Space Weather Science School

Lecture: The Sun-Earth Connection

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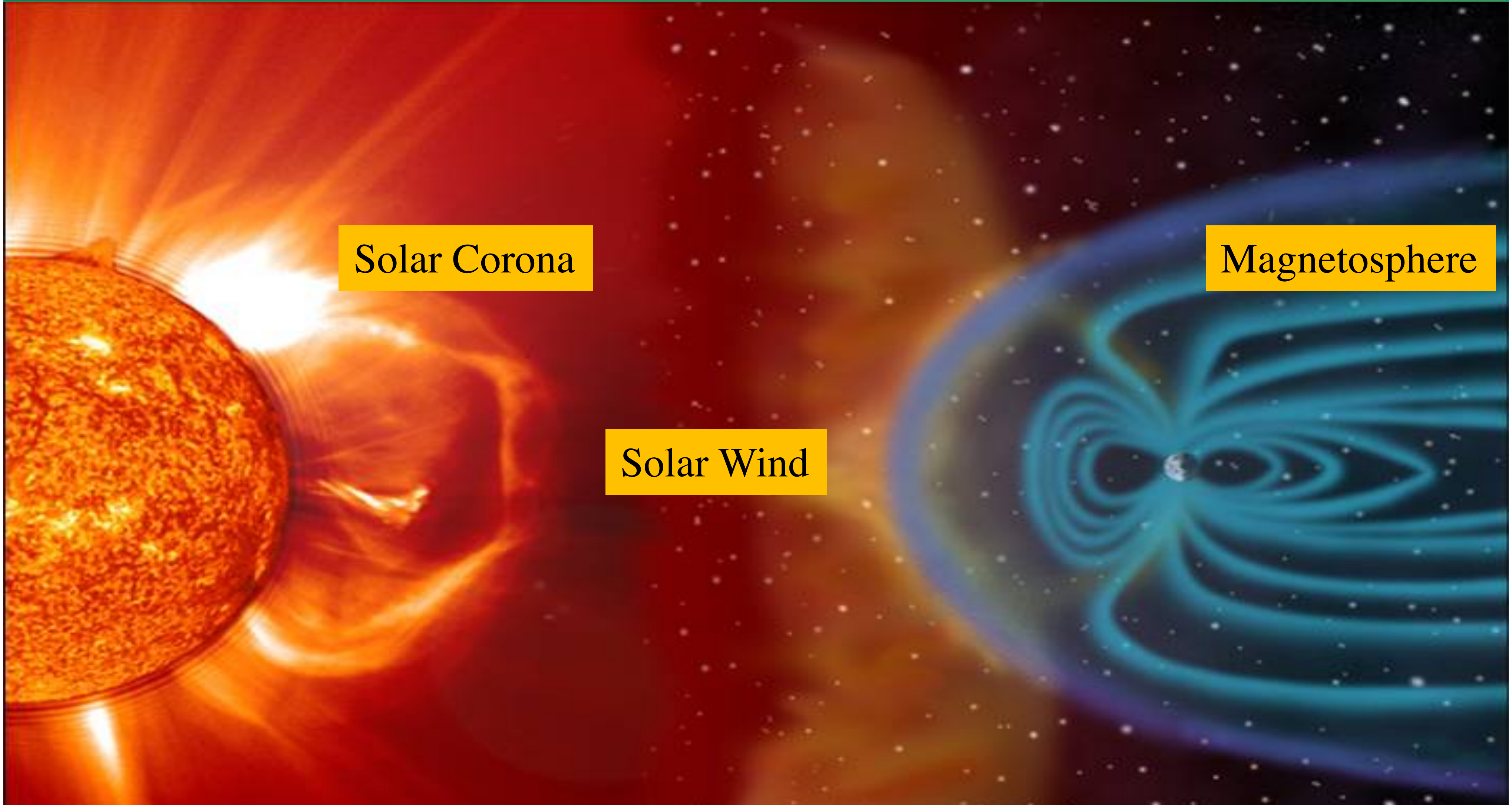
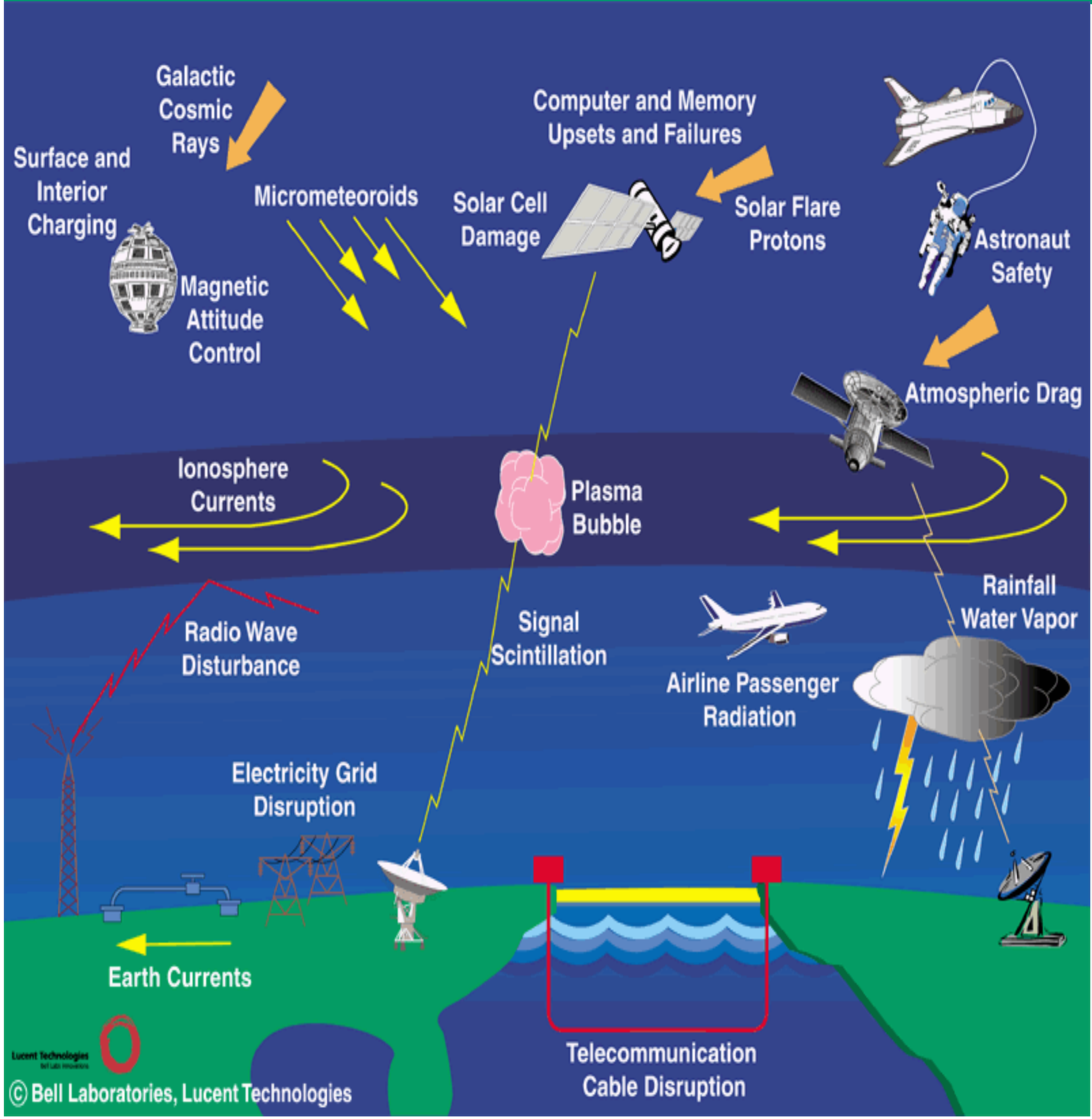
What is Space Weather?



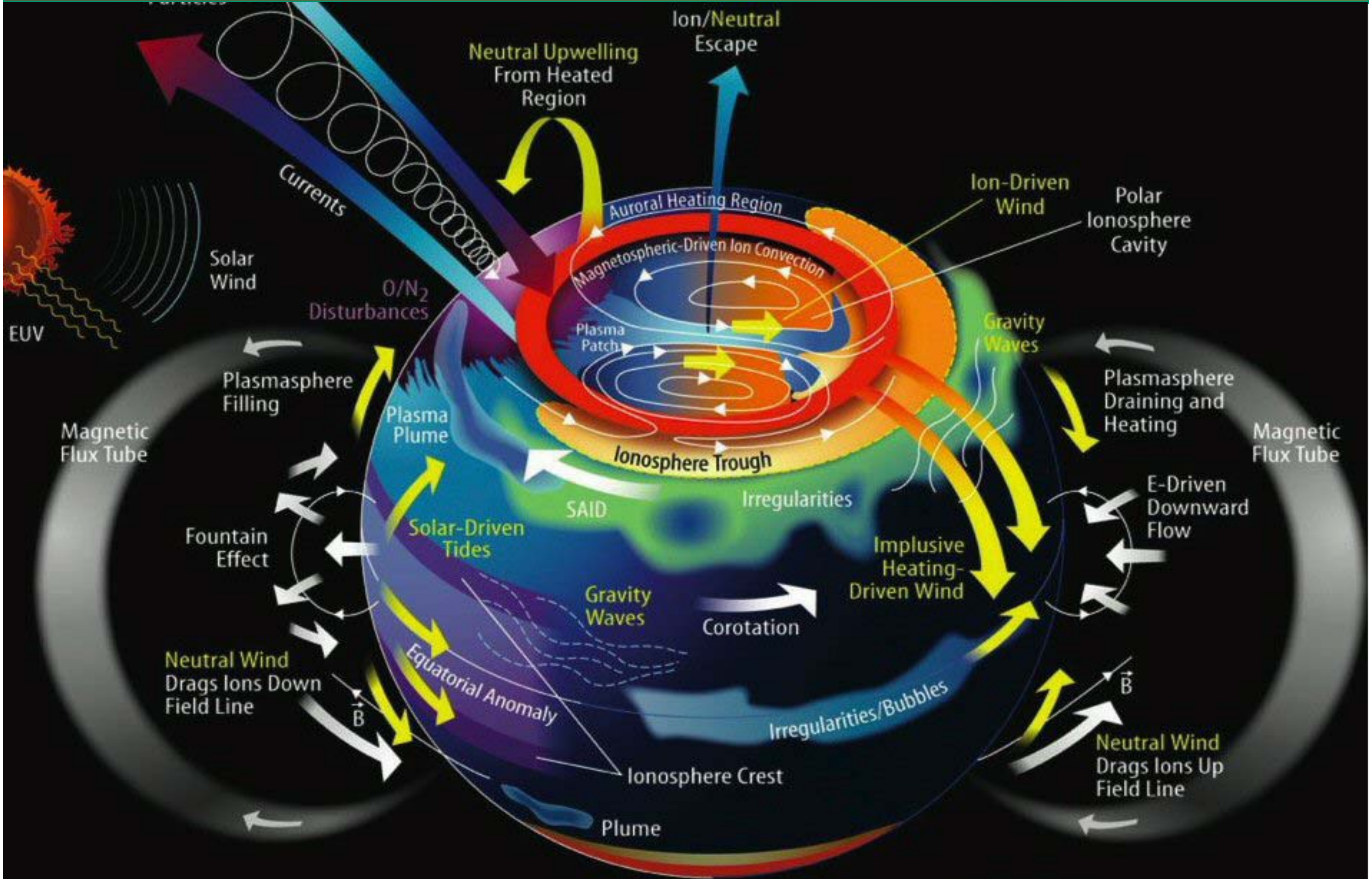
"Space Weather" refers to dynamic conditions on the Sun and how they perturb the near-Earth space environment to influence the reliability of space-borne and ground-based technological systems, and possibly endanger human life or health.

Space Weather Hazards

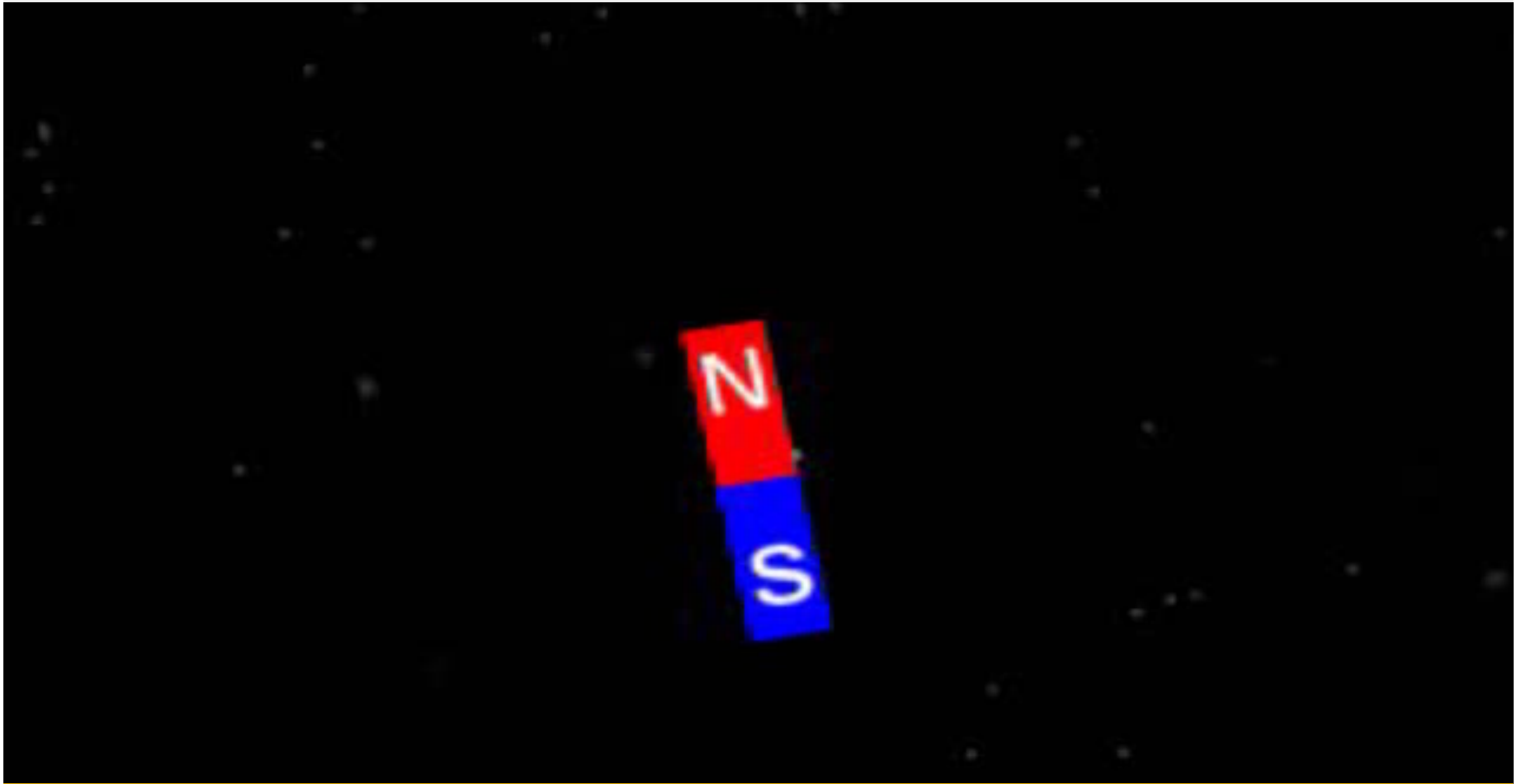


- Spacecraft radiation damage
- Spacecraft guidance anomalies
- Satellite drag (decreased life)
- Power grid disruption
- Human health (radiation)
- Deviation of airplanes
- Degraded navigation
- Disrupted communication
- Radar clutter
- Confused pigeons!

The Geospace System

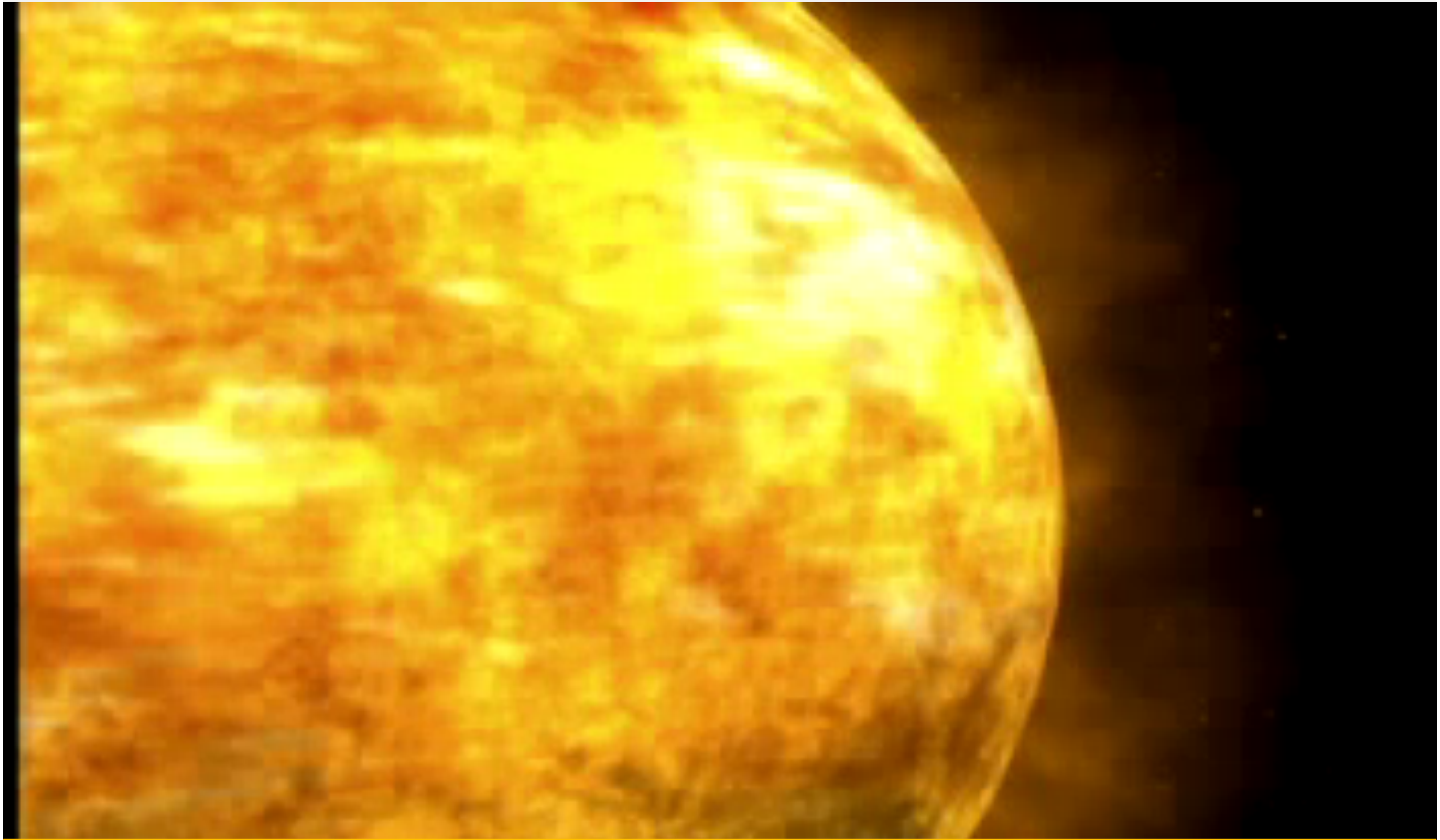


The Magnetosphere



- 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

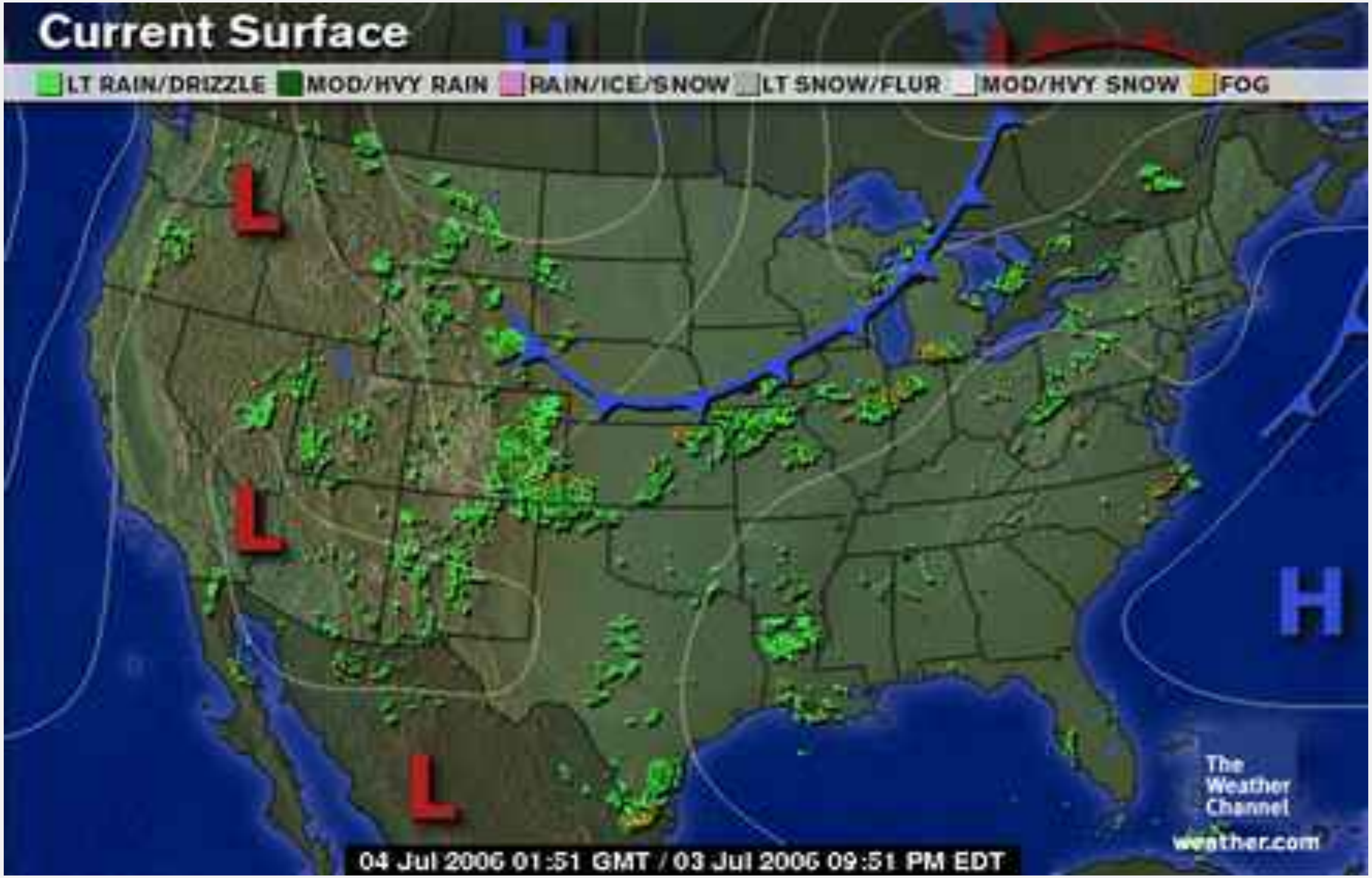


- The northern lights or "aurora" is a visual manifestation of space weather!

Aurora

- One manifestation of space weather dynamics is the Aurora (or "Northern Lights").
- Aurora is light produced when energetic charged particles impact the atmosphere.

The Space Weather Goal

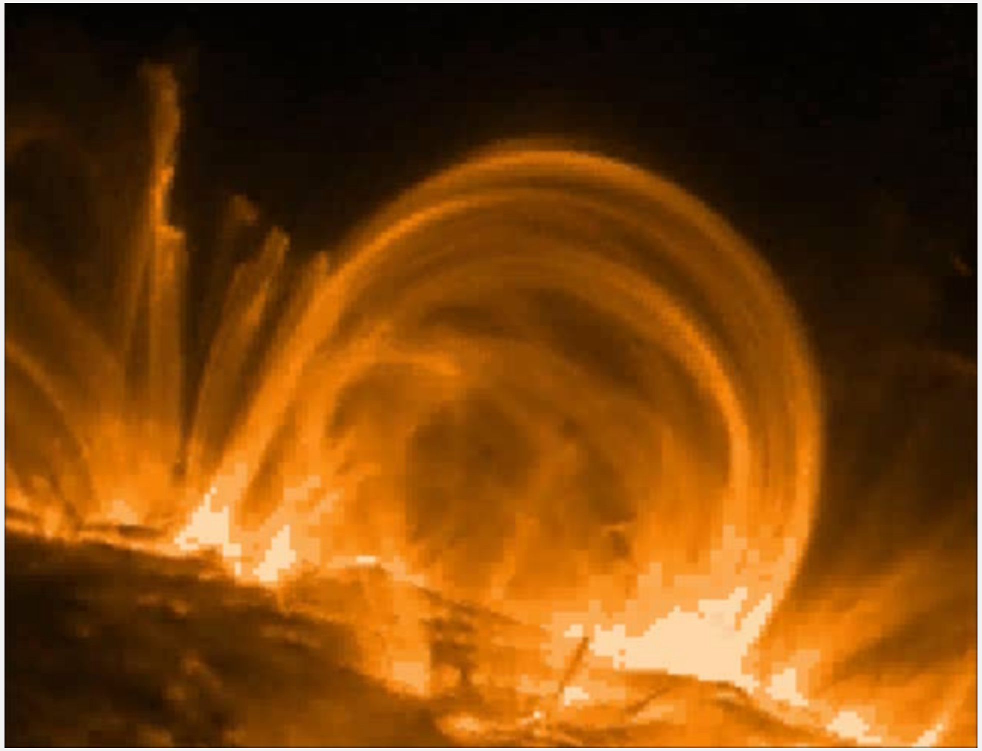


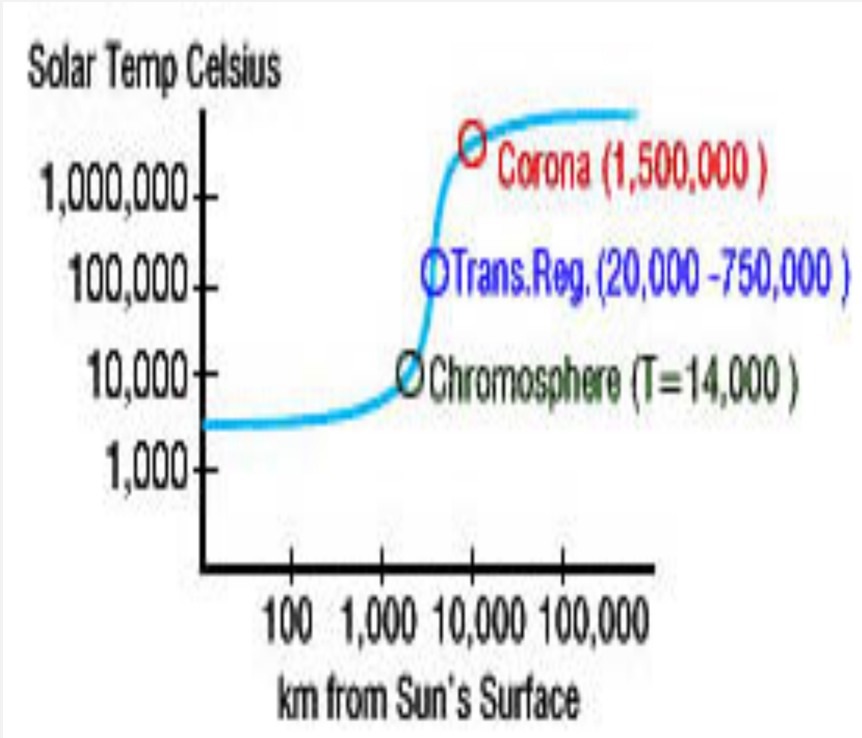
Is it a good day for a space-walk?

Solar Activity

Solar Atmospheric Regions

- To understand solar activity, we first need to know the structure of its atmosphere.
- Yes, like the planets, the Sun has a tenuous "atmosphere" which is highly dynamic.



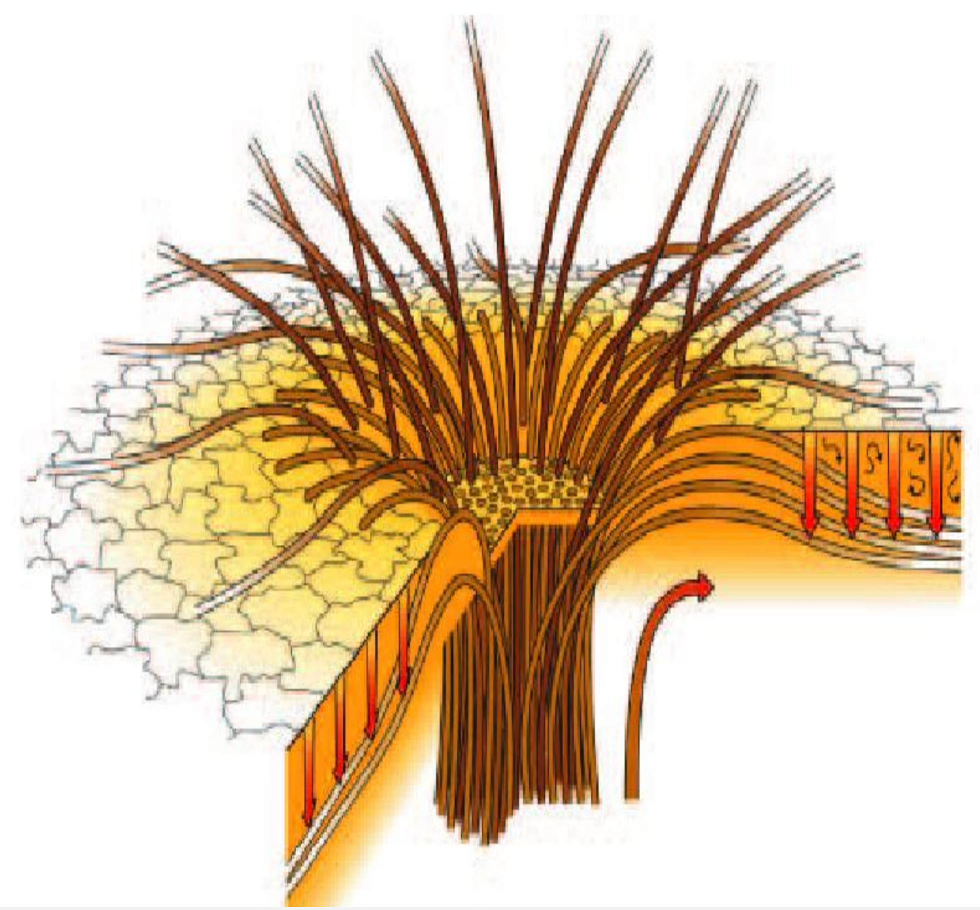


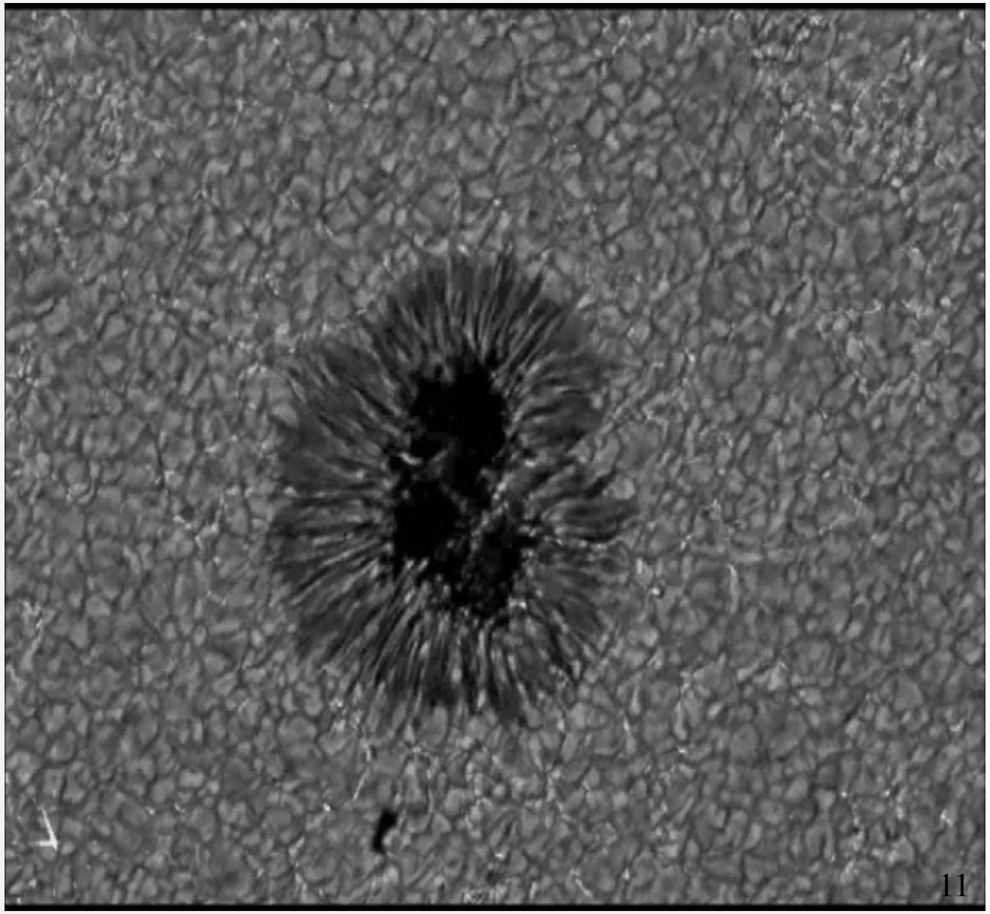
- The solar atmosphere is divided into four distinct regions, based on temperature:

- **Photosphere**
- **Chromosphere**
- **Transition region**
- **Corona**

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.

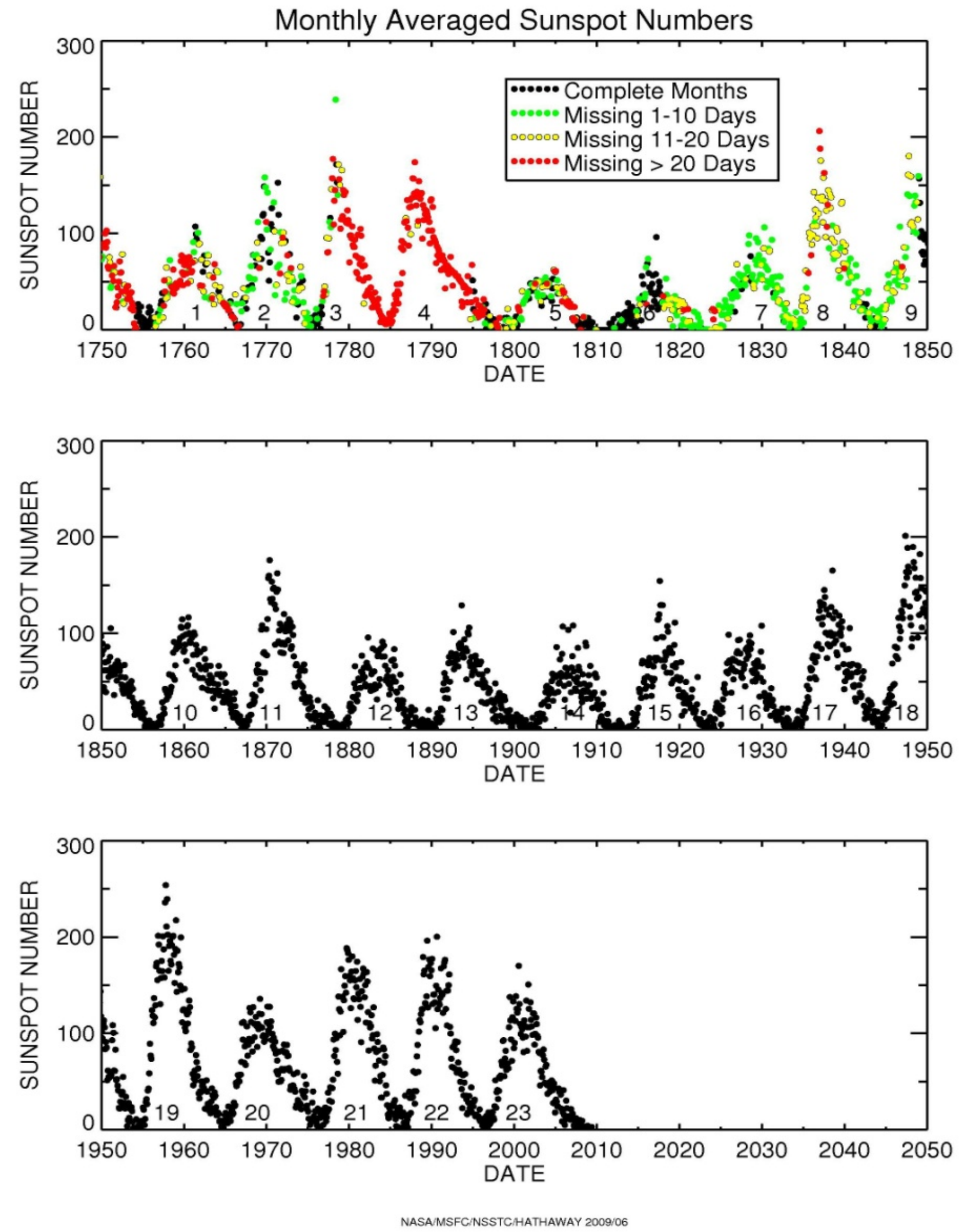




Sunspot Formation

- 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 Sunspot Cycle

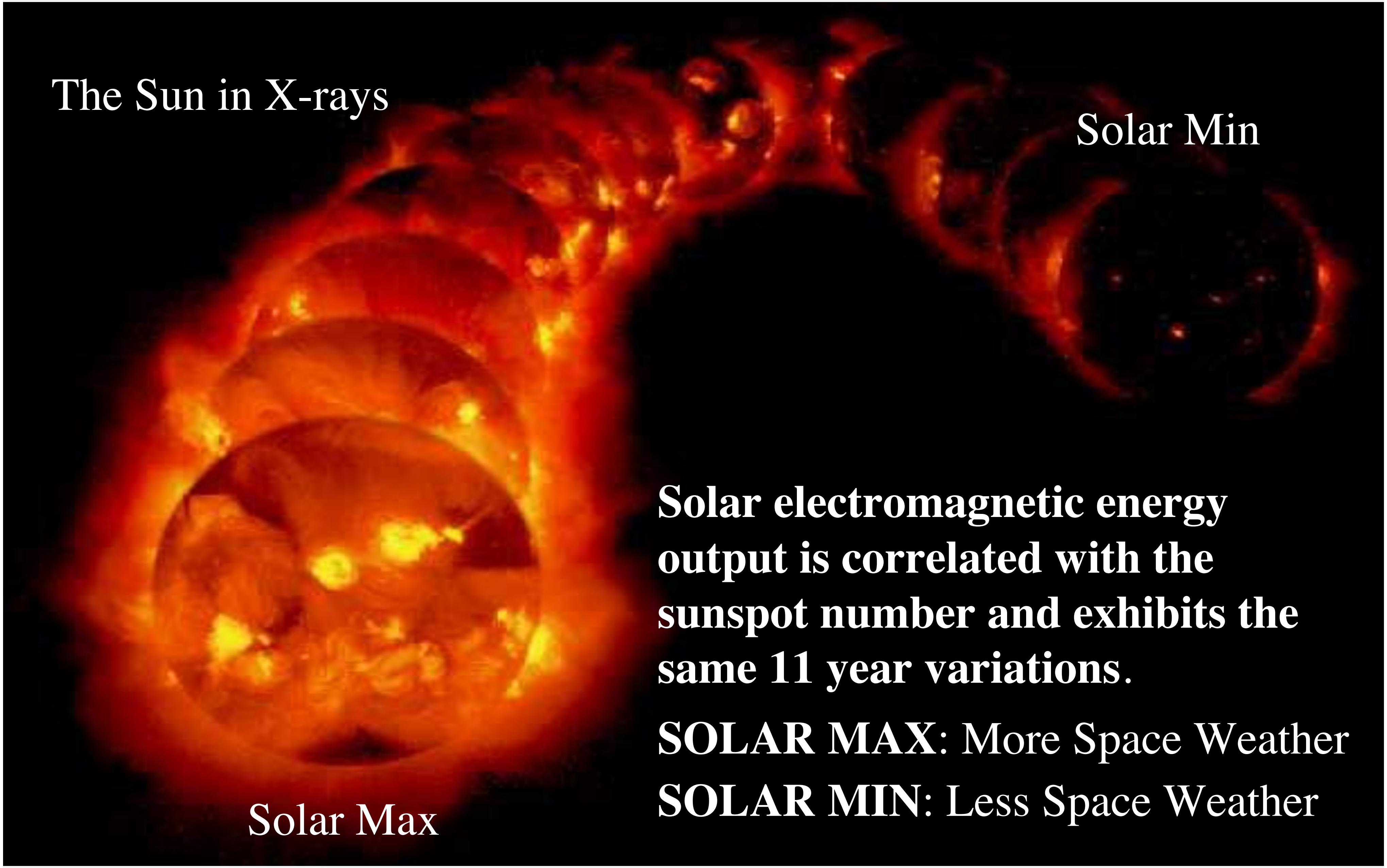


- Sunspots usually appear in groups that form over hours or days and last for several days or weeks.
- In 1844, Heinrich Schwabe was the first to identify an 11-year periodicity in the number of sunspot groups:

SOLAR MINIMUM: Few sunspots

SOLAR MAXIMUM: Many sunspots

The Solar Cycle



Solar electromagnetic energy output is correlated with the sunspot number and exhibits the same 11 year variations.

SOLAR MAX: More Space Weather

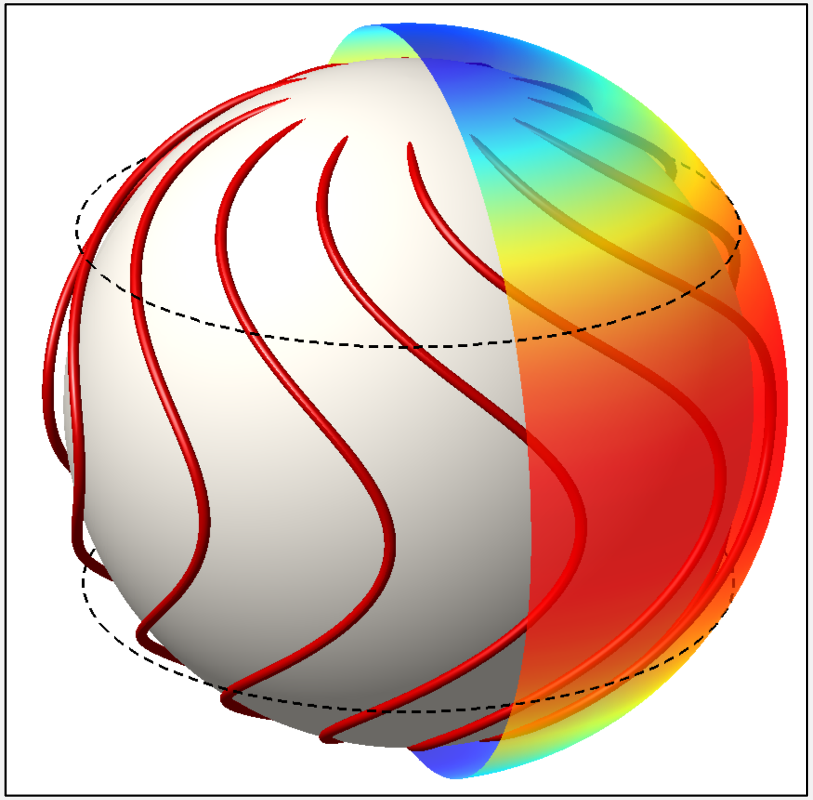
SOLAR MIN: Less Space Weather

The Sun's Magnetic Field: A Tangled Mess!

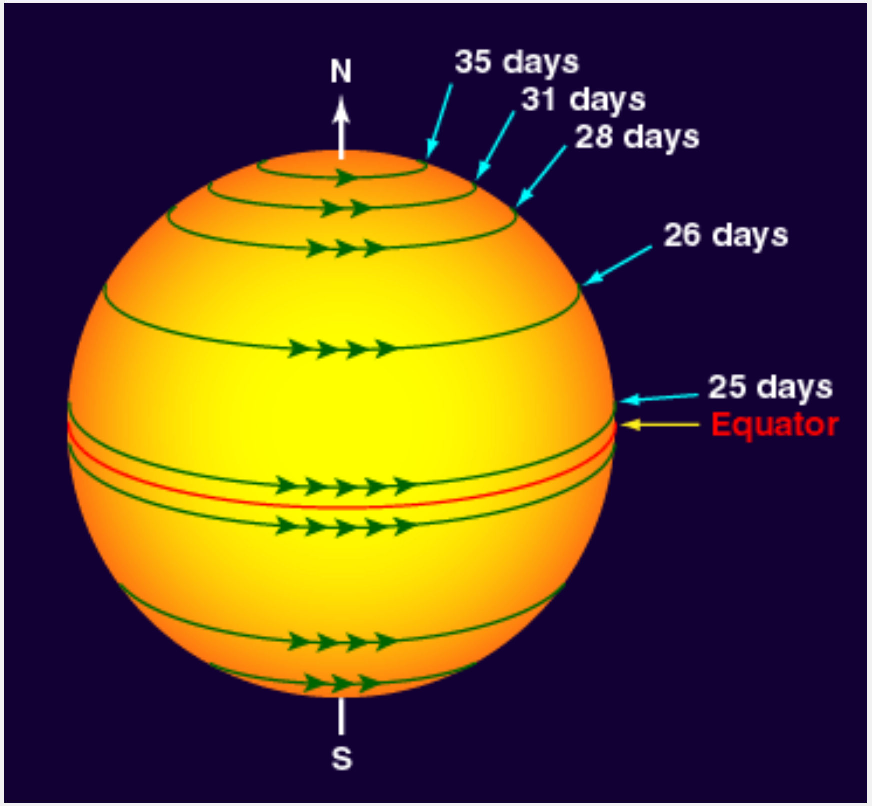
- Sunspots are produced when the Sun's magnetic field gets tangled.
- The Sun's magnetic field gets tangled because of two influences:

  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)



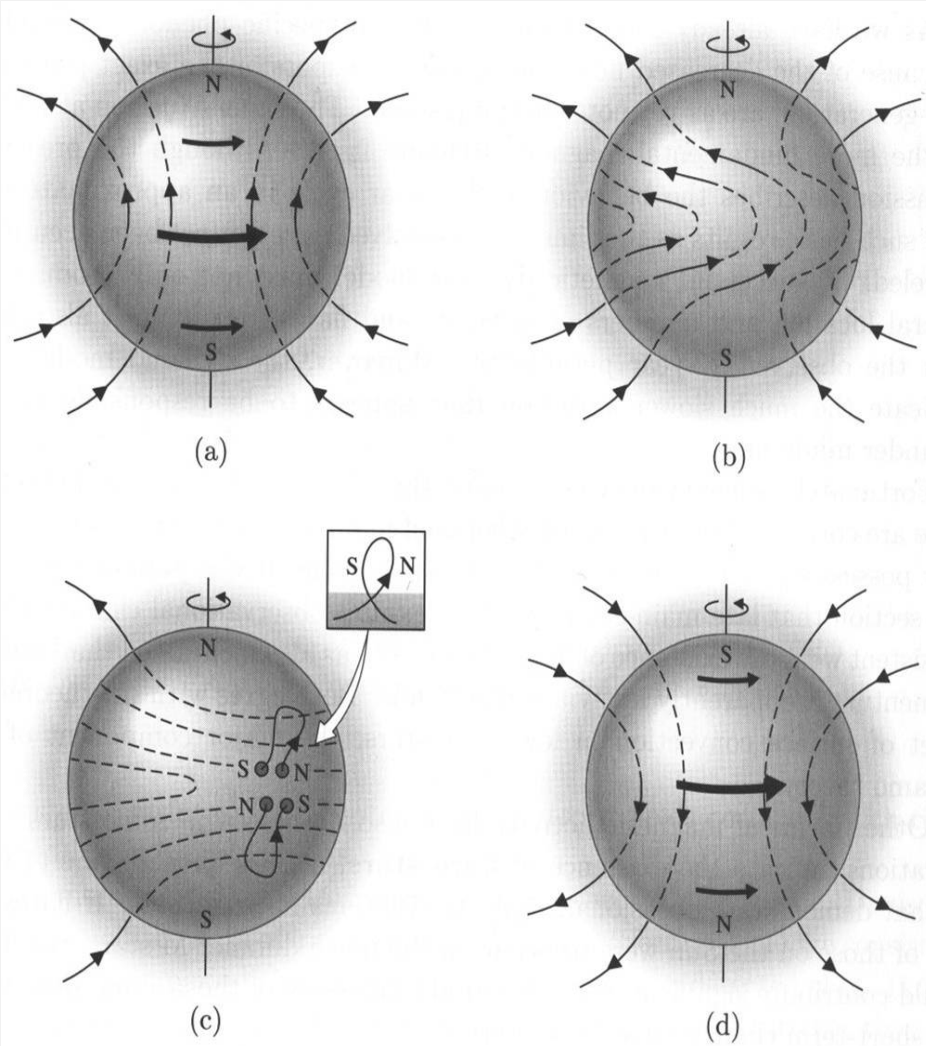
Near-Surface Solar Magnetic Field



Differential Solar Rotation

The Babcock Solar 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***":



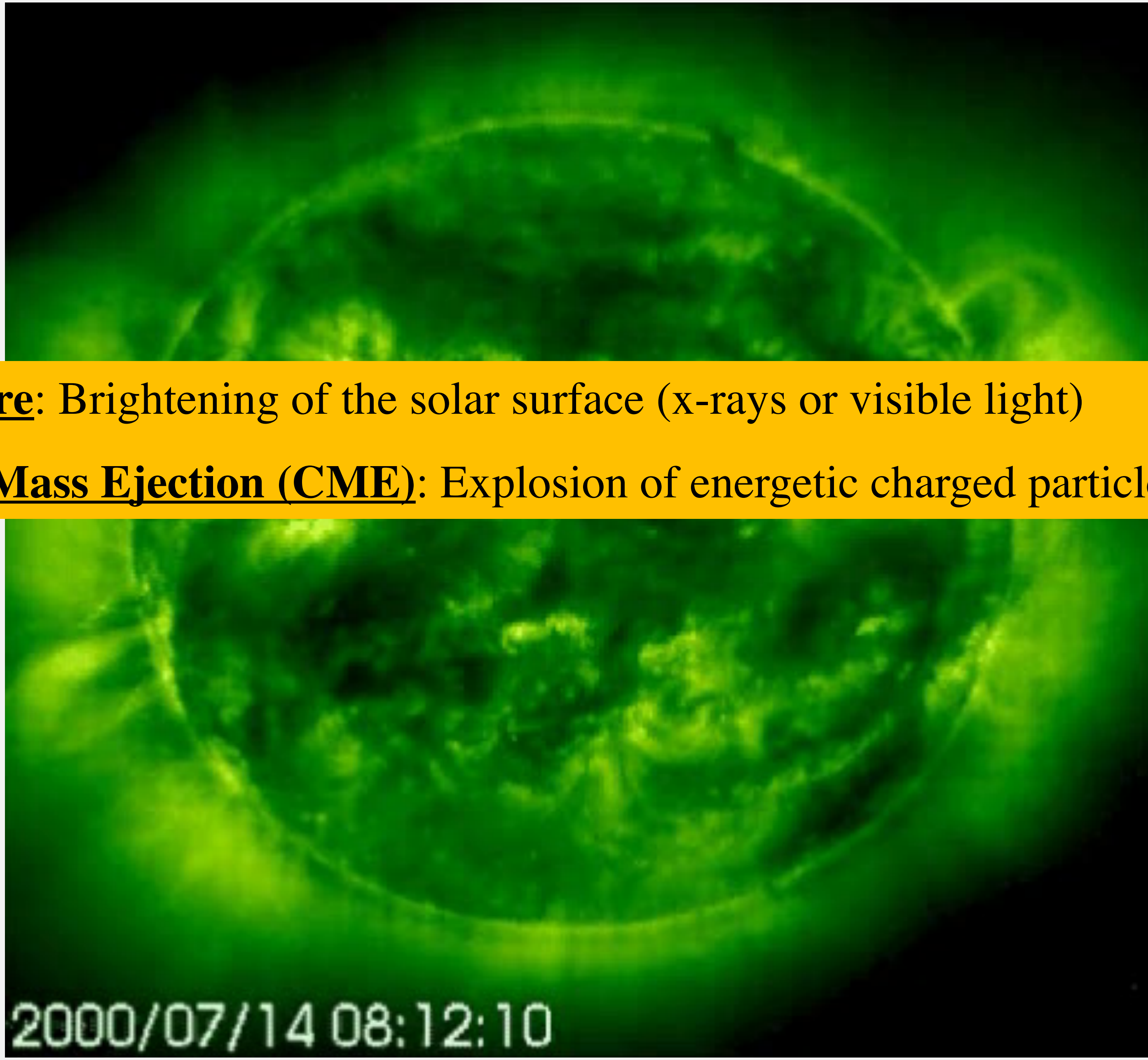
a) At solar minimum, a poloidal magnetic field (i.e. north-south) exists in a shallow layer just below the photosphere.

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.

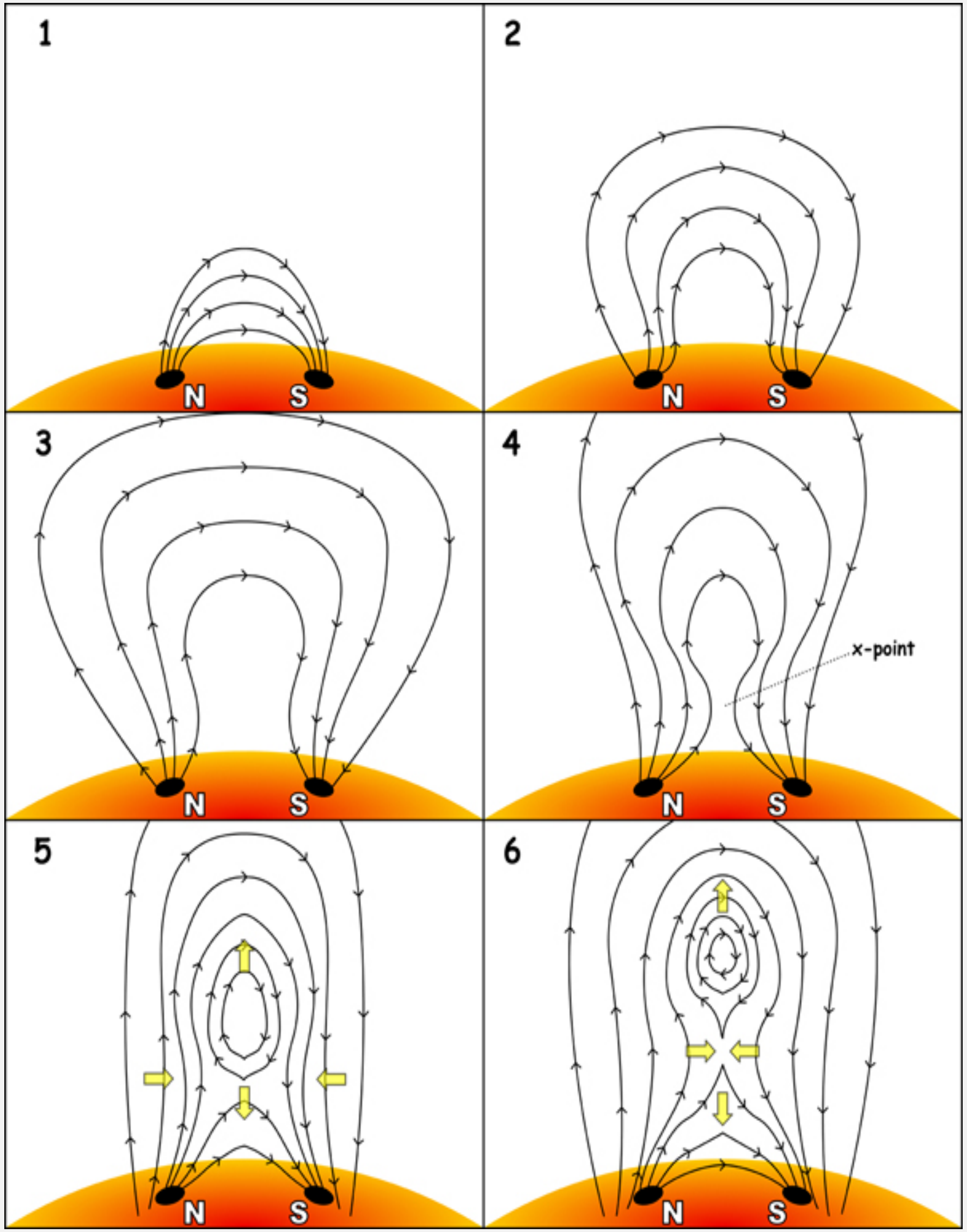
Solar Activity: The Bastille Day Event



<u>Solar Flare</u>: Brightening of the solar surface (x-rays or visible light)

<u>Coronal Mass Ejection (CME)</u>: 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

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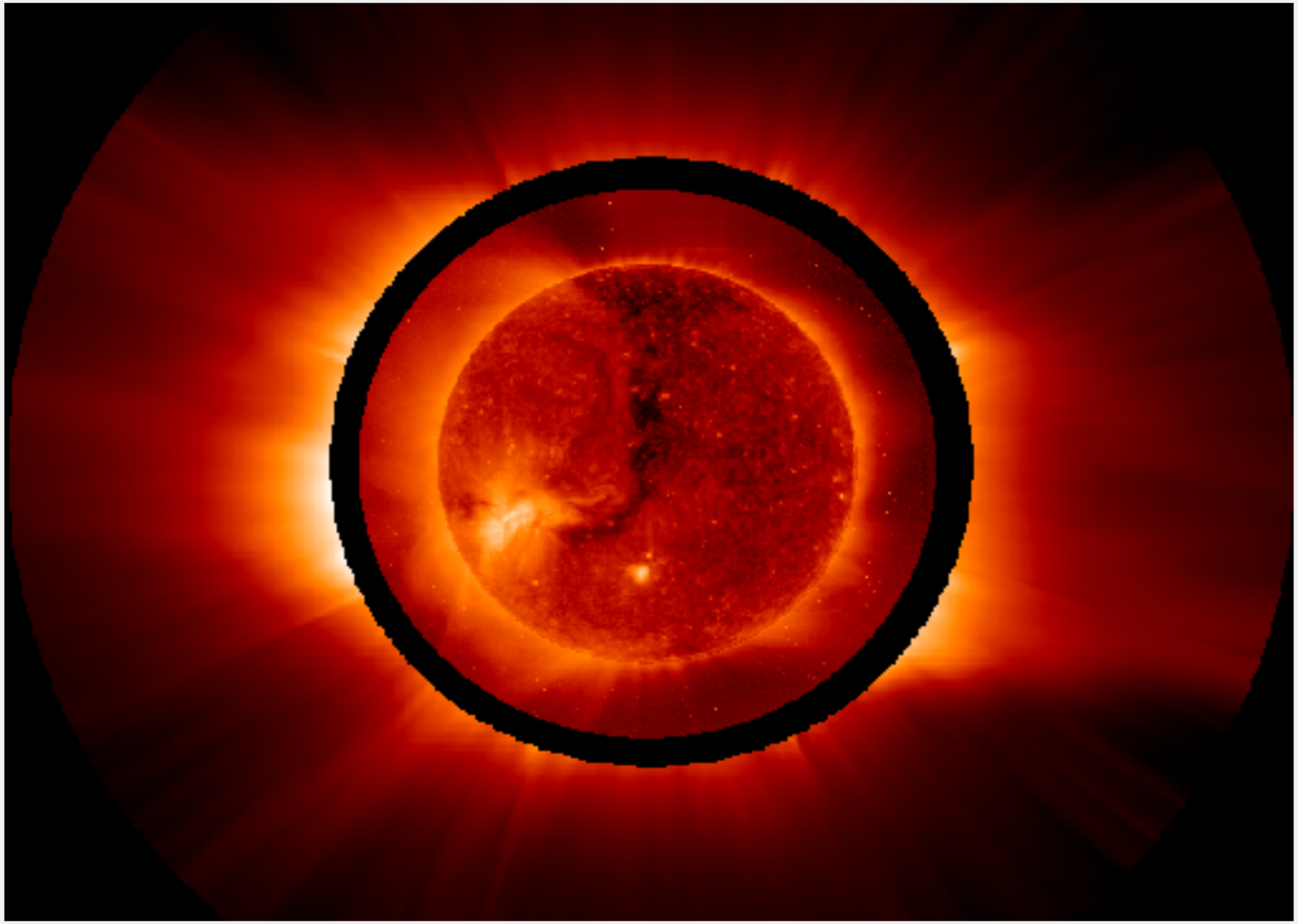
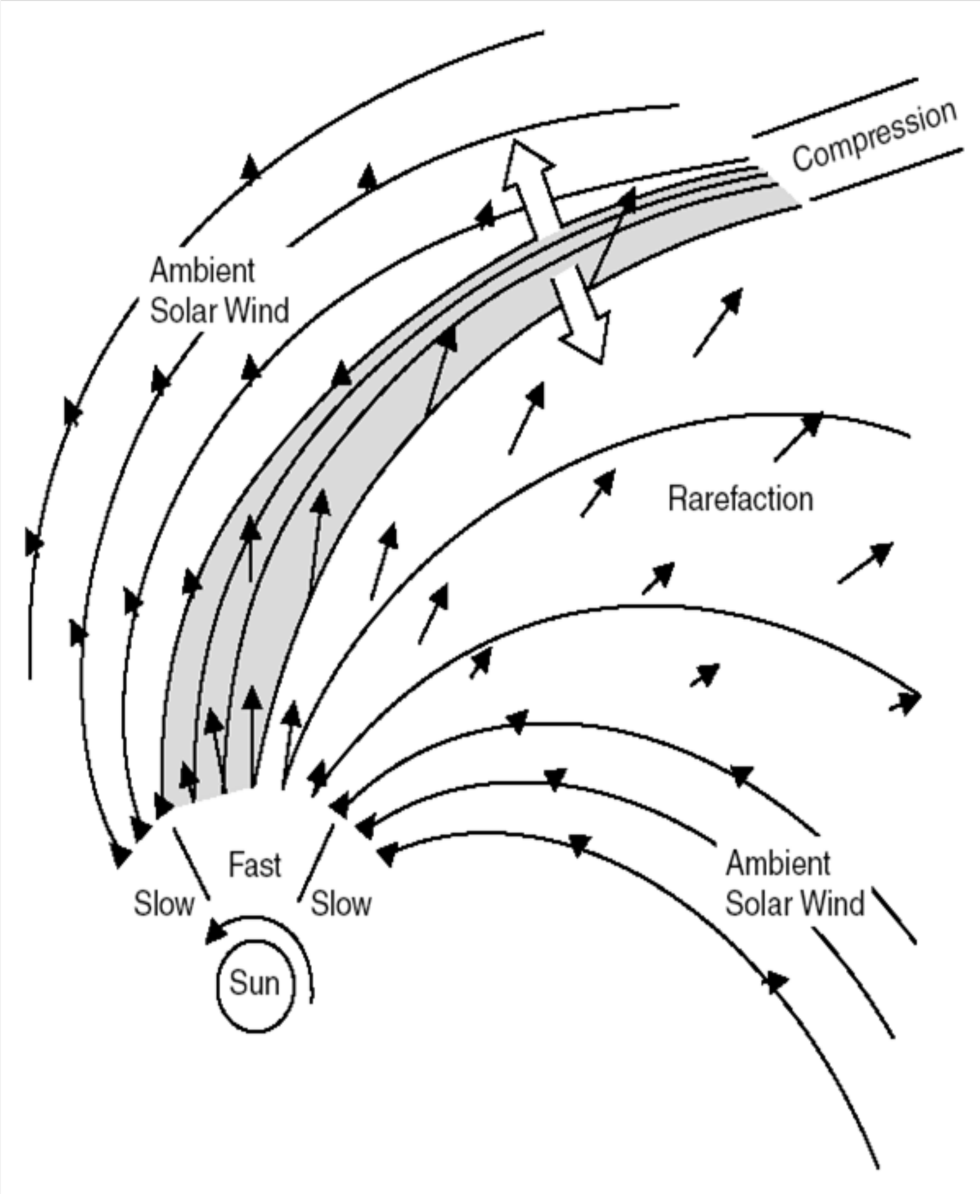
The Interplanetary Magnetic Field (IMF)

The Solar Wind



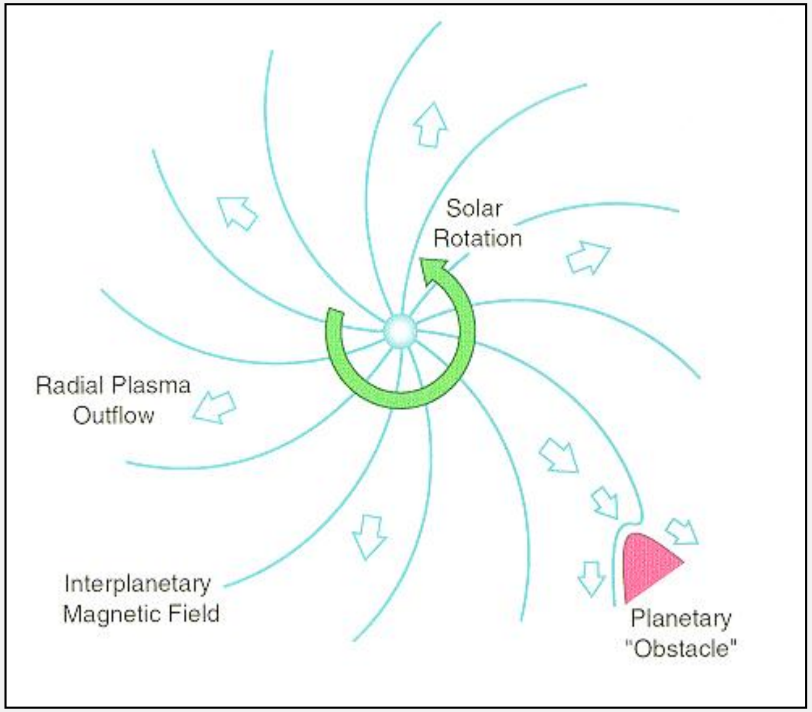
- The Solar Wind is the extension of the Sun's outer atmosphere, the Corona, which blows continuously throughout the solar system.
- Disturbances in the Sun's atmosphere (most notably, Coronal Mass Ejections) are transmitted to the near-Earth space plasma environment via the Solar Wind.

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.

The Interplanetary Magnetic Field (IMF)

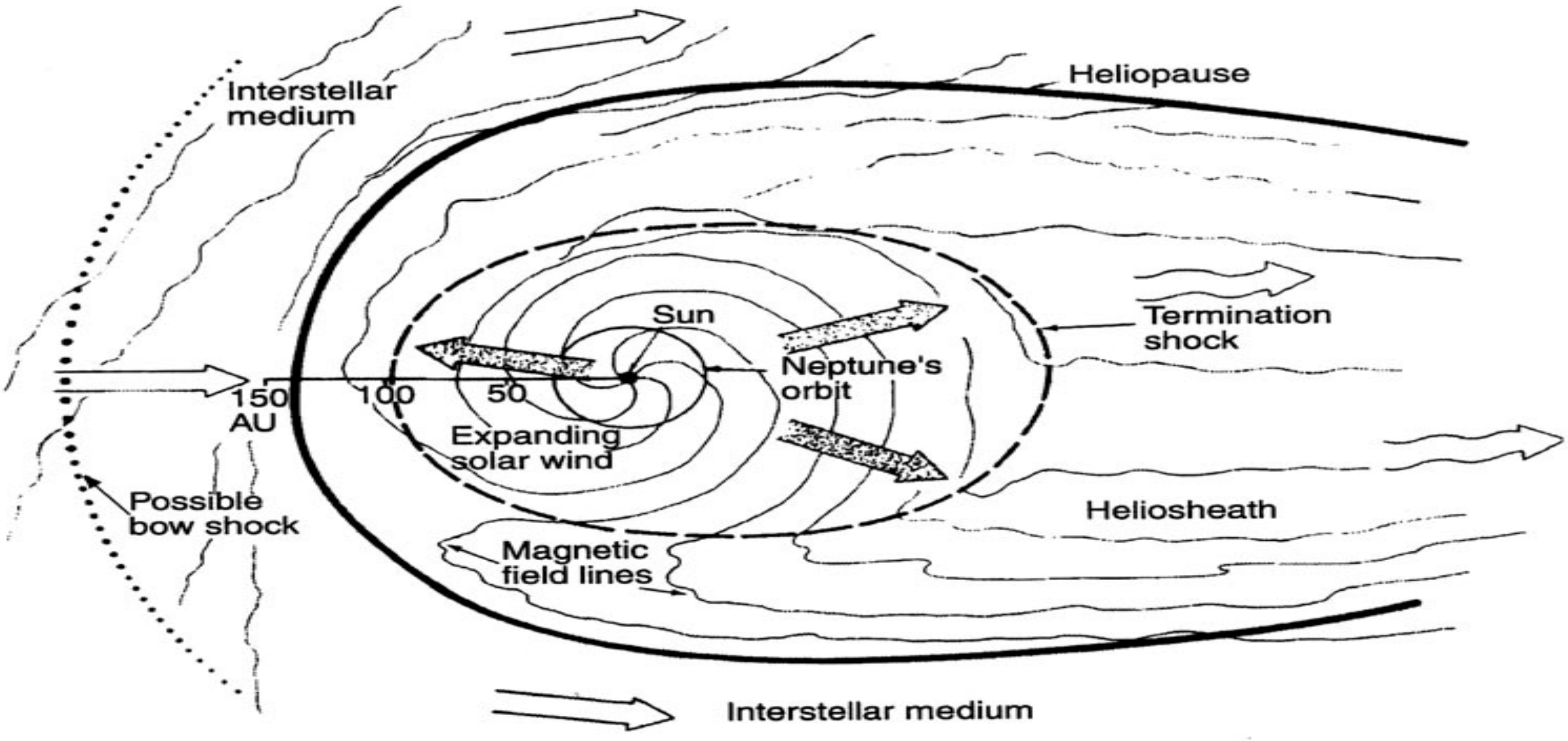


- As the Solar Wind leaves the surface of the Sun it drags the solar magnetic field outward into the Solar System. This is called the ***Interplanetary Magnetic Field*** (or IMF).
- The IMF plays a key role in controlling space weather activity through its interactions with the Earth's geomagnetic field (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 that produced by water sprayed out of a rotary lawn sprinkler.

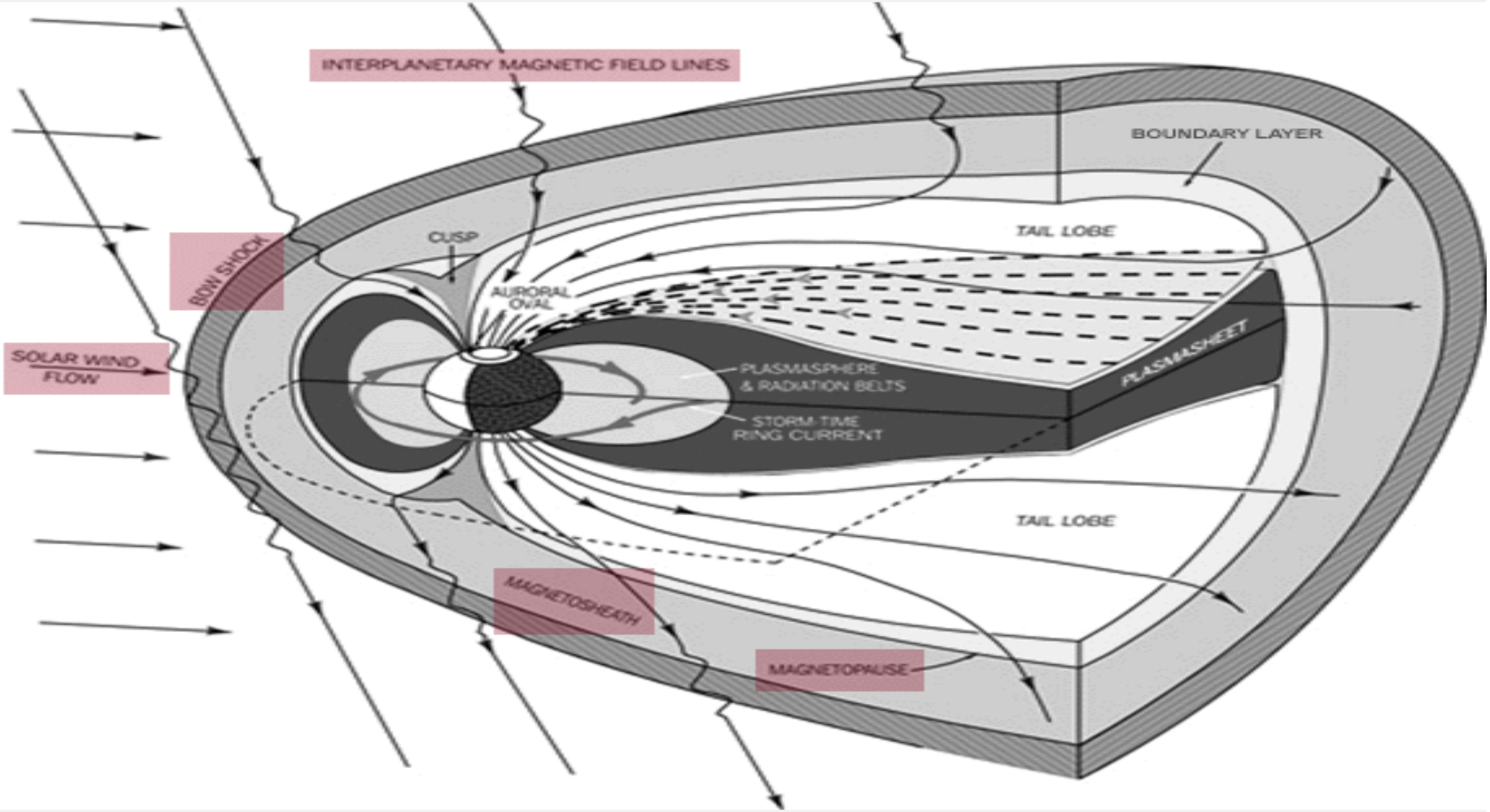
The Heliosphere: Where The Solar Wind Exists



- 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)

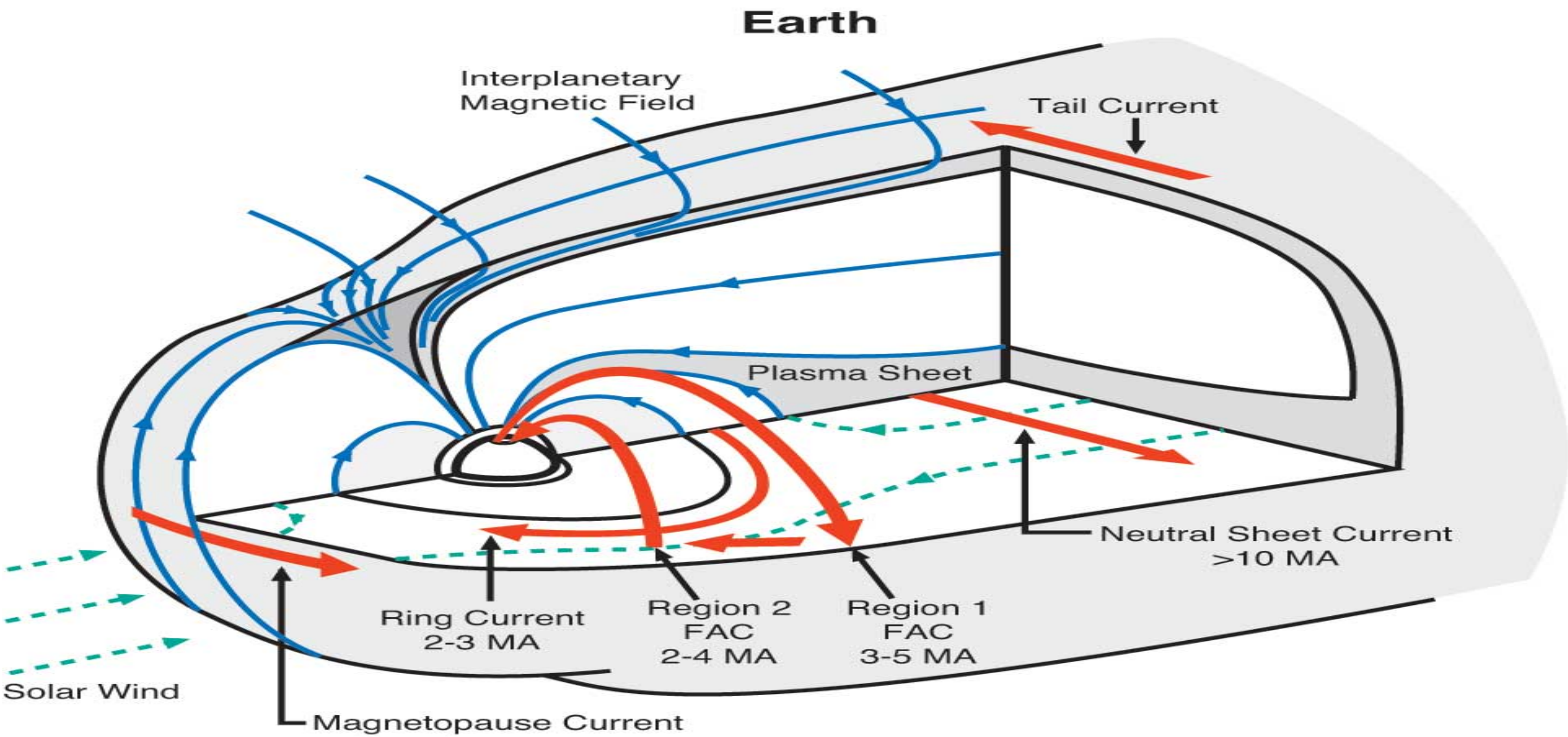
The Magnetosphere-Ionosphere

Regions of the Magnetosphere



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

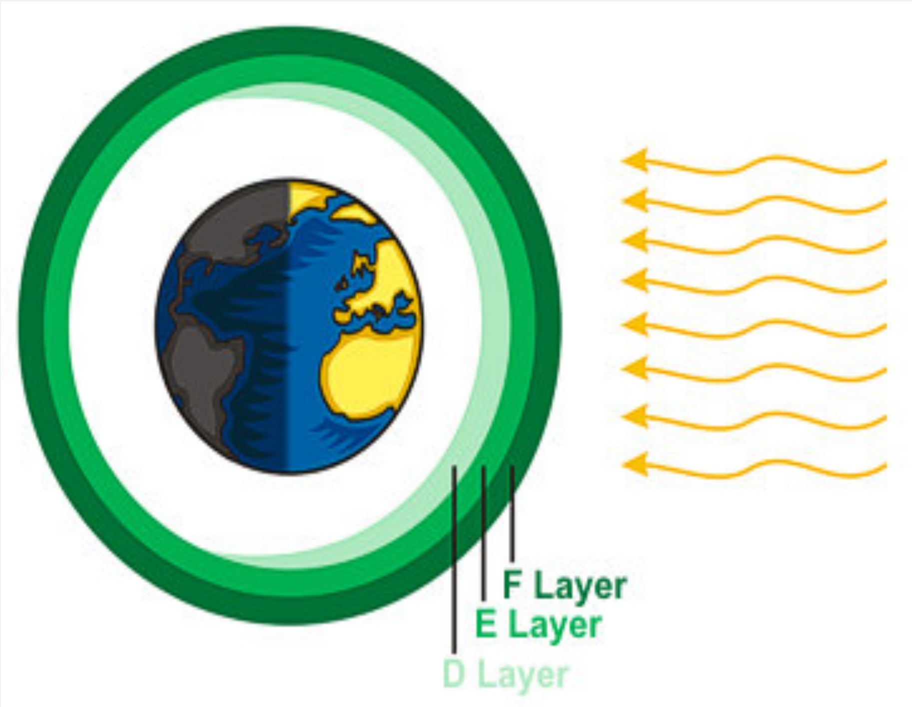
Magnetospheric Currents

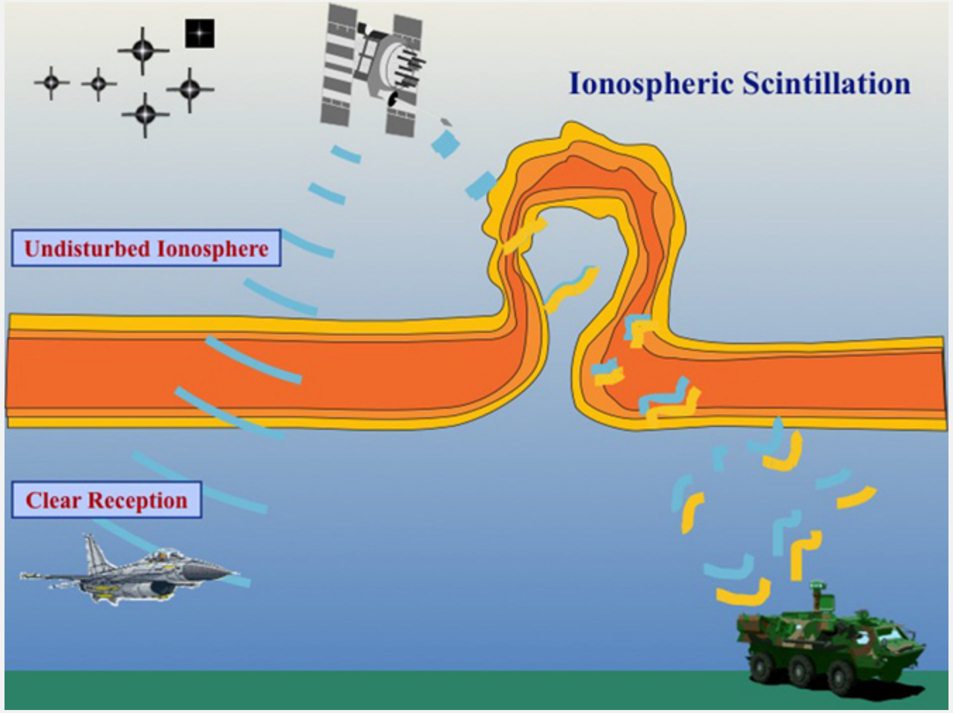


- The ***<u>Distorted Geometry</u>*** of the Magnetosphere is maintained by ***<u>Electric Currents</u>***:
  - Magnetopause Current, Tail Current, Neutral Sheet Current, Ring Current.
  - Currents also flow ***<u>along</u>*** Magnetic Field Lines into the upper atmosphere.

The Ionosphere

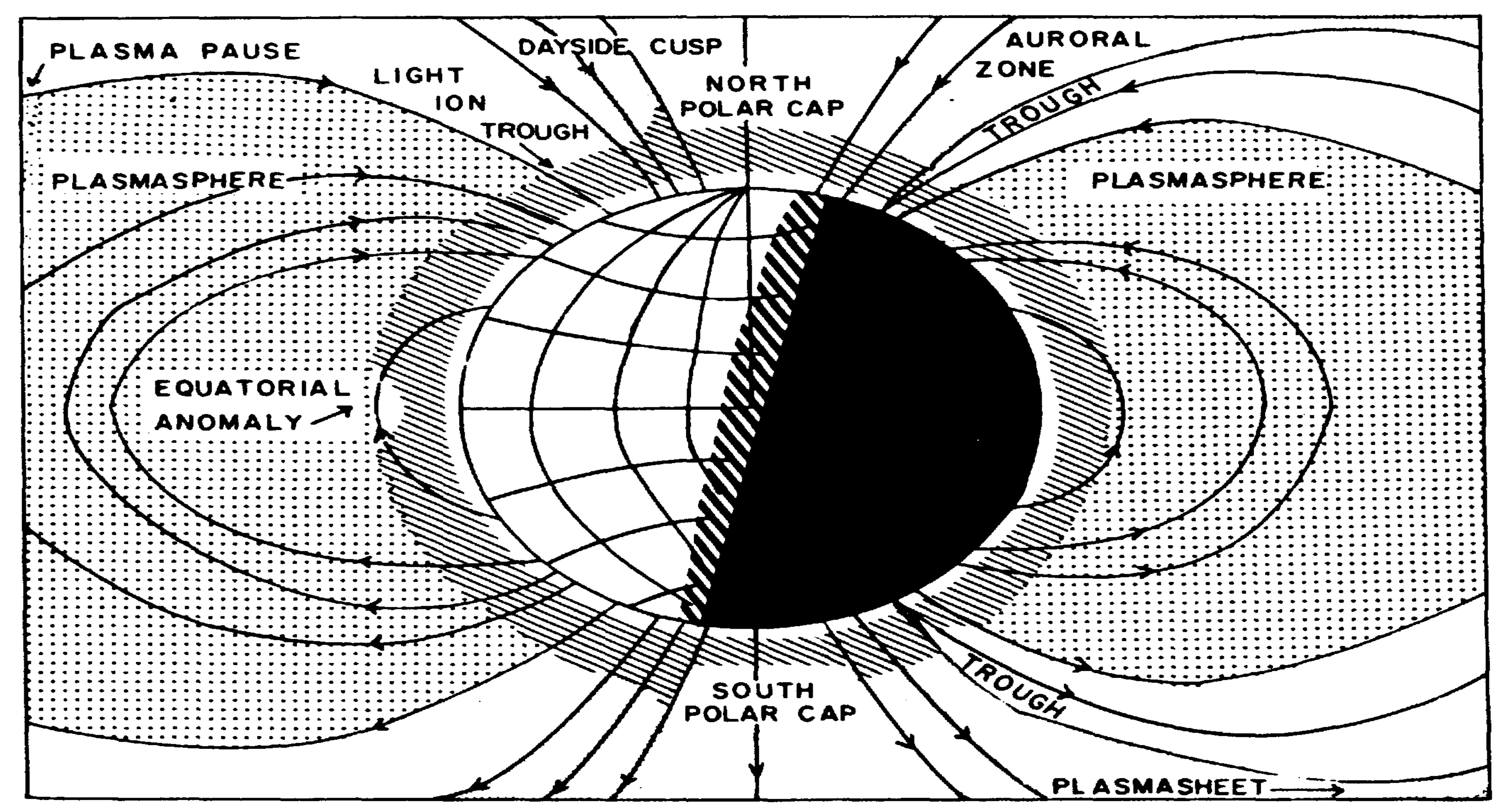
- The **<u>IONOSPHERE</u>** is the <u>charged</u> component of the Earth's upper atmosphere (i.e. a plasma). It starts at ~60-80 km altitude and extends to the edge of space.





- 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.

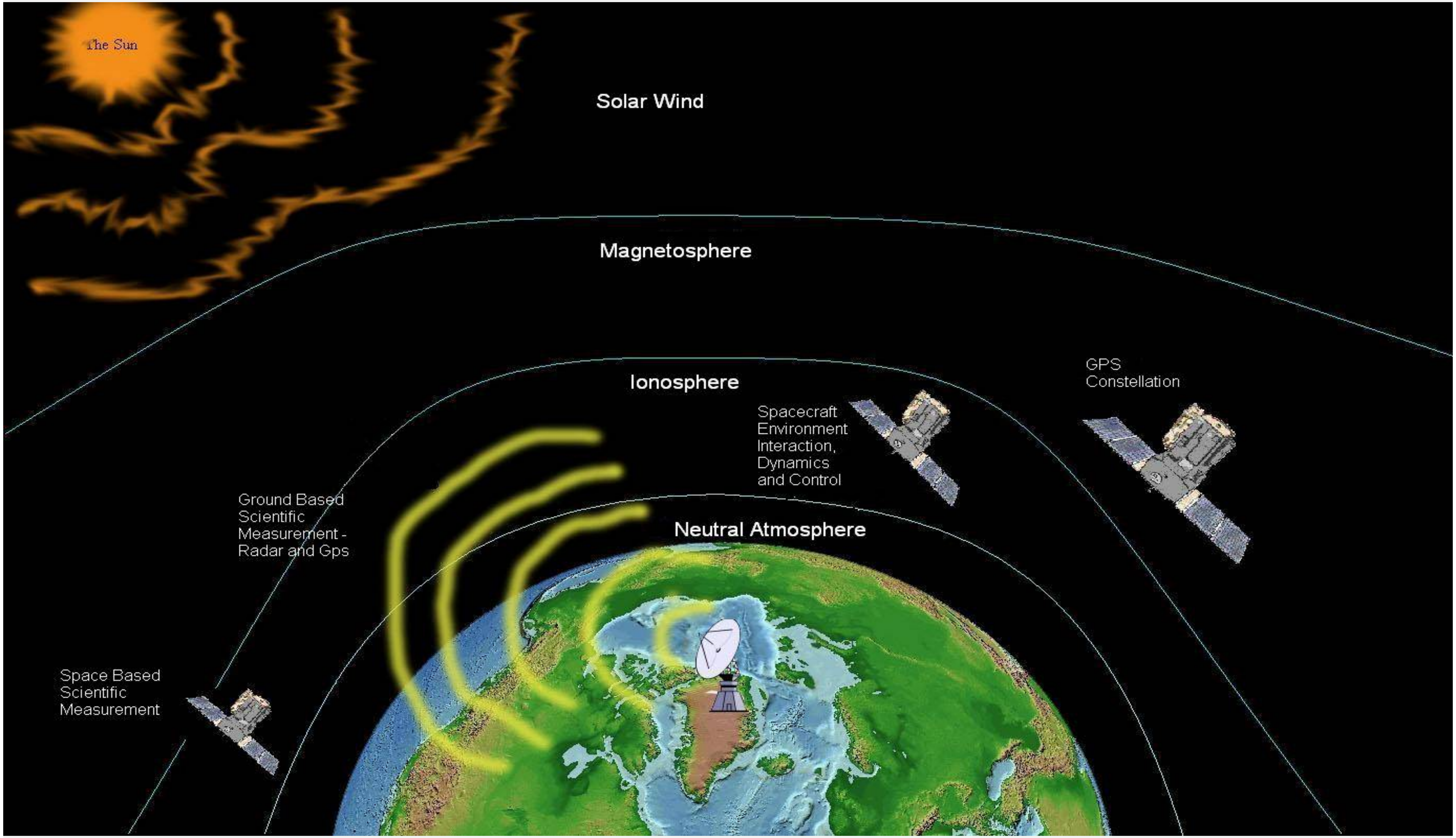
The Coupled Magnetosphere-Ionosphere



- 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 Monitoring

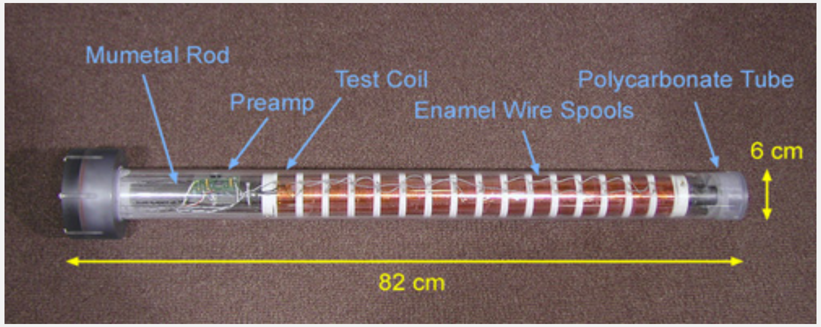
Space Weather Instrumentation

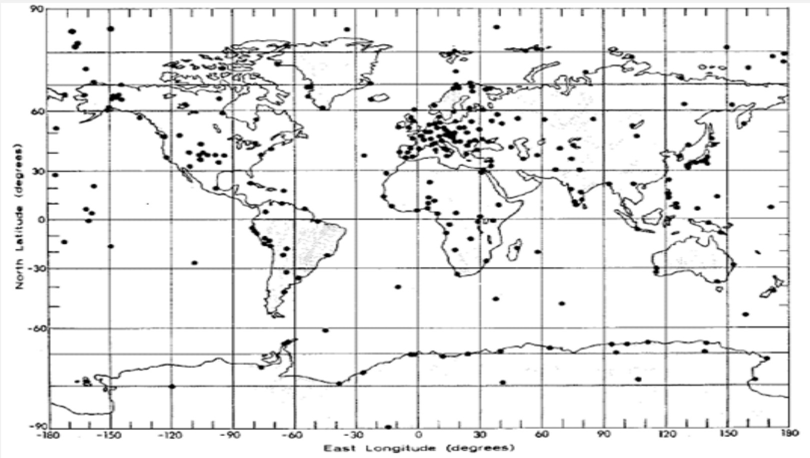


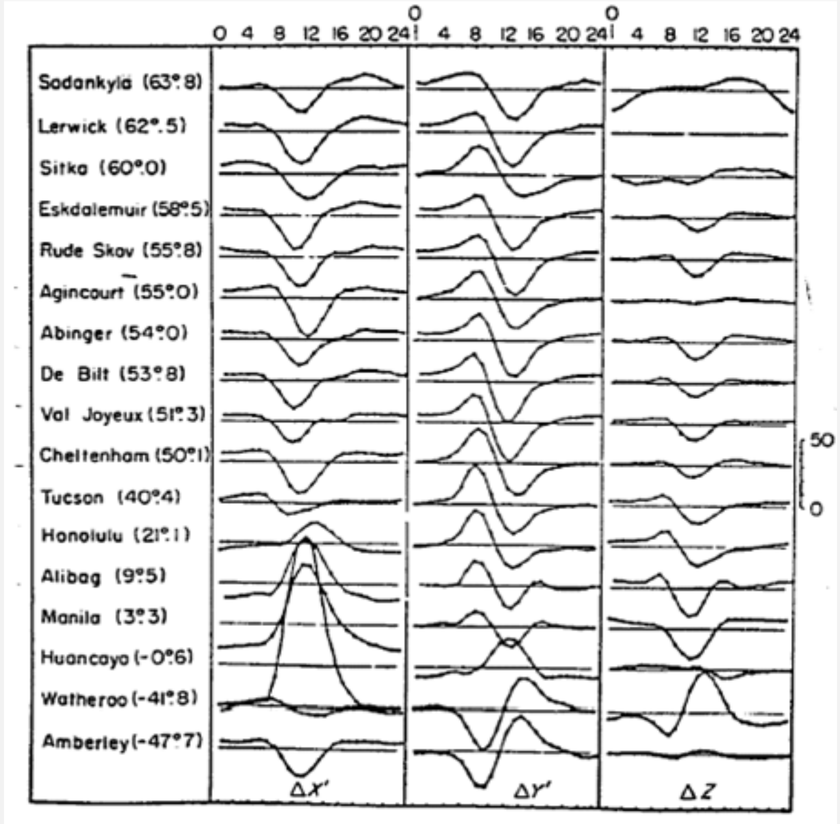
- Conditions in space can be monitored using either spacecraft or ground instruments.

Ground Magnetometers

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



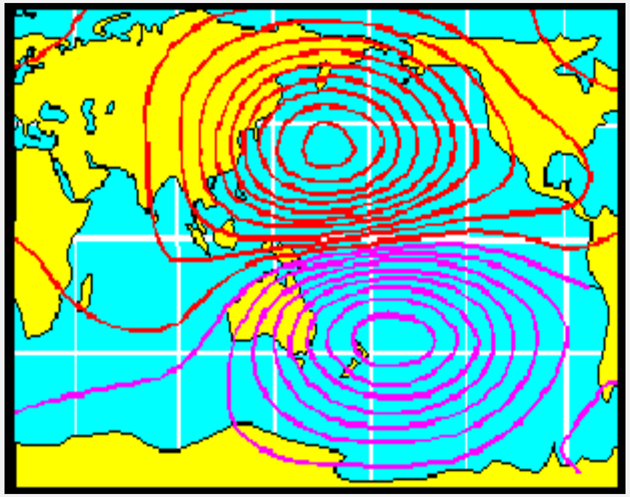




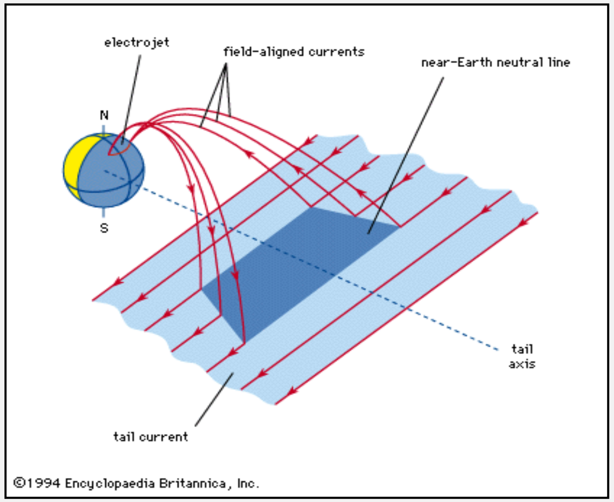
- Magnetometers are cheap and robust instruments that can be deployed anywhere.
- By analyzing worldwide magnetometer measurements it's possible to develop a dynamic picture of magnetosphere-ionosphere current systems (right figure).
- Several "***Magnetic Indices***" are produced by averaging magnetometer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

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

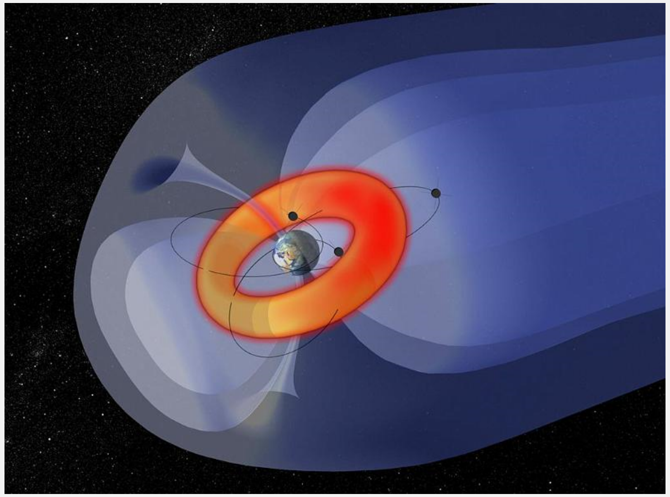
Kp Index



AE/AU/AL Indices



Dst Index



Kp ("Planetary") Index:

- Monitors *Worldwide Average* geomagnetic disturbance

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

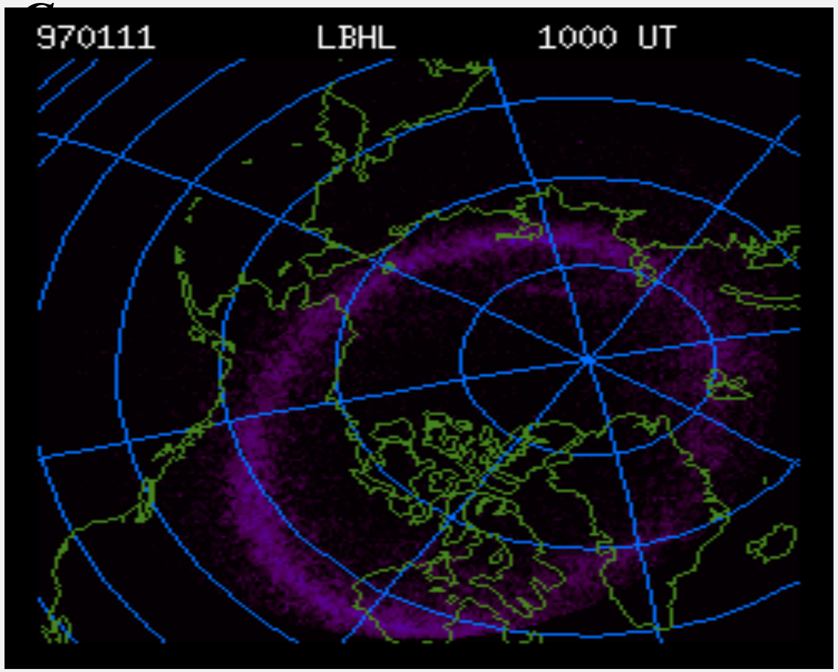
- Monitor magnetic disturbance produced by *Auroral Activity*.
- A period of enhanced AE/AU/AL is called an ***Auroral Substorm***.

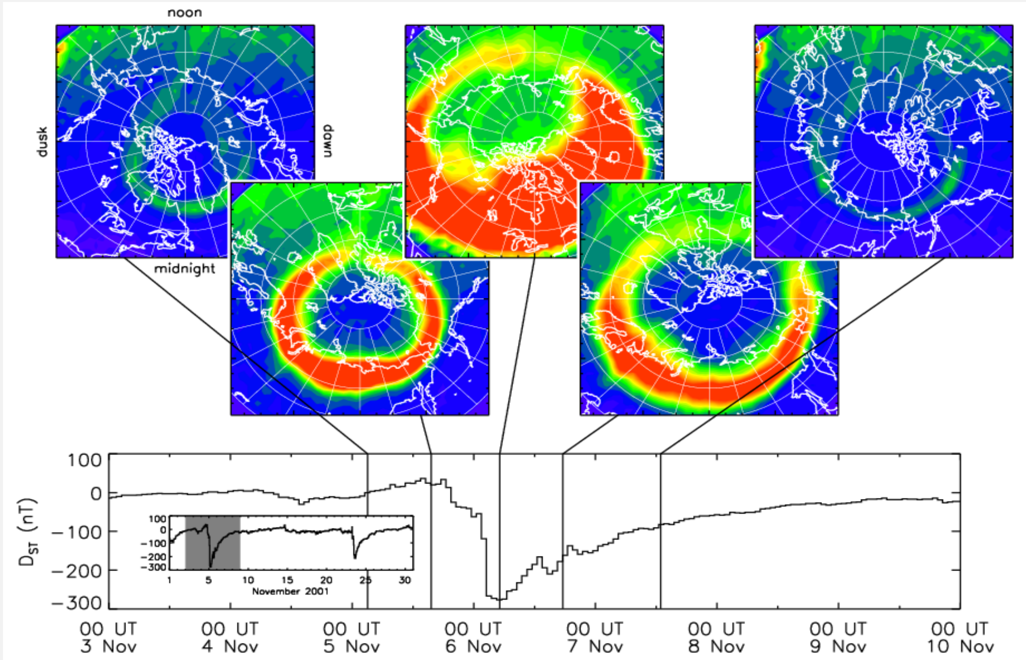
Dst ("Disturbance Storm-Time") Index:

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

Geomagnetic Storms vs Auroral Substorms

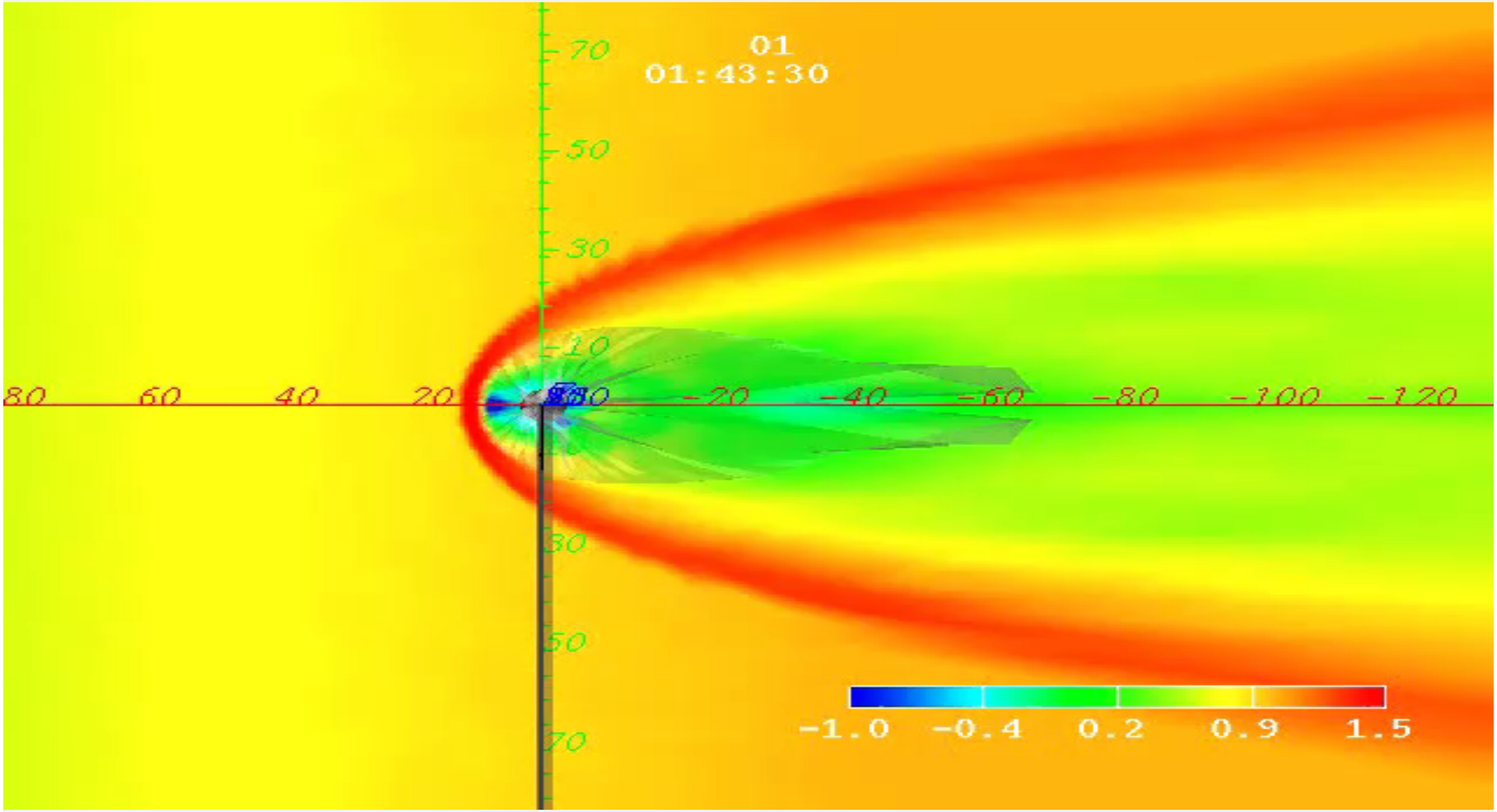
- An ***Auroral Substorm*** is a *short-lived* (1-3 hours) disturbance in which Solar Wind energy is transferred to the Magnetosphere and then into the ***Polar Ionosphere***.
- A ***Geomagnetic Storm*** is a *longer* (1-3 days) disturbance in which Solar Wind energy is deposited into the ***Polar Ionosphere***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





- 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.

Simulation of a Geomagnetic Storm

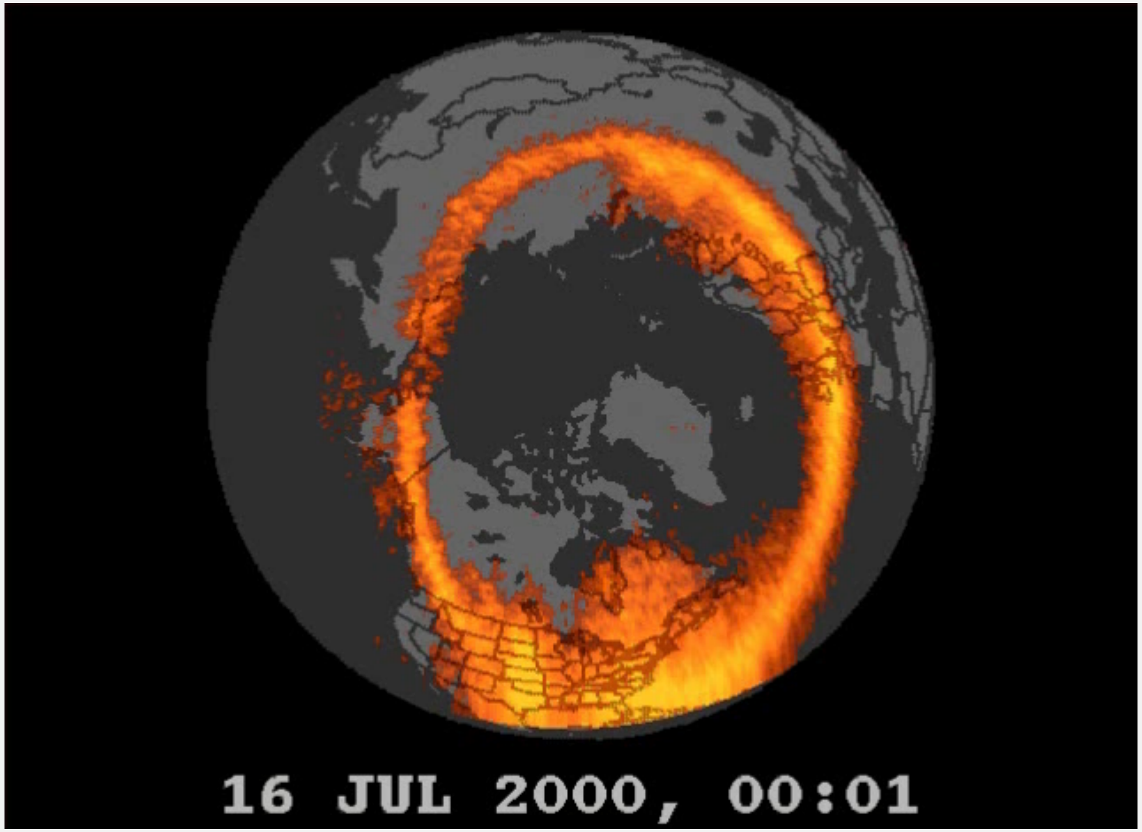


During a ***Geomagnetic Storm*** conditions in the Solar Wind and IMF are so abnormal that ***extreme distortions*** are produced in the geospace environment.

Geomagnetic Storms and Substorms

Substorms

- A ***Substorm*** is a magnetosphere-ionosphere disturbance in which Energy is transferred from the Solar Wind to the Magnetotail and then into the Ionosphere.



- One manifestation of a substorm is an enhanced display of aurora.
- This movie shows the auroral display seen by a spacecraft during a substorm which occurred in response to the "***Bastille Day Event***" on the sun.

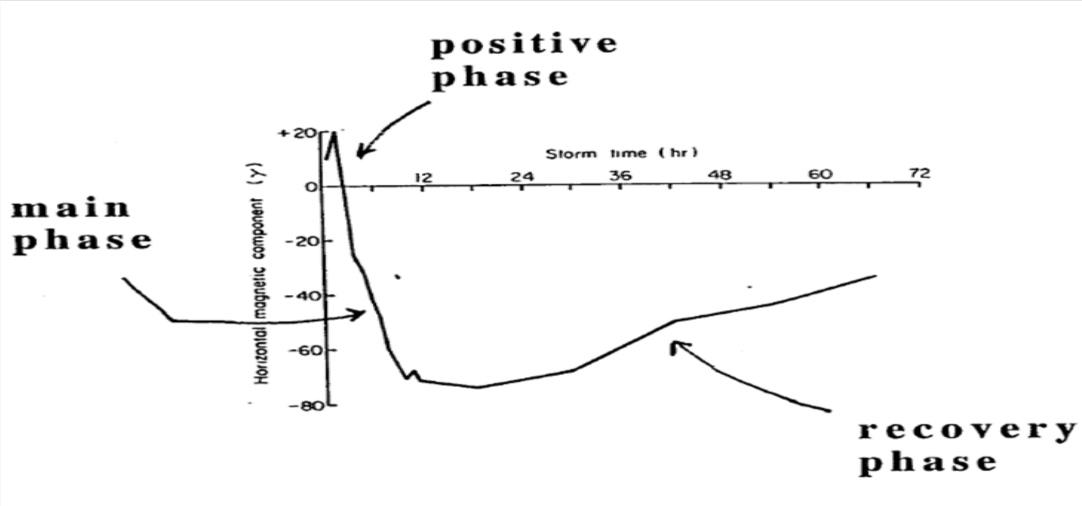
Geomagnetic Storms

- A ***Geomagnetic Storm*** is a *large* and *prolonged* disturbance in the coupled Magnetosphere-Ionosphere system (i.e. lasts for days rather than hours):
  - Enhanced Aurora (AE Index)
  - Enhanced Ring Current and Radiation Belts (Dst Index)
  - Expansion of auroral currents from high to middle latitudes (Kp Index)
- A Geomagnetic Storm is produced when:
  - The Interplanetary Magnetic Field (IMF) is *southward* for a long time, and/or
  - There is an *enhancement* in the Solar Wind density and/or speed
  - Basically, there has been a major disturbance on the Sun (e.g. CME)
- The Solar Wind features most associated with Geomagnetic Storms are:

  (1) High Speed Streams (i.e. produced by ***Coronal Holes***)

  (2) Magnetic Clouds (i.e. produced by ***Coronal Mass Ejections***)

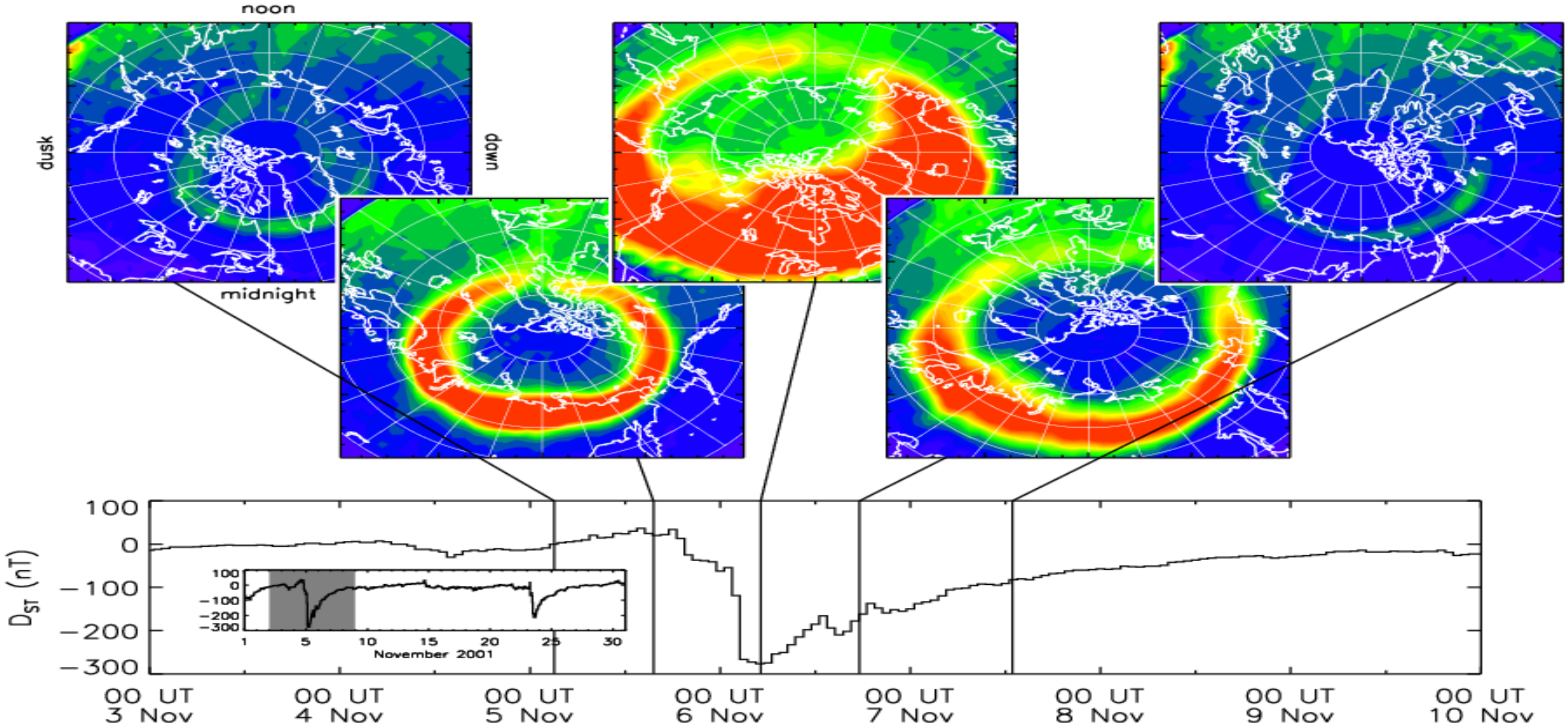
Geomagnetic Storm Phases



<u>NOTE</u>: Some Geomagnetic Storms also have a brief "Positive Phase" (i.e. enhanced Dst) produced by high solar wind pressure enhancing the magnetopause current.

- All Geomagnetic Storms have two phases:
- **<u>MAIN PHASE</u>:**
  - High Speed Stream or Magnetic Cloud arrives at Earth
  - Extreme southward IMF and high Solar Wind dynamic pressure
  - Sudden enhancement of energy in the Radiation Belts and Ring Current
  - Dst Index suddenly drops to large negative values
- **<u>RECOVERY PHASE</u>:**
  - Energy in the Radiation Belts and Ring Current gradually dissipates
  - Dst Index returns to normal levels over a period of a few days

Geomagnetic Storms vs Auroral Substorms



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