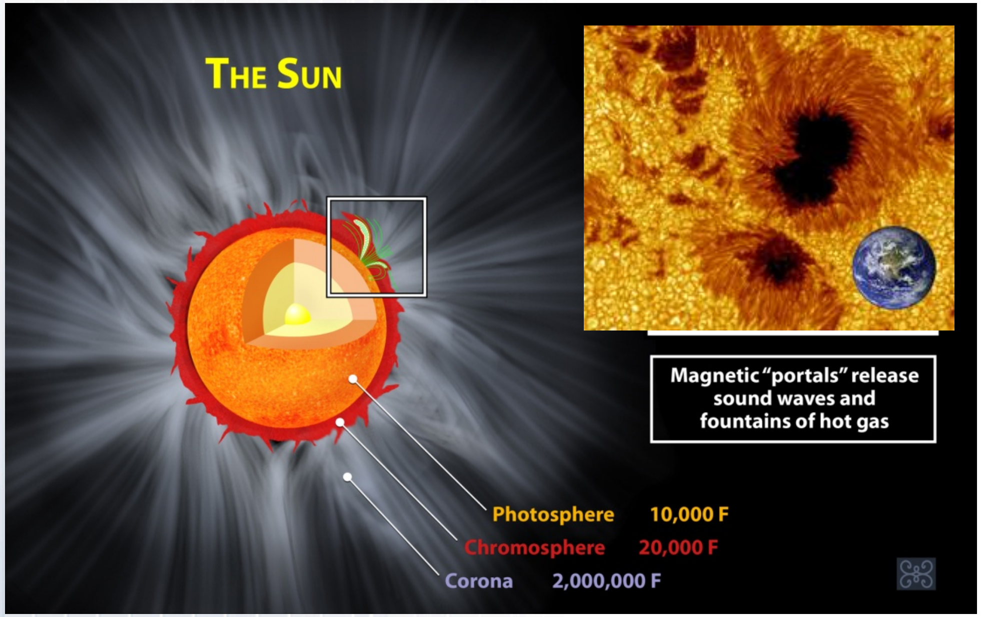
Forecasting the Next Solar Cycle for Radio Propagation: Separating Fact from Myth

Dr. Tamitha Skov

Antenna Forum
Dayton Hamvention & ARRL National Convention
17 May 2019

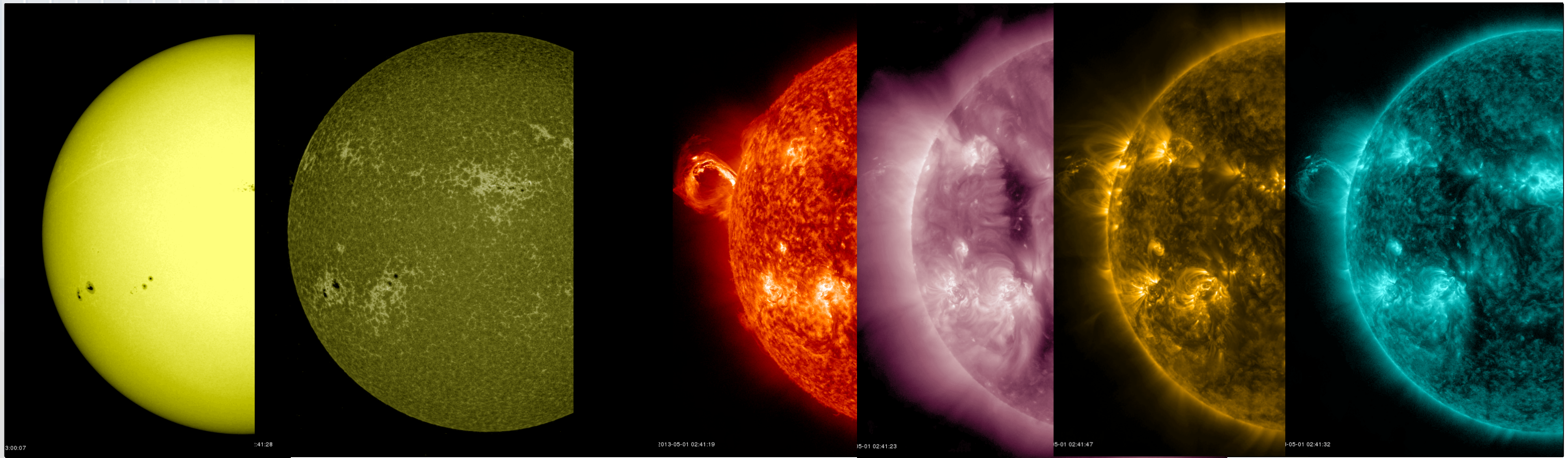
Our Complex Star is Always Changing



- **Giant fusion reactor that drives Space Weather**
- Dynamics are like a lava lamp with energy output as:
  - Electromagnetic radiation (from X-rays through radio waves)
  - Solar Wind (plasma & magnetic field)
  - Solar Flares (radio blackouts)
  - Solar Energetic Particles (SEPs) (a.k.a. solar radiation storms)
  - Coronal Mass Ejections (CMEs) (a.k.a. solar storms)

What do Space Telescopes See?

5700 °C ⟶ 6.3 Million °C

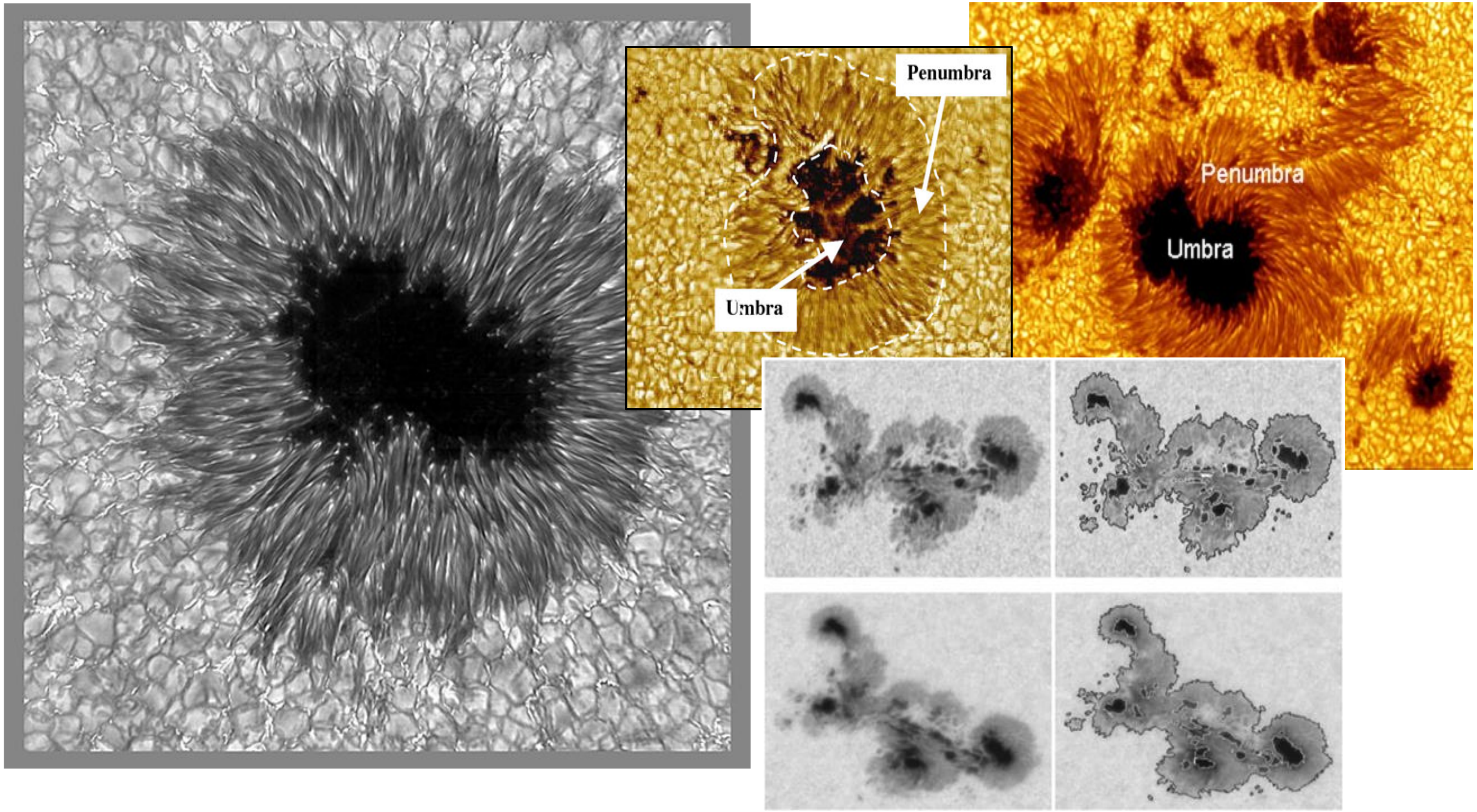


What are Sunspots & Why Do They Form?

Sunspot Umbra: the dark core of a sunspot, cooler than the surrounding photosphere because is suppresses convection. Average size is ~10000 km, but can be as large as 60000 km.

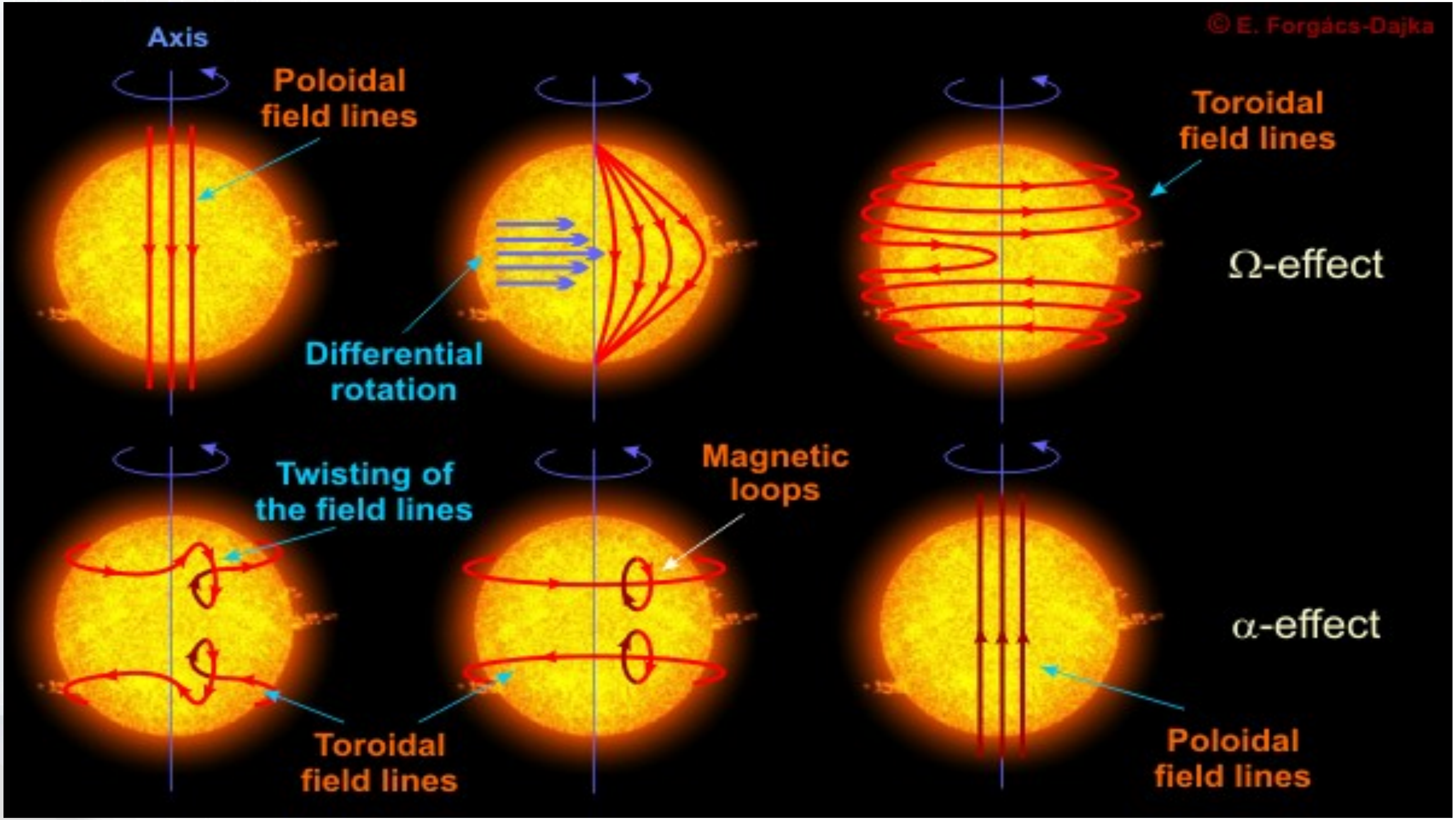
Sunspot Penumbra: the lighter areas, marked by a radial filamentary structure. Typical size is ~5000 km. Waves are observed to move across the penumbral structures. Structure is thought to be 'uncombed'.

Image credit: Friedrich Woeger, KIS, and Chris Berst and Mark Komsa - taken here at the Dunn Tower.



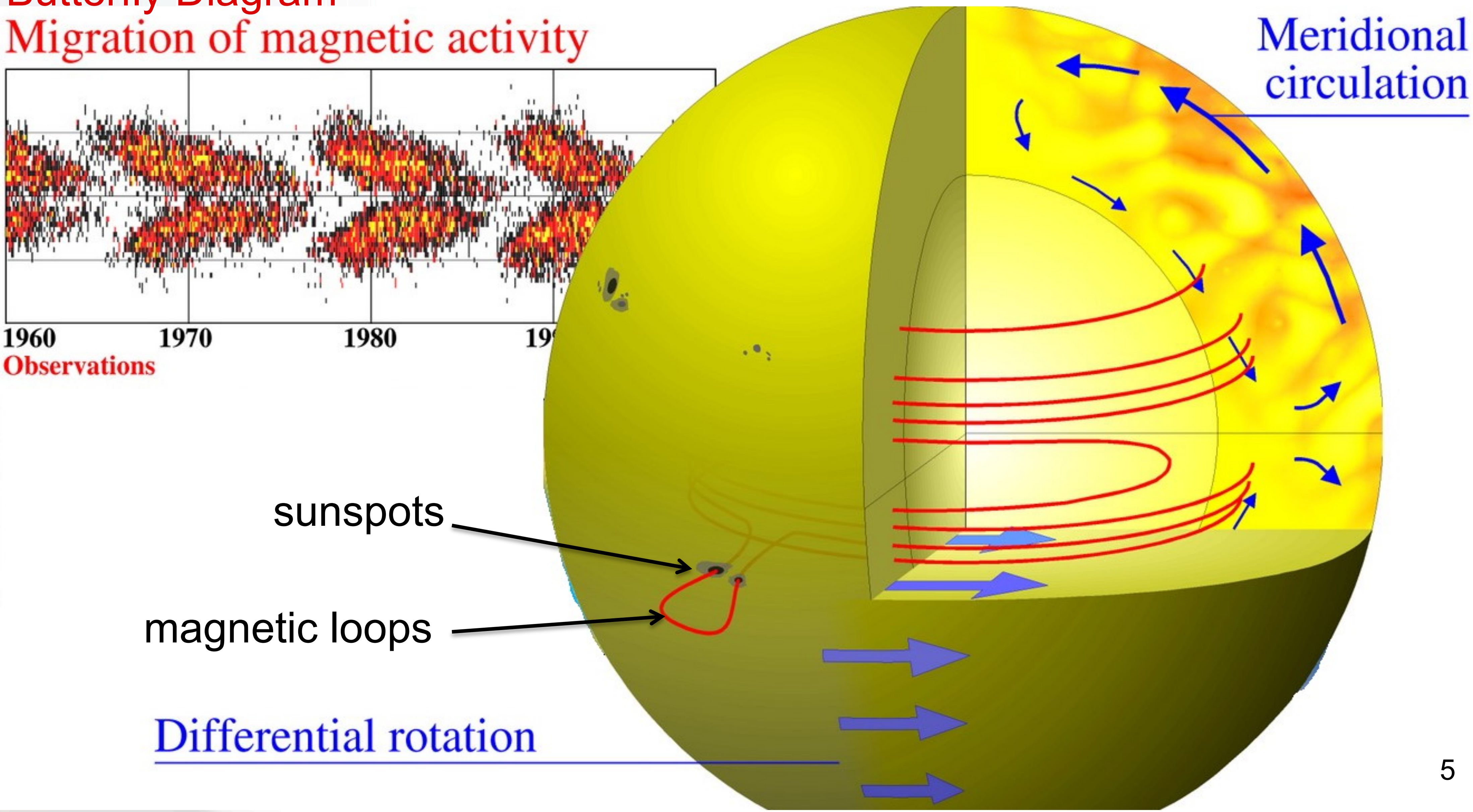
L. Győri et al, 2016

Its All Part of the Solar Dynamo

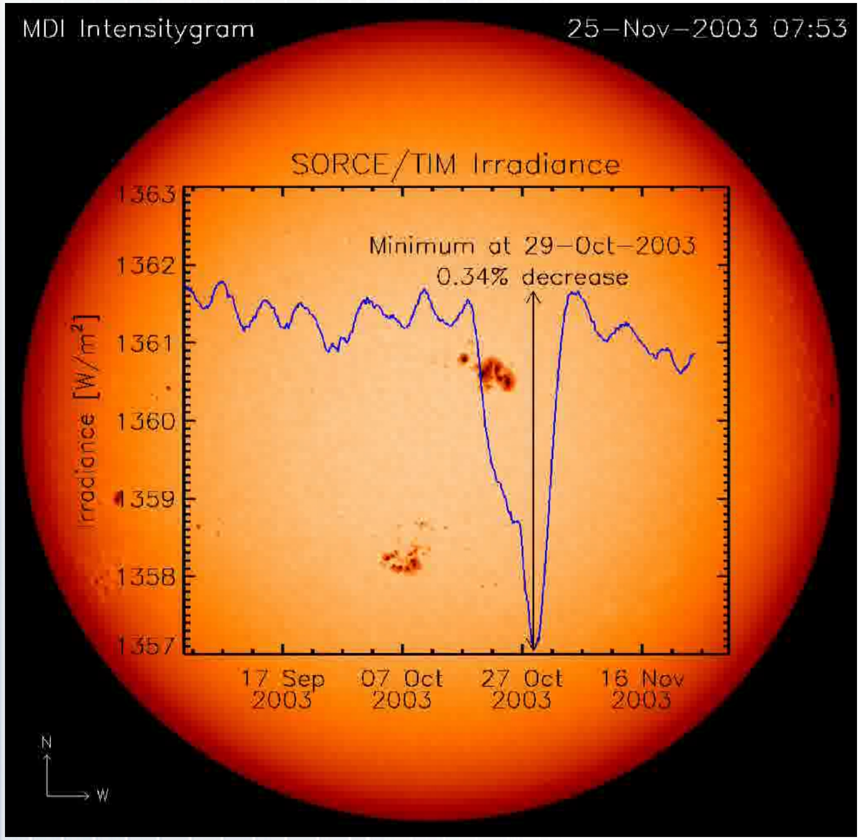

© E. Forgács-Dajka

Putting the Picture Together

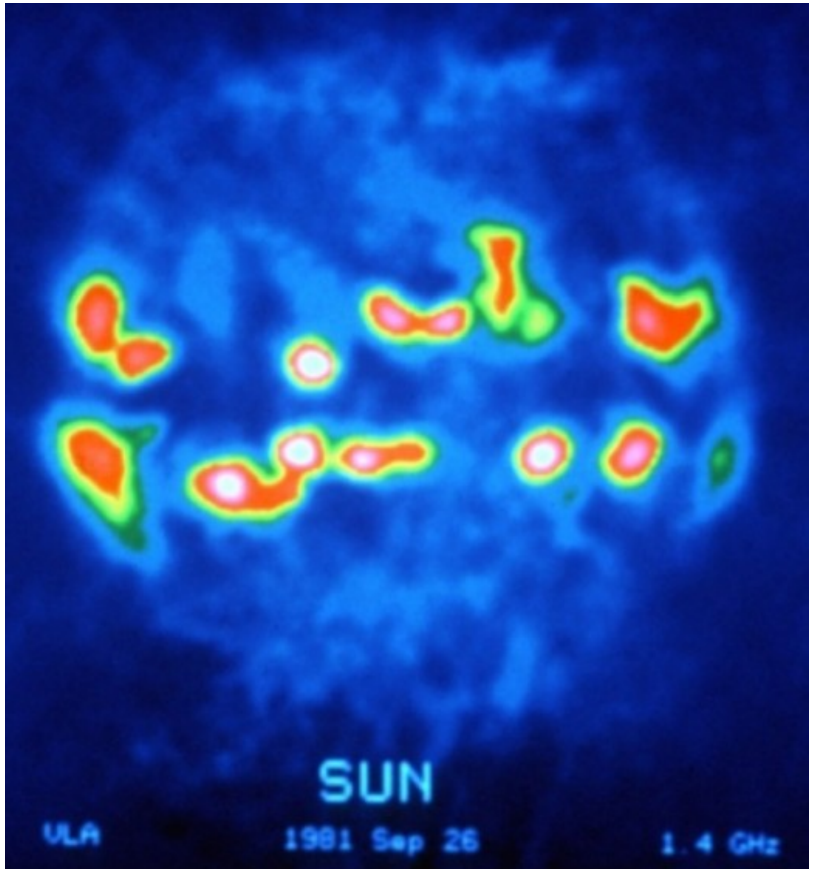
Butterfly Diagram



Sunspots are Visibly Dark but Radio Loud



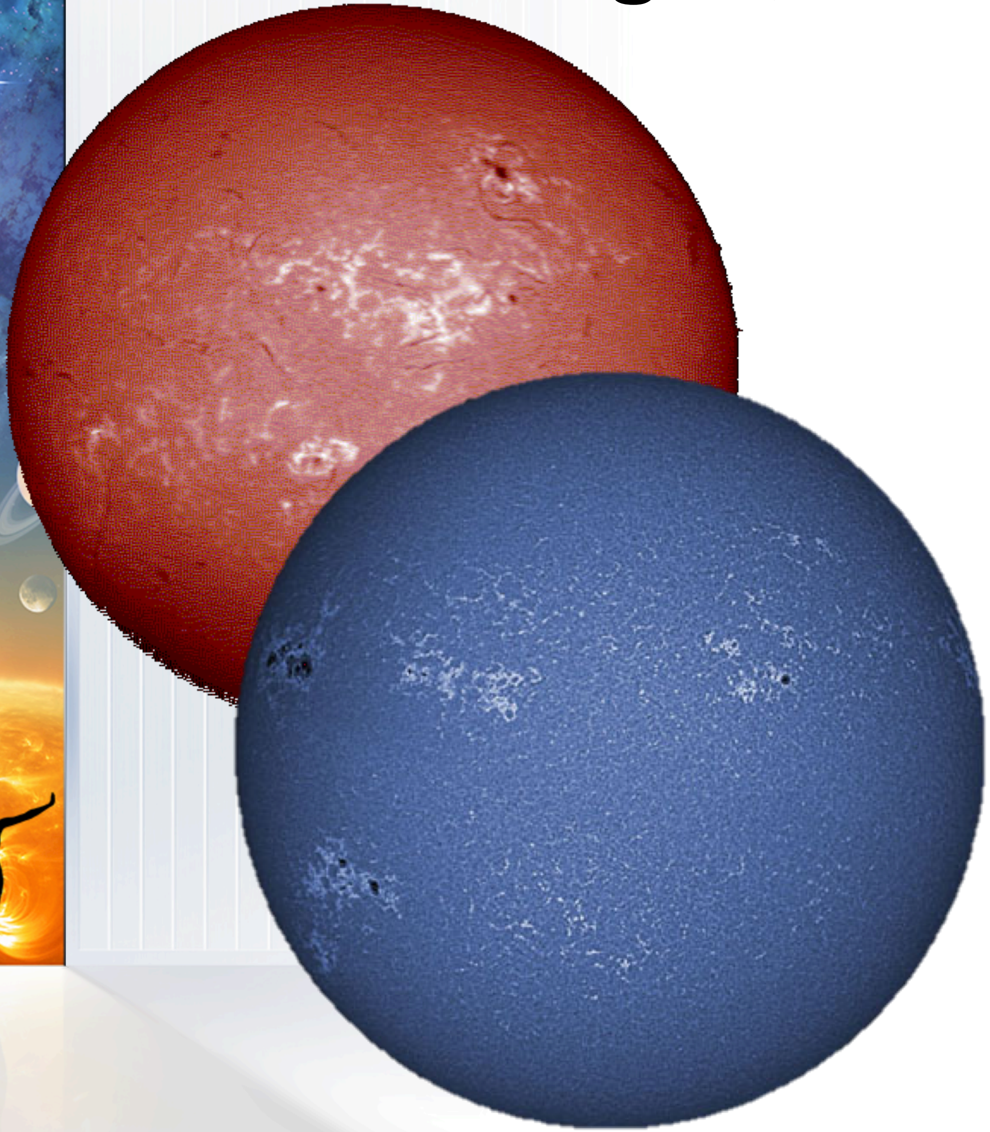
A sunspot group in 2003, observed by the Total Irradiance Monitor (TIM) radiometer on the SORCE satellite caused irradiance to drop by 0.34%.

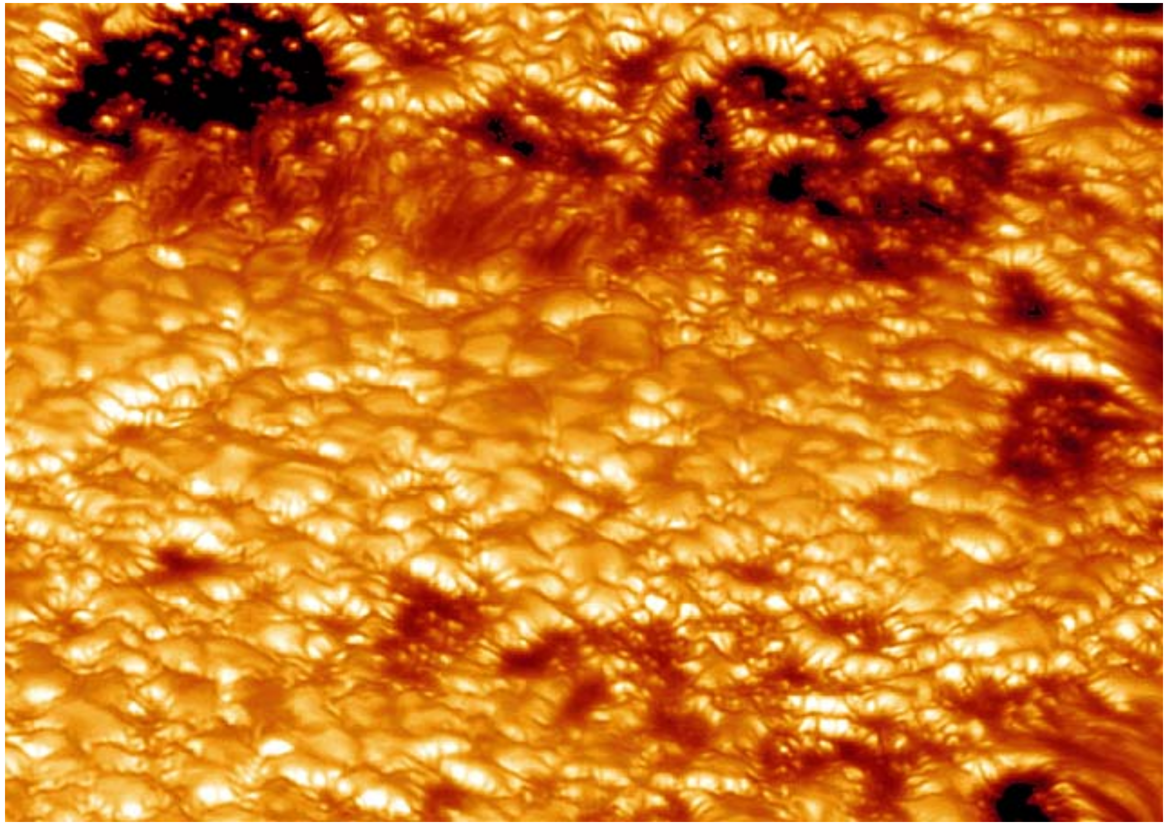


This 14 GHz image of the Sun by the Very Large Array (VLA) radio telescope shows the highest intensity radio waves come from a similar location as sun spots

TRACE showing a 8 GHz radio source directly above this sunspot on the limb

The Hidden Source of Solar Flux: Plages, Faculae, & Bright Points

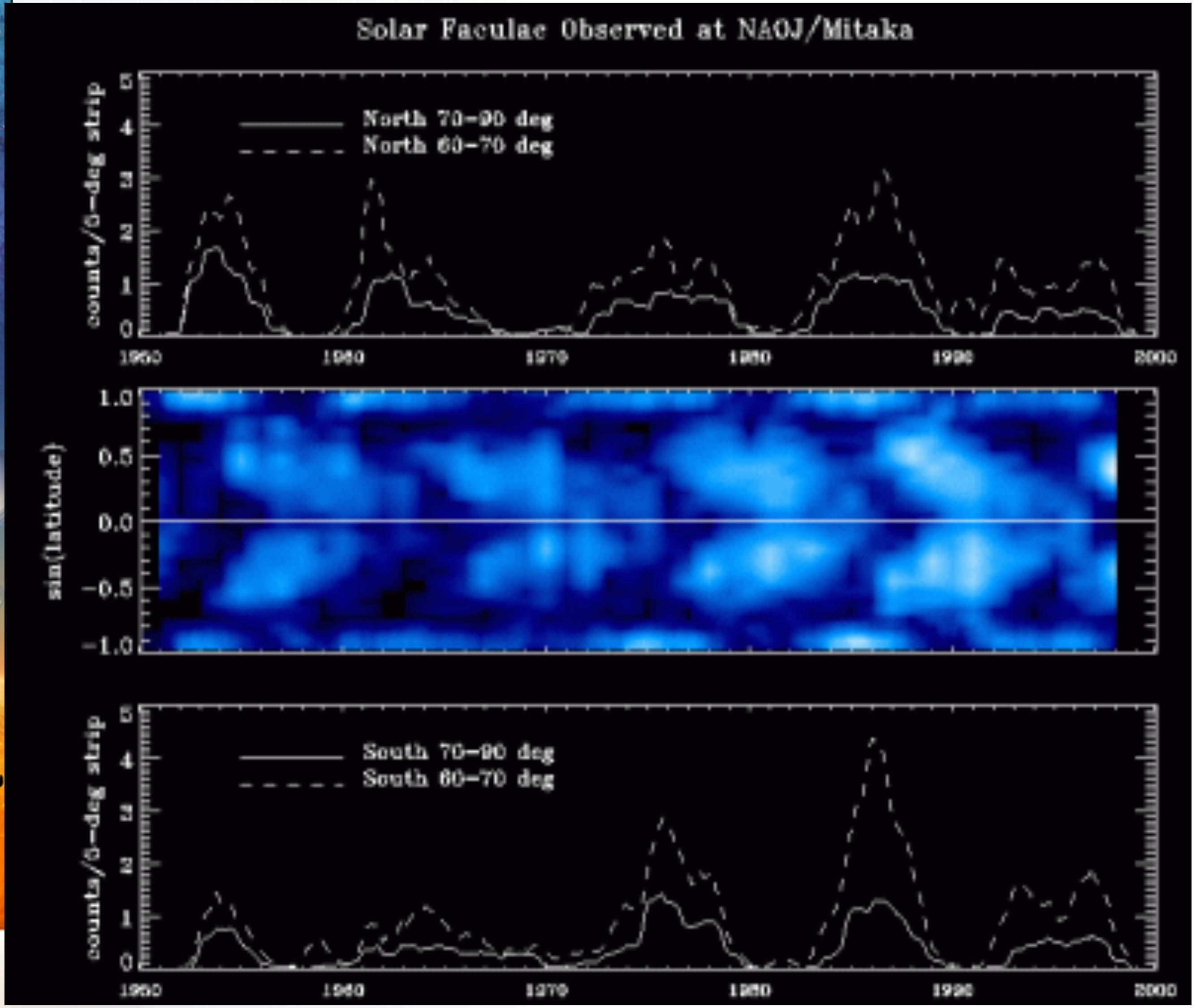




Individual faculae are bright spots on the walls of solar granules, the cells of hot plasma that bubble up to the Sun's surface from the convection zone.

Goran Scharmer / Royal Swedish Academy of Sciences

A Different Kind of Butterfly Diagram

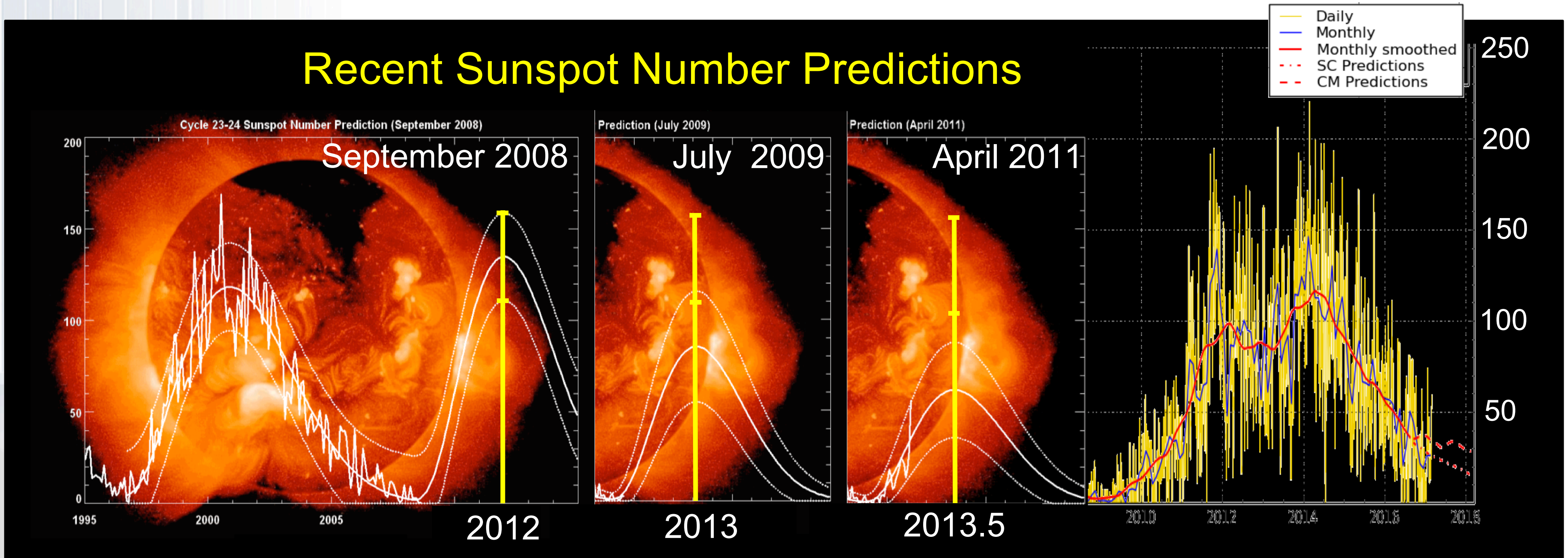


- Many but not all faculae are small bright patches seen around sunspots
- They exhibit a similar latitude distribution over time as sunspots (e.g. “The Butterfly Diagram”)
- These faculae can also be used to determine solar cycle variability
- Note that another kind of faculae appear in the polar regions of the Butterfly diagram
- These 'polar faculae’ are most numerous at the minimum of sunspot activity

https://solarwww.mtk.nao.ac.jp/en/db_faculae.html

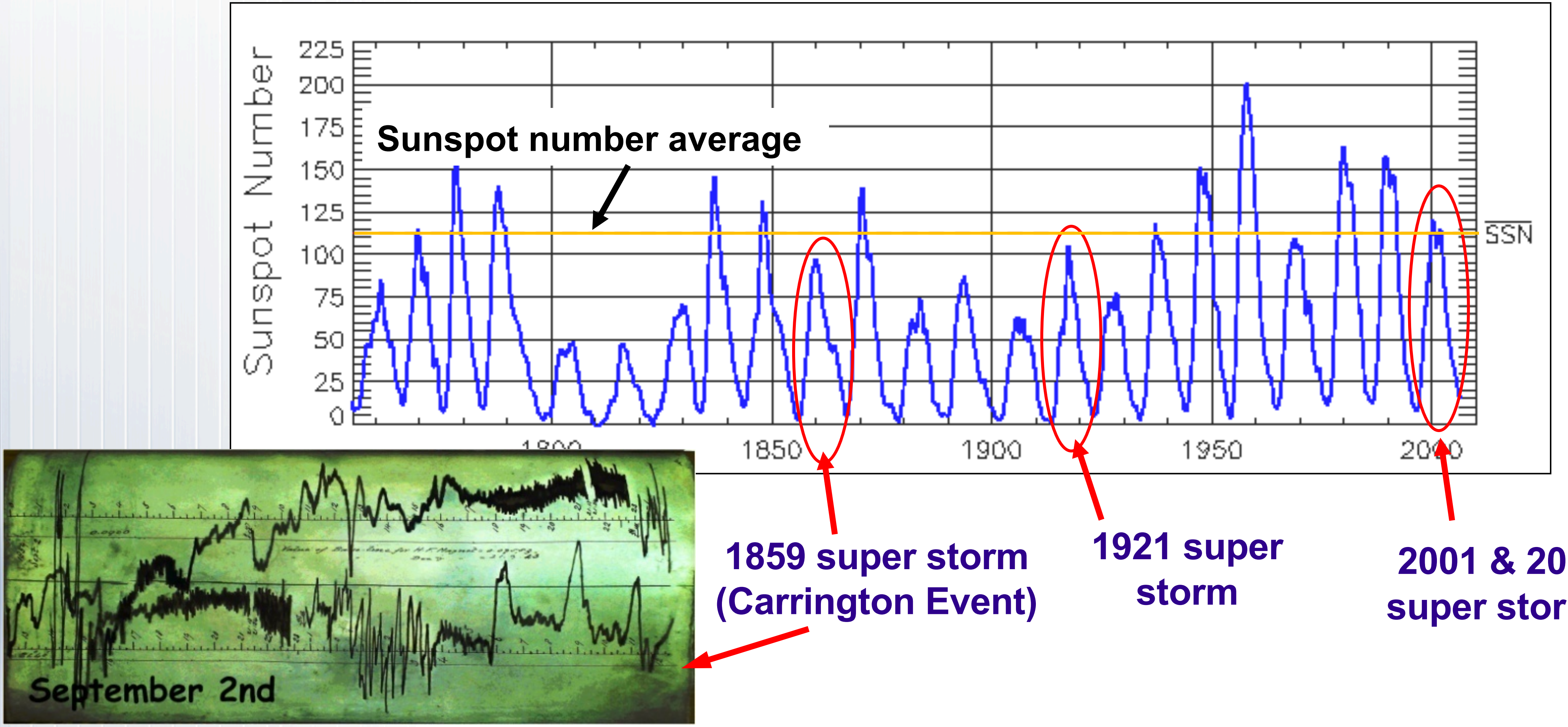
Solar Cycle 24: Where Are We Now?

- Recent solar cycles (since cycle 22) are showing dramatic changes, making predictions more complicated
- Consensus is we are not dipping into another Maunder Minimum
  - Cycle is slower, lower luminosity, lower activity at maximum, consistent with the “downward trend” exhibited since the activity “peak” in Cycle 22
  - Current weaker magnetic field strength also means higher cosmic ray flux through this minimum phase (which enhances radio propagation slightly)
  - Minimum in 2019-2020 difficult to predict due to hemispheric asymmetry
  - Evidence there is a higher probability of extreme events during these weaker cycles



Recent Sunspot Number Predictions

Dispelling Myths: Big Activity Can Occur During Small Solar Cycles!



1859 super storm (Carrington Event)

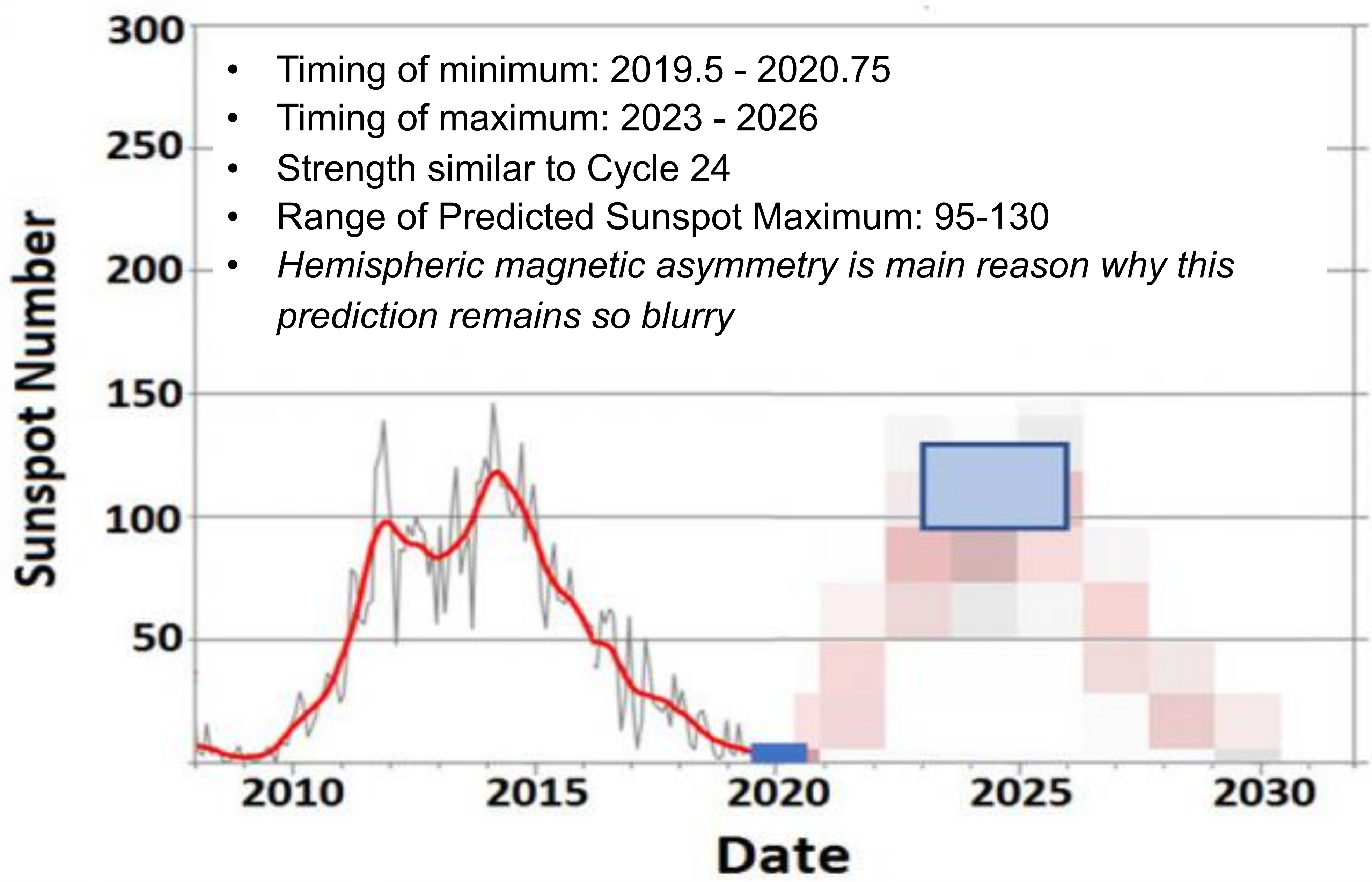
1921 super storm

2001 & 2003 super storms

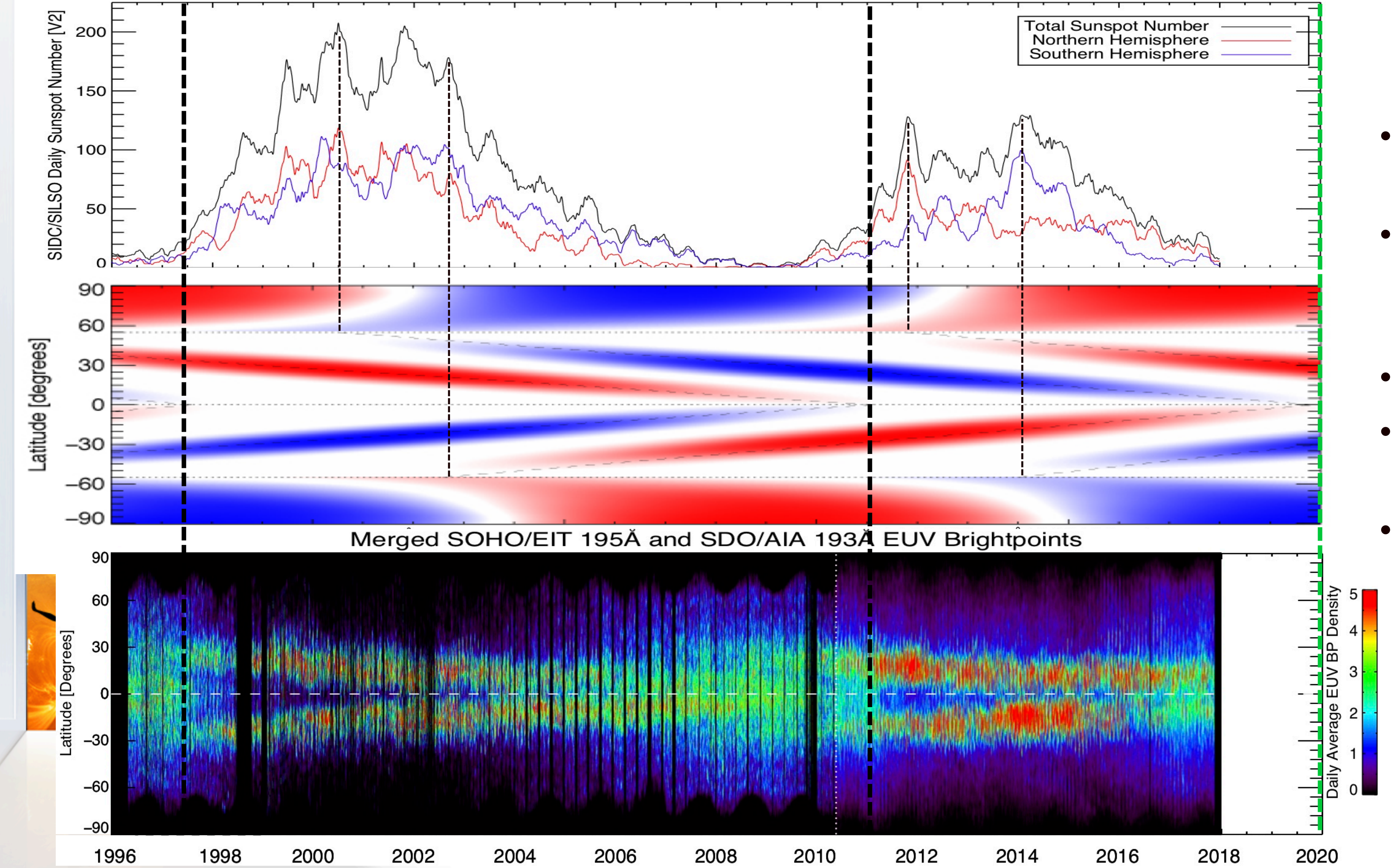
- Most of the largest geomagnetic storms on record occurred during smaller than average or average cycles like the one we are in now
- We saw several Carrington-class events in Cycle 24 (none directly hit Earth)

NOAA/SWPC Official Cycle 25 Prediction Remains Blurry

- Timing of minimum: 2019.5 - 2020.75
- Timing of maximum: 2023 - 2026
- Strength similar to Cycle 24
- Range of Predicted Sunspot Maximum: 95-130
- *Hemispheric magnetic asymmetry is main reason why this prediction remains so blurry*



Solar Cycle 24: Really, Where Are We Now?



Terminator
cycle 22/23

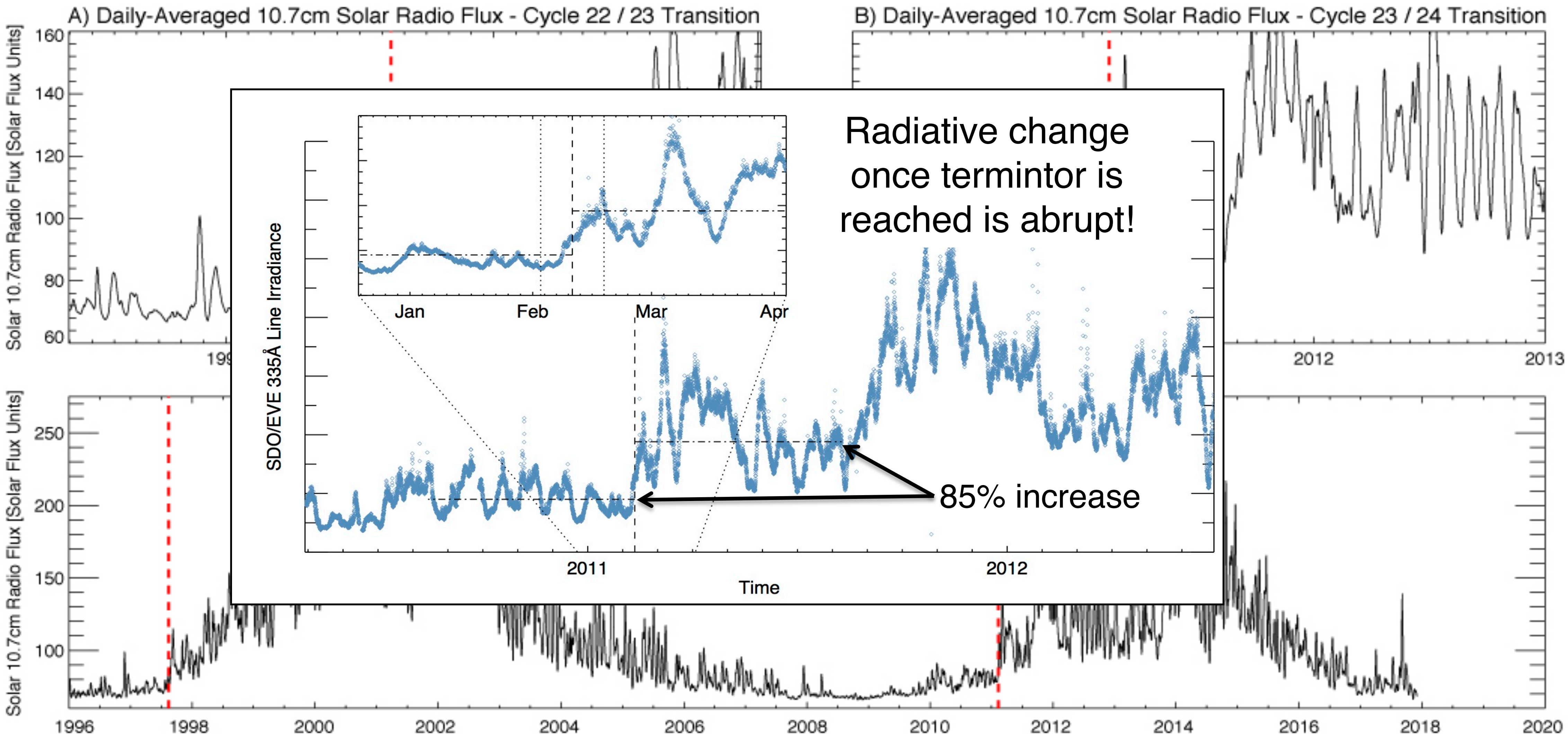
Terminator
cycle 23/24

Terminator
cycle 24/25?

- Returning to bright regions for predictions
- Solar Cycle 25 sunspots could begin as soon as late 2019
- Terminator comes in 2020
- Once terminator hits, solar flux increases abruptly
- Could see near 100% increase in solar flux within a few months of reaching terminator

McIntosh et al., 2014, 2019

How Quickly Will the Solar Flux Change?



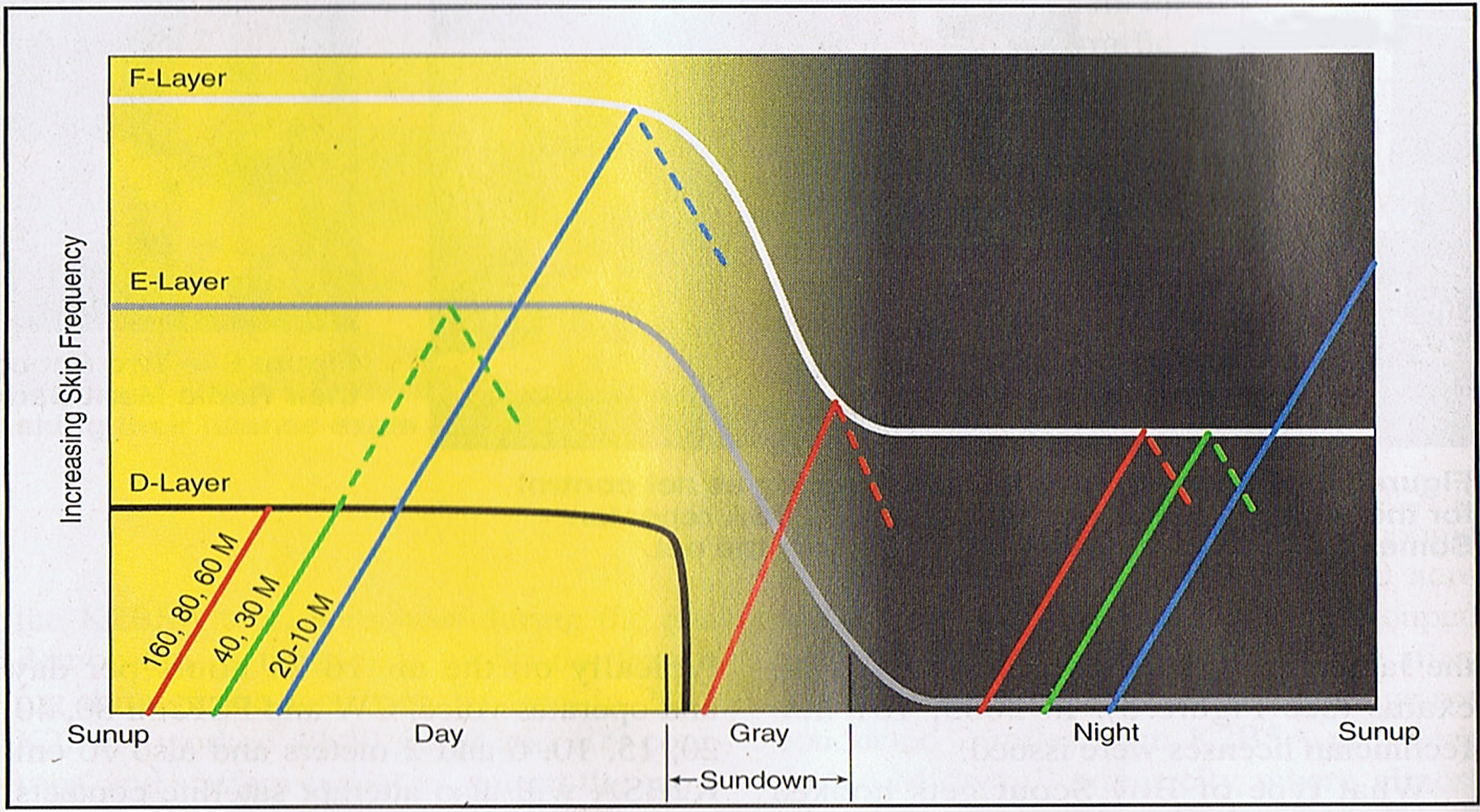
Radiative change once termintor is reached is abrupt!

85% increase

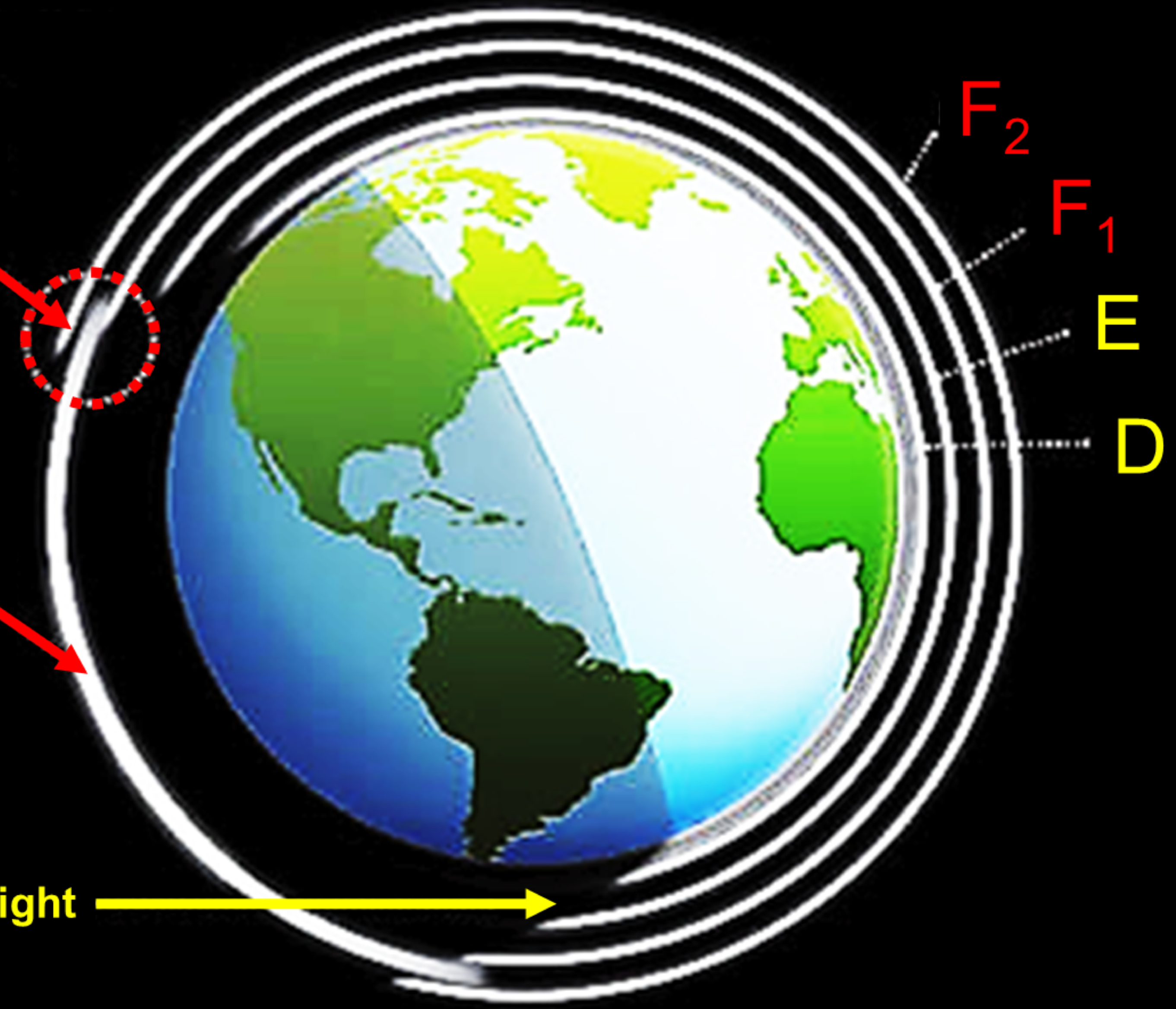
How is the Ionosphere Affected?

- Ionosphere is a charged plasma layer above the atmosphere comprised of ions and electrons
- It would be neutral but it gets charged from exposure mainly to the Sun’s UV radiation (e.g. F10.7 flux)
- This charged nature facilitates radio propagation
- During active space weather, extra energy caught in the Earth’s magnetic shield gets dumped into the ionosphere
- This energy (flow of charged particles) lights-up the plasma in the Earth’s ionosphere similar to a fluorescent lamp or neon sign
- Result is the aurora borealis (northern lights) and aurora australis (southern lights) along with changes in radio propagation
- Space weather effects enhance an already complex system

Three Temporal Regions of Signal Propagation



Why Do the Layers Change Gradually?



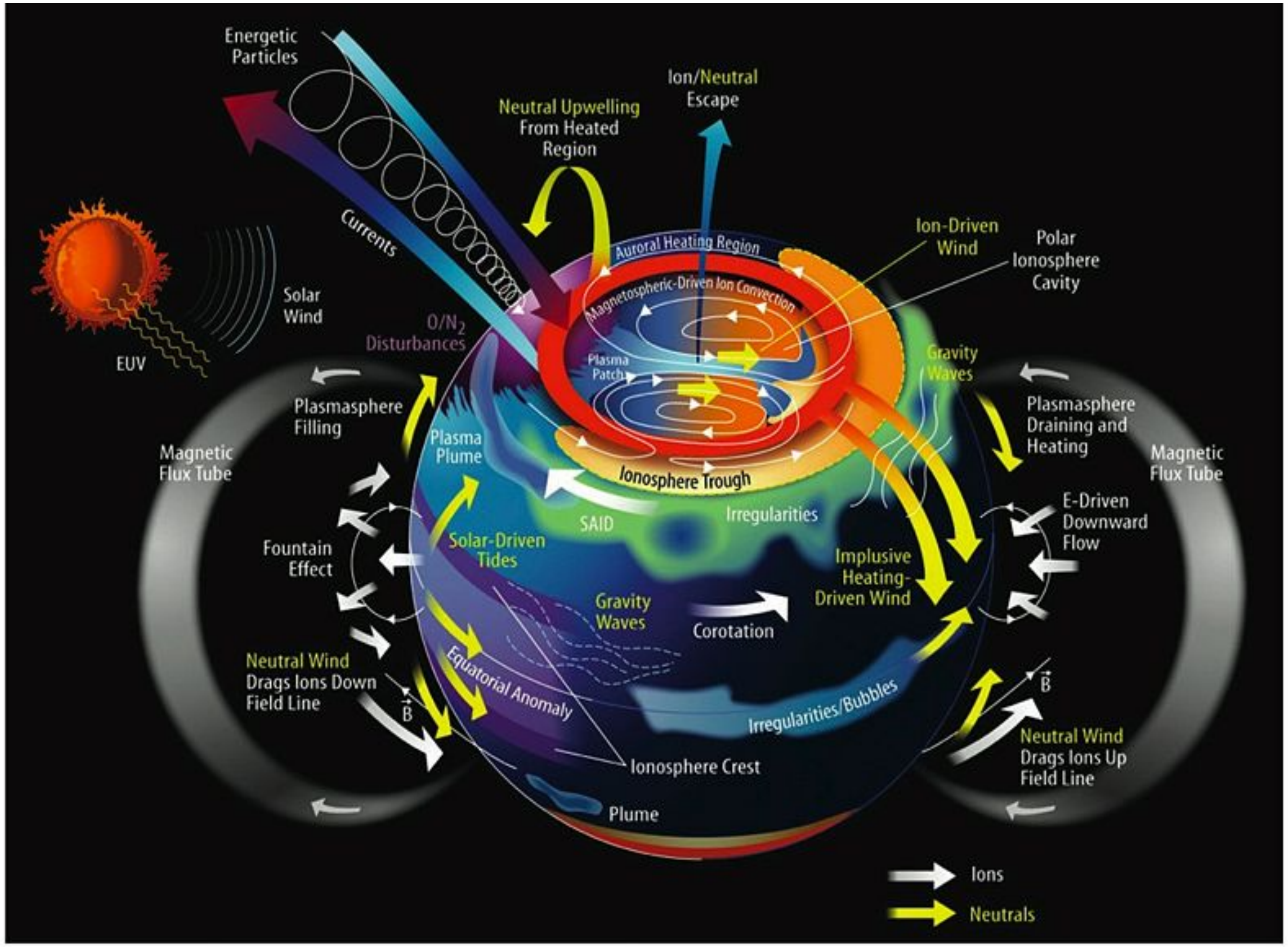
F1 & F2 combine at night

Single F region at night

D & E layers disappear at night

The Complex Ionospheric Weather Ballet

- All sorts of dynamic processes in the ionosphere
- Coupling to the neutral atmosphere beneath drives many micro-processes such as gravity waves, scintillation, plasma bubbles, winds and turbulence
    - Many of these are not well understood or characterized
    - terrestrial weather effects often complicate interactions
- Coupling to the magnetosphere above through processes such as particle precipitations along with variations in sunlight can generate waves, conductivity changes, density changes, and currents
    - Space weather effects often enhance these processes



Thank you Jerry K8VGL !

Until models improve, WSPR & Reverse Beacon network activity remain among the most reliable ways to probe real-time ionospheric radio propagation conditions

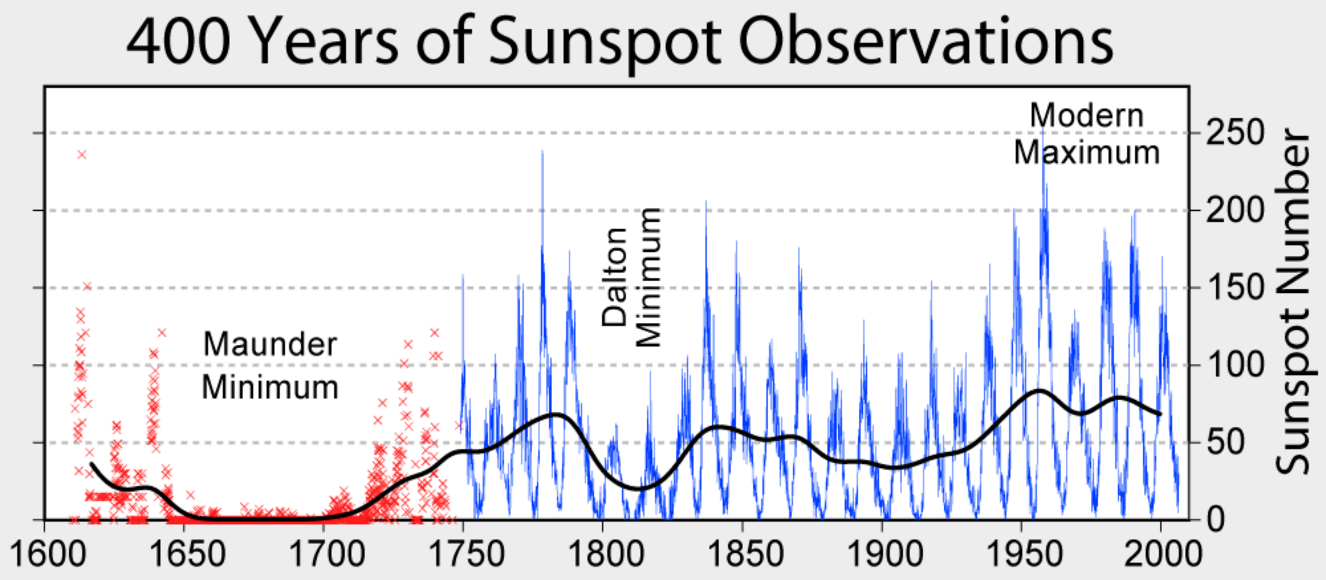
Conclusions

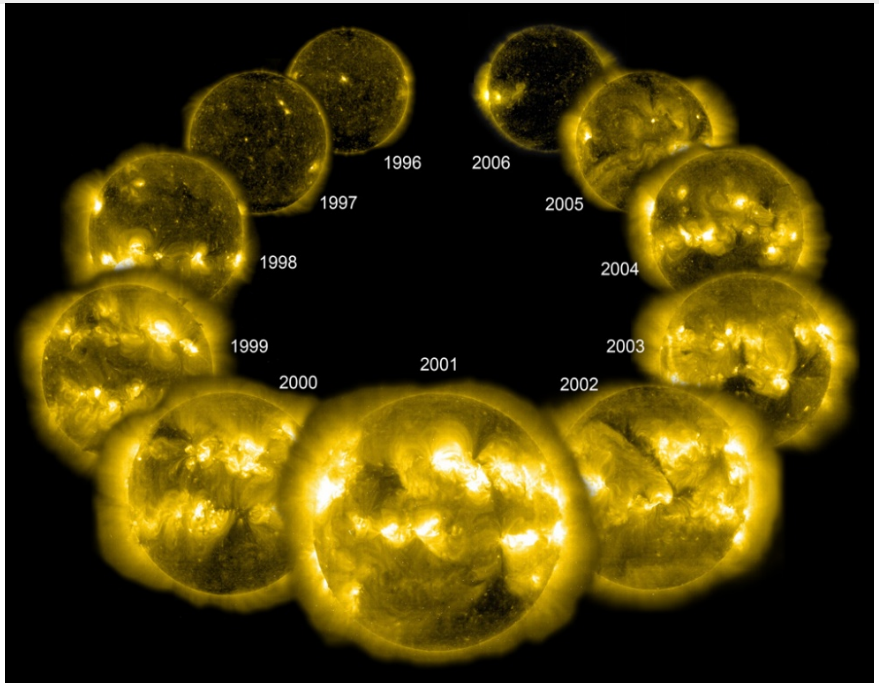
- NOAA Official Prediction for Cycle 25
  - *Timing of minimum: 2019.5 - 2020.75*
  - *Timing of maximum: 2023 - 2026*
  - *Strength: similar to Cycle 24*
  - *Range of Predicted Sunspot Maximum: 95-130*
- Cycle 25 will be another low activity cycle, but that doesn't mean activity stays low!
- Hemispheric magnetic asymmetry is main reason why prediction remains blurry
- Including dynamics of the Sun's magnetic dynamo (NCAR/UCAR predictions)
  - *Solar activity picks up end of 2019*
  - *Terminator (e.g. solar minimum) reached by early 2020*
  - *Once terminator reached, solar flux will rise quickly*
- However, Earth's ionosphere has a very complicated weather system
  - *Dynamics includes much more than just solar activity*
  - *Coupling to Earth's magnetic shield above and to the neutral atmosphere below make it extremely difficult to predict radio propagation on a given day*
  - *Until models improve, WSPR & Reverse Beacon network activity remain among the most reliable ways to probe real-time ionospheric radio propagation conditions*

Supplemental

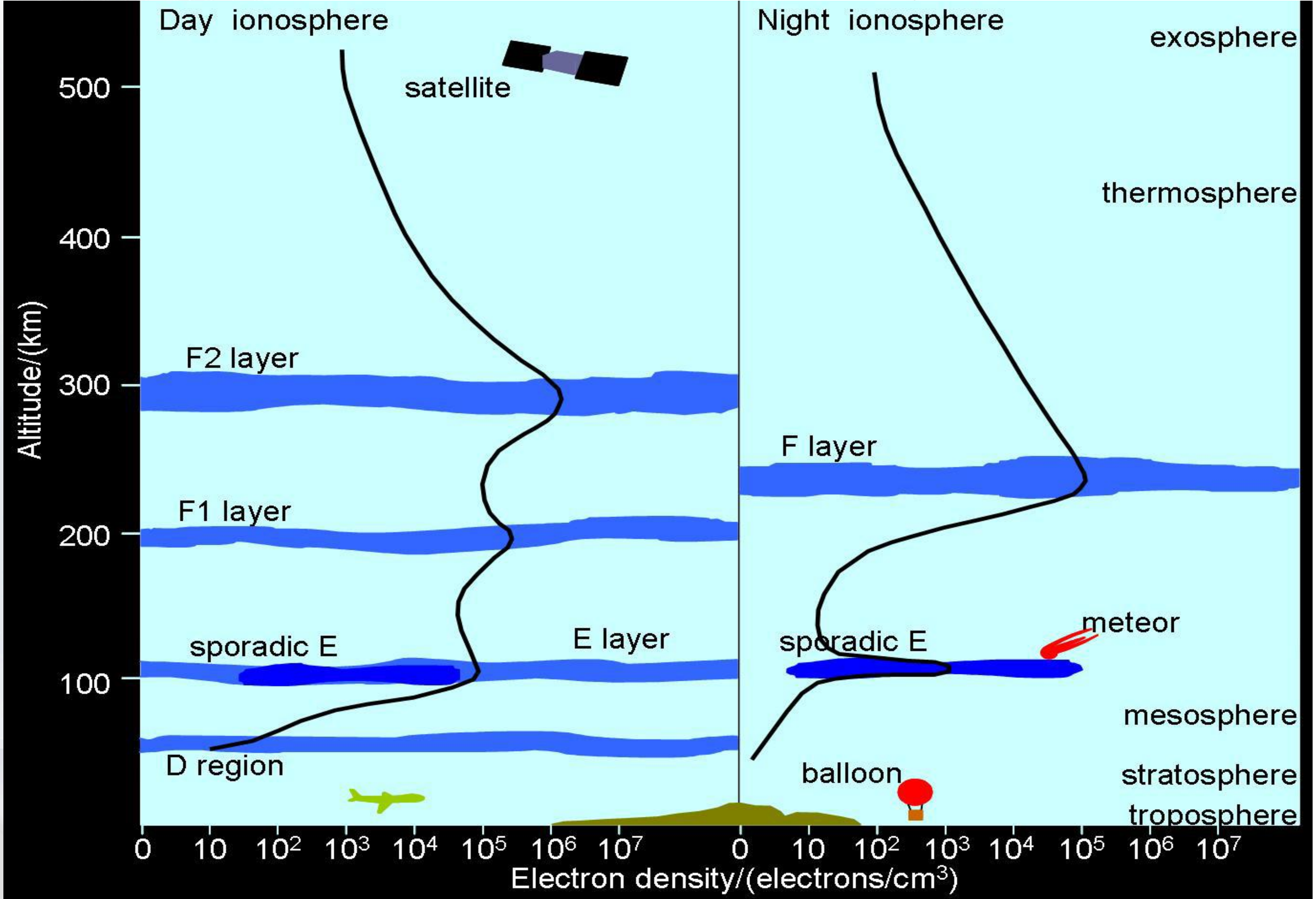
What Does Solar Variability Mean for Cycle 25?

- Sun's activity cycle has a quasi 11-year periodicity
- Solar magnetic field constantly reversing orientation
- Activity increases for few years surrounding field reversal (solar maximum) and decreases when field becomes ordered again (solar minimum)
- Other competing cycles cause deviations from 11-years and modulate the strength of the cycle over the long-term
- Sunspot numbers are used as a proxy for solar activity

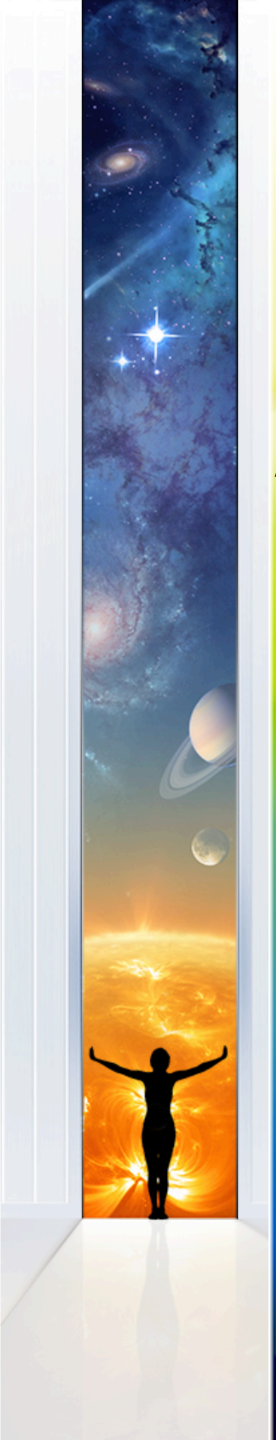


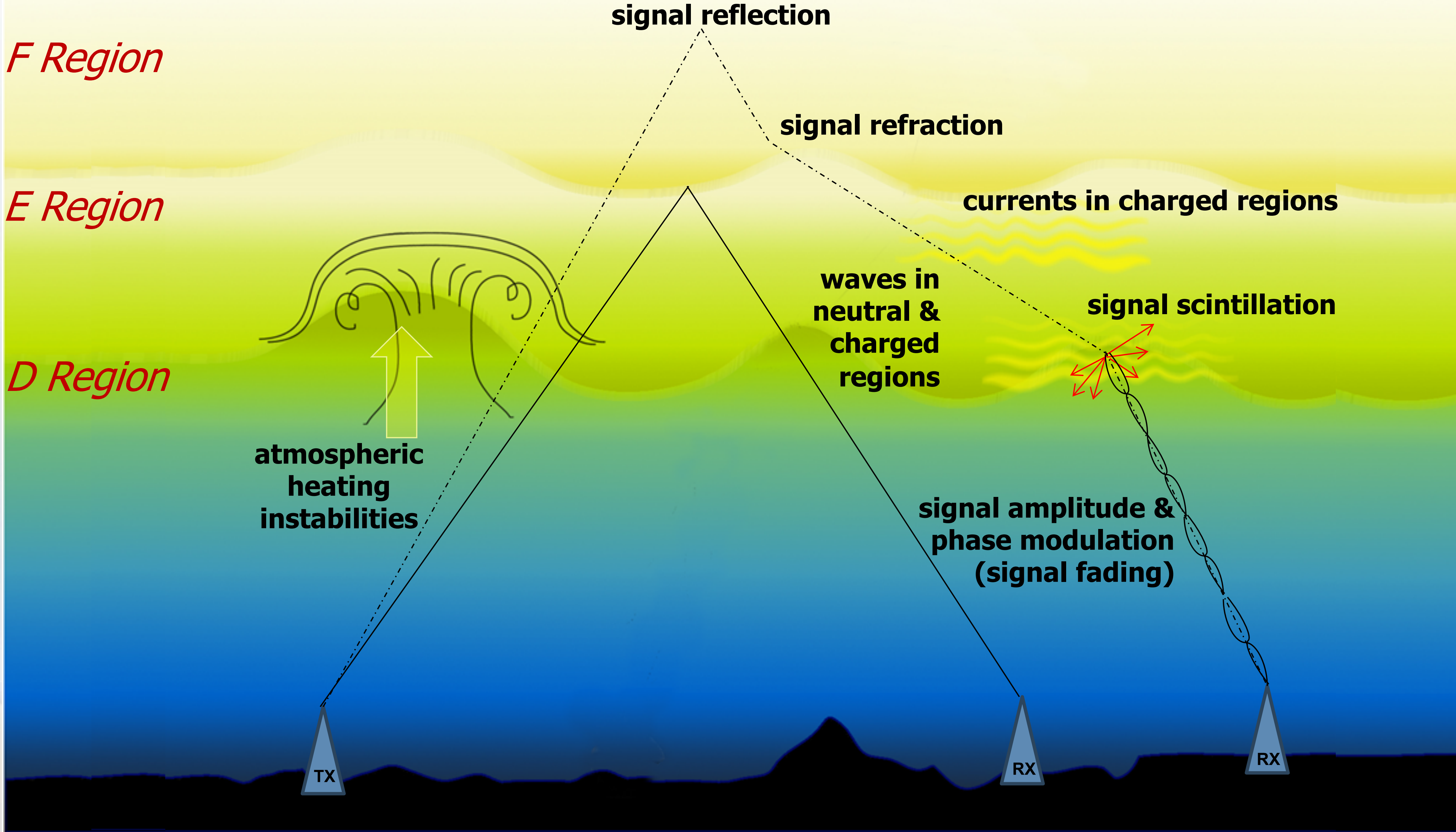


What are Ionospheric Layers?



Space Weather Effects on Radio Communications





F Region

E Region

D Region

signal reflection

signal refraction

currents in charged regions

waves in neutral & charged regions

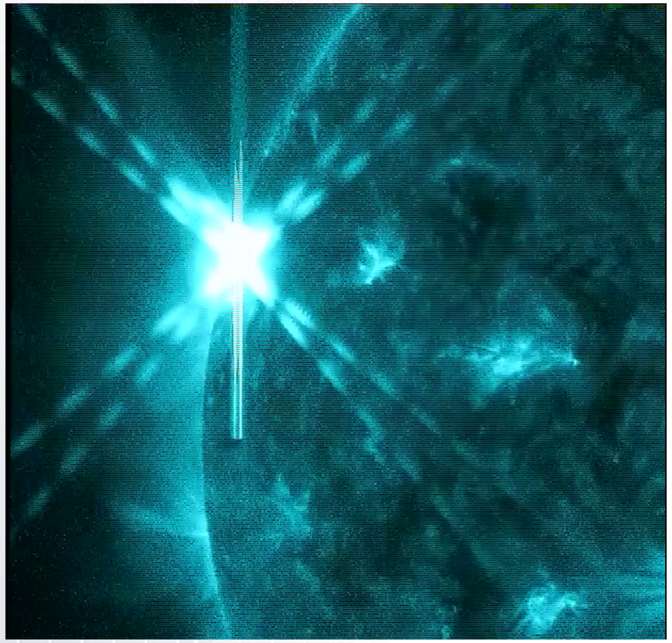
signal scintillation

atmospheric heating instabilities

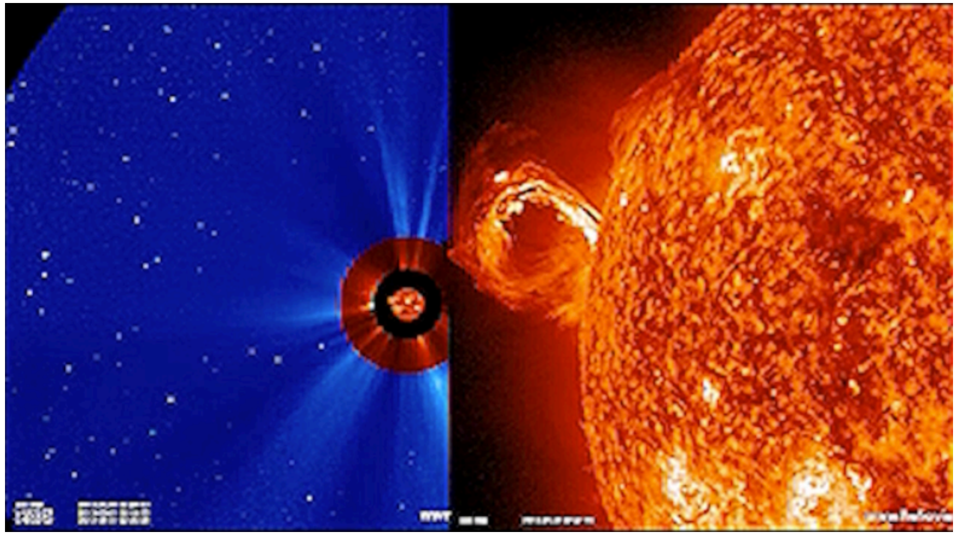
signal amplitude & phase modulation (signal fading)

Four Basic Types of Solar Phenomena Affecting Earth

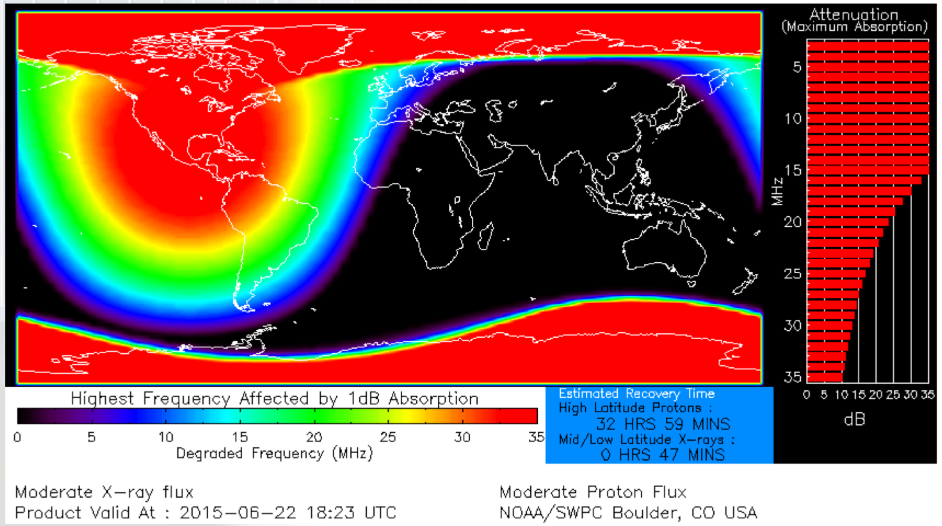
Solar Flares



Solar Storms (a.k.a. CMEs)



Solar Radiation Storms (a.k.a. SEPs)

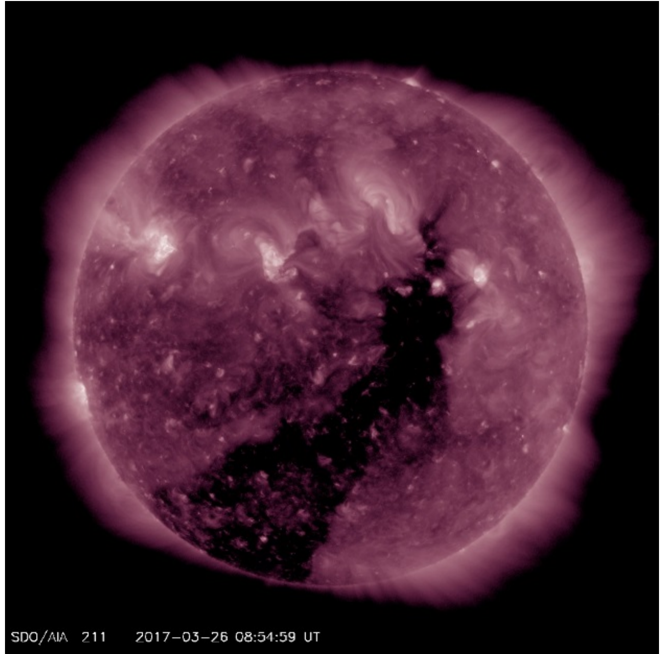


Estimated Recovery Time
High Latitude Protons :
32 HRS 59 MINS
Mid/Low Latitude X-rays :
0 HRS 47 MINS

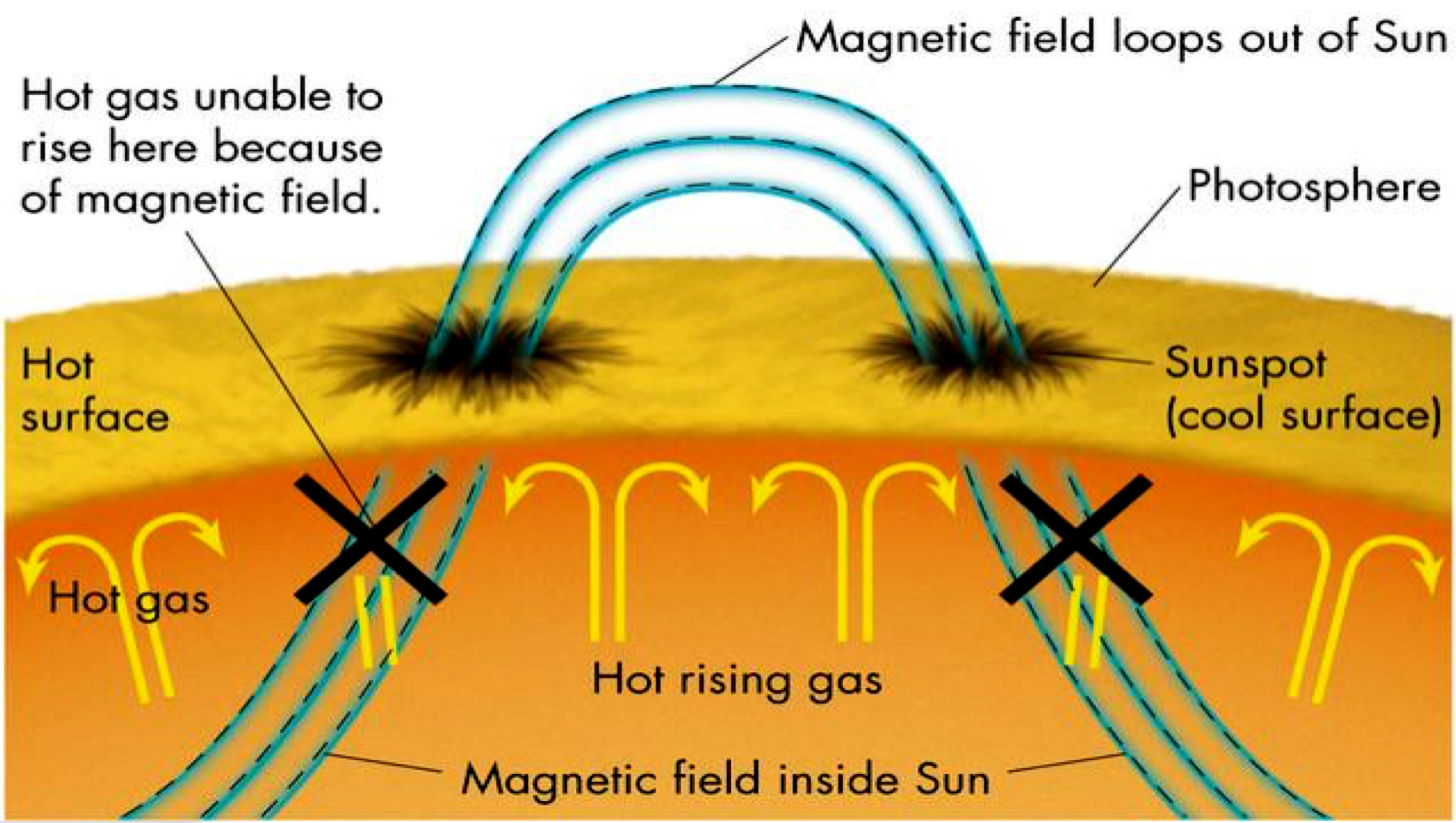
Moderate X-ray flux
Product Valid At : 2015-06-22 18:23 UTC

Moderate Proton Flux
NOAA/SWPC Boulder, CO USA

Coronal Holes (Fast Solar Wind)

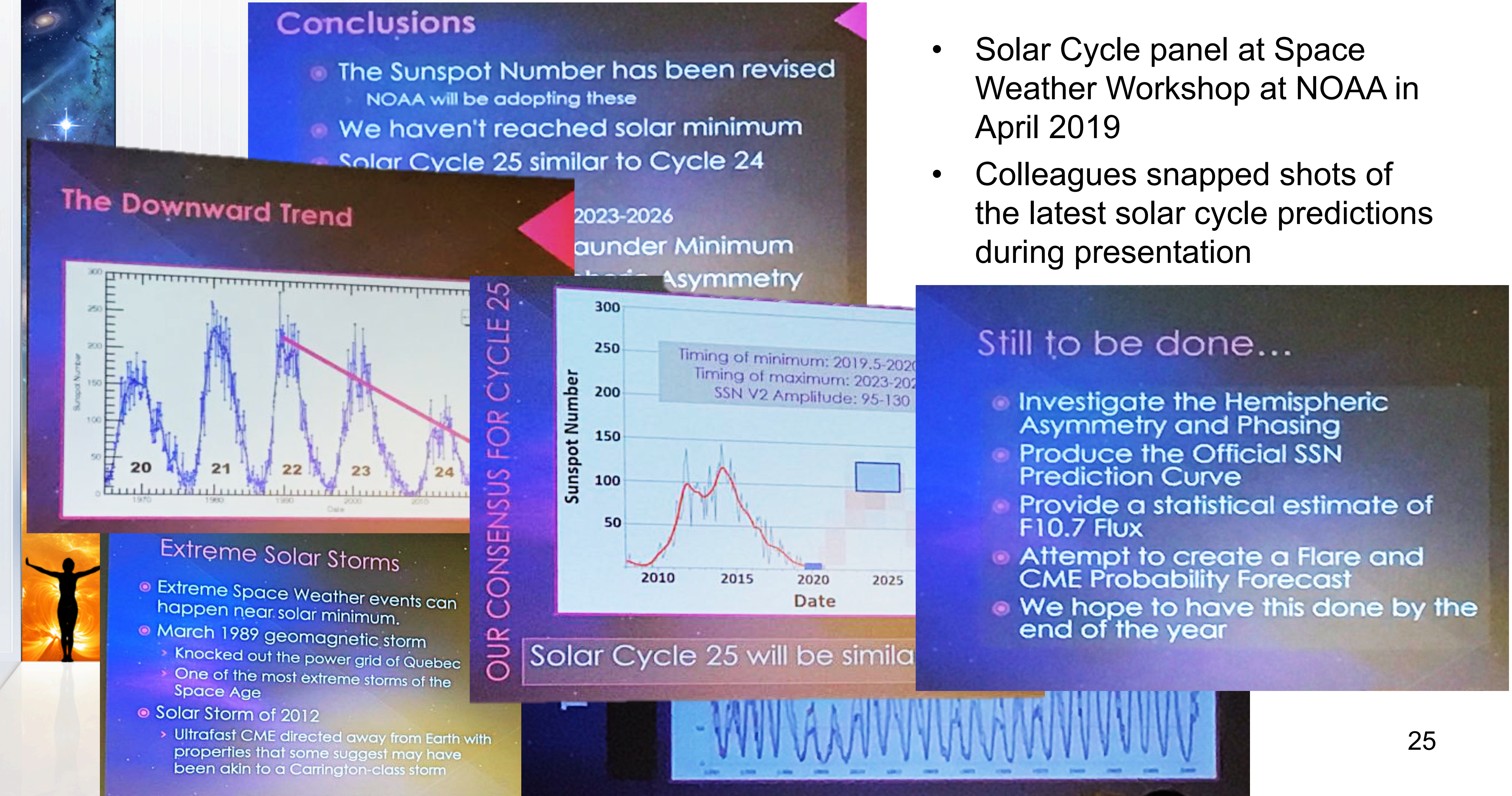


Magnetic Loops Make Sunspots Dark



Hot Off the Presses!

- Solar Cycle panel at Space Weather Workshop at NOAA in April 2019
- Colleagues snapped shots of the latest solar cycle predictions during presentation



Conclusions

- The Sunspot Number has been revised
  - NOAA will be adopting these
- We haven't reached solar minimum
- Solar Cycle 25 similar to Cycle 24

2023-2026

aunder Minimum

Asymmetry

The Downward Trend

OUR CONSENSUS FOR CYCLE 25

Timing of minimum: 2019.5-202
Timing of maximum: 2023-202
SSN V2 Amplitude: 95-130

Solar Cycle 25 will be simila

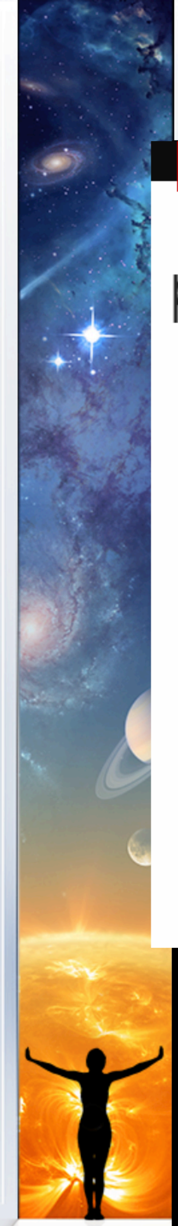
Extreme Solar Storms

- Extreme Space Weather events can happen near solar minimum.
- March 1989 geomagnetic storm
  - Knocked out the power grid of Quebec
  - One of the most extreme storms of the Space Age
- Solar Storm of 2012
  - Ultrafast CME directed away from Earth with properties that some suggest may have been akin to a Carrington-class storm

Still to be done…

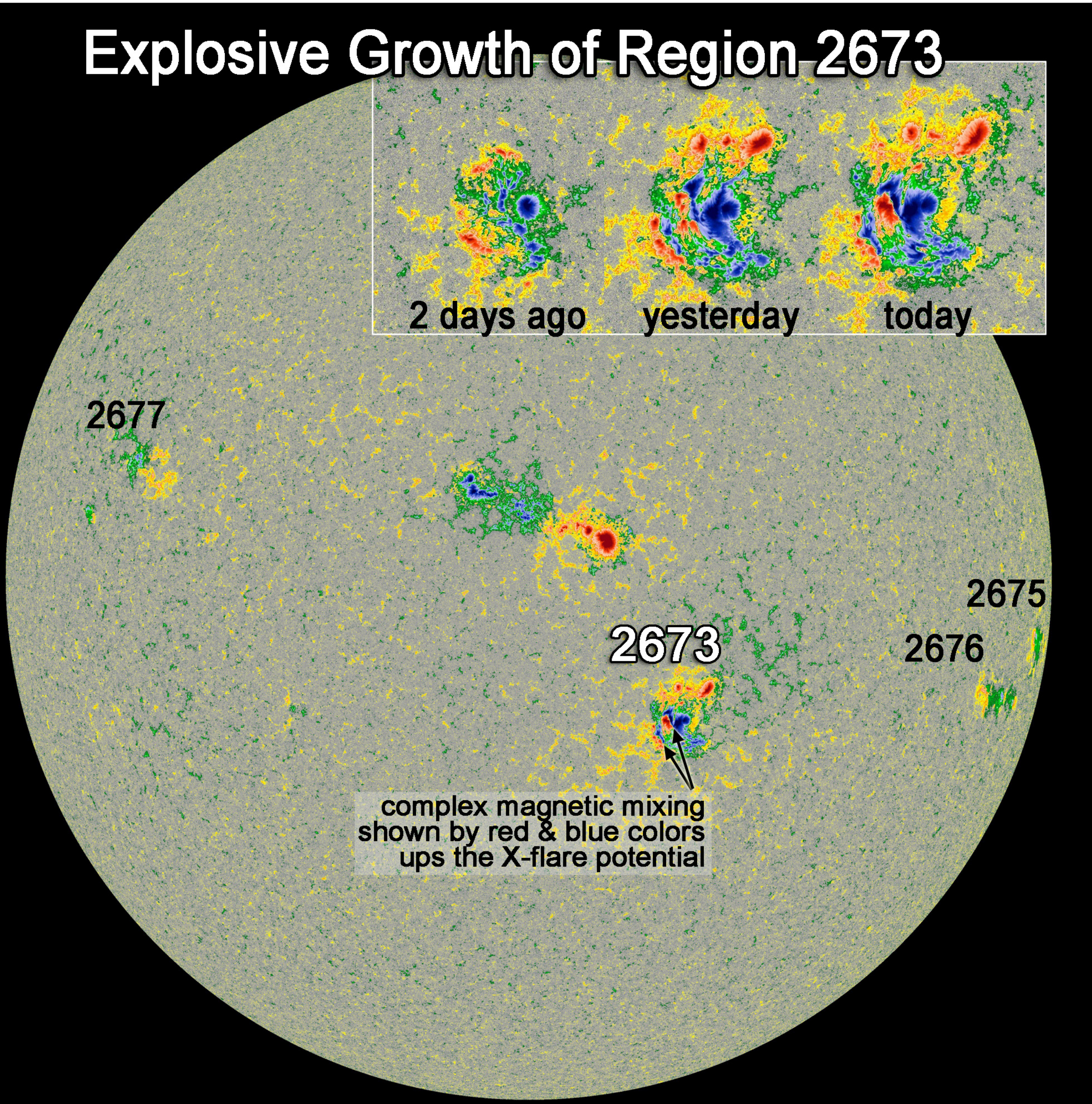
- Investigate the Hemispheric Asymmetry and Phasing
- Produce the Official SSN Prediction Curve
- Provide a statistical estimate of F10.7 Flux
- Attempt to create a Flare and CME Probability Forecast
- We hope to have this done by the end of the year

Perfect Storm: Hurricane Harvey, Irma, & Region 2673



Battered Texas town may be without power for weeks

RESIDENT CONNECTS WITH FATHER FOR 1ST TIME SINCE HARVEY HIT

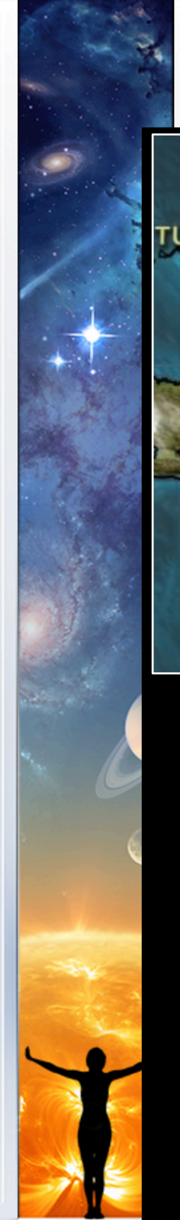


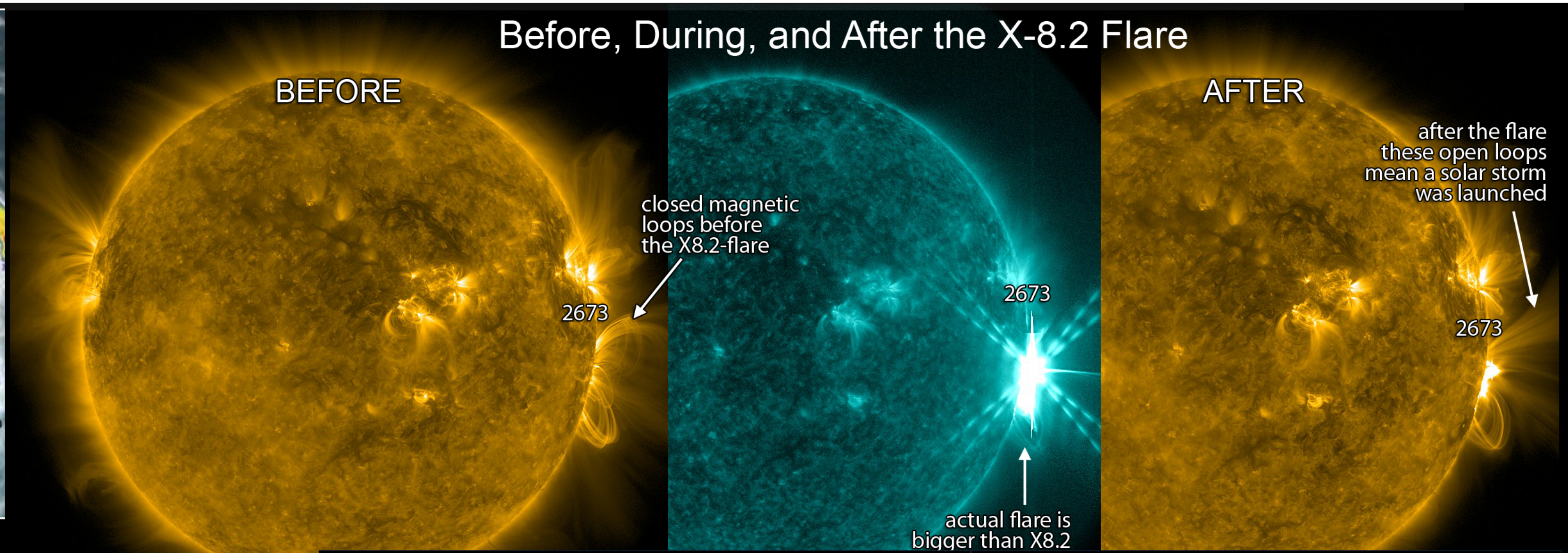
Explosive Growth of Region 2673

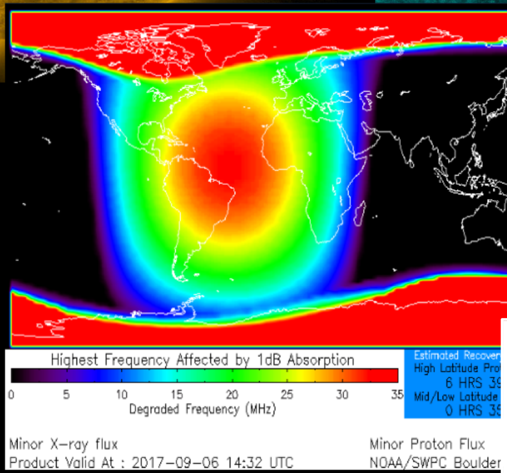
complex magnetic mixing shown by red & blue colors ups the X-flare potential

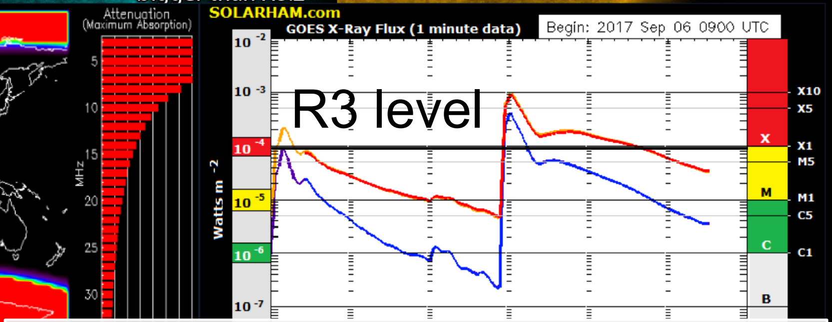
SDO/HMI Quick-Look Magnetogram: 20170905_020000

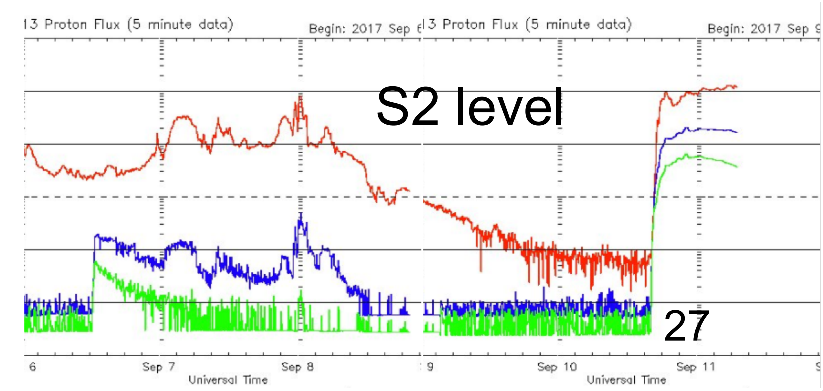
Perfect Storm: Hurricane Harvey, Irma, & Region 2673




Before, During, and After the X-8.2 Flare







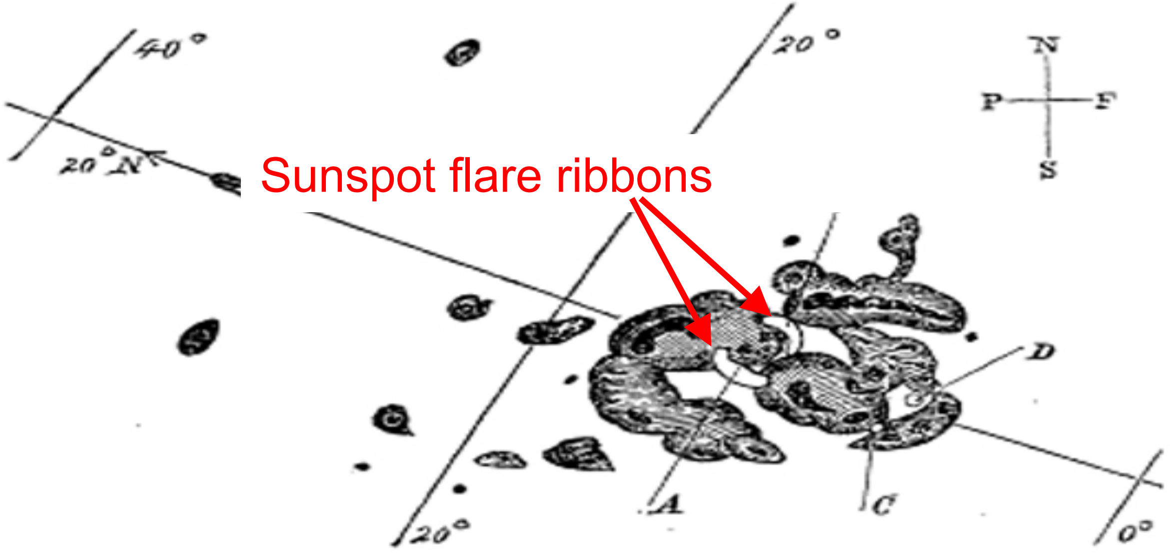
Region 2673 launched in a single week (Sep 3 – Sep 10):

- 4 X-class flares
  (R3 - R4 level radio blackout)
- 25 M-class flares
  (R1 - R2 level radio blackout)
- 2 Solar Radiation storms (S2 - S3 level)
- 2 Geomagnetic storms (G4 level)

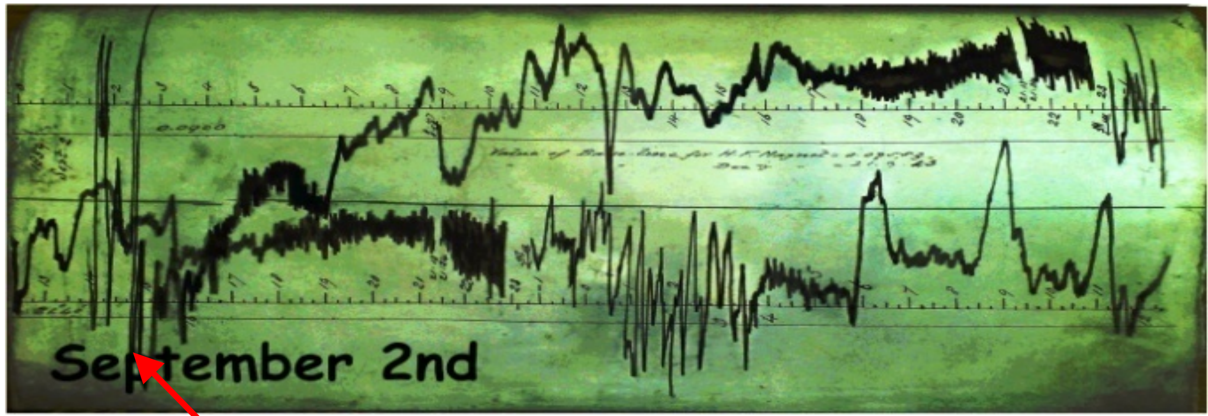
What About a Super-Super Storm?

Carrington Event September 2, 1859

- First ever recorded solar flare resulted in a massive solar storm
- Largest in last 500 years
- Three times larger than March 1989
- North American Telegraph system failed
- Telegraph systems functioned despite being un-plugged
- Worst hit operating stations sparked and burst into flame from electrical discharges, burning their operators
- Aurora so bright animals thought it was sunrise
- Auroral displays seen as far south as the Caribbean, Hawaii, and Singapore
- If occurred today, cause $2B worth of damage (National Academy of Sciences)

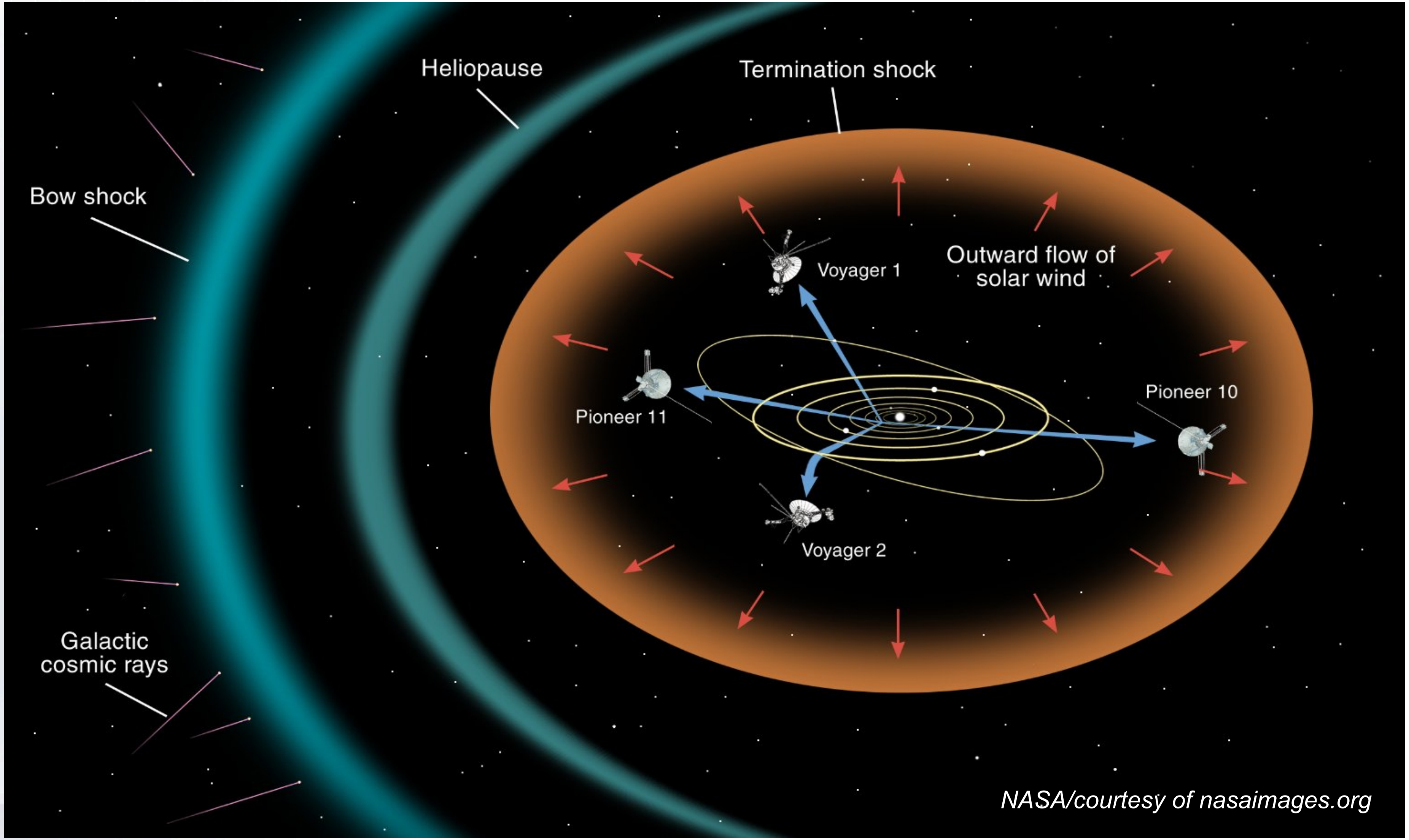


Sunspot flare ribbons



Earth magnetic field off-scale!

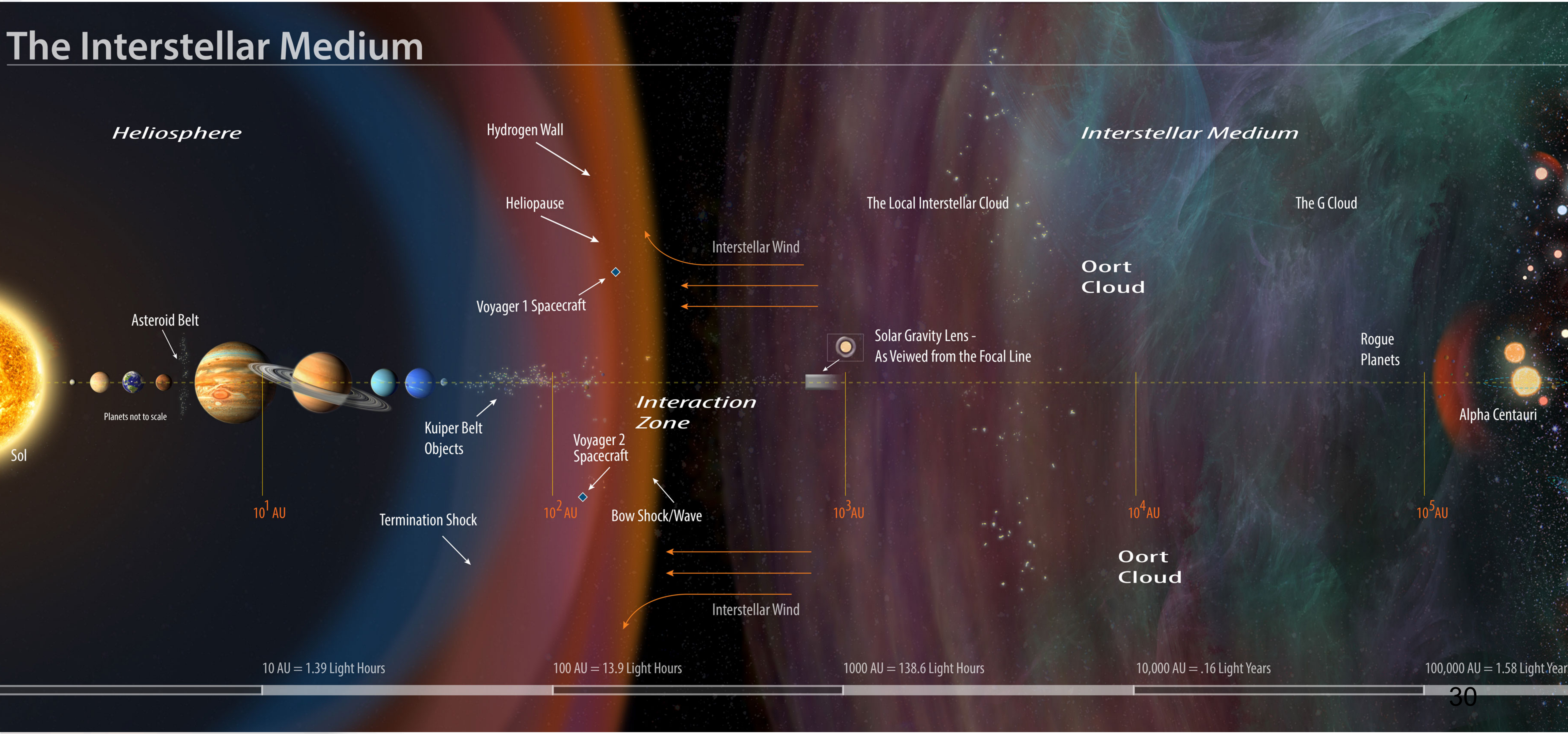
Heliosphere: The Shield of Our Solar System

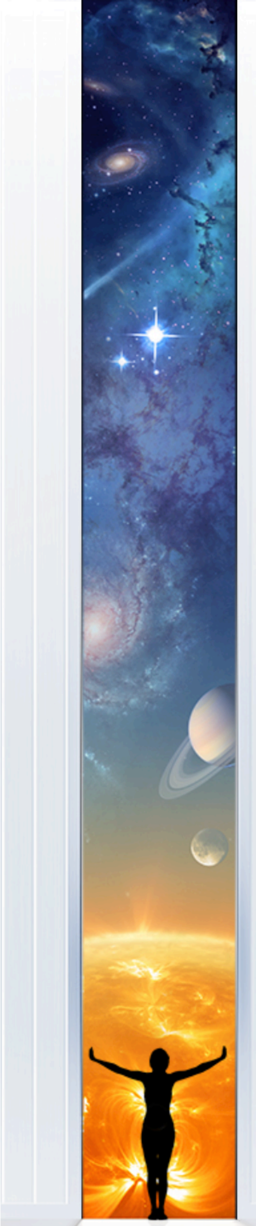


NASA/courtesy of nasaimages.org

Sun-Earth: 93 million miles– sunlight takes 8 minutes to travel to Earth
Sun-Pluto: 3.67 billion miles– sunlight takes 5.3 hours to travel to Pluto

Cosmic Ray Sources Beyond the Heliosphere



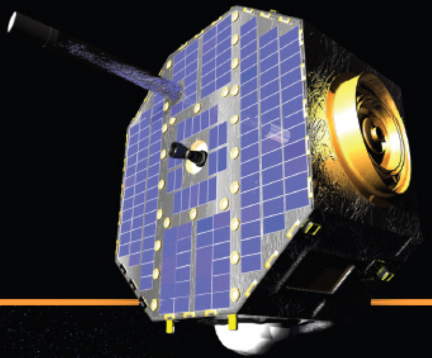


Heliosphere

The heliosphere is the outer atmosphere of the Sun and marks the edge of the Sun's magnetic influence in space. The solar wind that streams out in all directions from the rotating Sun is a magnetic plasma, and it fills the vast space between the planets in our solar system. The magnetic plasma from the Sun doesn't mix with the magnetic plasma between the stars in our galaxy, so the solar wind carves out a bubble-like atmosphere that shields our solar system from the majority of galactic cosmic rays.

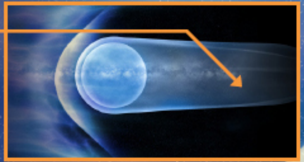
Interstellar Boundary Explorer (IBEX)

NASA's Interstellar Boundary Explorer (IBEX) is the first mission to map the heliosphere at the outer reaches of our solar system where the solar wind interacts with the interstellar space.



Heliotail

As the heliosphere travels through the interstellar medium, it leaves a long heliotail in its wake wave, much like a boat travelling through the water.



Bow Shock

Where the solar wind pushes against the competing force of the stellar wind, a bow (or shock) wave forms in front of the heliosphere.

Termination Shock

The point where the solar wind begins to interact with the local interstellar medium and slows down is called the termination shock.

Interstellar Space

Heliopause

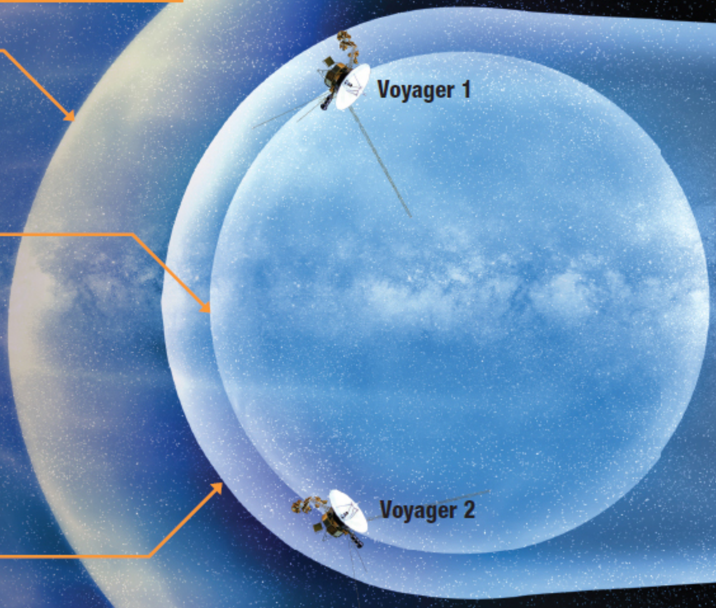
It is thought that the heliopause is where the solar wind is not strong enough to push back against the stellar wind and is stopped by the interstellar medium.

Heliosheath

The heliosheath is the region between the termination shock and the heliopause where the solar wind slows and compresses as it interacts with the interstellar medium.

Voyager 1 & 2

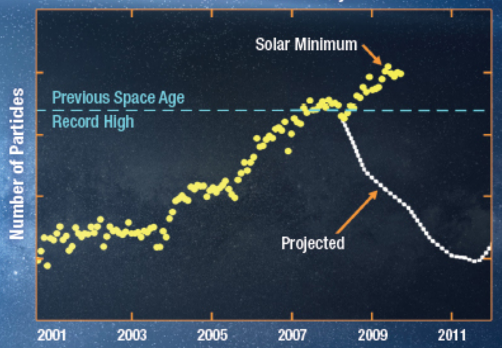
NASA's Voyagers 1 and 2 spacecraft have reached the inner-most boundary of the heliosheath—twice as far from the Sun as Pluto's orbit.



Variation of the Heliosphere

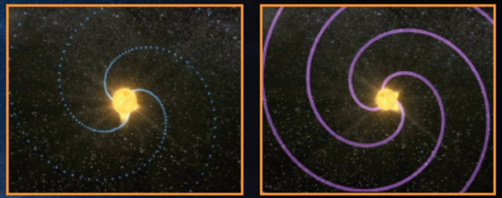
The number of cosmic rays entering our heliosphere has been measured since instruments could be placed in orbit above the Earth's protective atmosphere. Scientists monitoring the number of cosmic rays noticed that the number varies during the course of the solar cycle. During the prolonged solar minimum in 2009, the highest level of cosmic rays in the space age was recorded.

Amount of Cosmic Rays



Energetic Neutral Atoms

Neutral atoms from the interstellar medium can enter the heliosphere and mix with the charged particles of the solar wind. As a charged particle interacts with a neutral atom, the particle can capture an electron and become neutral itself. This exchange does not affect its direction or speed, but the particle is no longer bound to magnetic forces and travels in a straight line.

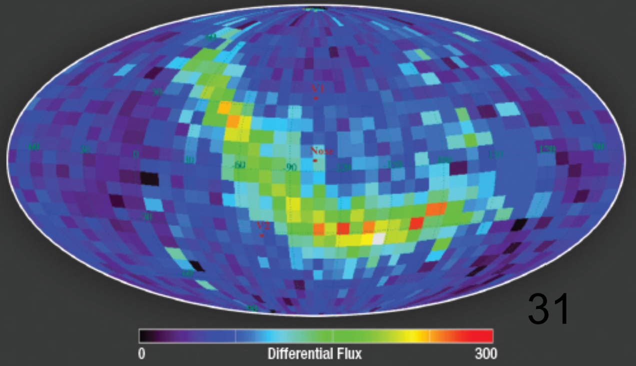


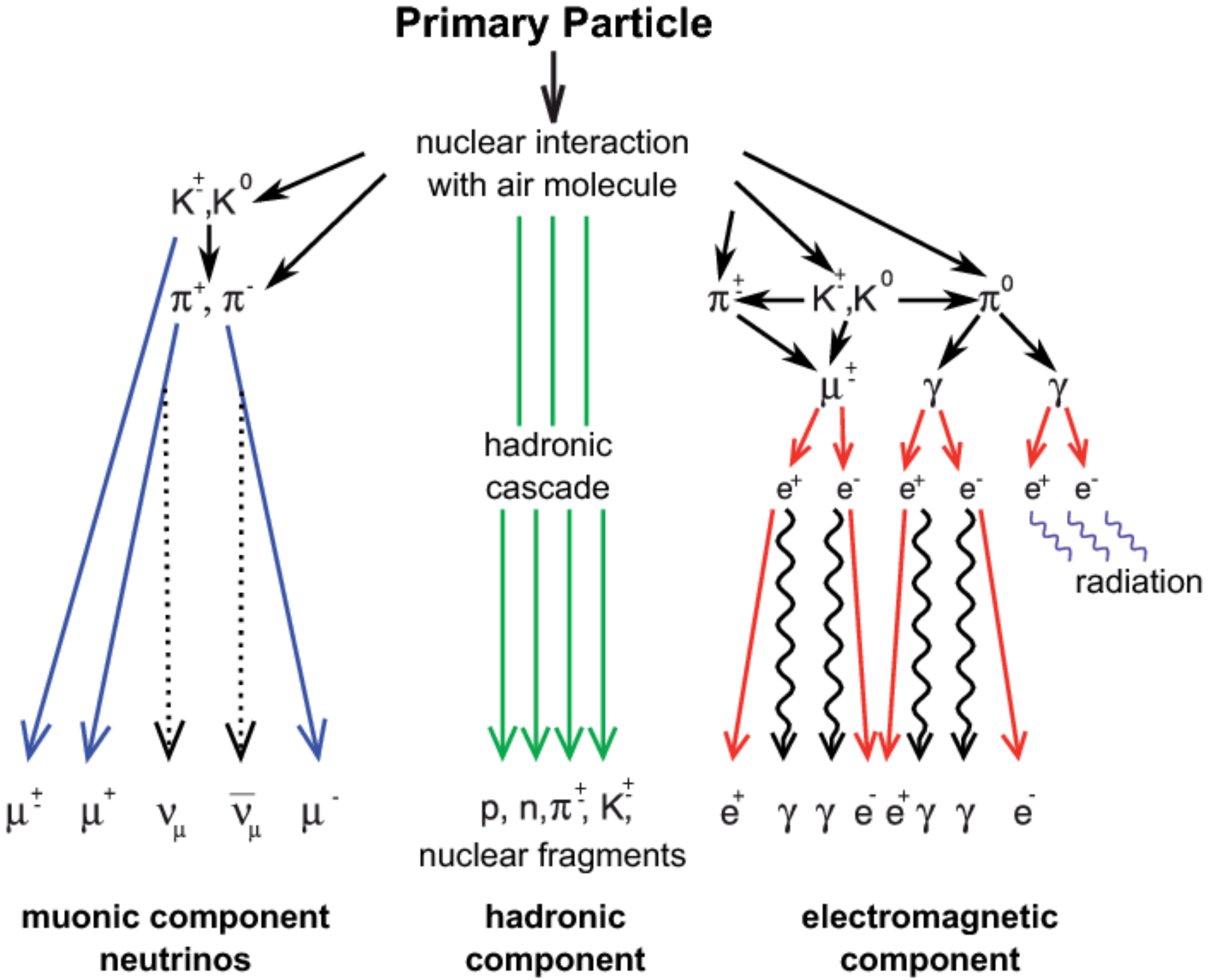
Solar Wind

The solar wind is a stream of charged particles ejected from the upper atmosphere of the Sun. It mostly consists of electrons and protons, and varies in temperature and speed over time. These particles can escape the Sun's gravity because of their high kinetic energy. The solar wind creates the heliosphere, a vast bubble that surrounds the Solar System.

Mapping the Heliosphere

NASA's Interstellar Boundary EXplorer (IBEX) spacecraft can detect and chart the origins of energetic neutral atoms (ENAs) that reach as far into the solar system as the Earth. From these data, an all-sky map of the boundary is created. These spectacular maps from IBEX found that most ENAs originate in a band or ribbon that spans the entire sky. This "ribbon" is linked to the magnetic field that exists outside the heliosphere, in the interstellar medium.





Primary Particle

nuclear interaction
with air molecule

$K^{\pm}, K^0$

π^+, π^-

$\mu^{\pm}$ μ^+ ν_μ $\bar{\nu}_\mu$ μ^-

hadronic
cascade

p, n, $\pi^{\pm}$, $K^{\pm}$,
nuclear fragments

$\pi^{\pm}$ $K^{\pm}, K^0$ π^0

$\mu^{\pm}$ γ γ

e^+ e^- e^+ e^- e^+ e^-

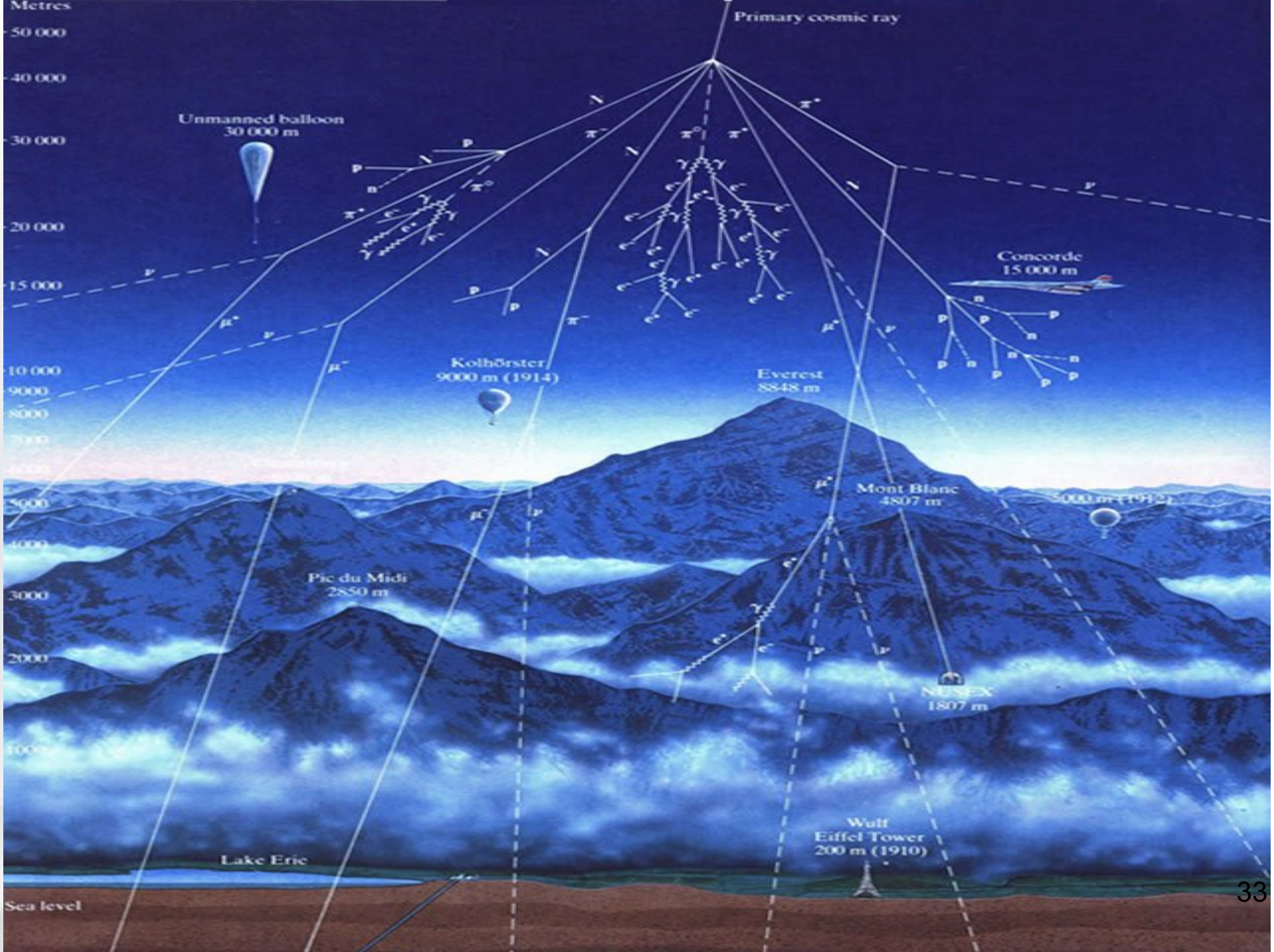
radiation

e^+ γ γ e^- e^+ γ γ e^-

muonic component
neutrinos

hadronic
component

electromagnetic
component


Metres
50 000
40 000
30 000
20 000
15 000
10 000
9000
8000
7000
6000
5000
4000
3000
2000
1000
Sea level
Primary cosmic ray
Unmanned balloon
30 000 m
Kolhörster
9000 m (1914)
Everest
8848 m
Concorde
15 000 m
Mont Blanc
4807 m
5000 m (1912)
Pic du Midi
2850 m
NUSEX
1807 m
Wulf
Eiffel Tower
200 m (1910)
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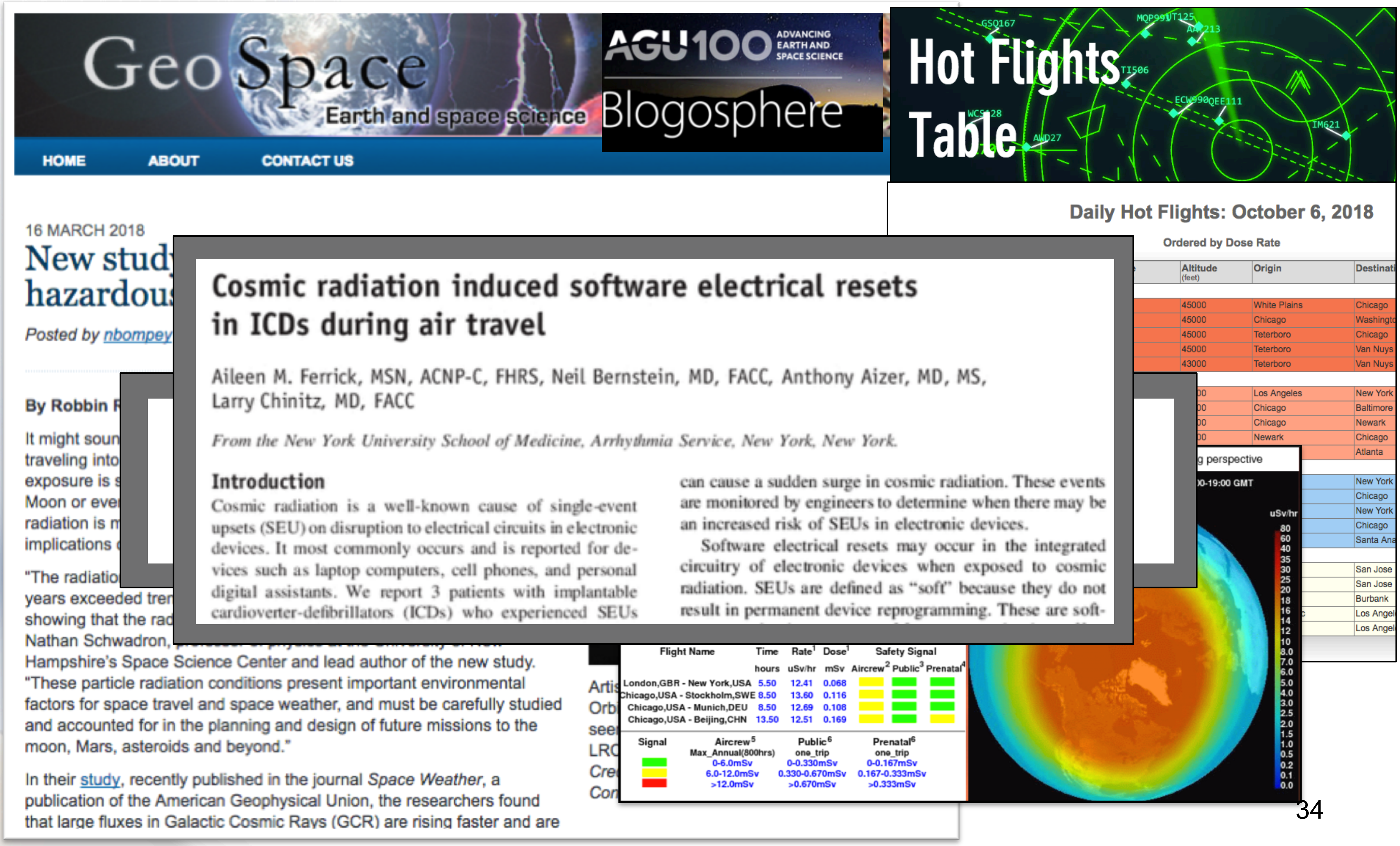

GeoSpace
Earth and space science

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Blogosphere

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16 MARCH 2018

New stud
hazardou

Posted by nbompey

By Robbin R

It might soun
traveling into
exposure is s
Moon or eve
radiation is n
implications

"The radiatio
years exceeded tre
showing that the rad
Nathan Schwadron,
Hampshire's Space Science Center and lead author of the new study. "These particle radiation conditions present important environmental factors for space travel and space weather, and must be carefully studied and accounted for in the planning and design of future missions to the moon, Mars, asteroids and beyond."

In their study, recently published in the journal *Space Weather*, a publication of the American Geophysical Union, the researchers found that large fluxes in Galactic Cosmic Rays (GCR) are rising faster and are

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Cosmic radiation induced software electrical resets in ICDs during air travel

Aileen M. Ferrick, MSN, ACNP-C, FHRS, Neil Bernstein, MD, FACC, Anthony Aizer, MD, MS, Larry Chinitz, MD, FACC

From the New York University School of Medicine, Arrhythmia Service, New York, New York.

Introduction

Cosmic radiation is a well-known cause of single-event upsets (SEU) on disruption to electrical circuits in electronic devices. It most commonly occurs and is reported for devices such as laptop computers, cell phones, and personal digital assistants. We report 3 patients with implantable cardioverter-defibrillators (ICDs) who experienced SEUs can cause a sudden surge in cosmic radiation. These events are monitored by engineers to determine when there may be an increased risk of SEUs in electronic devices.

Software electrical resets may occur in the integrated circuitry of electronic devices when exposed to cosmic radiation. SEUs are defined as "soft" because they do not result in permanent device reprogramming. These are soft-

Hot Flights Table

Daily Hot Flights: October 6, 2018

Ordered by Dose Rate

Altitude (feet)	Origin	Destinati
45000	White Plains	Chicago
45000	Chicago	Washingto
45000	Teterboro	Chicago
45000	Teterboro	Van Nuys
43000	Teterboro	Van Nuys
00	Los Angeles	New York
00	Chicago	Baltimore
00	Chicago	Newark
00	Newark	Chicago
		Atlanta
		New York
		Chicago
		New York
		Chicago
		Santa Ana
		San Jose
		San Jose
		Burbank
	c	Los Angel
		Los Angel

g perspective

00-19:00 GMT

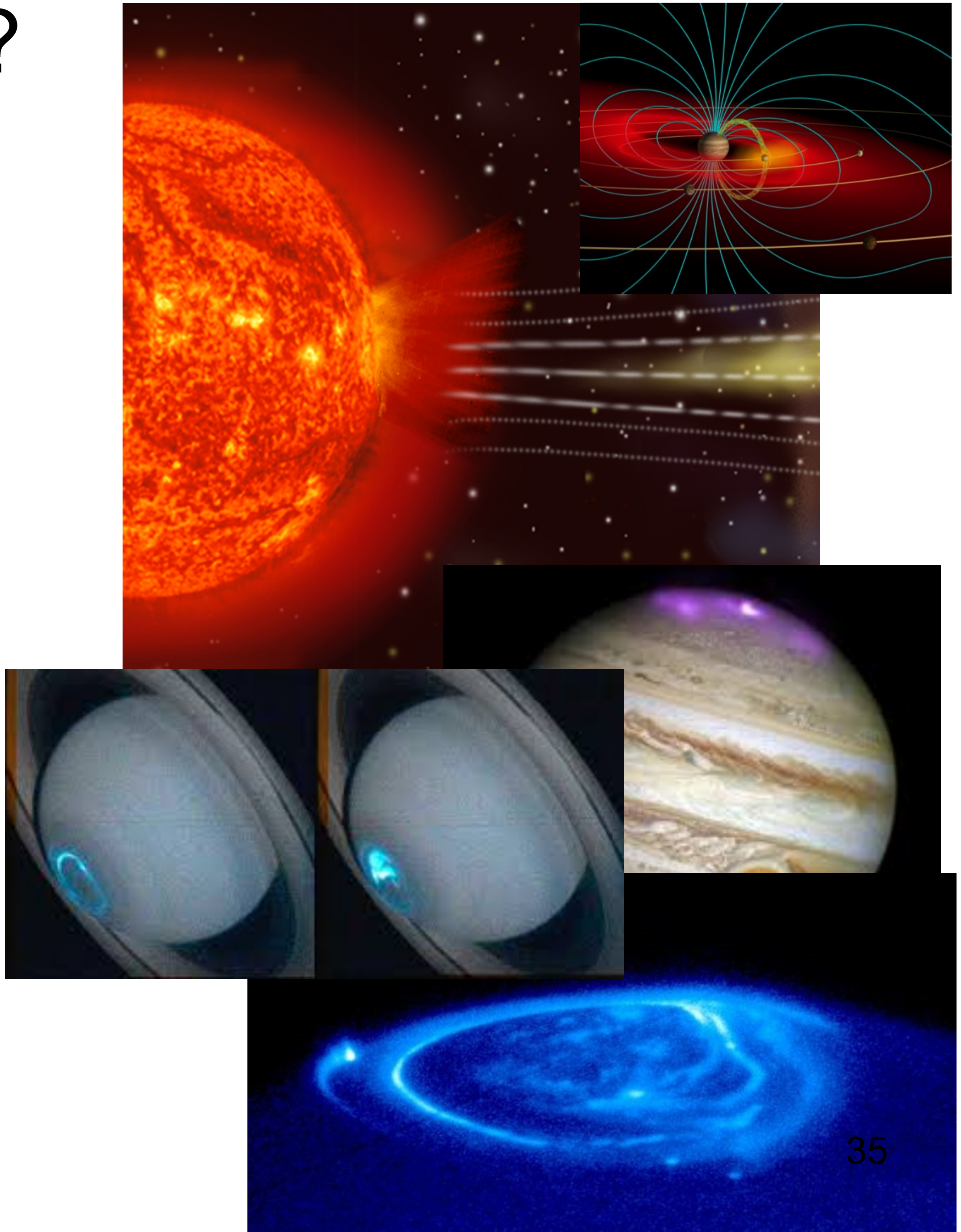
Flight Name	Time	Rate[1]	Dose[1]	Safety Signal		
	hours	uSv/hr	mSv	Aircrew[2]	Public[3]	Prenatal[4]
London,GBR - New York,USA	5.50	12.41	0.068	🟨	🟩	🟩
Chicago,USA - Stockholm,SWE	8.50	13.60	0.116	🟨	🟩	🟩
Chicago,USA - Munich,DEU	8.50	12.69	0.108	🟨	🟩	🟩
Chicago,USA - Beijing,CHN	13.50	12.51	0.169	🟨	🟩	🟨

Signal	Aircrew[5] Max_Annual(800hrs)	Public[6] one_trip	Prenatal[6] one_trip
🟩	0-6.0mSv	0-0.330mSv	0-0.167mSv
🟨	6.0-12.0mSv	0.330-0.670mSv	0.167-0.333mSv
🟥	>12.0mSv	>0.670mSv	>0.333mSv

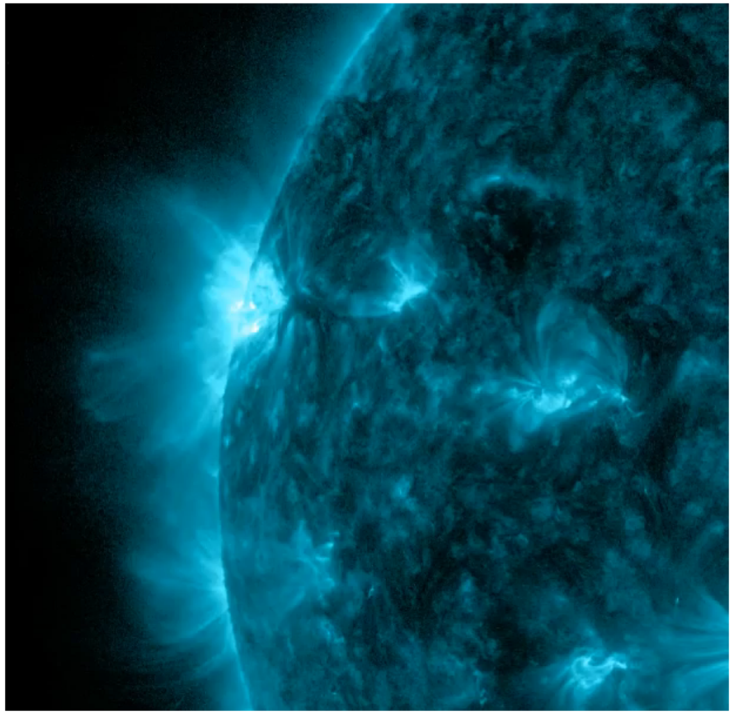
What is Space Weather?

Essentially Space Weather is:

- A planet’s interaction with its host star and the surrounding space environment
- More generally, it occurs at planets, moons, comets, asteroids, and other celestial bodies in the universe
- We see aurora at planets
  - Jupiter, Saturn, Uranus, and Mars
- We see effects at Moons
  - Io, Europa, Ganymede, and Titan
- Main effects are **Sun-driven**
- Other sources of space weather
  - Cosmic rays
  - Micrometeoroids & interstellar dust
  - Space junk



Solar Phenomena



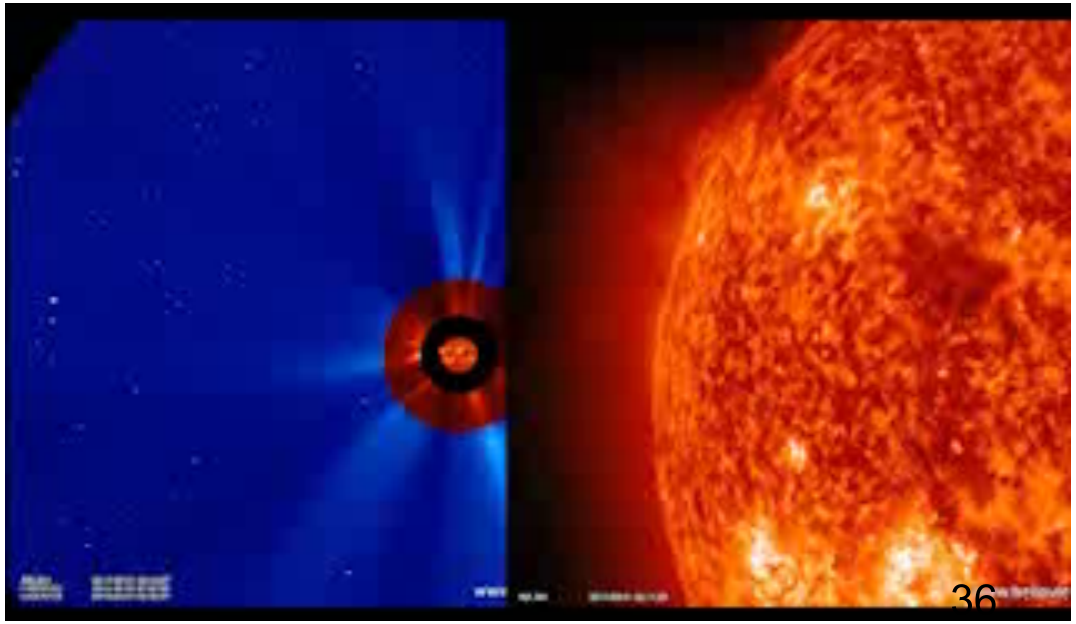
Quiet Sun

- Solar wind
  - *high speed streams (HSS)*
  - *Interplanetary shockwaves*

Active Sun

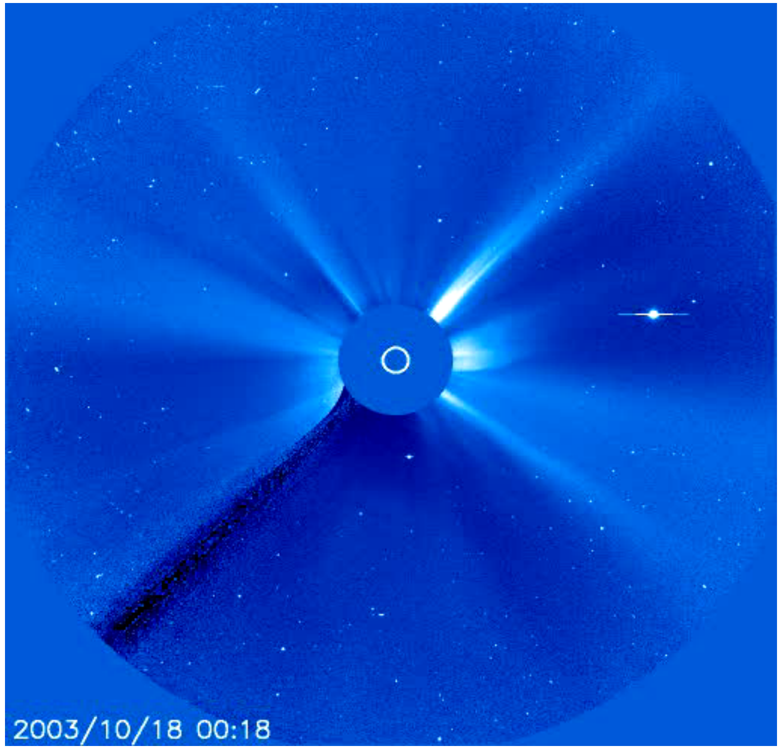
- Solar flares
  - *Release X-rays, radio bursts*
  - *Solar energetic particle storms (mainly protons and electrons)*
  - *Near speed of light travel*

    (~8 minutes to reach Earth)
- Coronal Mass Ejections (CMEs)
  - *Massive amount of solar plasma and enhanced magnetic fields*
  - *Drives strong shockwaves in space*
  - *Slow <1500 km/s*
  - *Travel to Earth in 2-5 days*
  - *Cause "geomagnetic storms" at Earth*



Way Far Out: Coronagraphs

- White light coronagraphs view beyond the corona into the solar wind
- LASCO on SOHO goes up to 30 solar radii (15 solar lengths)
- Typically use an occulting disk to block the Sun’s direct light
- Critical for viewing CMEs and forecasting geomagnetic storms using views from Earth (halo CMEs) & in quadrature (limb CMEs)
- The Heliospheric Imager (HI) on the STEREO spacecraft can image CMEs all the way to the Earth (1AU)

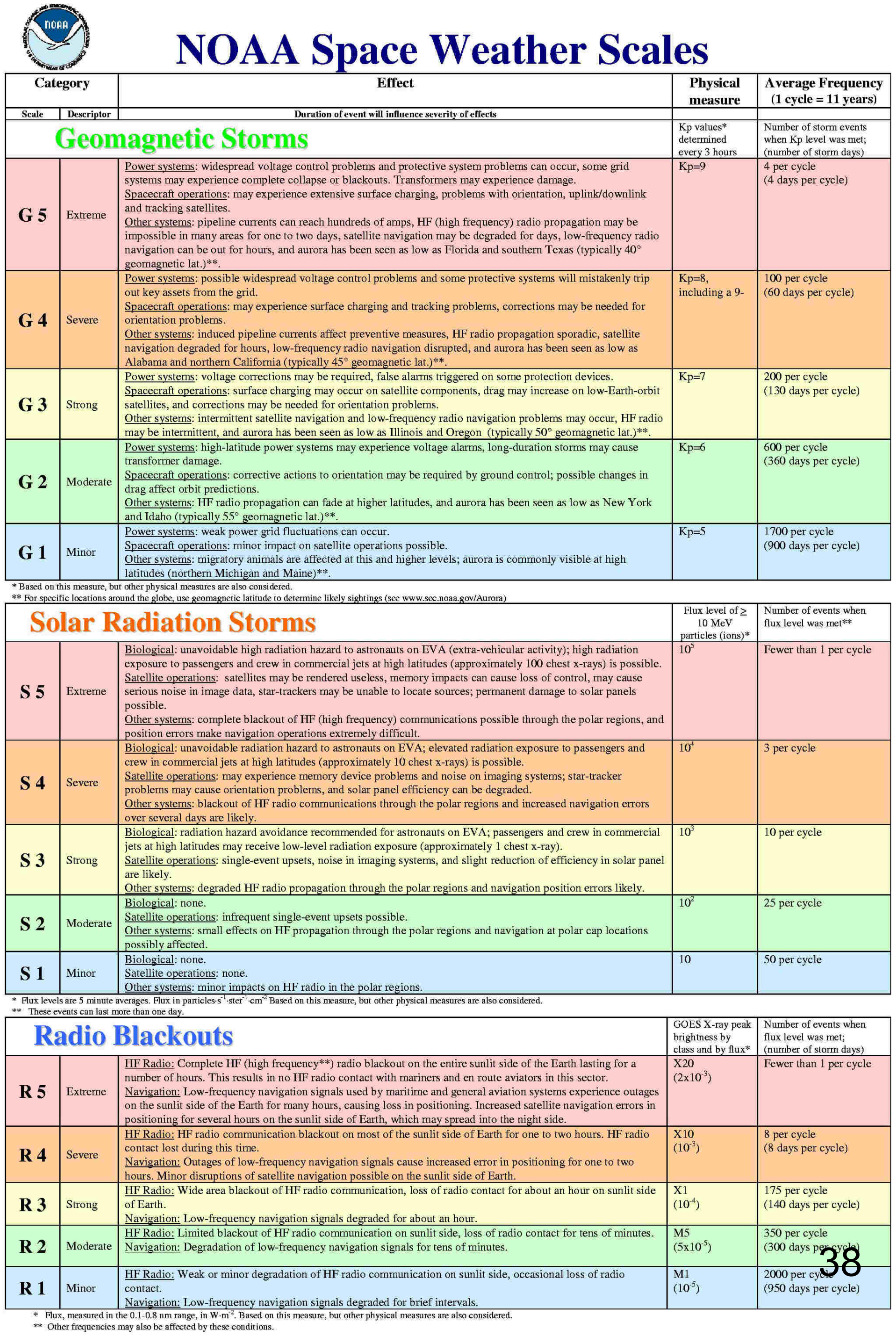


How Bad Can Space Weather Be?

3 Categories

- Geomagnetic Storms (CMEs)
- Solar Radiation Storms (Particle Events)
- Radio Blackouts (Solar Flares)

http://www.swpc.noaa.gov/noaa-scales-explanation



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, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp=5	1700 per cycle (900 days per cycle)

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

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

		Solar Radiation Storms	Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: none. Satellite operations: infrequent single-event upsets possible. Other systems: small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

		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, 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, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

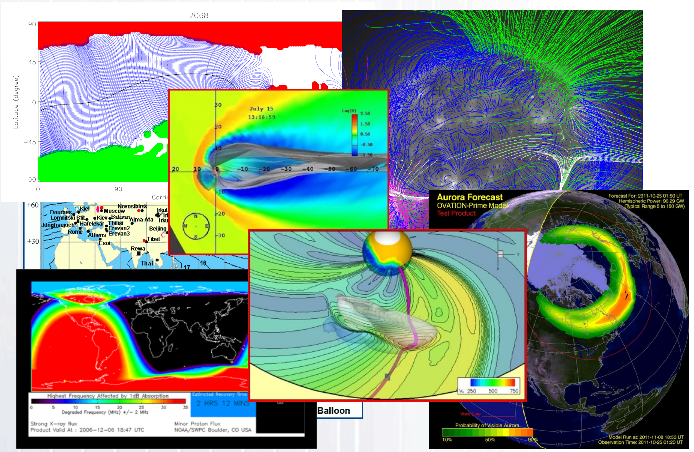
* Flux, measured in the 0.1-0.8 nm range, in W·m^{-2}. Based on this measure, but other physical measures are also considered.

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

Perfect Storm: Hurricane Harvey, Irma, & Region 2673

НА СОЛНЦЕ ПРОИЗОШЛА НОВАЯ МОЩНАЯ ВСПЫШКА

Space Weather Forecasting: A Return to the Sixties



Space Weather Prediction Centers

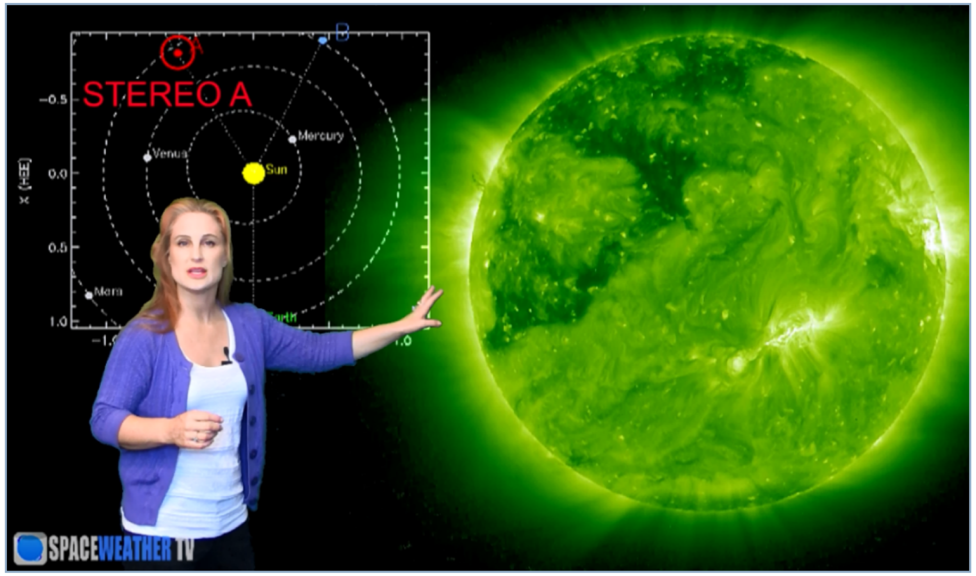
- Developed mainly as a response to super storms
- Models that predict solar fields, CME transit, magnetospheric responses→ solar storm alerts
- Radio blackouts, solar radiation storms→ FAA alerts
- Space & ground telescopes for 24/7 monitoring of Sun
- “Spaceship Earth” networks

~1960

Harry Volkman: Broadcast Meteorologist

Today

Tamitha Skov: Broadcast Space Meteorologist



Our Future Relies on Space

Reliance on Space is advancing:

- Satellite launch rate unprecedented
- wireless technologies
  - *GPS use ubiquitous, ADS-B*
  - *Satellite internet, TV, radio, social media connections*
  - *Google “O3B” satellites*
- Self-driving cars on the ground
  - *CA law passed in 2012 Google car can share public roads*
- Unmanned Aerial Vehicles (UAVs)
  - *FAA allowed drones to share commercial airspace in 2015*
- Space tourism
- The list goes on and on…

Big solar storm hitting Earth

By **Amanda Barnett**, CNN

updated 11:12 AM EDT, Tue September 16, 2014 | Filed under: Innovations

Solar flare races toward Earth

Source: CNN

Our Future Relies on Space

Reliance on Space is advancing:

- Are we prepared?
- Space weather is like the weather in your own backyard just a little further up.

Help me create the field of Space Weather Broadcasting! For more info visit:

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- ***Space Weather Woman*** *on Facebook*
- *SpaceWeatherWoman@gmail.com*

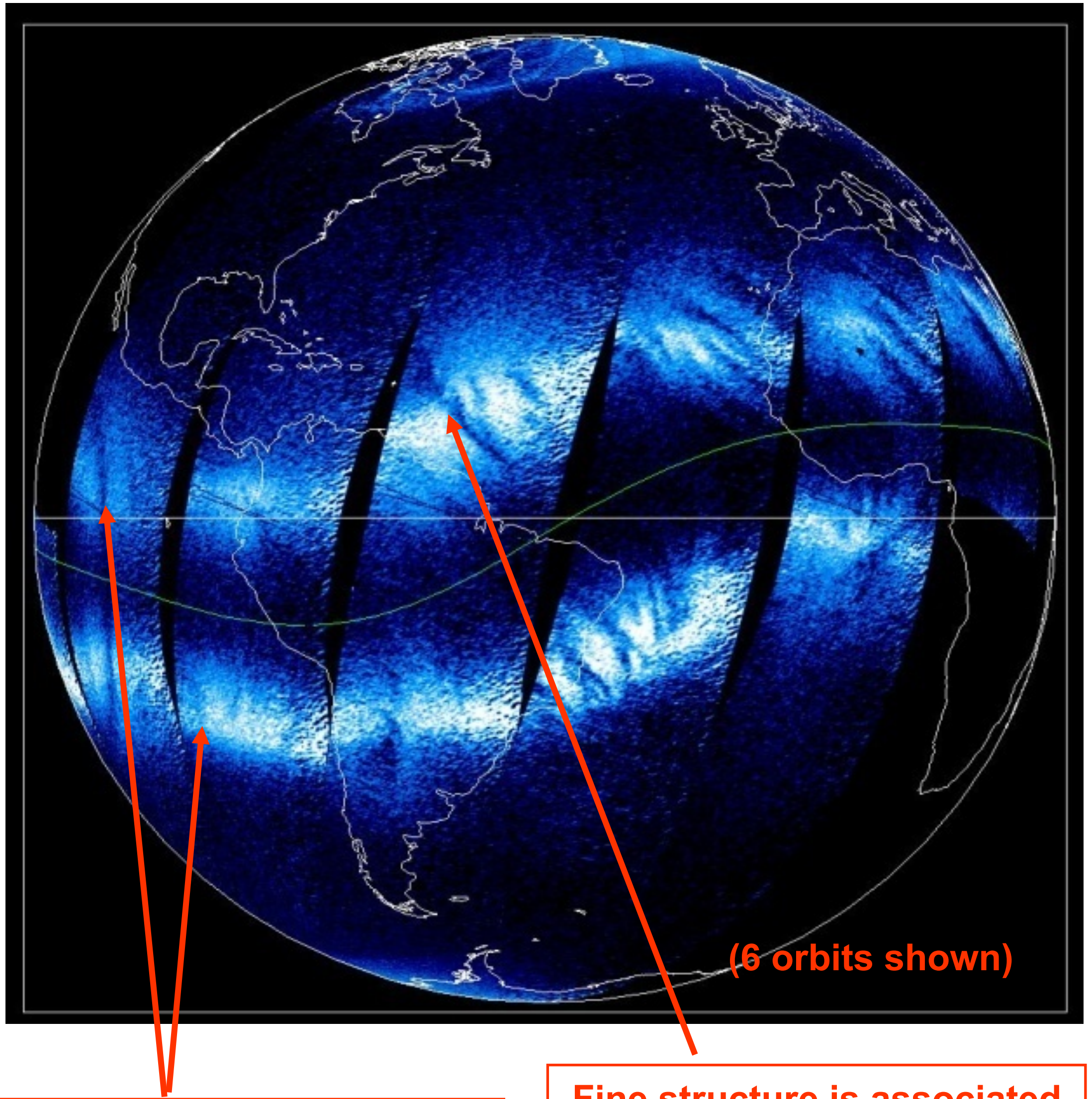
Big solar storm hitting Earth

By Amanda Barnett, CNN
updated 11:12 AM EDT, Tue September 16, 2014 | Filed under: Innovations

Solar flare races toward Earth

Effects of Ionospheric Scintillation

- Ionospheric scintillation is generated by irregularly structured ionospheric regions that cause refraction and scattering of trans-ionospheric radio signals
  - *When received at an antenna, these signals present random temporal fluctuations in both amplitude and phase*
- Effects on navigation systems
  - *Ionospheric scintillation causes signal power fading, phase cycle slips, receiver loss of lock, geo-location errors, etc. that degrade the quality of satellite navigation and communications systems*
- Shown is GUVI data aboard NASA weather satellite



Bright regions on either side of geomagnetic equator are the high-density "Appleton Anomaly"

Fine structure is associated with scintillation regions