution in Space Weather
a new era of Prediction Forecasting

How Artificial Intelligence is Transforming Solar Forecasting

- Artificial intelligence is becoming a cornerstone of modern **space-weather prediction**, offering faster, more accurate insights into solar activity and its effects on Earth.
- Traditional models depend on physics-based simulations of the Sun, solar wind, and magnetosphere, but these systems struggle with the Sun’s chaotic and nonlinear behavior.
- **AI** bridges this gap by learning patterns directly from **vast datasets of solar observations.**

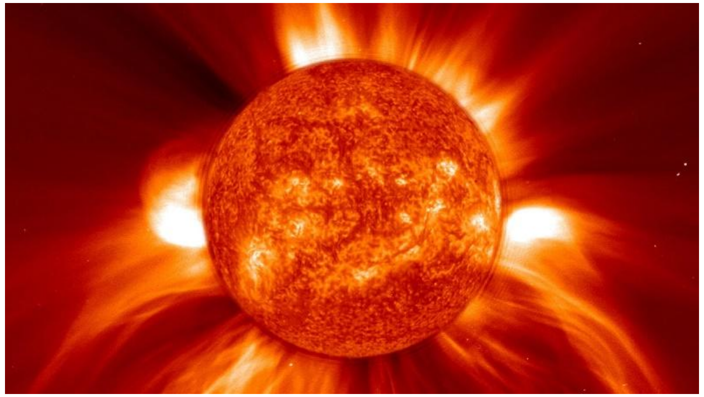
AI in Solar Flare Prediction



- Machine-learning algorithms (especially deep neural networks) analyze:
- sunspot magnetic complexity,
- historical flare catalogs (GOES X-ray records),
- magnetograms from SDO/HMI,
- EUV images from SDO/AIA.

AI models can **forecast flare probabilities hours to days in advance** with accuracy that now exceeds many conventional methods.

CME (Coronal Mass Ejection) Detection and Tracking



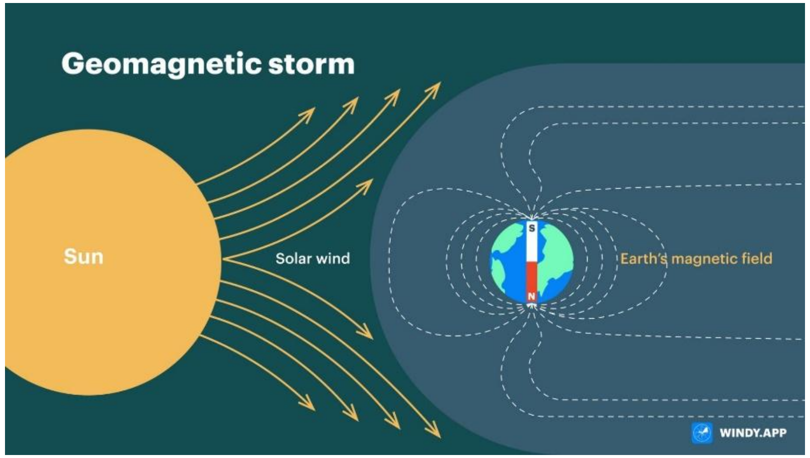
AI automatically identifies CMEs in coronagraph images (SOHO/LASCO, STEREO).

Deep-learning models segment CME structures and predict:

1. their direction,
2. speed,
3. arrival time at Earth,
4. potential geomagnetic severity.

This reduces human processing time from hours to minutes.

Predicting Geomagnetic Storms and K-index

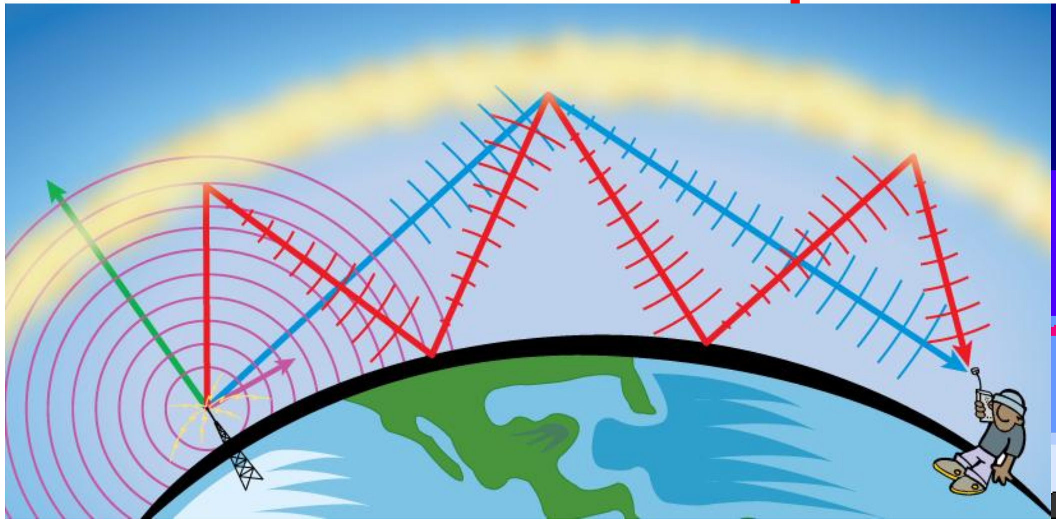


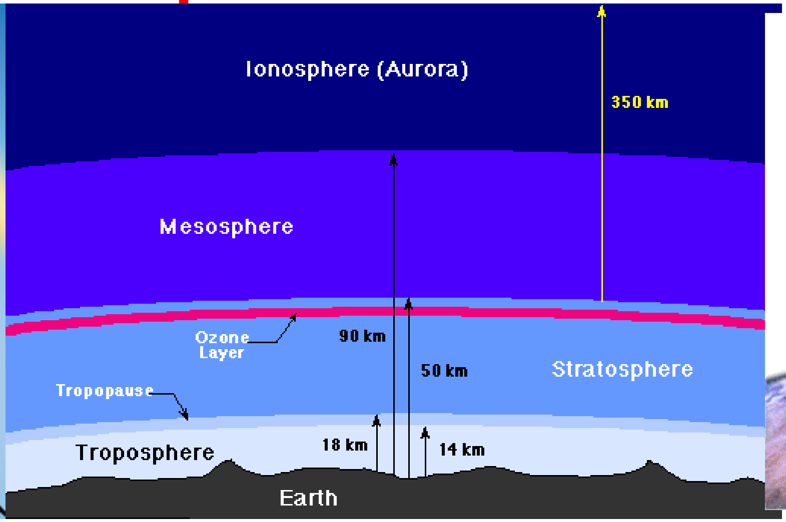
- **AI** models, trained on solar-wind data from ACE, DSCOVR, and Parker Solar Probe, estimate:

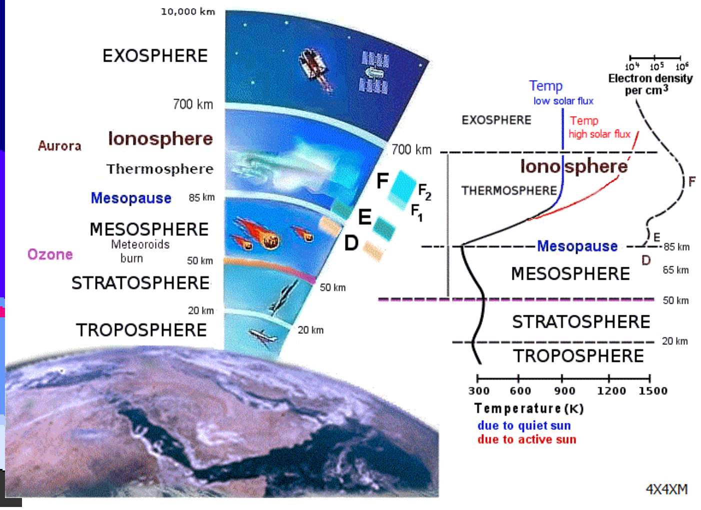
1. upcoming Kp index,
2. expected geomagnetic storm level (G1–G5),
3. substorm intensification.

They combine solar-wind velocity, density, IMF orientation, and high-dimensional patterns that are difficult to model analytically.

Ionospheric Response Forecasting







For radio-communication impacts (R-scale):

- **AI** predicts D-region ionization during solar flares. (the lowest layer of the ionosphere, located at altitudes of approximately 50–90 km)
- Models simulate HF blackout regions in real time.
- GNSS error forecasting becomes more accurate.

This directly helps aviation, maritime communications, and military systems.

AI Onboard Spacecraft

New missions (like ESA's Vigil and NASA's future monitoring satellites) use onboard **AI** for:

- autonomous CME detection,
- spacecraft protection maneuvers,
- prioritizing high-value telemetry.

This is essential because communication delays prevent quick reaction during sudden solar events.

AI-Assisted Space-Weather Early Warning Systems

AI integrates multi-source data:

- solar telescopes,
- coronagraphs,
- solar-wind monitors,
- geomagnetic indices,
- ionospheric sensors.

It produces real-time alerts faster than human-centered workflows.

AI is revolutionizing space-weather science by enabling:

- **faster flare and CME forecasting,**
- **better prediction of geomagnetic storms,**
- **real-time ionospheric impact modeling,**
- **autonomous space-mission protection.**

As solar activity rises toward Solar Cycle 25 maximum, AI tools are becoming critical for global infrastructure resilience: satellites, aviation, navigation, power grids, and HF communications.


THANK
YOU