



## Máster Universitario en Ingeniería Aeronáutica

### The Space Environment

### Preliminaries. Space weather

*Página web de la Asignatura basada en la web del Prof. Dr. L. Conde  
:<https://plasmalab.aero.upm.es/~lcl/EntornoEspacial/>*

Entorno Espacial. MUIA. **PLASMALAB-ETSIAE-UPM.**

Departamento de Física Aplcada FAIAN-ETSIAE



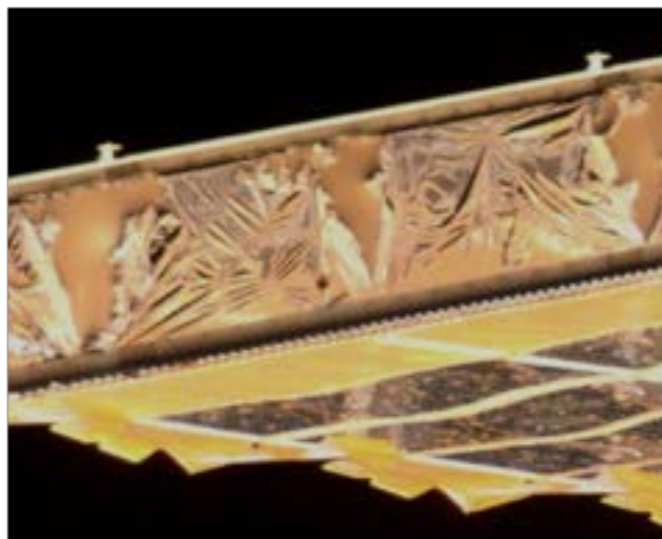
# The space environment

The space is not empty and both spacecraft and its environment are active media. The first emits neutral gas, particles, radiation, ... and interacts with particles, electromagnetic radiation, electric charges present in its surroundings. Usual environment of spacecrafts depends on their orbit and results from the combination of several components. It can be defined as:

*The environment to which a spacecraft is subjected consists of a combination of the ambient (typically a function of the orbit) and that generated by the spacecraft itself. The combination of both can give rise to synergic deleterious effects on the vehicle.*

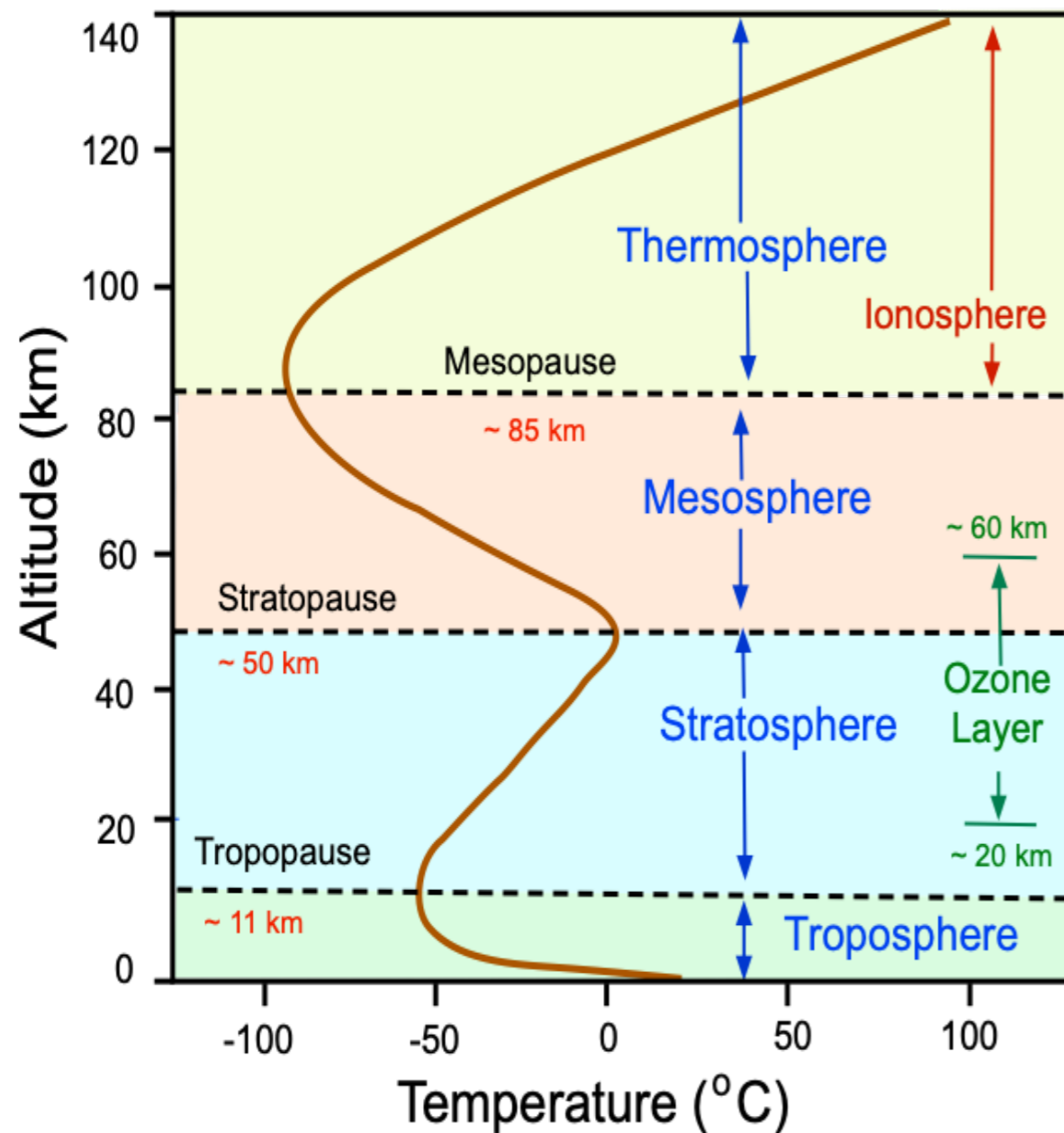
Main elements of the spacecraft environment are:

- **Neutral gas:** local or exhausted by the vehicle itself it has a variable composition.
- **Plasmas:** Physical media composed of electrons and ions with different energies, that also are chemically active.
- **Radiation:** High energy particles (corpuscular) such as electrons, protons, etc., from solar wind and/or radiation belts and electromagnetic radiation of solar origin (including temperature effects).
- **Solid particles:** Micrometeoroids, space dust and debris orbiting the Earth.



- **Practical example:** In LEO orbits (160-200 km) atomic oxygen is produced by the decomposition of  $O_2$  in the neutral atmosphere by collisions of high energy particles (electrons and protons) of solar origin.
- The average speed of a LEO spacecraft is of 7-8 km/s and the energy (4-5 eV) atomic oxygen impacting its surface is sufficient to break the chemical bonds of many materials that can become oxidized.
- Photograph shows damage of Kapton surfaces of ISS solar panels after one-year exposure.

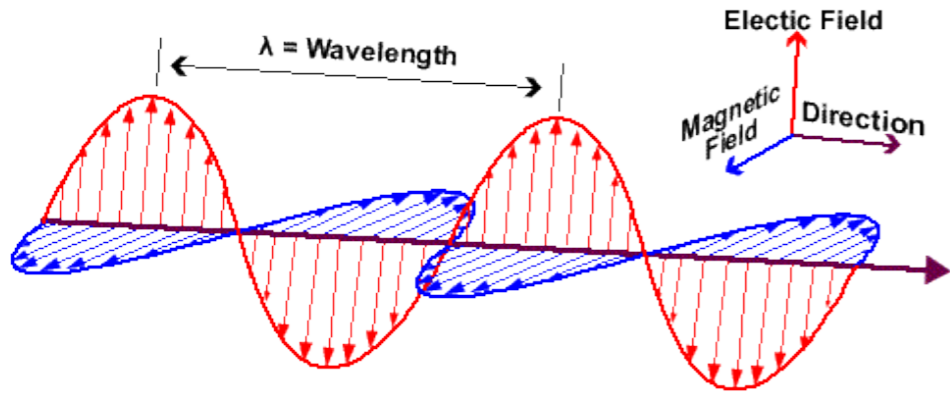
# The Earth's atmosphere



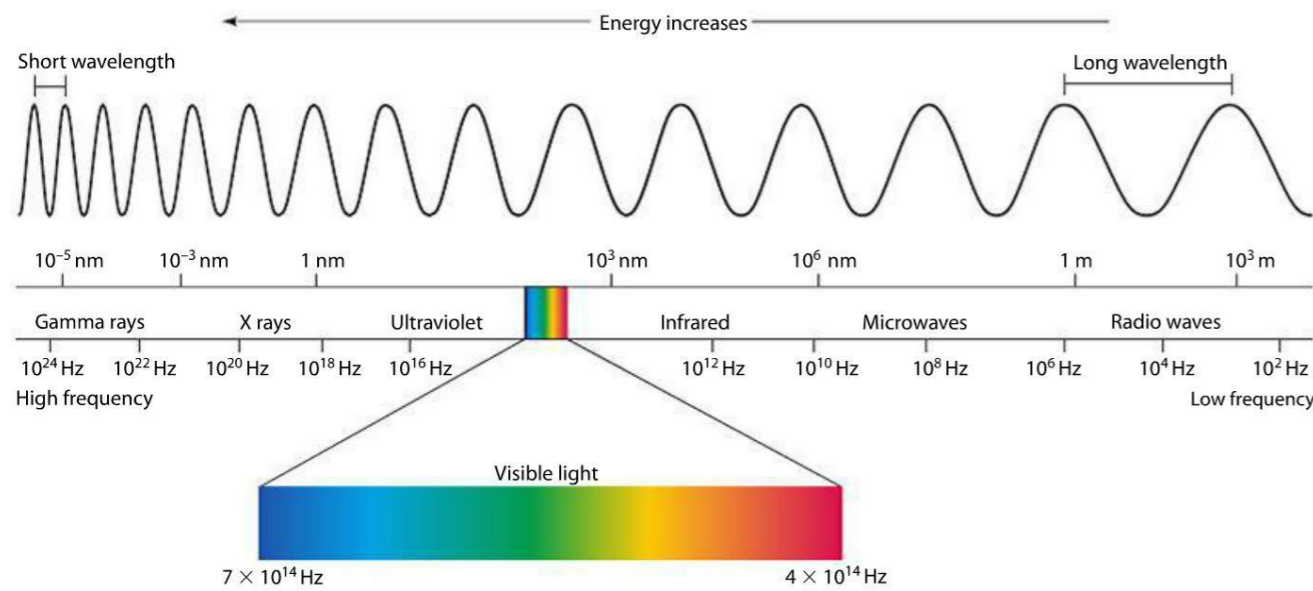
- The terrestrial atmosphere can be understood as formed by concentric spherical layers separated by **changes in temperature** called **pauses** (tropopause, stratopause, ...).
- The **vertical temperature profile** of the ionosphere is mainly due to the absorption of solar radiation and the different energy transfer processes between atoms and molecules.
- For altitudes over 85 km the radiation from the sun produces the photoionization of atmospheric gases and ionosphere and thermosphere overlap.

| Name   | Meaning         | Altitude |                 |
|--------|-----------------|----------|-----------------|
| Tropo  | Mixing/changing | 0-11 km  | Surface weather |
| Strato | Layer           | 11-50 km | Ozone layer     |
| Meso   | Middle          | 50-85 km | Coldest region  |
| Thermo | Heat            | > 85 km  | Outer space     |
| Iono   | To go           | > 85 km  | Aurora, etc.    |

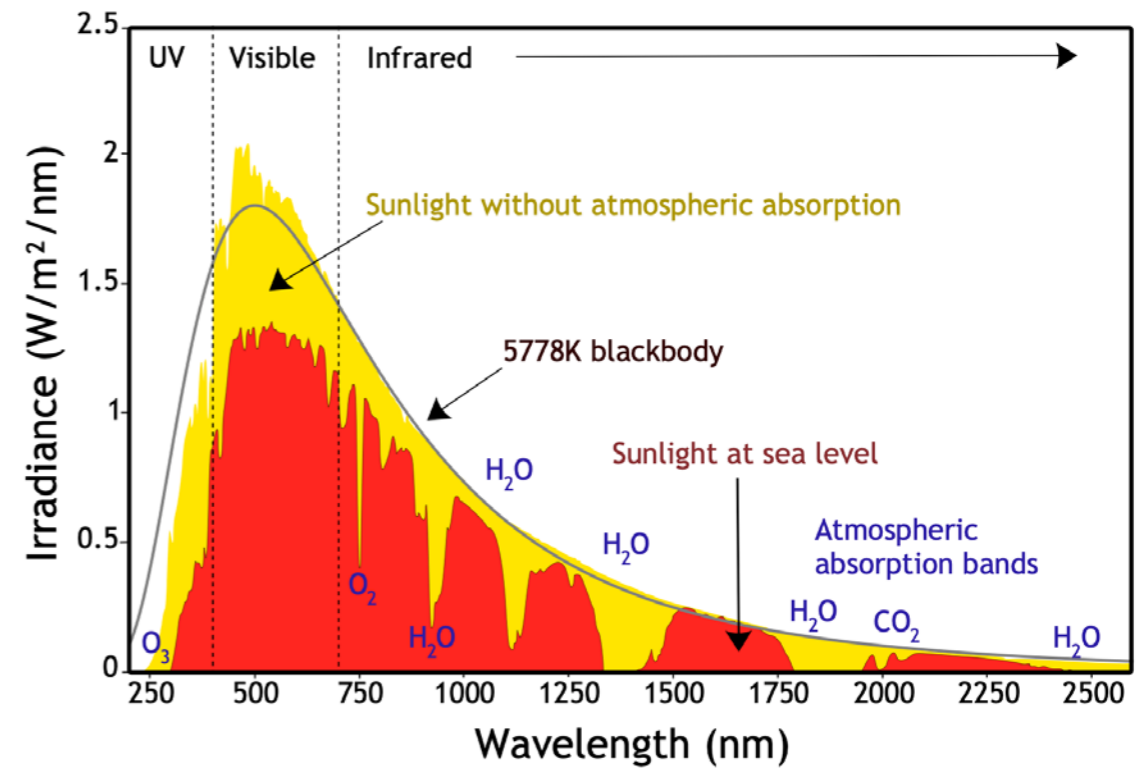
# The electromagnetic spectrum and solar radiation at Earth's orbit



- Linearly polarized sinusoidal (monochromatic) electromagnetic wave in vacuum.



Spectrum of Solar Radiation (Earth)

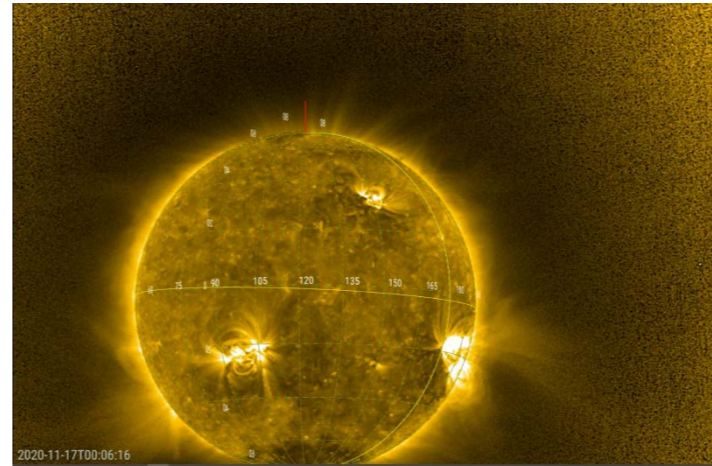


- Phase speed  $c$ , frequency  $\nu$ , wavelength:  $\lambda = c/\nu$
- Energy density:  $u = \left( \epsilon_0 \frac{|E|^2}{2} + \frac{|B|^2}{2\mu_0} \right)$
- Photon energy:  $E = h \nu$

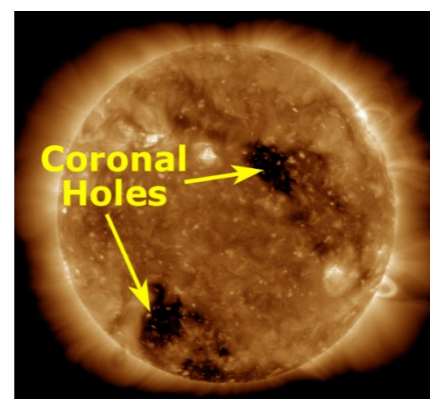
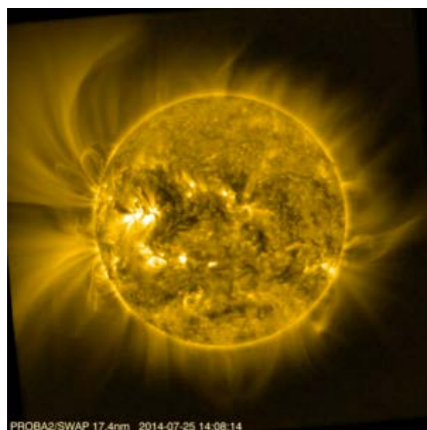
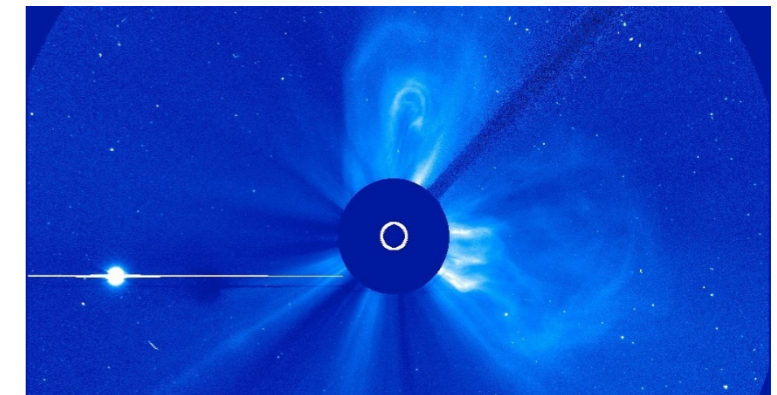
| Band name                | Abbreviation | $\nu$           | $\lambda$        | Some applications   |
|--------------------------|--------------|-----------------|------------------|---|
| Extremely low frequency  | ELF          | 3 - 30 Hz       | $10^6 - 10^4$ km | Communication with submarines   |
| Super low frequency      | SLF          | 30 - 300 Hz     | $10^4 - 10^3$ km |   |
| Ultra low frequency      | ULF          | 300 Hz - 3 kHz  | $10^3 - 10$ km   | Wireline telephony, fax machines.   |
| Very low frequency       | VLF          | 3 - 30 kHz      | 100 - 10 km      | Wireline telephony, time signals.   |
| Low frequency            | LF           | 30 - 300 kHz    | 10 - 1 km        | Navigation, AM broadcasting (Europe and Asia), amateur radio.   |
| Medium frequency         | MF           | 300 kHz - 3 MHz | 1 km - 100 m     | AM broadcasting, amateur radio, magnetic resonance imaging, wireless telegraphy.  |
| High frequency           | HF           | 3-30 MHz        | 100 - 10 m       | Shortwave broadcasts, amateur radio   |
| Very high frequency      | VHF          | 30 - 300 MHz    | 10 - 1 m         | FM broadcasts, TV broadcasts, radars, line-of-sight AA & AG aviation telecommunications.  |
| Ultra high frequency     | UHF          | 300 MHz - 3 GHz | 1 m - 10 cm      | TV broadcasts, microwave ovens, radars, microwave communications, wireless LAN Bluetooth, L-Band radars, cell phones, GPS, <a href="#">satellite phones (L and S bands)</a> .   |
| Super high frequency     | SHF          | 3 - 30 GHz      | 10 - 1 cm        | Radio astronomy, microwave communication/devices, wireless LAN, <a href="#">communication satellites</a> , <a href="#">satellite TV broadcasting</a> , <a href="#">weather satellites</a> , <a href="#">satellite radio</a> . |
| Extremely high frequency | EHF          | 30 - 300 GHz    | 10 - 1 mm        | Radio astronomy, <a href="#">satellite broadcasting</a> , <a href="#">communication satellites</a> , <a href="#">weather satellites</a> , wireless Lan 802.11 and internet.   |
| Terahertz high frequency | THS          | 300 GHz - 3 THz | 1 - 0.1 mm       | Experimental medical imaging to replace X-rays, terahertz computing/communications. Remote sensing.   |

# Energy and mass emissions

- **Sunspots** are points of **lower luminosity** in the solar photosphere due to areas with **lower temperatures** than their surroundings. They are grouped in pairs or groups near the equator, *forming loops*.



- **Solar flares** are violent, localized **emissions of electromagnetic energy** (X-rays,  $\gamma$  radiation) produced by the **conversion of magnetic field into kinetic energy** of charged particles. They last from minutes to hours and reach the Earth's orbit.
- **Coronal mass ejections** are **gigantic emissions of matter and energy** from the chromosphere and corona that can escape the gravitational field and **pass through the solar system**, propagating along magnetic field lines. With speeds of hundreds of km/s they reach the earth in days.

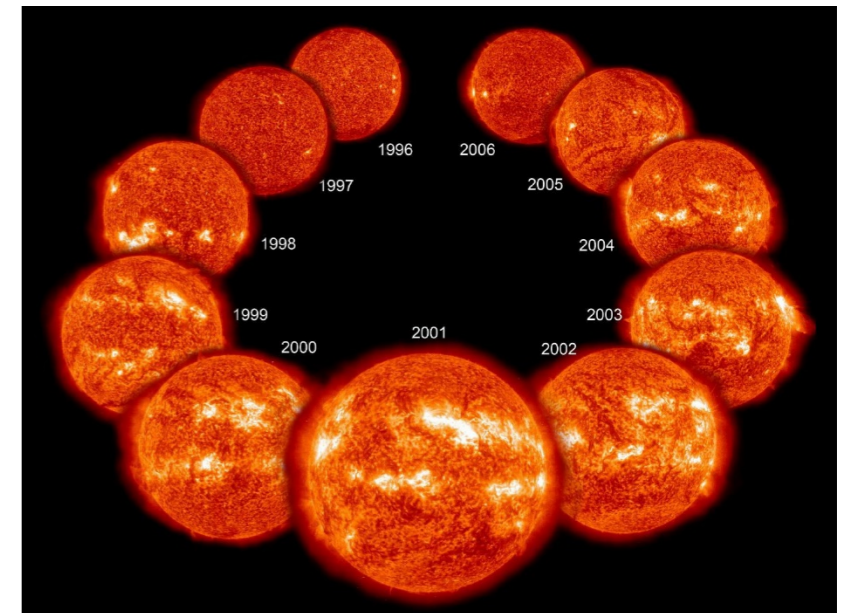
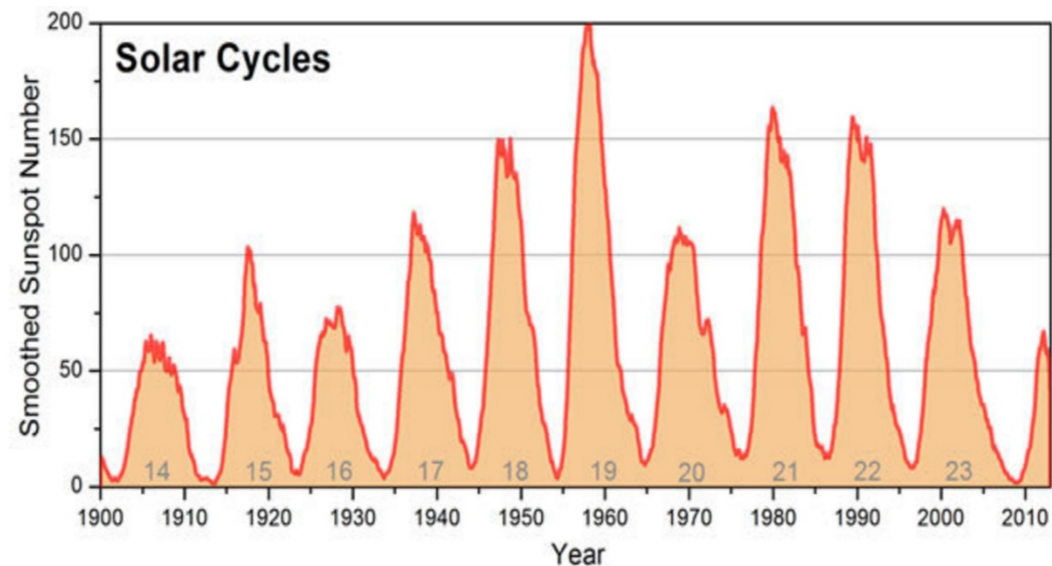
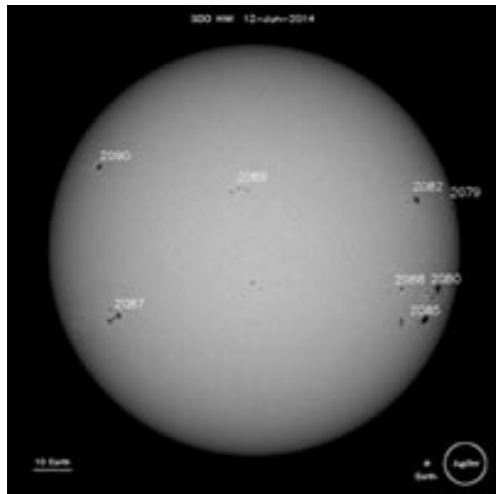


- Photographs show **coronal holes** observed in the ultraviolet and X-rays bands. They show areas of the Sun surface with lower density and temperature that ejects matter along the interplanetary magnetic field lines.

Graphic material in this slide is courtesy of NASA and ESA

# The solar cycle

- The Sun is a sphere of charged particles that generate a powerful **magnetic field that changes polarity every 11 years** in a process called the **solar cycle**. It can be characterized by evaluating the number of *sunspots*, which are related to the explosive emission of energy by the photosphere as solar activity increases, among other parameters.

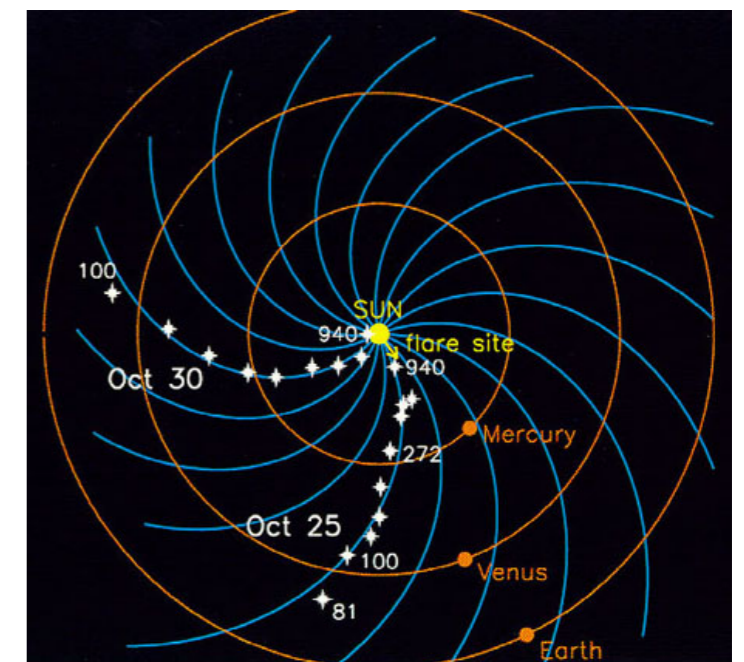
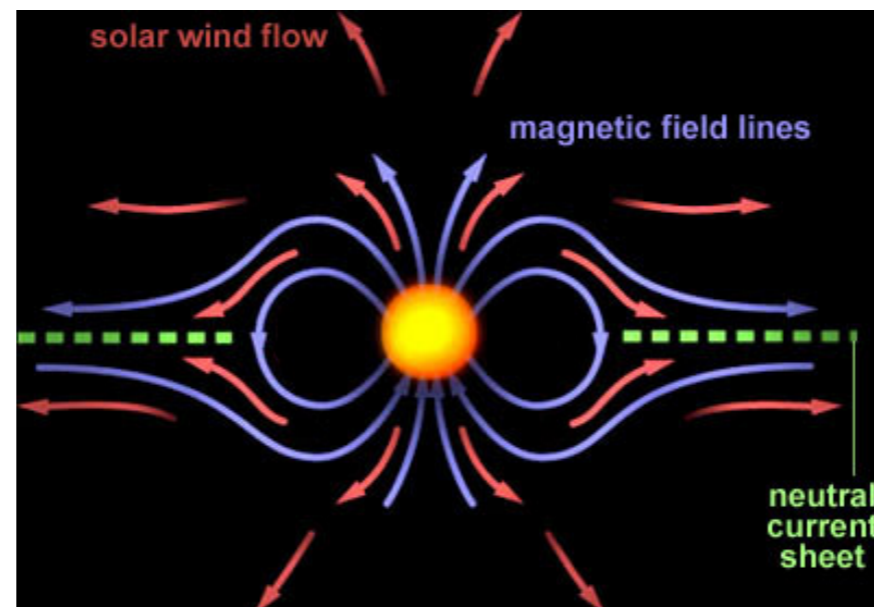
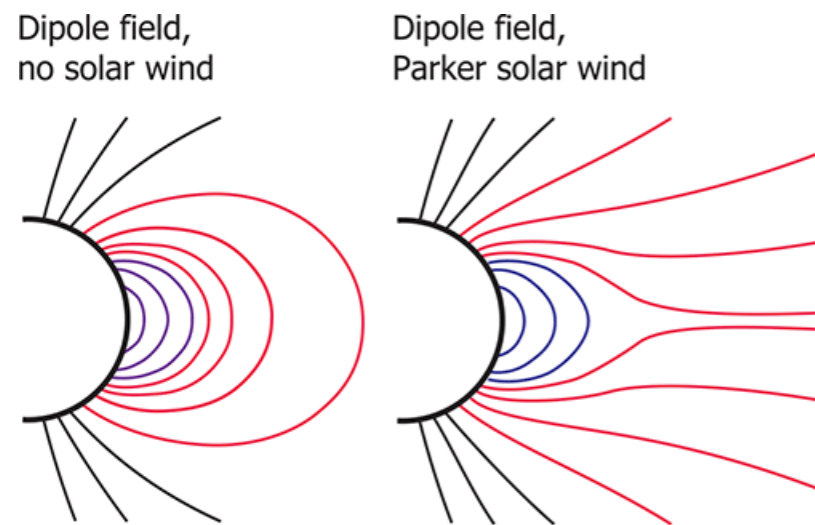


- Sunspots and average number observed since 1900 showing the solar cycle. Courtesy NOAA Space weather training page.

- The solar EIR image in the 3040 nm wavelength light (extreme UV) along the solar cycle. Courtesy ESA/NASA/SOHO)

# Solar wind and the interplanetary magnetic field

- The **solar wind** is a stream of **charged particles** (electrons, protons and helium nuclei) emitted by the solar corona with energies *between 0.5 and 10 keV*.
- The **magnetic field of the sun rotates**, and the **resulting spiral field lines** of the sun are transported by the solar wind particles.
- The sun and solar winds produce a **complex interplanetary magnetic field (IMF)** that reaches the orbits of the planets and **interacts with the terrestrial geomagnetic field**.

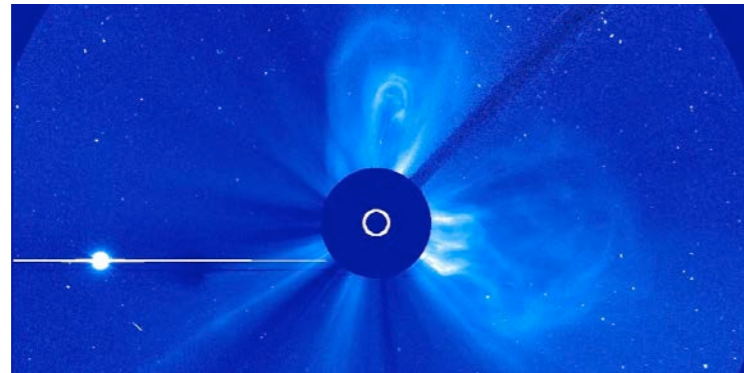


Magnetic field lines of a planet (left) and the dipole field of the sun together with the solar wind.

Graphic representation of the spiral field lines of the IMF.

# Solar plasmas

The sun ejects *huge amounts of charged particles in explosive events* called coronal mass ejections (CME) , solar flares, etc. These plasma flows move along the interplanetary magnetic field lines. Note, the images have false colors since a filter is used to block the radiation.



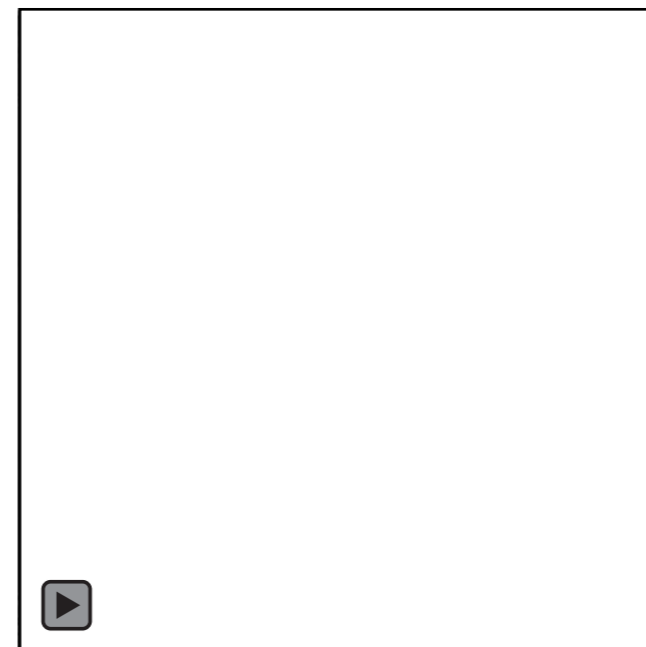
*Coronal mass ejection* on April 20, 2013. The bright spot on the left is planet Venus



These impressive images evidence the complex structure of the *sun chromosphere*.

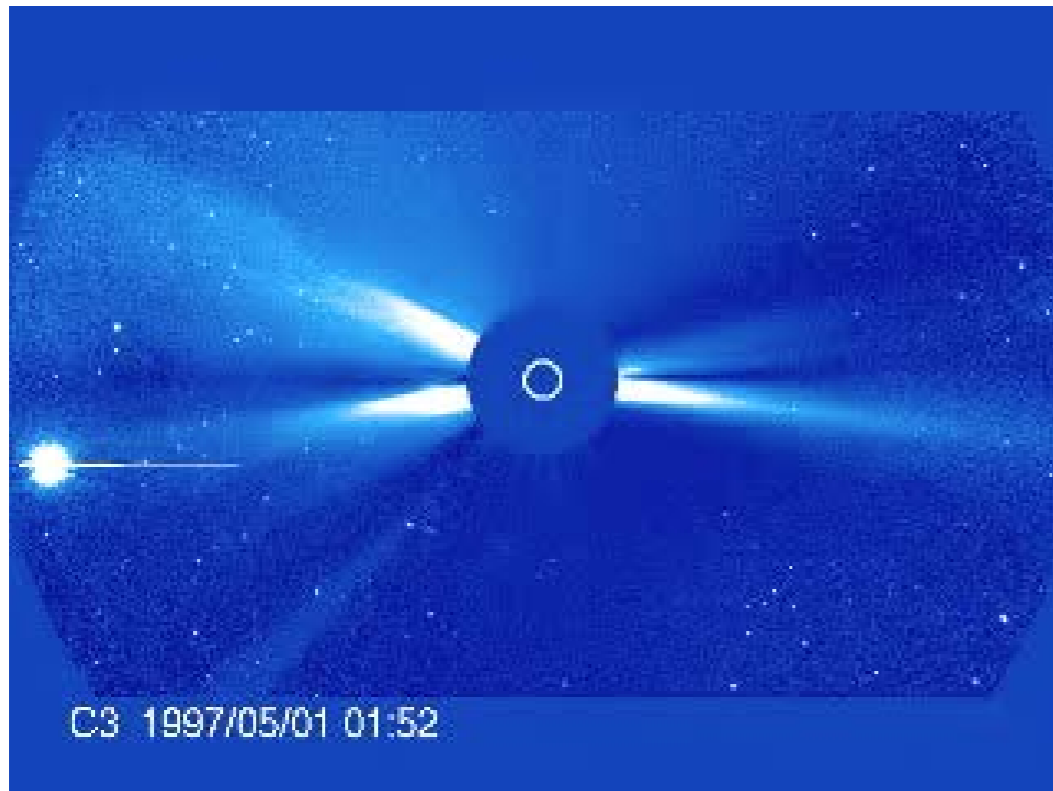


We can see a *solar flare* in action by courtesy of NASA, note the video time scale is not realistic



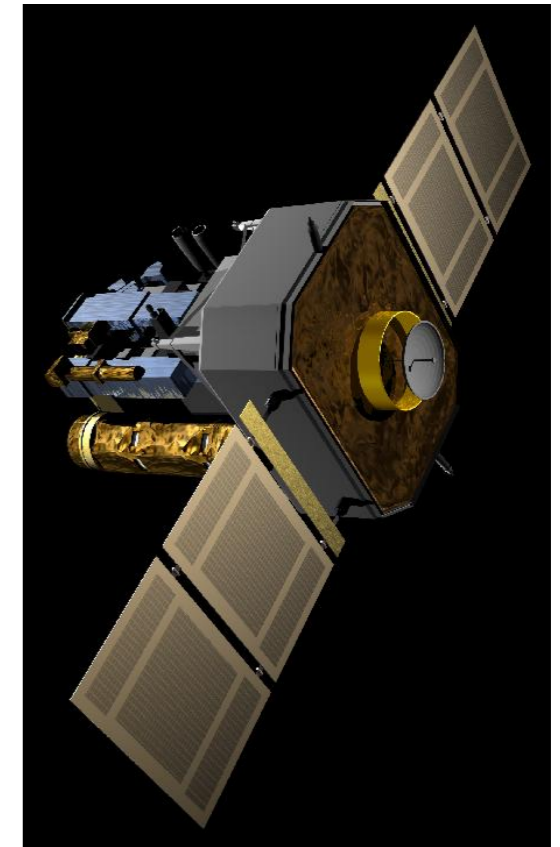
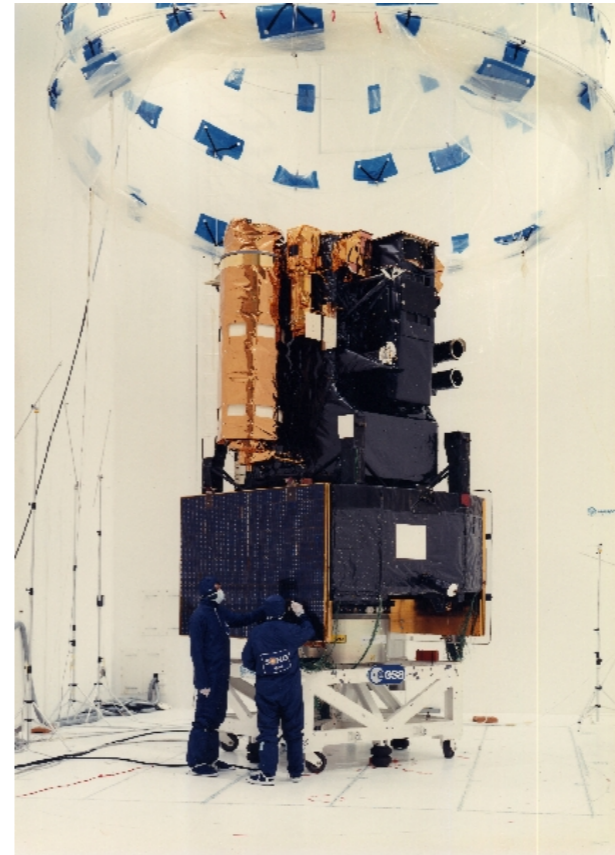
# The Solar and Heliospheric Observatory (SOHO)

- Solar flares seen by the large angle and spectrometric coronagraph (LASCO) instrument of SOHO.



Graphic material in this slide is courtesy of NASA and ESA

<https://soho.nascom.nasa.gov>



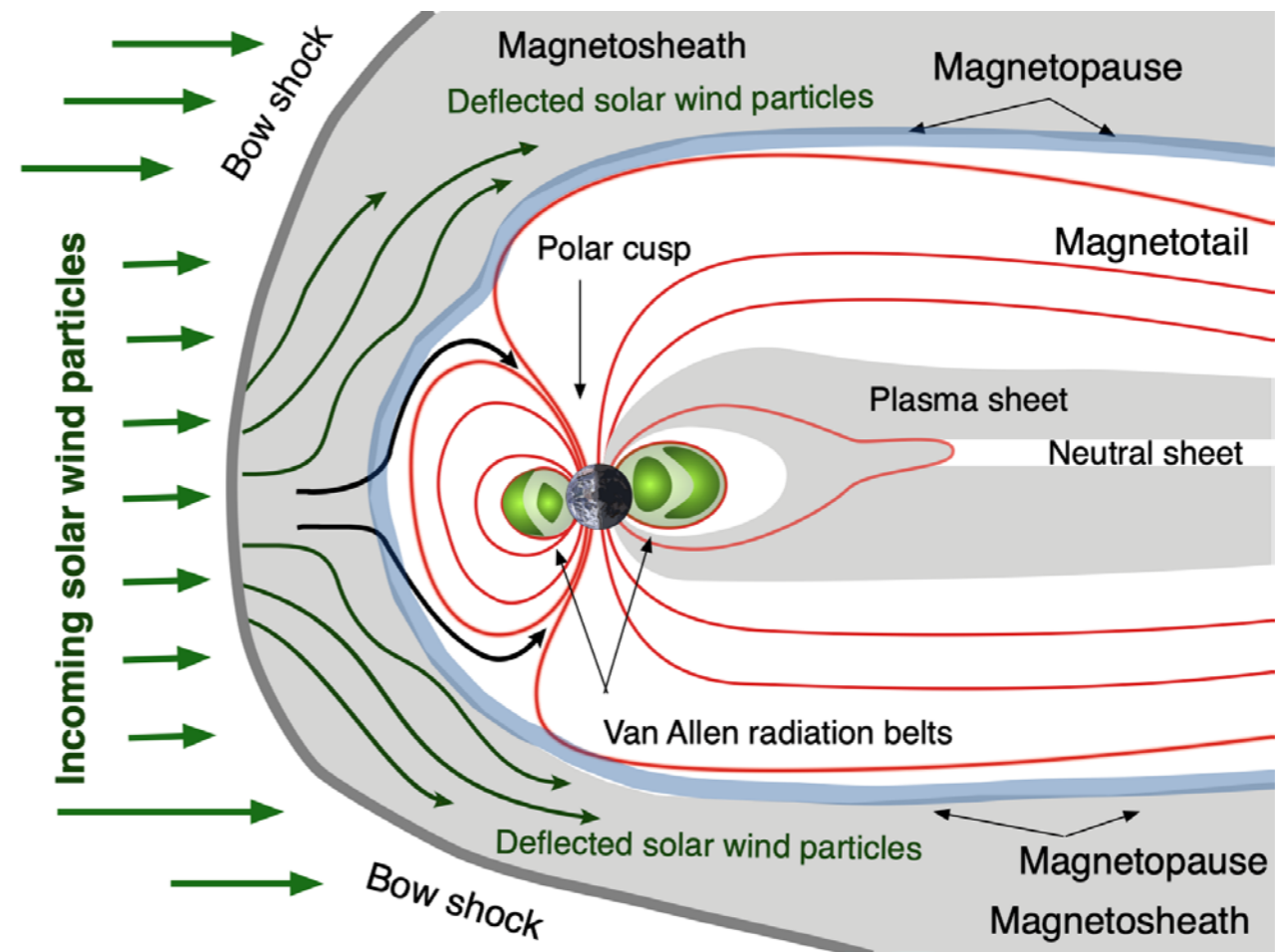
- SOHO satellite launched in 1995 was built in Europe by EADS Astrium and is an ESA/NASA cooperative project.
- It carries 12 scientific instruments on board.
- Moves around the sun slowly orbiting around the first Lagrangian point (L1, 1,5 Mkm), locked Earth-Sun line.

# The Earth-Sun connection, the magnetosphere

The electrons and ions transported along the interplanetary magnetic field of solar origin and interact with the Earth's geomagnetic field (a dipole  $11^\circ$  degrees inclined with respect to the planet axis). The solar wind is diverted by the field lines that are in turn affected by the flow of charged particles and the resulting complex structure is called *magnetosphere*



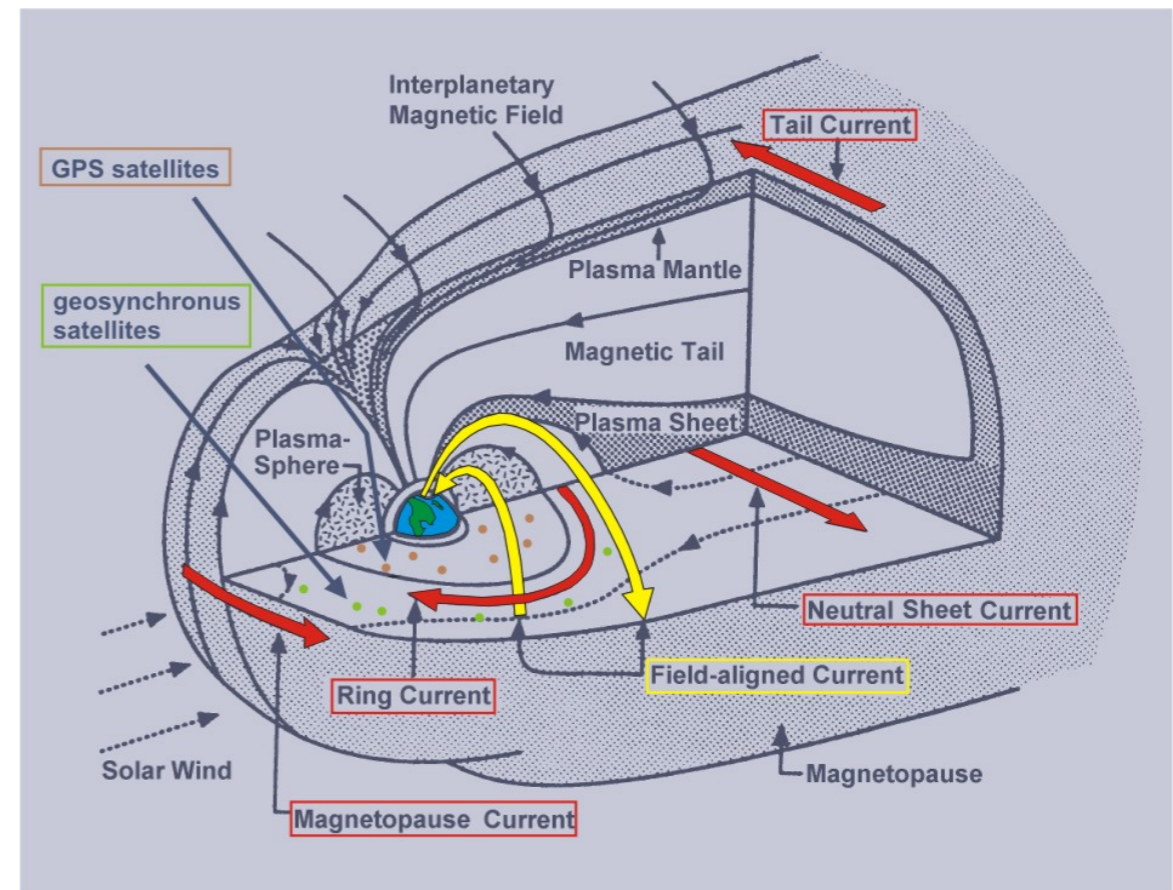
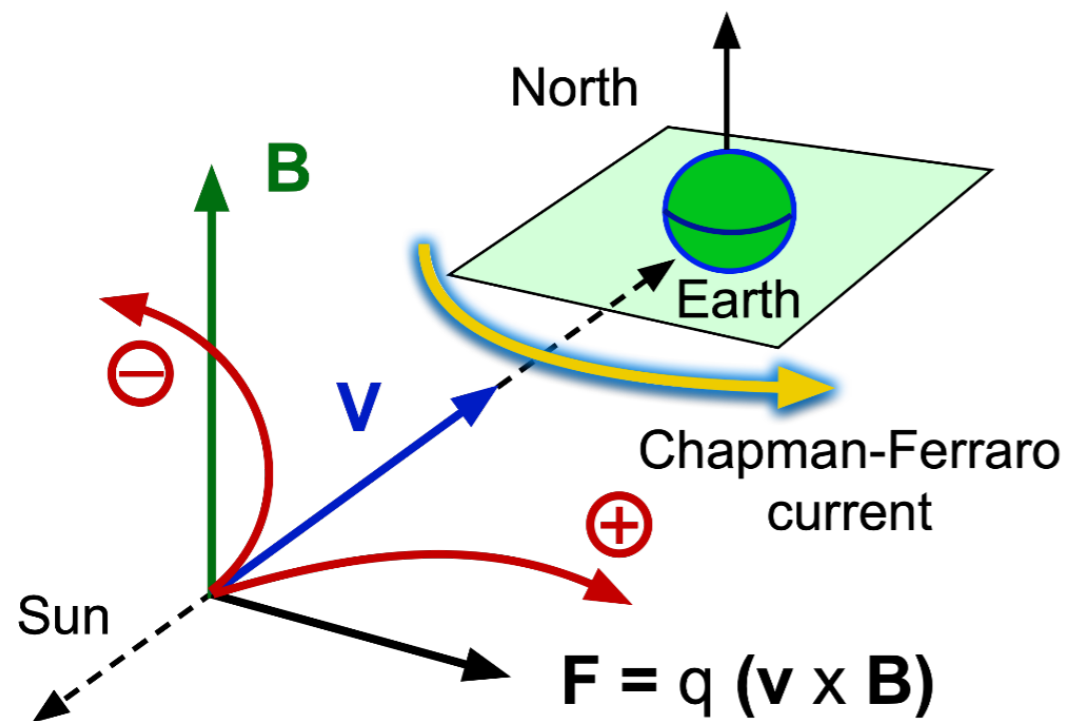
The aurora borealis seen from the ground (top) and from the space station (bottom).



Transversal cross section of the Earth's magnetosphere

# The Earth's magnetosphere

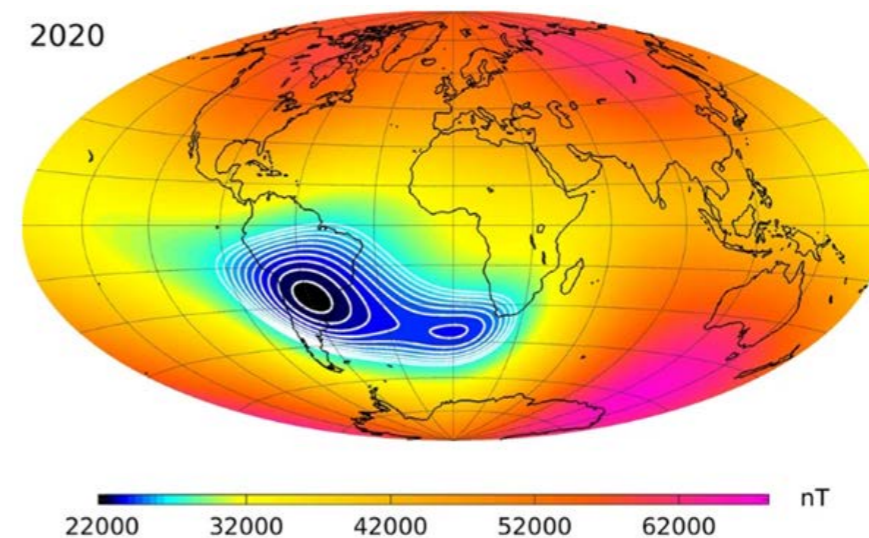
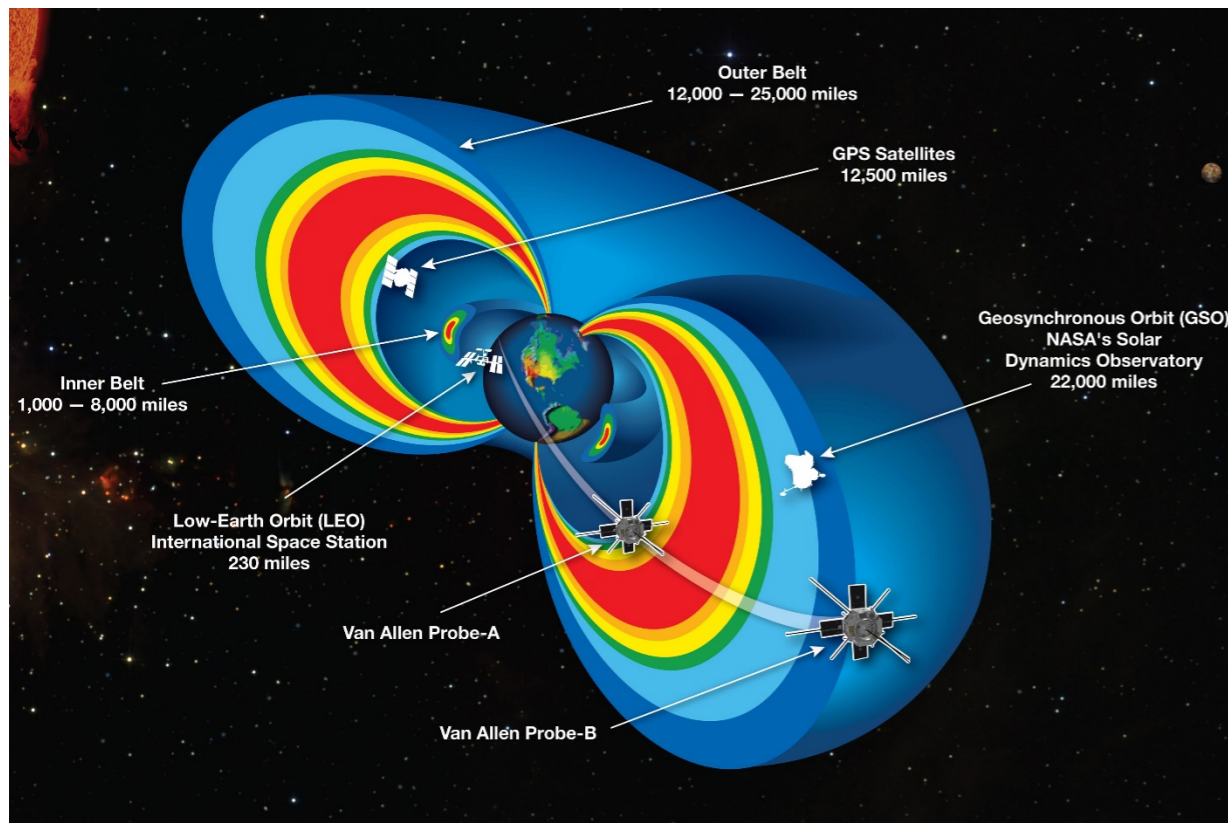
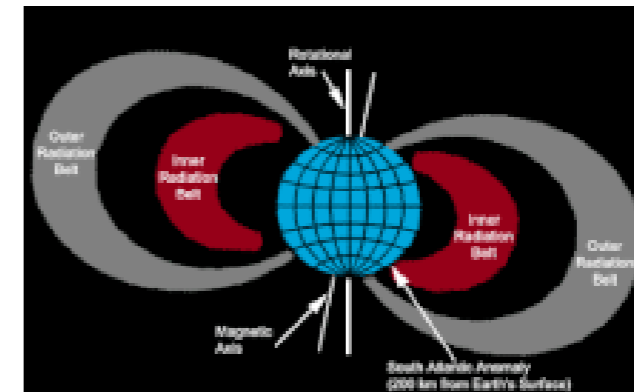
- The **magnetosphere around** the Earth is a **magnetic bubble** formed by the **interaction of the solar wind** (plasma of ions and electrons that moves at 450 km/s) **with the geomagnetic dipole field**.
- It includes both Van Allen belts, extends between **10-6.5  $R_E$  on the day side** to **900  $R_E$**  at night, and has a width of approximately 40-60  $R_E$ .
- The **outer magnetosphere** is the distorted part, and the region *where the terrestrial dipole field dominates is called the inner magnetosphere*. It includes the plasmasphere and the ionosphere, which rotate with the movement of the Earth.



From Kivelson and Russel. "Introduction to space physics". Cambridge University Press. (1995).

# Van Allen radiation belts

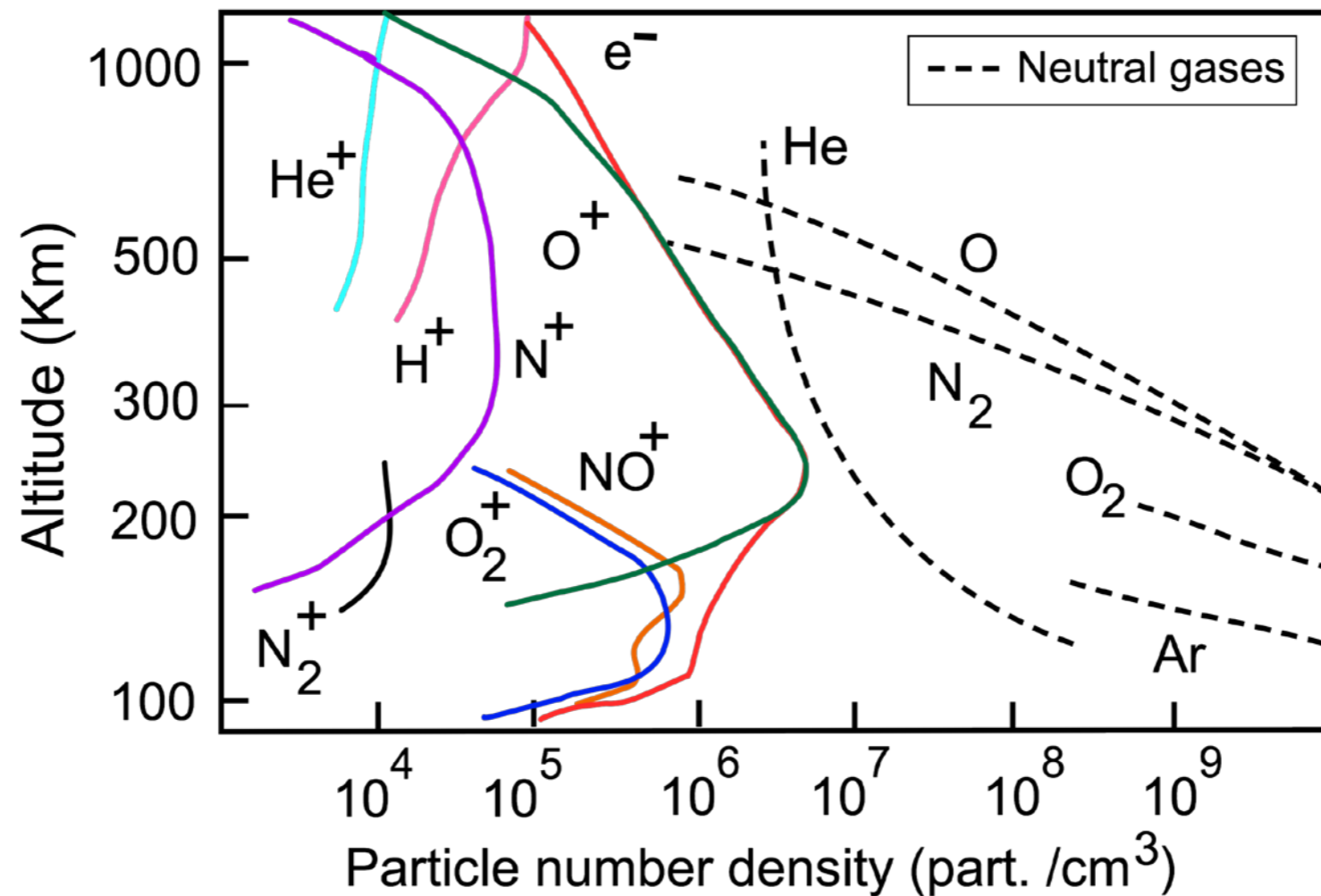
- The **two belts** overlap with the plasmasphere and contain trapped energetic particles. The external one is composed of ions and electrons, it extends between **13,400-58,000 km**. The innermost between **640-9,700 km** is separated from the more external by a particle-free zone.
- The **South Atlantic Anomaly** is the region where the innermost Van Allen Belt is the closest to the Earth's surface. The effect is caused by the non-concentricity of the Earth and its magnetic dipole.



Strength of Earth's magnetic field ( $10^{-9}$  T) from C.C. Finlay et al. *Earth, Planets and Space* **72**, 156 (2020).

# The Earth's ionospheric plasma

The dotted black curves are for neutral particles and the red line is the altitude dependent electron density. The complex physicochemical structure of the Earth's ionosphere is not the subject of the present talk.



# Space Weather

The physical properties of Earth's environment change with solar activity, as does its surface weather. The concept of **space weather** is closely connected with the environment to which satellites are subjected.

- Space weather is an emerging field within space science that **studies how the sun influences the Earth's environment and the social and technological impact of such interaction.**
- Special weather conditions **can affect or destroy Earth-orbiting satellites**, the health and safety of astronauts, and the reliability of satellite navigation and communications systems.

*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 and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite communications, navigation, and power electric distribution grids, leading to a variety of socioeconomic losses.*

US National Space Weather Program Strategic Plan, 1995

Office of the Federal coordinator for Meteorological Services and supporting Research.

FCM-P30-1995. Washington DC

Due to the relevance of space weather conditions for human activity, these are routinely monitored by governments, and the information is openly shared with the public:

- US National Weather Service: <https://www.swpc.noaa.gov>
- Agencia Estatal de Meteorología (Spain): <https://spaceweather.aemet.es/>