SPACE WEATHER 101

How Our Star and Its Phenomena Lead to Aurora and Affect Our Daily Lives

About Me

Hardcore, Passionate, Obsessive, Successful Aurora Chaser - 40 Auroras Captured Across 10 States, 3 Countries

Outdoor Adventure & Night Sky Photographer

Space Weather Scholar in the Millersville University SWEN Graduate Program

Speaker/Teacher/Communicator of Aurora & Space Weather to Adults and Kids Alike

Day Job: International Higher Education

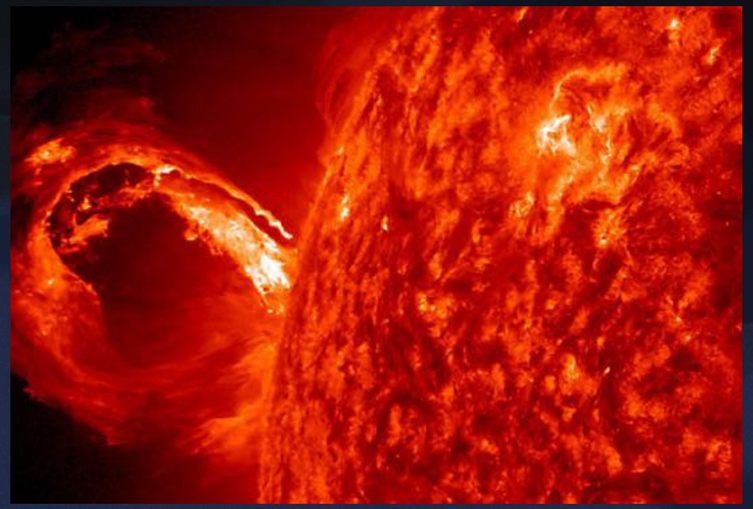






The Key Questions

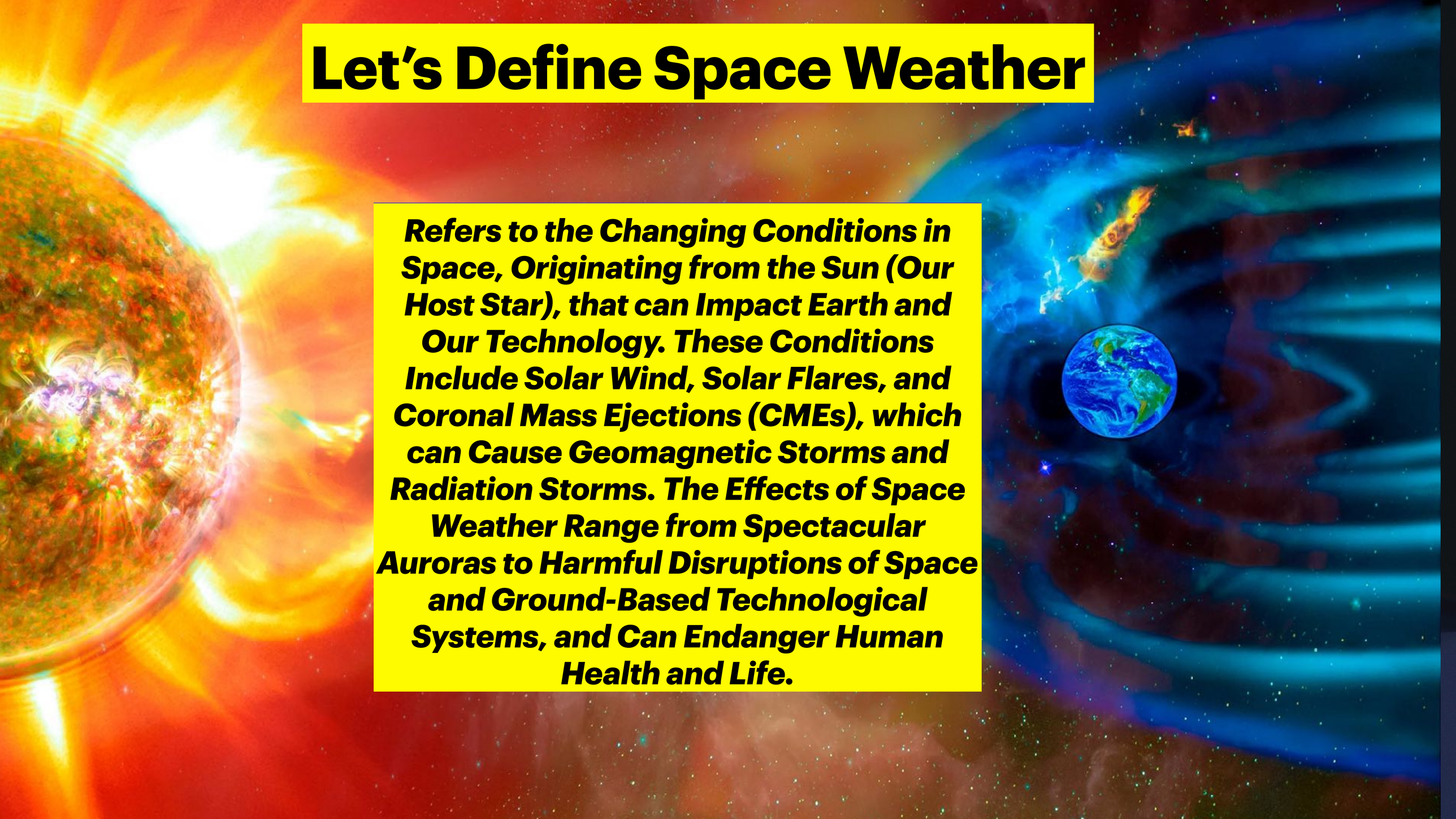
- What is Space Weather?
- What Are the Effects & Phenomena?
- What Are the Real and Potential Impacts to Us - And Why Should We Care?
- How Does Having at Least a Base Understanding Help with Aurora Chasing?



Today's Topics

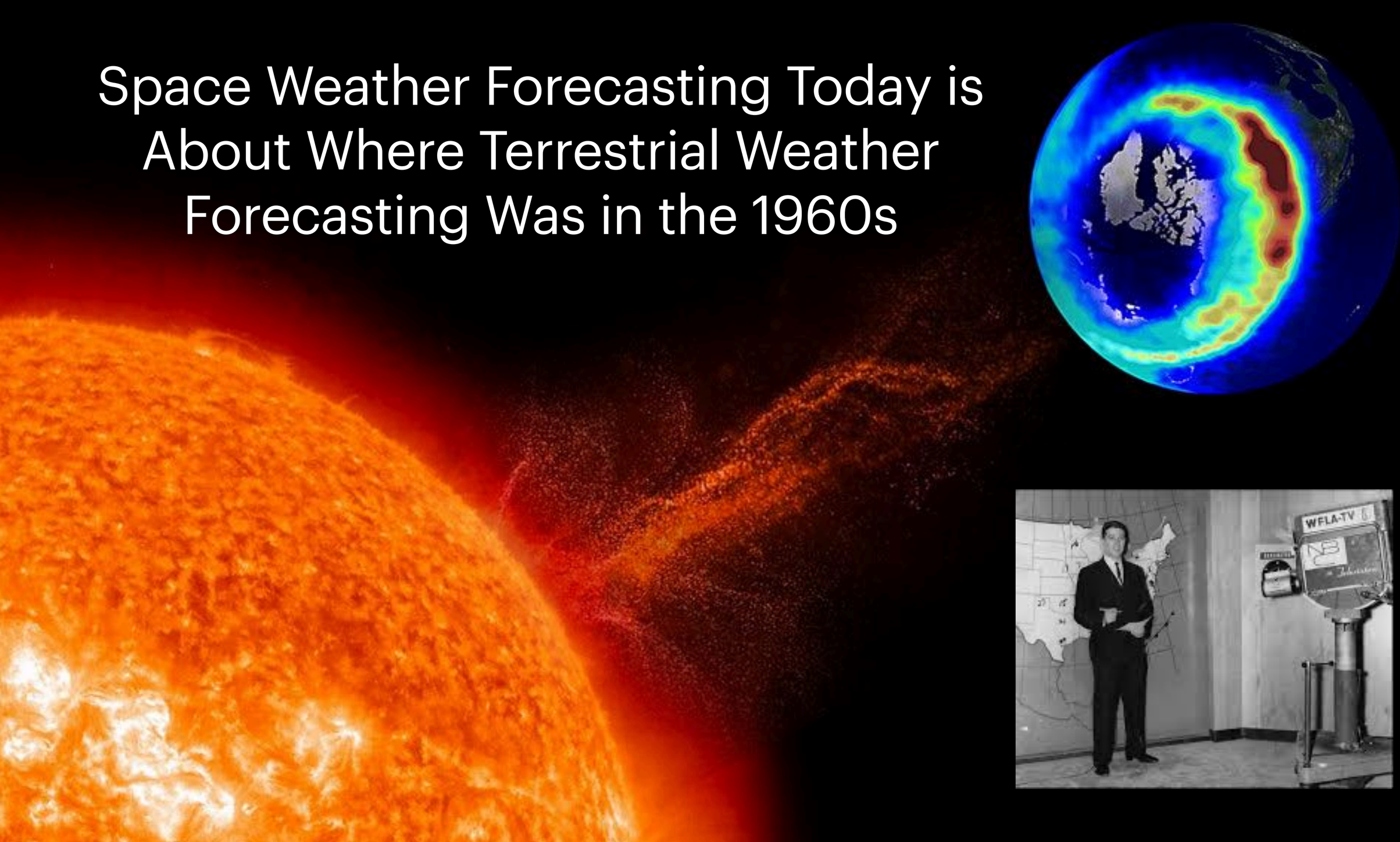
- Space Weather - Let's Define It
- NOAA's Space Weather Prediction Center
- Space Weather Policy and the Federal Government
- How Space Weather Impacts Us
- Notable Space Weather Events in History
- Hype, Fear Mongering & Hollywood
- The Sun-to-Earth Space Environment
- Overview of The Solar Cycle and Sunspots
- Phenomena - The Four Pillars of Space Weather
- A Quick Dive into Solar Flares & CMEs
- Measuring Impacts of the Phenomena
- Auroras, Forecasting, Tools & Tips
- Resources for Further Learning

Let's Define Space Weather



Refers to the Changing Conditions in Space, Originating from the Sun (Our Host Star), that can Impact Earth and Our Technology. These Conditions Include Solar Wind, Solar Flares, and Coronal Mass Ejections (CMEs), which can Cause Geomagnetic Storms and Radiation Storms. The Effects of Space Weather Range from Spectacular Auroras to Harmful Disruptions of Space and Ground-Based Technological Systems, and Can Endanger Human Health and Life.

Space Weather Forecasting Today is About Where Terrestrial Weather Forecasting Was in the 1960s

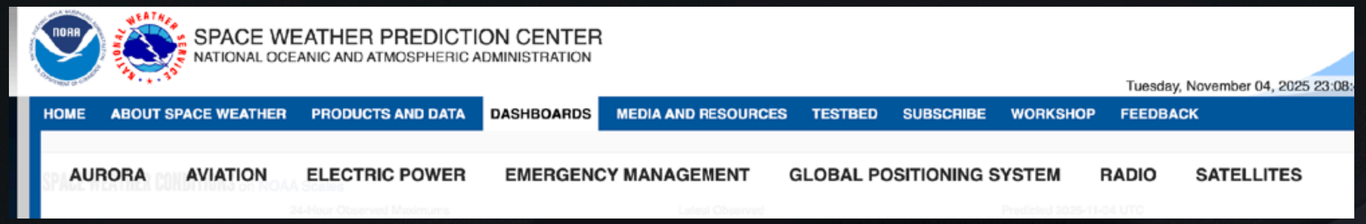


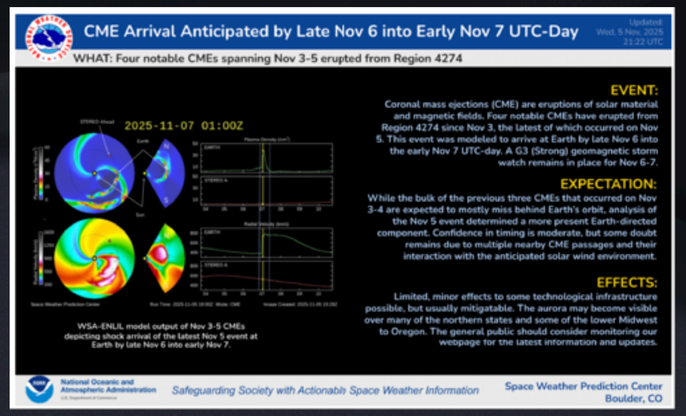
NOAA’s Space Weather Prediction Center

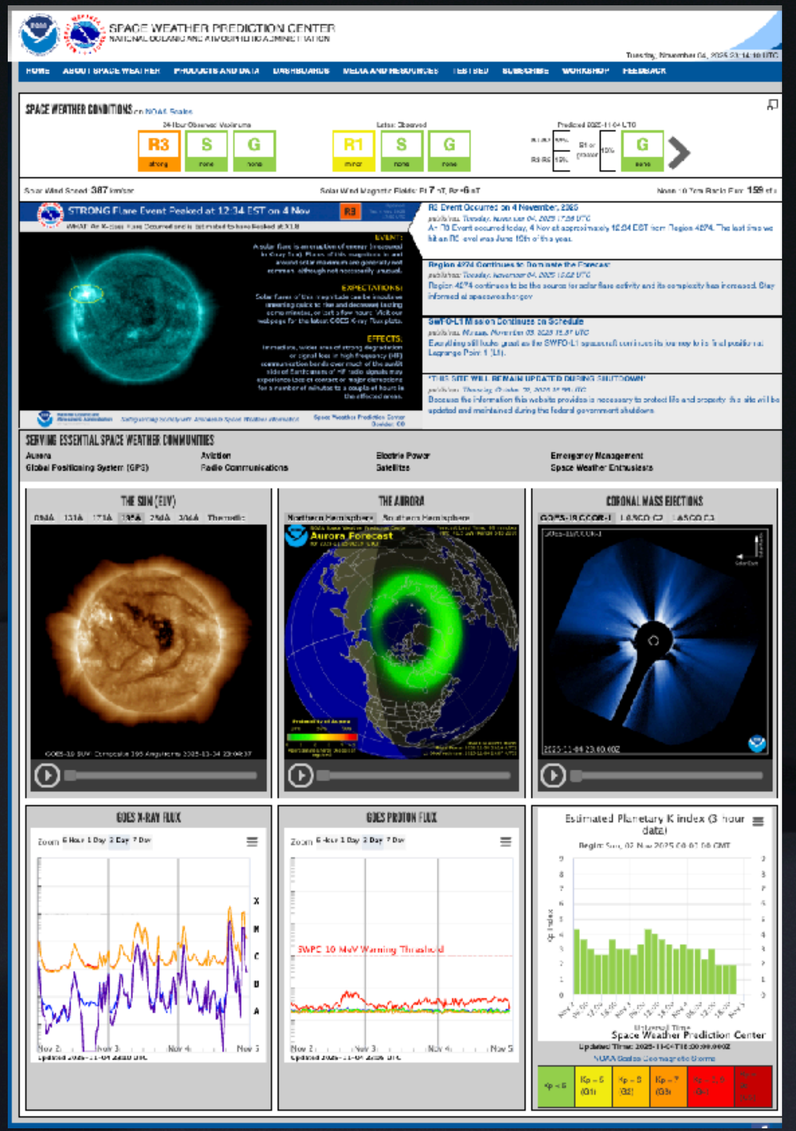
The Official U.S. Space Weather Forecasting Agency (spaceweather.gov)

SWPC’s Mission is:

To deliver space weather products and services that meet the evolving needs of the nation. The Space Weather Prediction Center gathers, in real time, the available data that describes the state of the Sun, Heliosphere, Magnetosphere, and Ionosphere to form a picture of the environment from the Sun to the Earth. With this information, forecasts, watches, warnings and alerts are prepared by the Space Weather Prediction Center and issued to anyone affected by space weather.







SEVERE Geomagnetic Storm ALERT – 24 March UTC-Day

G4

WHAT: Geomagnetic responses increased and G4 levels first reached 24 March at 12:04 am EDT

What is a severe geomagnetic storm?

A severe disturbance in Earth's magnetic field

What you or your agency should do?

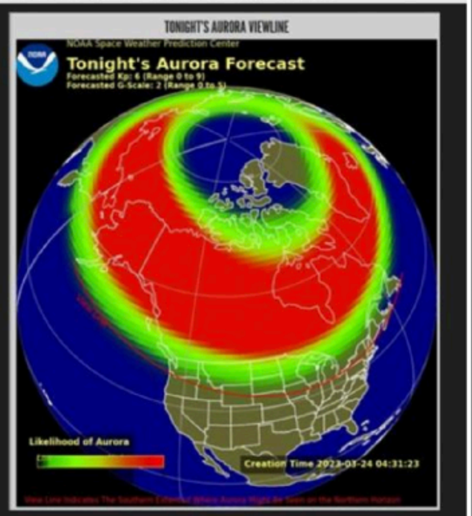
Keep updated about storm status and progression. Those under or near the 30-minute predicted auroral extent may look for the aurora if at night and should weather conditions permit

Possible Technology Effects

Power Grid:
possible widespread voltage control problems

Spacecraft Operations:
increased possibility of surface charging; atmospheric drag risk on Low Earth Orbiting (LEO) satellites;

Other:
More frequent and longer periods of GNSS (i.e. GPS) degradation possible



National Oceanic and Atmospheric Administration

Safeguarding Society with Actionable Space Weather Information

Space Weather Prediction Center
Boulder, CO

Strongest Solar Flare of this Solar Cycle

Updated
2023 Dec 14
1900 EST

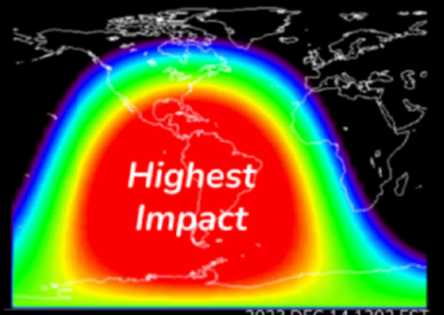
WHAT: Multiple Aviation Communication Impacts Associated with this Event

Amazing Event - likely one of the largest solar radio events ever recorded

Radio communication impacts between approximately 1200 - 1400 EST Thu

CWSUs report degraded communications across Nation
- ZKC, ZMP, ZAU, ZNY, ZOB
- "... Never seen anything like this..." - ZOB

Possible Earth-directed Coronal Mass Ejection (CME) being analyzed



2023 DEC 14 1202 EST

National Oceanic and Atmospheric Administration

Safeguarding Society with Actionable Space Weather Information

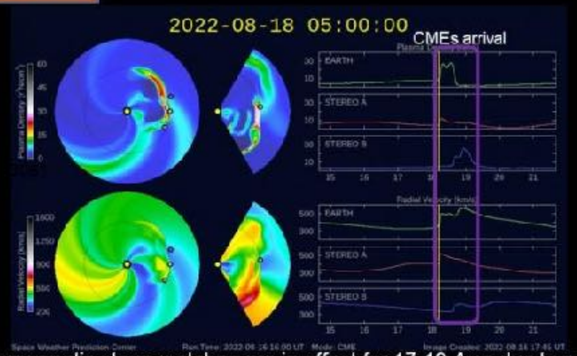
Space Weather Prediction Center;
Boulder, CO

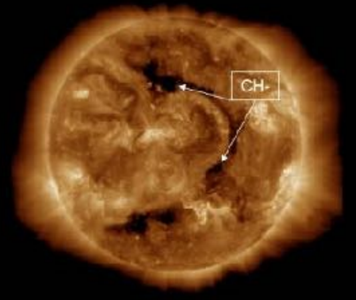
18 Aug
G3
Strong

MINOR-STRONG Geomagnetic Storm Watches for 17-19 Aug

17 Aug **G1** Minor

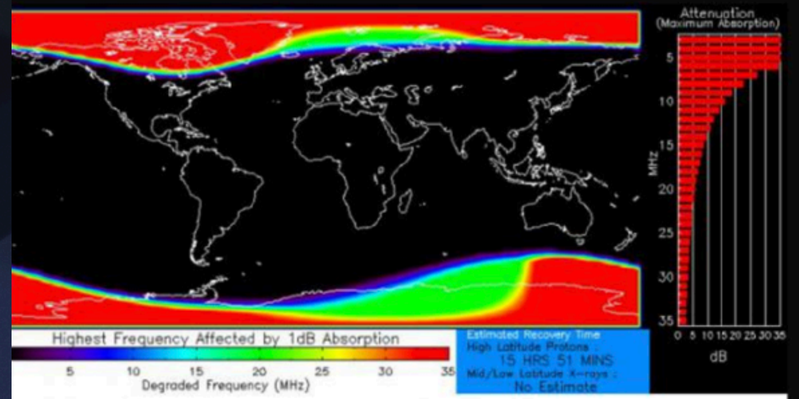
19 Aug **G2** Moderate





Geomagnetic storm watches are in effect for 17-19 Aug due to coronal high speed stream (CH HSS) and coronal mass ejection (CME) influences. A lengthy CH is anticipated to effect Earth first, on 17 Aug, with likely G1 conditions. An escalation to G3 storm levels is now probable on 18 August due to several CMEs combining and beginning to arrive. Conditions are anticipated to remain favorable for G2 levels on 19 Aug.

Radiation Storm Warning remains in Effect
10/1630 – 14/2359 UTC



Current Condition

S1

POSSIBLE EFFECTS

Communication: Minor impacts to polar HF propagation

Space Weather Has Attention & Support at the White House

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

U.S. Strategic National Risk Assessment, Executed in Support of Presidential Policy

Threat/ Hazard Group	Threat/Hazard Type	National-level Event Description
Natural	Animal Disease Outbreak	An unintentional introduction of the foot-and-mouth disease virus into the domestic livestock population in a U.S. state
	Earthquake	An earthquake occurs within the U.S. resulting in direct economic losses greater than $100 Million
	Flood	A flood occurs within the U.S. resulting in direct economic losses greater than $100 Million
	Human Pandemic Outbreak	A severe outbreak of pandemic influenza with a 25% gross clinical attack rate spreads across the U.S. populace
	Hurricane	A tropical storm or hurricane impacts the U.S. resulting in direct economic losses of greater than $100 Million
	Space Weather	The sun emits bursts of electromagnetic radiation and energetic particles causing utility outages and damage to infrastructure
	Tsunami	A tsunami with a wave of approximately 50 feet impacts the Pacific Coast of the U.S.
	Volcanic Eruption	A volcano in the Pacific Northwest erupts impacting the surrounding areas with lava flows and ash and areas east with

USAF Space Weather Operations Center

- **USAF SpWOC:** DoD's only space environment observing, analysis, and forecast capability at all three security enclaves
- **Dissemination Methods:** AF Weather Web Services, e-mail, phone
- **Volume:** ~35,000 products per day (~34,500 automated)
- **Manning:** 24/7 Operations (1 shift lead, 1 forecaster, 1 analyst)

USAF Space Weather Analysis and Forecasting supports warfighter mission planning, execution, and anomaly attribution

Executive Order March 2025 from the Trump Administration

PRESIDENTIAL ACTIONS

Achieving Efficiency Through State and Local Preparedness

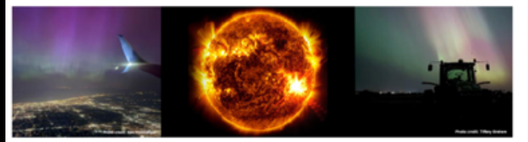
Executive Orders | March 19, 2025

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered:

Section 1. Purpose. Commonsense approaches and investments by State and local governments across American infrastructure will enhance national security and create a more resilient Nation. Federal policy must rightly recognize that preparedness is most effectively owned and managed at the State, local, and even individual levels, supported by a competent, accessible, and efficient Federal Government. Citizens are the immediate beneficiaries of sound local decisions and investments designed to address risks, including cyber attacks, wildfires, hurricanes, and space weather. When States are empowered to make smart infrastructure choices, taxpayers benefit.

Space Weather Advisory Group (SWAG)

National Weather Service

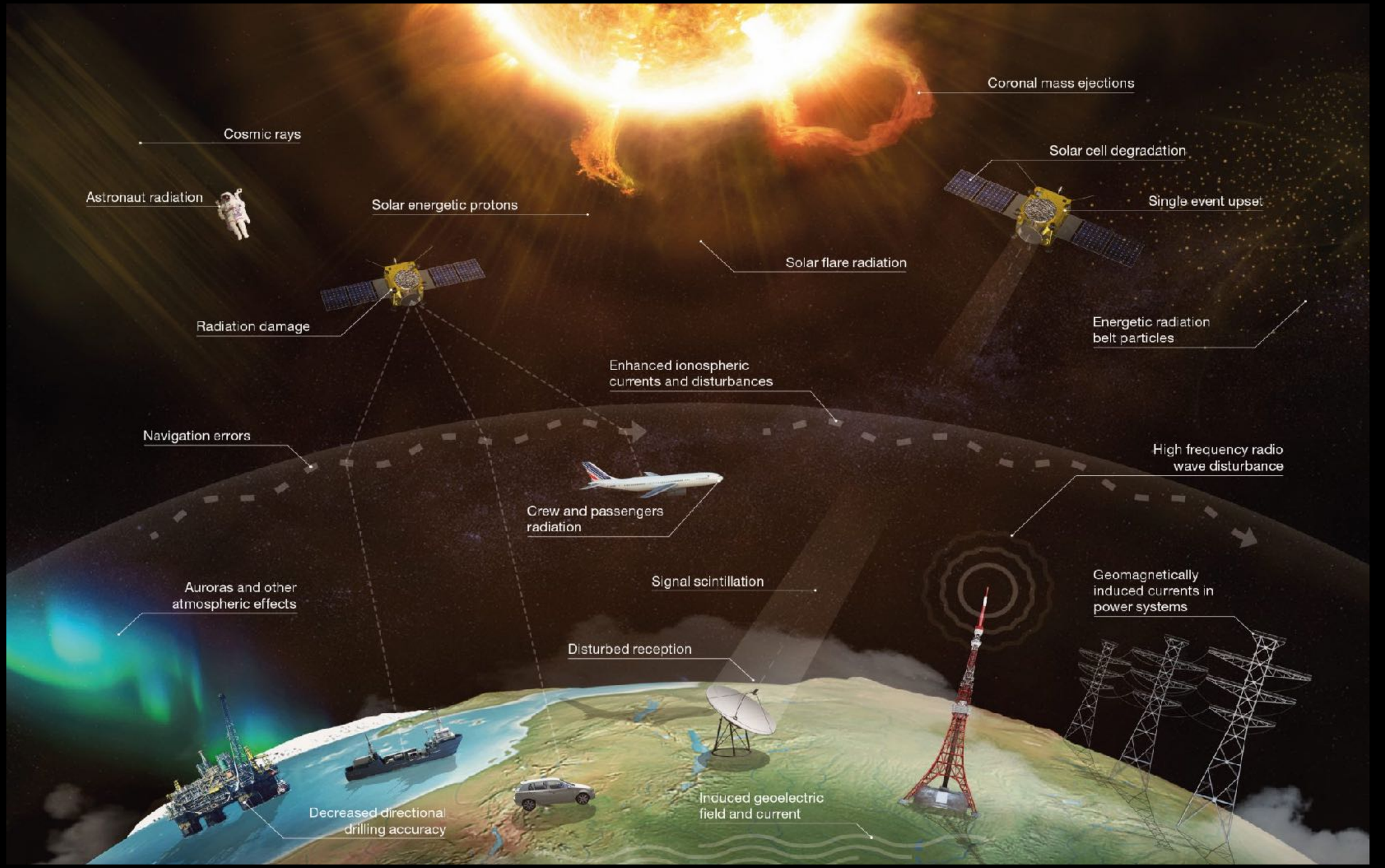


Since its establishment as a Federal Advisory Committee in 2021 under the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act of 2020 (Public Law 115-181), 51 U.S.C. § 60601(f), the Space Weather Advisory Group (SWAG) actively fulfills its mandate to advise the Space Weather Interagency Working Group ("Interagency Working Group") on advancing the Nation's space weather capabilities.

The United States depends on reliable space weather forecasting and preparedness to protect critical infrastructure, national security, and economic interests. Space weather events – such as solar storms and geomagnetic disturbances – can disrupt communications, navigation, power grids, and satellite operations, posing significant risks to both government and commercial sectors. The SWAG plays a crucial role in advising the Interagency Working Group on policies and strategies to enhance the nation's ability to prepare for, mitigate, respond to, and recover from space weather events. Composed of non-government representatives from academia, the commercial space weather sector, and the end-user community, the SWAG provides a broad range of perspectives and expertise to ensure that national space weather policies and services meet the needs of all stakeholders.

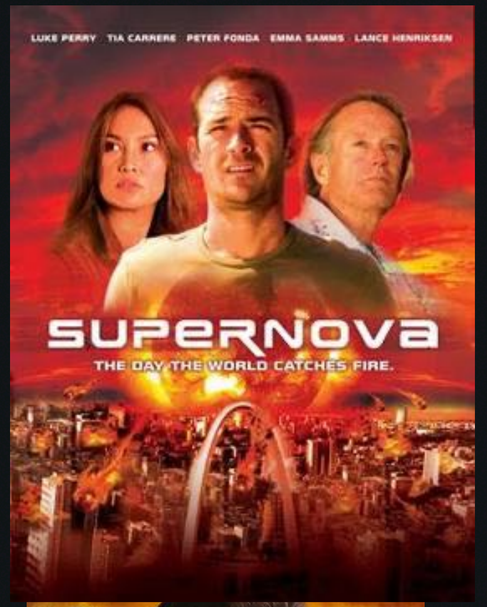
Besides Aurora, How Does Space Weather Affect Us? (“Just A Few” Ways… 😱)

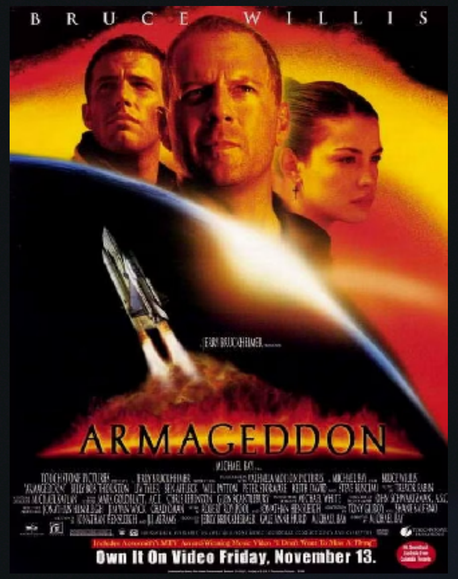
DEPARTURES
SEARCH & RESCUE
ice
NYSE
432.43
CN
DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

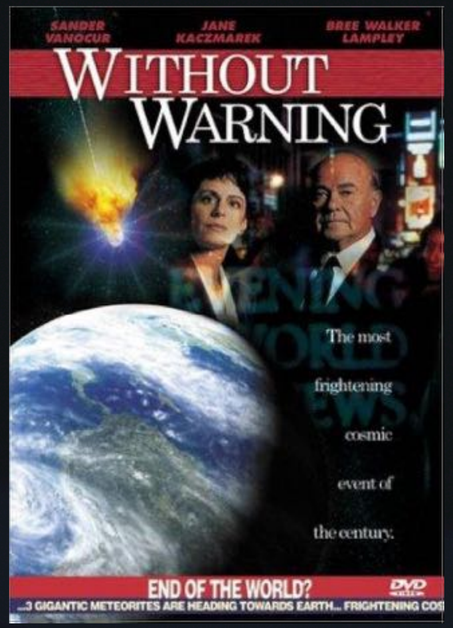

Coronal mass ejections
Cosmic rays
Solar cell degradation
Astronaut radiation
Solar energetic protons
Single event upset
Solar flare radiation
Radiation damage
Energetic radiation belt particles
Enhanced ionospheric currents and disturbances
Navigation errors
High frequency radio wave disturbance
Crew and passengers radiation
Auroras and other atmospheric effects
Signal scintillation
Geomagnetically induced currents in power systems
Disturbed reception
Decreased directional drilling accuracy
Induced geoelectric field and current

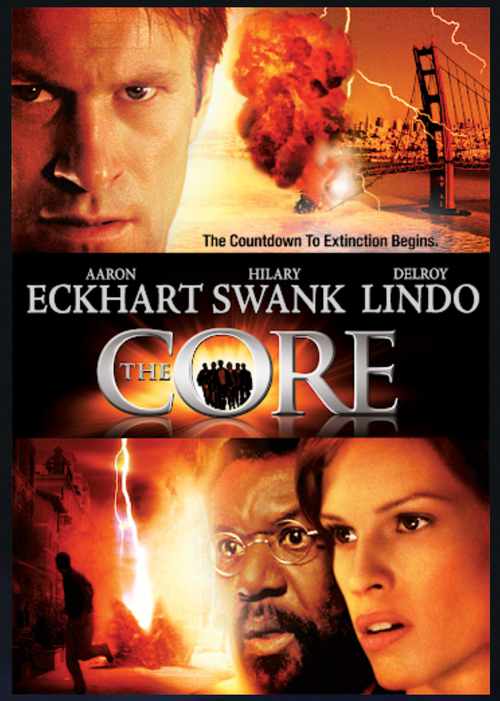
Beware: Misinformation and Fear Mongering

Hollywood Loves Sensationalizing Space Weather

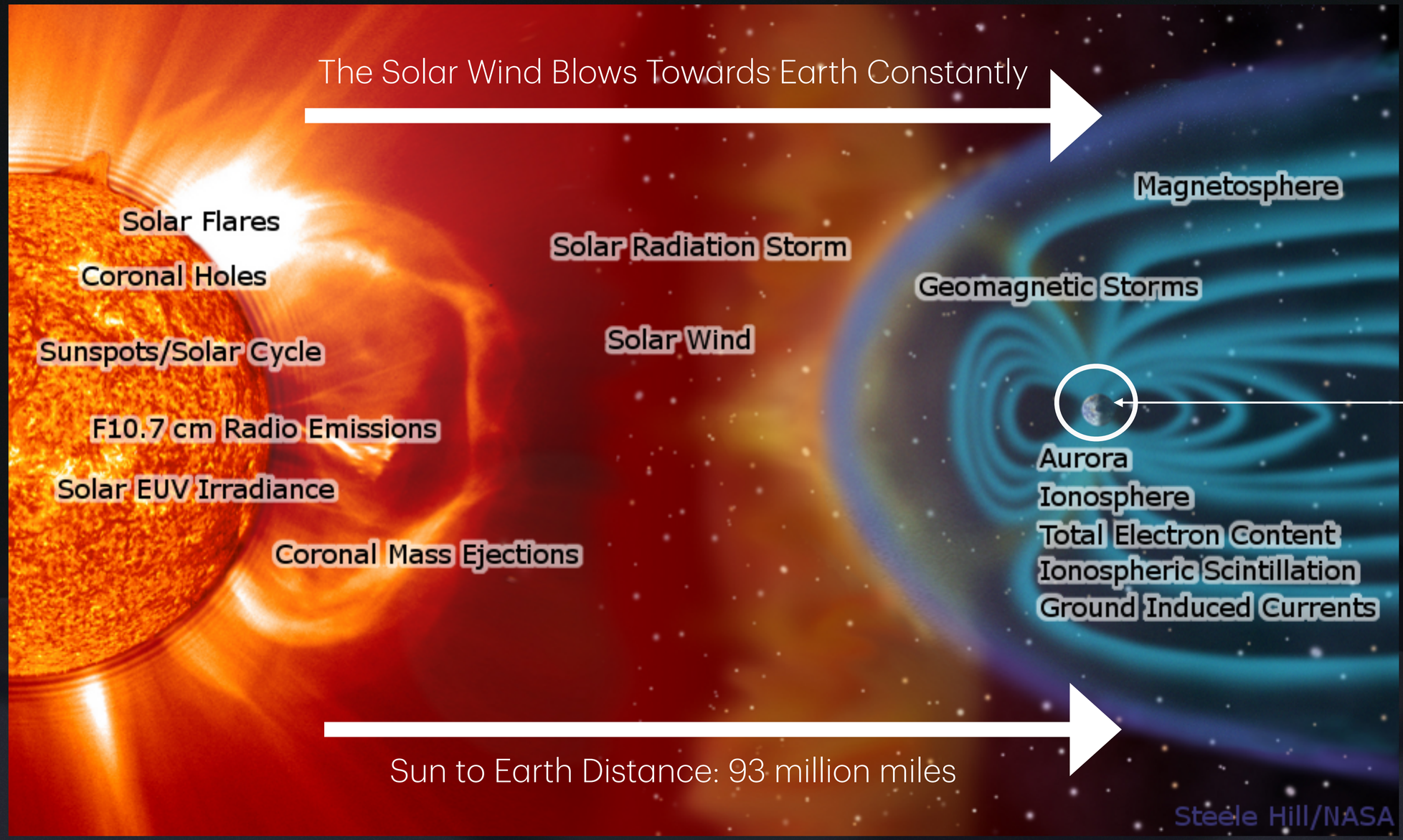


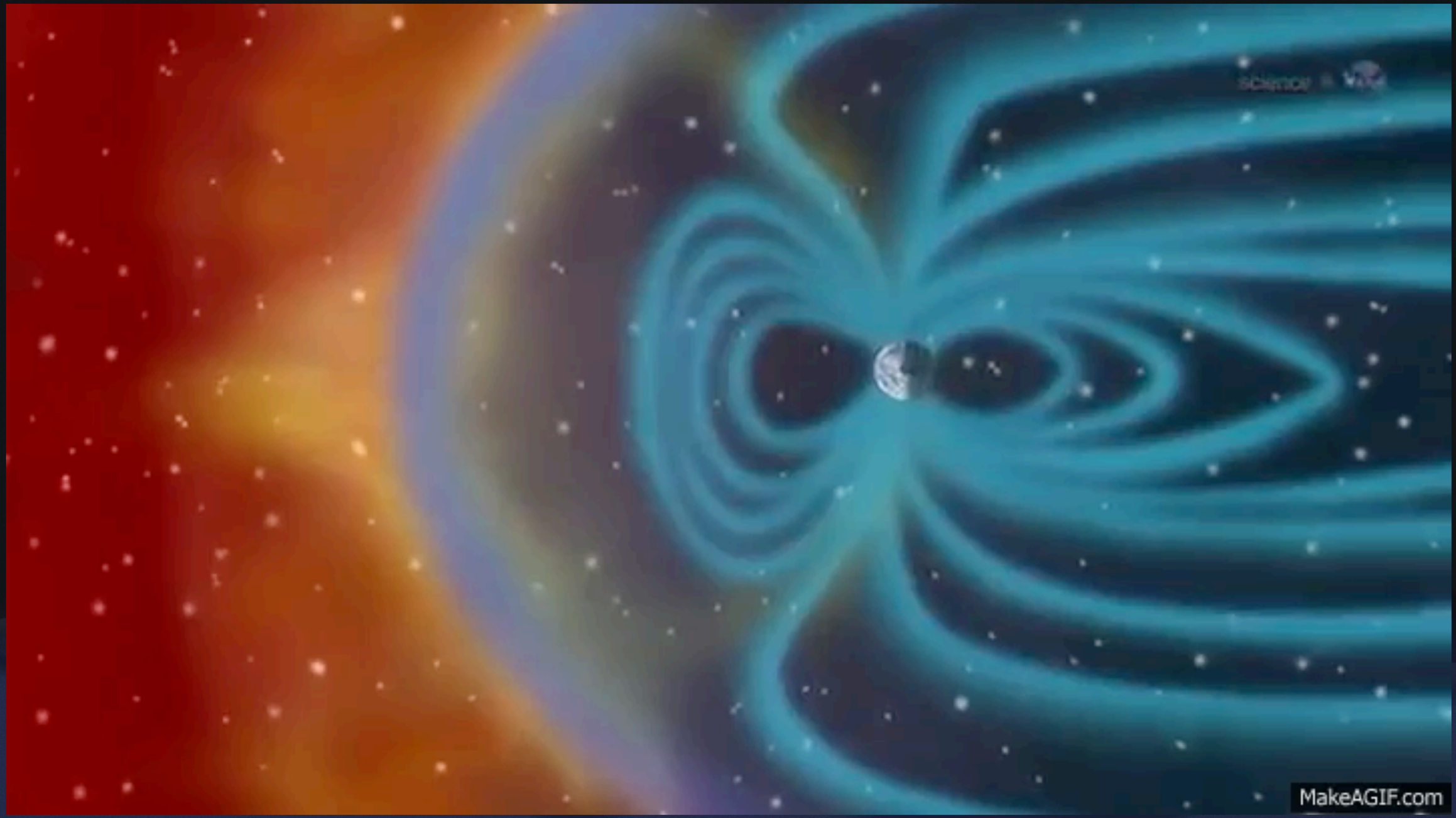


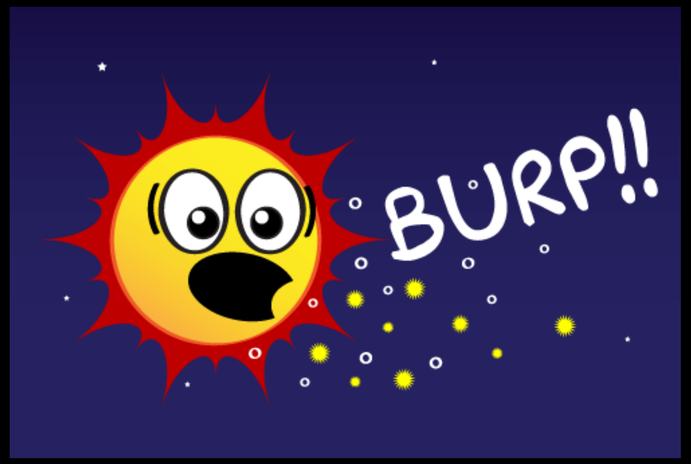


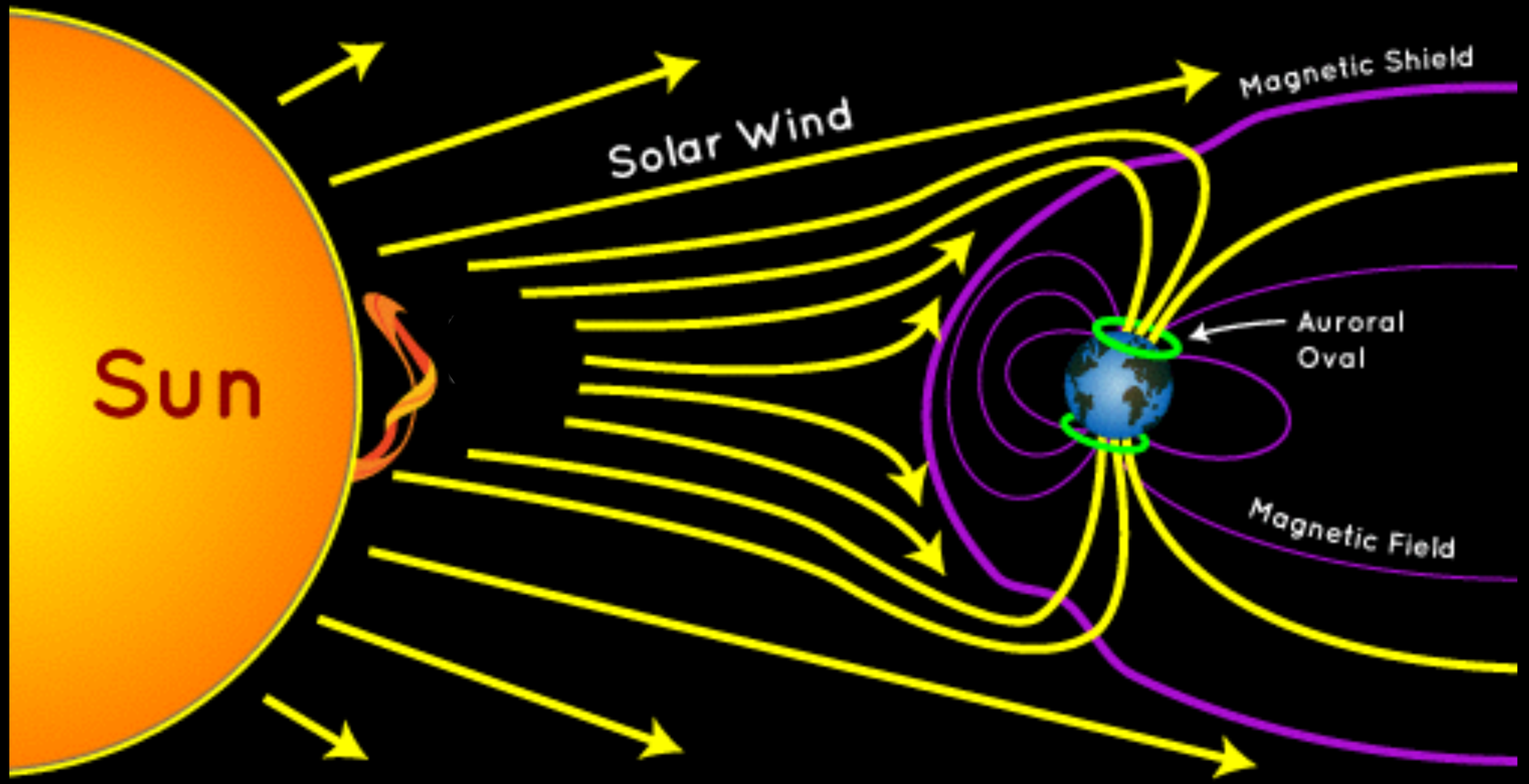


Space Weather Starts with the Sun

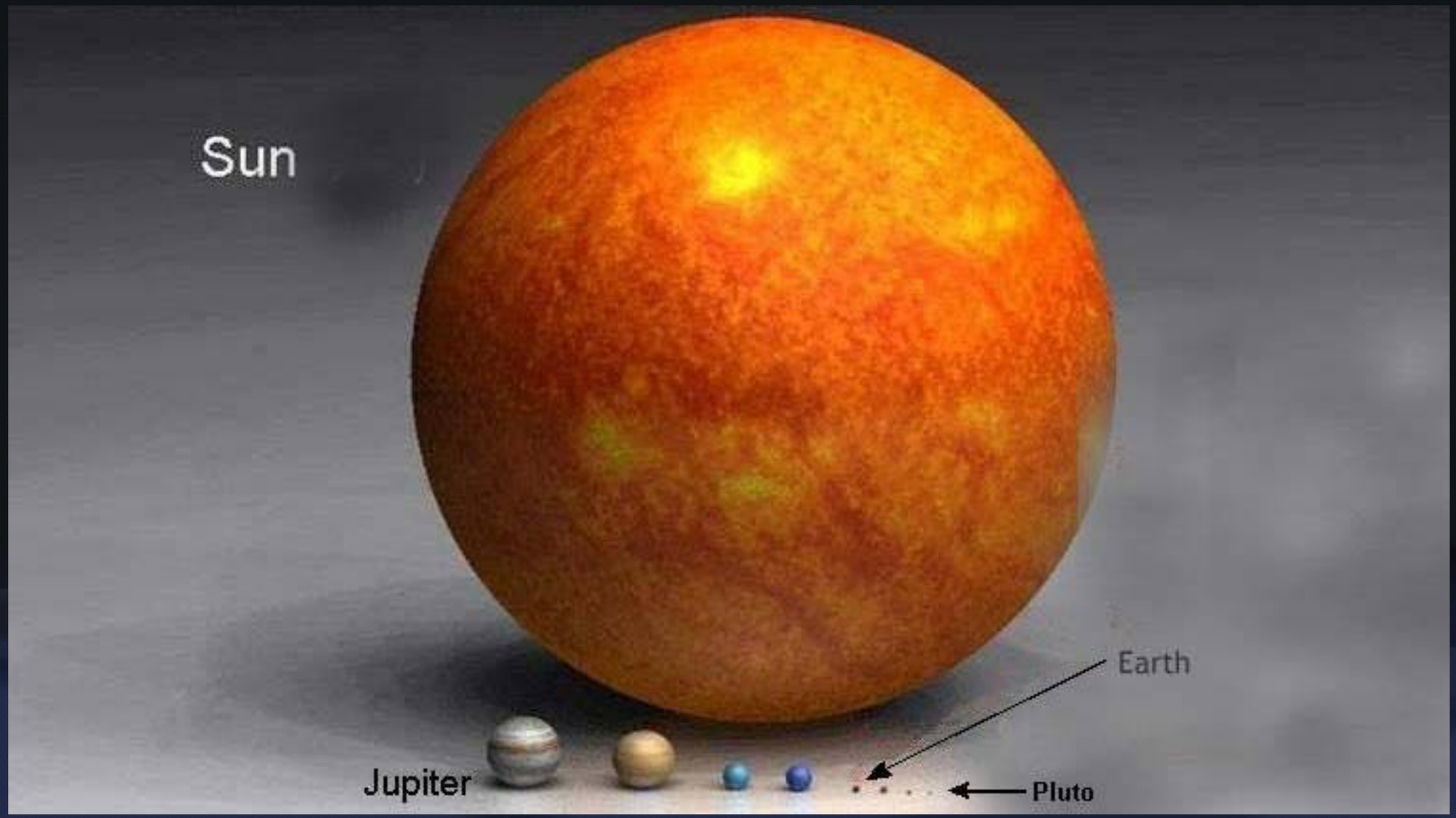



MakeAGIF.com

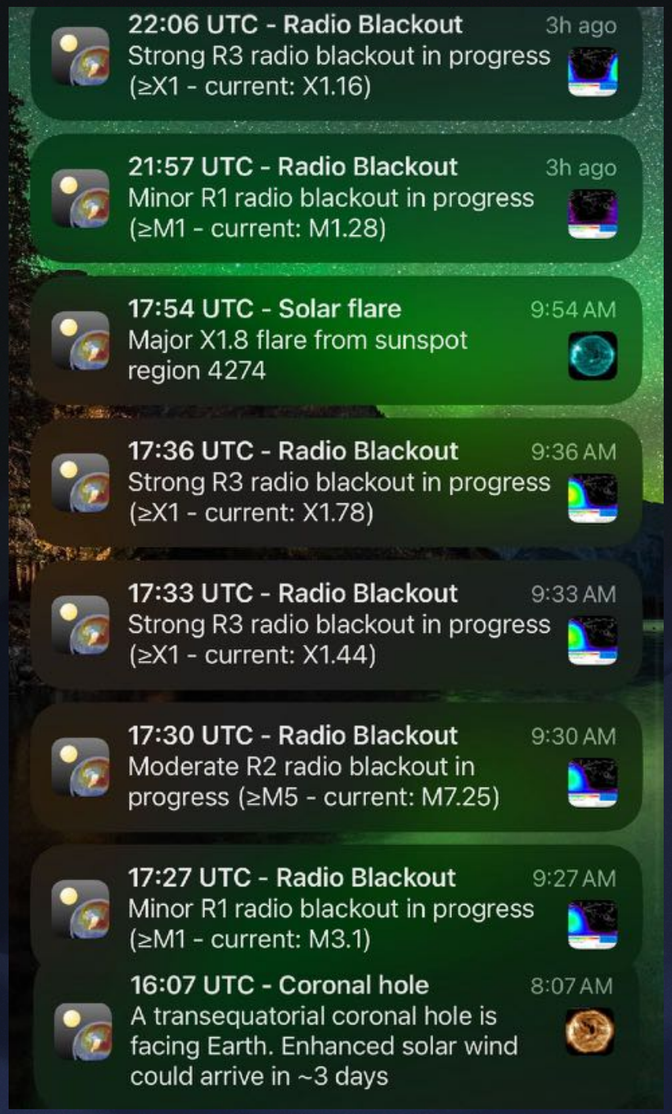

BURP!!

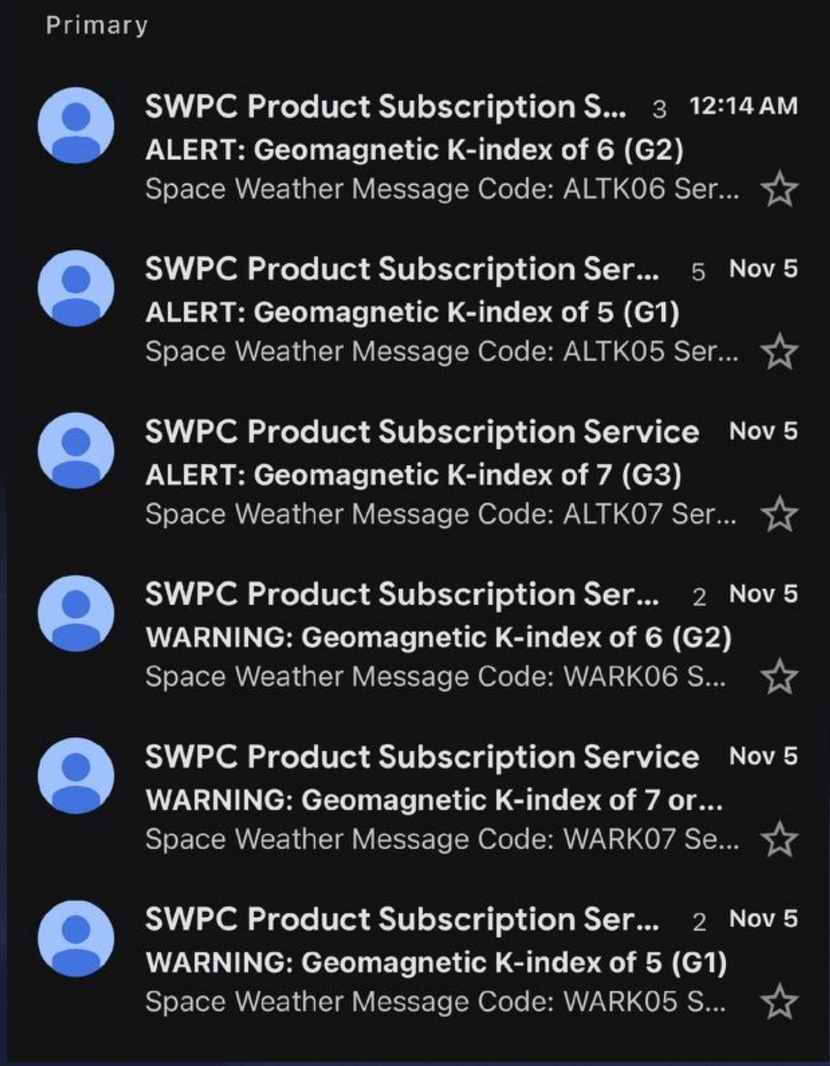

Sun
Solar Wind
Magnetic Shield
Auroral
Oval
Magnetic Field

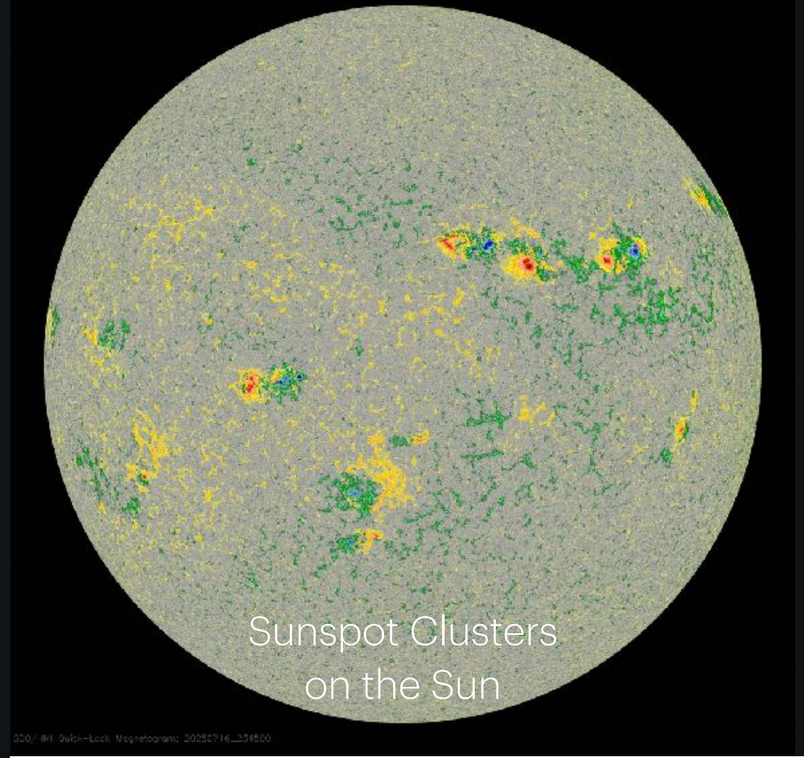
The Sun Compared to Earth



When the Sun Gets Busy

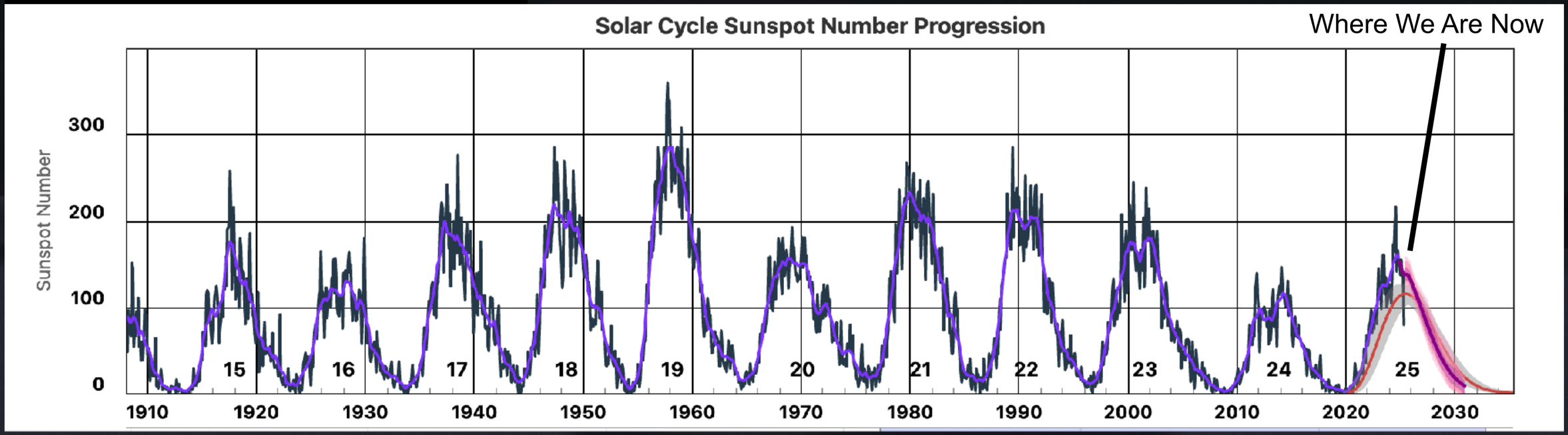






The Solar Cycle

- Average 11-year period where the sun's magnetic field reverses, going between Solar Maximum and Solar Minimum, measured by the number of sunspots
- Current cycle (25) peaked last fall so we are in the early stages of the declining phase which will last until approx. 2032 when the next cycle begins anew
- SC 25 is an "average" cycle - bigger than the last (SC24) but smaller than the previous three



The Solar Cycle is Declining….BUT

Oklahoma

Indiana

Buffalo NY

Houston

Pittsburgh

Good News for Aurora Chasers!

Many of the Largest Solar Storms in History Have Happened When the Sun is Quiet

(Images from the Great Halloween Aurora Oct. 2003)

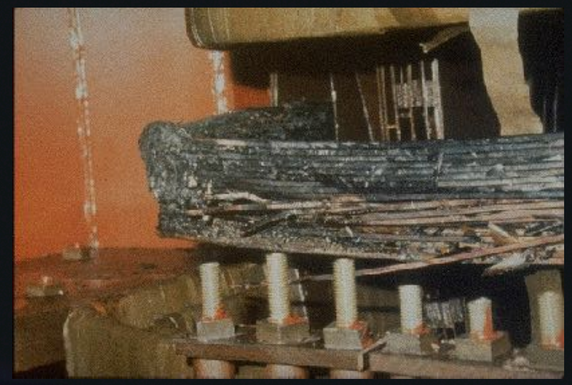
Notable Space Weather Events in History

Carrington Storm - September, 1859

- *Most significant event on record. Telegraph system impacted worldwide. Aurora down to Central America*

Extreme Solar & Geospace Storm - August, 1972

- *Sea mines spontaneously detonated off the coast of Vietnam; Radiation storm could have killed Apollo mission astronauts in space*



Hydro-Quebec Blackout March, 1989

- *9 hour blackout across Quebec in frigid winter temps; Severely damaged N.J. power transformers; US grid anomalies*

Operation Anaconda - March, 2002 Afghanistan

- Three US Special Forces soldiers killed; Satellite communications during military operations disrupted

Halloween Solar Storms - Oct-Nov, 2003

- Billions in damages to satellites; lost spacecraft; Partial grid collapse in Sweden; Flights disrupted & rerouted; Chaos to polar operations

Hurricanes Harvey & Irma Perfect Storm - Aug-Sept, 2017

- HF radio comms disrupted; First responders unable to communicate during search & rescue ops

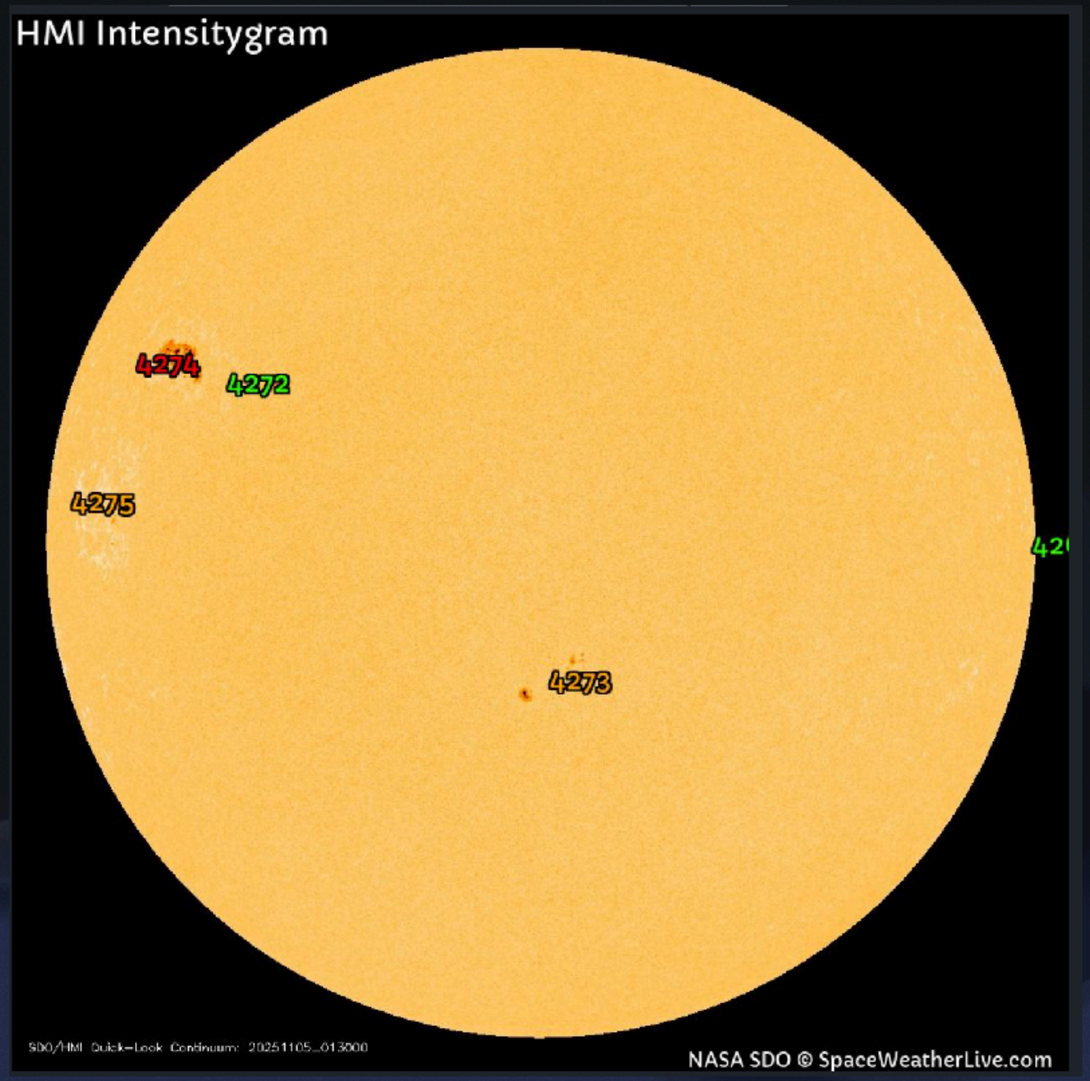
SpaceX Starlink Loss - February, 2022

- *38/49 satellites lost due to increased “drag” caused by launch during geomagnetic storm*

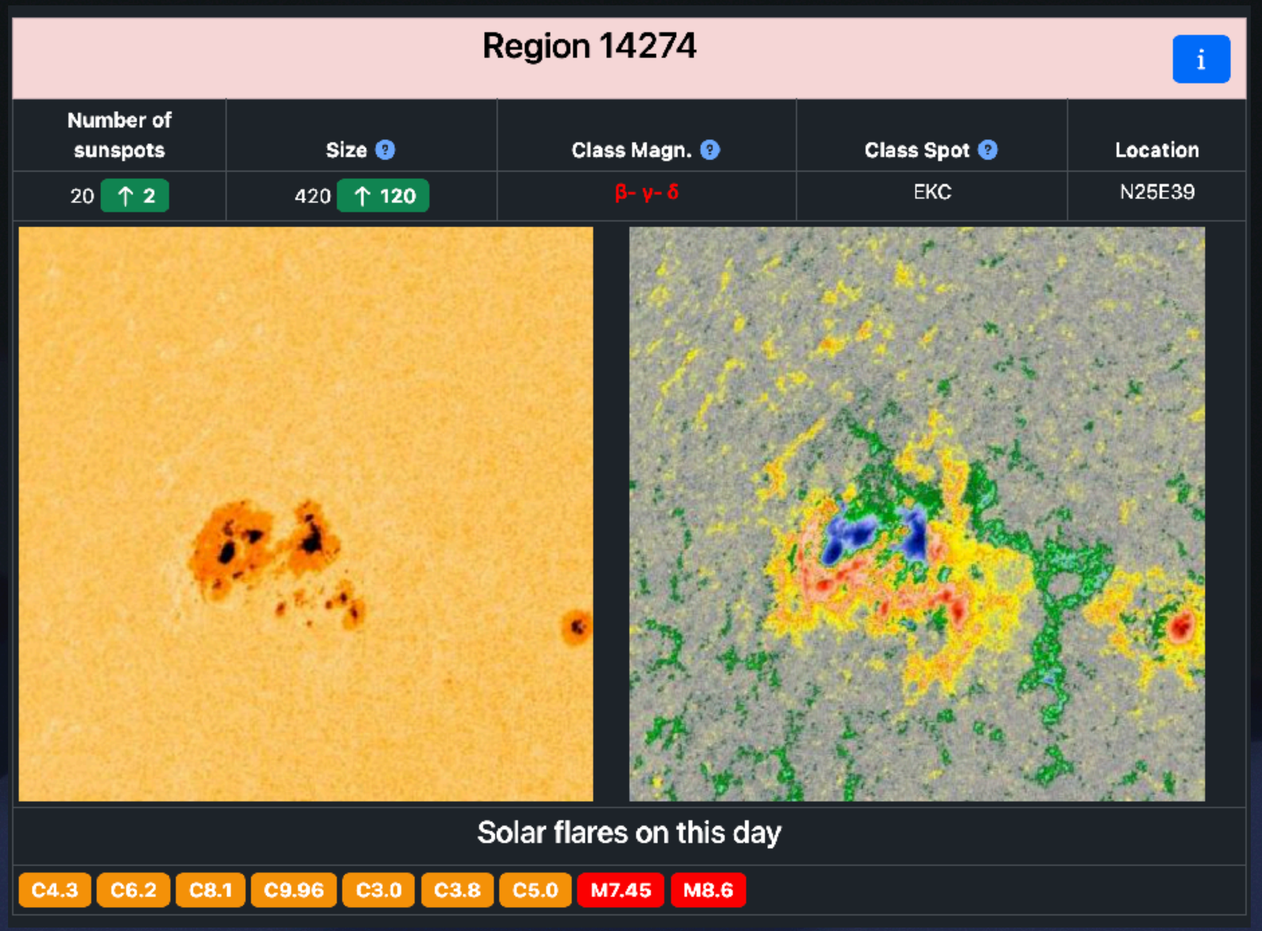
Half Billion $$$ Farming Loss - May 2024

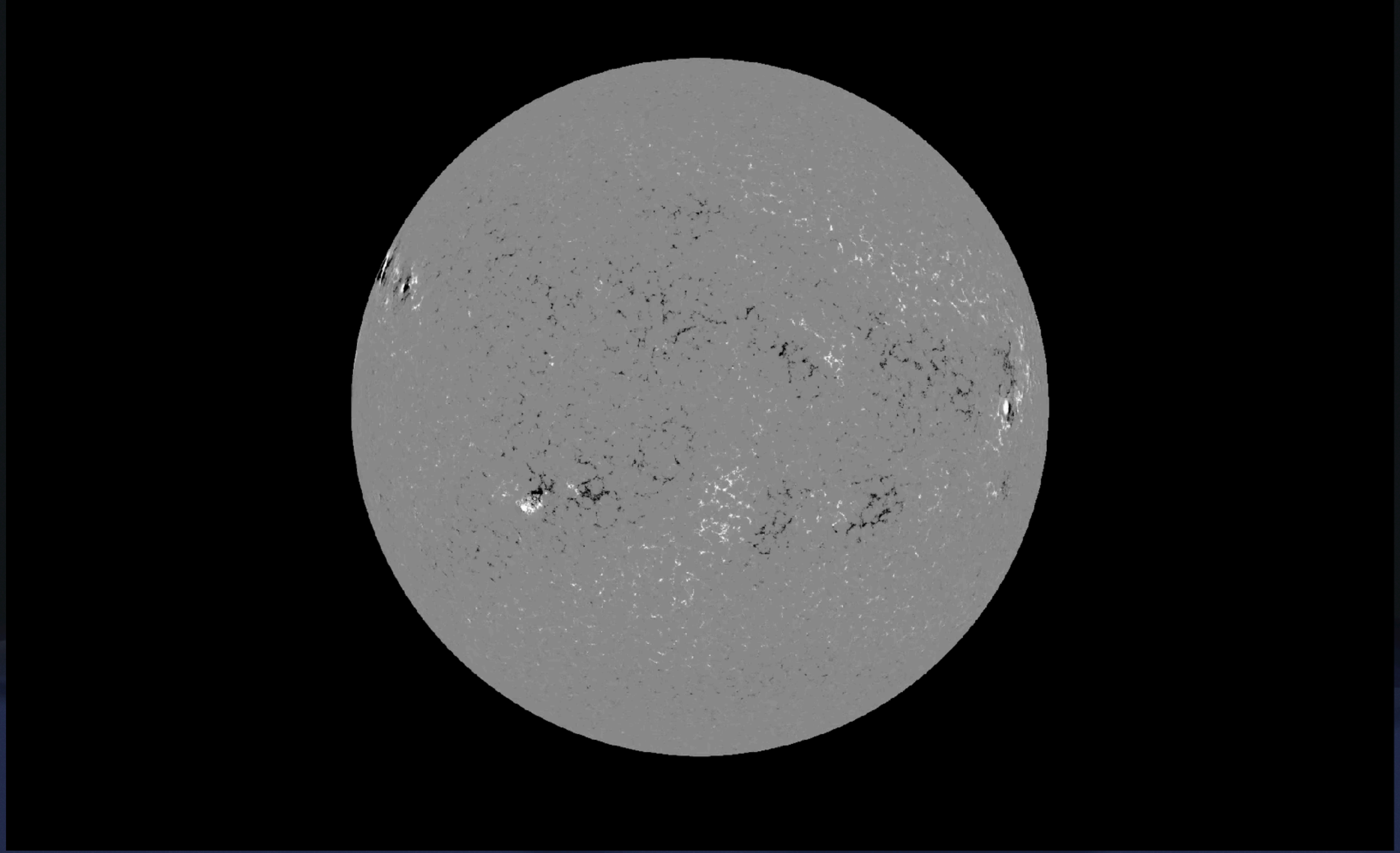
- *GPS navigation errors affected precision agriculture in the Midwest; Auroras in all 50 states & many countries that usually would not get Aurora*

Sunspots & Their Significance



Sunspots Are a Source of Space Weather





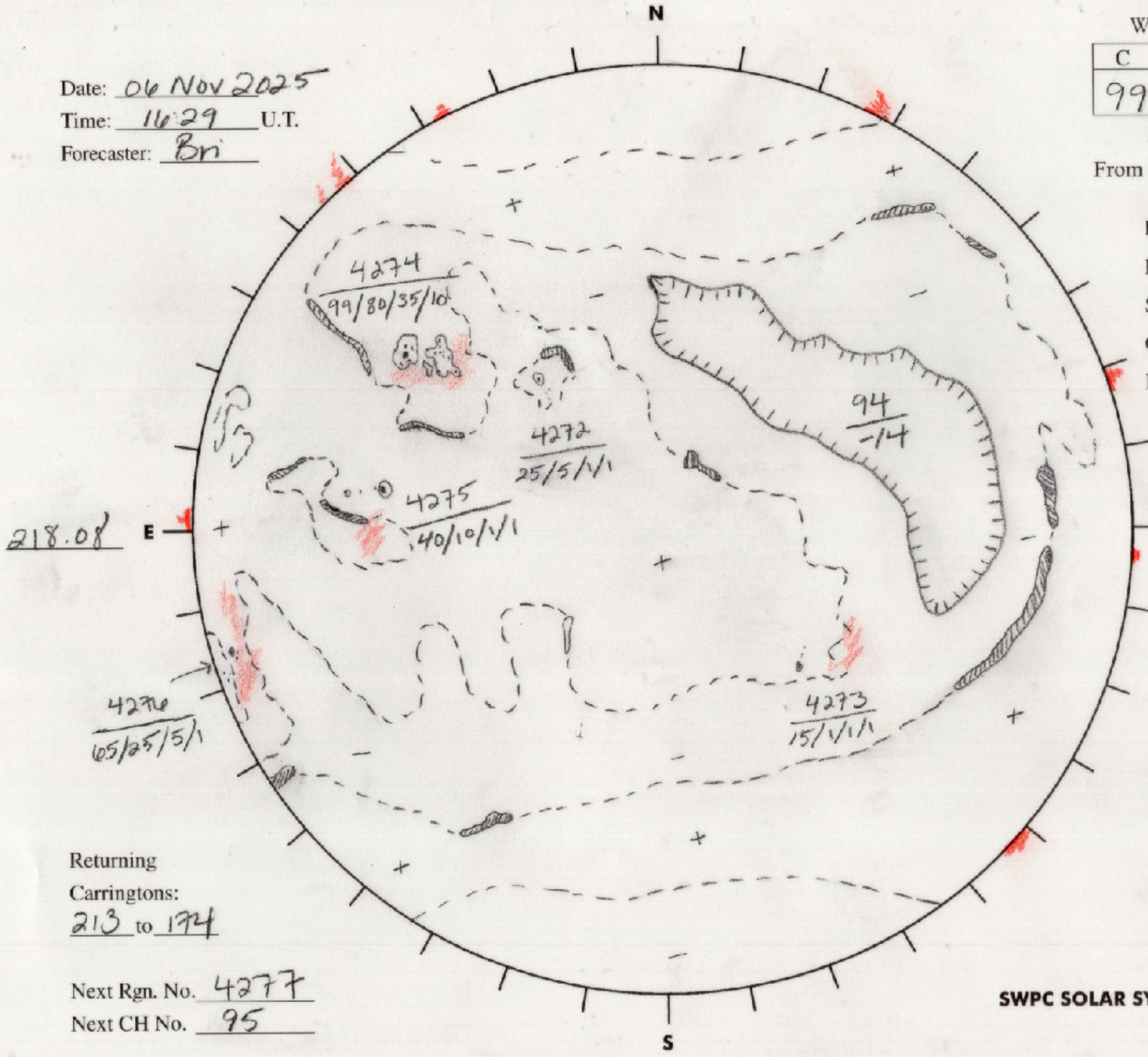
Date: 06 Nov 2025
Time: 16:29 U.T.
Forecaster: Bri

Whole Disk Forecast

C	M	X	P
99	80	35	20

24 Hour Forecast
From 0000 U.T. to 0000 U.T.

Data:
H-alpha. 16:29 U.T.
Sunspots 16:00 U.T.
CH 16:17 U.T.
Mag. 16:00 U.T.



218.08

W 38.08

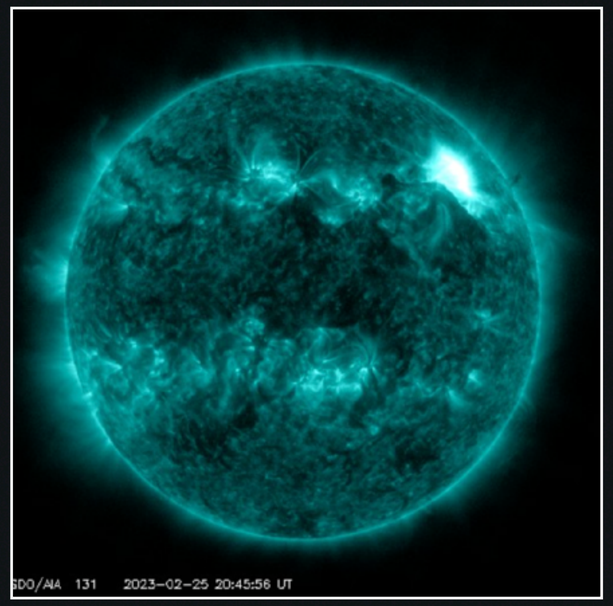
L_t 308.08
B_t 3.79
P_t 23.36

Returning Carringtons:
213 to 174

Next Rgn. No. 4277
Next CH No. 95

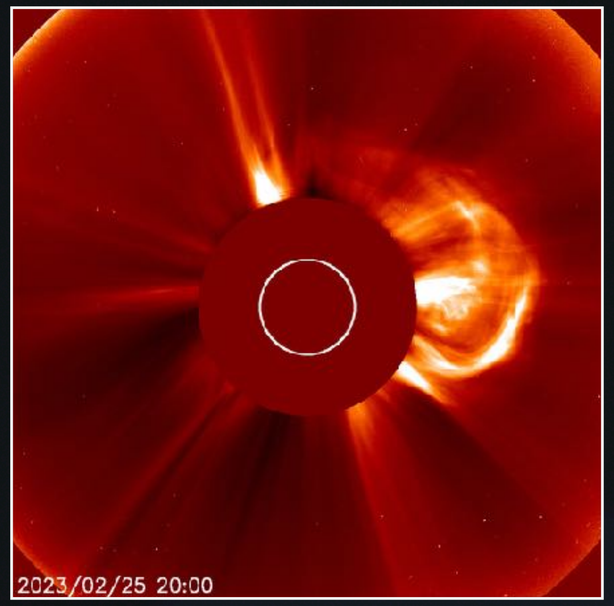
SWPC SOLAR SYNOPTIC ANALYSIS

Phenomena: The Four Pillars of Space Weather



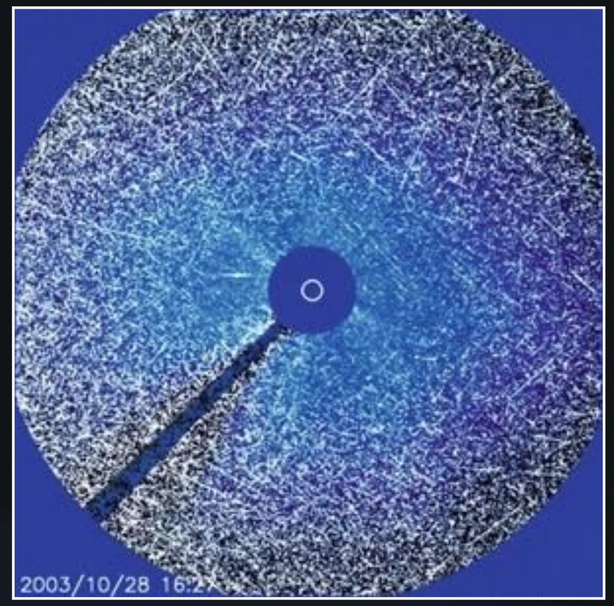
Solar Flares

- Do not cause aurora
- Sometimes have associated CME
- Arrive in 8 minutes
- Cause HF radio blackouts & low frequency navigation issues
- Strength from minor to extreme



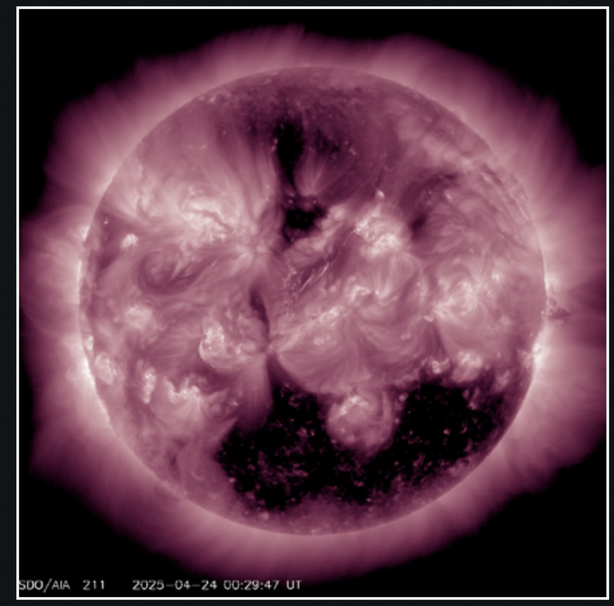
Coronal Mass Ejections

- A prime cause of aurora - but need to be Earth-directed
- Also referred to as Solar Storms
- Arrive in 1-4 days based on speed
- Strength from minor to extreme
- Multiple CMEs can happen and produce days of Aurora



Solar Radiation Storms

- Also called SEPs - Solar Energetic Particle events
- Do not cause aurora
- Cause radio blackouts in the polar regions
- Strength from minor to extreme
- Hazardous to spacecraft, astronauts, airline crew & PAX



Coronal Holes

- A cause of aurora, by enhancing solar wind speed
- Affect Earth in 3-5 days once they turn onto the center disk
- Have either a positive or negative polarity (“SNAP”)
- Most common on the declining phase of the solar cycle

More on Solar Flares

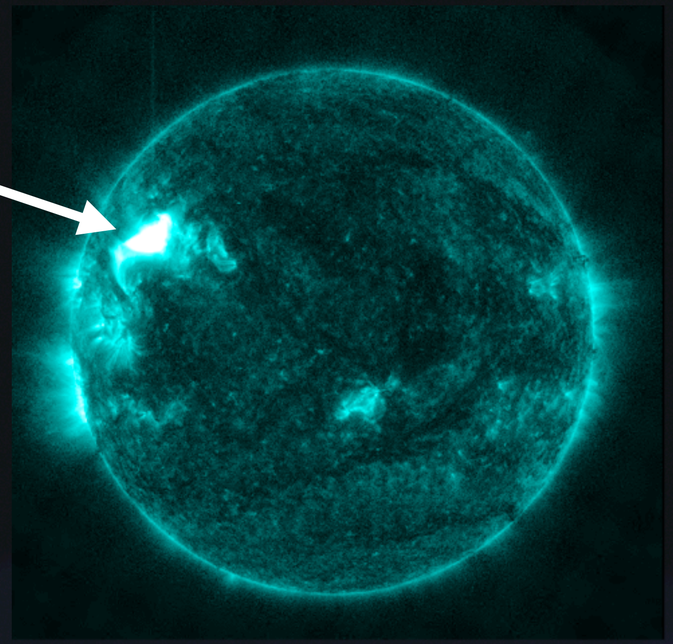
What: Burst of electromagnetic radiation seen in the form of light

When: Arrives at Earth in 8 minutes; can last for hours

Where: Affects Earth's dayside

Why: Ionization of Earth's Ionosphere - specifically the D-Layer

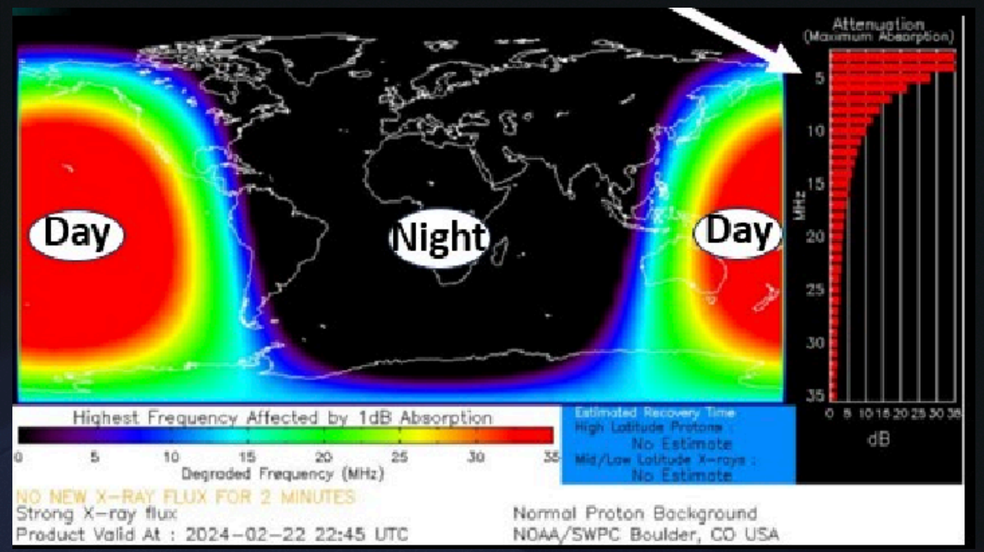
How: Radio coms, primarily HF use the ionosphere to travel & can become degraded or absorbed due to a Radio Blackout on a Scale of 1-5



Scale	Measurement
R5 - Extreme	X20
R4 - Severe	X10
R3 - Strong	X1
R2 - Moderate	M5
R1 - Minor	M1

→Can, but not always, result in a CME

→"D-Rap" Model shows areas & frequencies affected



NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

URL: *www.swpc.noaa.gov/NOAAscales*

April 7, 2011

More on CMEs

Tip: CMEs = Solar Storms

What: Eruption of plasma & charged particles

When: Arrives at Earth in 1-4 days, can last for hours to days

Where: Affects Earth's high & mid-latitude regions

Why: Disturbance to Earth's magnetic field

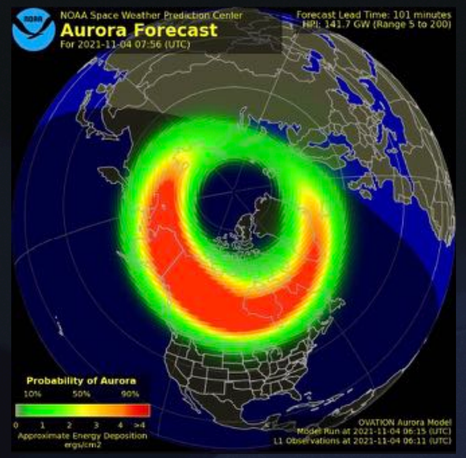
How: Degradation to HF radio coms & GPS signals; disruptions to satellites & power grids due to energy transfer in the environment; & cause Auroras

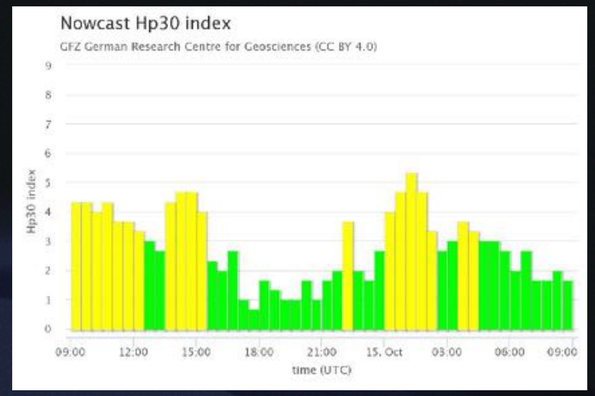
Measurement: Strength based on Geomagnetic Storm Scale of 1-5

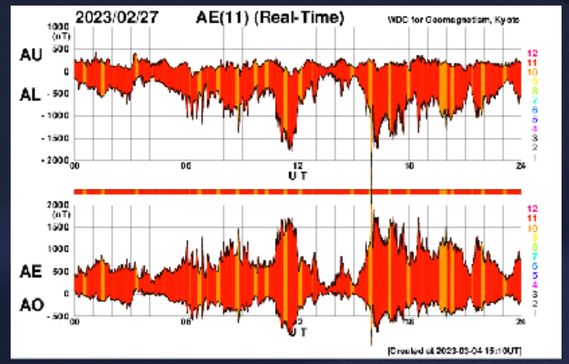
→CMEs can, but not always, be associated w/ a solar flare

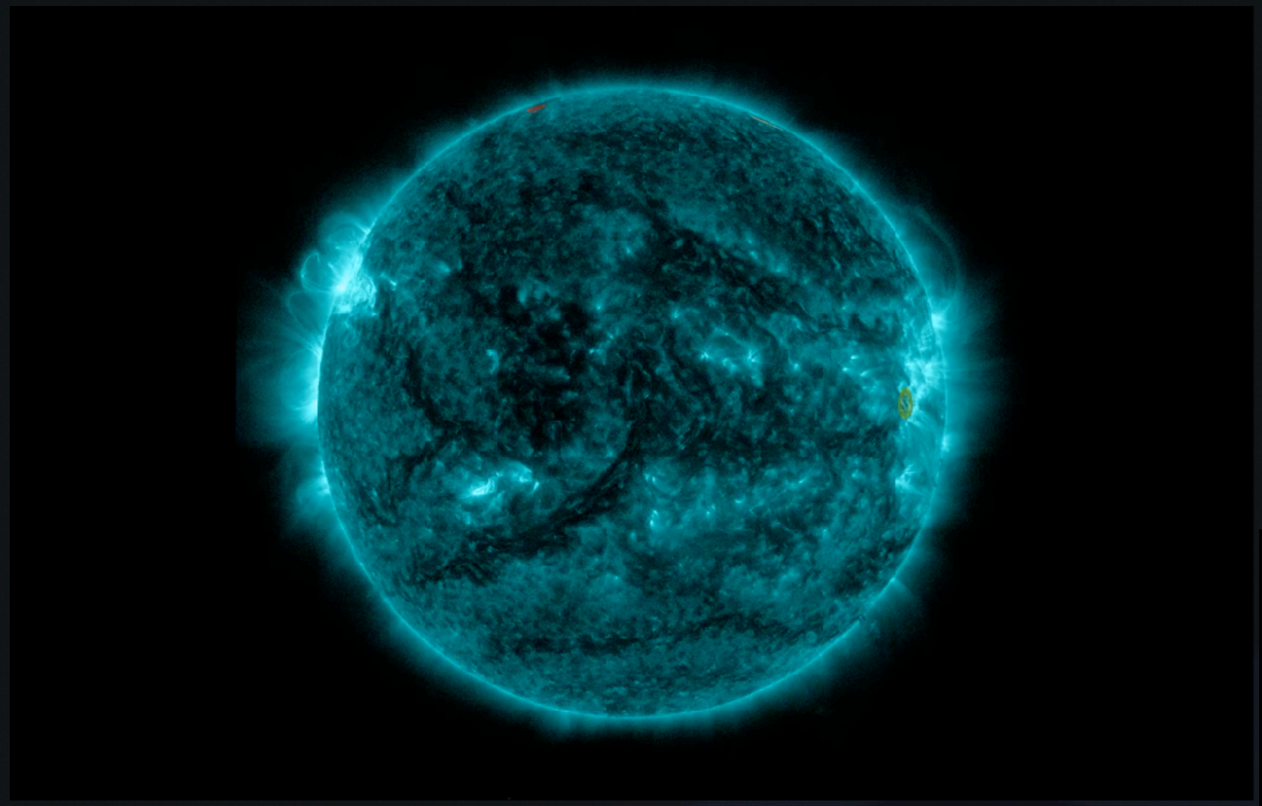
→CMEs must be launched in Earth's direction in order to impact our magnetic field, cause Aurora etc

→Strength of geomagnetic storm from CMEs is measured by ground-based magnetometers

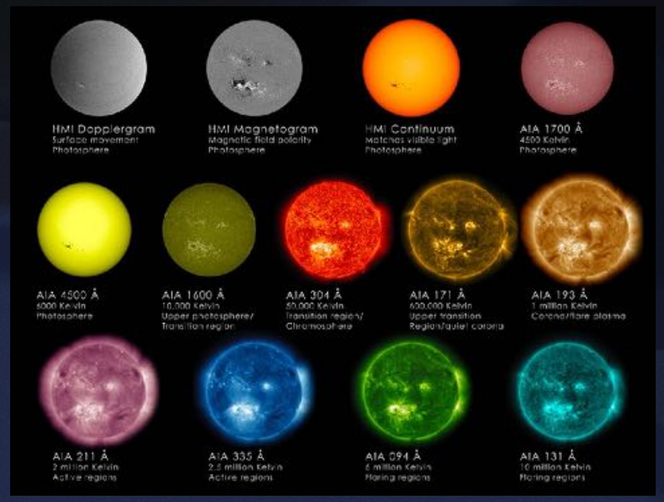


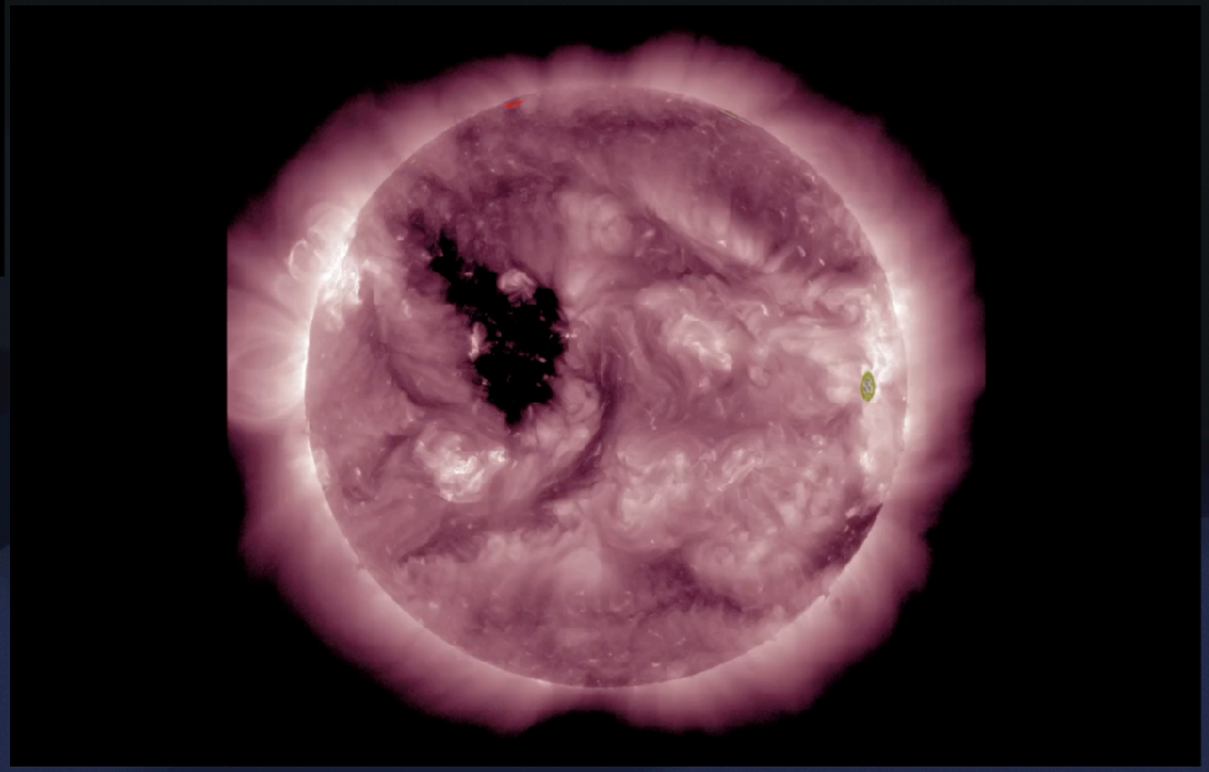




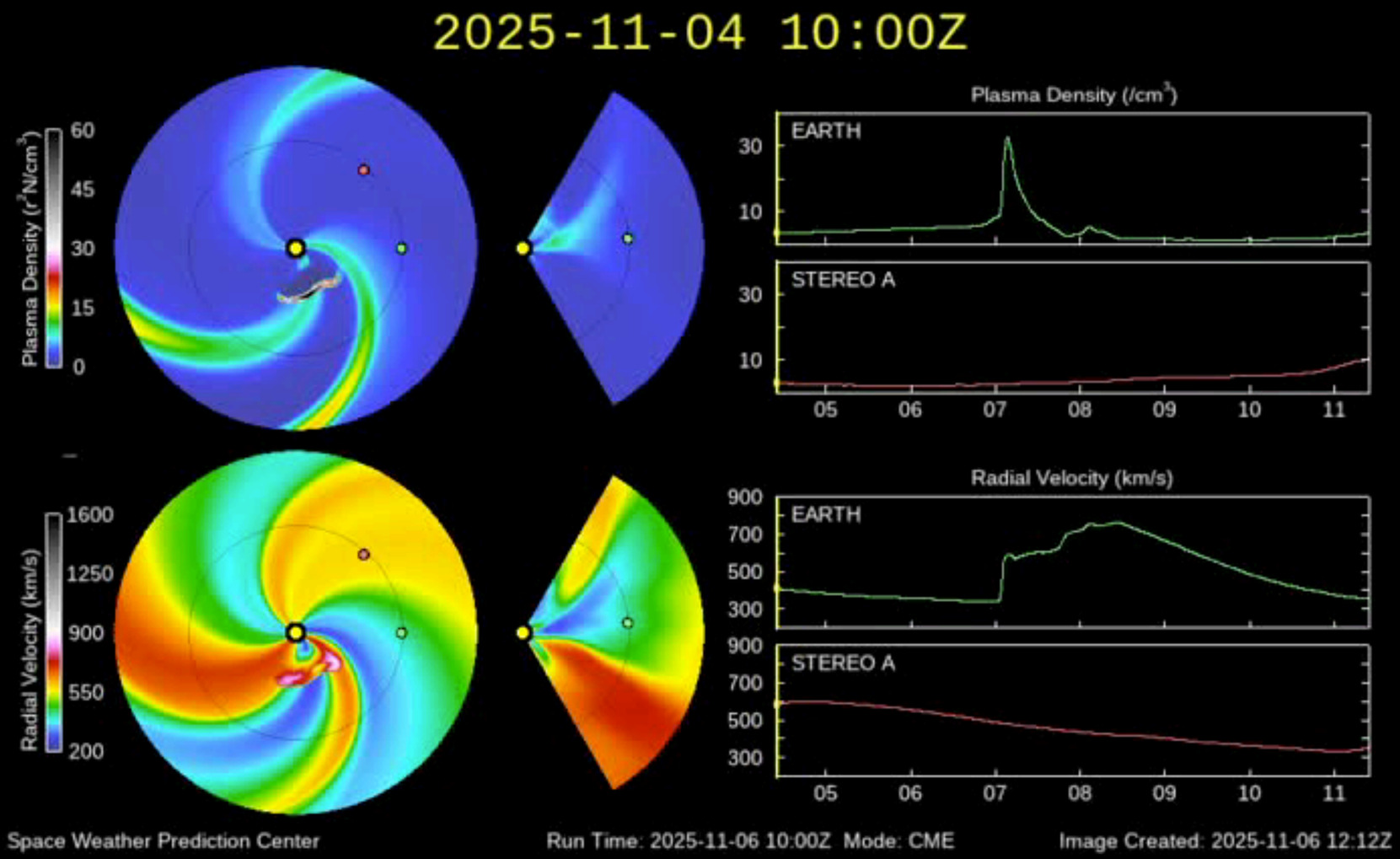


Wavelengths of Light - How Scientists View the Sun - from NASA's Solar Dynamics Observatory (SDO) Spacecraft





ENLIL Model - Visualizing Solar Storms Launched Off the Sun



NOAA Space Weather Scales

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

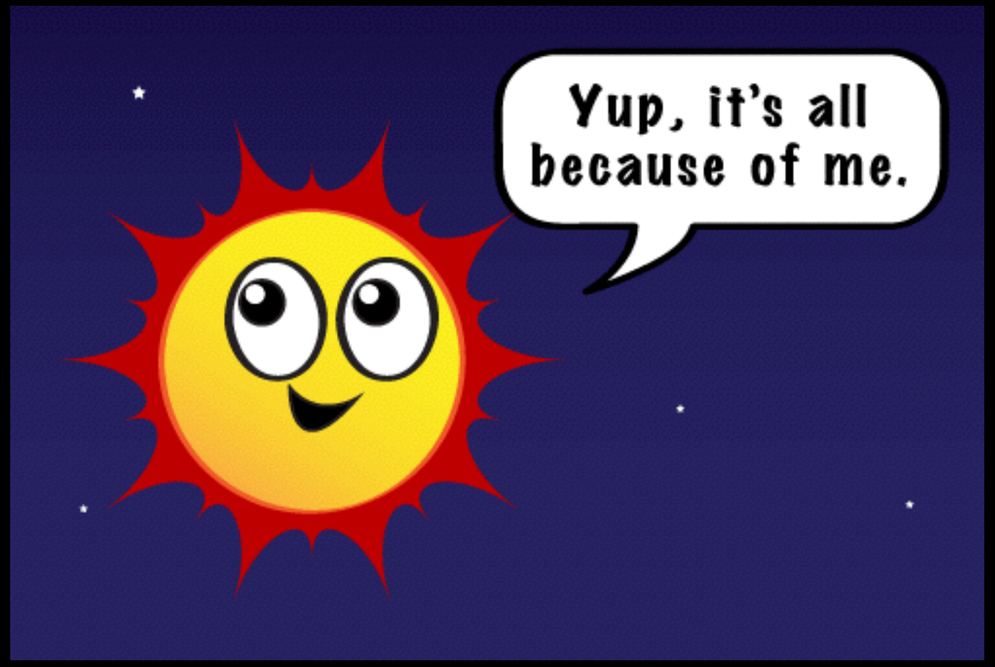
* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.swpc.noaa.gov/Aurora)

Auroras & Forecasting

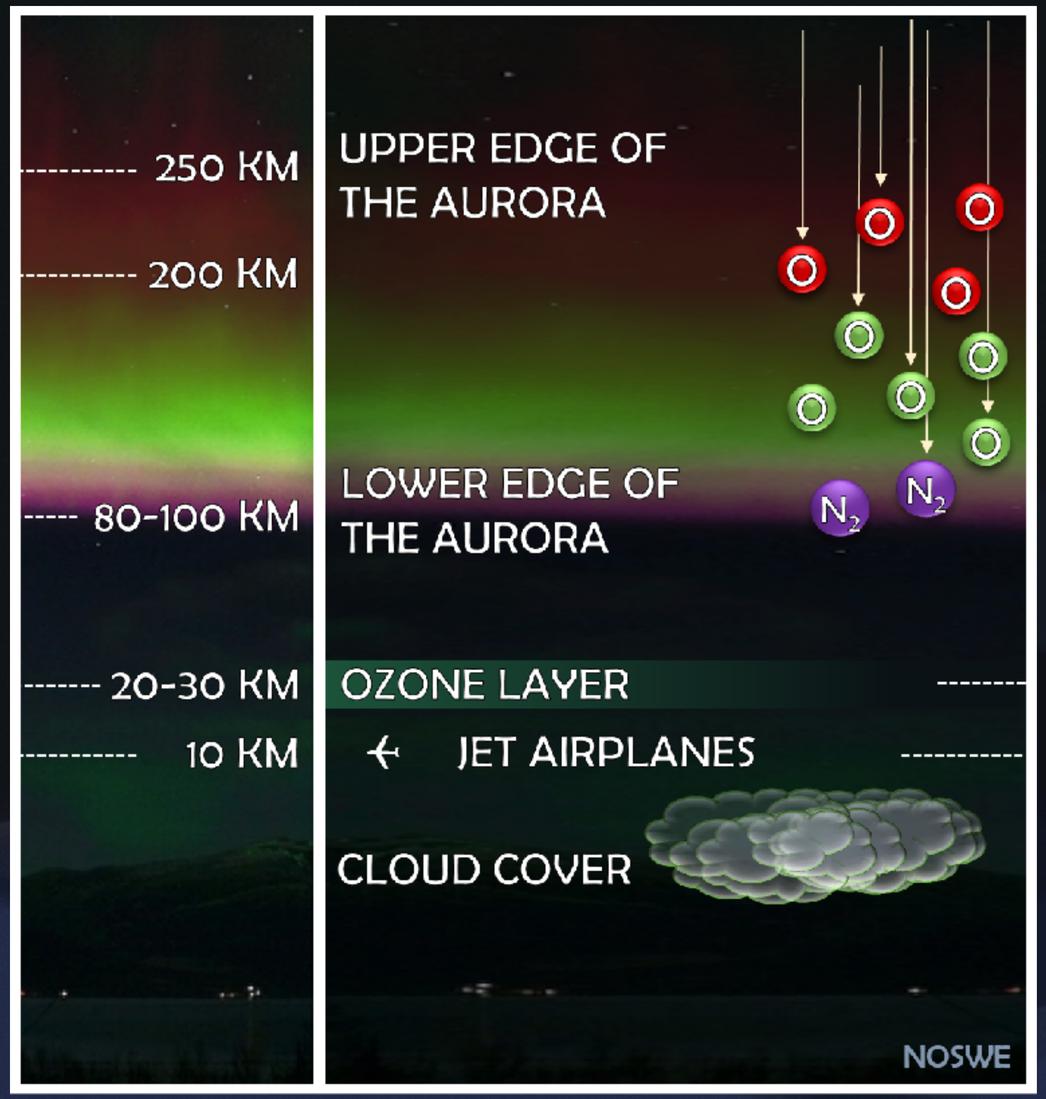
Maine - May 2024 - The “Gannon” Storm

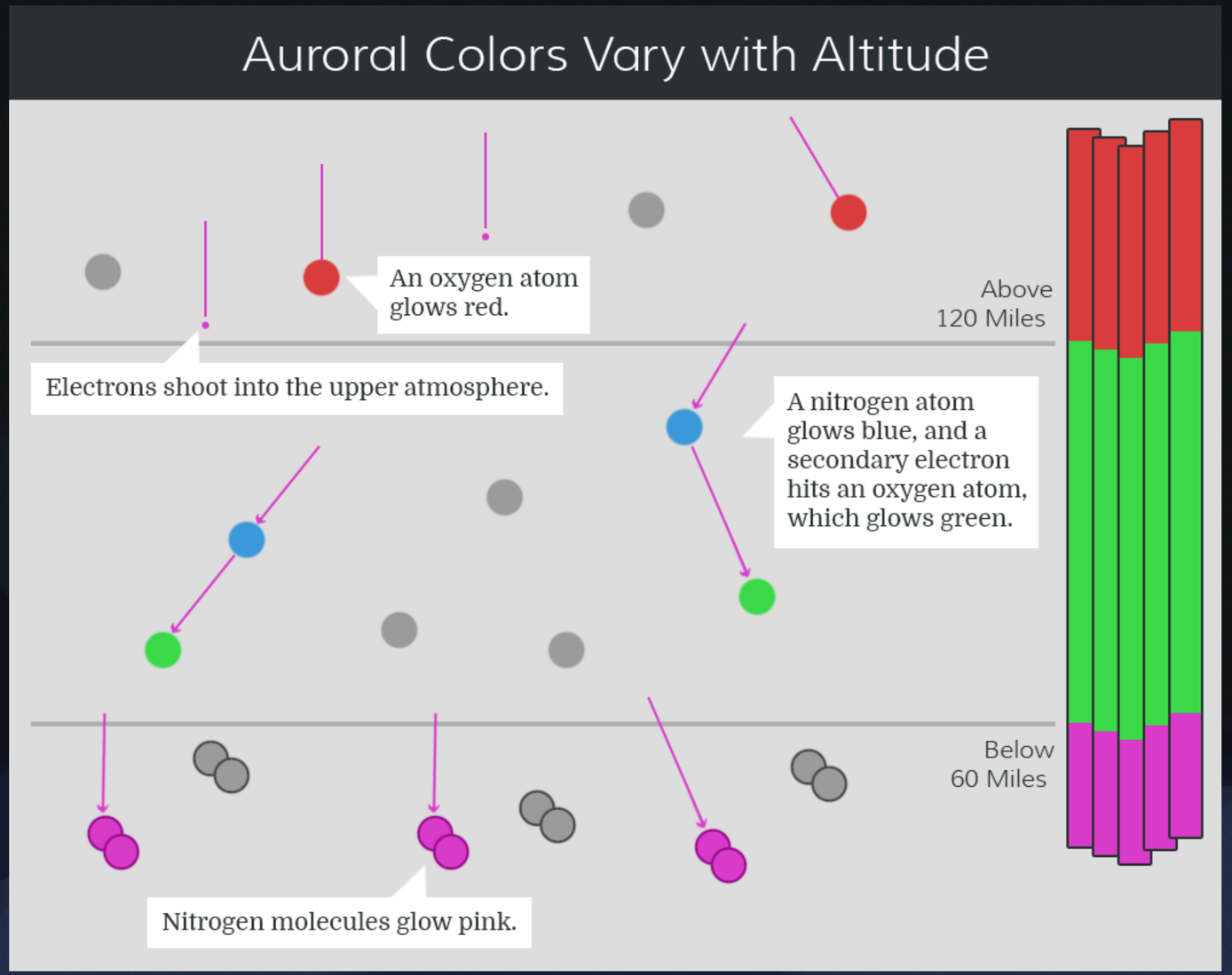
What are Auroras & What Causes Them?



- Beautiful, colored lights that periodically appear in the night sky
- Aurora is caused by chunks of superheated plasma and charged particles that explode off the surface of the sun that sometimes get carried towards Earth by the Solar Wind
- The Solar Wind is always blowing - usually around 400km/hour but can get to over 700 km/hour
- Sometimes those chunks penetrate Earth's Magnetic Shield and interact with gases in our Atmosphere - causing the Aurora colors

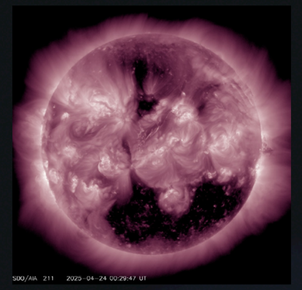
Colors and Location of the Aurora

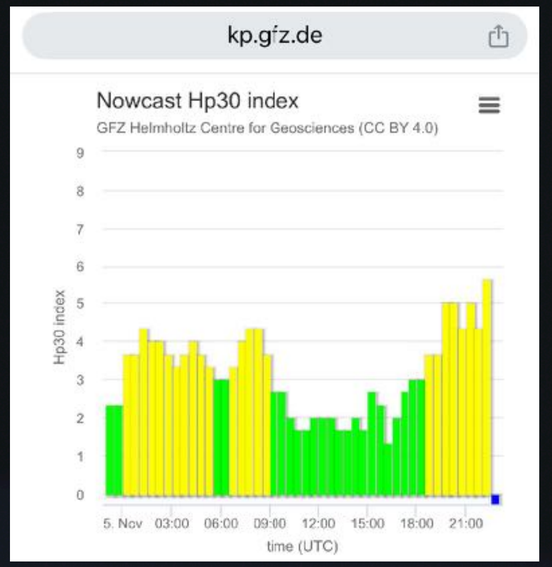


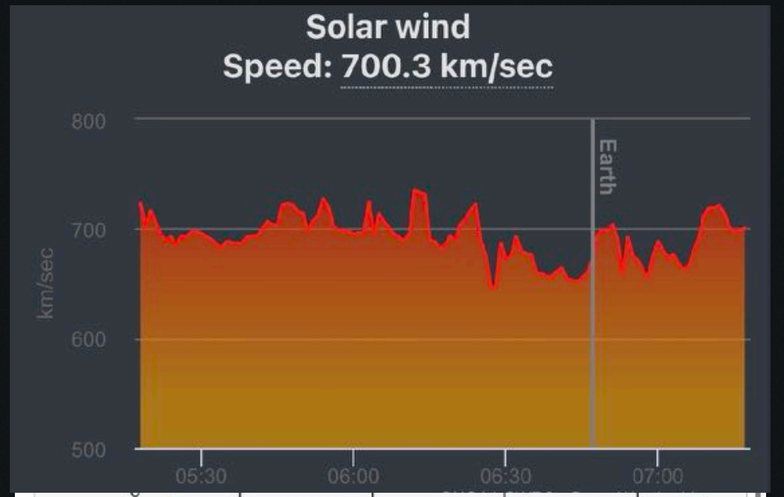


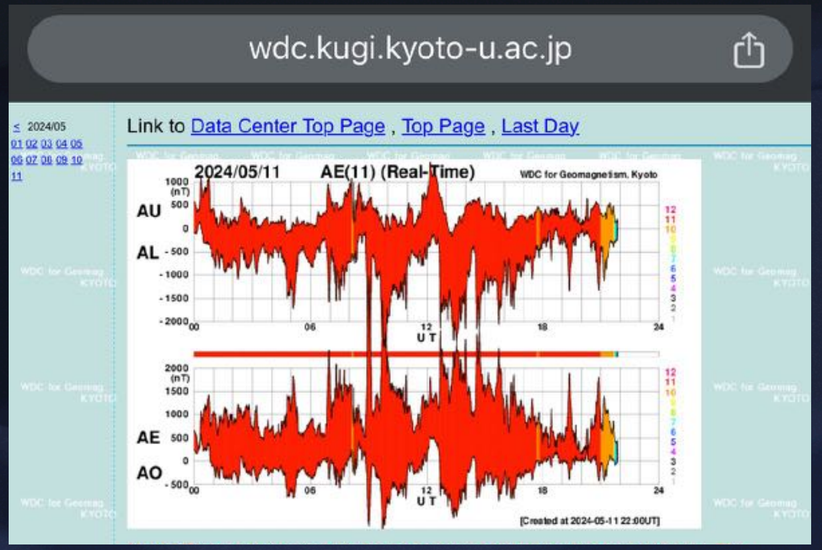
Tips for Aurora Chasers

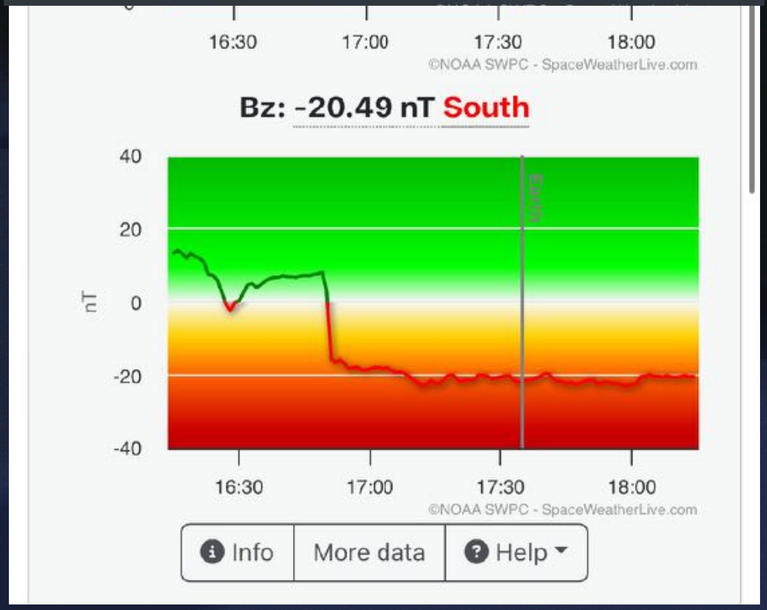
- Sunspot activity and complexity
- CME direction (Need to be Towards Earth) and speed
- Solar flare intensity (M,X Class) & is there an associated CME?
- Coronal hole effects
- Speed of the solar wind
- Bz direction (Want SOUTH)
- Magnetometer Data (Don’t Use KP - Use HP!)
- Monitor Real-Time Sightings on Webcams, Social Media & Aurorasauras





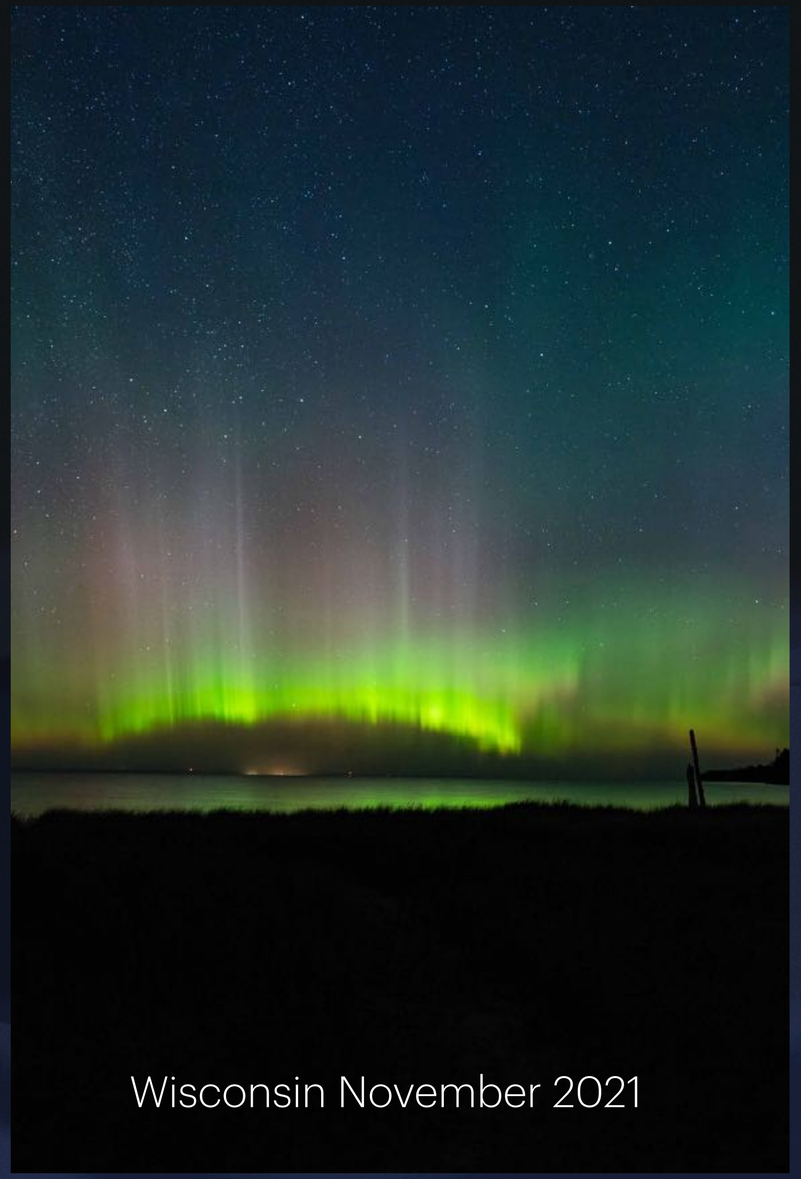






Substorms: The Secret Sauce of Aurora Chasing

Alaska September 2025

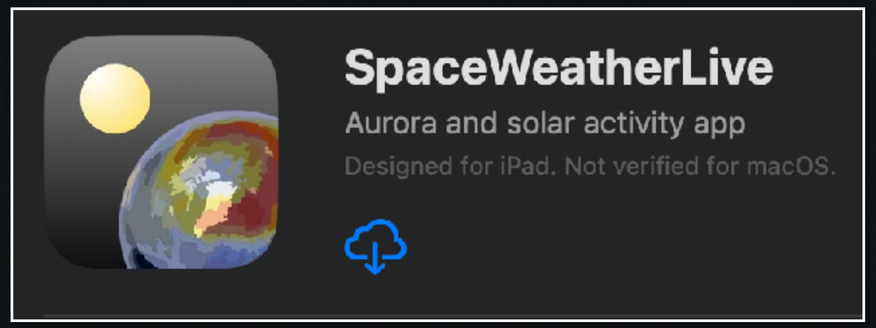


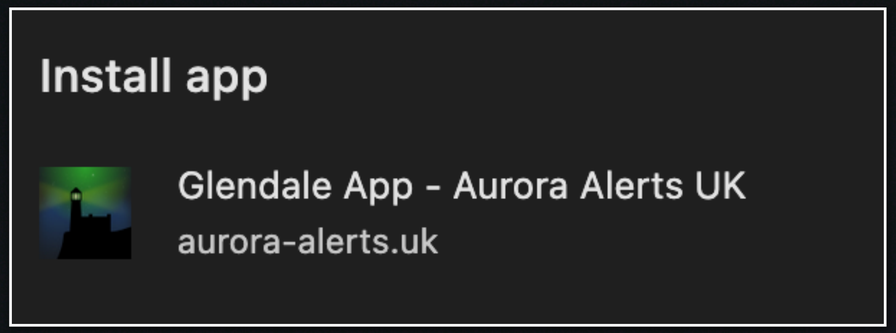
Wisconsin November 2021

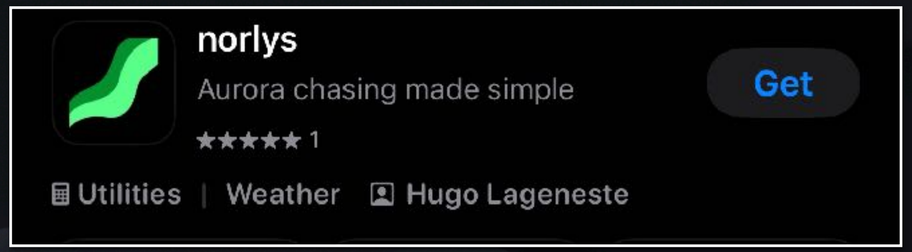
Maine June 2025

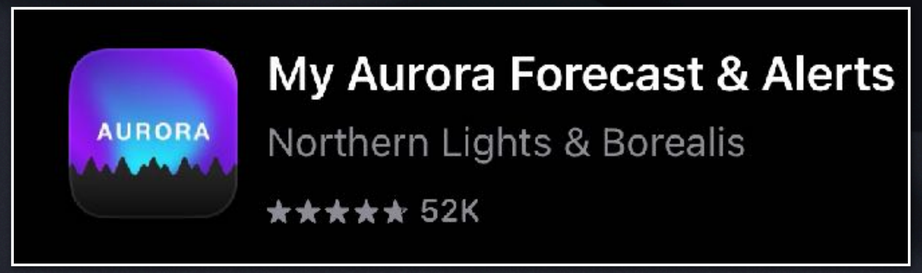
Tools I Use for Planning and Chasing

Washington State September 2022



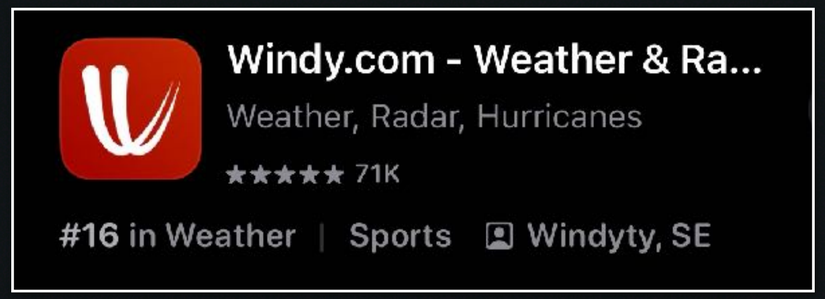


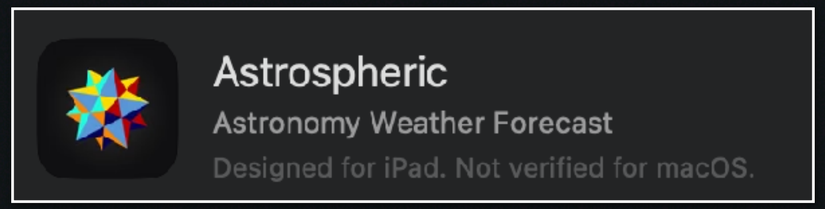


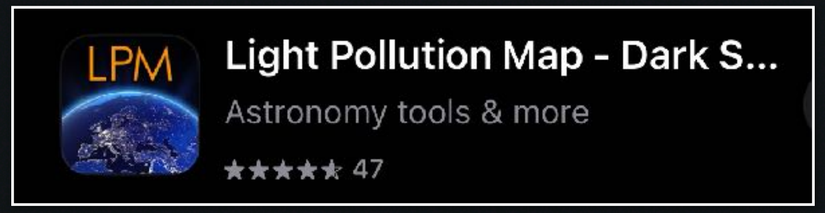


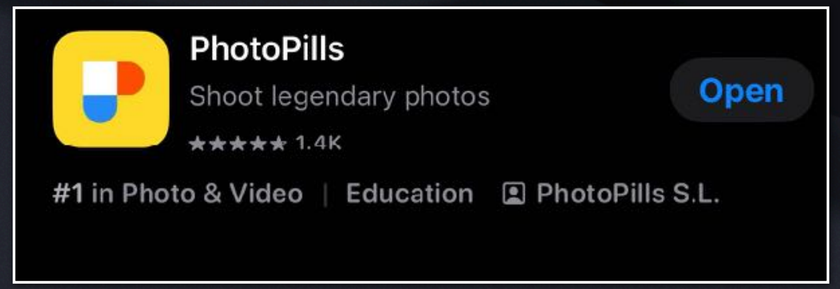
Aurora Apps

- Reality: most Aurora apps aren't reliable
- But, several I recommend:
  - Space Weather Live - best app for space weather data - also a great website with tons of info & historical data (Free & $)
  - Glendale - best app for substorms - go to website to download & install on phone
  - Norlys - Like Glendale, website to download & install on phone. Good graphical interface.
  - My Aurora Forecast - ONLY for their live cameras around the globe







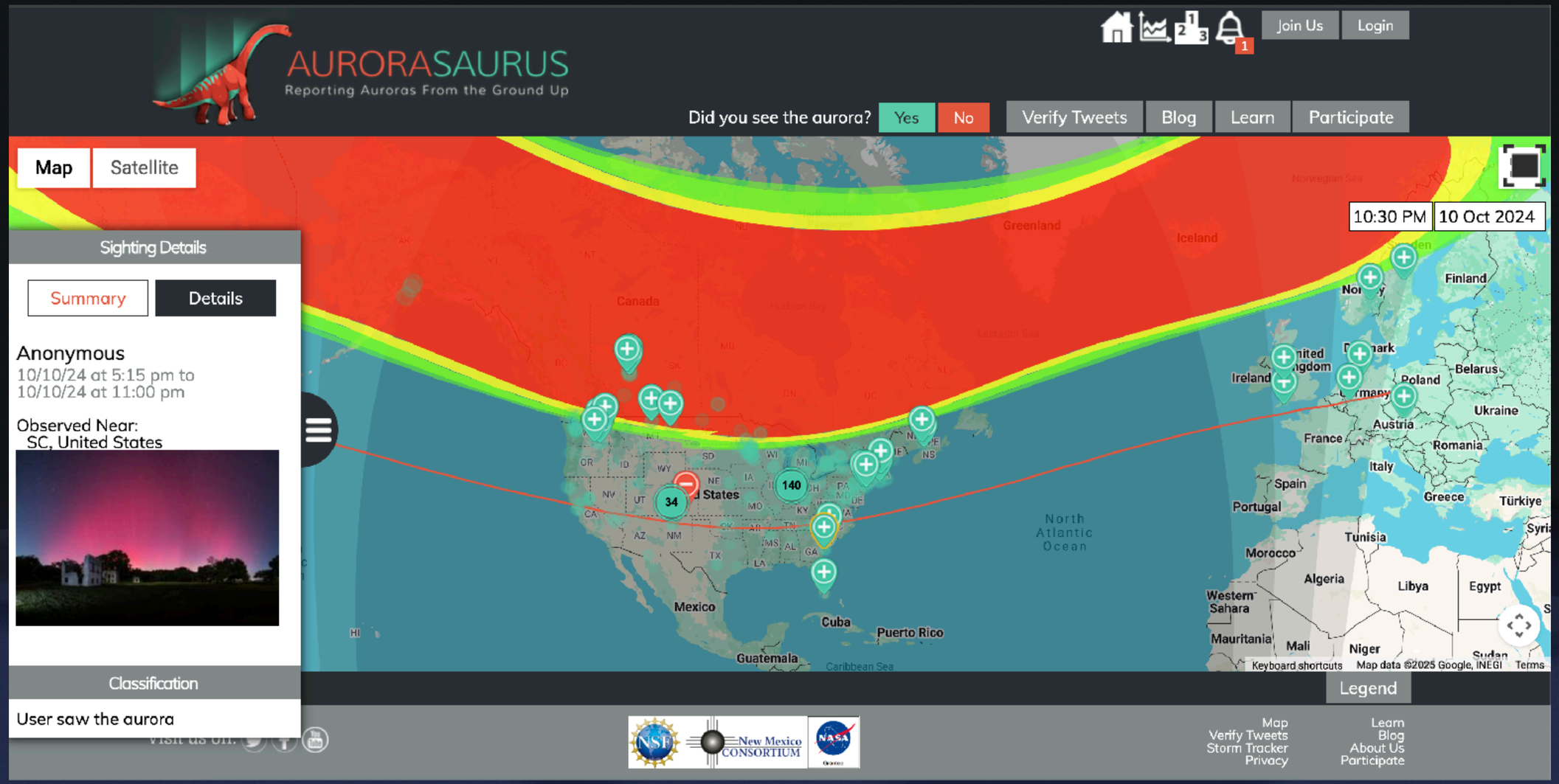


Weather/Cloud/Light Pollution Apps

- These are on my phone & used often:
  - Windy - best app for weather data & maps; highly accurate clouds forecasts (Free & $)
  - Astrospheric - another good cloud (& smoke) app, includes aurora forecast too
  - Light Pollution Map - very helpful for finding dark-sky (and light-polluted) areas
  - Moon Phases & Lunar Calendar - know what phase the moon is for a given date & plan around it
  - PhotoPills - (best photo planning app) - not specifically for Aurora, but has helpful tools including sun, moon & twilight phases & night augmented reality ($)

Aurorasauras

Citizen Science Aurora Reporting Initiative - Great Tool for Aurora Reporting & Sightings

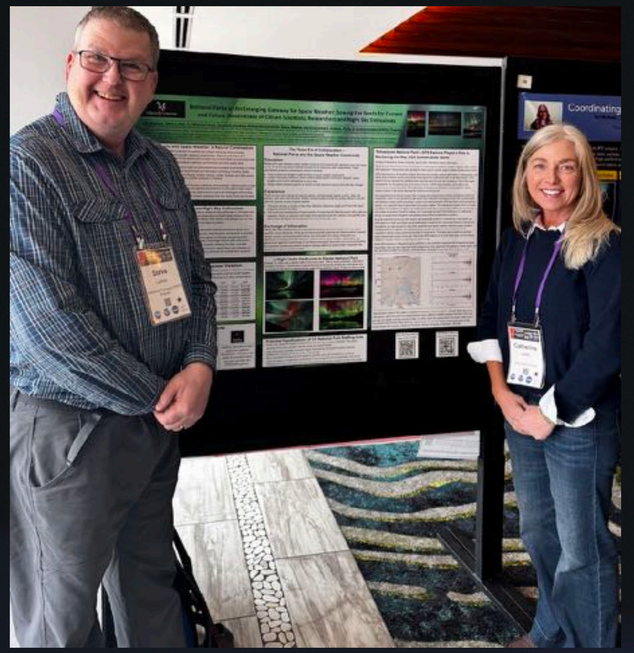


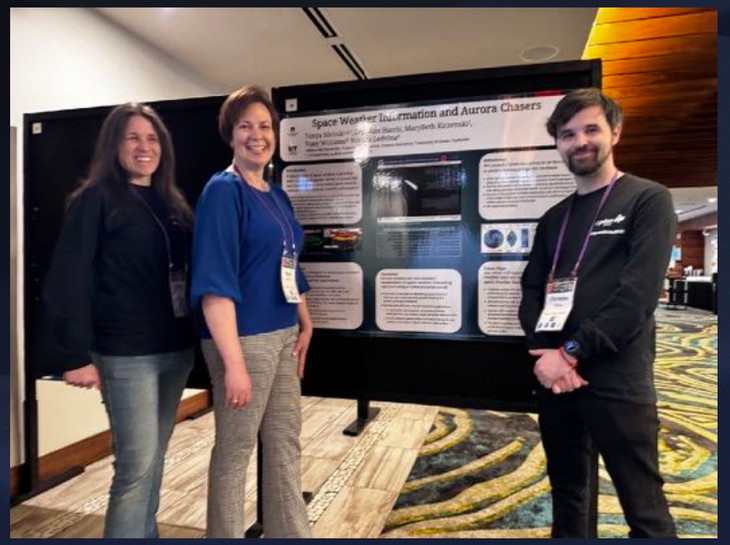
aurorasauras.org

Resources for Further Learning

https://cpaess.ucar.edu/meetings/space-weather-workshop-2025

Annual Space Weather Workshop Week - Open to All - Every Spring, in Boulder, Colorado & Can Attend Online





Thank You!

Stay in Touch

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