Space Weather Core Concepts

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Summary

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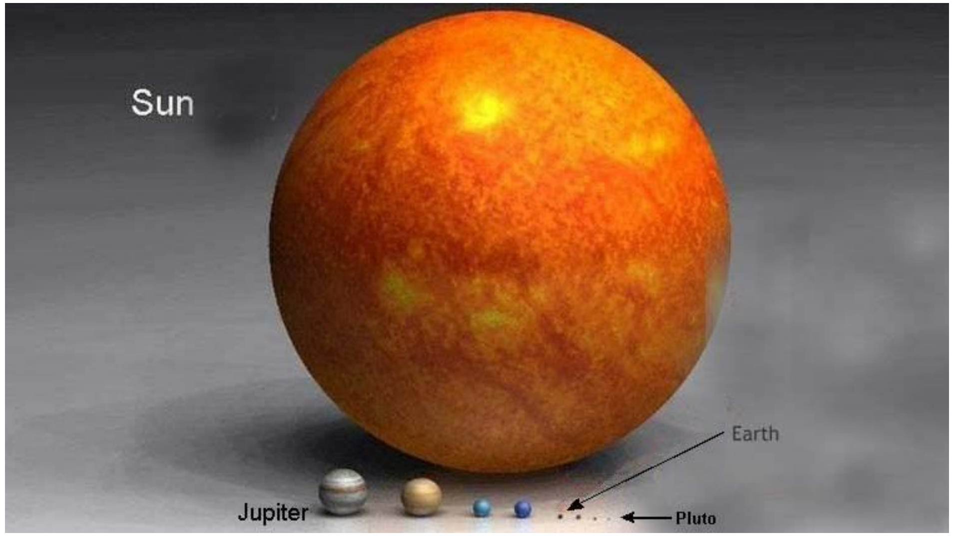
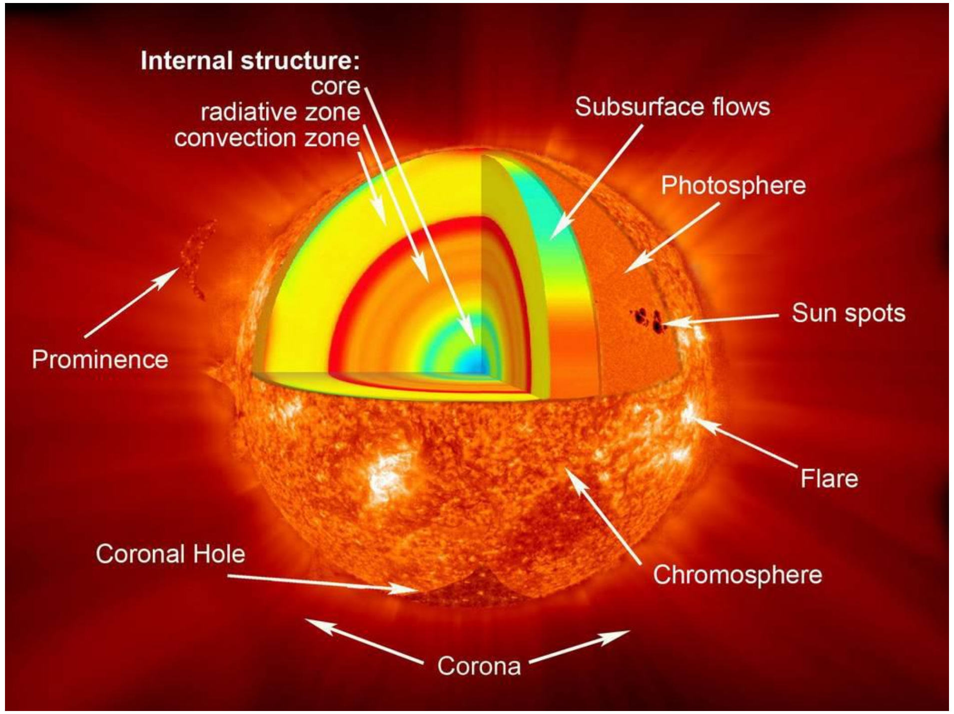
WHAT IS SPACE WEATHER ?

Sun-Solar Wind-Magnetosphere-Ionosphere-Thermosphere

Space Weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems.

The Sun and it's Properties

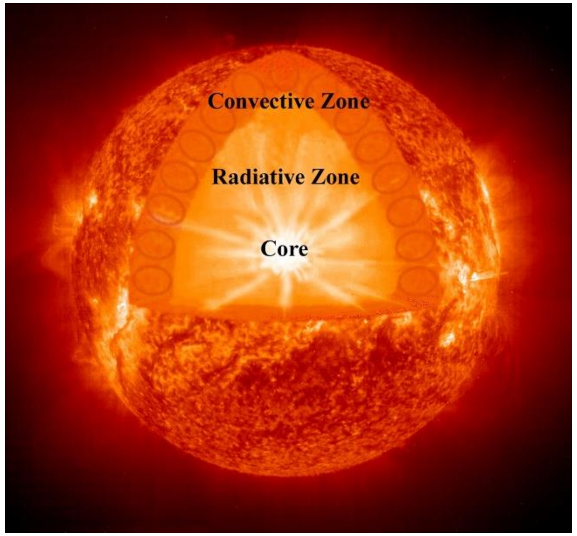


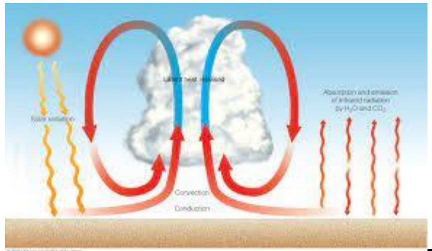


An ordinary star at the center of the solar system.

Gravity at the core is so strong that nuclear fusion turns hydrogen into helium. This energy works its way to the surface over thousands of years.

In the outer 1/3, energy is transported by convective overturning. This motion of ionized gas creates a magnetic field.





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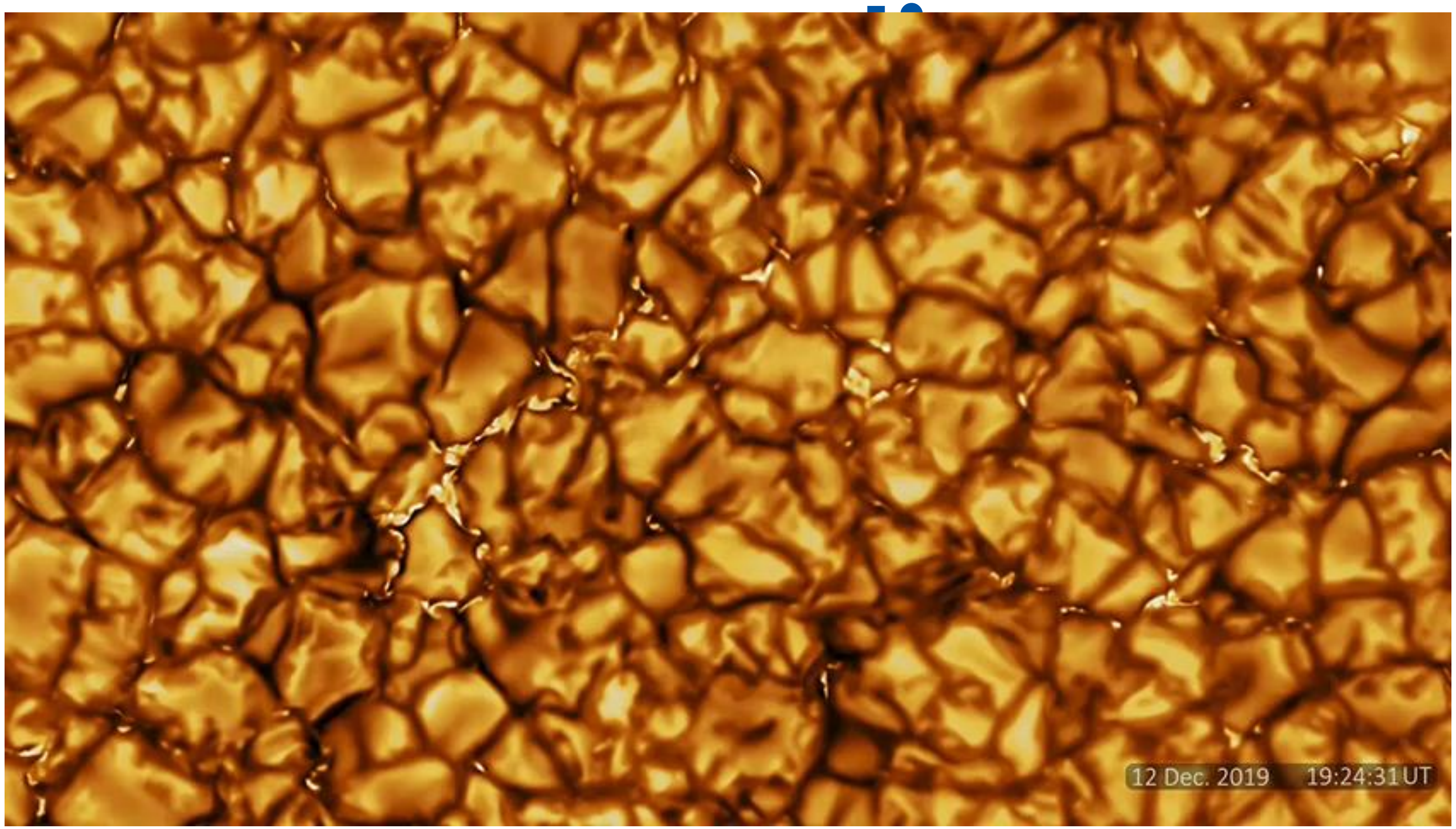
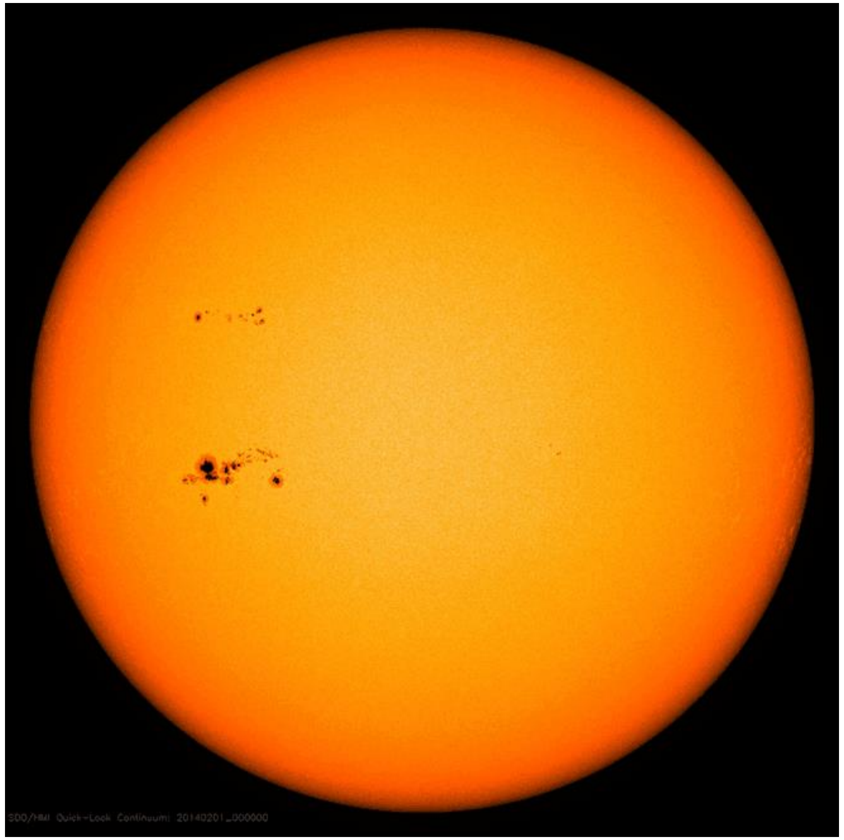
The Sun and it's Properties

- ✓ The Sun is a huge, glowing sphere of hot gas known as plasma.
- ✓ Most of this hot gas is hydrogen (about 70%) and helium (about 28%).
- ✓ Plasma is the fourth state of matter.
- ✓ The surface temperature of the Sun is approximately 6000 degrees Celsius.
- ✓ The age of the Sun is estimated to be around 4.6 billion years.
- ✓ The distance from Sun to the Earth is about 149 million km.
- ✓ The Sun has a diameter of about 1,391,000 km. This is about 109 times the diameter of Earth. The Sun weighs about 333,000 times as much as Earth. It is so large that about 1million planet Earths can fit inside of it.

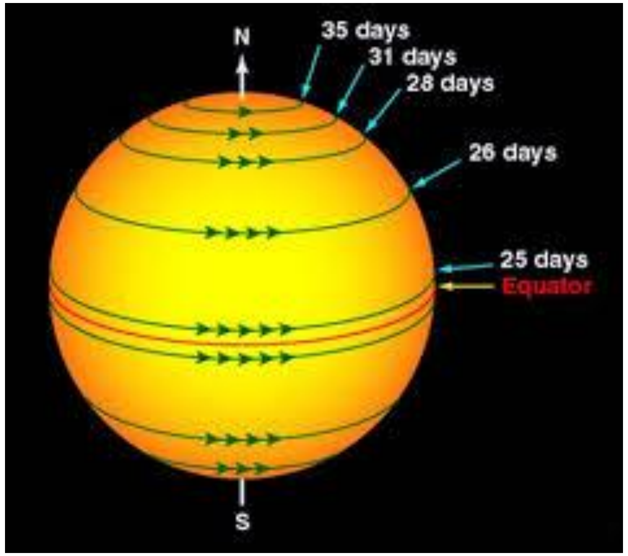
Close up of the surface: constant



Sun in visible light



- The Sun rotates with a period of about 27 days near the equator.
- The Sun rotates slower at the poles and takes about 35 days for a full rotation
- Unlike the Earth, there are no permanent features on the Sun. There are magnetic structures that emerge and last for a few months, then dissipate.



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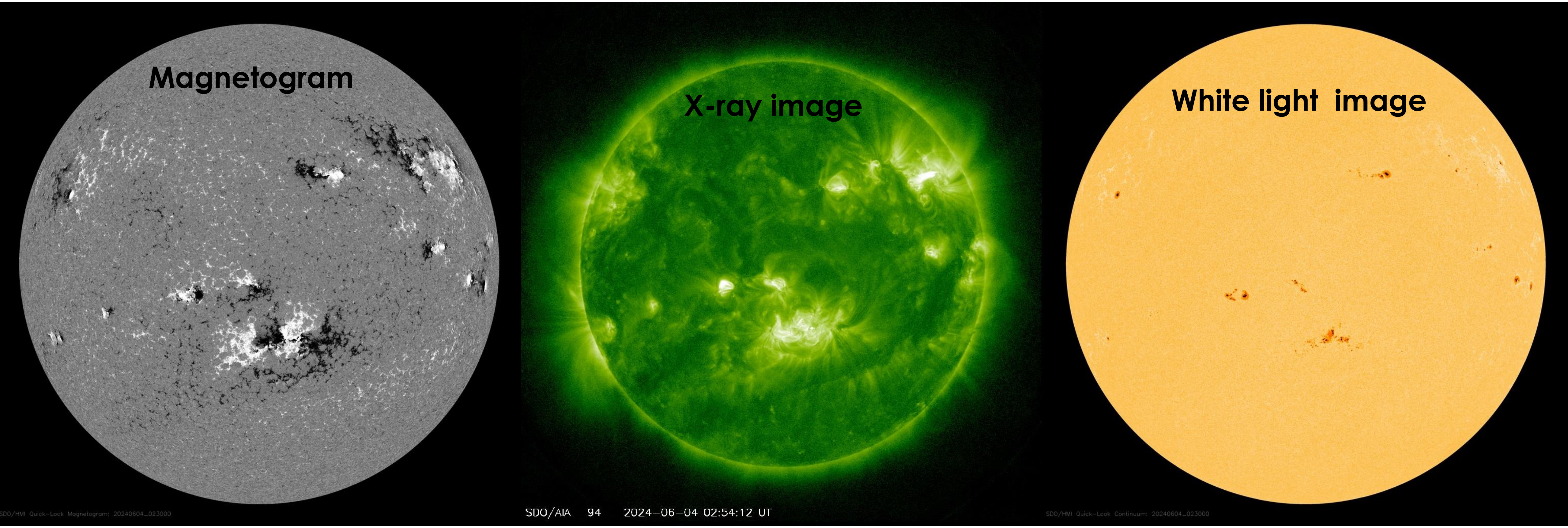
Active Regions and Sunspots

- Active regions are areas on the Sun with very strong magnetic fields. Sunspots are dark areas and cooler parts of the Sun's surface caused by massive changes in the Sun's magnetic field.



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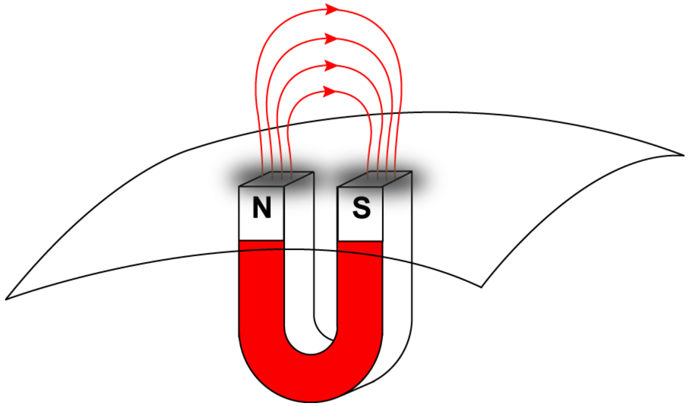
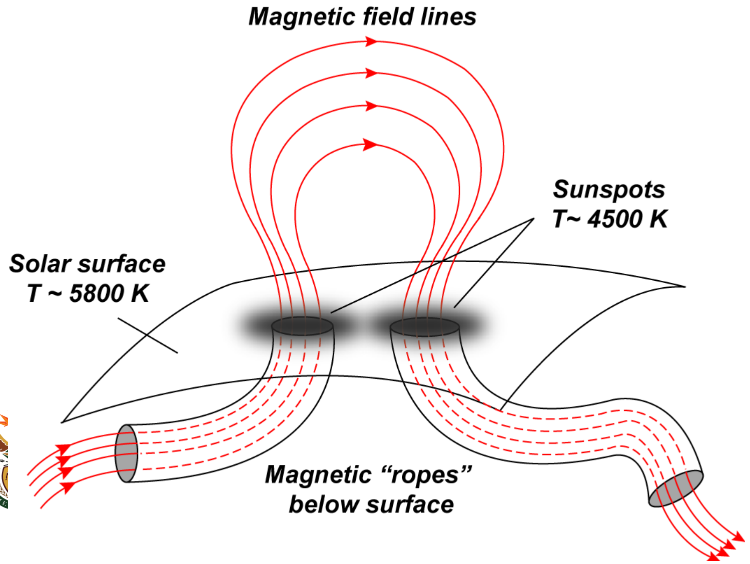
Active Regions and Sunspots

The formation of sunspots





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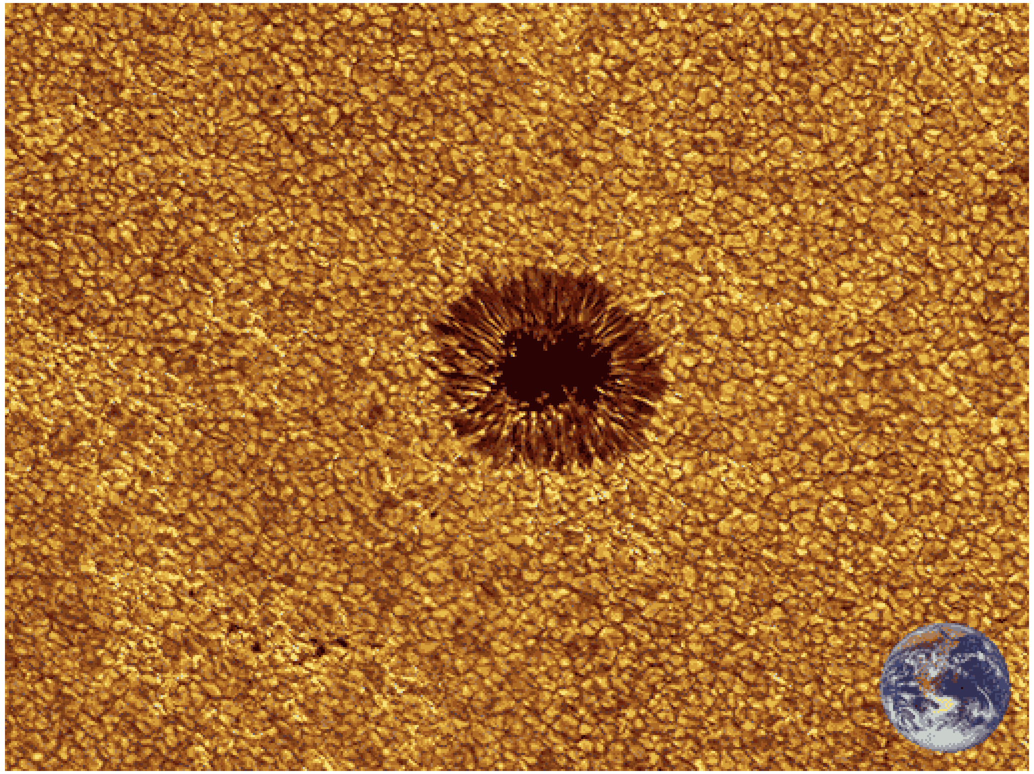
Active Regions and Sunspots

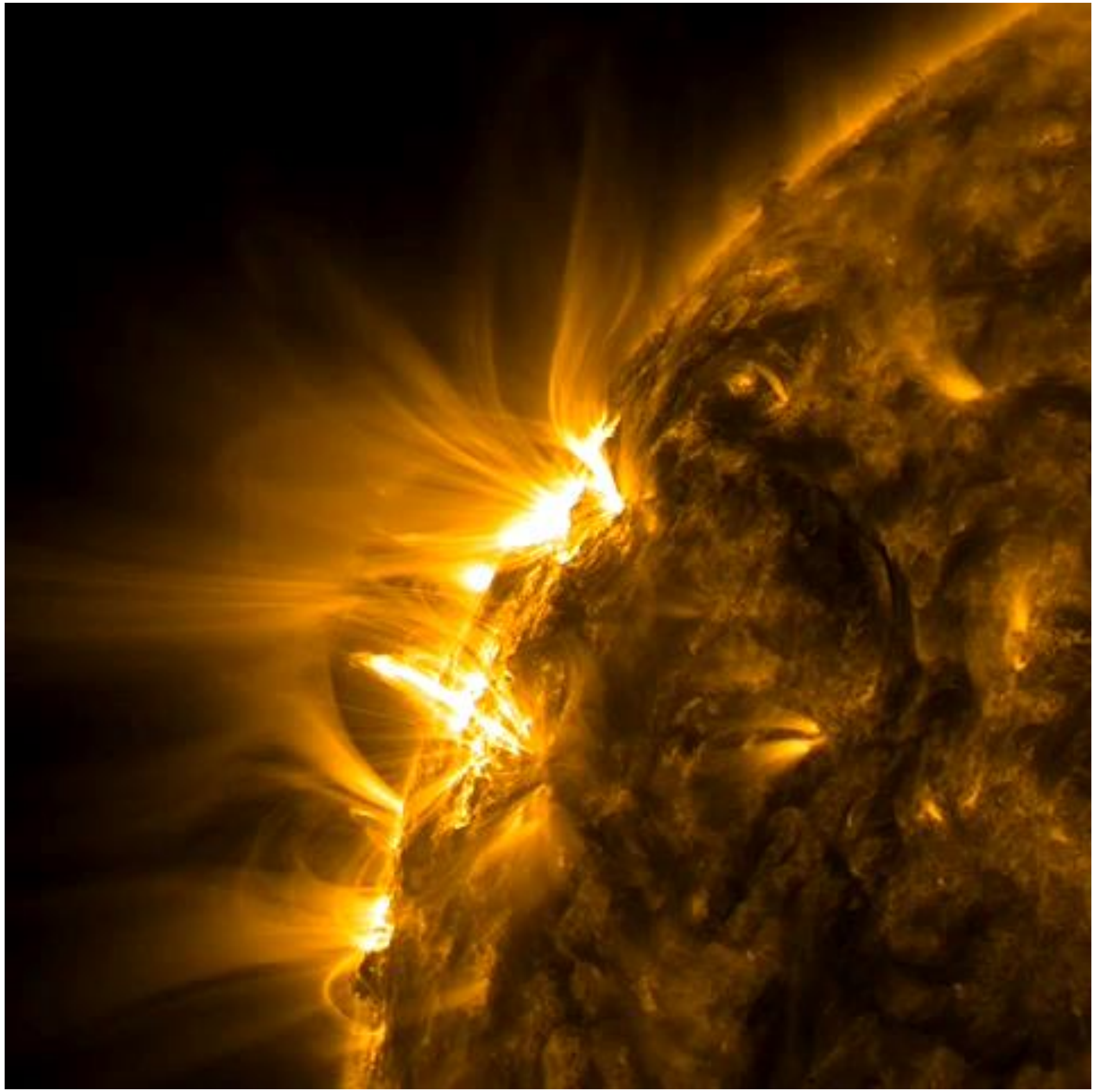
Sunspot

- A sunspot is part of a larger structure known as an Active Region.
- Sunspots are dark, but only last about one rotation.
- The bright region surrounding a sunspot is known as "facula" and can last for several rotations.
- The interplay between bright faculae and dark sunspots causes variations in solar irradiance.



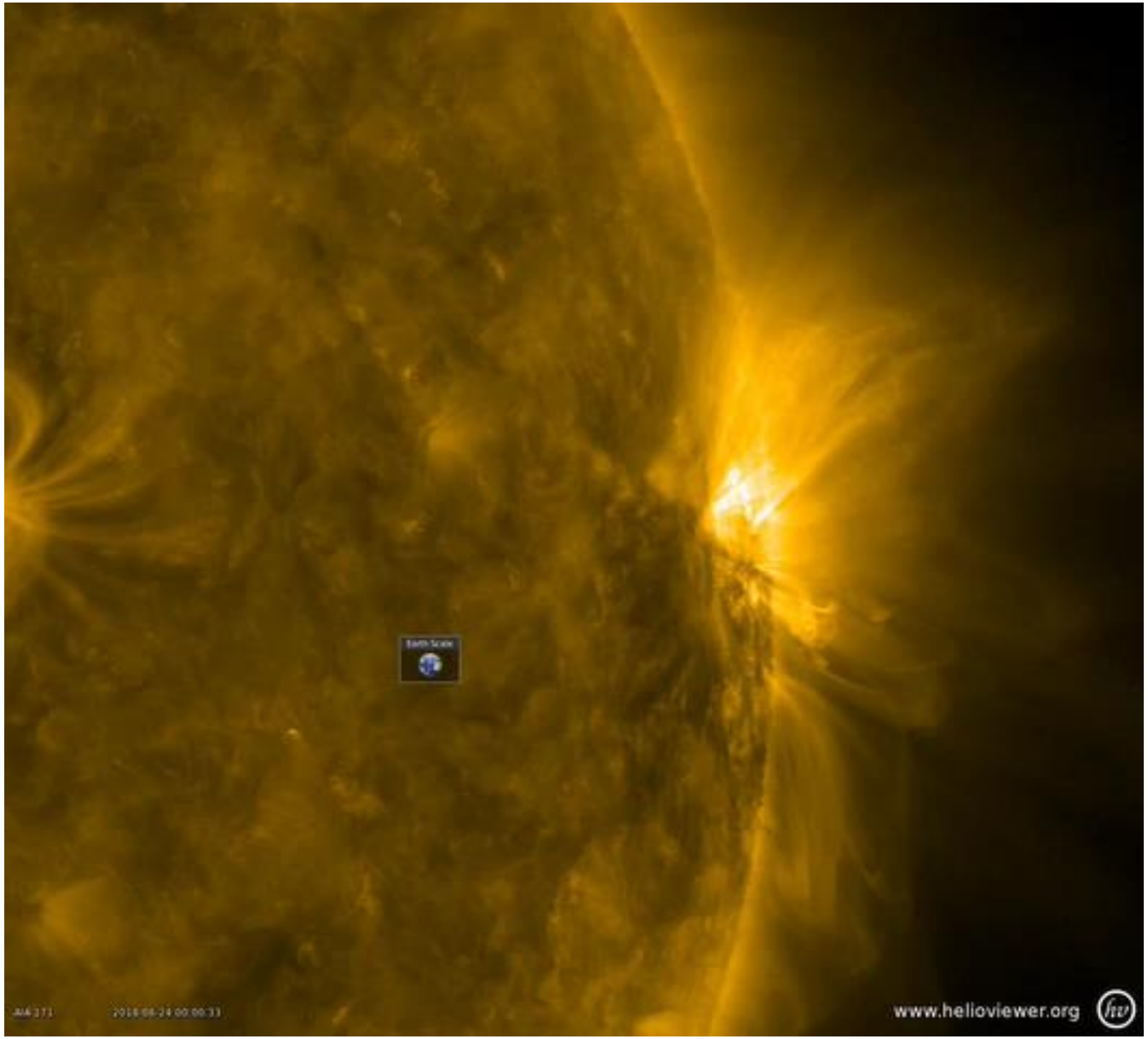
Active Regions and Sunspots

- Sunspots usually come in pairs (positive and negative polarities), connected by strong magnetic field.
- Charged particles (plasma) stay trapped in the magnetic field.
- The plasma illuminates the magnetic structures.

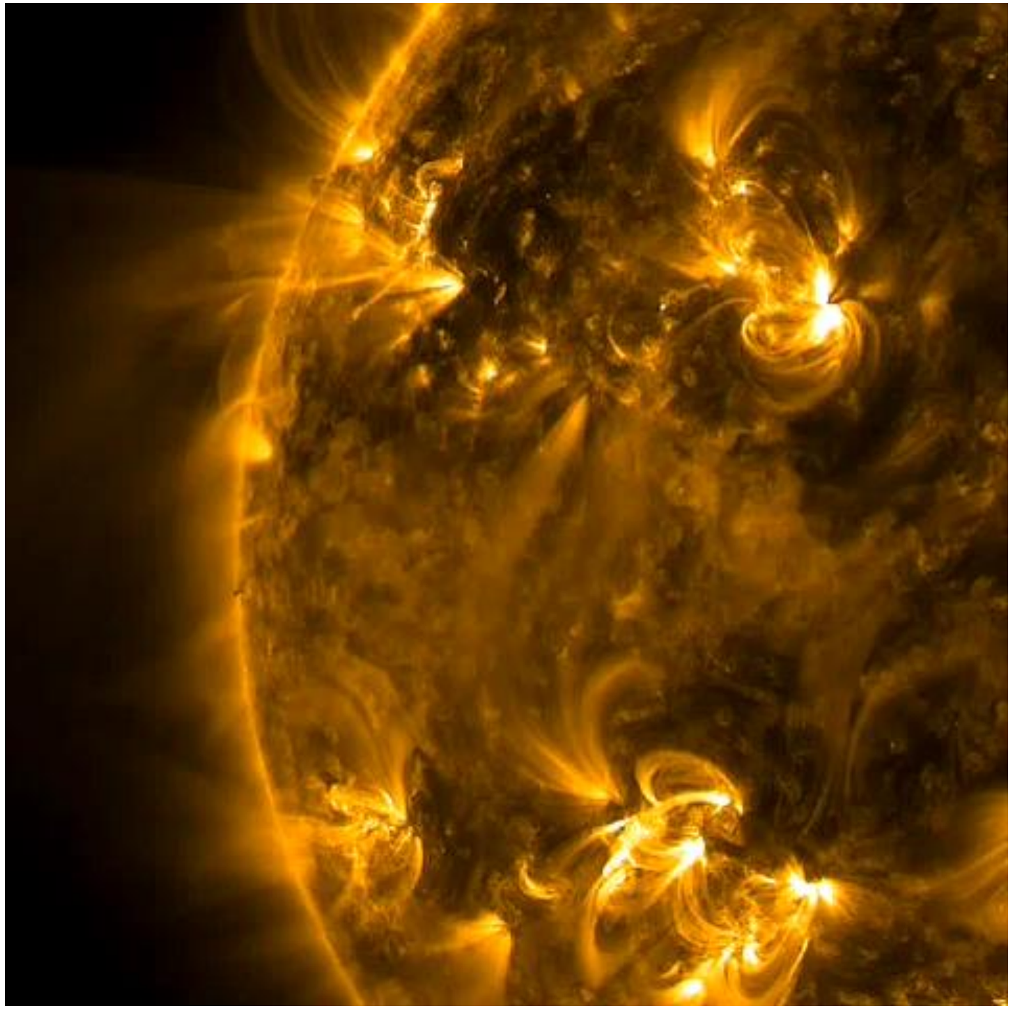


Active Regions and Sunspots

Earth to scale



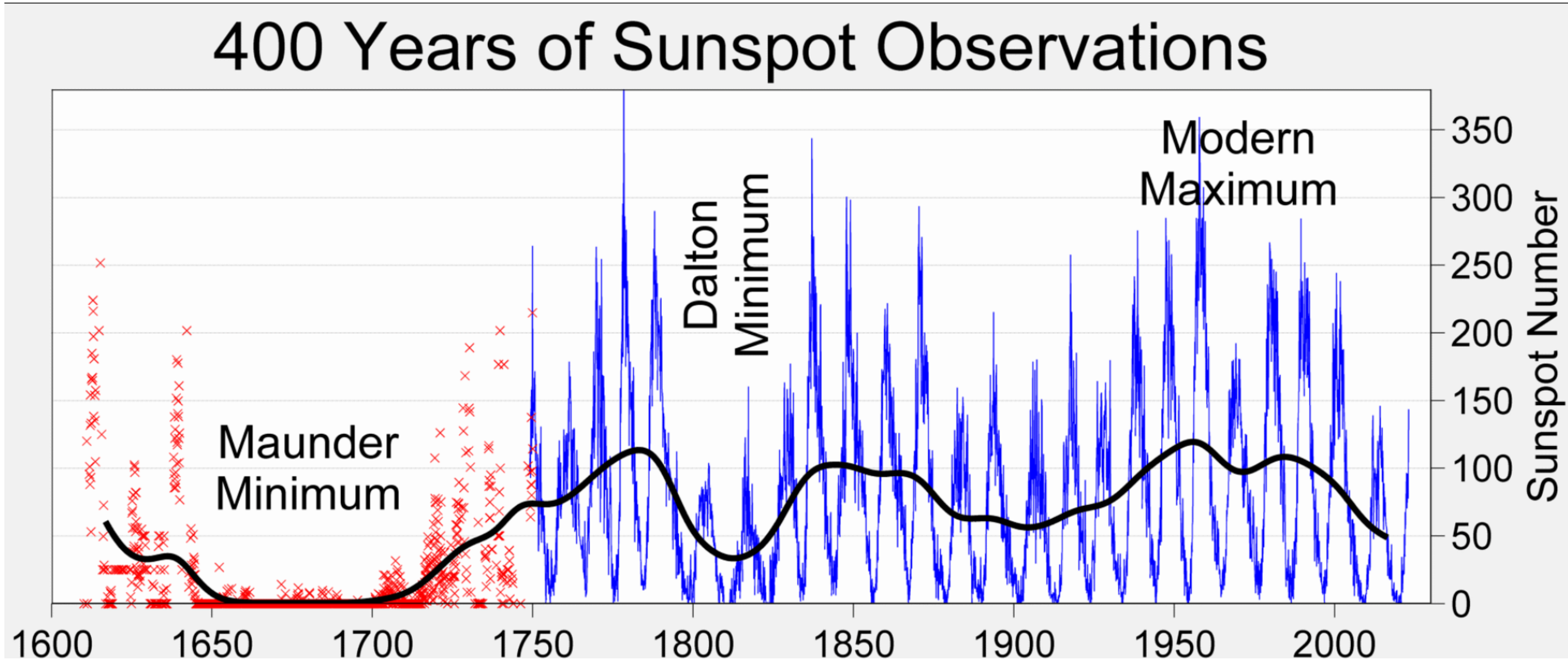
- Connection between active regions can extend very far.
- Remember how large the Sun is compared to the Earth!

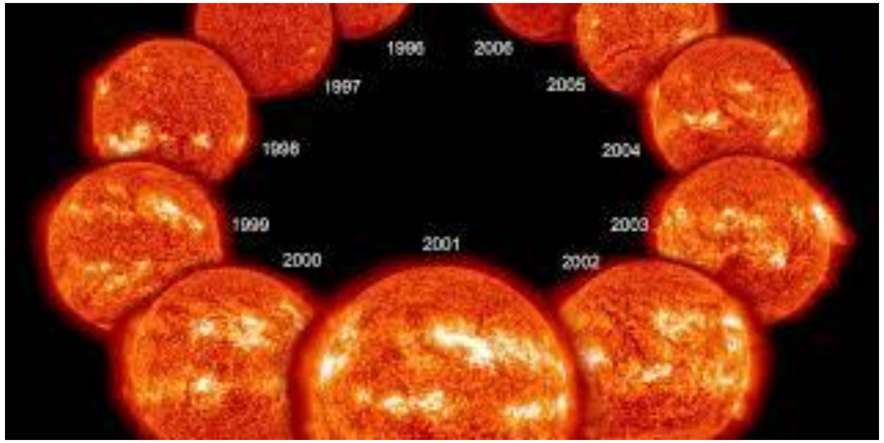


Solar Cycle Activities

- The solar cycle is a nearly periodic 11-year change in the Sun's activity measured in terms of variations in the number of observed sunspots on the Sun's surface.

- During solar cycle, there is a period of minimum activity to a period of a maximum activity back to a period of minimum activity. This is commonly known as solar minimum and solar maximum.





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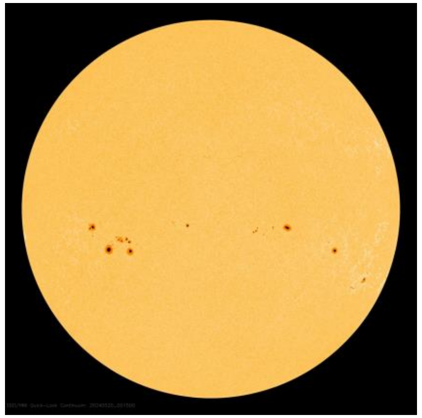
The Solar Cycle Activities



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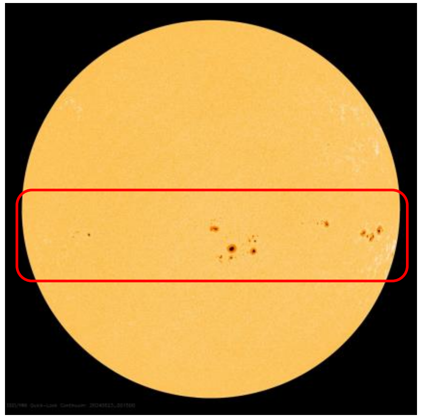

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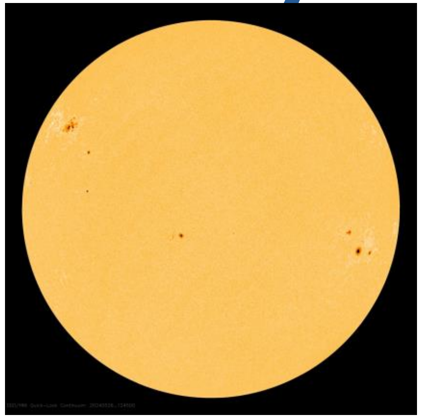

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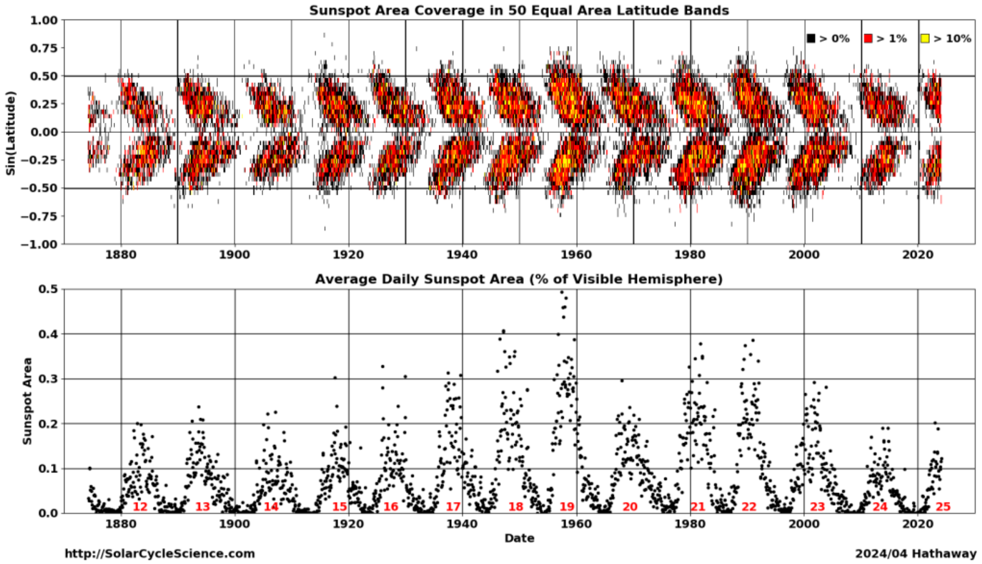
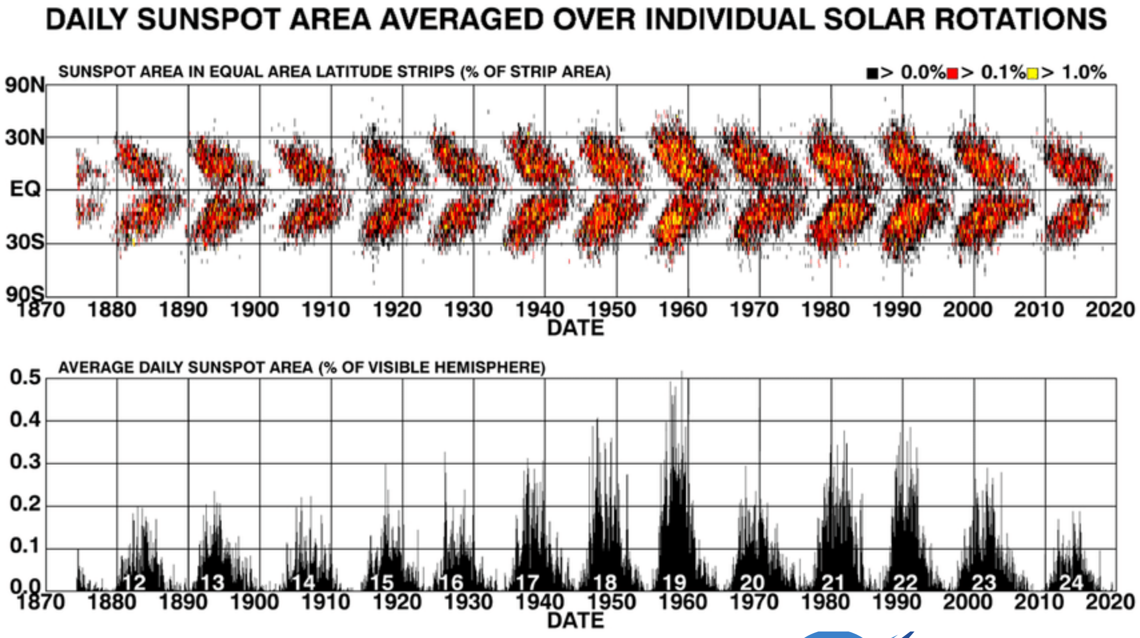
- The emergence of active regions on the Sun is an integral feature of the solar dynamo mechanism





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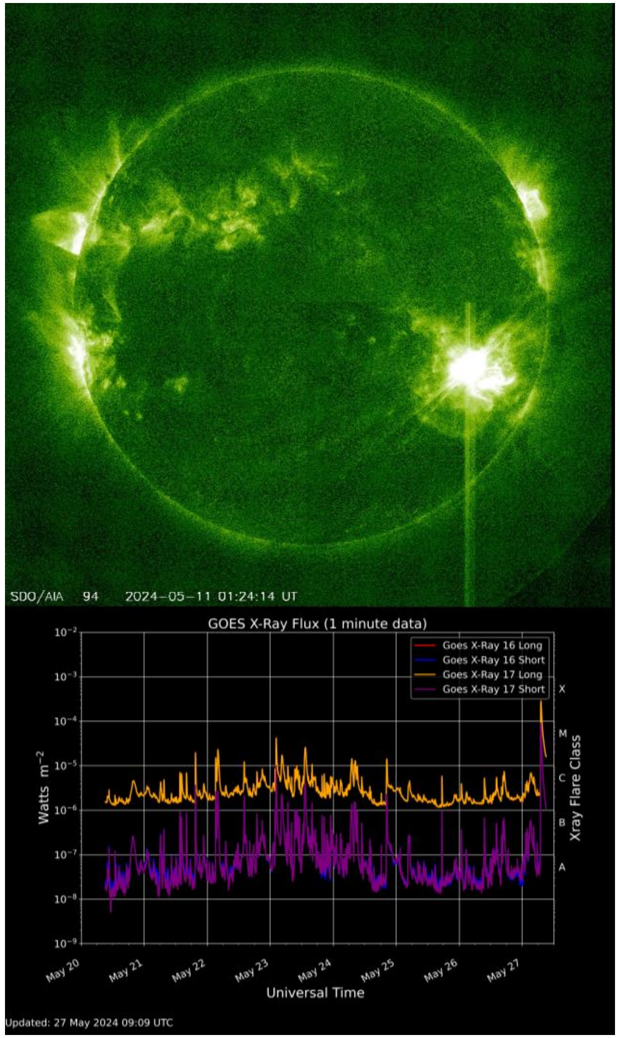
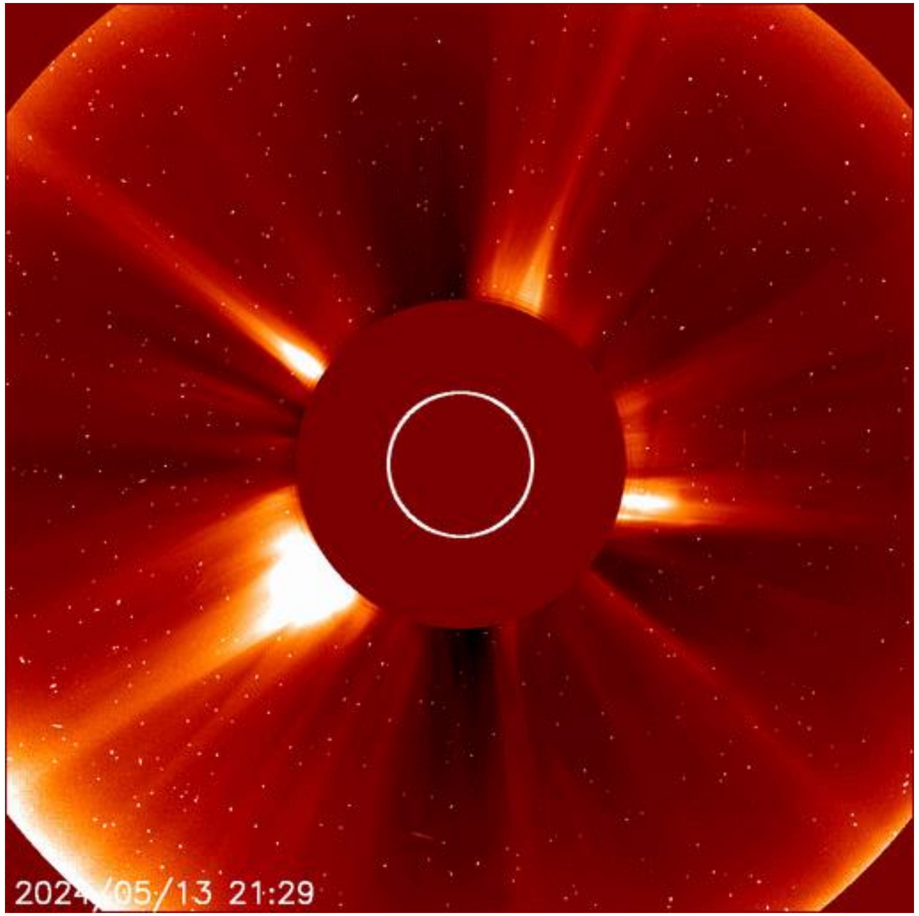
Solar Storm Events

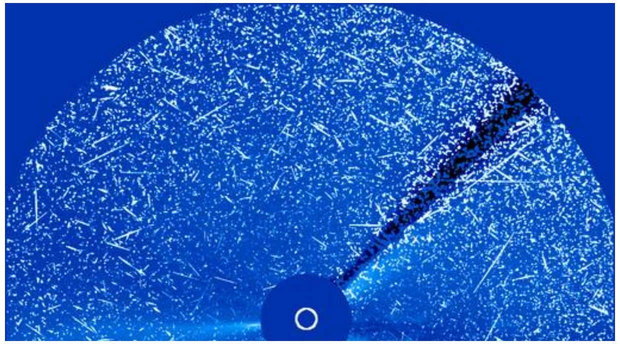
Solar Flares

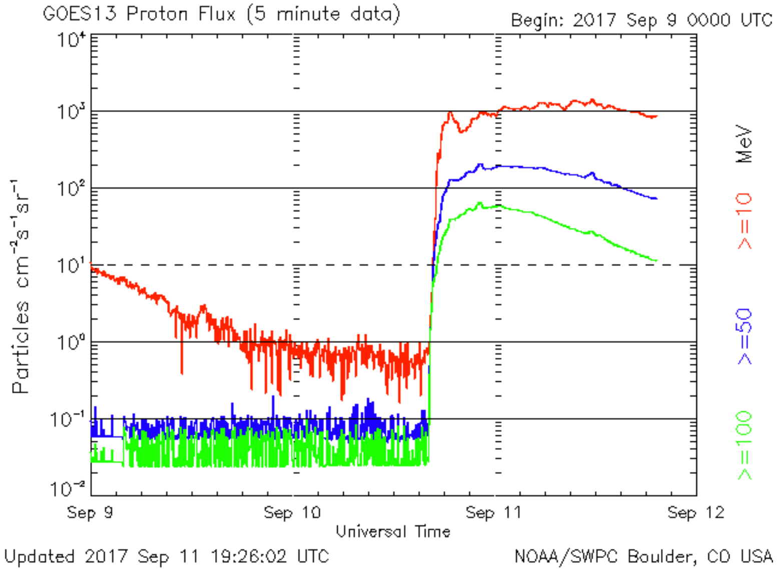


Coronal Mass Ejection (CME)



Solar Energetic Particles (SEPs)





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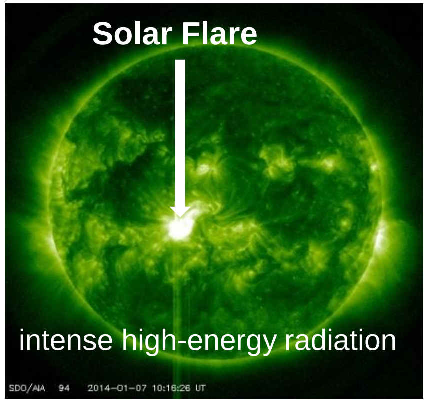

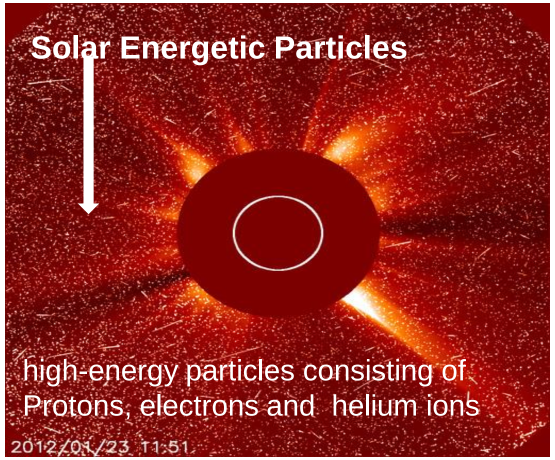

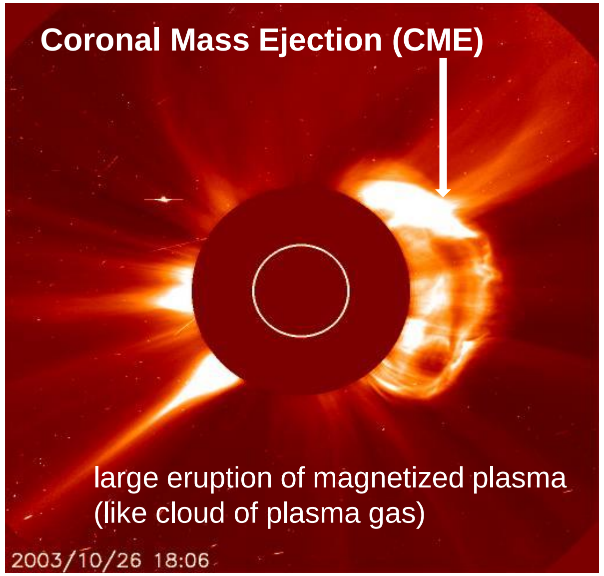

Solar Flares

- Arrive at Earth in 8 minutes
- Increase ionization in the ionosphere
- Disrupt HF radio communication
- Impacts:
  - Airline communication
  - HF radio operators
  - DoD Communications
  - Satellite Communications

Solar Energetic Particles

- Arrive at Earth in 15 minutes to few hours
- Increase ionization in the high latitude ionosphere
- Ionizing radiation penetrates into the atmosphere
- Disrupt HF radio communication
- Impacts:
  - Airline communication
  - HF radio operators
  - DoD Communications
  - Radiation exposure to pilots & crew
  - Astronauts (radiation)
  - Satellite failures

Coronal Mass Ejection (CME)

- Arrive at Earth in 1-4 days
- Accelerate particles within the magnetosphere and into the ionosphere
- Impacts:
  - HF radio communication
  - Radio Navigation (GPS)
  - Electric Power Grids and pipelines
  - Increased Satellite Drag
  - Aurora

Summary: Core Concepts

- ✓ Is the Sun a start? Y/N
- ✓ How hot is the Sun?
- ✓ 6000 degrees Celsius
- ✓ How many Earths could fit inside the Sun?
- ✓ About 1 million Earths
- ✓ What is the distance between the Sun and the Earth?
- ✓ 149 million km
- ✓ How long is a full rotation of the Sun near the equator?
- ✓ 27-day rotation


THANK YOU

Space weather impact on aviation systems or Technological Infrastructure

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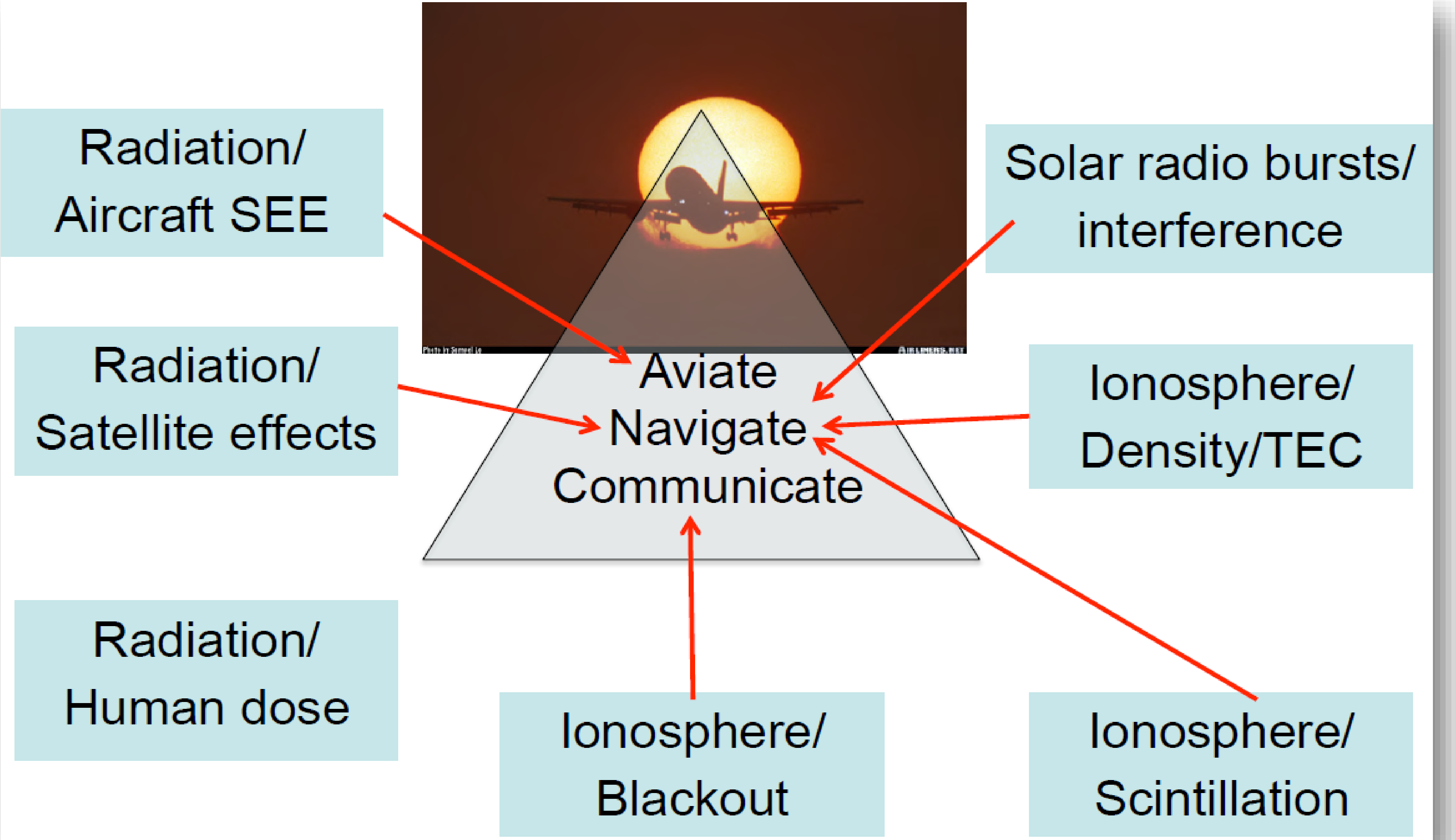


Radiation/
Aircraft SEE
Solar radio bursts/
interference
Radiation/
Satellite effects
Aviate
Navigate
Communicate
Ionosphere/
Density/TEC
Radiation/
Human dose
Ionosphere/
Blackout
Ionosphere/
Scintillation

WHY SHOULD WE CARE ABOUT SPACE WEATHER

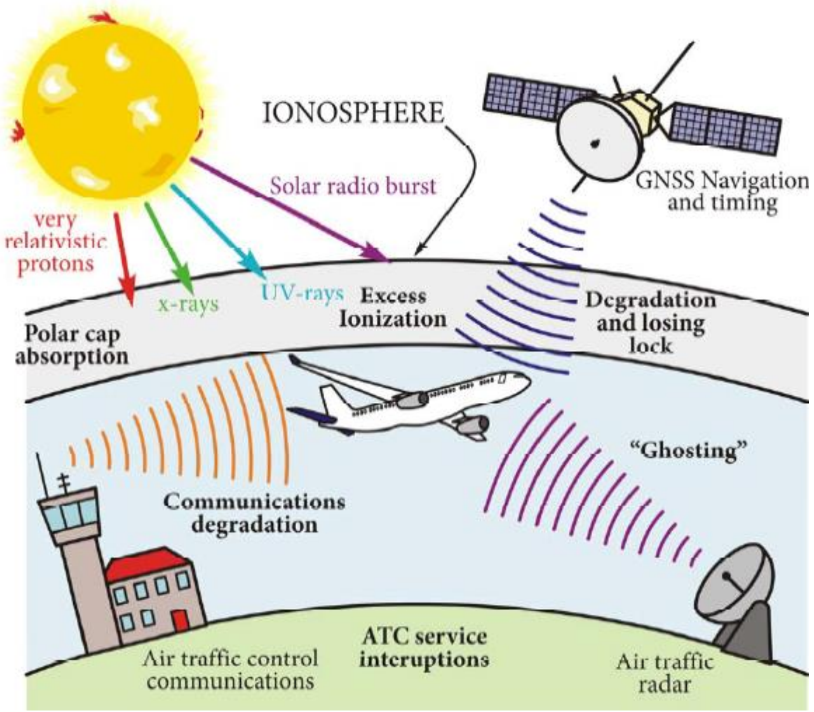
- Technology continues to play an ever-increasing role in our society and the potential for space weather to impact our daily lives and the economy is growing.
- Technological infrastructure, including the power grid, transport systems, communication, and electronic systems are vulnerable to space weather effects caused by the Sun.
- Space weather can cause significant disruption to everyday technologies such as Position, Navigation and Timing (PNT) systems (for example Global Navigation Satellite Systems (GNSS)), satellites, and radio communications, as well as our critical infrastructure such as transportation networks, and the electricity grid.

WHY SHOULD WE CARE ABOUT SPACE WEATHER

Space Weather Impacts on Aviation

Impact of Space Weather Impact on Aviation in the following areas:

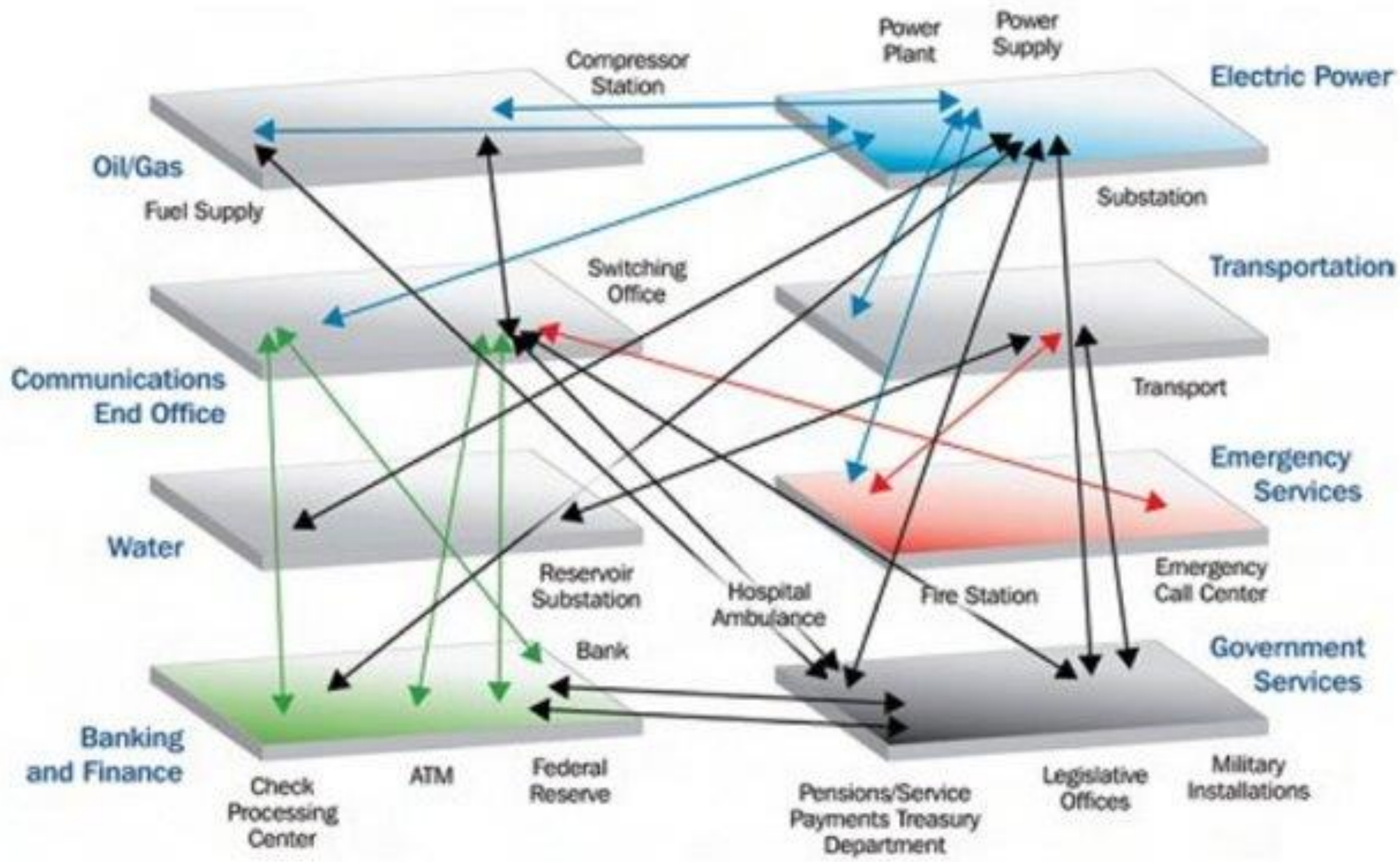
- ❑ HF communications,
- ❑ Satellite (loss of lock, scintillation, damages on electronics),
- ❑GPS/GNSS
- ❑ Radiation exposure.



HF radio communication is used by the aviation industry, the shipping industry, emergency responders, the amateur radio operator ("ham") community (Frissell et al., 2022, 2019), and the military (Balch et al., 2004; Kelly et al., 2014).

Mobile phone networks and global navigation satellite system (GNSS) timing services can also be affected and debilitated by solar flare radio noise (Kintner et al., 2009; Cannon et al., 2013).

Space weather impact: Interdependencies



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Space weather can lead to a cascade of catastrophic failures of power supply, emergency services, water, satellite communication, transportation, financial, and other essential infrastructure.

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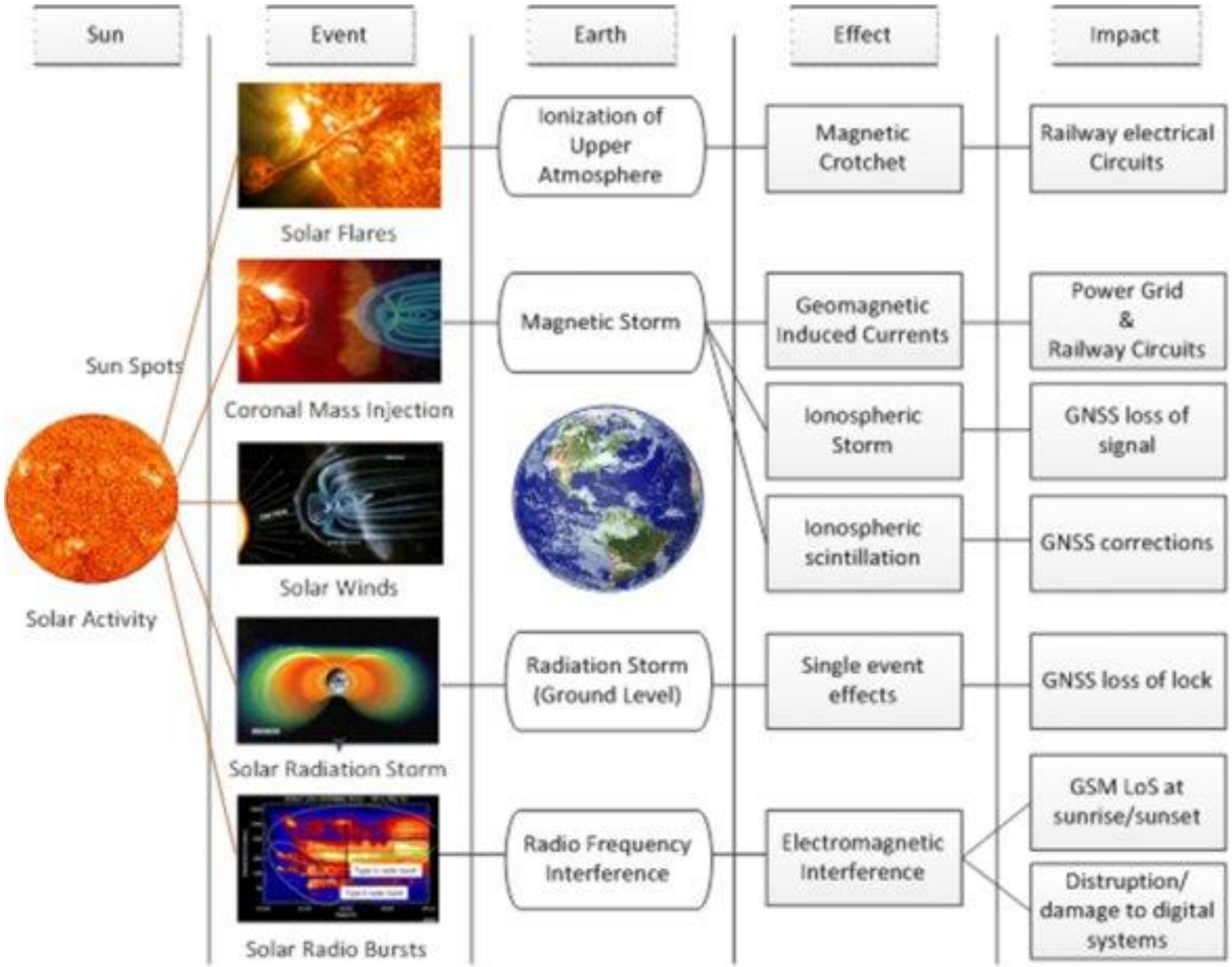
Space weather impact



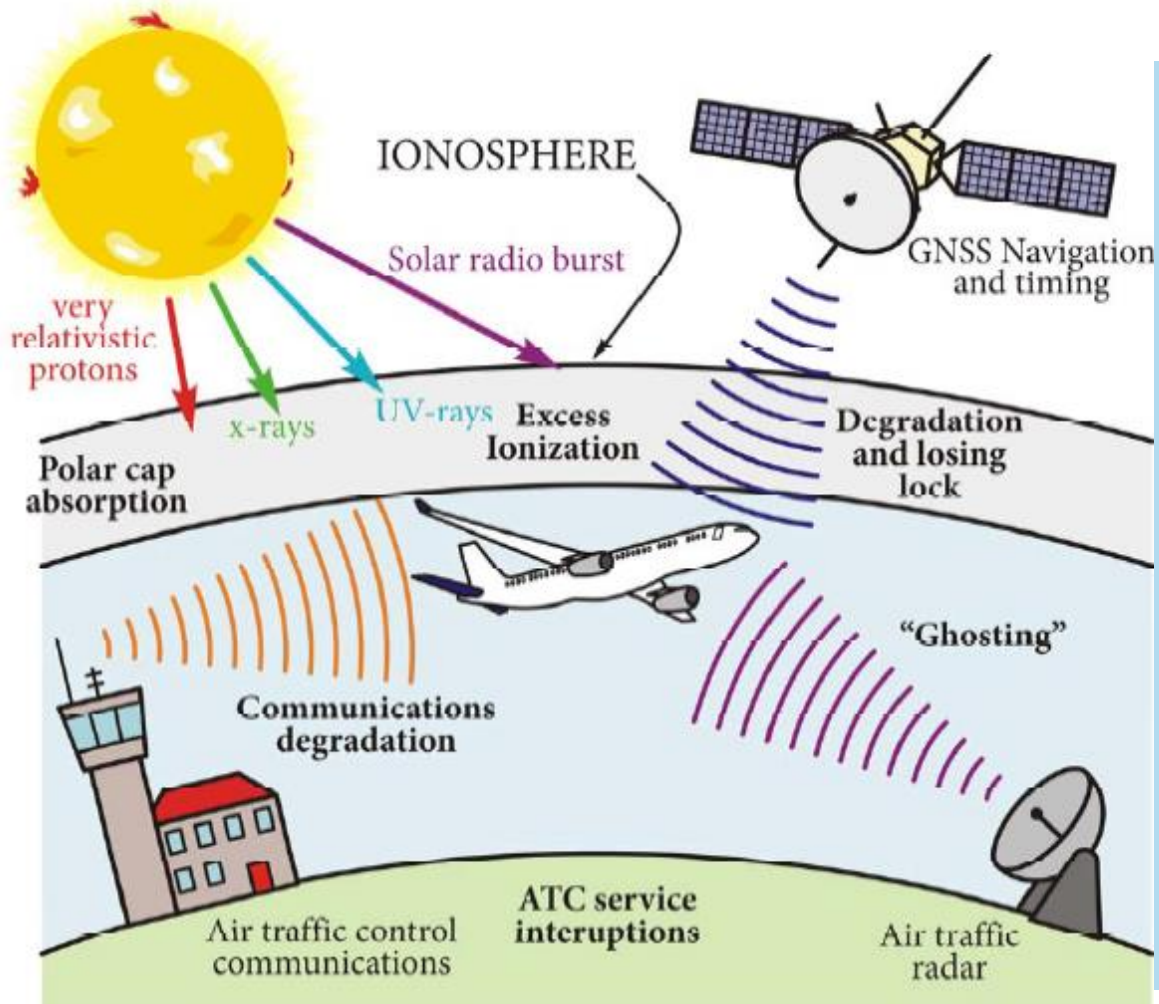
Aviation related systems and Space Weather

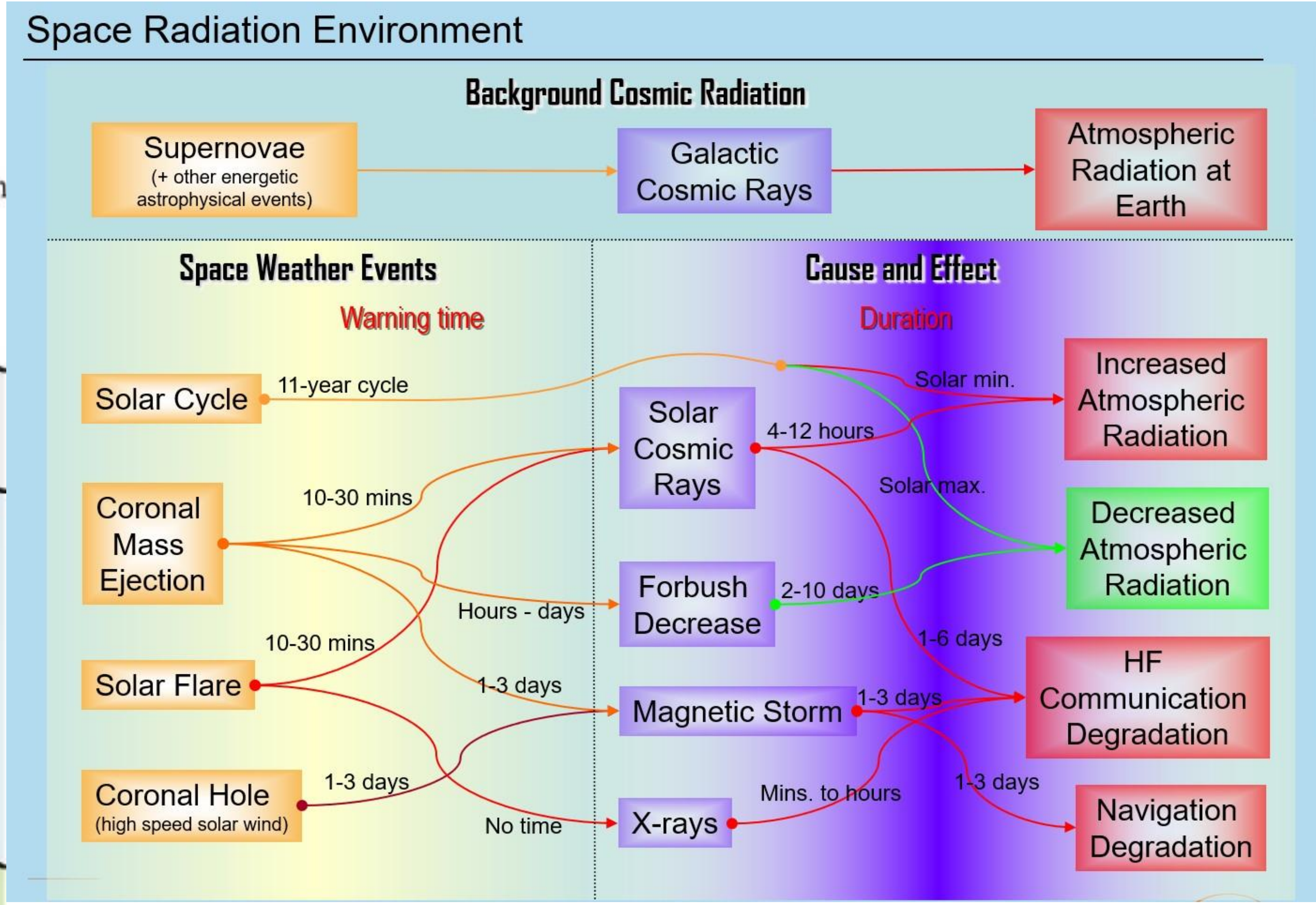
SOLAR EVENT	Solar Flare				CME		Solar Wind	Galactic Cosmic Rays	
SECONDARY EFFECT	X-Ray Emissions	Ultraviolet emissions	Radio Bursts	Solar Energetic Protons (SEPs)	Plasma	Solar Energetic Protons (SEPs)	Enhances Radiation Belts		
EFFECT ON EARTH SYSTEM	Increase Ionosphere Density	Ionospheric disturbances			Geo-magnetic Storms		Aurora	Radiation	Ionospheric Scintillation
AVIATION-RELATED SYSTEMS: Passengers/Crew (Biological)				X	X	X		X	
Avionics				X		X		X	
HF Communication	X	X		X	X	X			
GPS/WAAS	X	X	X	X	X	X	X		X
Satellites (Navigation, Communication)	X	X	X	X	X	X	X	X	X
Low Frequency Communication	X		X		X				
ATC facilities		X			X				

- ❑ unexpected loss of communications; HF voice and data link, i.e., controller pilot data link communications (CPDLC), on routes where that manner of communications is used
- ❑ Poor or unusable performance in satellite communications;
- ❑ Degraded performance of navigation and surveillance that rely on GNSS and Automatic dependent surveillance-broadcast (ADS-B) and/or automatic dependent surveillance – contract (ADS-C) anomalies;
- ❑ Sporadic loss-of-lock of GNSS, especially near the equator and post-sunset;
- ❑ Unanticipated non-standard performance of on-board electronics resulting in reboots and anomalies; u Issues related to radiation exposure by aircrew and passengers
- ❑ Communication and navigation form the key functions in modern air traffic management(ATM) they are cornerstones that ensure the safety and efficiency in air traffic.
- ❑ Either the degradation or interruption of communication or navigation, whether on the air routes or near the airports are common reasons for flight delays.
- ❑ Malfunctions of communication and navigation system could be directly attributed to the geomagnetic field fluctuations and ionospheric disturbances driven by SWEs.

https://doi.org/10.1051/swsc/2018029
http://dx.doi.org/10.1029/2018SW001932
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2004GL021467#

Overview of the multiple routes by which space weather events can impact aviation.





Example of Impacts on Radar system

- On November 4th, 2015, several European air traffic authorities reported issues with operations of secondary air traffic radar systems at or near local sunset
- Belgocontrol, the air traffic authority in Belgium, reported issues with a secondary A/C radar.
- False echoes, representing non-existing planes, were observed only in the direction of the Sun during two periods of time: disruptions of the air traffic over the southern part of Sweden occurred on that day resulting in a de facto partial closure of the airspace and delayed arrivals and departures according to reports in the media (The Local, 2015).
- Based on publicly available information from the Swedish air traffic authority (Luftfartsverket; hereafter LFV), ATC secondary surveillance radar systems could not display proper information to the air traffic controllers, which lead the authorities to reduce aircraft movements for safety reasons (**Luftfartsverket, 2015**).
- **A.J. Andersson, 2017** indicates that for this event that a simultaneous series of ATC radar disturbances occurred at several sites in Sweden starting around 14:19 UT.
- On November 4th, 2015, an Air Greenland plane landing at Thule Airbase in Greenland at 14:49 UT experienced technical issues above 4000 feet altitude with a conflicting report between an ILS localizer (at 109.5 MHz) indicating a correct alignment with the runway and the autopilot being unable to hold on that same position information. The landing went without further complications. After the flight the ILS equipment's were checked for malfunction but were cleared of any defect.

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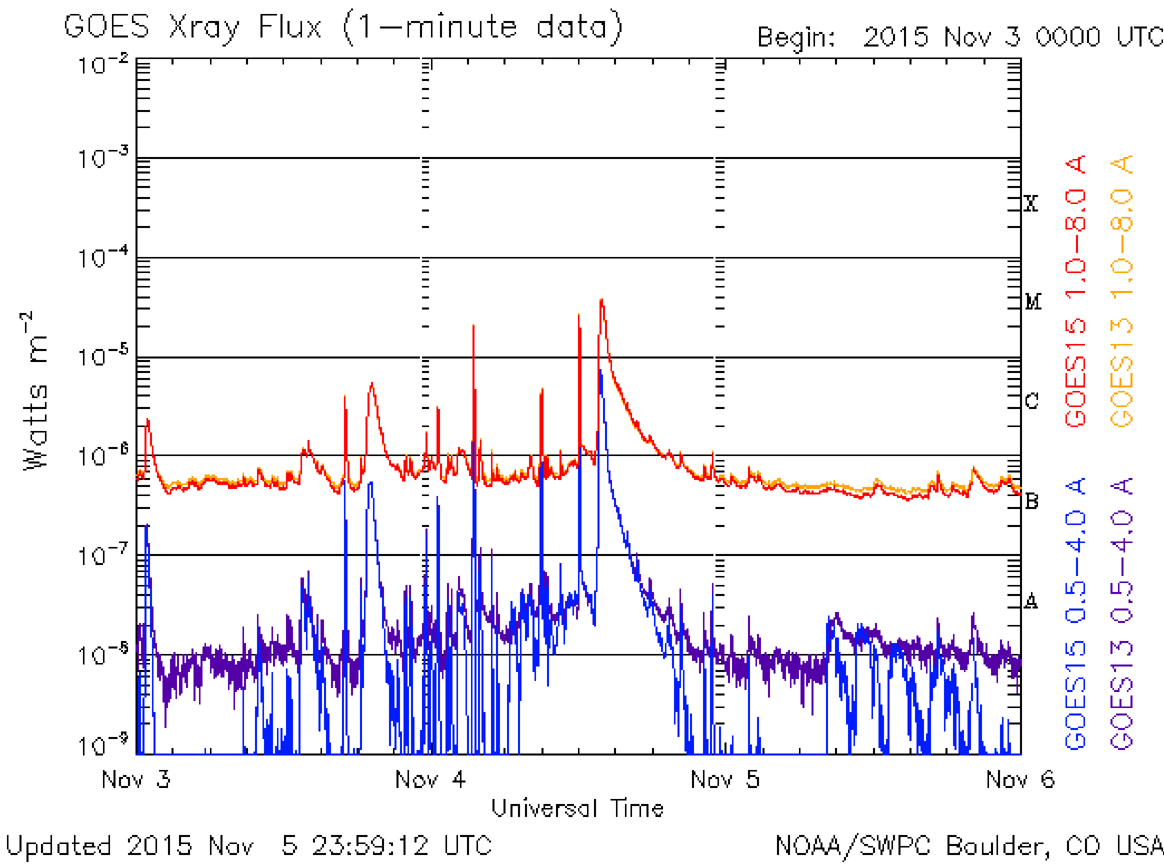
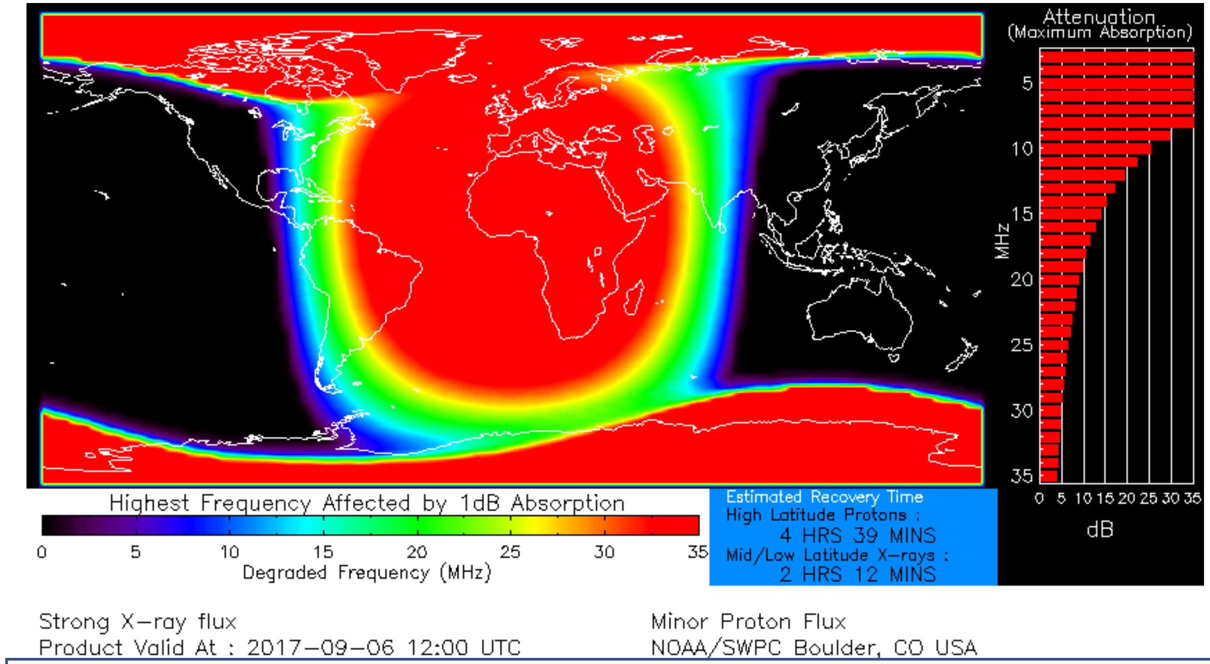


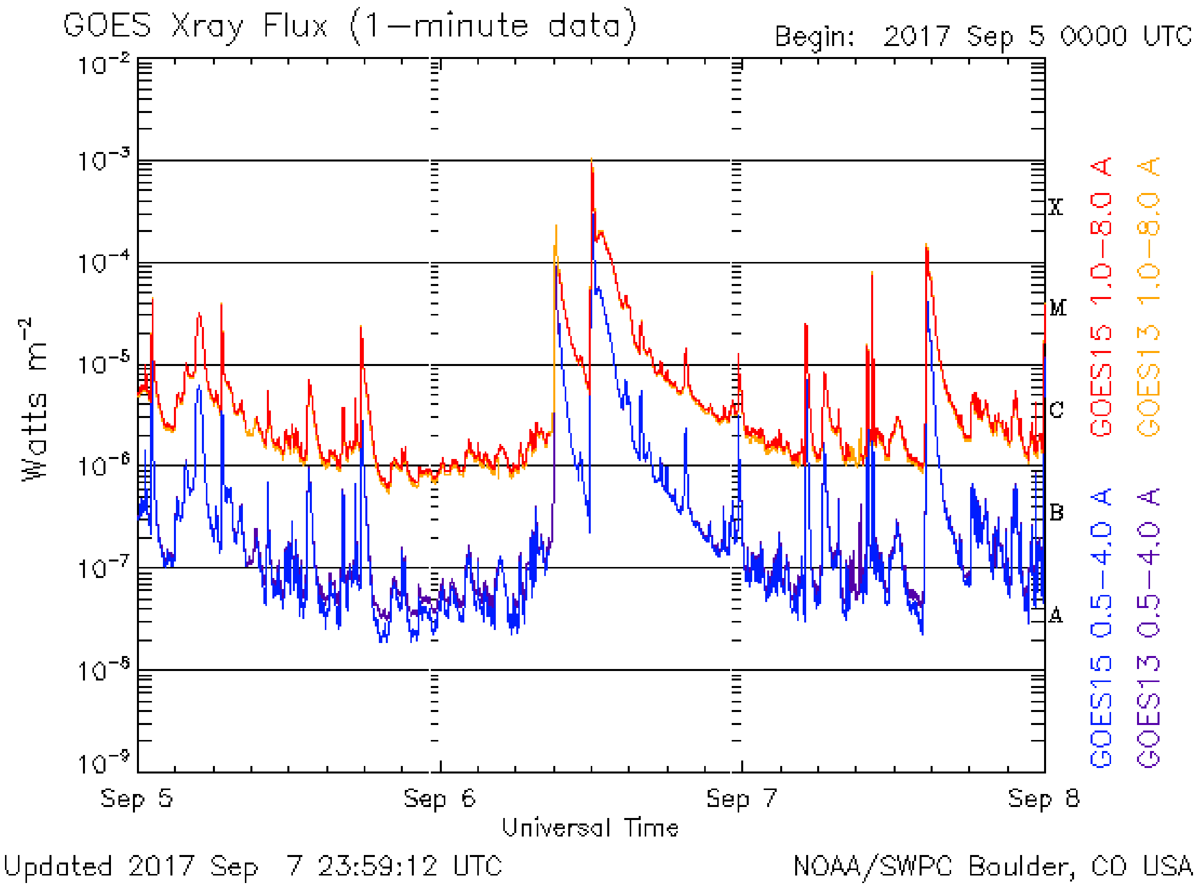
Impacts on HF Communications



D-region absorption (D-RAP)

- The D-region of ionosphere has largest effect on highest frequency (HF) Comms and low frequency (LF) navigation systems. The map indicates an area of the ionospheric D-region absorption during a solar flare event as well as the estimated recovery time.
- The solar flare on the sunlit side degrade the HF radio communication and this can last anything between few minutes to hours
- In 2017 during the event NOAA reports that high frequency radio, used by aviation, maritime, ham radio, and other emergency bands, was unavailable for up to eight hours. For example, civil aviation reported a 90-minute loss of communication with a cargo plane.
- Many of these flares will produce HF radio wave absorption across the sunlit side of the Earth - strong absorption in the case of X flares

- Example of X9.3 –class solar flare observed on the 6th September 2017 at ~ 12:04 UT. This is ~15:04 local time. The example shows strong radio blackout over Europe, Africa and the Atlantic Ocean.



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Example of regional Impact of space weather on HF communications.

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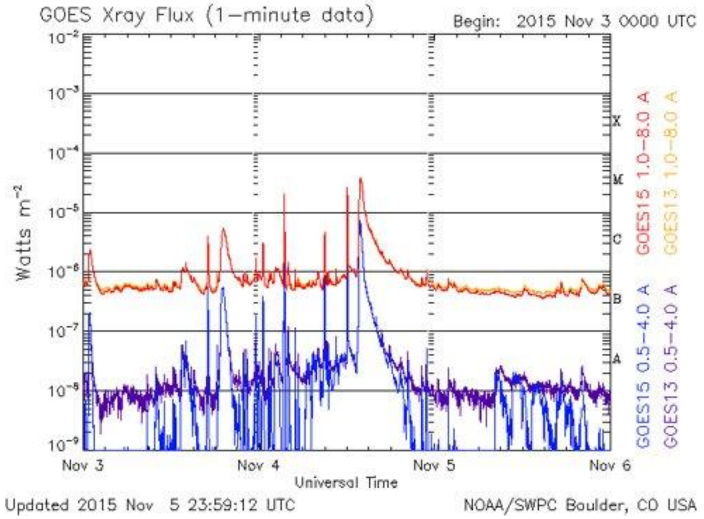

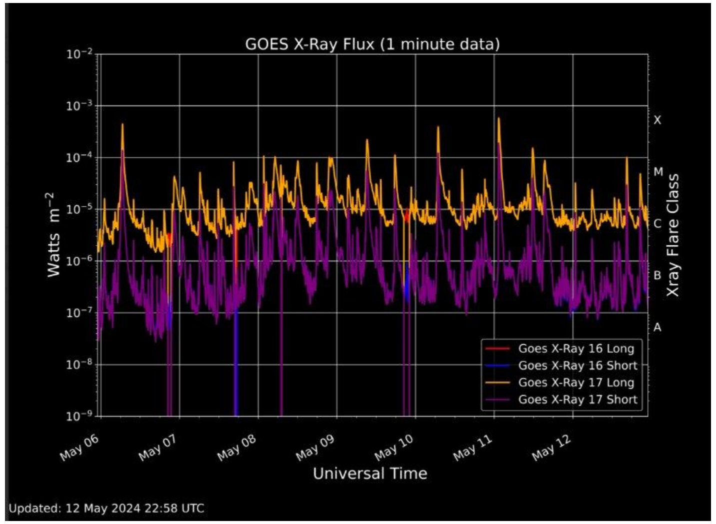

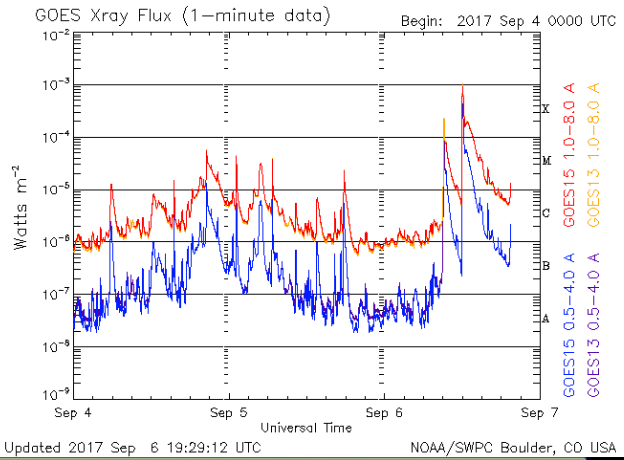

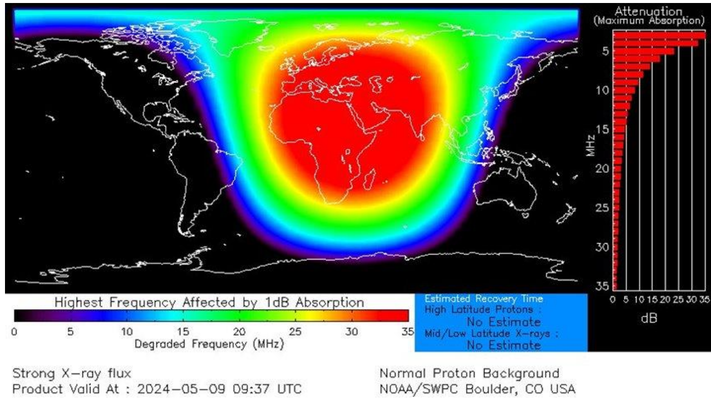

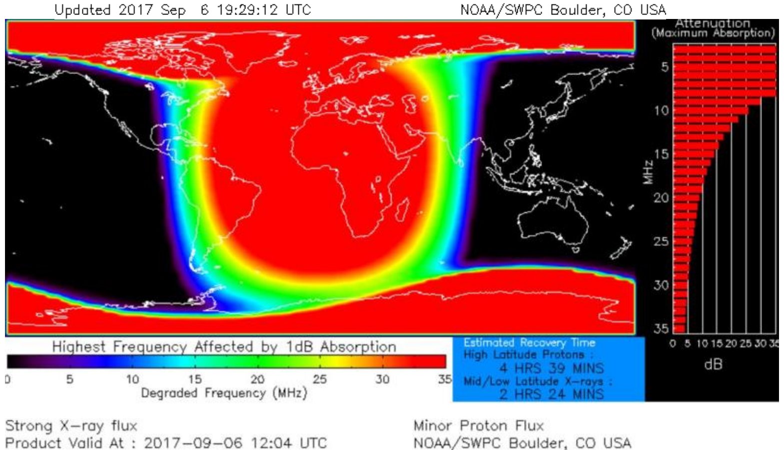

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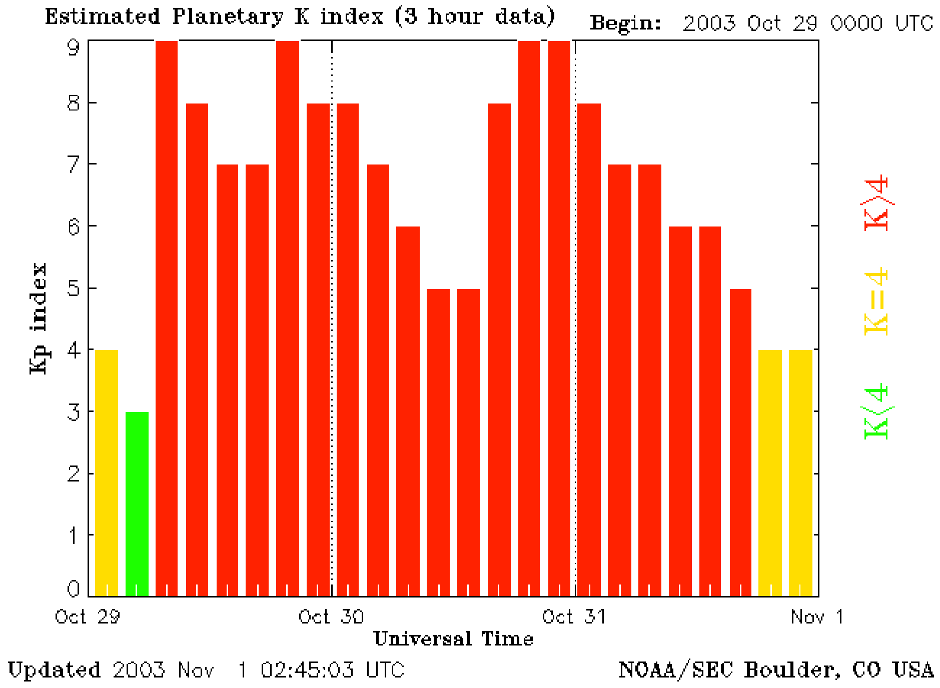
Example of space weather impact on GNSS(WAAS)



- During the storms of 2003, the GNSS Wide Area Augmentation System (WAAS), which operates over North America, lost vertical navigation capability for many hours, and the performance of differential systems was significantly impaired (NSTB/WAAS Test and Evaluation Team, 2004).
- The US Wide Area Augmentation System (WAAS) was affected. For a 15-hour period on the 29 October and an 11 hour period on the 30 October, the ionosphere was so disturbed that the vertical error limit was exceeded and WAAS was unusable for precision approaches.
- 2003 Halloween solar storms During the declining phase of the solar cycle the Sun unexpectedly burst into activity. A number of CMEs and flares resulted from a very large and complex group of sunspots. These resulted in geomagnetic storms that caused outages in high frequency (HF) communication systems, fluctuations in power systems and minor to severe impacts on satellite systems.
- This included two Inmarsat satellites (used by the aviation industry) of which one required manual intervention to correct its orbit and the other went offline due to central processor unit (CPU) failures. These were just two of forty-seven satellites reported to have service interruptions lasting from hours to day.

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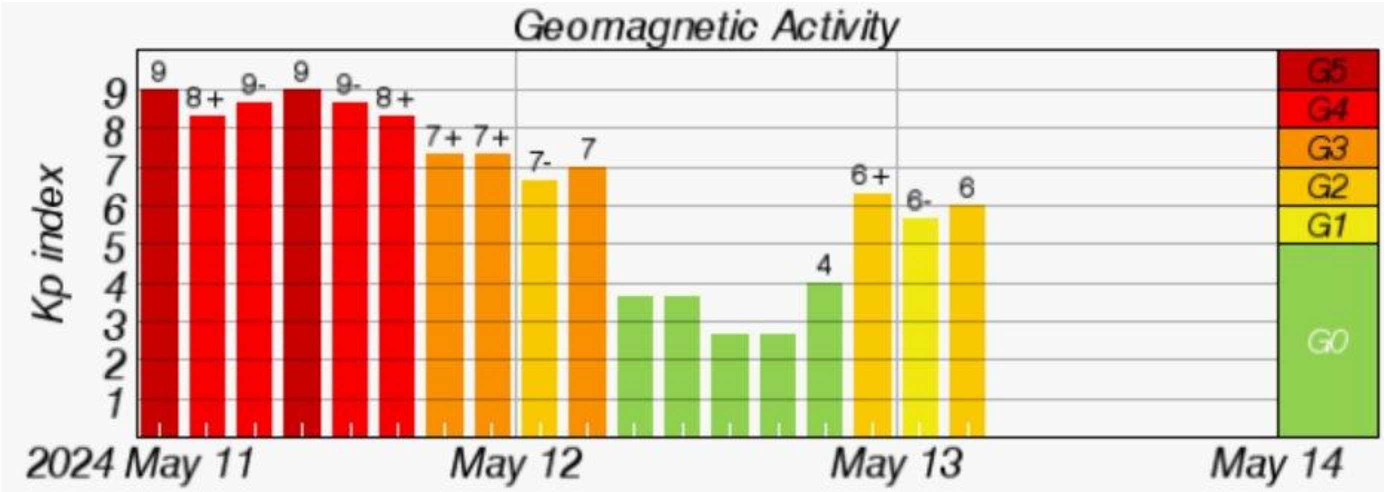

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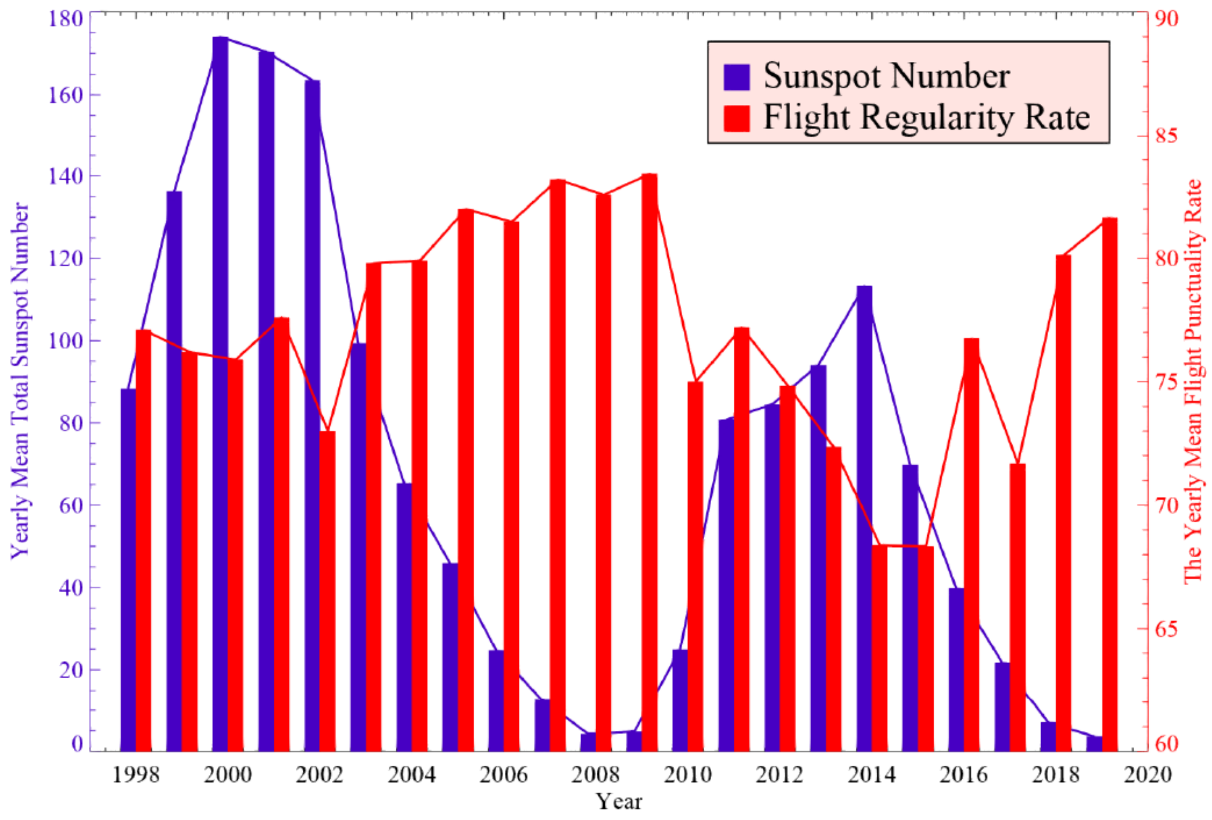
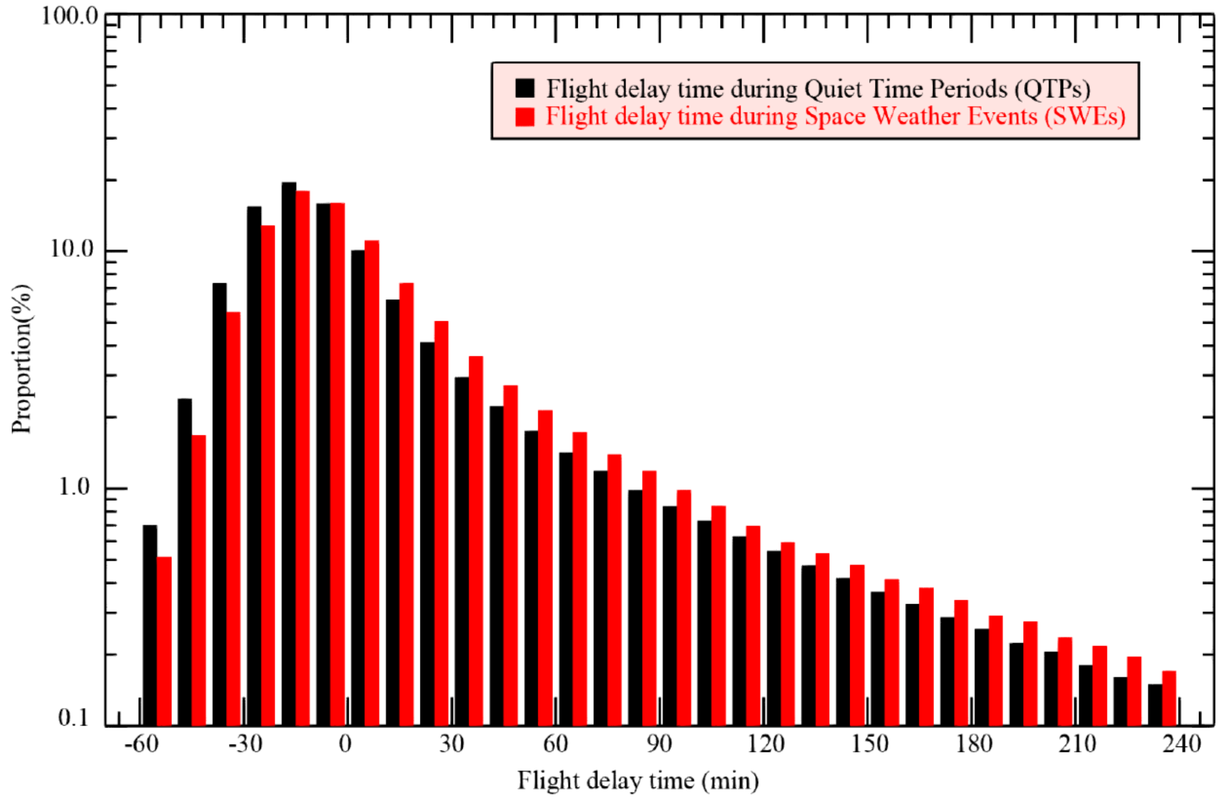
SWx impact on flight operation: flight delays





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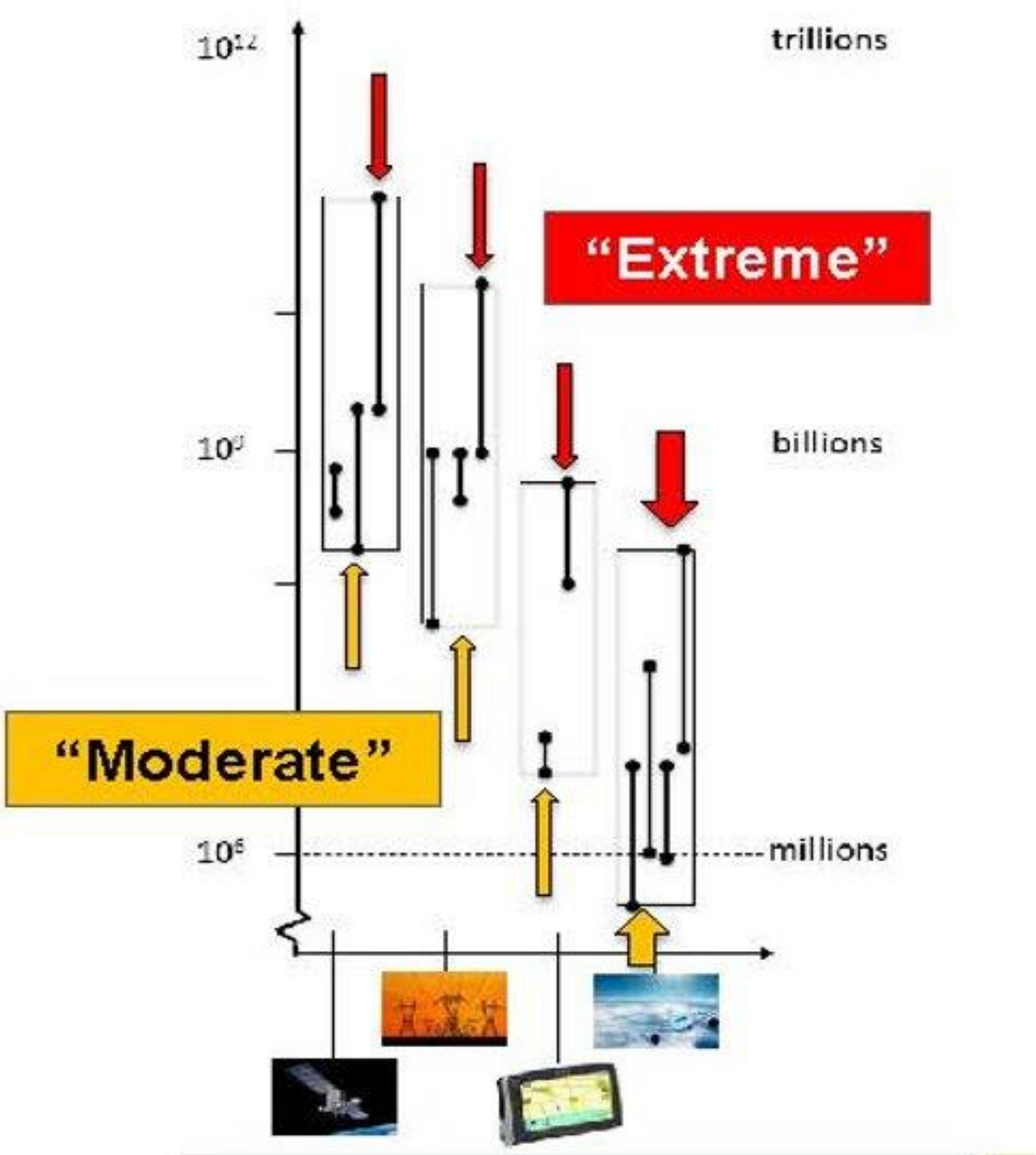
ECONOMIC IMPACT OF SPACE WEATHER done elsewhere



Satellite Technology
- cost of engineering & loss of applications
- Moderate , 1 satellite
- Extreme , 10 – 100 satellites

Energy
- Wide-spread blackouts
- Moderate , R 600 million in losses
- Extreme , R 1 – R 2 trillion in losses
- Recovery could be 4 – 5 years

Communication & Navigation
- Loss of GNSS capability
- GNSS outage could cost $1 billion / day
- Can have devastating social and economic repercussions

Security
- Radio blackout in all cases
- Severe economic repercussions

Transport
- aviation, rail, maritime

Mitigation measures for space weather impact

The topical challenge for effective mitigation of significant space weather events is to forecast or detect such events in due time and to provide the relevant information in the right form to the right persons at the right time.
Mitigating the effect of space weather is a difficult process and the best form of mitigation is to stop the event from occurring clearly, this is not an option in this case.
Therefore, the remaining options are to:

- Raise awareness of space weather events and their impact;
- provide notice of impending storms that will allow the impacted industry to take the necessary steps to minimise or prevent the potential effect of their systems.
- Data sharing between the SWx experts and the industry to analyze and evaluate system's performance during the event to determine the level of impact that the event might have caused.

- Increasing awareness of the impact on the different sectors: Firstly there is a need to understand the different technological systems that are used and their potential vulnerabilities to space weather;
- Satellite failure and GNSS-based applications: A back-up to satellite communication and navigation should remain available.

CONCLUSION

- Space Weather events can create vulnerabilities within our technology dependencies and is a risk to the 4IR.
- The susceptibility of society to space weather is increasing due to its reliance on services provided by vulnerable infrastructures and interdependencies between infrastructures.
- Interdependencies between critical infrastructures need to be better understood and assessed to improve the resilience to potential cascading effects caused by space weather.
- Space-weather impacts on critical infrastructures can be potentially very costly due to ripple effects to other sectors.
- Targeted research efforts in collaboration with industry are necessary to close knowledge gaps concerning the consequences and probabilities of extreme events and to understand how standard preparedness assumptions would be challenged under these conditions.
- SANSA has established an operational capability for Space Weather information provision and Magnetic Technology services for the African region
- SANSA is able to provide unique solutions on the African continent to space and non-space sectors solving challenges in safety and security, maritime, energy, transport, agriculture and mining
- SANSA looks forward to working with the different sectors to enable the mitigation of risks from the near-Earth space environment

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