Space Weather: An Introduction

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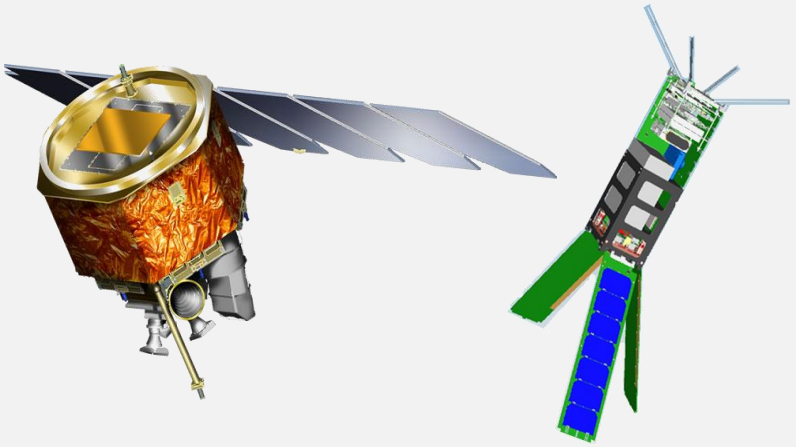
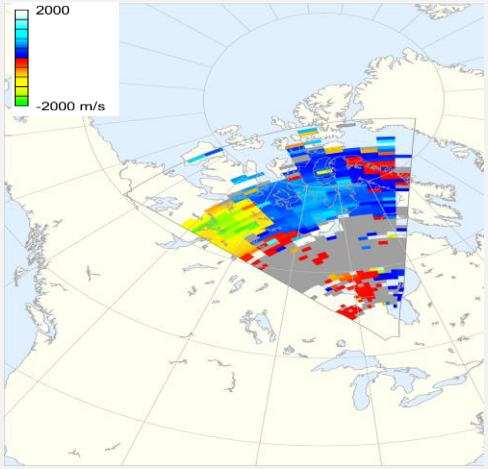
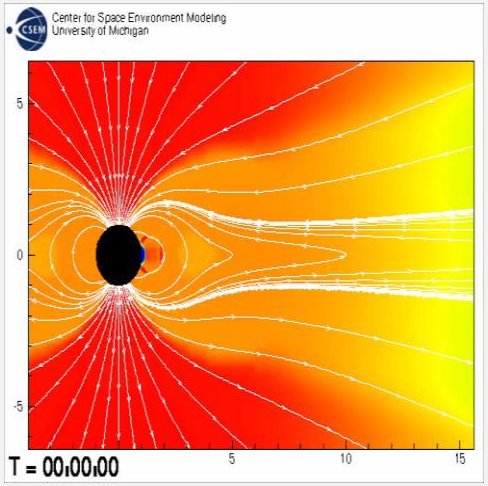
Space@VT: What Is It?

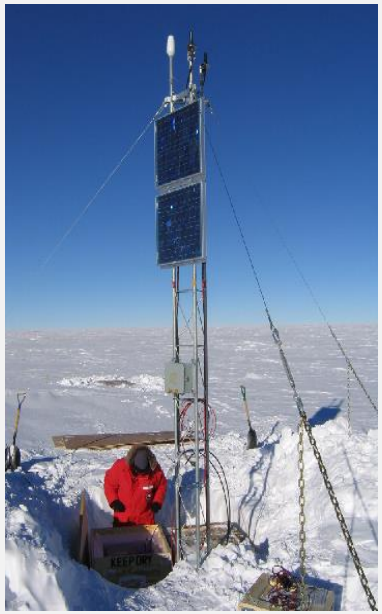
Space Research At Virginia Tech (Space@VT)

- Space-Based Instrument Development
- Ground-Based Autonomous Observatories
- Space Weather Radars (SuperDARN)
- Space Plasma Simulations
- Spacecraft Structures and Propulsion
- Science of the Space Environment









Space@VT Teaching Faculty

Faculty Member	Department	Research Expertise
Dr. Colin Adams	AOE	Spacecraft Propulsion
Dr. Scott Bailey (Director)	ECE	Space-Based Instruments
Dr. Joseph Baker	ECE	Space Weather Radars
Dr. Robert Clauer	ECE	Ground-Based Instruments
Dr. Greg Earle	ECE	Space-Based Instruments
Dr. Scott England	AOE	Space-Based Instruments
Dr. Elena Lind	ECE	Atmospheric Remote Sensing
Dr. Mark Psiaki	AOE	Satellite Navigation
Dr. Mike Ruohoniemi	ECE	Space Weather Radars
Dr. Wayne Scales	ECE	Space Plasma Simulations
Dr. Kevin Shinpaugh	AOE	Spacecraft Dynamics/Control
Dr. Leonard Smith	ECE	Uncertainty Quanitification

The VT SuperDARN-MIST Group

- **Tenured & Research Faculty**
  - Dr. Mike Ruohoniemi — Professor
  - Dr. Joseph Baker — Professor
  - Dr. Bharat Kunduri — Assistant Research Professor
  - Dr. Zhonghua Xu — Research Scientist
  - Dr. Xueling Shi — Research Scientist
  - Dr. Shibaji Chakraborty — Postdoctoral Fellow
  - Dr. Shane Coyle — Postdoctoral Fellow
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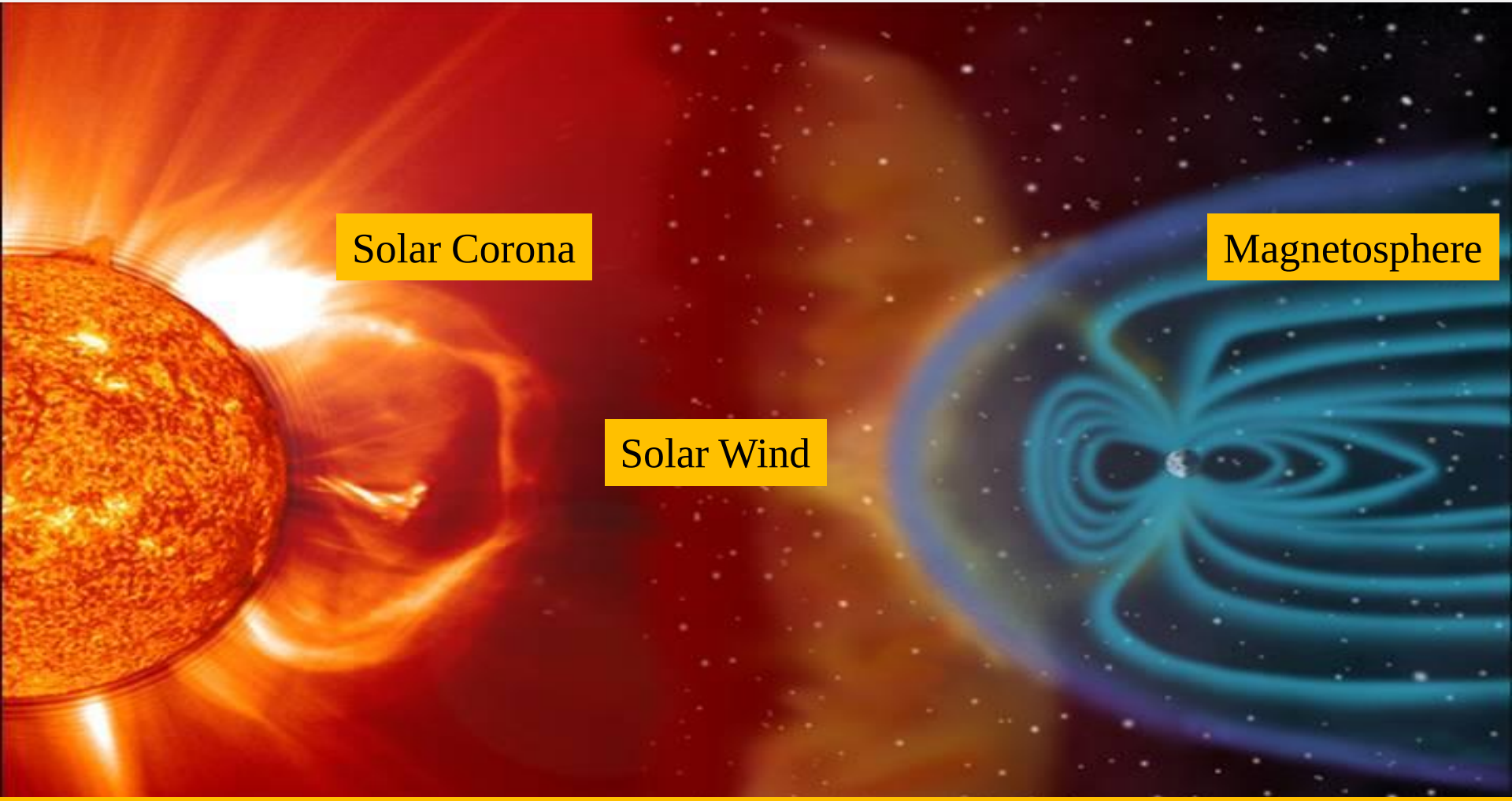
- **Current Graduate Students**
  - Ms. Veronica Romanek — M.S. Student
  - Mr. Tristen Wanner — M.S. Student
- **Current Undergraduate Students**
  - Mr. Spencer Forsling — Computer Engineering Student
  - Mr. Preston Pitzer — Electrical Engineering Student

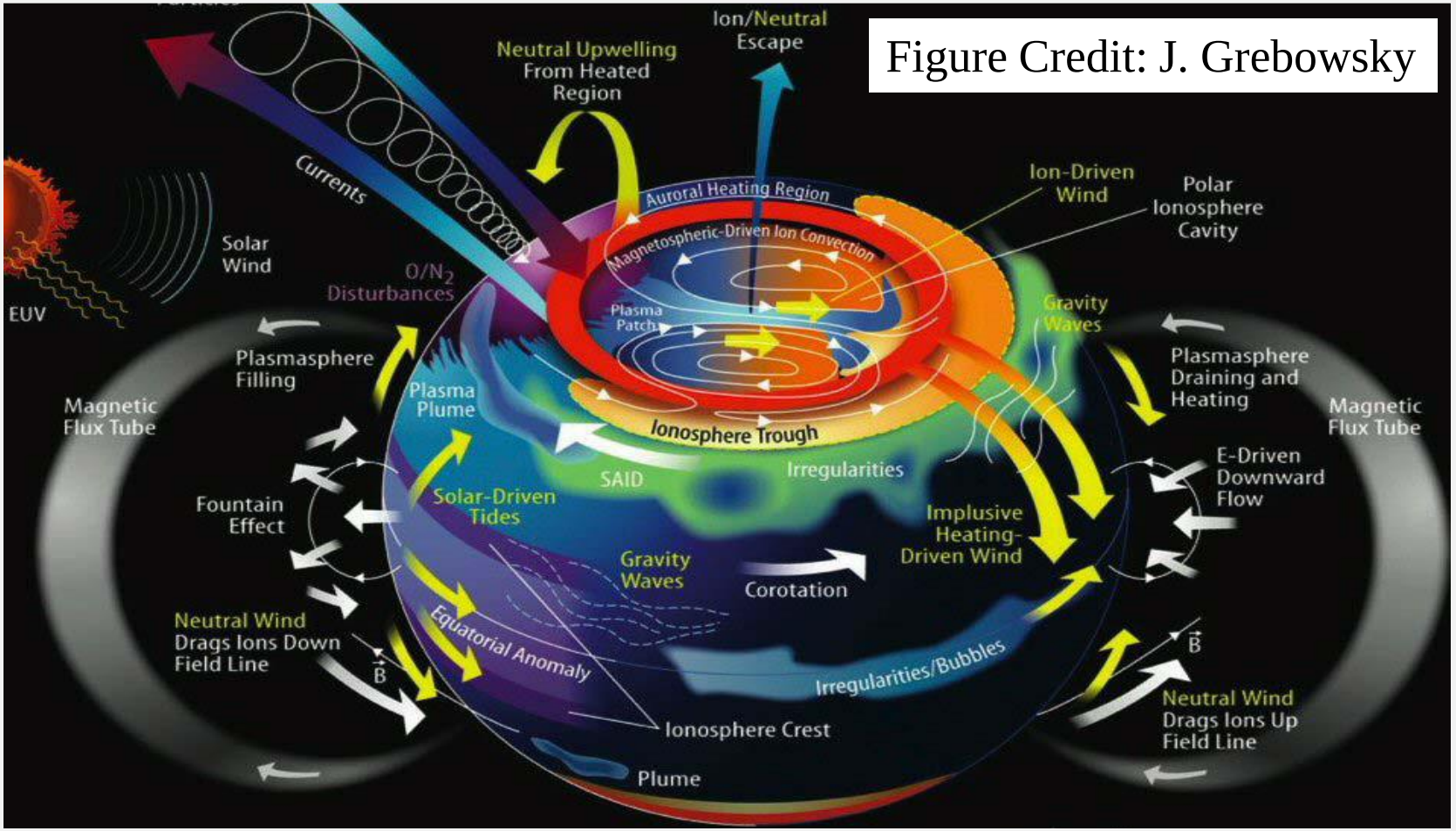
Space Weather: What Is It?

What Is Space Weather?



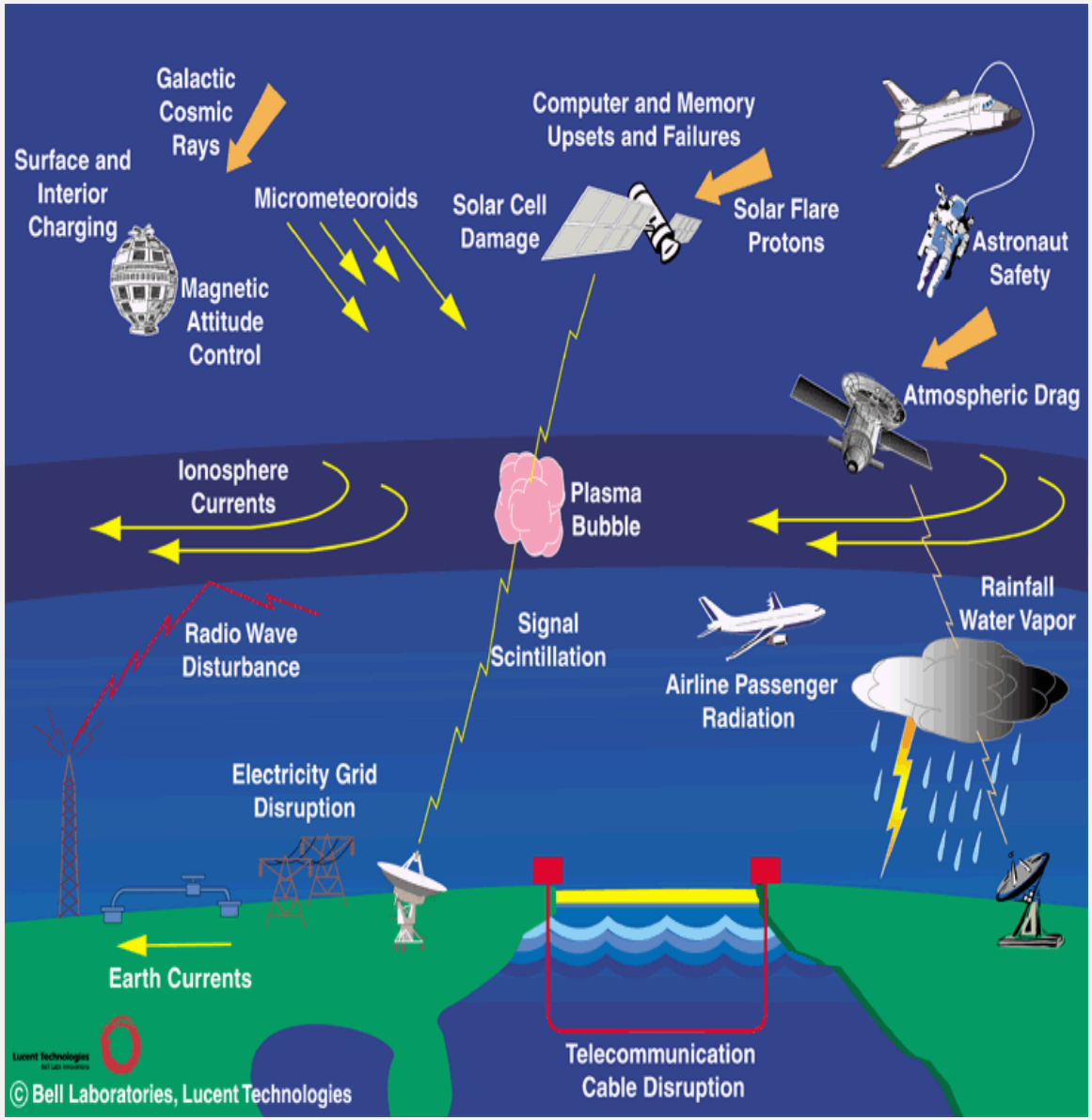
“Space Weather” refers to dynamic conditions on the Sun and how they perturb the near-Earth space environment to influence the reliability of space-borne and ground-based technological systems, and possibly endanger human life or health.

Space Weather Science: The Geospace System



- Primary drivers for the high latitude region are the magnetosphere & solar wind.
- Primary drivers for the low latitude region are solar heating & neutral processes.
- The mid latitude region is something in between…….

Space Weather Hazards: A Few Examples



- Spacecraft damage (radiation)
- Astronaut Health (radiation)
- Increased satellite drag
- Disruption to the Power Grid
- Degraded navigation
- Disrupted communication
- Deviation of airplanes
- Increased radar clutter
- And confused pigeons!

Hart et al. Frontiers in Zoology 2013, 10:80
http://www.frontiersinzoology.com/content/10/1/80

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RESEARCH Open Access

Dogs are sensitive to small variations of the Earth's magnetic field

Vlastimil Hart[1], Petra Nováková[1], Erich Pascal Malkemper[2†], Sabine Begall[2†], Vladimír Hanzal[1], Miloš Ježek[1], Tomáš Kušta[1], Veronika Němcová[1], Jana Adámková[1], Kateřina Benediktová[1], Jaroslav Červený[1] and Hynek Burda[1,2*]

Abstract

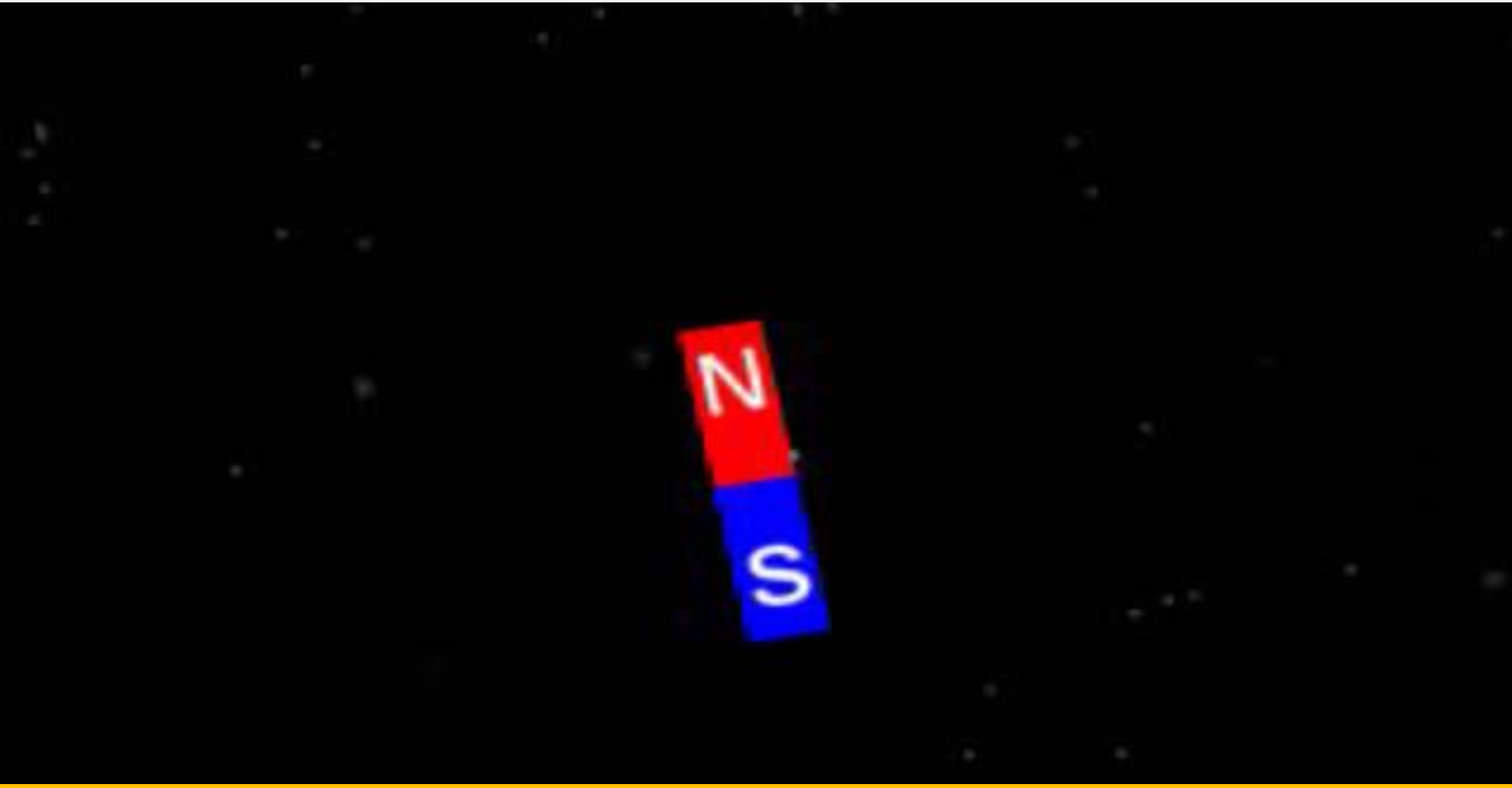
Introduction: Several mammalian species spontaneously align their body axis with respect to the Earth's magnetic field (MF) lines in diverse behavioral contexts. Magnetic alignment is a suitable paradigm to scan for the occurrence of magnetosensitivity across animal taxa with the heuristic potential to contribute to the understanding of the mechanism of magnetoreception and identify further functions of magnetosensation apart from navigation. With this in mind we searched for signs of magnetic alignment in dogs. We measured the direction of the body axis in 70 dogs of 37 breeds during defecation (1,893 observations) and urination (5,582 observations) over a two-year period. After complete sampling, we sorted the data according to the geomagnetic conditions prevailing during the respective sampling periods. Relative declination and intensity changes of the MF during the respective dog walks were calculated from daily magnetograms. Directional preferences of dogs under different MF conditions were analyzed and tested by means of circular statistics.

Results: Dogs preferred to excrete with the body being aligned along the North–South axis under calm MF conditions. This directional behavior was abolished under unstable MF. The best predictor of the behavioral switch was the rate of change in declination, i.e., polar orientation of the MF.

Conclusions: It is for the first time that (a) magnetic sensitivity was proved in dogs, (b) a measurable, predictable behavioral reaction upon natural MF fluctuations could be unambiguously proven in a mammal, and (c) high sensitivity to small changes in polarity, rather than in intensity, of MF was identified as biologically meaningful. Our findings open new horizons in magnetoreception research. Since the MF is calm in only about 20% of the daylight period, our findings might provide an explanation why many magnetoreception experiments were hardly replicable and why directional values of records in diverse observations are frequently compromised by scatter.

Keywords: Magnetoreception, Magnetosensitivity, Magnetic field, Magnetic storm, Magnetic alignment, Dog, Canid, Mammal

Space Weather: The Magnetosphere



- The “Magnetosphere” is the magnetic environment of the Earth which provides our ***first*** line of defense against energetic charged particles (or “radiation”) from the Sun.
- The atmosphere is our ***second*** line of defense.

Space Weather Dynamics

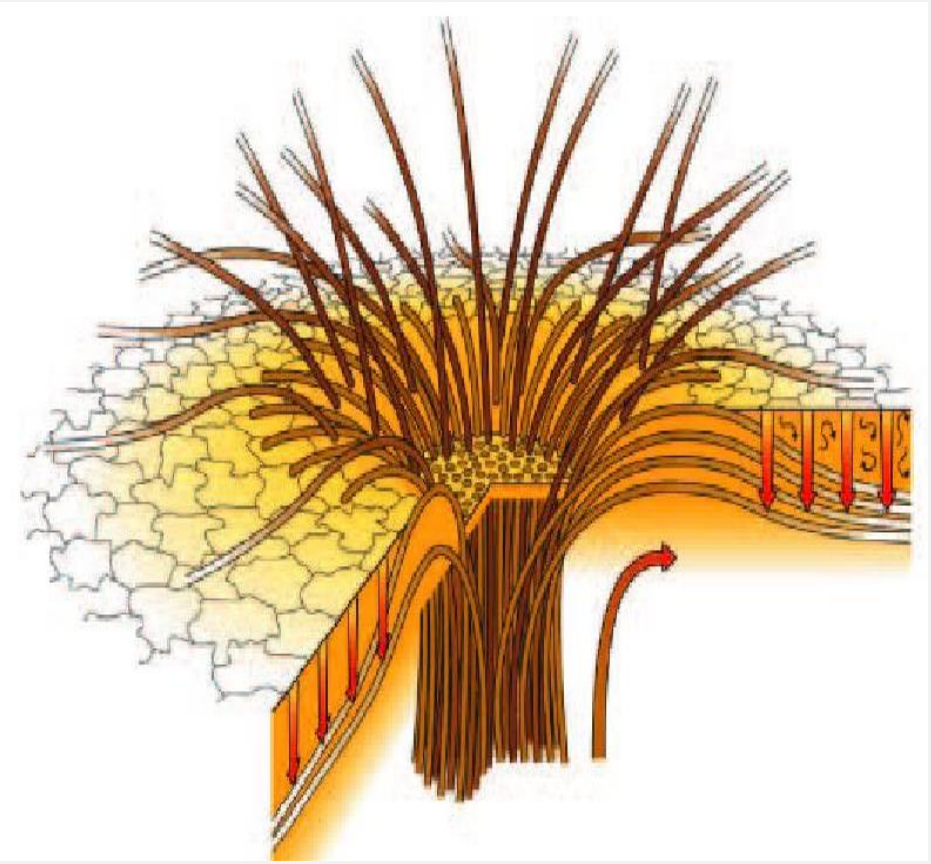
- The northern lights or “aurora” is a visual manifestation of space weather!

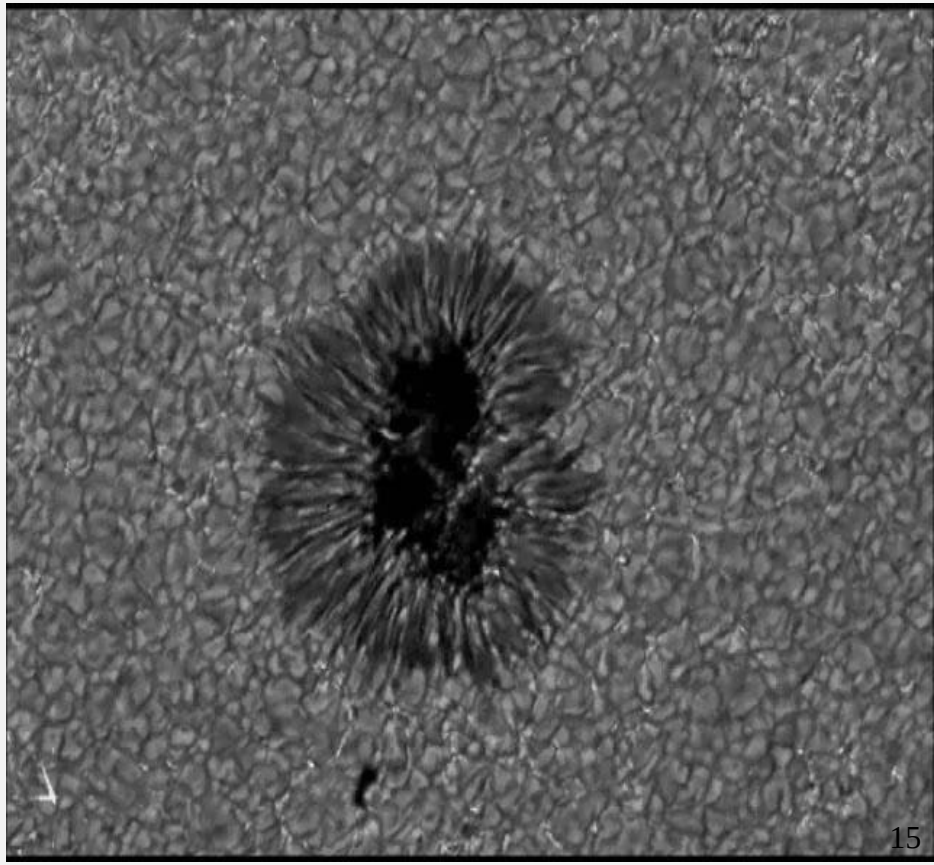
Space Weather Research: The Longterm Goal

Space Weather: Solar Activity

Solar Activity: Sunspots

- The origin of most manifestations of space weather can be traced back to sunspots.
- Sunspots are relatively cold regions on the Sun's "surface" (or "photosphere") which form when bundles of intense magnetic field erupt from below.
- The strong magnetic field strength inhibits convection of hot material from below.

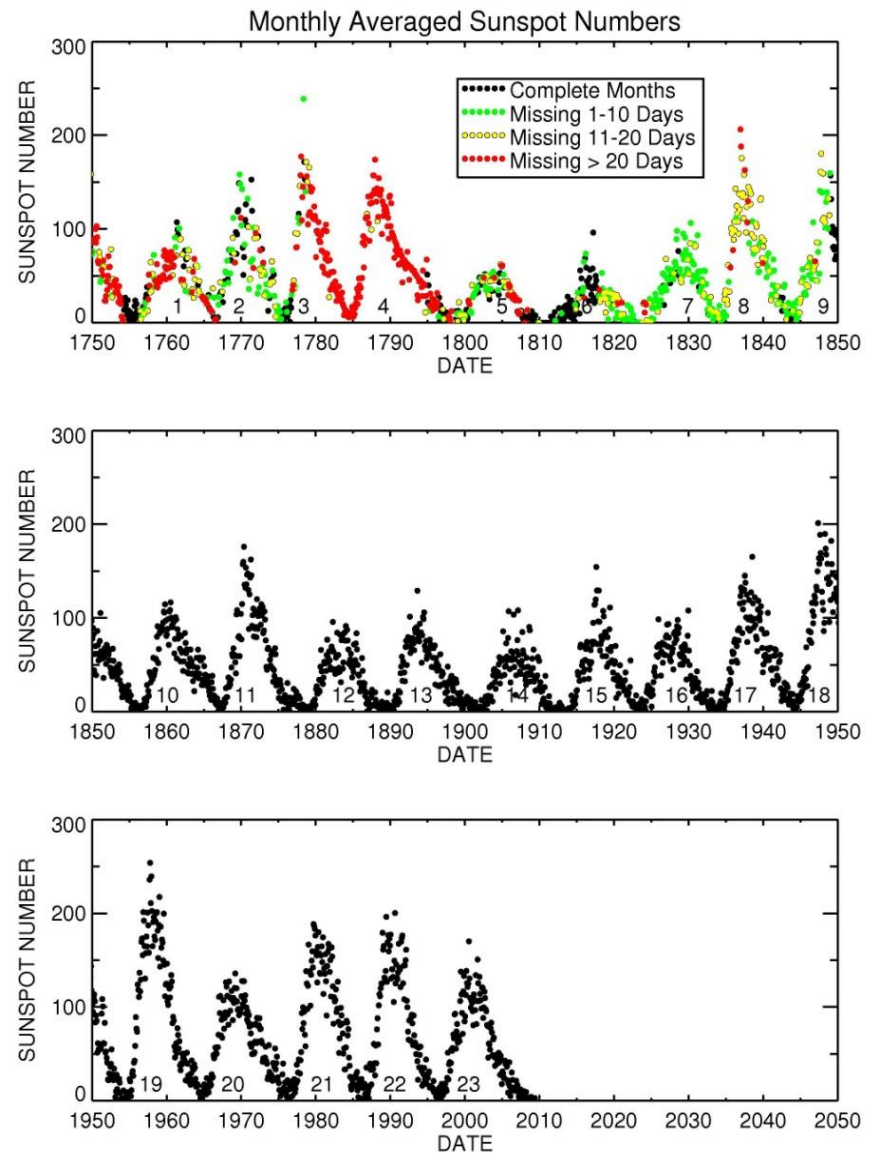


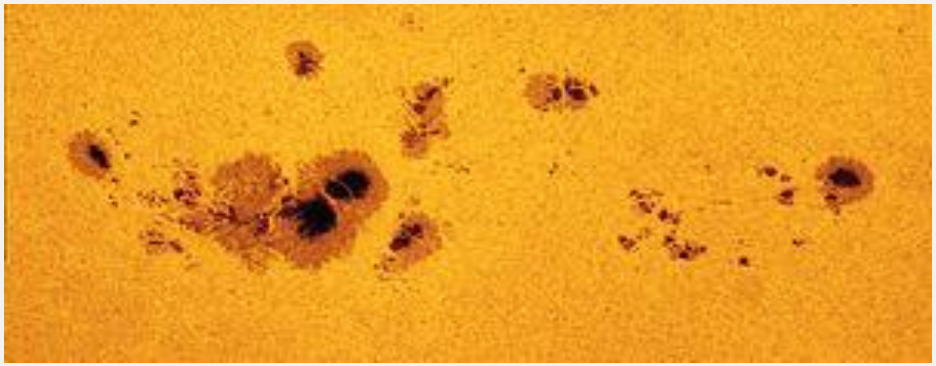


Sunspots: How They Form

- Sunspots form when a bundle of magnetic field lines bursts through the photosphere.
- Sunspots form in pairs which are often linked by a bright loop or "***prominence***".

The Solar Cycle: The Solar Cycle



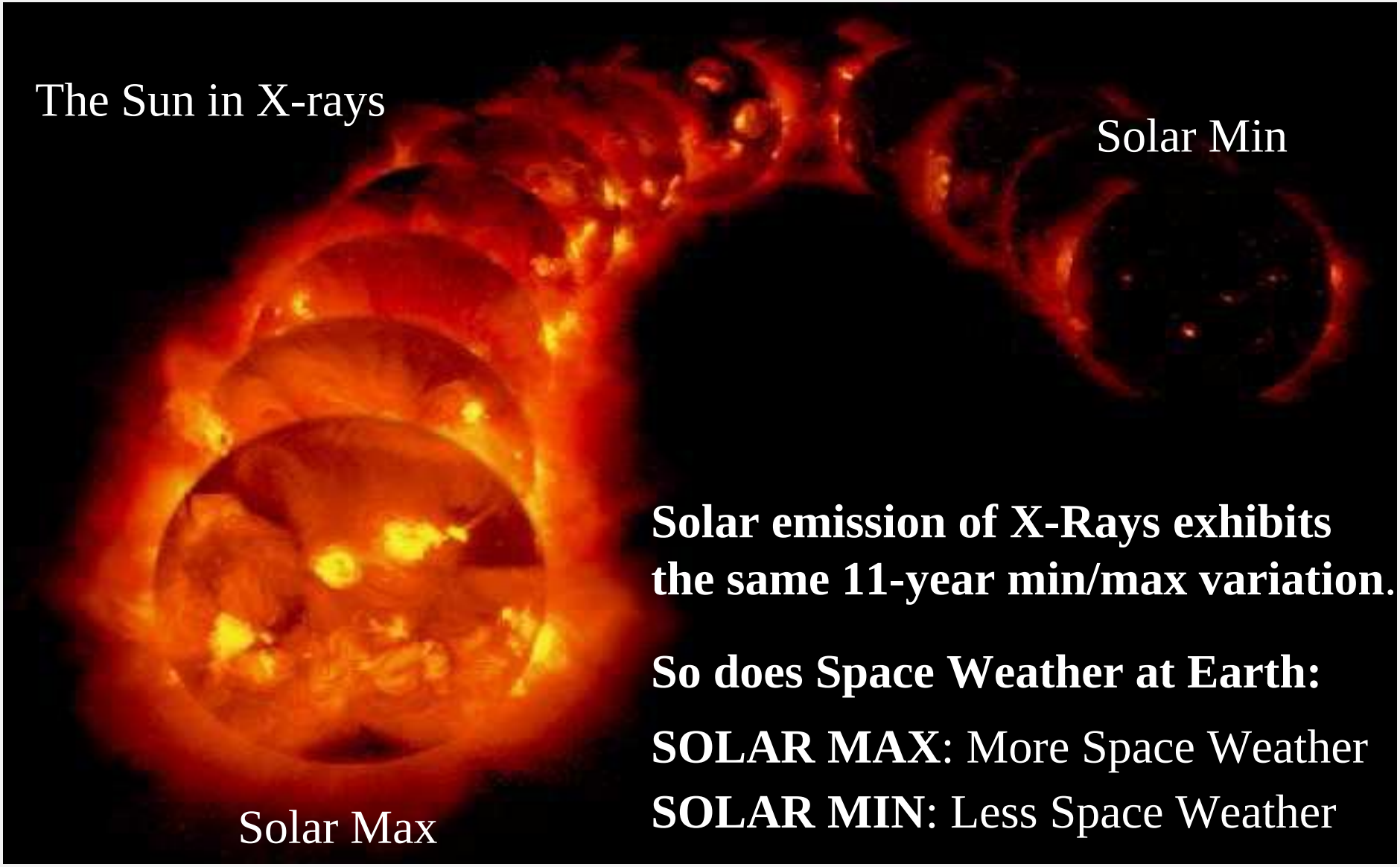


- Sunspots were *"discovered"* by Galileo in 1609 AD. However, Chinese observations date back to 28 BC.
- Sunspots usually appear in groups that form over hours or days but can last for several days or weeks.
- In 1844 Heinrich Schwabe was the first person to identify an 11-year periodicity in the number of sunspot groups:

SOLAR MINIMUM: Few sunspots

SOLAR MAXIMUM: Many sunspots

The Solar Cycle: X-Ray Emissions



Solar emission of X-Rays exhibits the same 11-year min/max variation.

So does Space Weather at Earth:

SOLAR MAX: More Space Weather

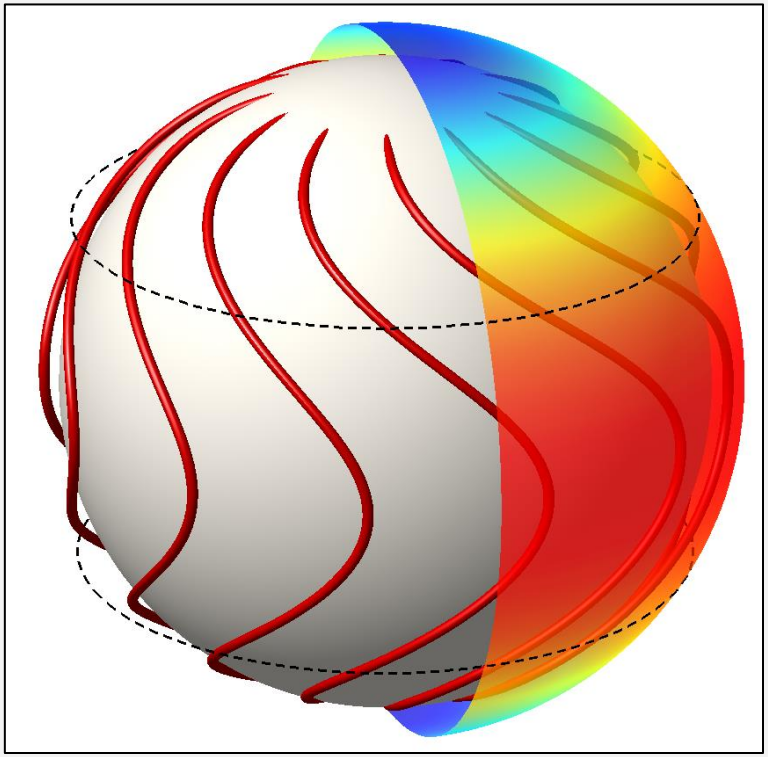
SOLAR MIN: Less Space Weather

The Sun's Magnetic Field: A Tangled Mess!

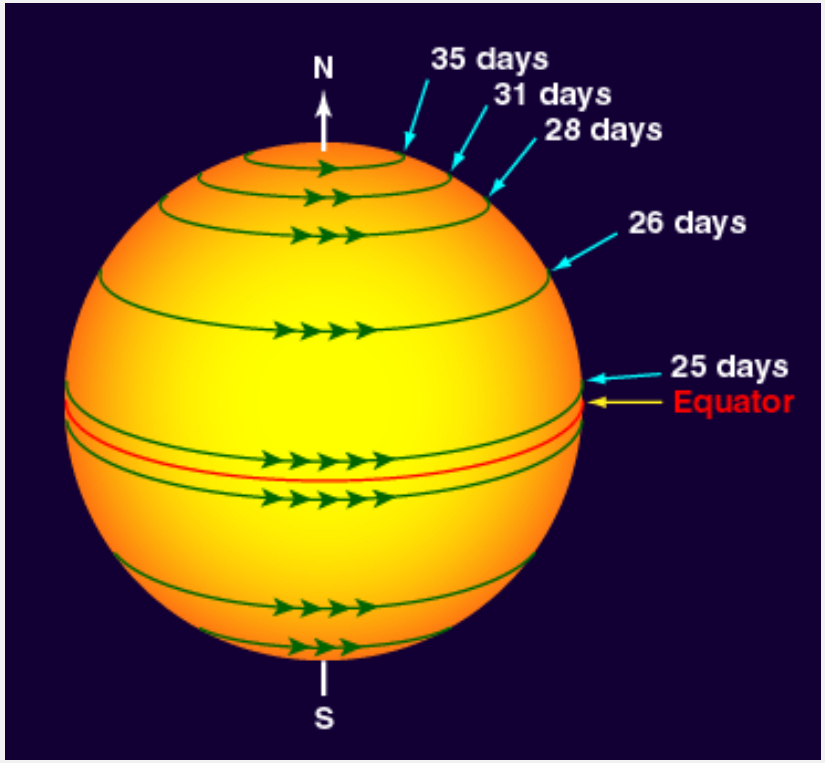
- Sunspots are produced when the Sun's magnetic field gets tangled.
- The Sun's magnetic field gets tangled because of two influences:

  1) It is generated close to the surface rather than the central core (left figure)

  2) The Sun rotates faster at the equator than the poles (right figure)



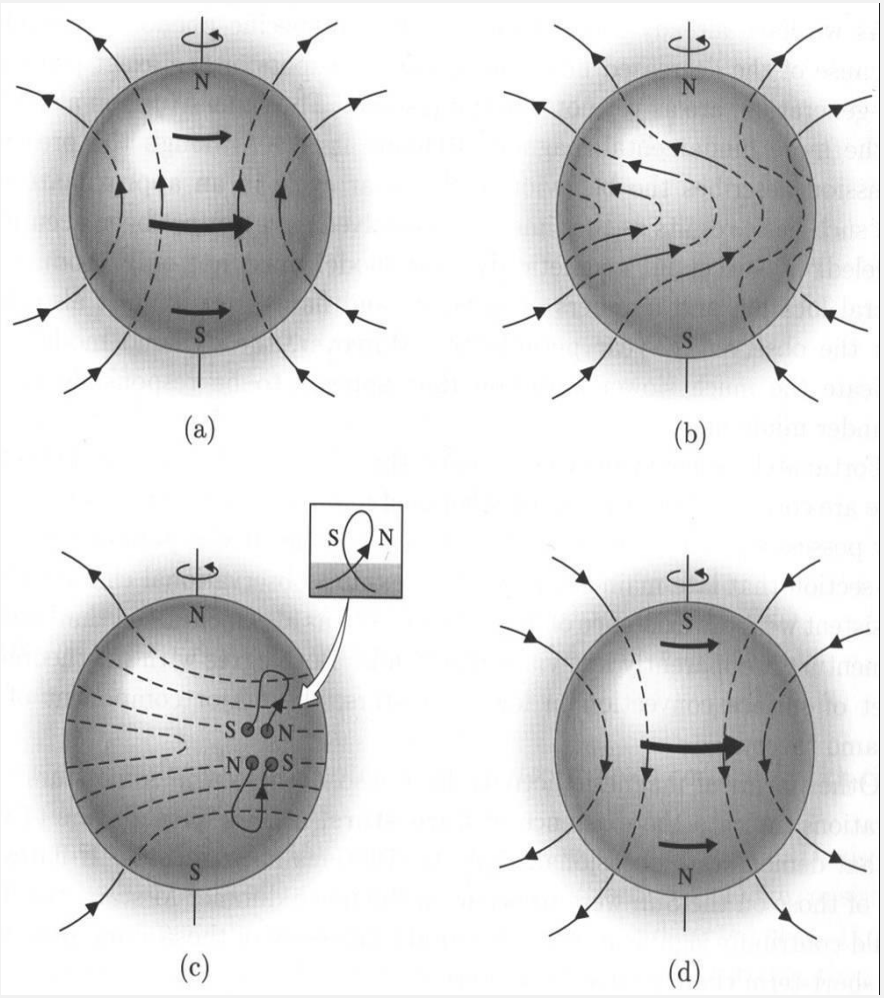
Near-Surface Solar Magnetic Field



Differential Solar Rotation

Solar Activity: The Babcock Dynamo

- The basic explanation for the sunspot activity cycle and how it is controlled by an evolving magnetic structure is called the "***Babcock Solar Dynamo***":



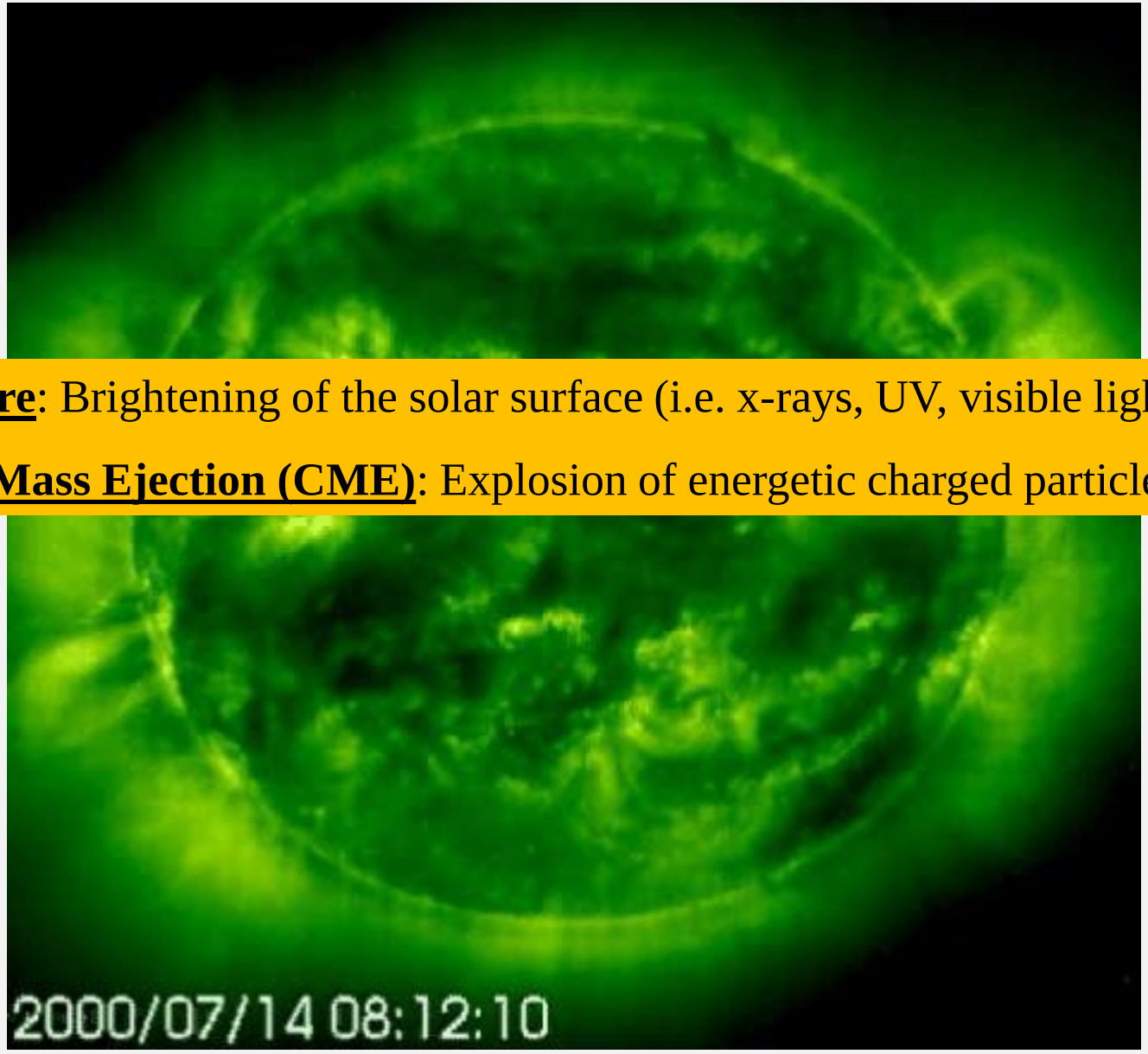
a) At solar minimum, a poloidal magnetic field (i.e. north-south) exists in a shallow layer just below the visible surface (i.e. photosphere).

b) Different rotation rates at the poles and equator distorts the shape from a weak poloidal field (i.e. north-south) to an intense tangled toroidal field (i.e. east-west).

c) Buoyancy of hot plasma produces eruptions of magnetic loops through the surface of the photosphere producing connected pairs of sunspots with opposite polarities.

d) Magnetic tension pulls the sunspots toward the solar equator where leading pairs cancel each other and the polar field has now reversed direction.

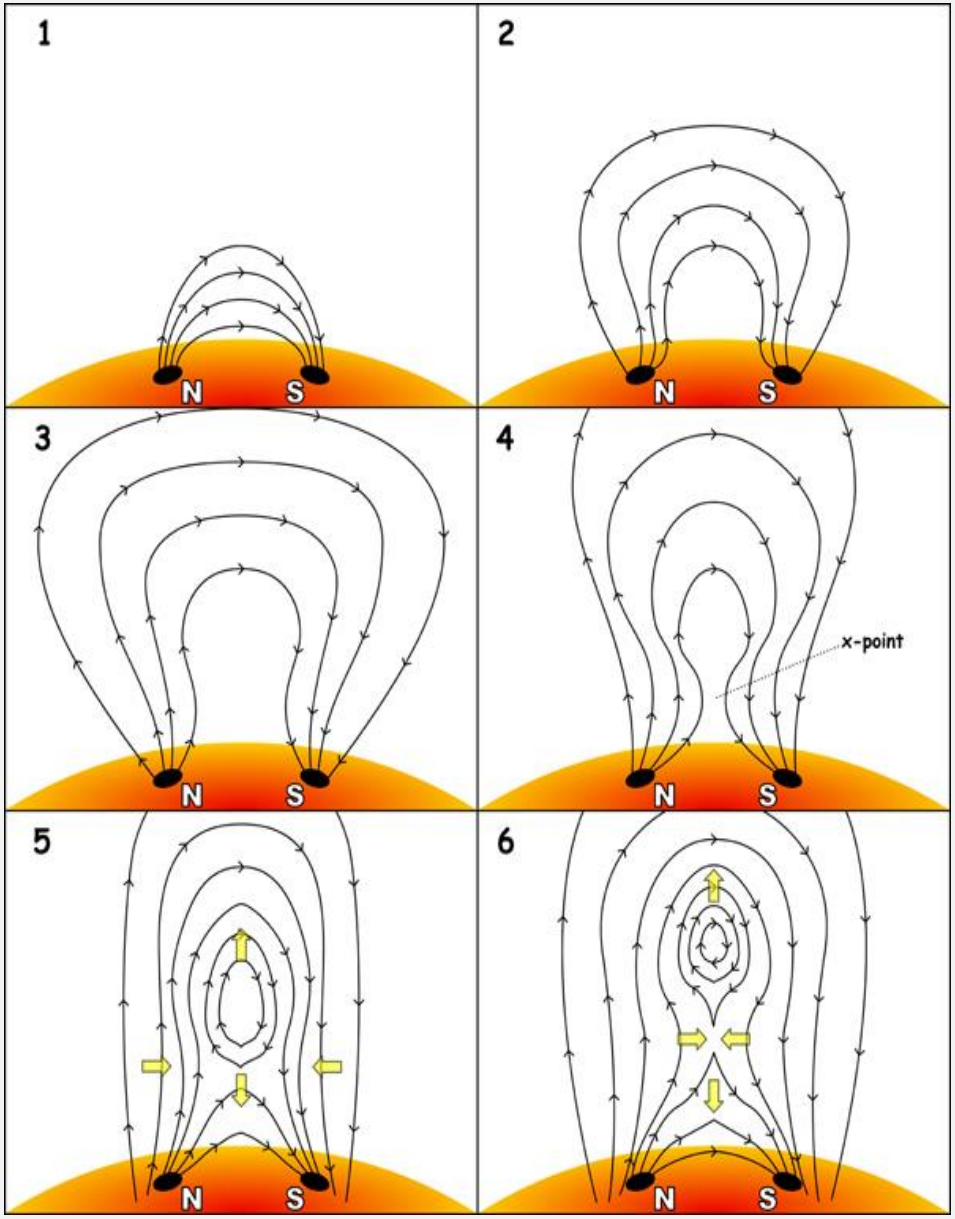
Solar Activity: The Bastille Day Event



Solar Flare: Brightening of the solar surface (i.e. x-rays, UV, visible light, etc.)

Coronal Mass Ejection (CME): Explosion of energetic charged particles (i.e. stuff)

Solar Flares and Coronal Mass Ejections



Solar flares occur when:

1) Hot plasma forces magnetic loops to burst through the solar surface.

2) Where they grow…

3) And grow…

4) Until, they become pinched or twisted.

Then….

5) Oppositely directed magnetic field lines meet and annihilate via a process called "***Magnetic Reconnection***" which converts magnetic energy into kinetic energy and electromagnetic waves.

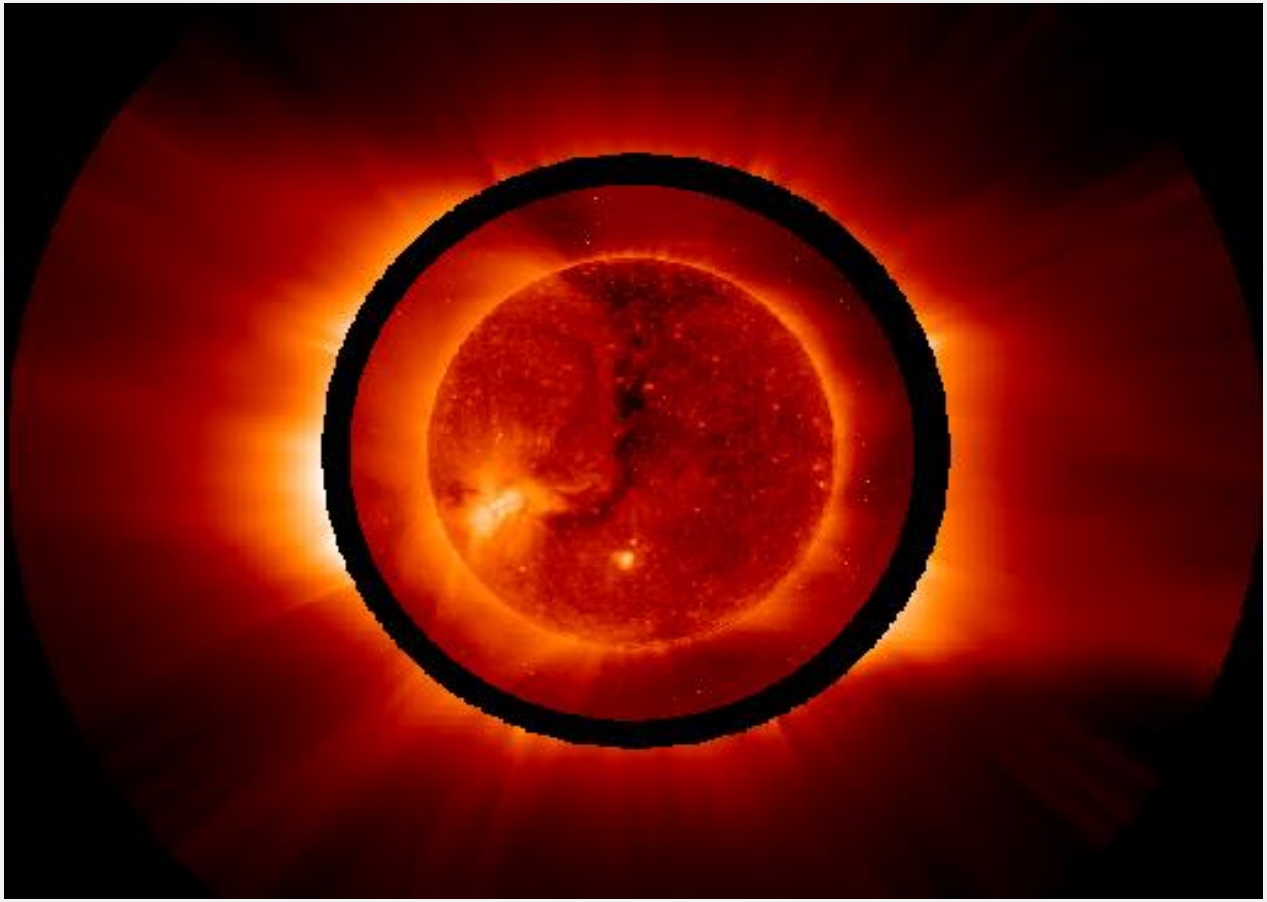
6) In the process, a magnetic bubble of hot dense plasma called a "***Coronal Mass Ejection***" is often ejected.

The Solar Wind

&

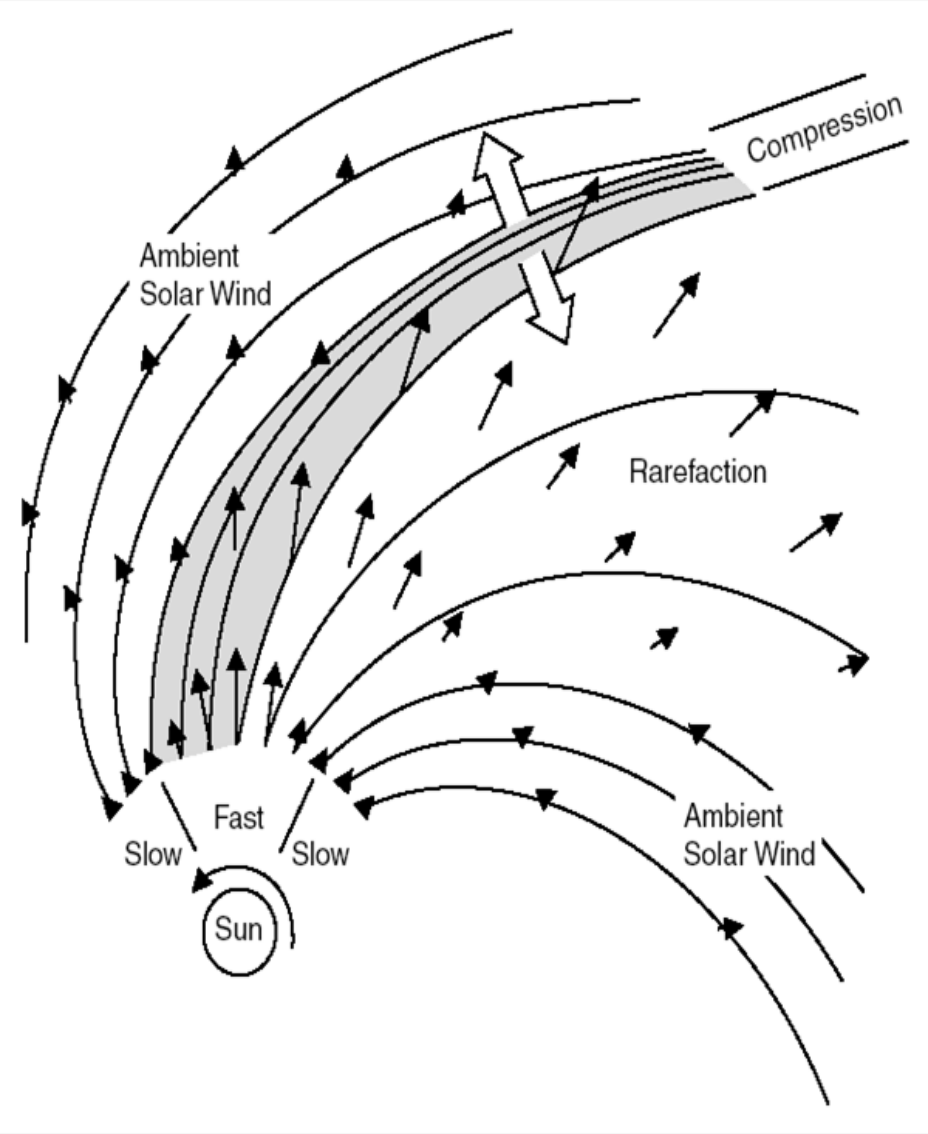
The Interplanetary Magnetic Field (IMF)

Space Weather: The Solar Wind



- **<u>DEFINE</u>**: The ***<u>Solar Wind</u>*** is the extension of the Sun's outer atmosphere, the *Corona*, which blows continuously throughout the solar system.
- Disturbances in the Sun's atmosphere (most notably, CMEs) are transmitted to the near-Earth space plasma environment via the *Solar Wind*.

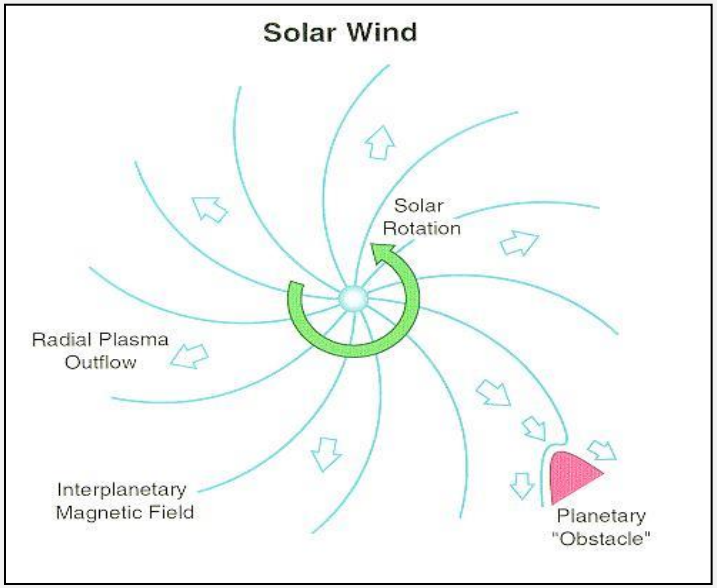
The Solar Wind: High Speed Streams



- Active regions on the sun (e.g. large Sunspot groups) produce higher velocity Solar Wind than surrounding quiet regions.
- A ***High Speed Stream*** from an active region will "catch up" with slower streams ahead of it and produce a high-pressure (compression) region between the streams or "***shock***".
- This compressed region of high density solar wind can then have severe space weather impacts when it reaches Earth orbit 2-3 days later.

Space Weather: The IMF

- **DEFINE**: The *Interplanetary Magnetic Field* (or IMF) is the remnant component of the Sun's magnetic field dragged outward by the solar wind through the Solar System.



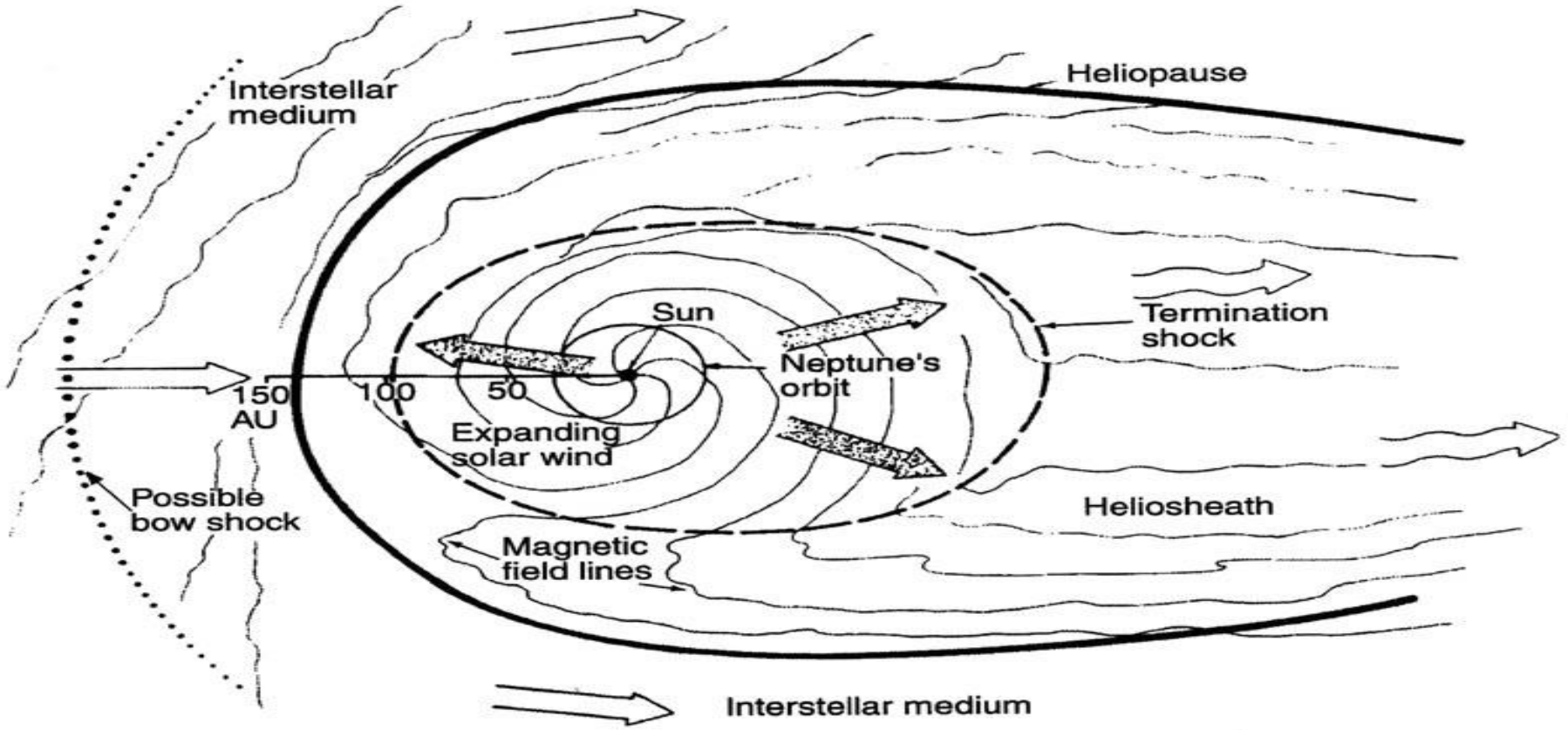
- The IMF plays a key role in controlling space weather activity through its interactions with the Earth's geomagnetic field (more later).
- The Interplanetary Magnetic Field (IMF) has a distinctive spiral shape produced by the combined influence of two factors:

  (1) Radial outward motion of the Solar Wind

  (2) Azimuthal rotation of the sun

- The spiral shape of the IMF is thus similar to that produced by water sprayed out of a rotary lawn sprinkler.

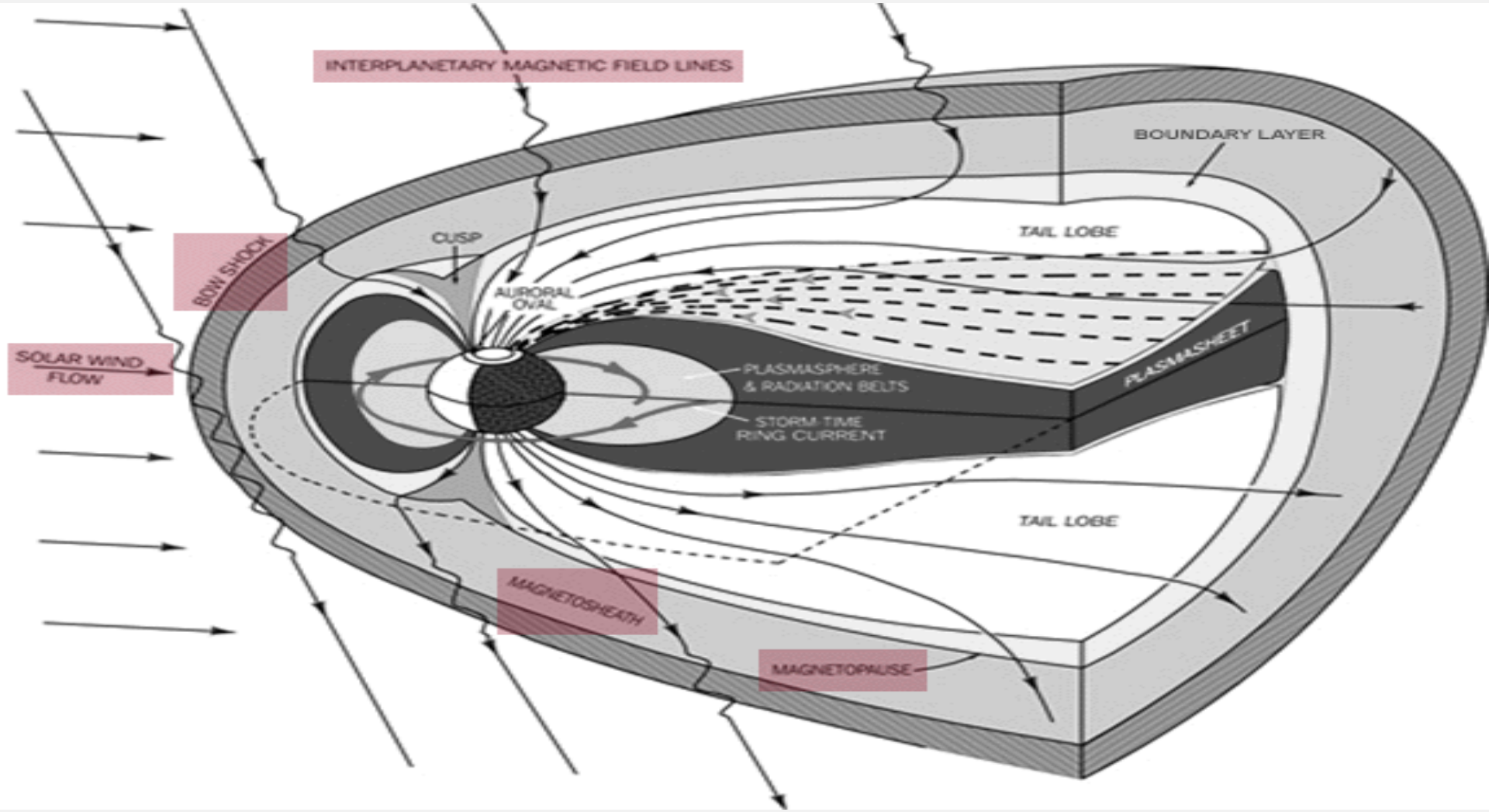
The Heliosphere: Where The Solar Wind Exists



- Eventually, the Solar Wind's influence becomes negligibly small and it terminates.
- The region of space in which the Solar Wind exists is called the "***Heliosphere***".
- Outside the Heliosphere is the "***Interstellar Medium***" (i.e. the Galaxy)

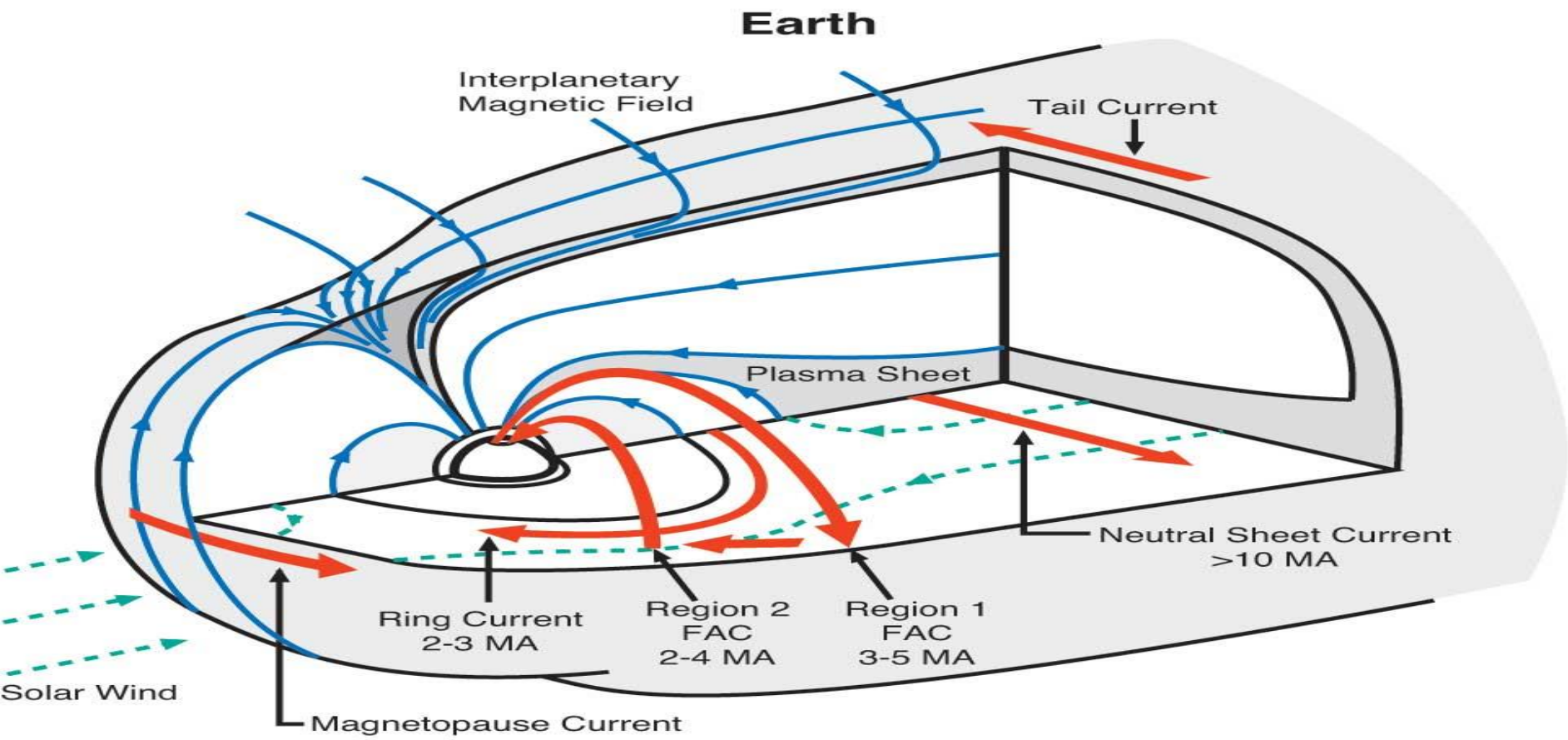
Space Weather: The Magnetosphere-Ionosphere

Space Weather: The Magnetosphere



- **DEFINE**: The "***Magnetosphere***" is the region of near-Earth space in which the dominant space plasma influence is the Earth's ***Geomagnetic Field***.

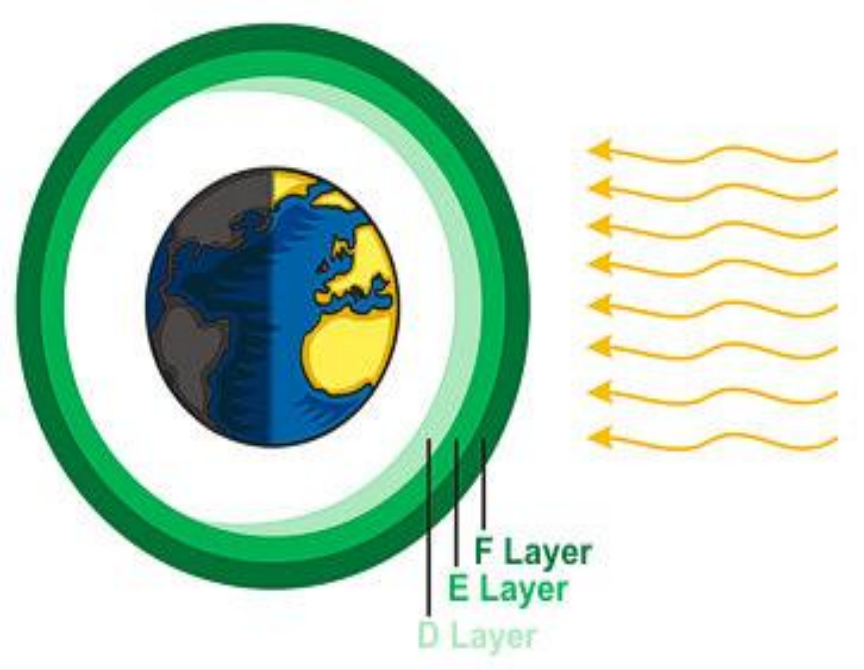
Space Weather: Magnetospheric Currents

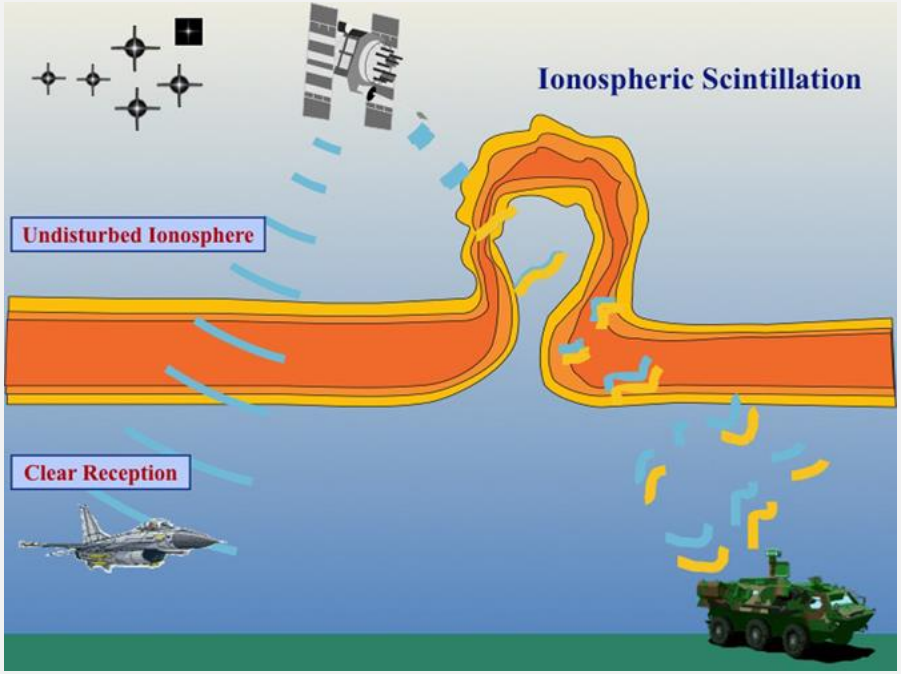


- The ***Distorted Geometry*** of the Magnetosphere is maintained by ***Electric Currents***:
  - Magnetopause Current, Tail Current, Neutral Sheet Current, Ring Current.
  - Also, currents flow ***along*** Magnetic Field Lines into the Atmosphere/Ionosphere.

Space Weather: The Ionosphere

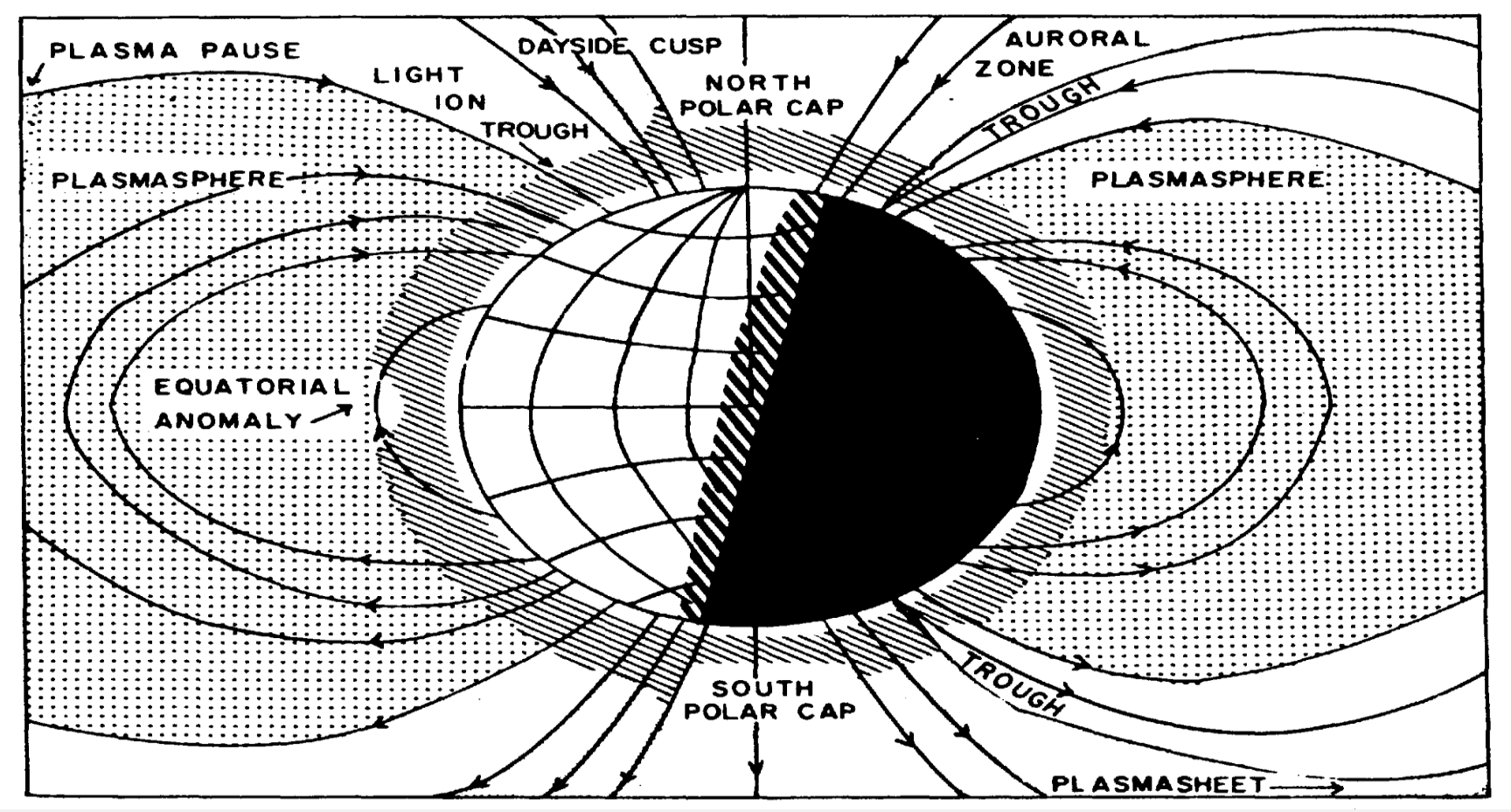
- **DEFINE**: The **IONOSPHERE** is the charged portion of Earth's upper atmosphere (i.e. a plasma). It starts at ~60-80 km altitude and extends to the edge of space.





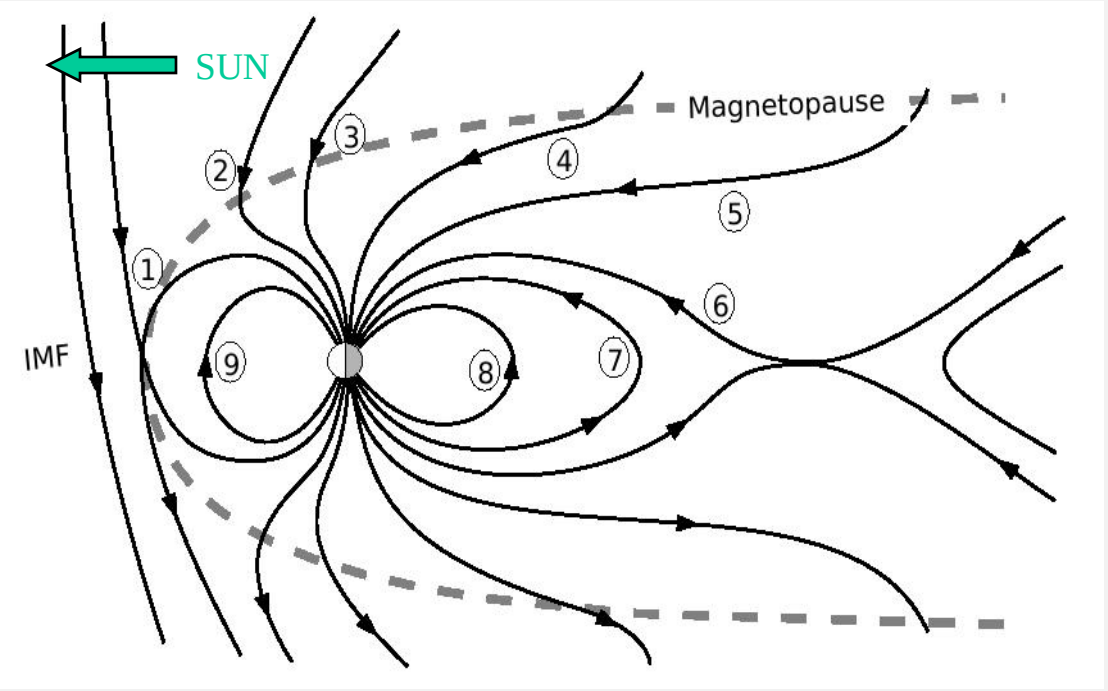
- The primary source of the ionosphere is solar electromagnetic radiation in the EUV and X-Ray regions, so it's thicker during daytime, and organized in layers.
- During space weather events, the ionosphere thickens and becomes turbulent which can disrupt radiowave signals used for communication and navigation.

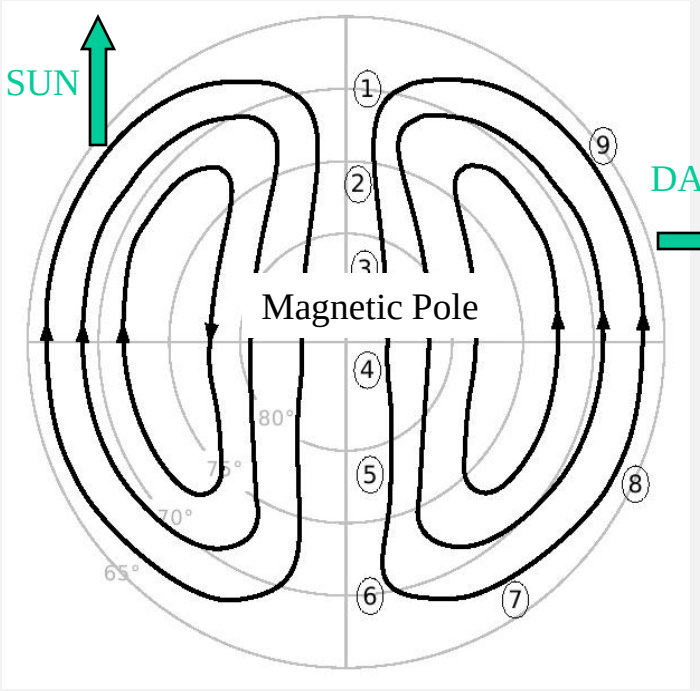
The Coupled Magnetosphere-Ionosphere



- The Ionosphere can be considered the lower boundary of the Magnetosphere.
- The two regions are coupled by electric fields transmitted along magnetic field lines.
- Ionospheric observations can thus be used to study Magnetospheric Dynamics.

Space Weather: The Ground-Based Perspective

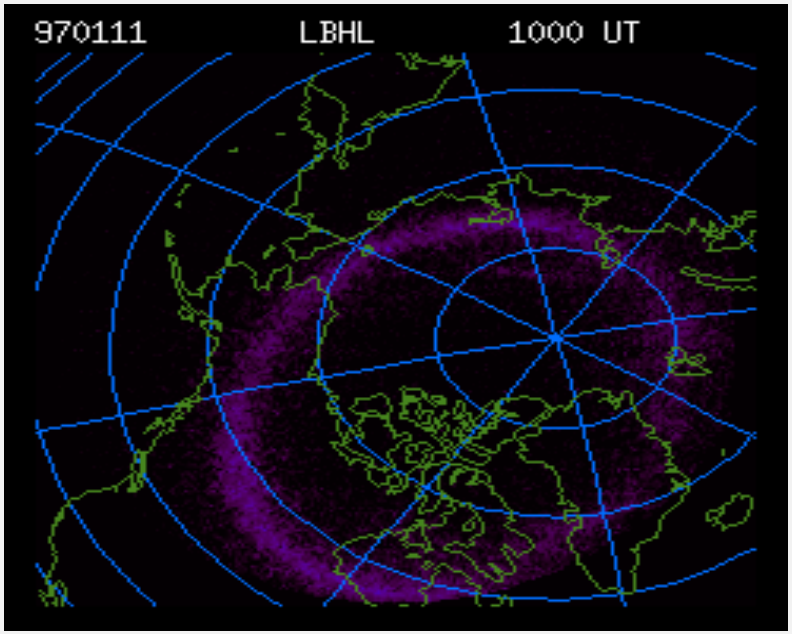


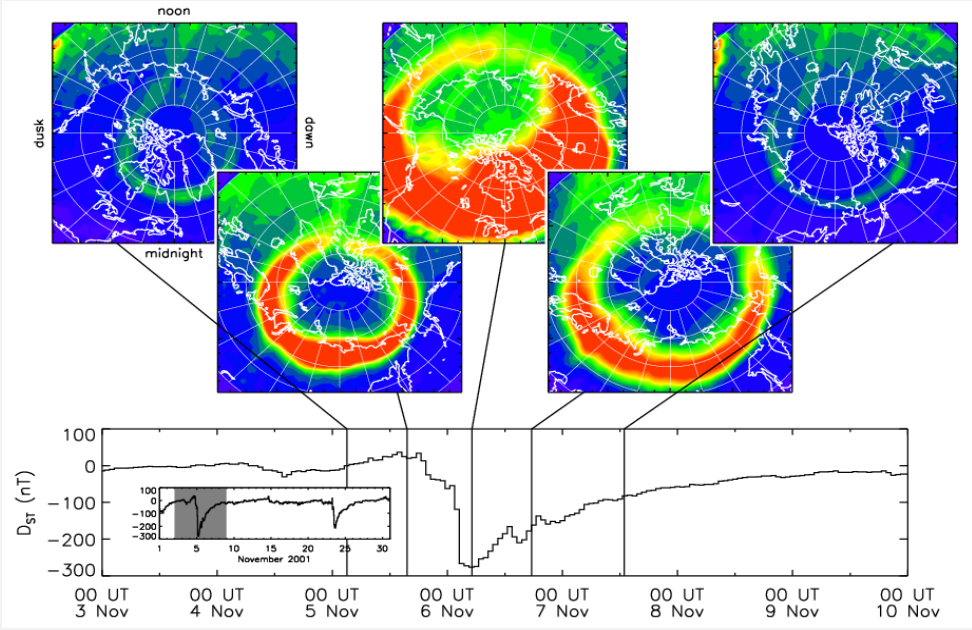


- Electric fields and currents generated out in space (left) are transmitted along magnetic field lines into the polar atmosphere where they produce aurora and drive a two-cell pattern of plasma circulation in the "ionosphere" (right).
- Thus, ground-based instruments (e.g. radars and auroral imagers) can be used to monitor the large-scale structure of space weather disturbances from below.
- This is what SuperDARN does – which is *much* cheaper than using spacecraft!

Space Weather Activity: Storms & Substorms

- **DEFINE**: An ***Auroral Substorm*** is a *short* (1-3 hours) disturbance in which Solar Wind energy is transferred to the Magnetosphere and then the ***Polar Ionosphere***.
- **DEFINE**: A ***Geomagnetic Storm*** is a *longer* (1-3 days) disturbance in which Solar Wind energy is deposited in the ***Polar Ionosphere*** AND ***Inner Magnetosphere.***

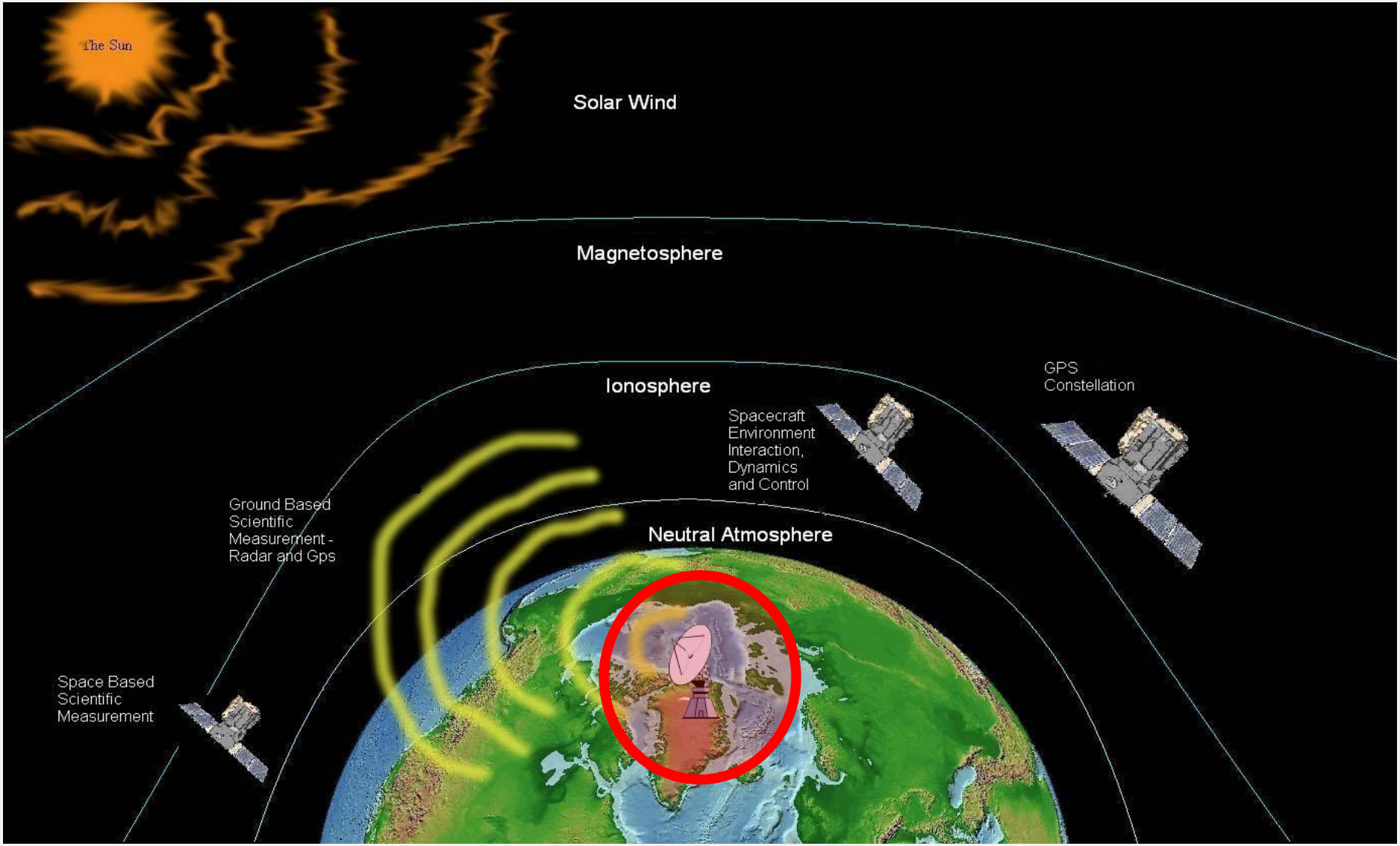




- A Geomagnetic Storm usually contains several embedded Auroral Substorms.
- This is how the Substorm got its name – it is a “sub”-component of a Storm.
- However, it is now known that Substorms also occur during non-storm periods too.

Space Weather Monitoring: Instrumentation

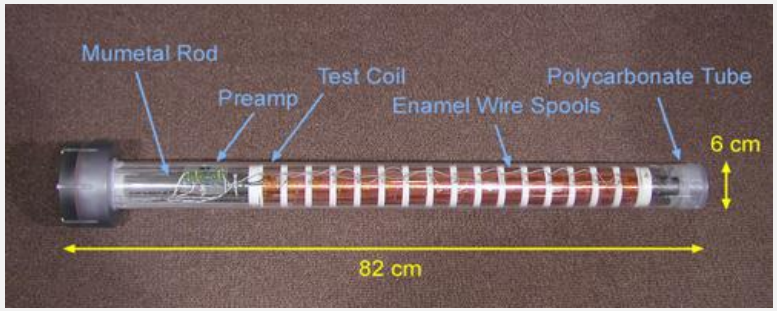
Space Weather Instrumentation

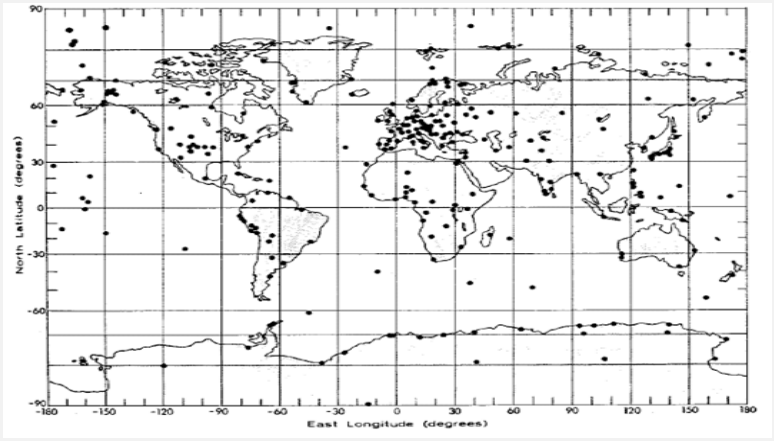


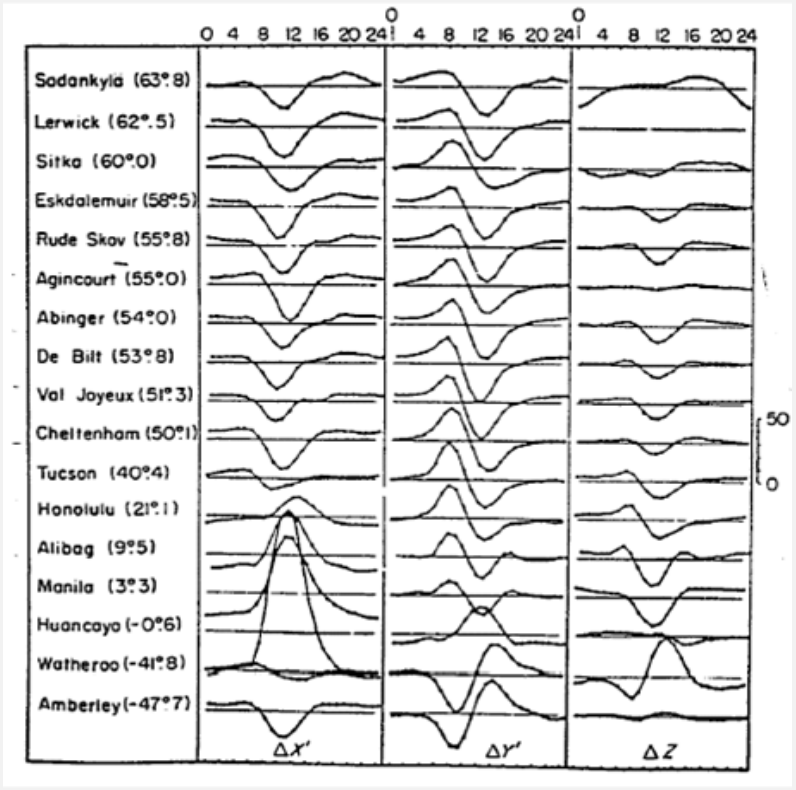
- Conditions in space can be monitored using spacecraft and ground instruments.

Ground Magnetometers

- A ***Magnetometer*** is an instrument that measures fluctuations in Magnetic Field



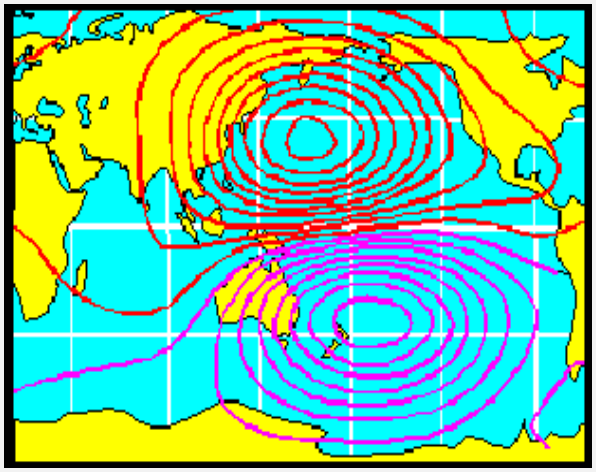




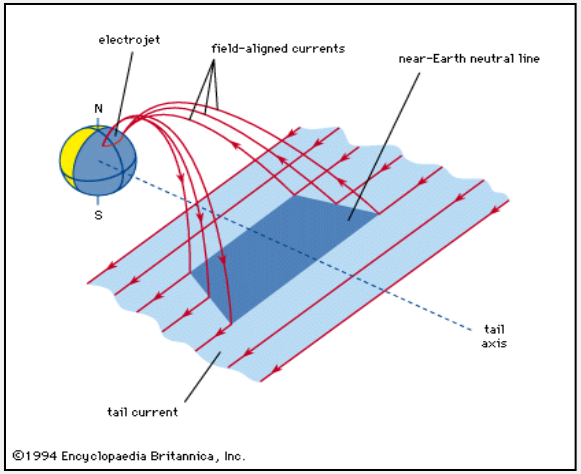
- Magnetometers are cheap and robust instruments that can be deployed anywhere.
- By analyzing worldwide magnetometer measurements it's possible to develop a dynamic picture of magnetosphere-ionosphere current systems (right figure).
- Several "***Magnetic Indices***" are produced by averaging magnetometer data.

Magnetic Indices: Kp, Dst and AE/AU/AL

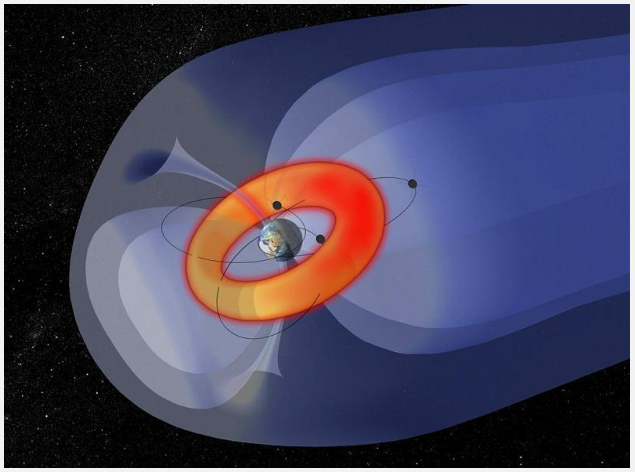
Kp Index



AE/AU/AL Indices



Dst Index



Kp ("Planetary") Index:

- Monitors *Worldwide Average* geomagnetic disturbance

AE/AU/AL ("Auroral Electrojet") Indices:

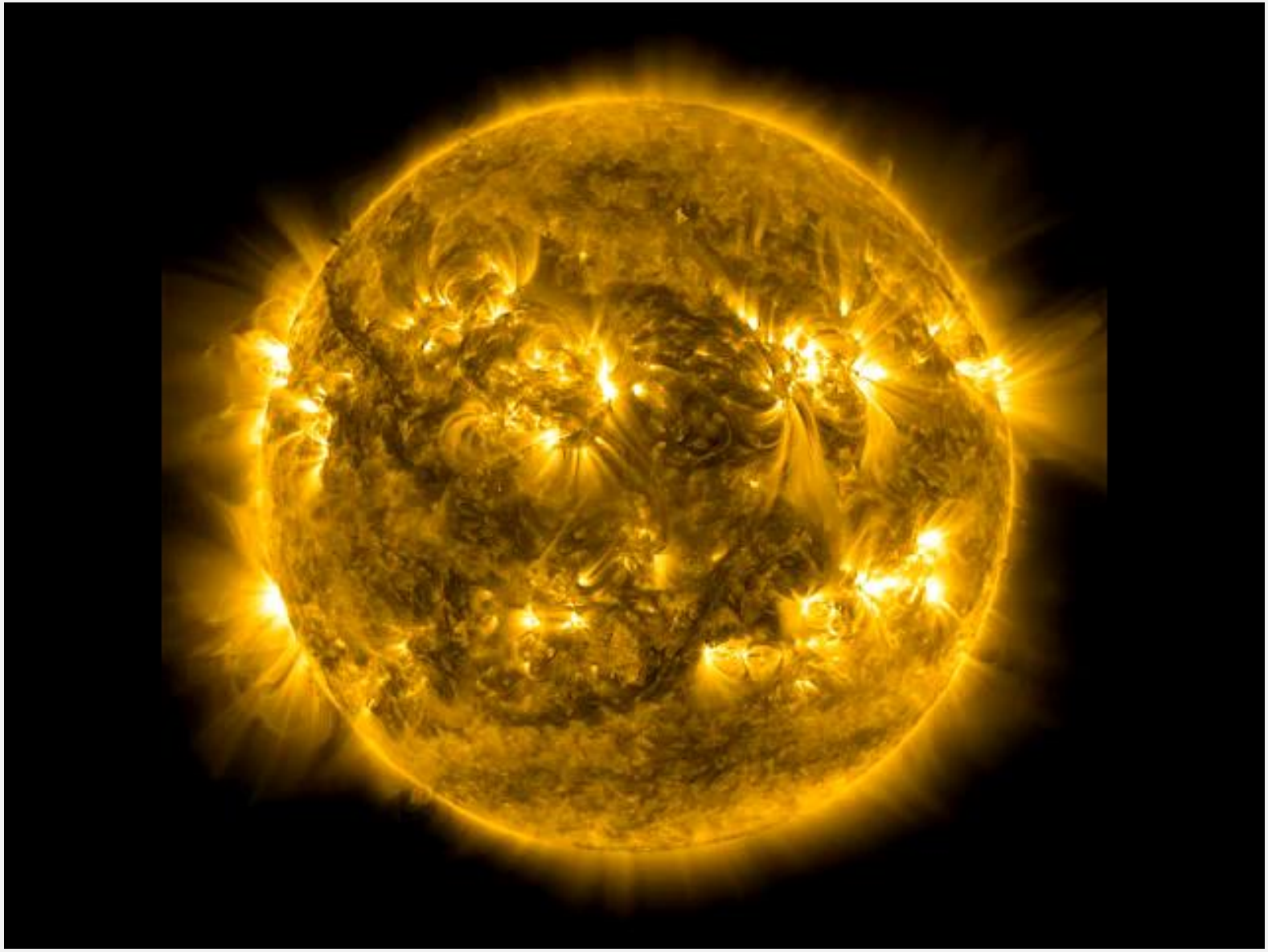
- Monitor magnetic disturbance produced by *Auroral Activity*.
- A period of enhanced AE/AU/AL is called an ***Auroral Substorm***.

Dst ("Disturbance Storm-Time") Index:

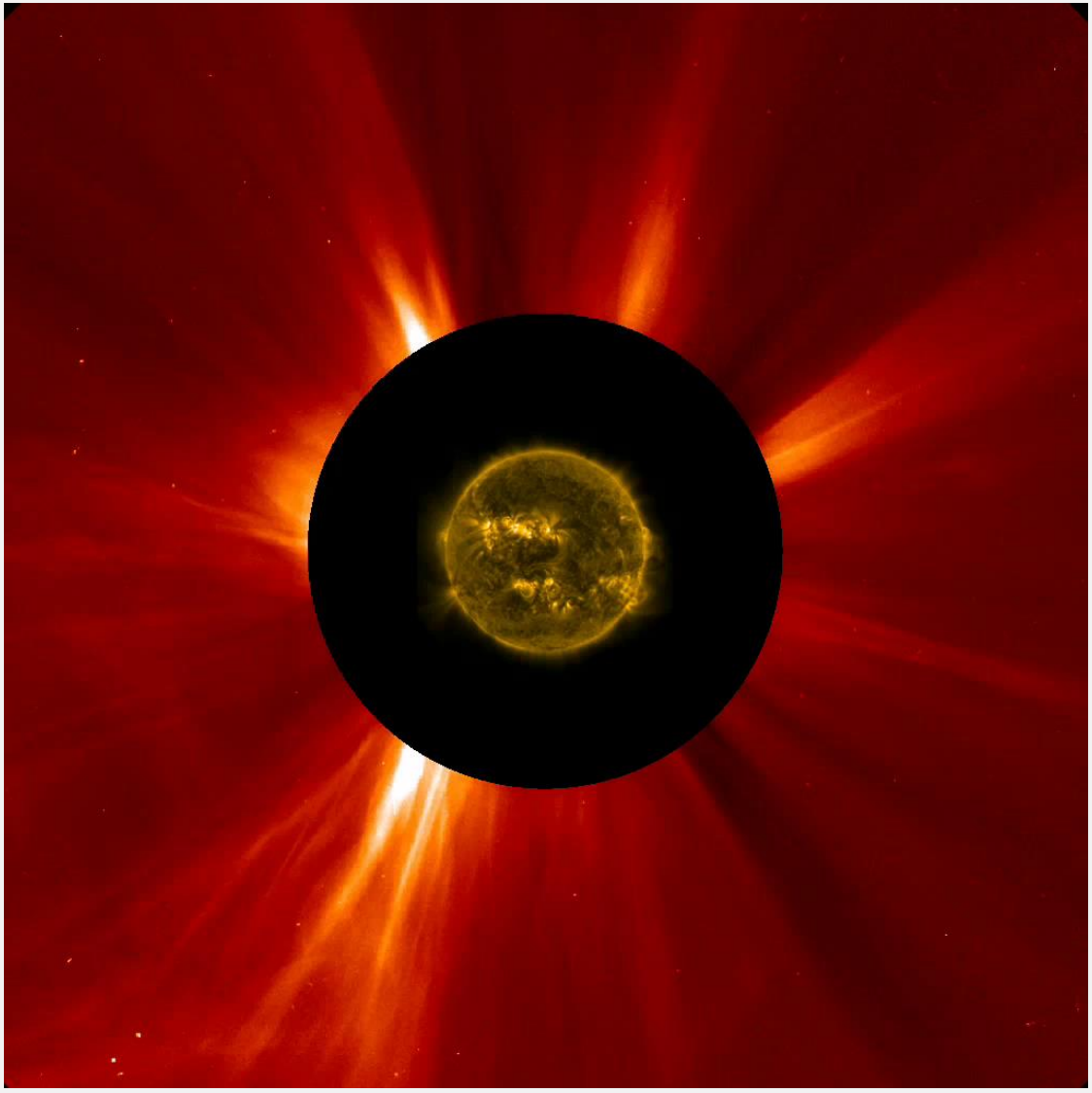
- Monitors the strength of the *Ring Current and Radiation Belts*.
- A period of enhanced Dst is called a "***Geomagnetic Storm***".

Space Weather: A Few More Movies

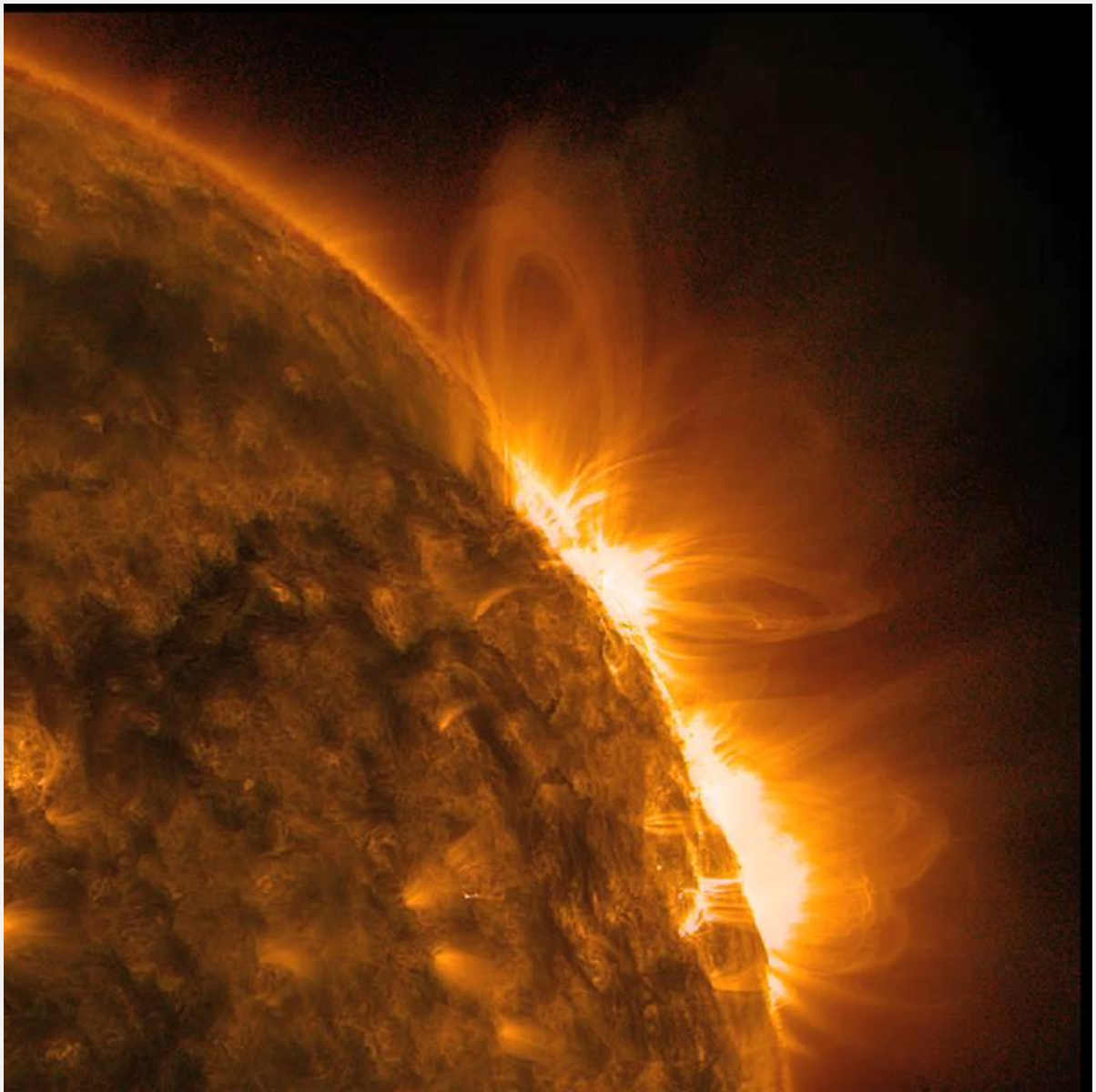
Space Weather: More Movies



Space Weather: More Movies



Space Weather: More Movies



Space Weather: More Movies