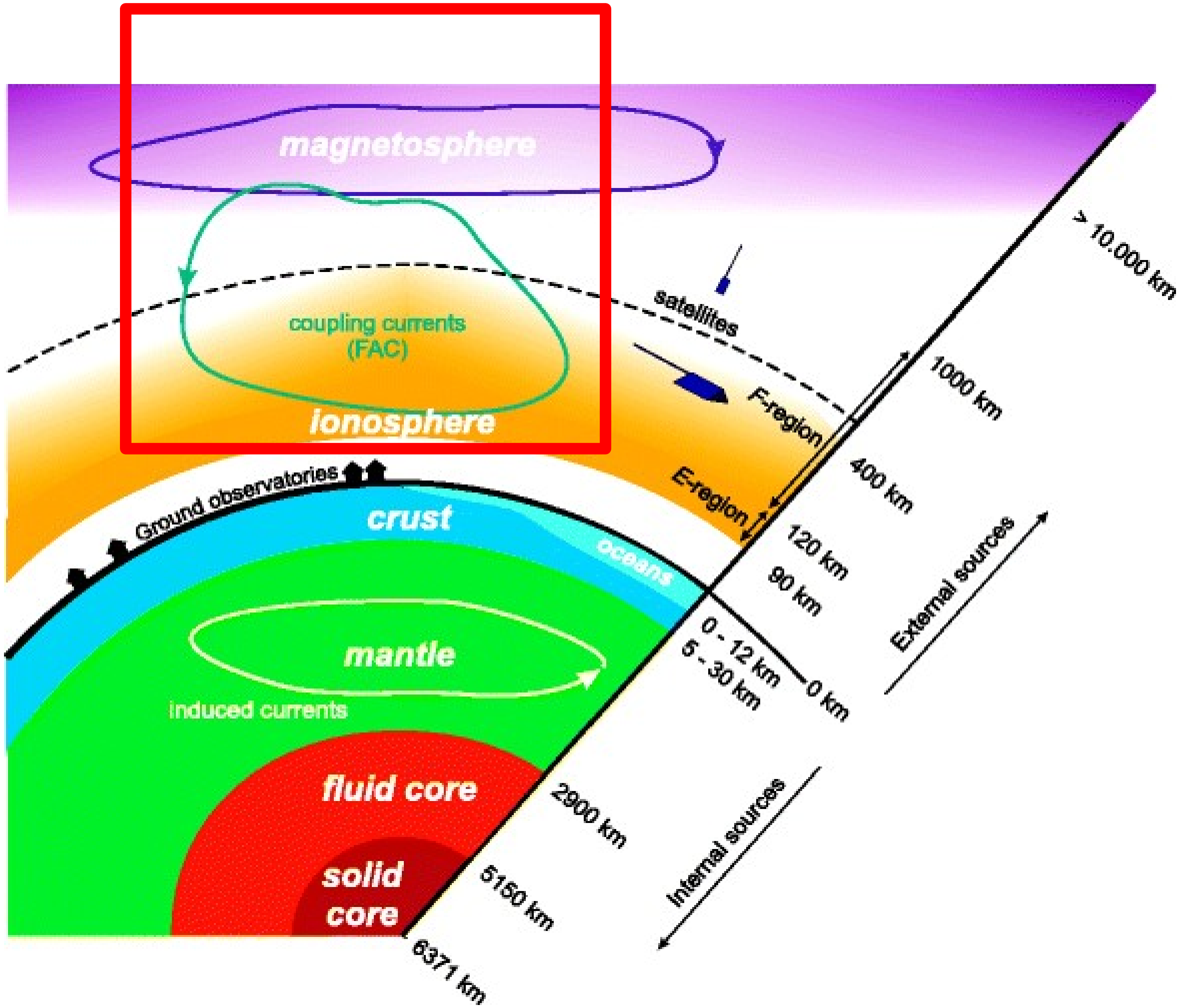
Chapter 8
Geospace

Previously



Sources of the Earth's magnetic field.

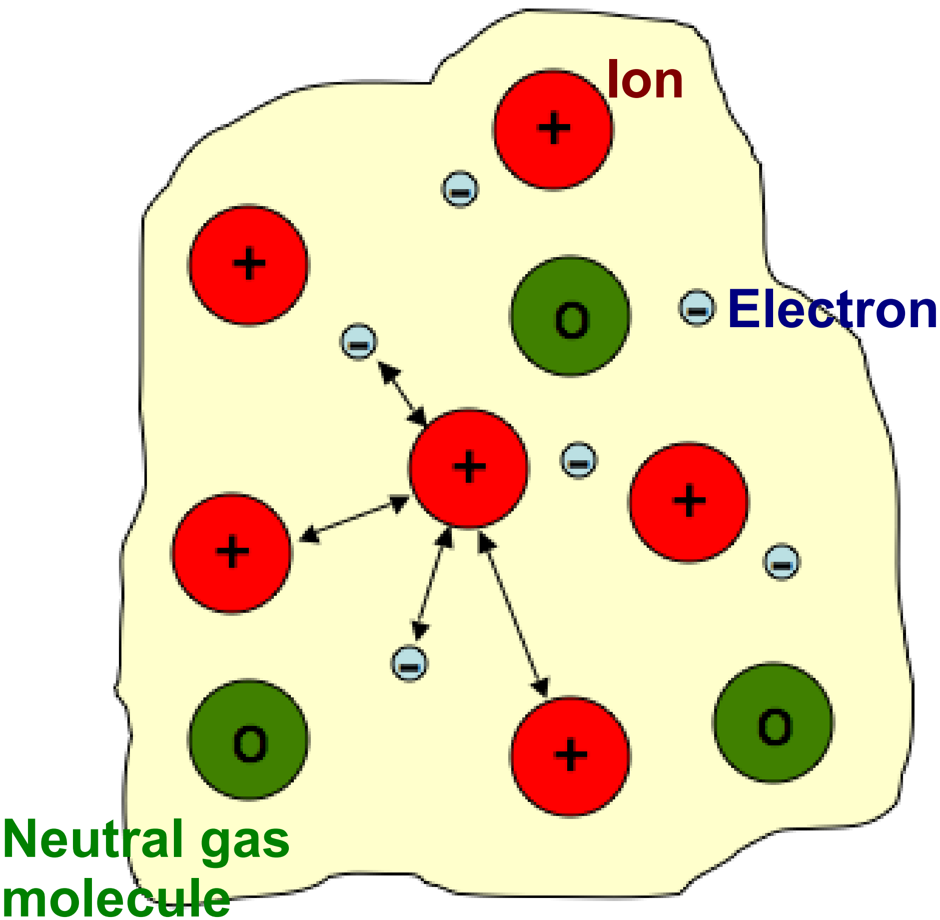
Content

- Basic concepts
- The Sun and solar wind
- Near-Earth space
- About other planets

Basic concepts

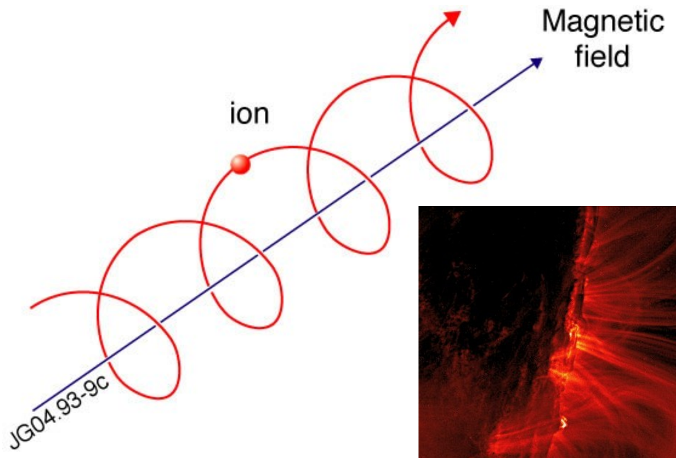
Plasma

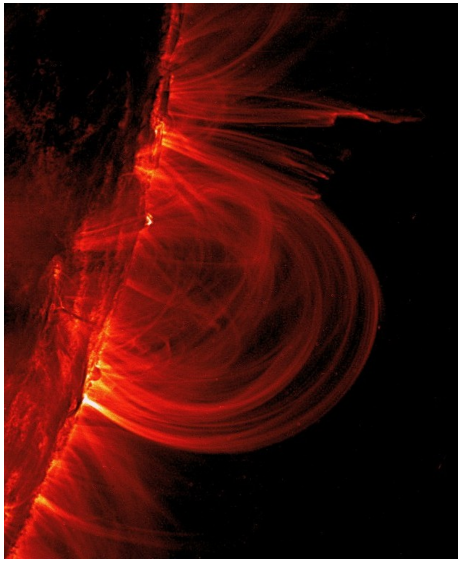
- The molecules of an ionized gas, plasma, have lost their outer electrons.
- Plasma consists of positively and negatively charged particles such that the overall charge of a plasma is zero.
- Because of the free electrons and ions plasma can conduct electric current.



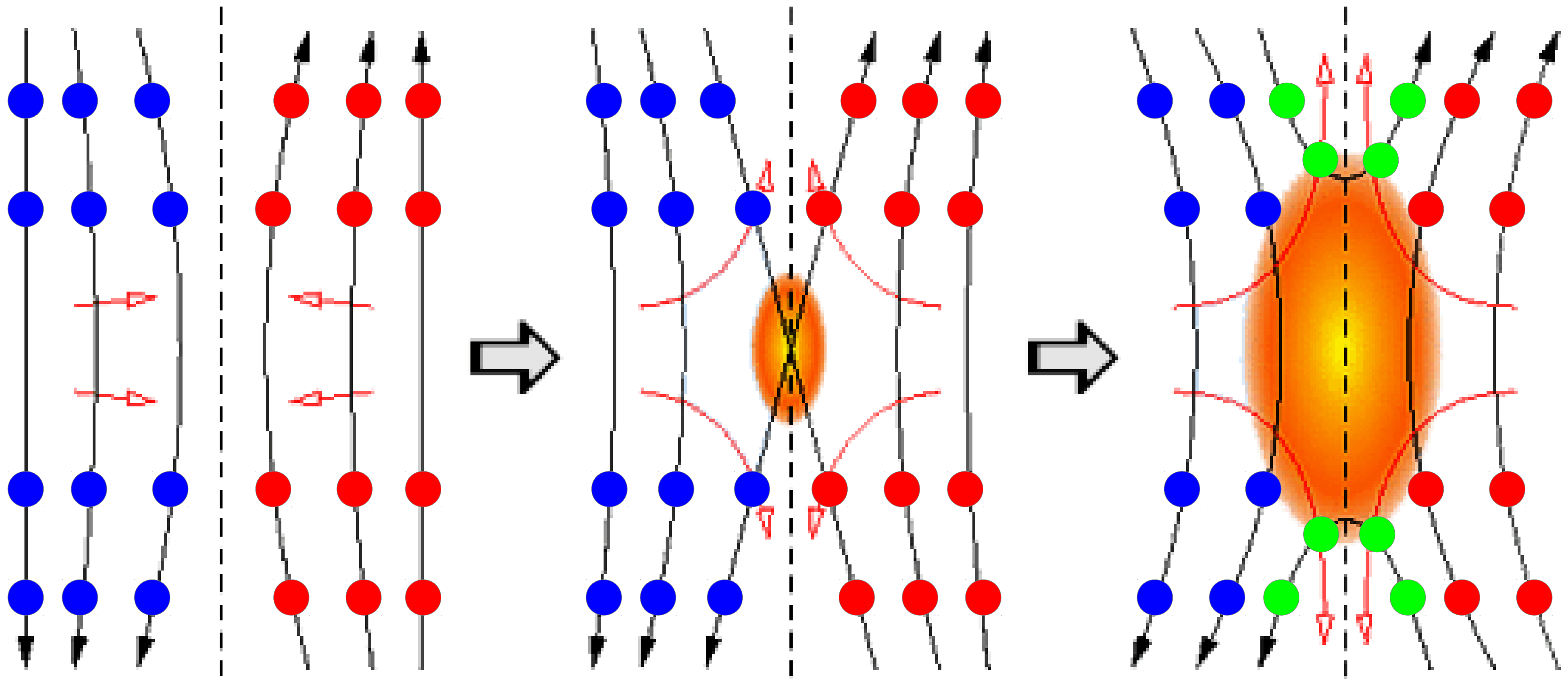
Magnetized plasma

- In a magnetic field, a charged particle will follow a helical trajectory around a magnetic field line.
- Thus, the magnetic field guides the motion of the charged particles but the charged particles also carry the magnetic field with them.





Magnetic reconnection

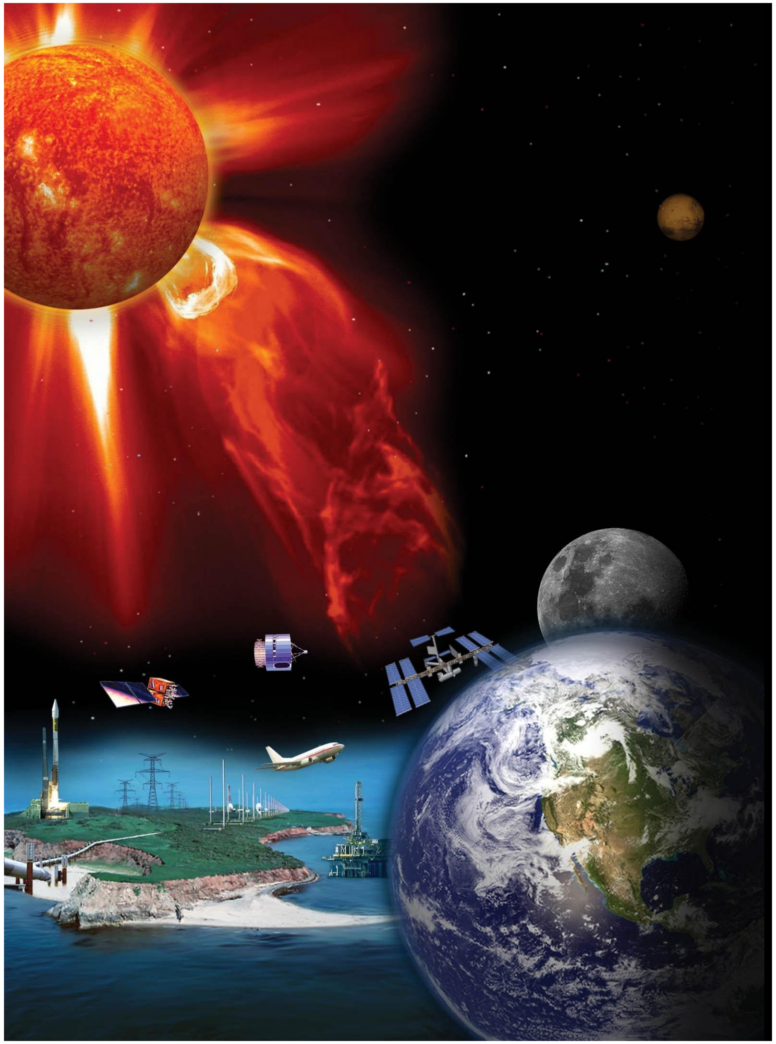


Reconnection can mix two populations of magnetized plasma.

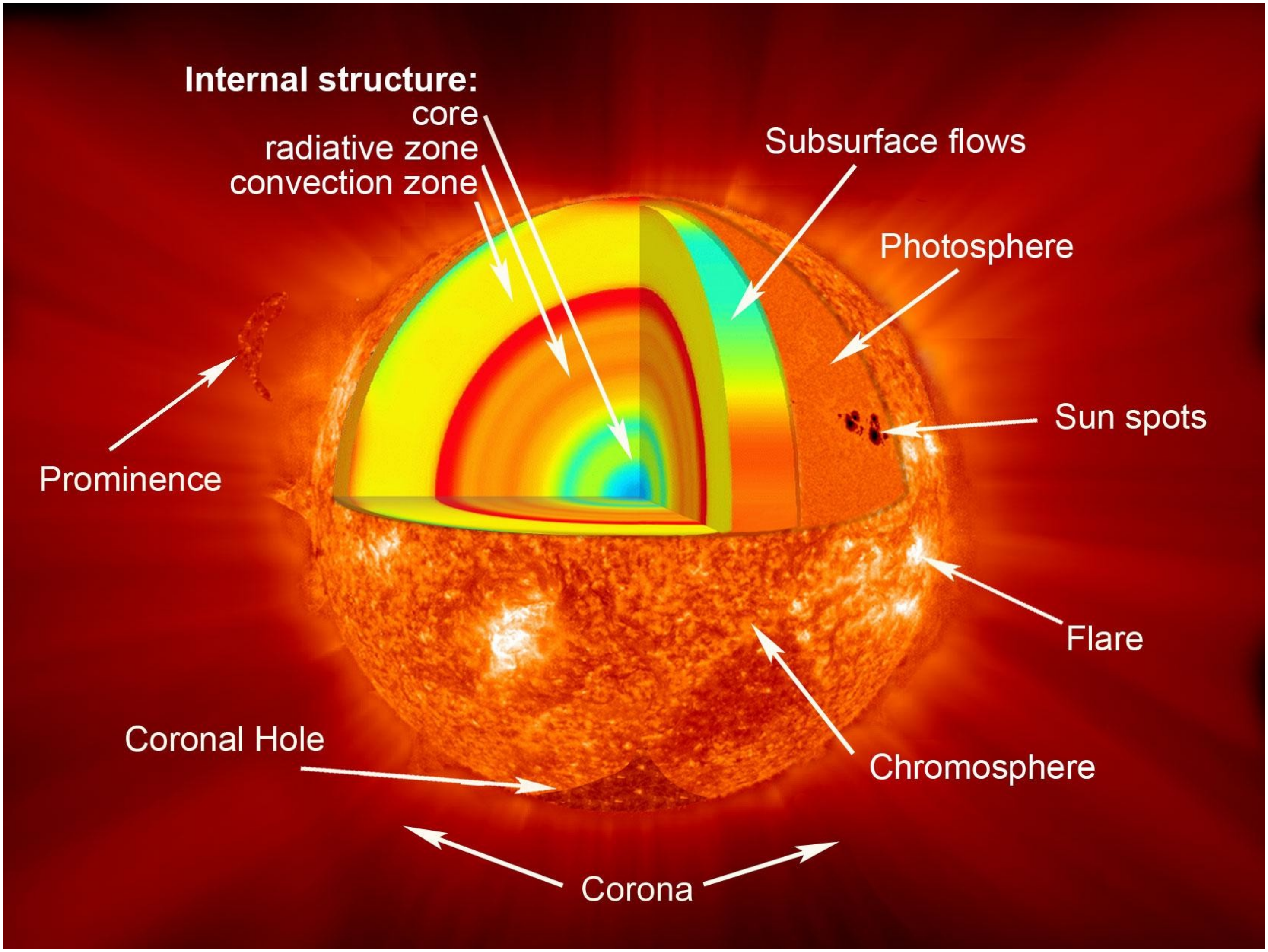
The Sun and solar wind

The Sun

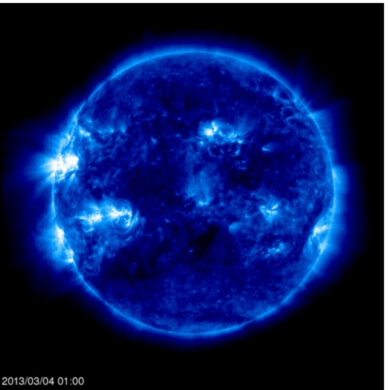
- The origin of space weather phenomena.
- The effects are transmitted to the Earth via
  - Electromagnetic radiation in ~8 min.
  - Energetic particles in ~20 min.
  - Solar wind in ~80 h.

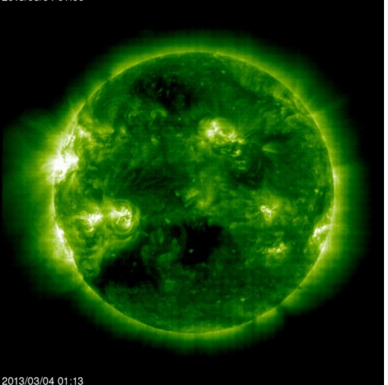


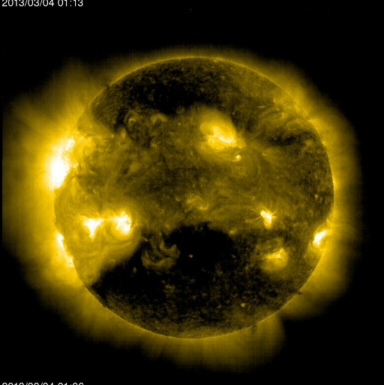
The Sun's structure

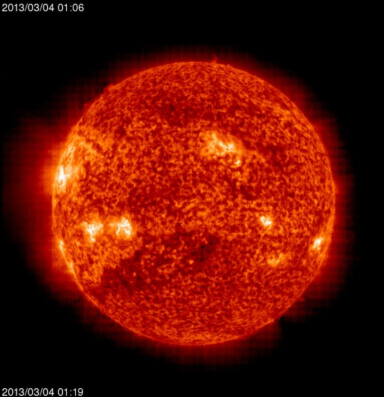


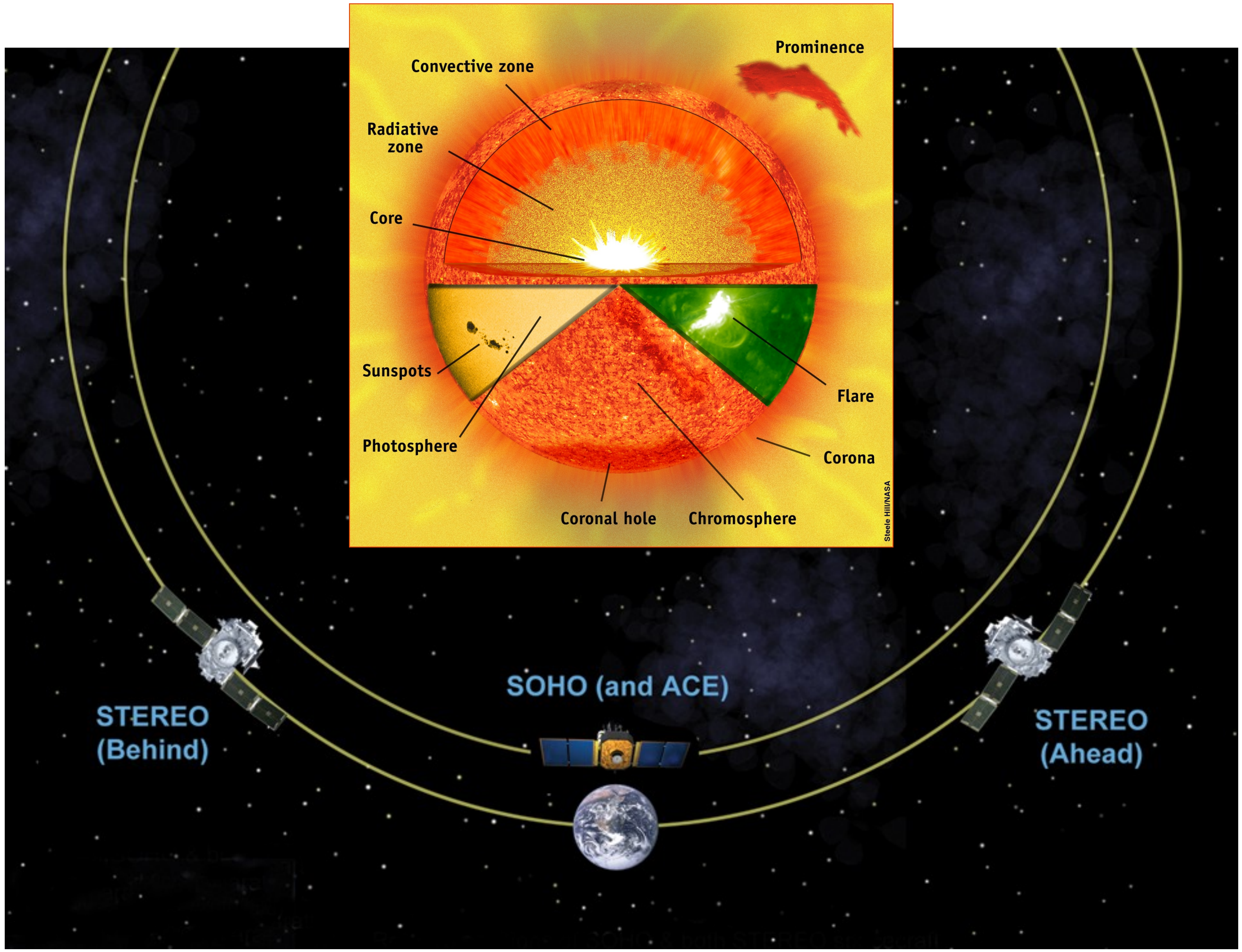
Monitoring the Sun

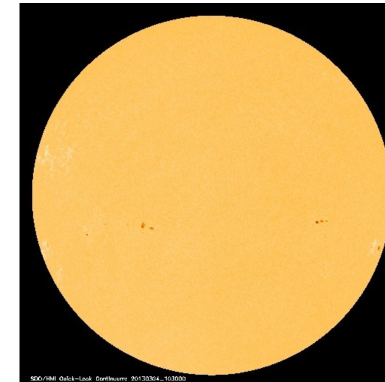


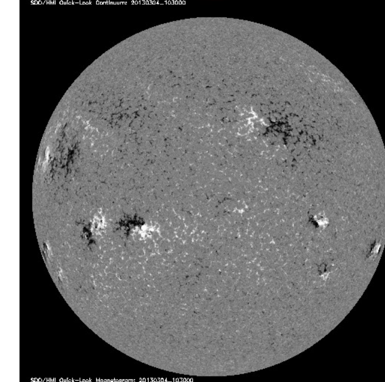


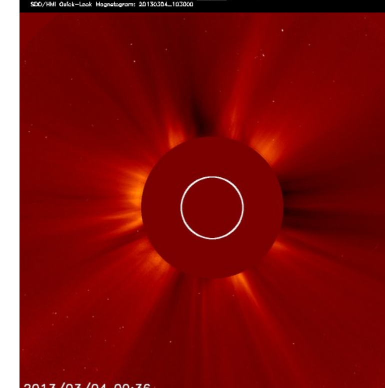


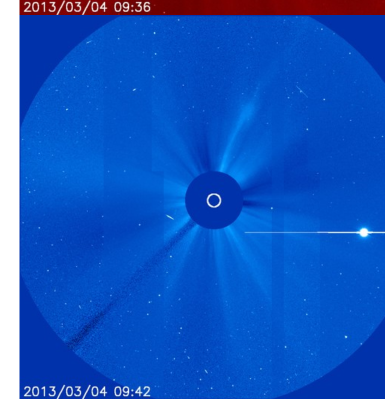










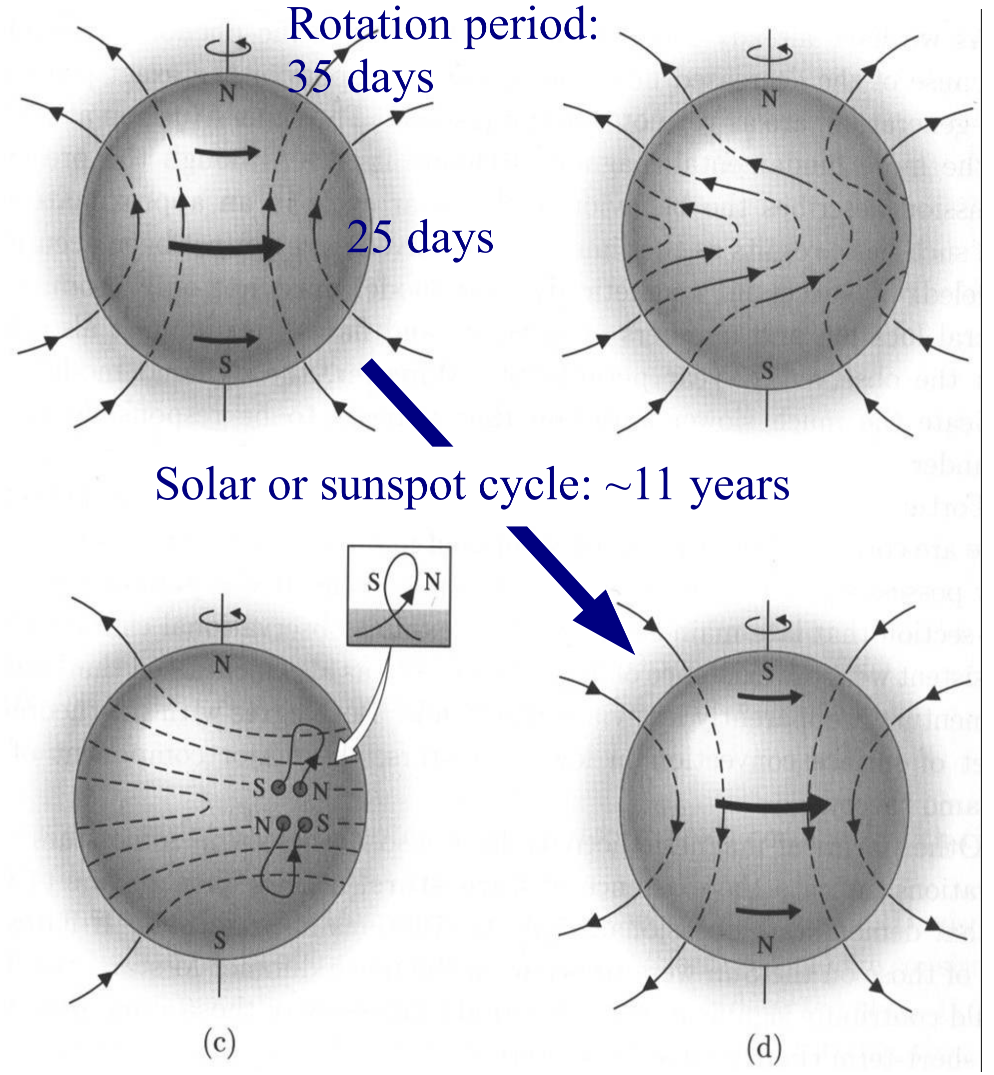


Solar atmosphere at different wavelengths.

Top: Photospheric magnetic field.
Bottom: Corona.

The Sun's magnetic field

Solar minimum

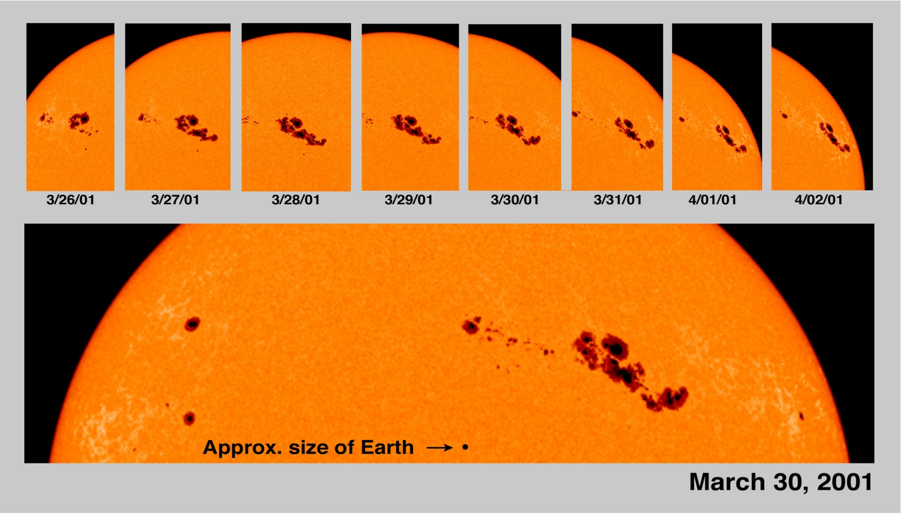


Solar maximum

Solar minimum

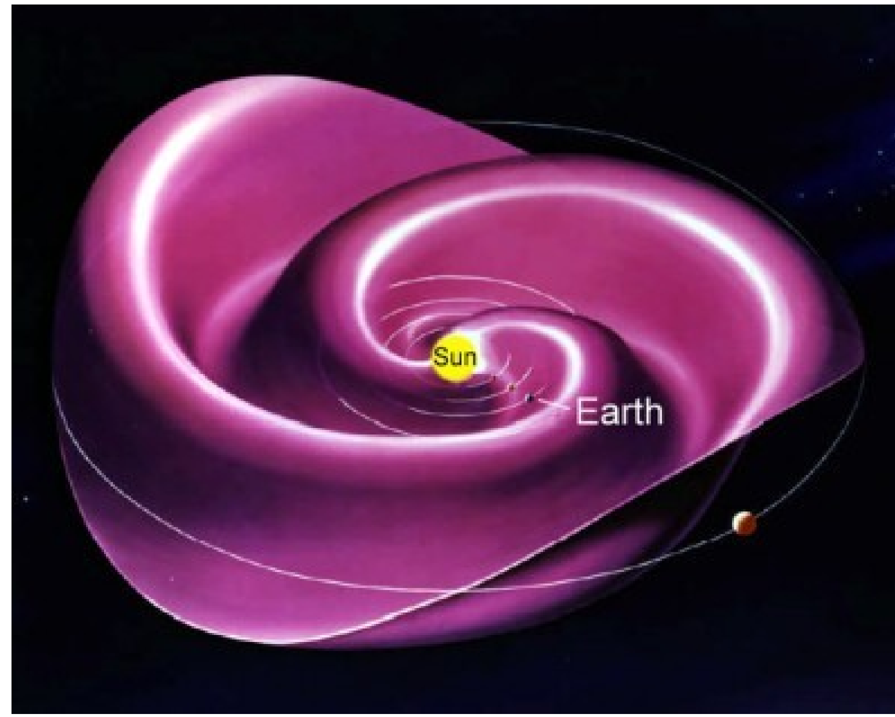
Sunspots and active regions

- In visible light, active regions appear as sunspot groups.
- Sunspots appear on the photosphere as dark regions compared to their surroundings.
  - Caused by an intense magnetic field that inhibits convection, forming areas of reduced surface temperature.
  - Because of the Sun's rotation (~27 day period), sunspots seem to move across the solar disc.



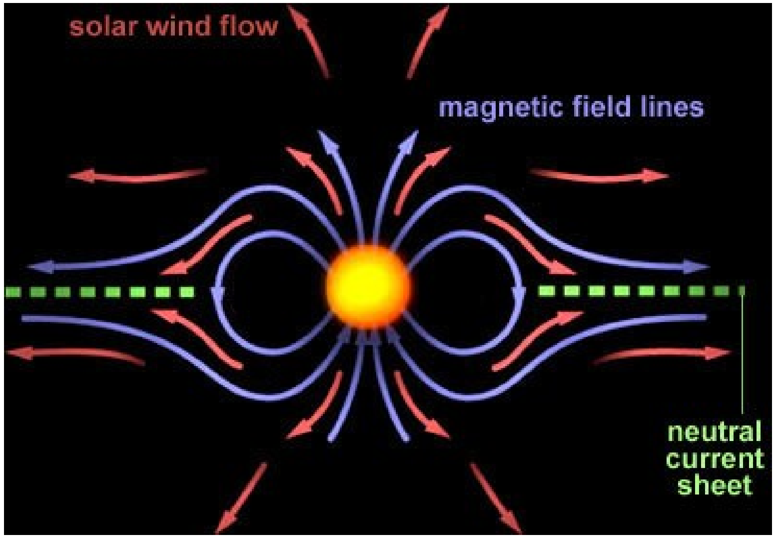
Solar wind

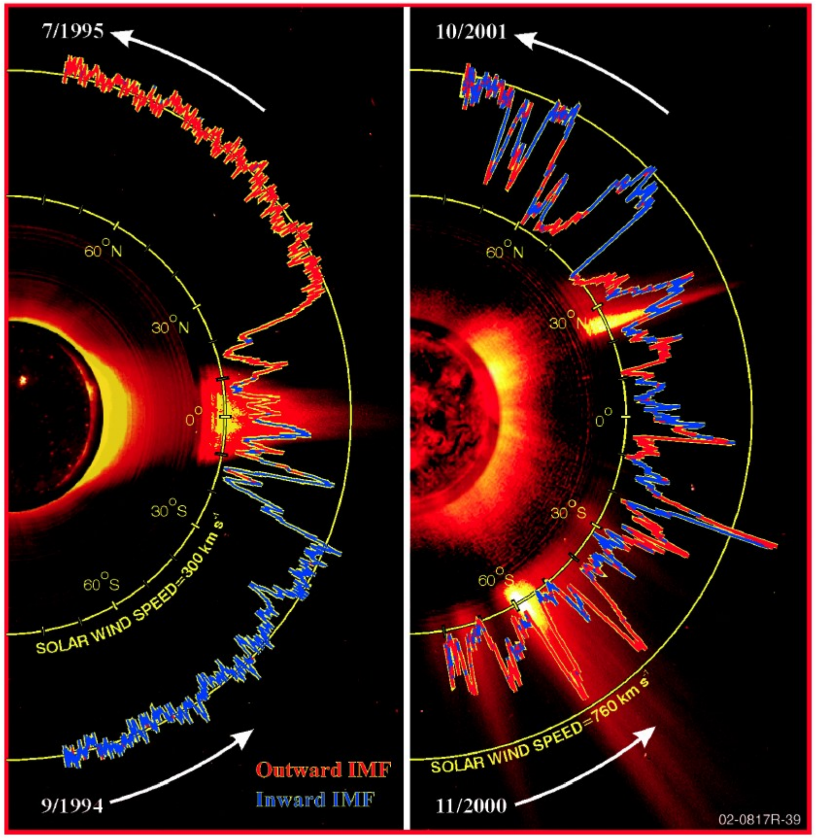
- A continuous stream of charged particles (mainly electrons and protons) escaping from the solar corona into interplanetary space.
- The solar wind carries the Sun's magnetic field with it. This field is called the interplanetary magnetic field (IMF).
- At the Earth's orbital distance:
  - Density: 6.5 particles/cm3 (0.4-100)
  - Speed: 400 km/s (200-900)
  - Magnetic field: 6 nT (0.2-80).



The IMF field lines form a spiral, because one end is attached to the surface of the rotating Sun.

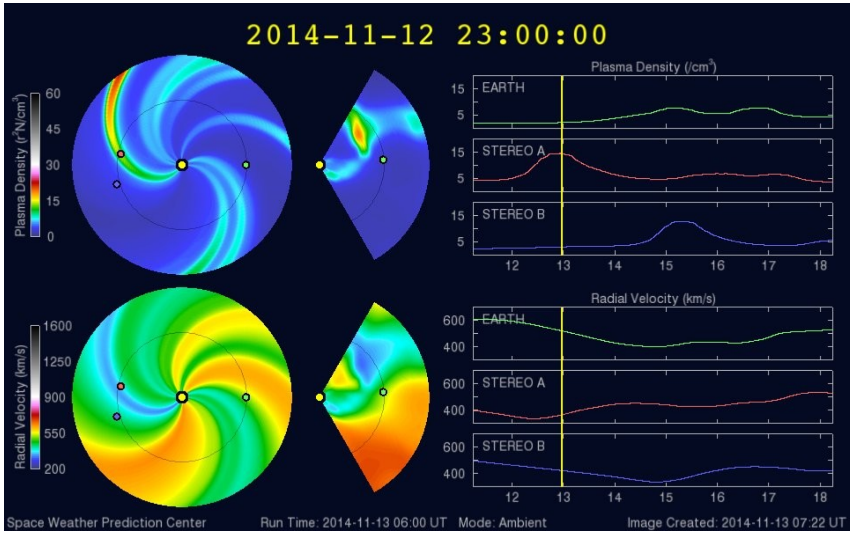
- Slow solar wind (~400 km/s) originates from regions of closed magnetic field lines near the Sun's equator.
- Fast solar wind (~600 km/s) originates from regions of open magnetic field lines called coronal holes.



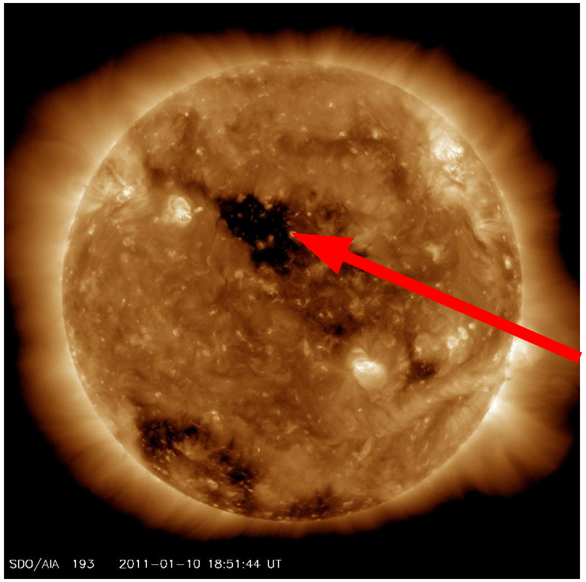


Solar minimum Solar maximum

- The Earth typically encounters slow solar wind.
- Occurrences of high-speed solar wind streams impacting the Earth can be estimated by examining the locations of coronal holes.



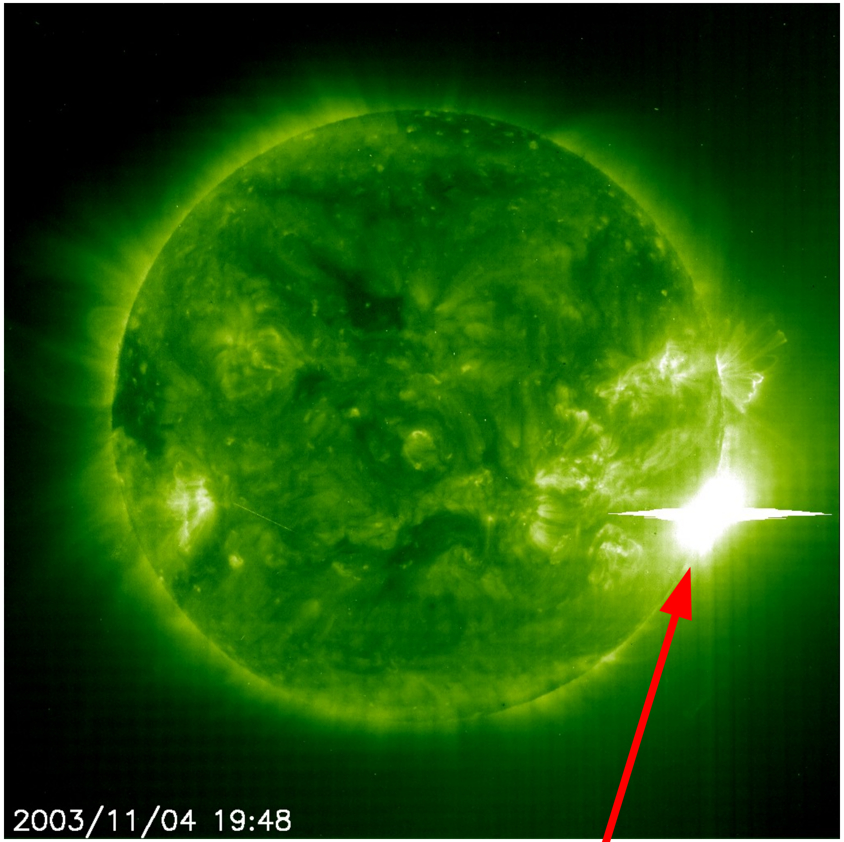
NOAA's Enlil solar wind model.



EUV picture of a coronal hole taken by the Solar Dynamic Observatory satellite on 10 January 2011.

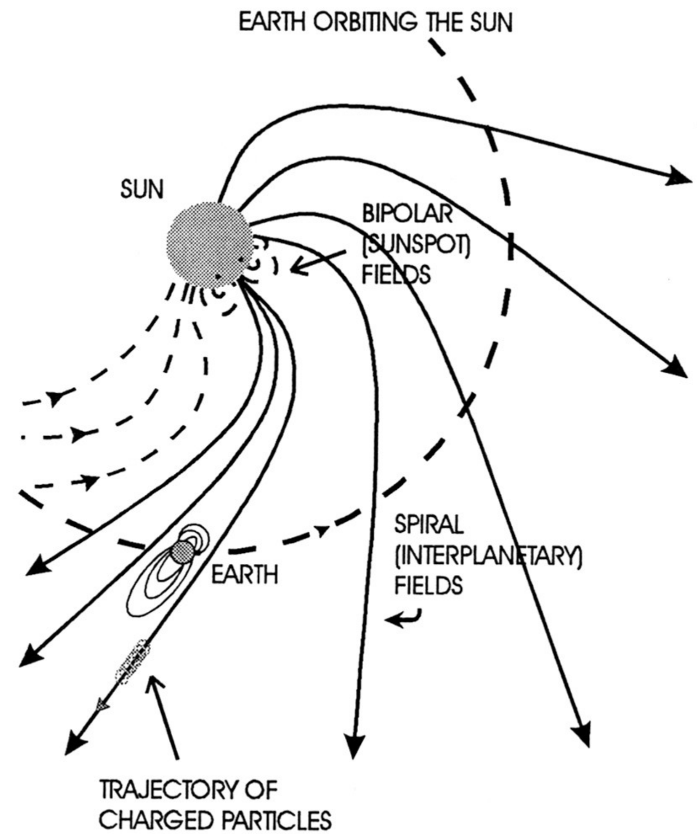
Solar flares

- A few minute brightening above the solar surface in an active region.
- Mainly observed at UV, X-ray and gamma radiation wavelengths.
- In addition to electromagnetic radiation, a flare releases high-energy particles into interplanetary space.

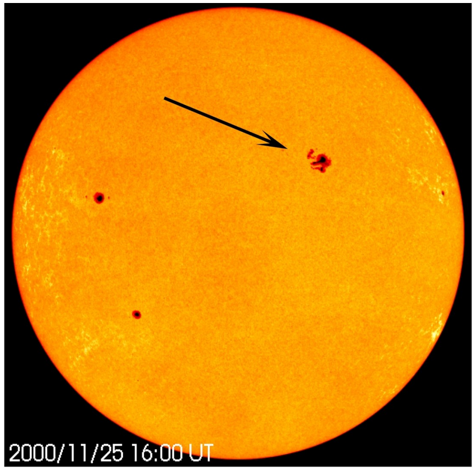


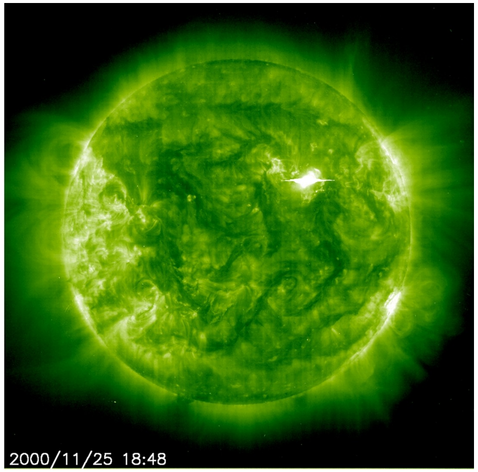
EUV picture of a solar flare on the **west** limb taken by the SOHO spacecraft.

- High-energy protons travel in space along the IMF field lines.
- Protons from the west limb are most likely to be directed to the Earth by the spiral IMF.
- Electromagnetic radiation from a flare occurring anywhere on the Earthward side of the Sun can reach the Earth.



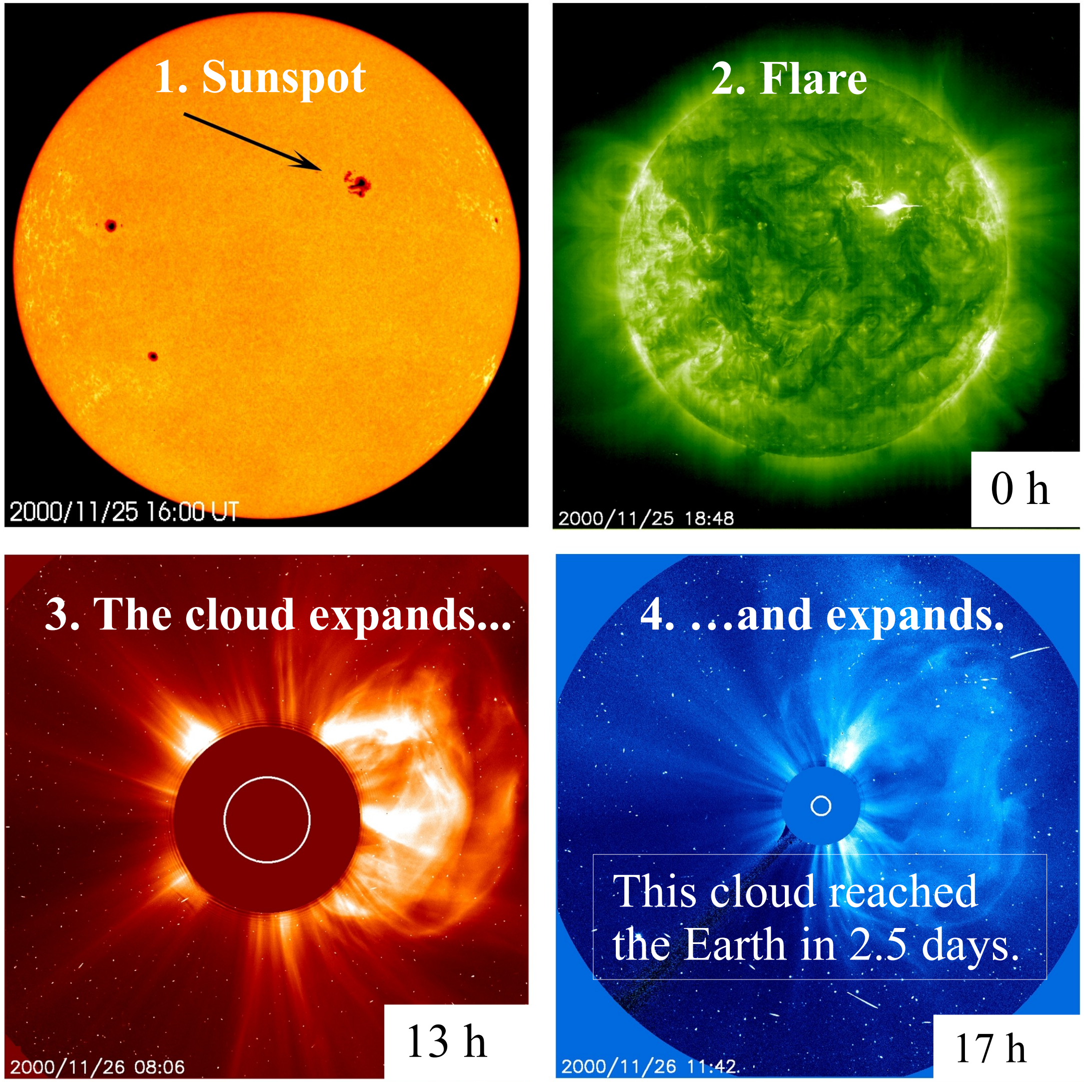
- At the moment, it is not possible to forecast solar flares. However, it is possible to estimate occurrence probabilities by examining the active regions on the Earthward side of the Sun.
- The electromagnetic radiation from a flare propagates at the speed of light, so a warning before arrival at the Earth is not possible.
- High-energy protons have a short lead-time: they arrive at the Earth from 20 min to hours after the electromagnetic radiation.
- The exact shape of the IMF is not known; it is not possible to know whether the protons will hit the Earth or miss it.



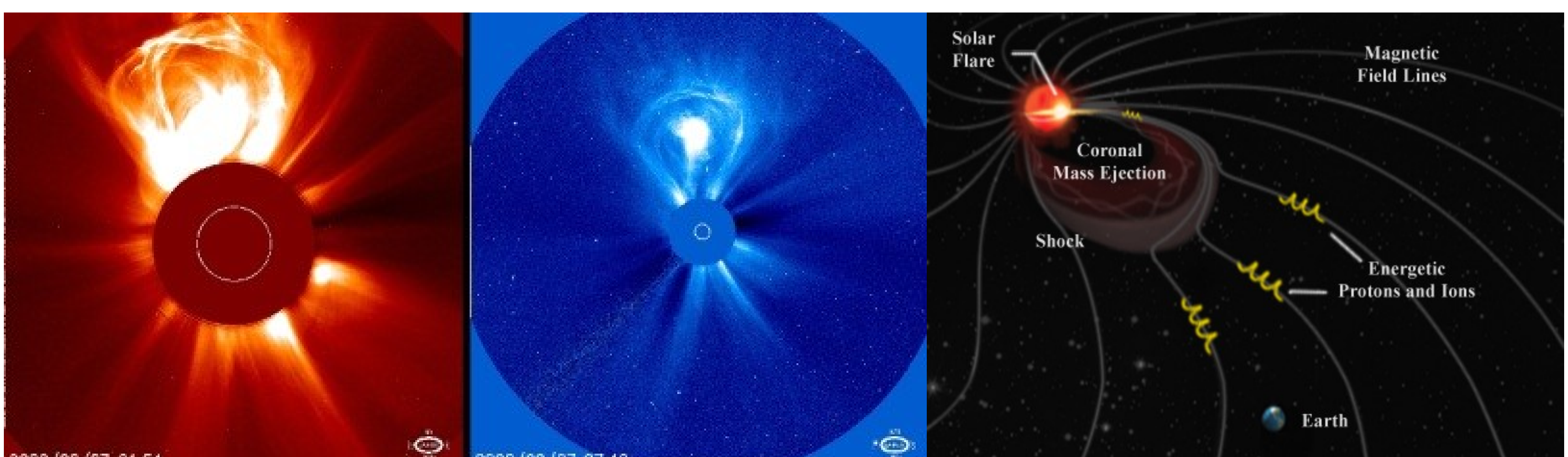


Coronal mass ejections (CME)

- Clouds of magnetized plasma.
- Occurence rate: ~0.8/day at solar minimum, ~3.5/day at solar maximum.
- Often, but not always, associated with solar flares.
- A shock formed in the solar wind in front of a fast CME can accelerate solar wind protons to high energies.

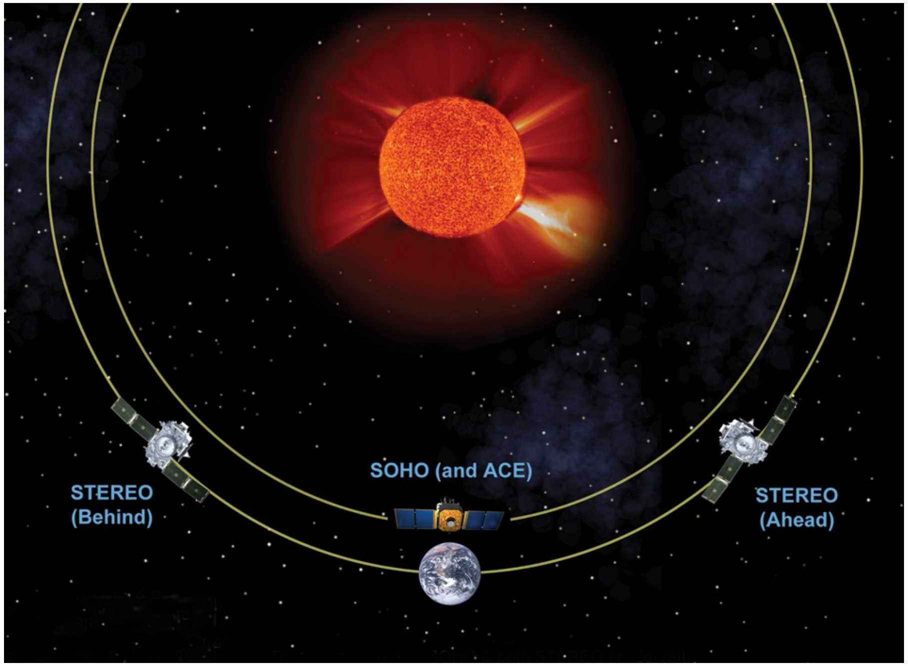


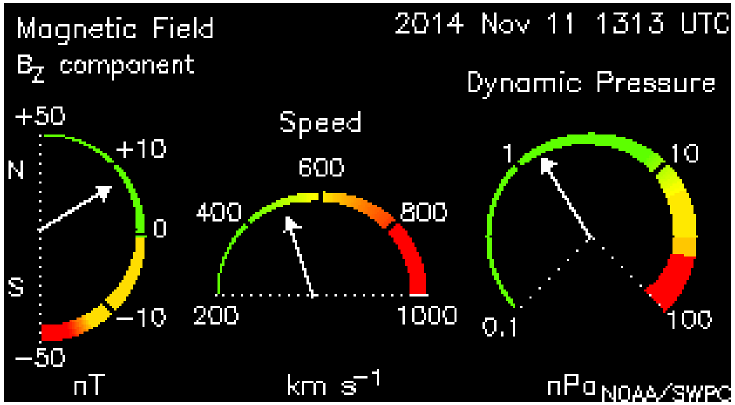
- After a CME has left the Sun, it can be detected in coronagraph images, providing a lead-time of a day or two before the CME impacts the Earth.
  - Not all CMEs are directed toward the Earth.
  - It is difficult to estimate if an apparently Earthward directed CME will hit the magnetosphere directly, only glance it, or miss completely.
  - The time-of-arrival estimate is uncertain.
  - High-energy protons accelerated by the shock can be expected at the Earth until the leading edge of the CME has passed the Earth.
  - It is not possible to determine the **direction of the magnetic field** in the CME from remote observations.



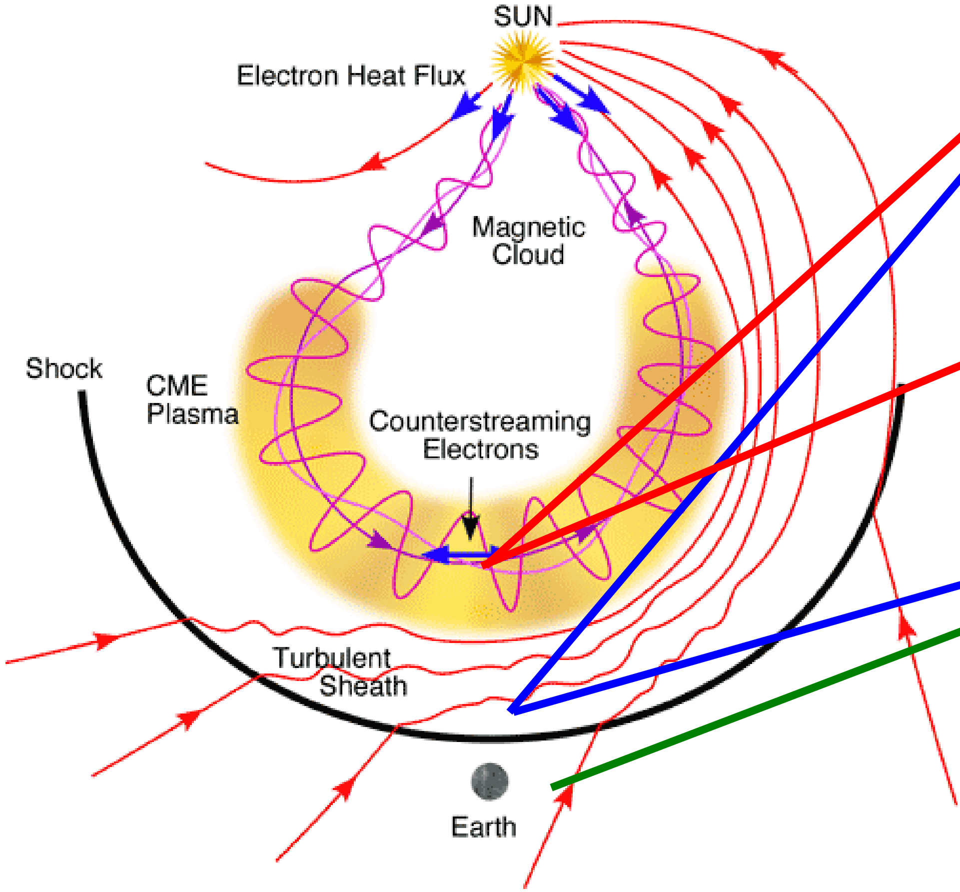
Monitoring the solar wind approaching the Earth

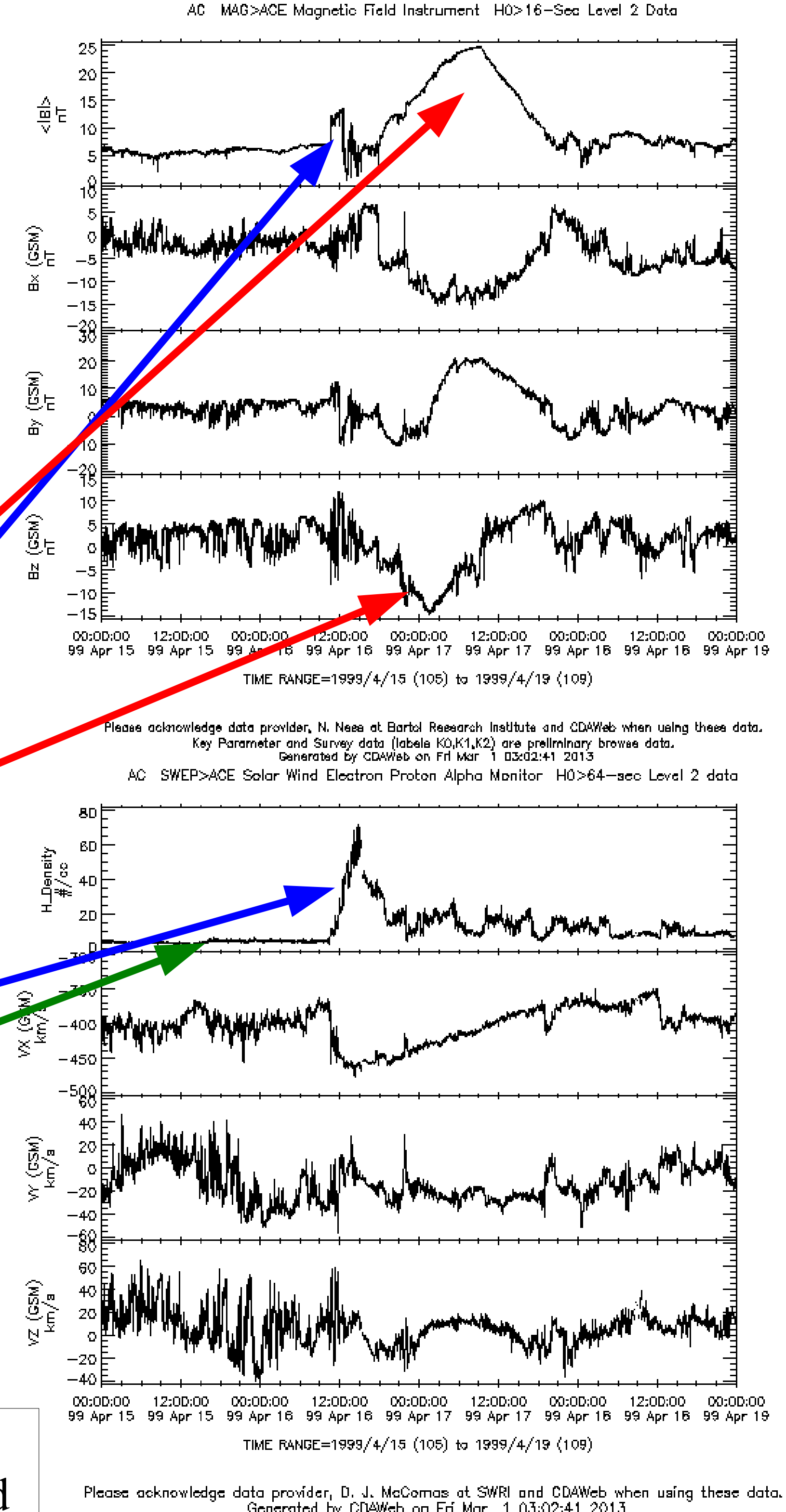
- When a CME or other solar wind disturbance passes the ACE satellite, a measurement can be obtained, and the effects estimated more accurately.
- The lead-time before the disturbance arrives at the Earth is less than an hour.





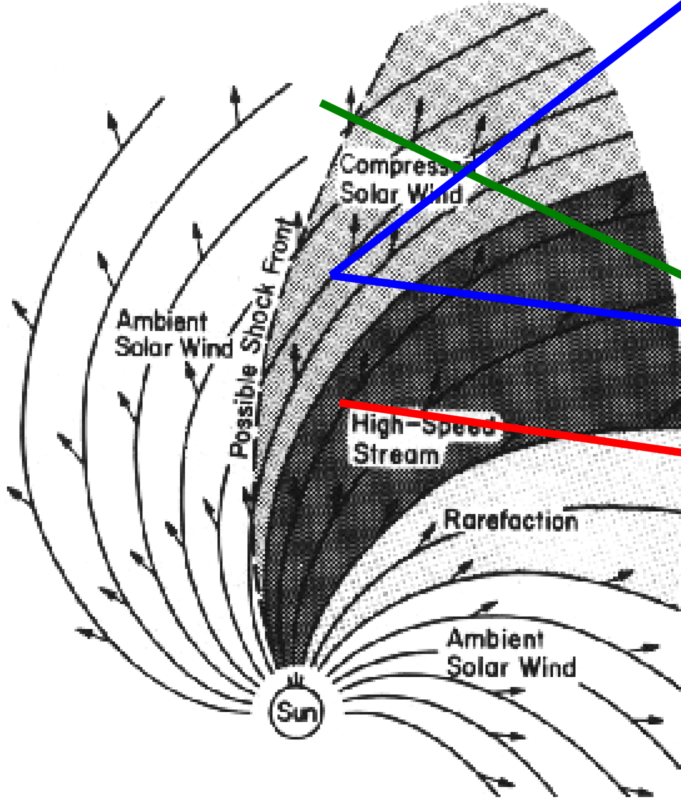
A CME observed by ACE

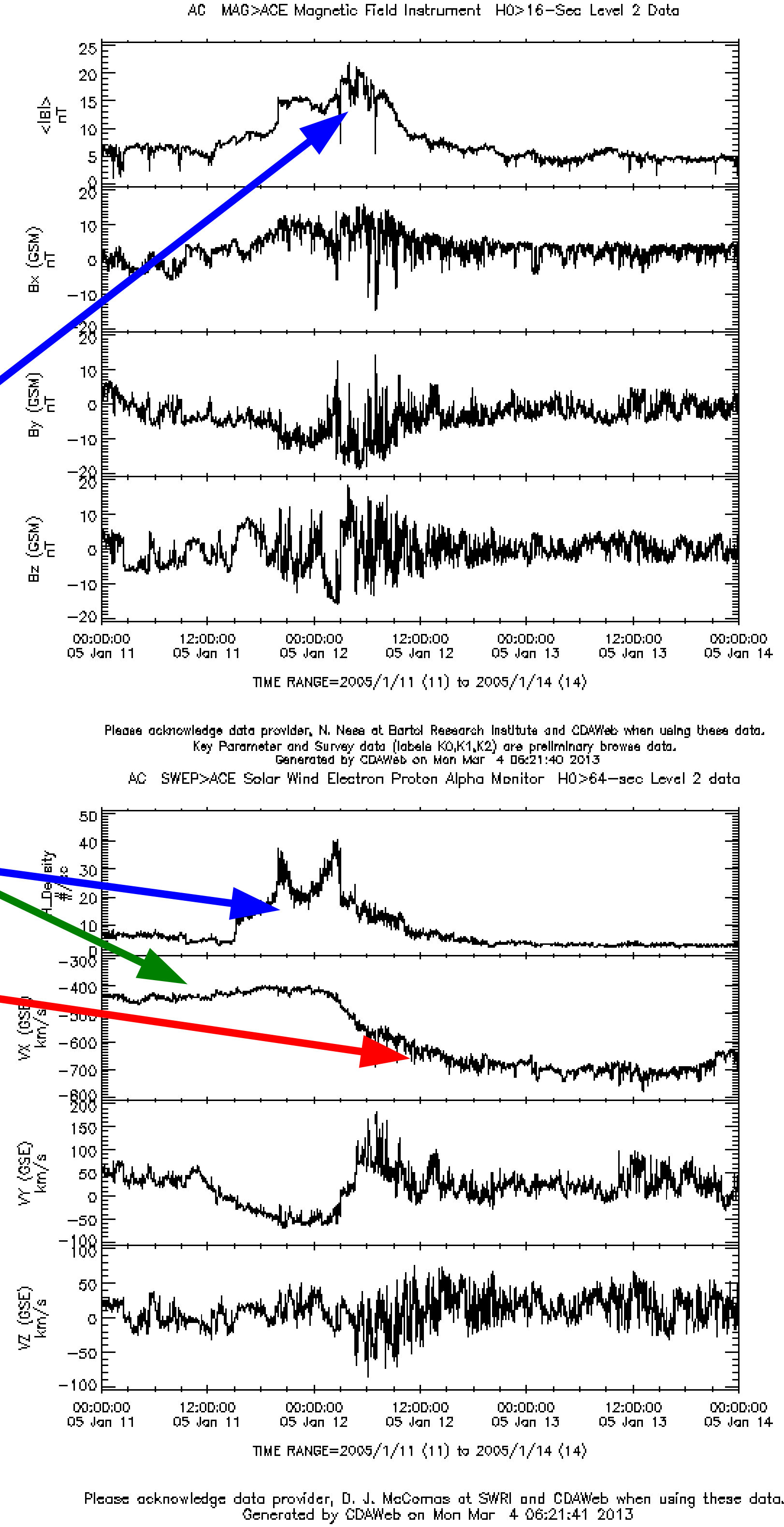




ACE real-time data:
http://www.swpc.noaa.gov/products/ace-real-time-solar-wind

A high-speed stream observed by ACE

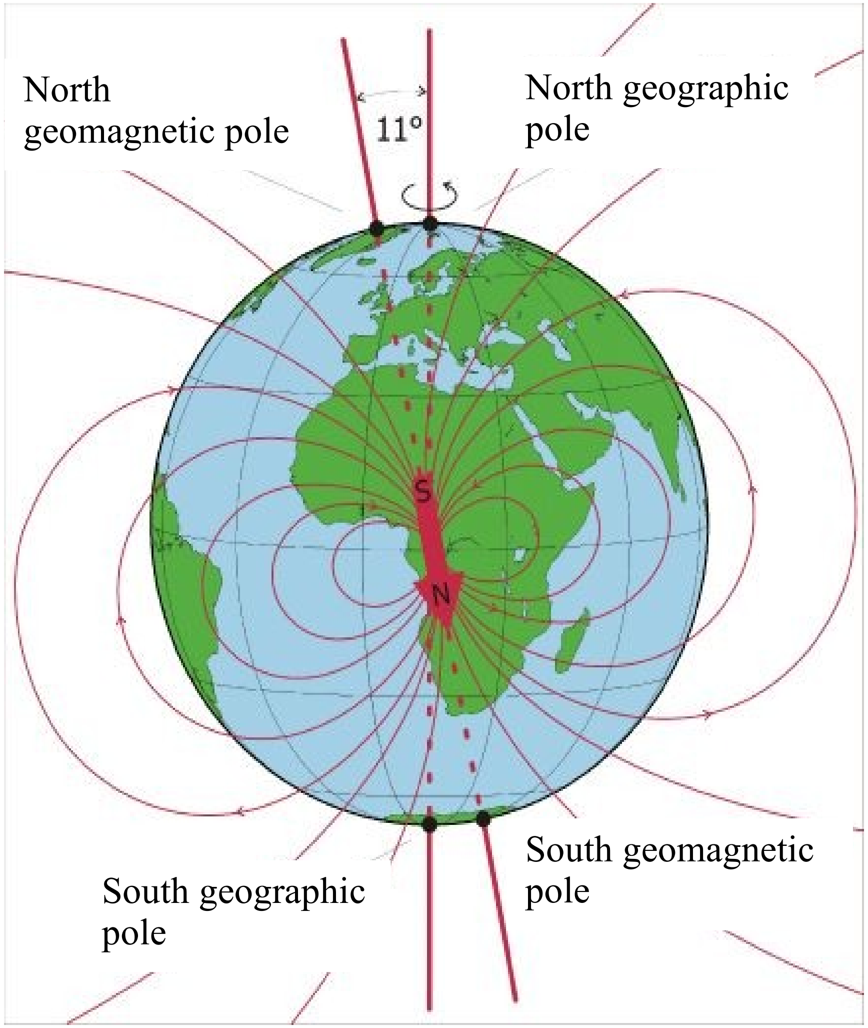




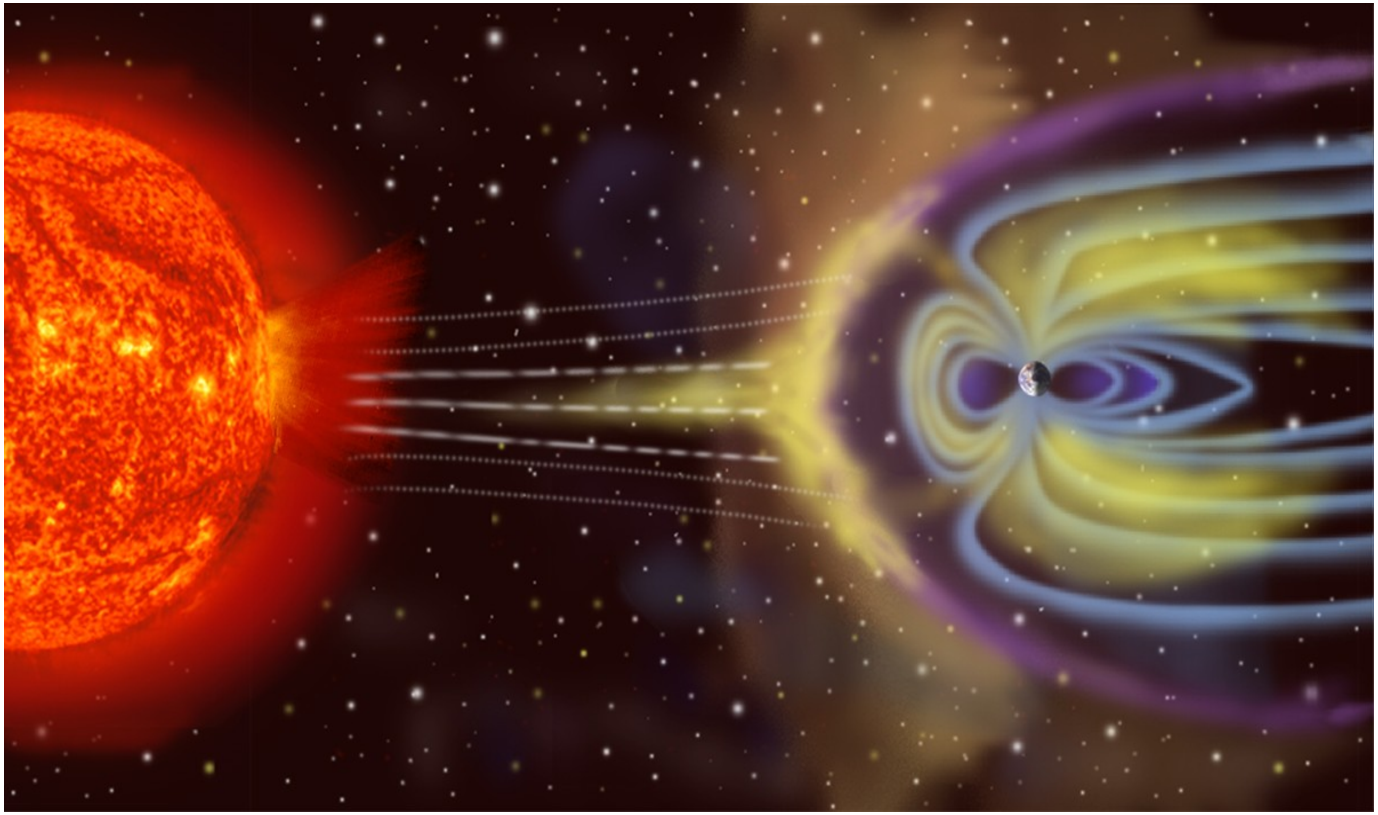
Near-Earth space

The Earth's magnetosphere

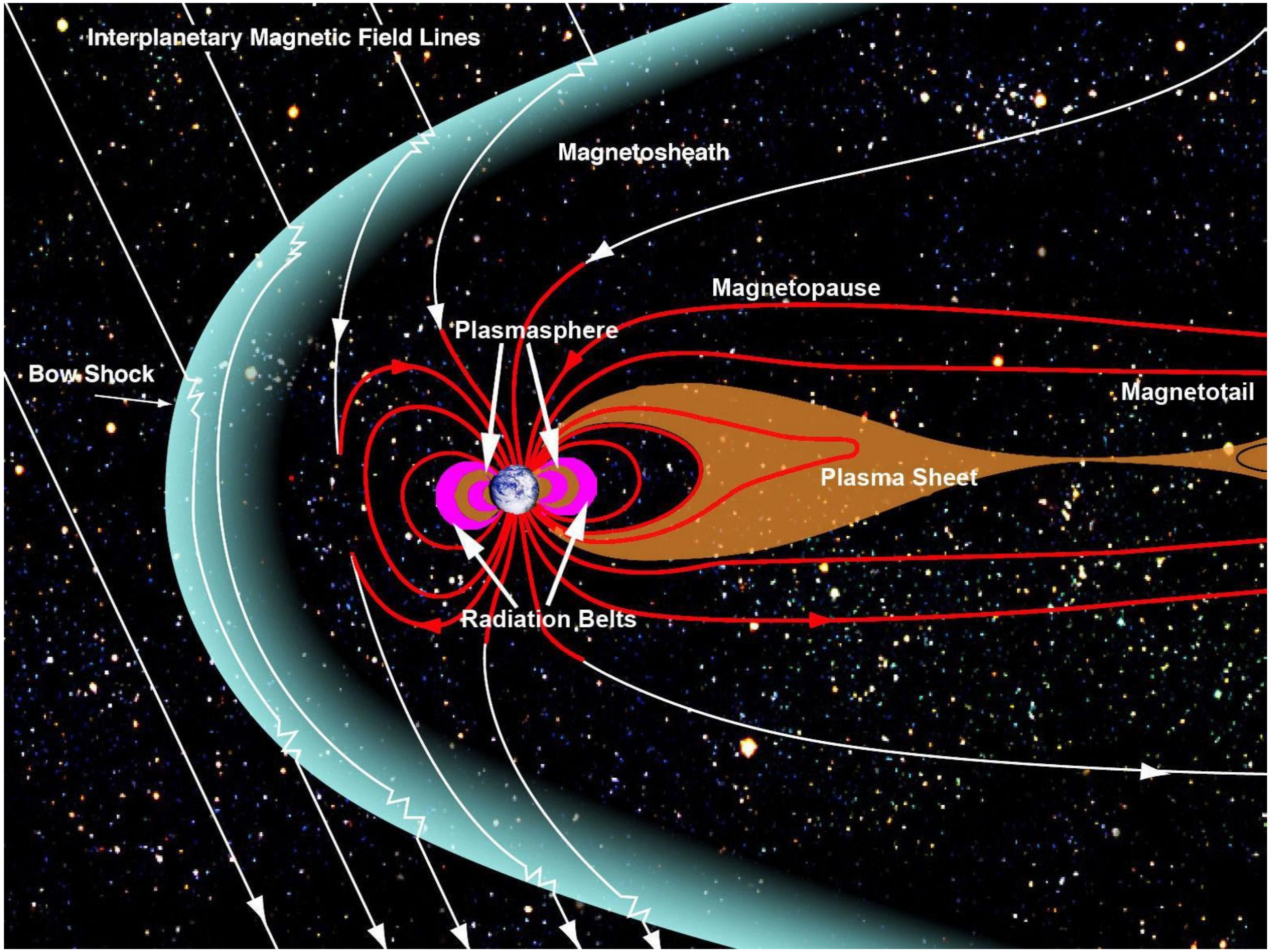
- A magnetosphere is the area of space near an astronomical object in which charged particles are controlled by that object's magnetic field. Near the surface of the object, the magnetic field lines resemble those of a magnetic dipole.



- Farther away from the Earth's surface the solar wind compresses the Earth's magnetic field on the dayside and stretches it to a long tail on the nightside.

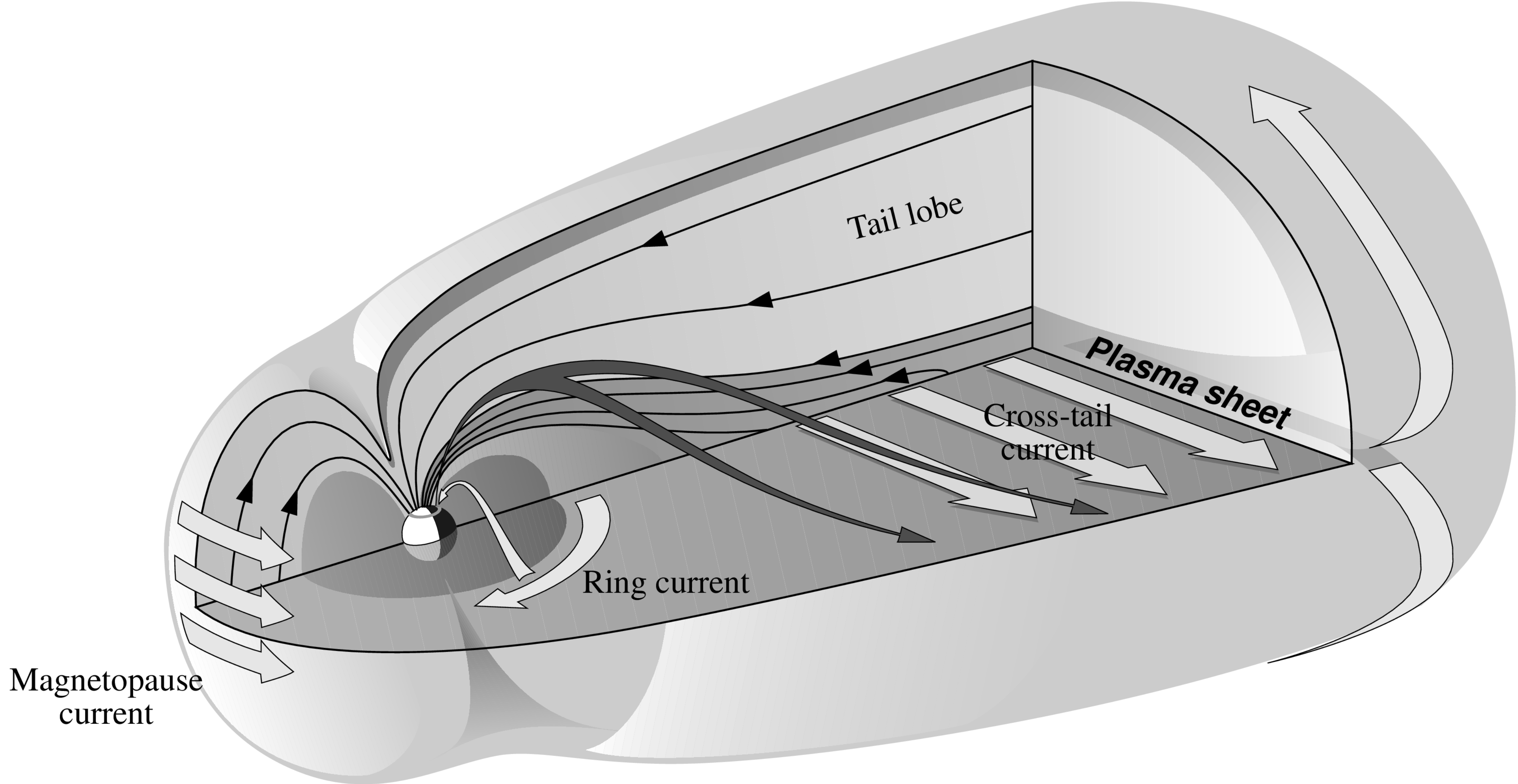


Structure of the Earth's magnetosphere

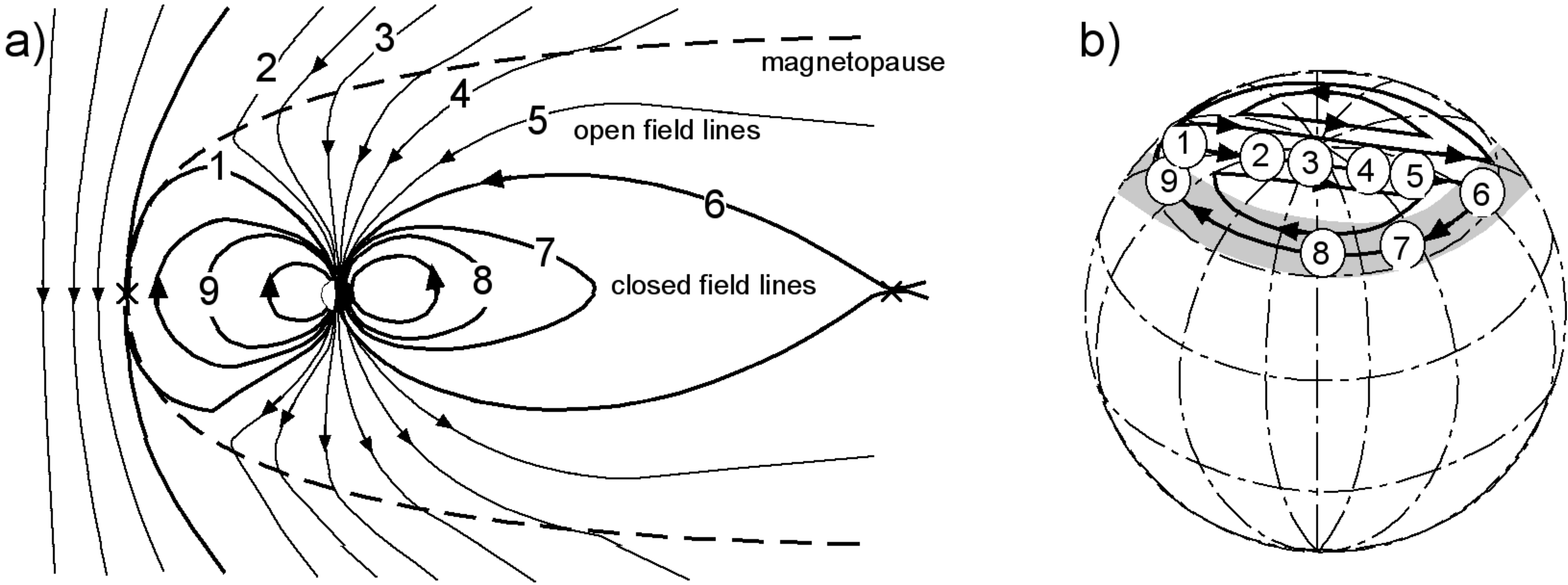


Pressure balance between the solar wind dynamic pressure on the outside and the magnetic pressure on the inside determine the distance of the magnetopause from the center of the Earth.

Magnetospheric current systems

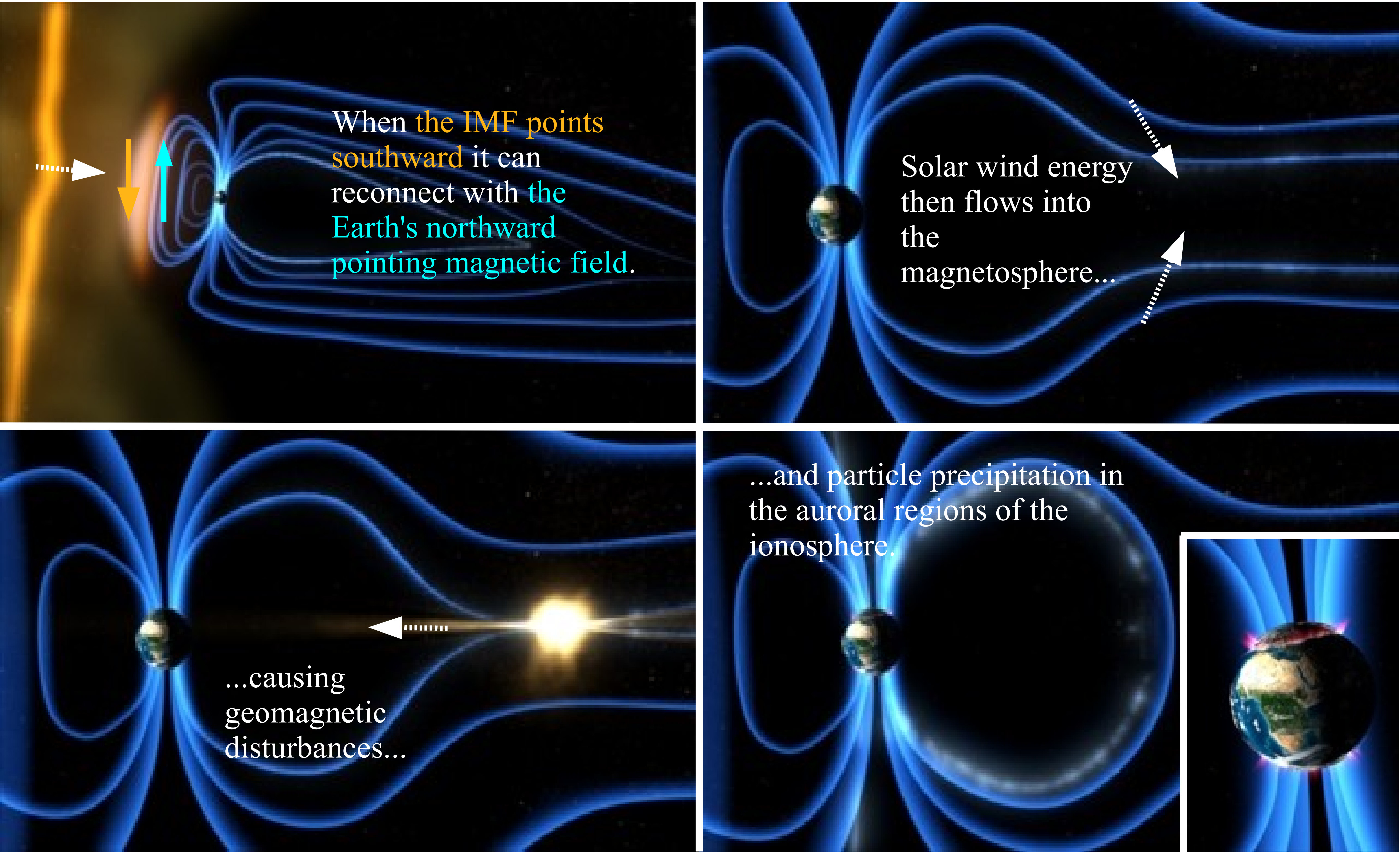


Plasma convection



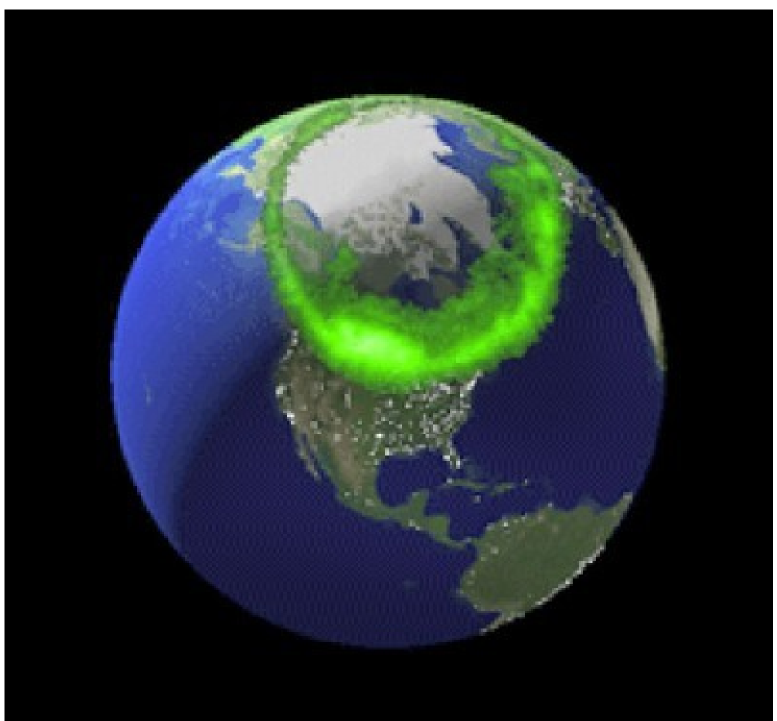
Convection of plasma in the magnetosphere, driven by the solar wind, maps along the Earth's magnetic field to the polar ionospheres. Illustration by M. Palmroth after Dungey (1961).

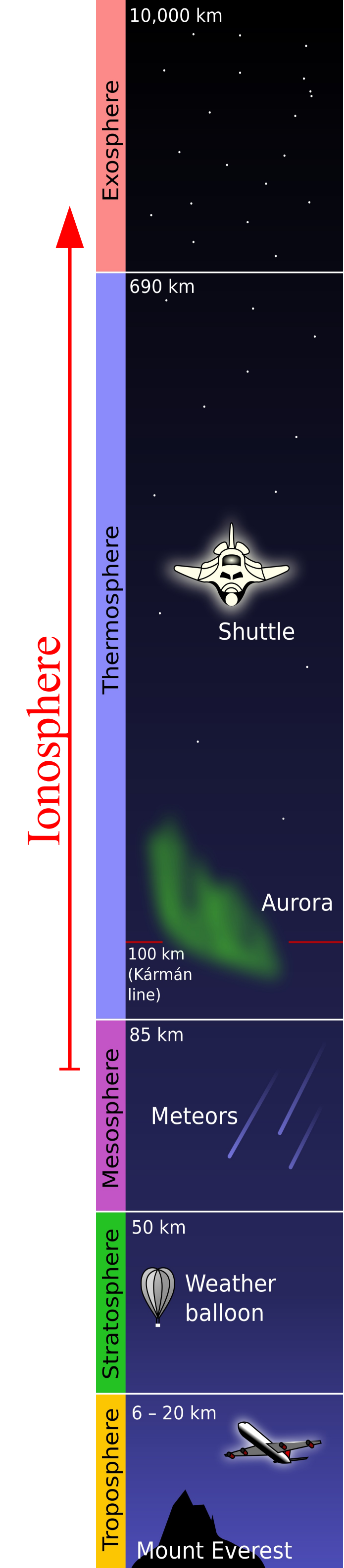
In reality, the most typical response of the magnetosphere to increased solar wind driving is not steady convection. Instead, the solar wind energy is first stored into the tail after which it is explosively released. This cycle is called the substorm.



The Earth's ionosphere

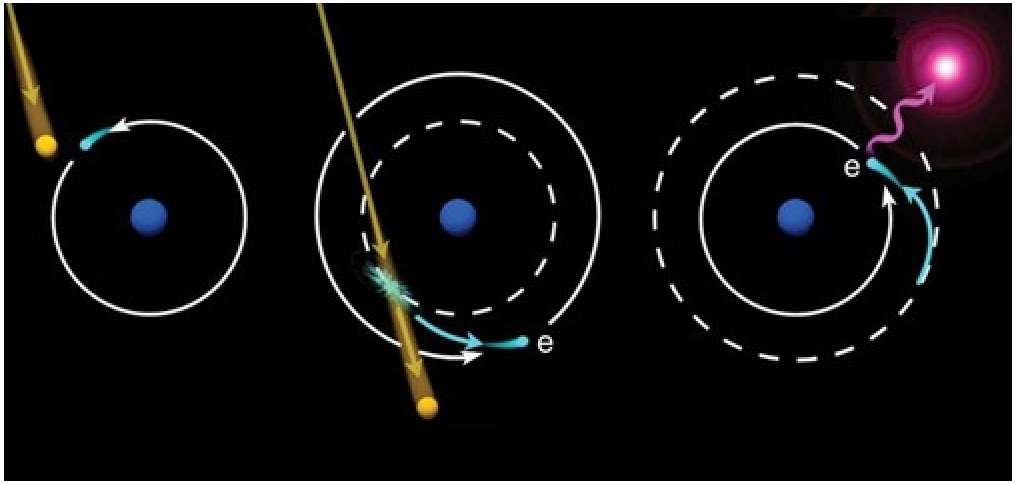
- The weakly (0.1-1%) ionized part of the upper (~60-1500 km altitude) atmosphere.
- Mainly produced by
  - photoionization due to solar EUV radiation.
  - impact ionization due to particles precipitating from the magnetosphere.

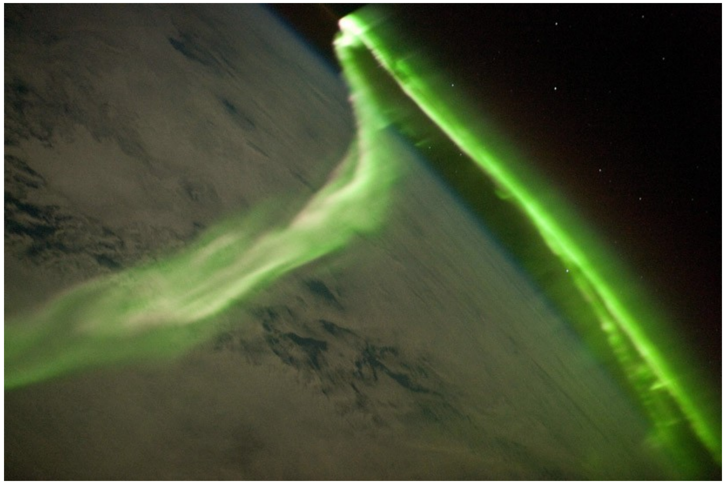




Auroral light

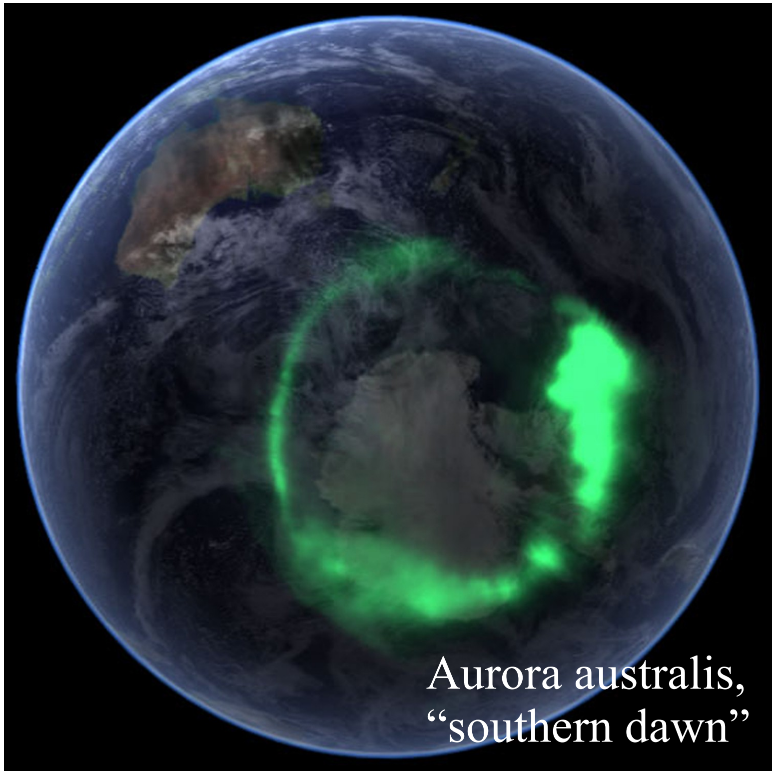
- Auroral light is caused by collisions of precipitating energetic particles with atmospheric atoms and molecules.
- Atmospheric particles are excited or ionized by the collisions. As they return to ground state, the excitation energy is lost by the emission of a photon.





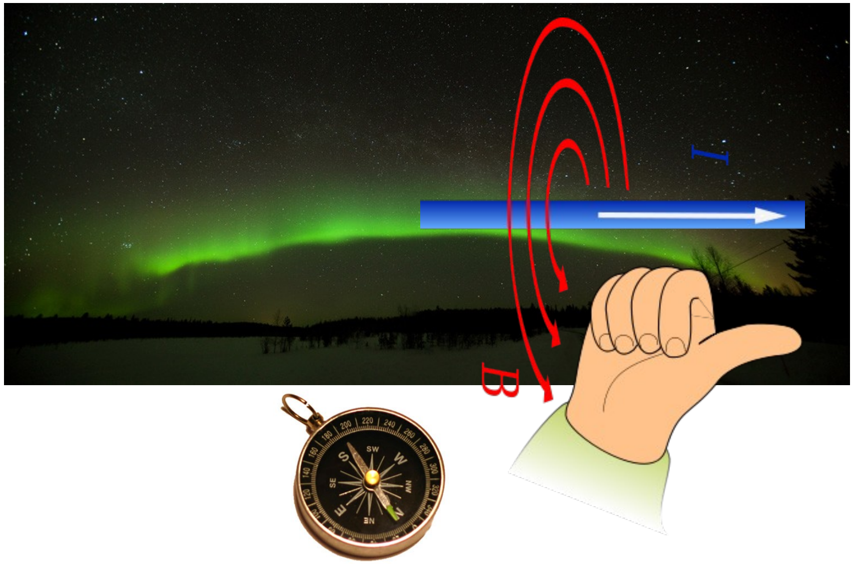
Auroral regions

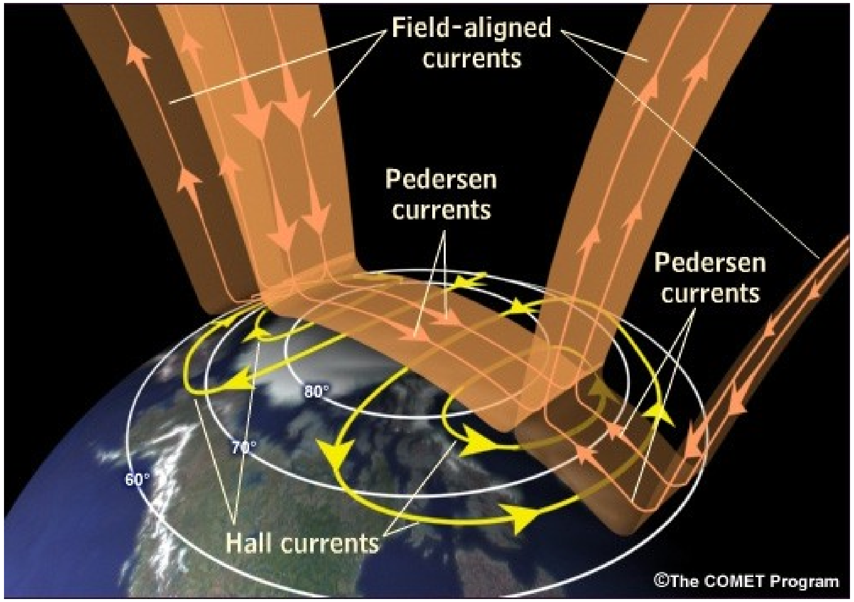
- Auroral regions are geographic regions, where auroras are commonly observed during nominal geomagnetic activity conditions.
  - In Finland, Lapland.
- The Earth's magnetic field directs the charged particles from the magnetosphere to band-like regions surrounding the geomagnetic poles.
- These auroral ovals exist at all times, but their location, width, and brightness vary with the level of geomagnetic activity.
- During a geomagnetic storm, the auroral ovals will brighten and expand toward the equator.



Ionospheric electric currents

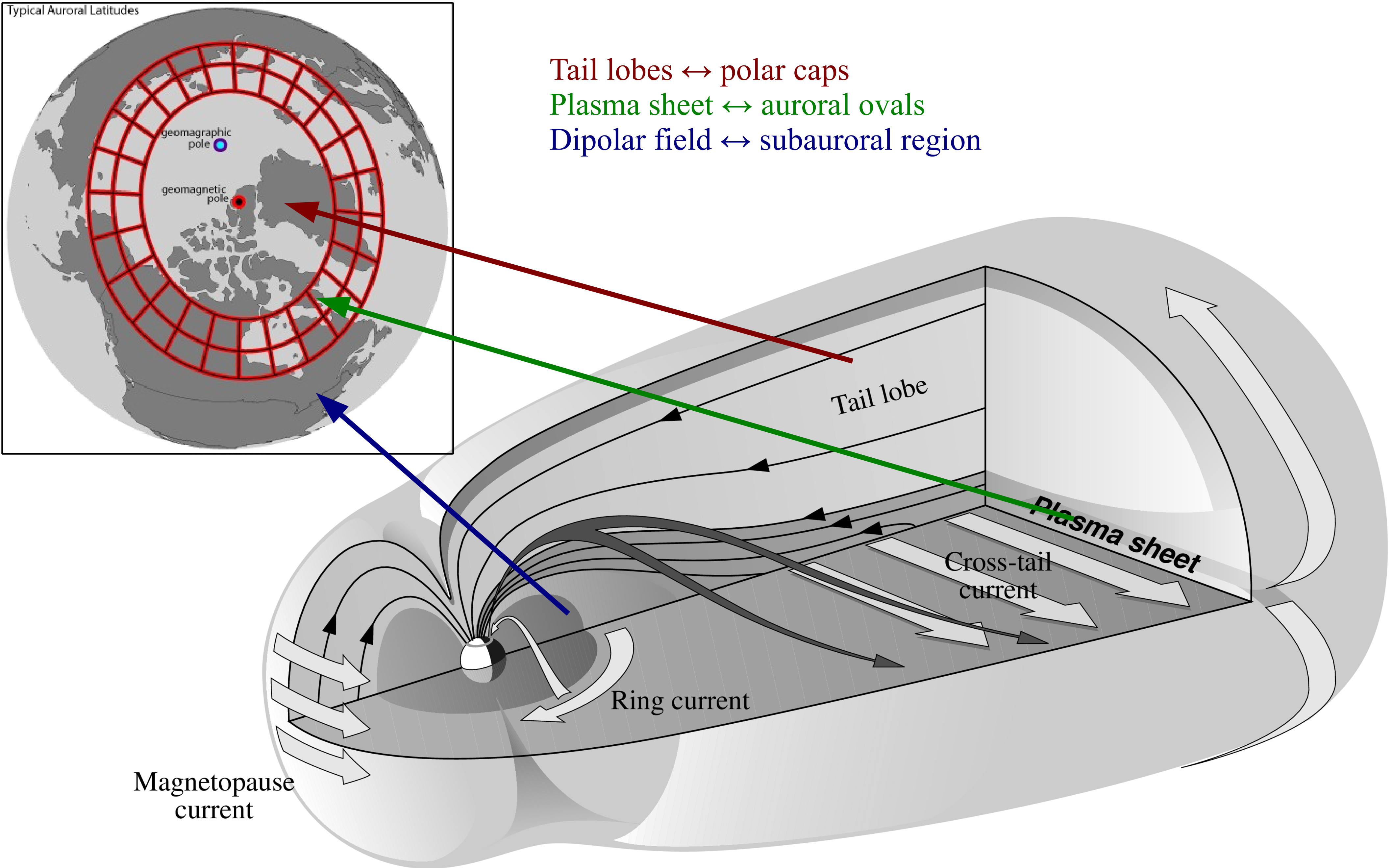
- During strong auroral activity a compass needle shows deflections.
- Negatively charged electrons precipitating from the magnetosphere to the ionosphere along the magnetic field lines carry electric current in a direction opposite to their motion.
- The disturbance magnetic field generated by the ionospheric electric currents can be measured on the ground by magnetometers.





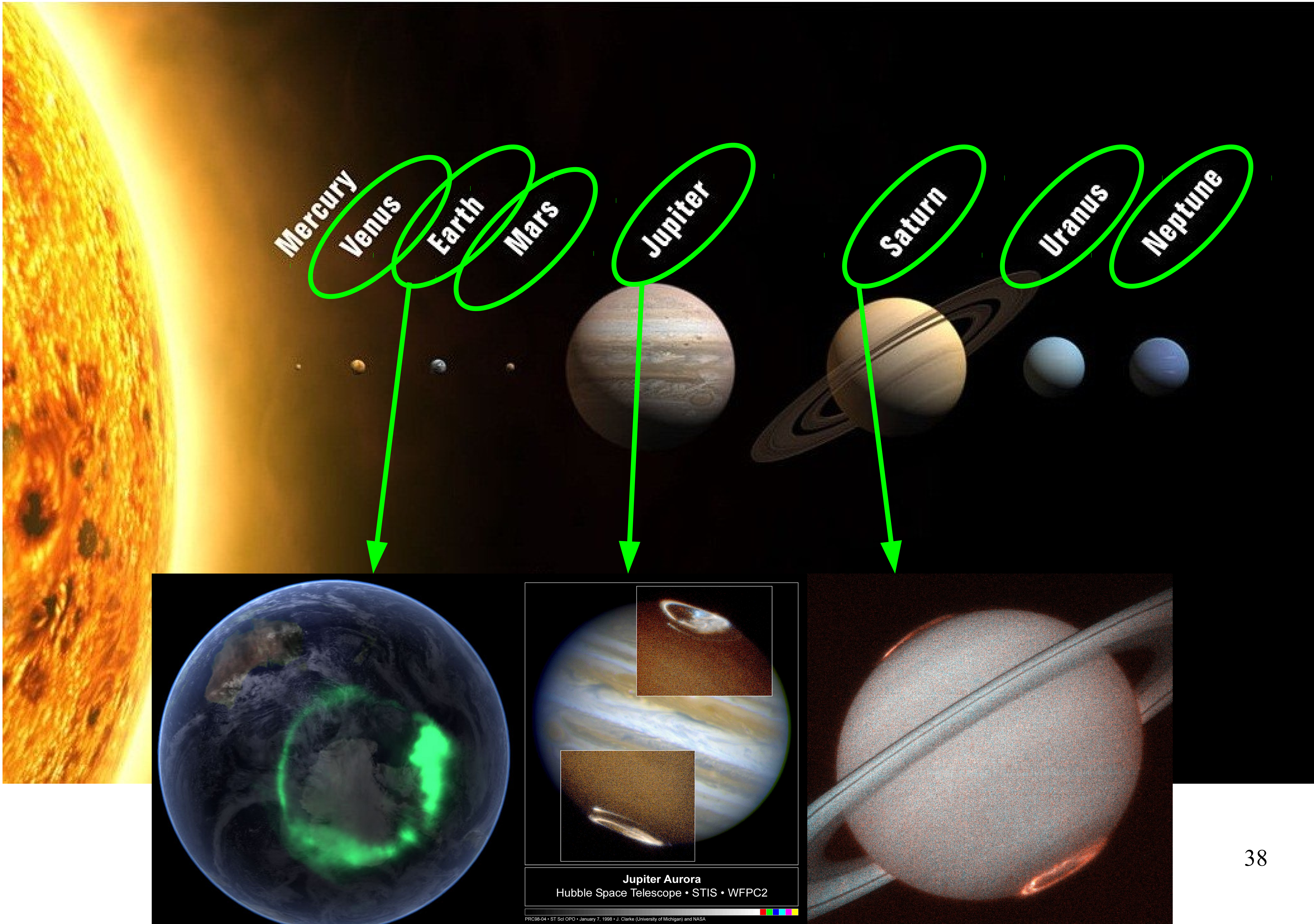
Magnetically conjugate regions

Tail lobes ↔ polar caps
Plasma sheet ↔ auroral ovals
Dipolar field ↔ subauroral region

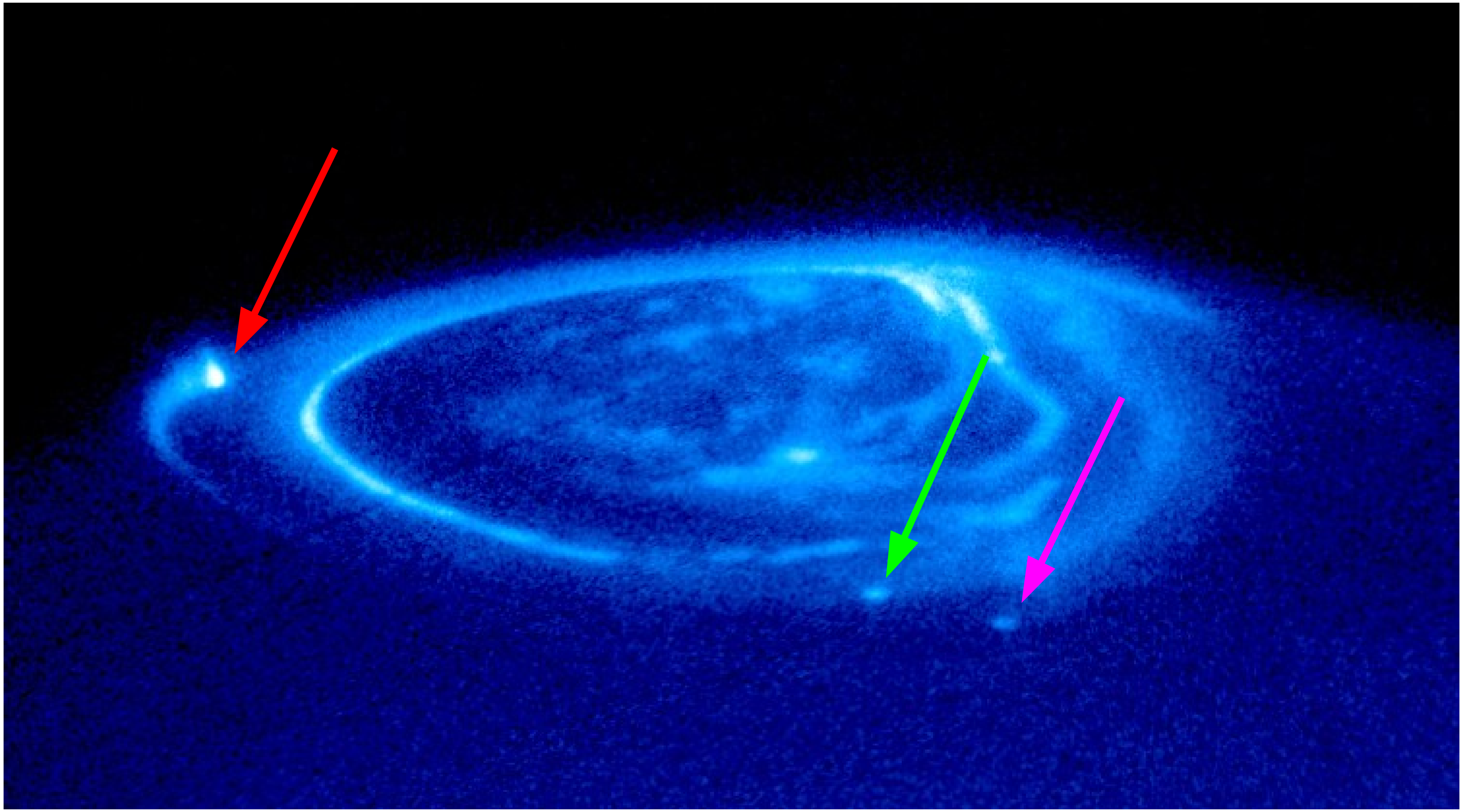


Auroras have also been observed on other planets

Images from: http://hubblesite.org/, http://earthobservatory.nasa.gov



Auroras on Jupiter

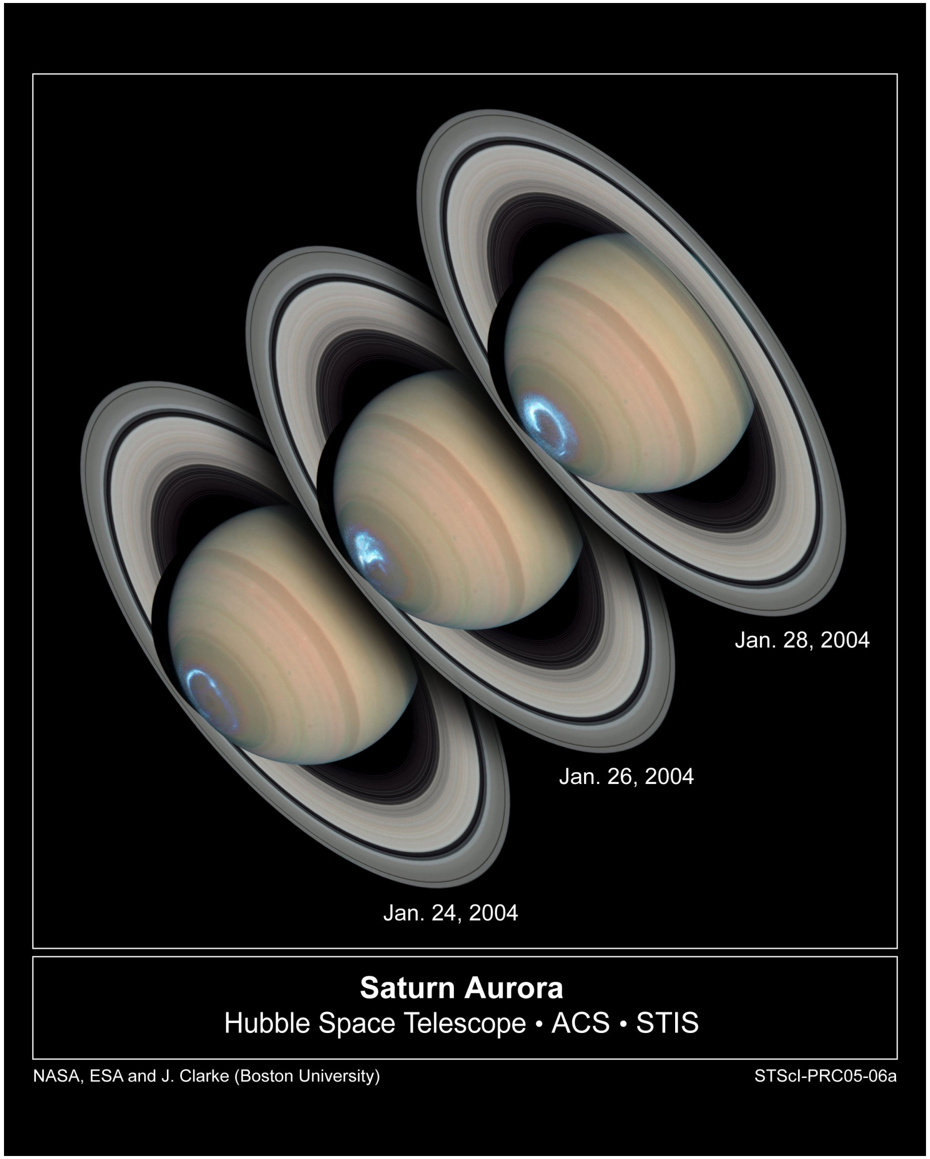


This ultraviolet image of Jupiter was taken with the NASA Hubble Space Telescope Imaging Spectrograph (STIS) on November 26, 1998. The image shows the main oval of the aurora, which is centered on the magnetic north pole, plus more diffuse emissions inside the polar cap. Though the aurora resembles the same phenomenon that crowns Earth's polar regions, the Hubble image shows unique emissions from the magnetic "footprints" of three of Jupiter's largest moons. These points are reached by following Jupiter's magnetic field from each satellite down to the planet. Auroral footprints can be seen in this image from Io, Ganymede, and Europa.

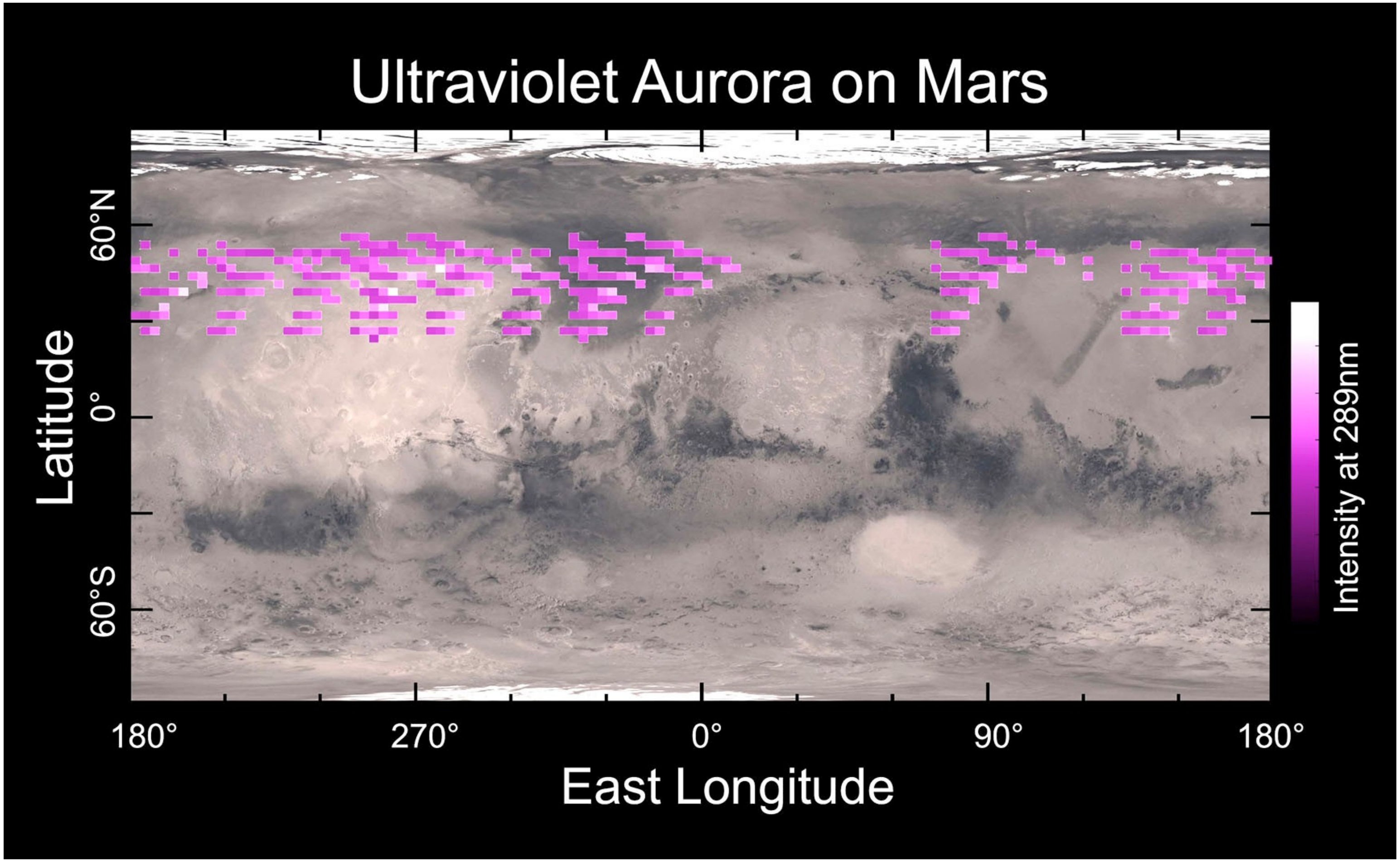
- Jovian auroral storms, like Earth's, develop when electrically charged particles trapped in the magnetic field surrounding the planet spiral inward at high energies toward the north and south magnetic poles. When these particles hit the upper atmosphere, they excite atoms and molecules there, causing them to glow.
- The electrons that strike Earth's atmosphere come from the sun, and the auroral lights remain concentrated above the night sky in response to the solar wind, as Earth rotates underneath. Earth's auroras exhibit storms that extend to lower latitudes in response to solar activity.
- Jupiter's auroras are caused by particles spewed out by volcanoes on Io, one of Jupiter's moons. These charged particles are then magnetically trapped and begin to rotate with Jupiter, producing ovals of auroral light centered on Jupiter's magnetic poles in both the day and night skies.

Auroras on Saturn

- Seen from space, Saturn's aurora appear as rings of glowing gases circling the planet's polar regions.
- Observations made by Hubble and the Cassini spacecraft, while enroute to the planet, suggest that Saturn's auroral storms are driven mainly by the pressure of the solar wind rather than by the Sun's magnetic field.
- The aurora's strong brightening on Jan. 28, 2004 corresponds with the recent arrival of a large disturbance in the solar wind. The image shows that when Saturn's auroras become brighter, the ring of light encircling the pole shrinks in diameter.
- In this picture, the auroral display appears blue. In reality, the aurora would appear red to an observer at Saturn.

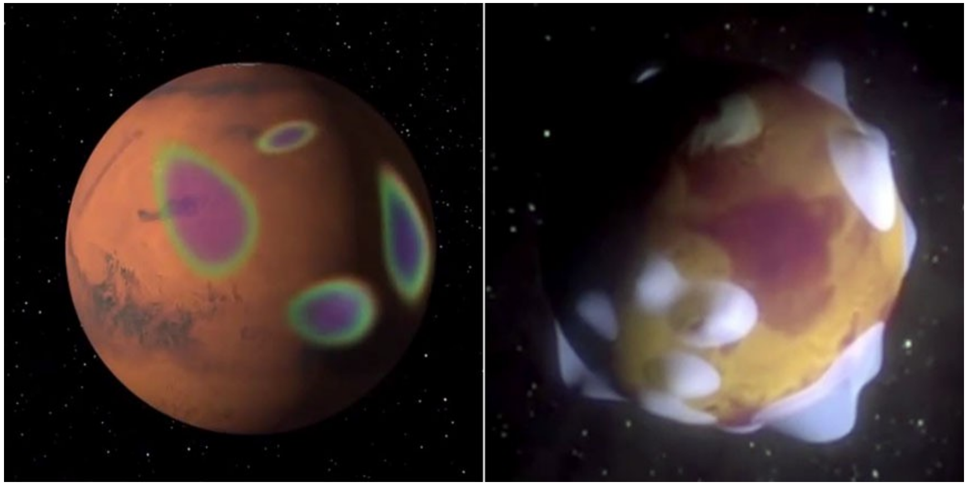


Auroras on Mars



A map of MAVEN's Imaging Ultraviolet Spectrograph (IUVS) auroral detections in December 2014 overlaid on Mars' surface. The map shows that the aurora was widespread in the northern hemisphere, not tied to any geographic location. The aurora was detected in all observations during a 5-day period. Credits: University of Colorado

- While the solar wind produces auroras at both Earth and Mars, they originate in radically different ways:
  - At Earth, charged particles from the Sun are guided to the Earth's polar regions by the global magnetic field lines.
  - Mars has no such global magnetic field. Instead, there are many locally magnetic regions. Particles arriving from the Sun seem to precipitate into the atmosphere anywhere. Magnetic fields in the solar wind drape across Mars, even into the atmosphere, and the charged particles just follow those field lines down into the atmosphere.



Mars has magnetized rocks in its crust that create localized, patchy magnetic fields (left). In the illustration at right, we see how those fields extend into space above the rocks. Credit: NASA

“*He who looks long upon the aurora soon goes mad.*”
- Inuit saying

Photo by Mikko Syrjäsuo

Nevanlinna, H., Revontulihavainnot Suomessa, 1748-2009, Finnish Meteorological Institute Reports 2009:3. http://hdl.handle.net/10138/14079