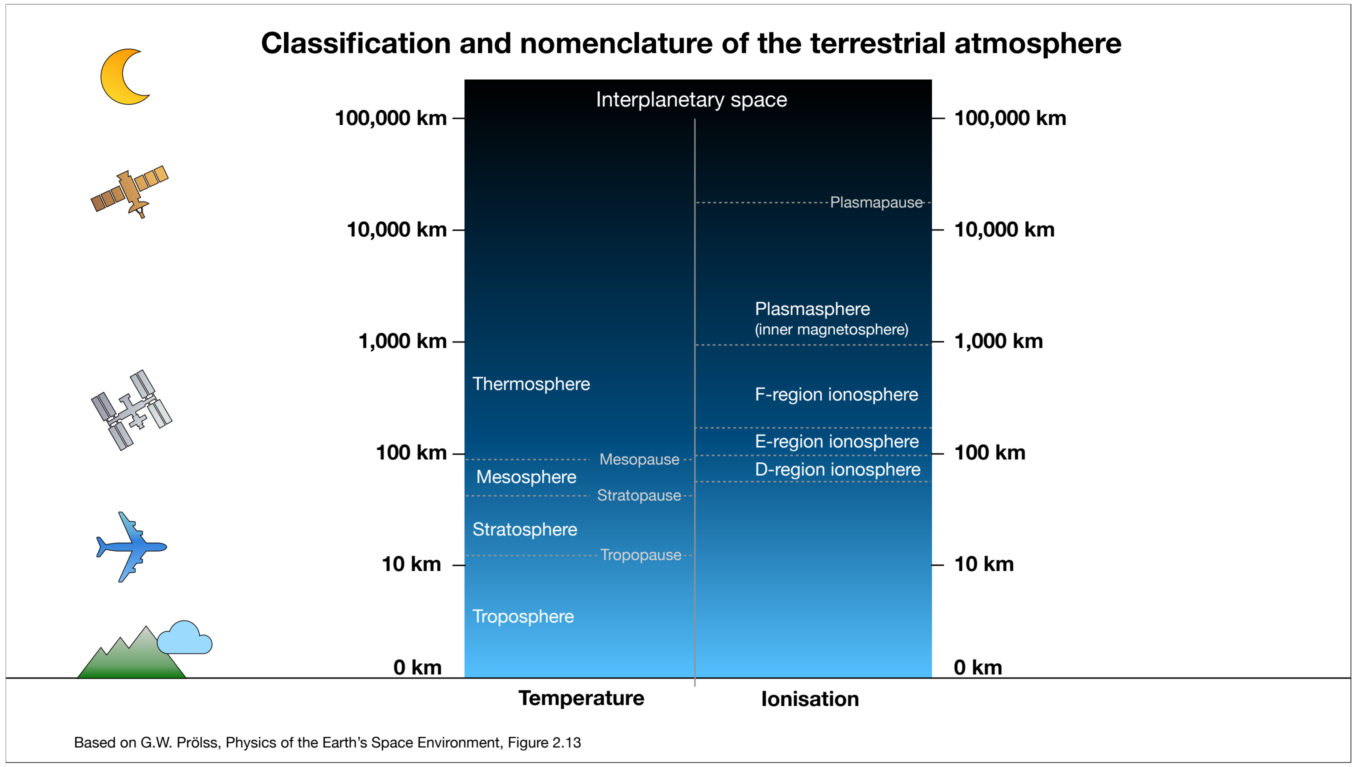
Earth’s neutral atmosphere: troposphere, stratosphere, mesosphere and thermosphere
Earth’s charged atmosphere: the ionosphere and plasmasphere
Magnetosphere



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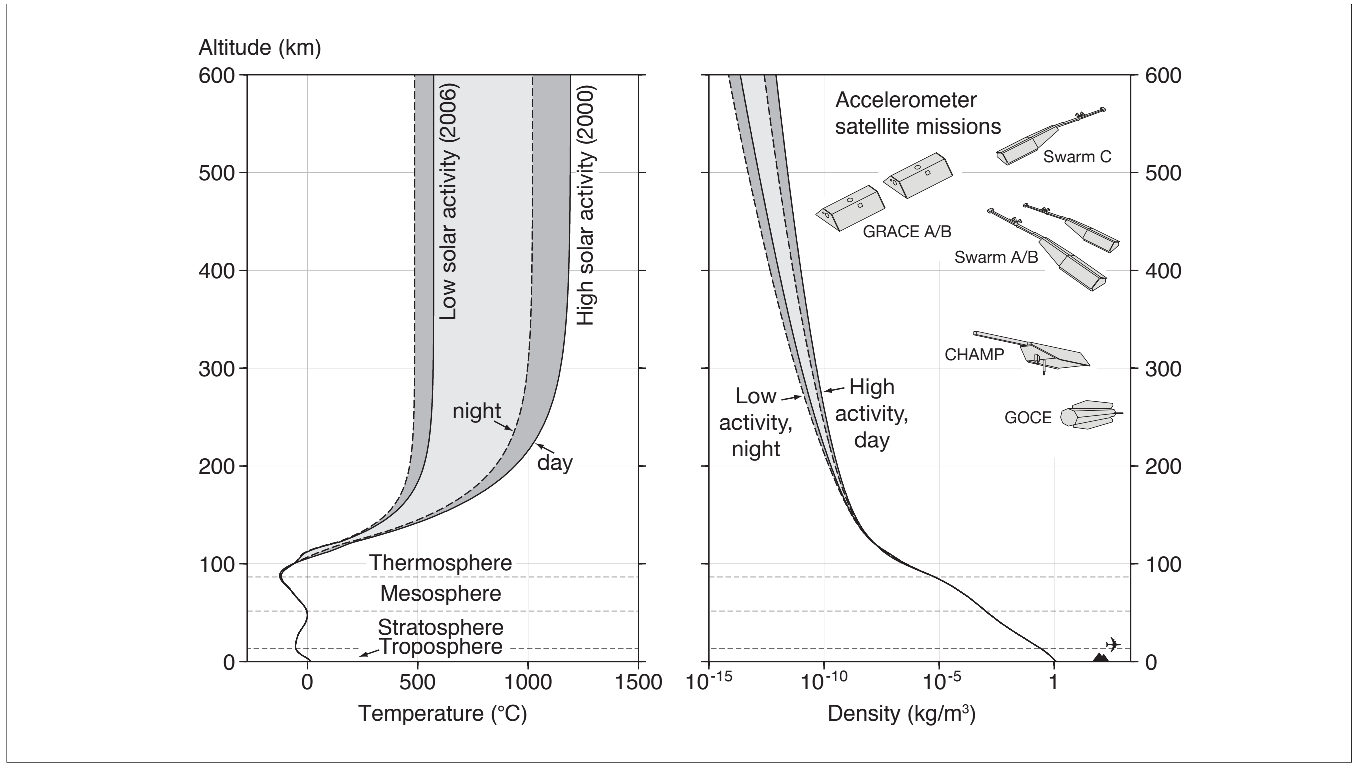


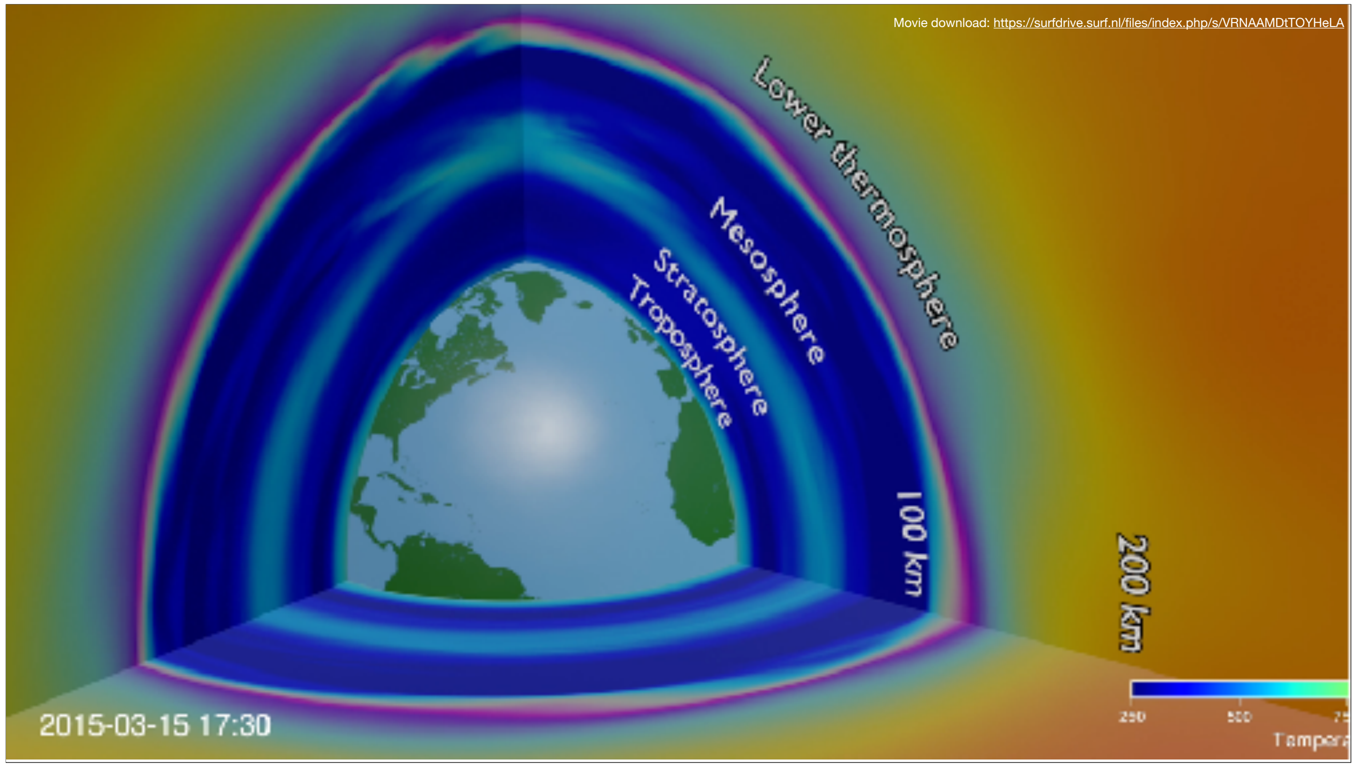
From Doornbos, Eelco & Foerster, Matthias & Fritsche, Bent & Helleputte, Tom & van den IJssel, Jose & Koppenwallner, Georg & Uhr, Hermann & Rees, D. & Visser, Pieter & Kern, Michael. (2023). Air Density Models Derived from Multi-Satellite Drag Observations.

It is in the higher layers that space weather becomes relevant and where you see the impact of the solar cycle.

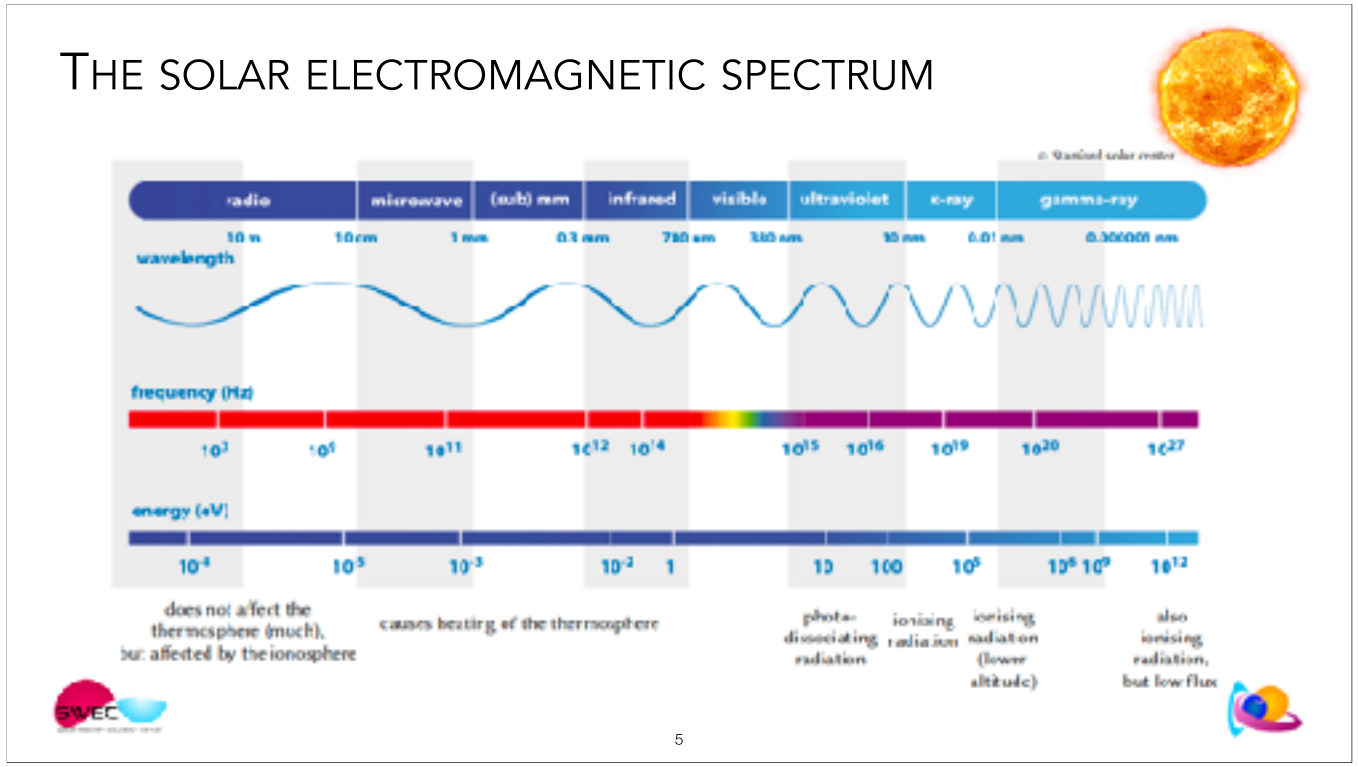
https://www.researchgate.net/publication/228814094_Air_Density_Models_Derived_from_Multi-Satellite_Drag_Observations/link/02e7e52e909d0f21d8000000/download

Graph showing how the temperature of the atmosphere changes with altitude. The different atmospheric layers (troposphere, stratosphere, mesosphere and thermosphere) are defined by alternating increases and decreases in temperature. The temperature reaches a maximum value in the thermosphere. The graph is based on the NRLMSISE-00 model.

Density profiles of Earth's atmosphere, from the NRLMSISE-00 model, shown together with the approximate orbital altitudes of current and future accelerometer-carrying satellite missions.
shows the approximate altitudes of these missions, in relation to density profiles for day and night and low and high solar activity conditions. Density variations of up to several orders of magnitude occur throughout the altitude ranges of these satellites as a function of the local time and solar activity cycle. **It can also be noted that satellites at higher altitudes will not only experience**
lower atmospheric densities, but will also experience greater density variability.



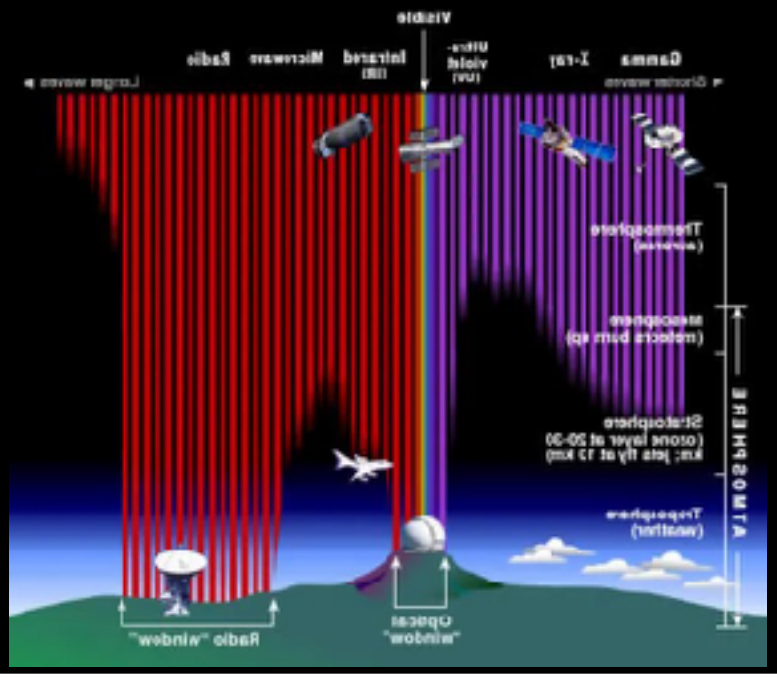
Higher up, you see daily variations in the temperature



The thermosphere contains mostly atomic gases (produced by photodissociation) rather than molecular ones (O2, N2, CO2,…). Most important are O, H, and He.

Different parts of the EM spectrum are relevant, for different reasons.
Note: besides EM-radiation, ionisation is also produced by high-energy particles (especially in polar region).

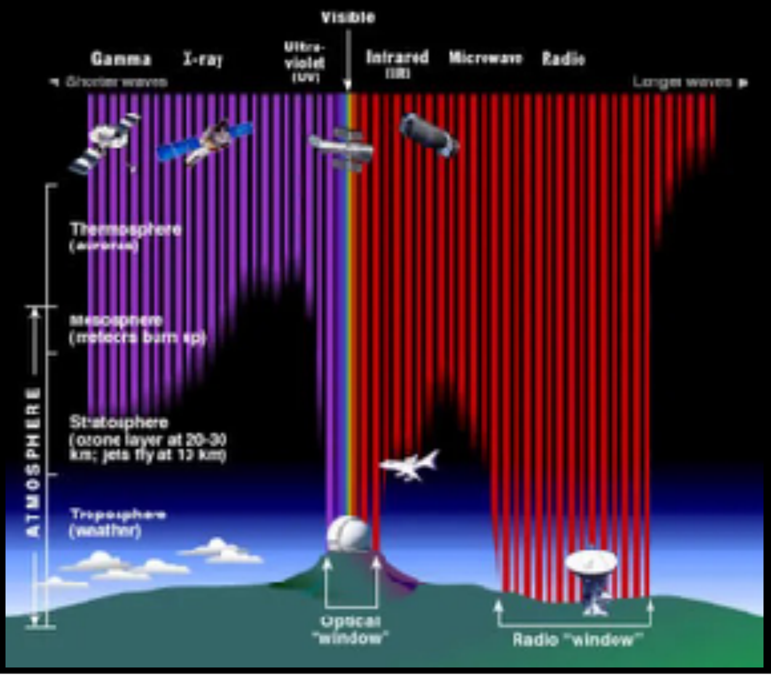
Electromagnetic radiation penetration depth



Different wavelengths penetrate the atmosphere to different altitudes.
For the ionising frequencies: higher energy means penetration to lower altitudes.

Thermosphere mostly composed of atomic O, produced by photodissociation.
Solar EUX and X-rays ionise part of the O, creating free electrons.
Once produced, O+ does not easily recombine into neutral O unless a catalyst is available.

Electromagnetic radiation penetration depth



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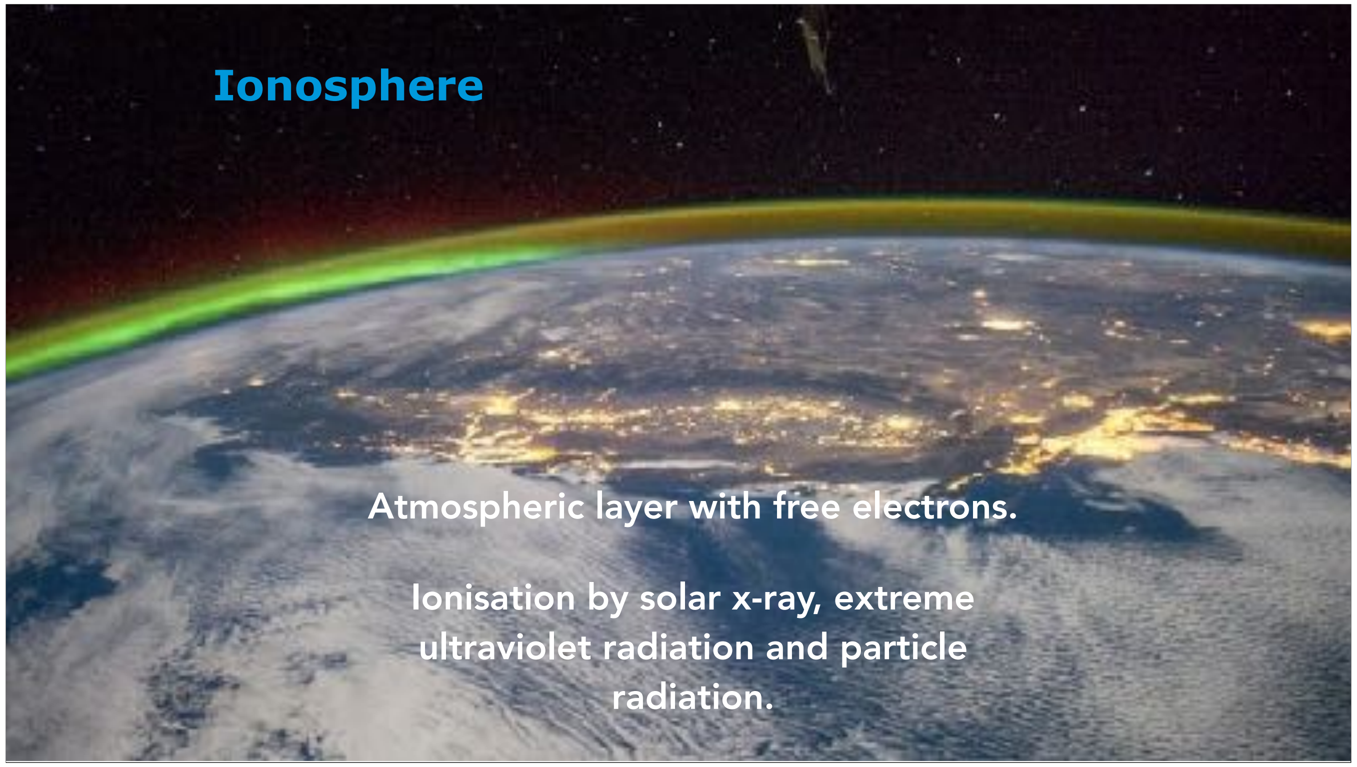


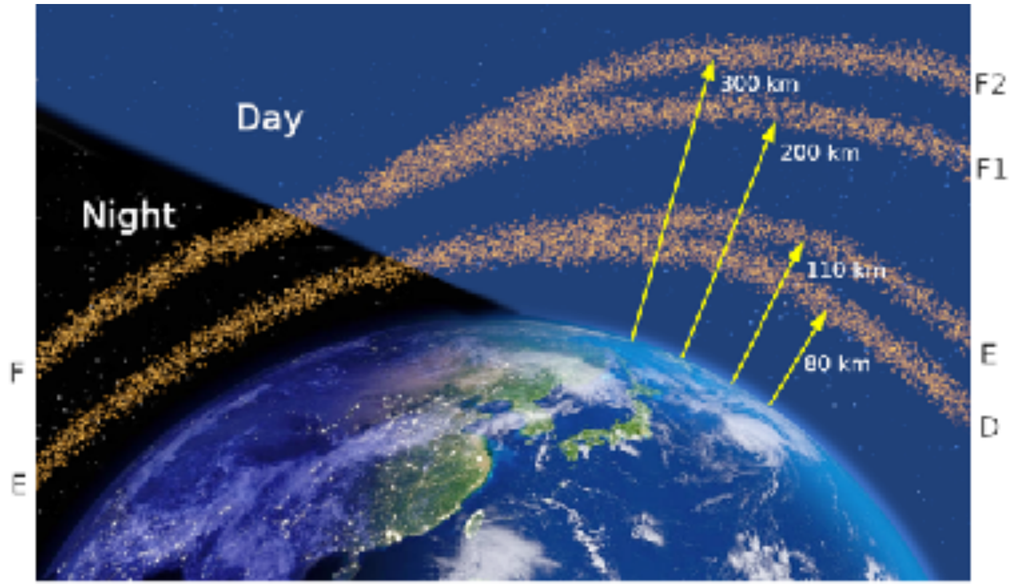
The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. ionospheric structures and peak densities in the ionosphere vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances.

The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases in the sunlit atmosphere and decreases on the shadowed side. Although the Sun is the largest contributor toward the ionization, cosmic rays make a small contribution. Any atmospheric disturbance affects the distribution of the ionization.

The ionosphere is a **dynamic system controlled by** many parameters including **acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field**. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric events.

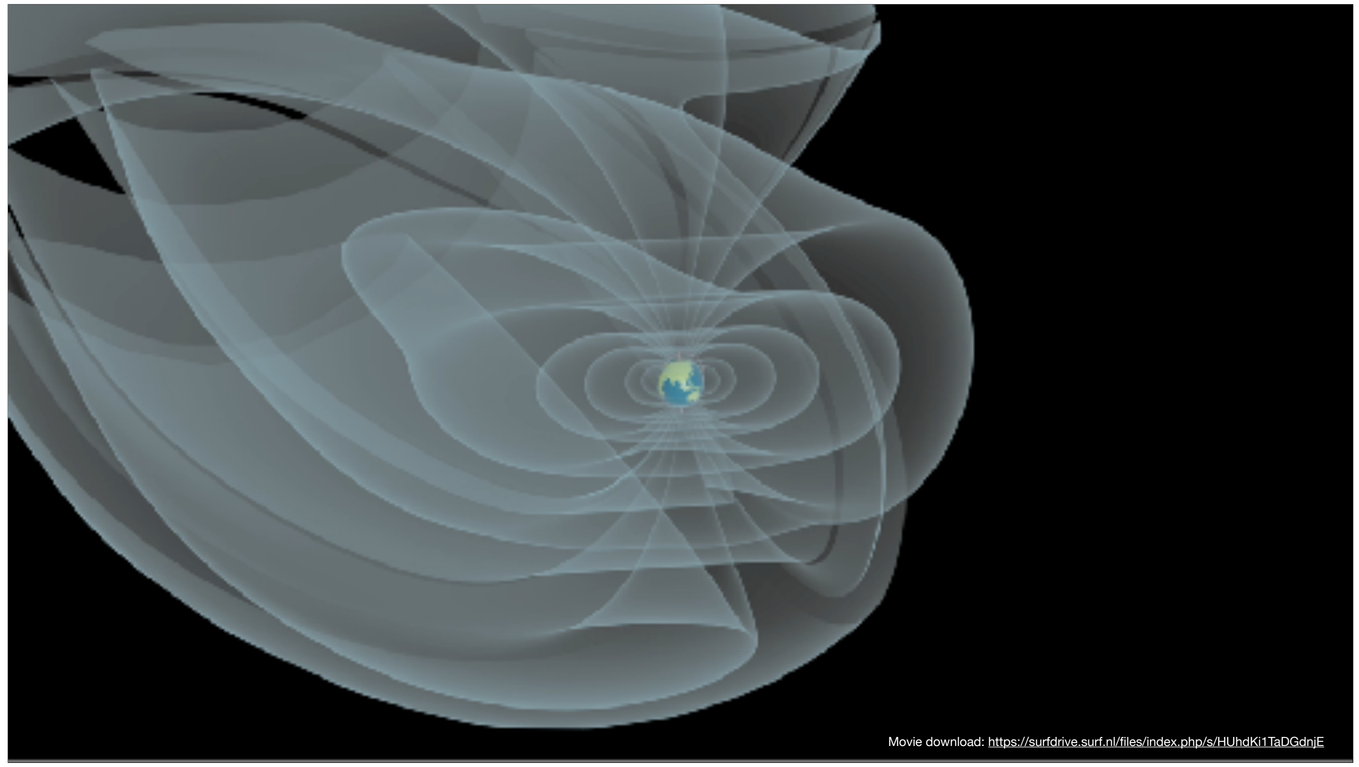
The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.

Ionosphere

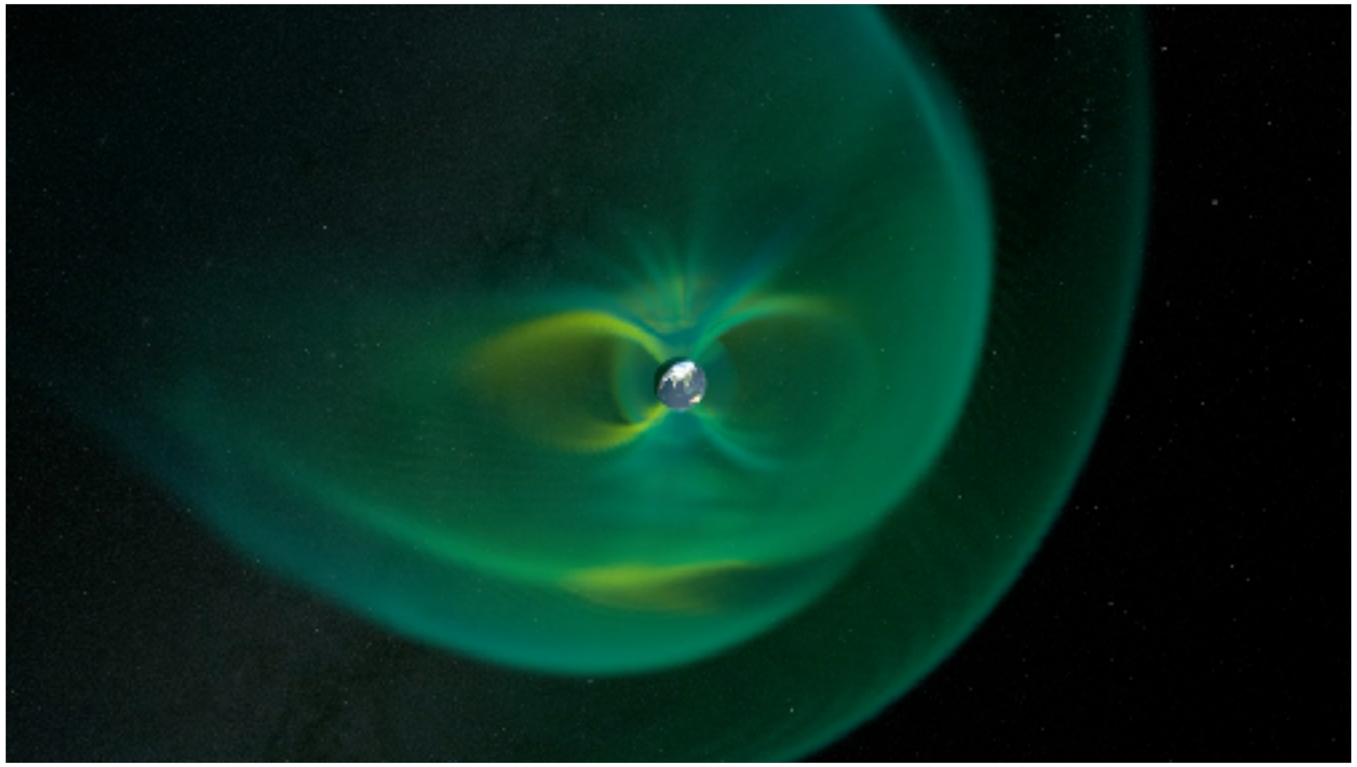


http://www.nerc-bas.ac.uk/public/uasd/magneto/ionosp/intro.html

The ionosphere is a relatively thin shell around the earth between about 70 and 1000 km above the earth's surface. It is the transition region between the dense, electrically neutral atmosphere below and the very thin, ionised plasmasphere and magnetosphere above. When the plasma up above is caused to move, magnetic field lines communicate this motion down to the ionosphere as if they were pieces of string tying the different plasma regions together. However, ions cannot move so easily in the ionosphere because they must wade through a sea of neutral particles which slow them down by frequent collisions. Yet the smaller electrons manage to dodge the neutral particles and move freely. As a result of the different electron and ion motions horizontal electrical currents flow in the ionosphere which cause magnetic perturbations on the ground. The motions can also help generate waves in the ionosphere that move with the electrons and can be detected by radars.
The ionosphere acts as both a help and hindrance to long distance radio communication. The ionosphere helps by reflecting high frequency (HF) radio waves around the globe. It hinders by slowing down and absorbing all radio waves. The effects are very small on very- and ultra-high frequency (VHF and UHF) radio waves, but they can be important where radio waves from satellites are used for precise global positioning. The effects can be more severe on HF radio waves. Sometimes the HF ionospheric mirror won't reflect at all or it will reflect waves in the wrong direction.



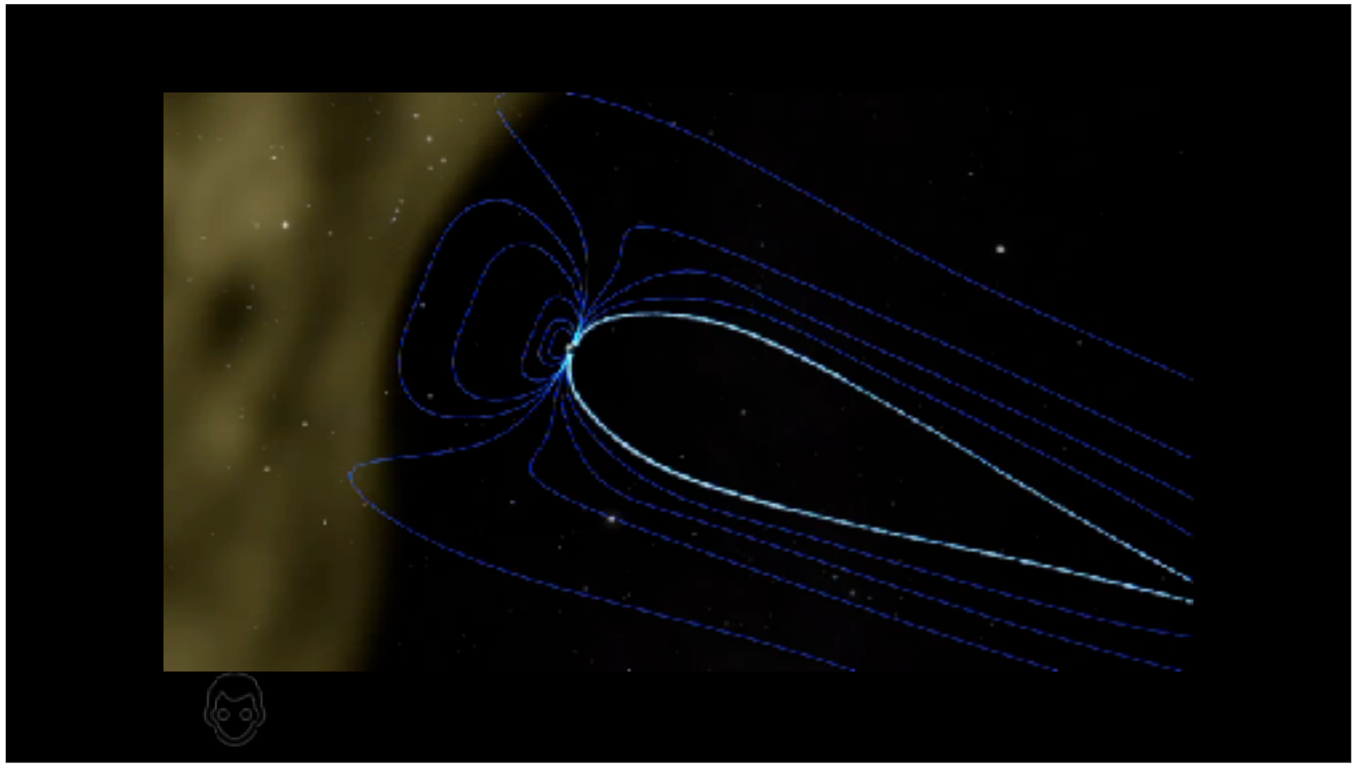
Donuts - radiation belts



The geomagnetic field

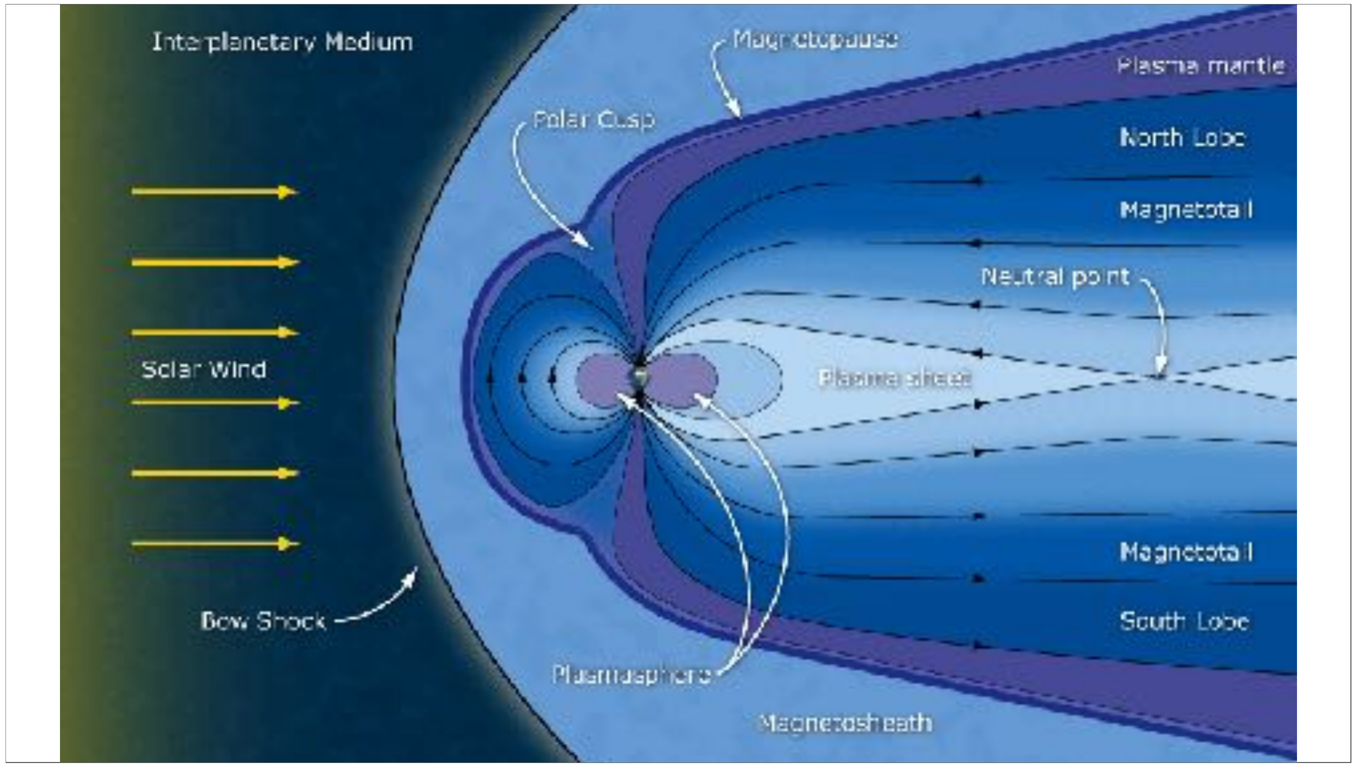
The Earth has an internal magnetic field. That field is produced in the Earth’s interior. It is changing slowly. (The magnetic poles move with a speed of about 10 km/year.)
It has this particular form due to the solar wind.

The magnetosphere is the region around Earth that is dominated by the geomagnetic field. The magnetospheric plasma originates in part in the ionosphere; the rest is captured solar wind material.



Solar wind

1 of the three space weather phenomena: light, plasmawind, energetic particles



The solar wind is a magnetized plasma. It encounters the environment of the Earth, which also turns out to be a magnetized plasma. Indeed, the Earth has an internal magnetic field. That field is produced in the Earth's interior. It is changing slowly. (The magnetic poles move with a speed of about 10 km/year.)

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Magnetosphere is a highly dynamical system
https://www.researchgate.net/figure/Structure-of-Earth-magnetosphere-with-magnetopotentials-in-blue-inner-radiation-belt-in_fig3_351130787
Structure of Earth magnetosphere with magnetopotentials in blue, inner radiation belt in green, and outer radiation belt in red.

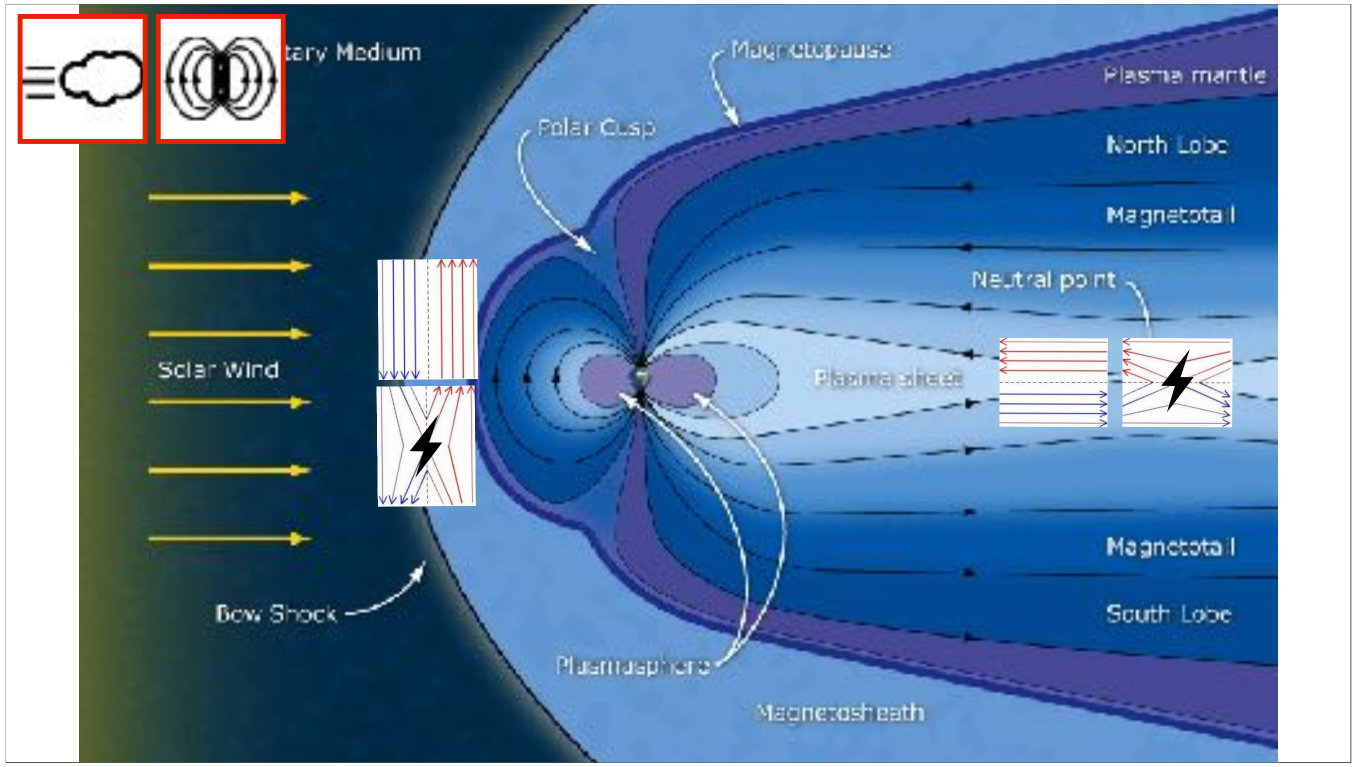
The magnetosphere consists of a (1) bow shock, where the solar wind (the stream of protons from the Sun) is slowed; (2) the magnetosheath behind the bow shock that contains thermalized solar plasma; (3) the magnetopause, where the thermalized solar plasma pressure is balanced by the plasma pressure generated by the magnetosphere; (4) the magnetotail, where the magnetic field is stretched out by the solar wind behind the dipole; and (5) the plasmasphere, where plasma is trapped by the magnetic field. The radiation belts are formed in the plasmasphere of the Earth's magnetosphere.

When the plasma up above is caused to move, magnetic field lines communicate this motion down to the ionosphere as if they were pieces of string tying the different plasma regions together.

Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an "image" in the ionosphere, and conversely. We identify the following regions:

- Magnetopause ↔ footpoints of the cusps
- Tail lobes ↔ polar caps
- Plasma sheet ↔ auroral oval
- Plasmasphere ↔ ionosphere at low latitude

During low magnetic activity, the plasmasphere overlaps with the Van Allen radiation belts



Magnetosphere - ionosphere coupling

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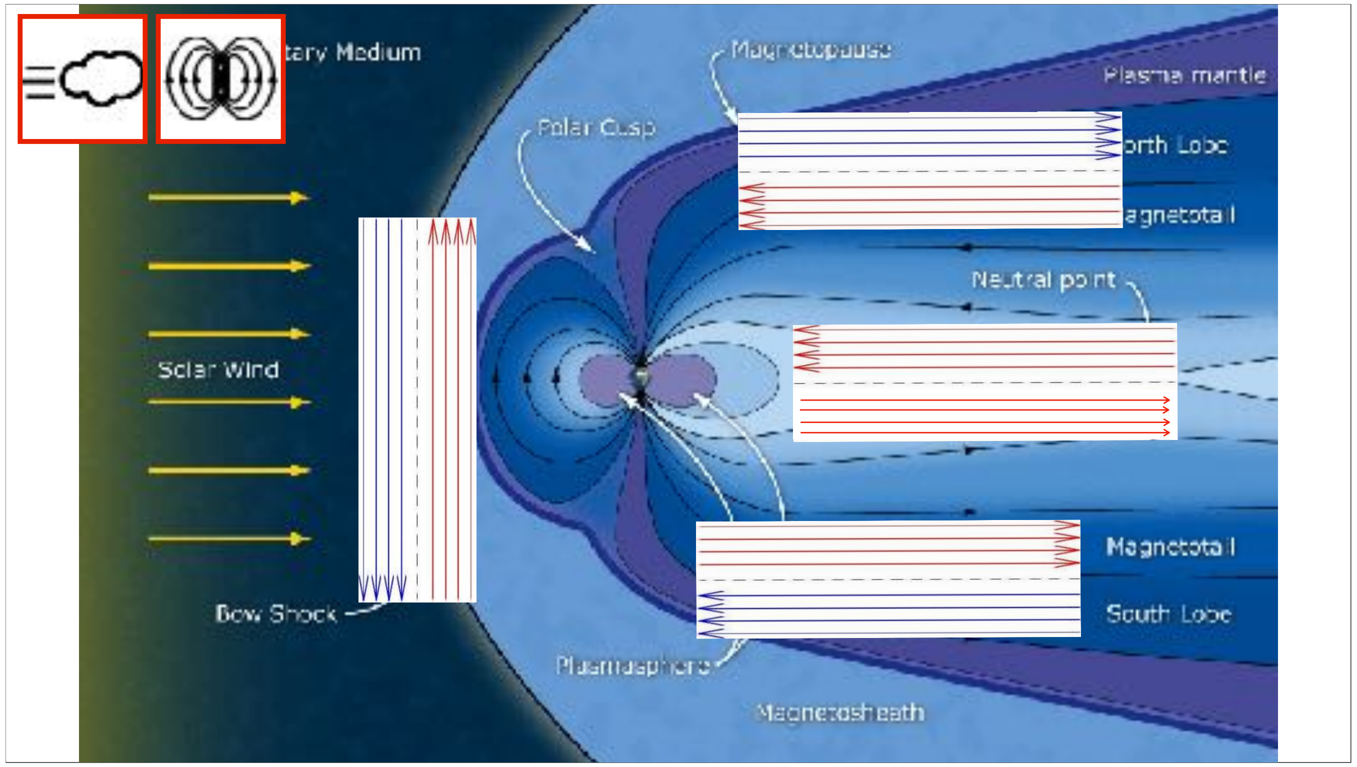

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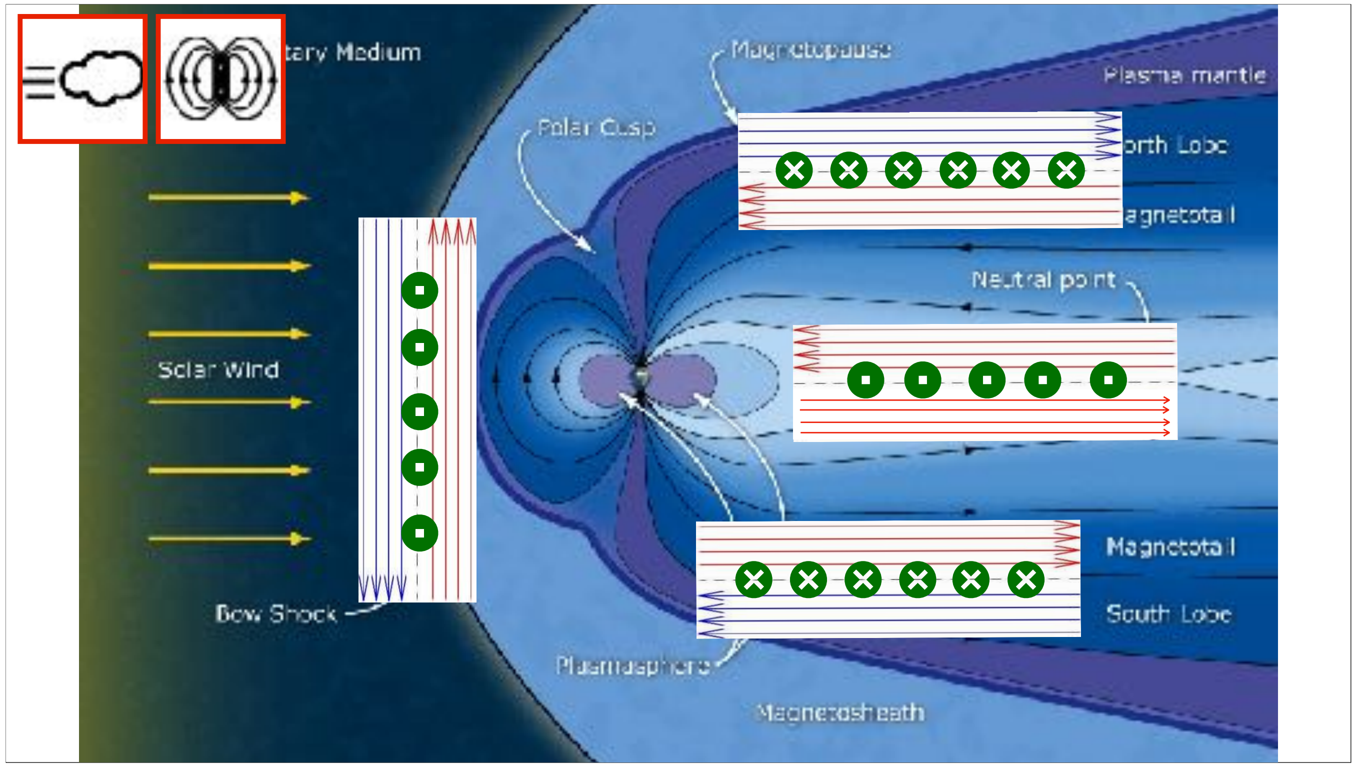

Tail current
Magnetopause current
Neutral sheet current

Magnetosphere - ionosphere coupling

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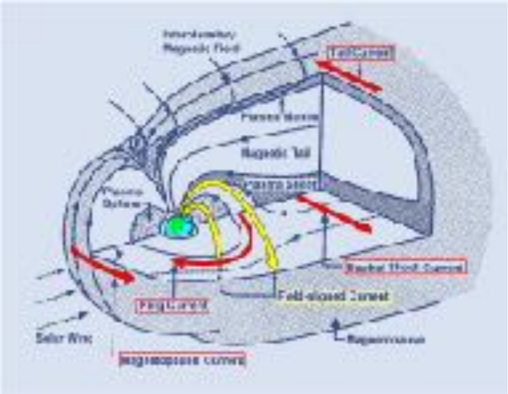
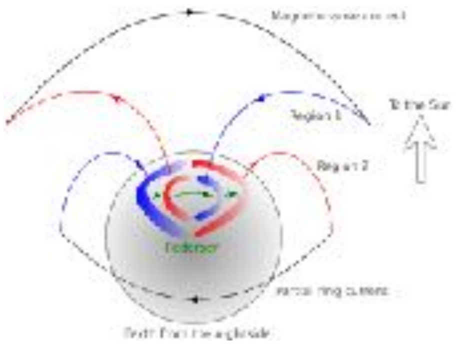
Currents





Magnetosphere-ionosphere coupling
Field aligned currents along the magnetic field lines, connect the magnetospheric currents with ionospheric currents. The Pedersen and Hall currents are two main currents in the lower ionosphere. They are localized in the ionospheric D and E regions.
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Current sheets in plasmas store energy by increasing the energy density of the magnetic field. Many plasma instabilities arise near strong current sheets, which are prone to collapse, causing magnetic reconnection and rapidly releasing the stored energy.

Between field lines there can always be changes in field strength or direction. Consequently, electric currents flow there:

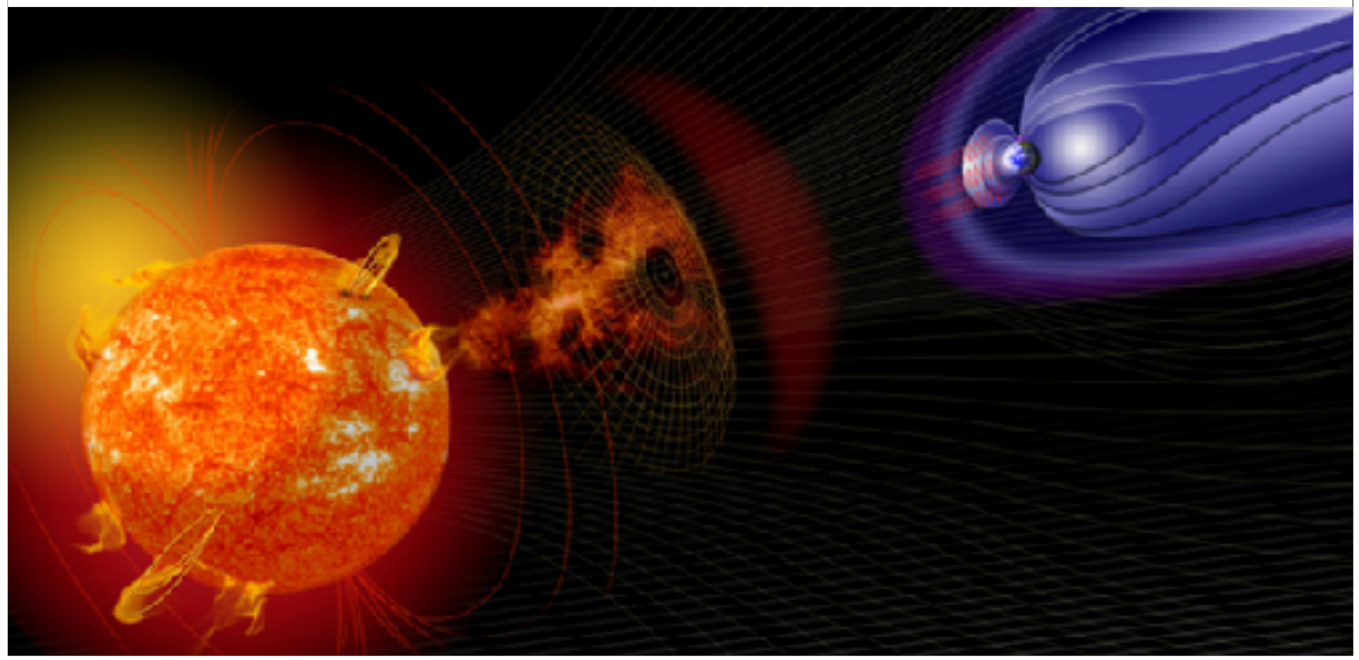
- Magnetopause current
- Neutral sheet current
- Ring current

The magnetopause interfaces two regions with different magnetic field. It therefore must be a current sheet : it carries the magnetopause current responsible for the change in magnetic field.
When solar wind comes close to the Earth, it cannot easily penetrate the Earth's internally generated magnetospheric magnetic field. The magnetopause, a surface boundary separating the two different regions, is formed. The kinetic pressure of the solar wind compresses the terrestrial magnetic field on the dayside, and this is associated with magnetopause current flowing across the magnetopause.

http://www.nerc-bas.ac.uk/public/uasd/instrums/magnet/mpausej.html
This current flows at a distance of more than 10 Earth radii (RE) from the Earth's surface and is the outermost boundary of the terrestrial environment. Here ionised particles flowing from the Sun - the solar wind - encounter the Earth's magnetic field and are deflected by it. Ions are deflected one way, electrons the other. As a result, a current flows. The current is such as to confine the Earth's magnetic field within the current sheet boundary in a region known as the magnetosphere. The magnetospheric magnetic field inside the boundary exerts a pressure on the boundary which must be in balance with that exerted by the solar wind plasma outside. This requirement determines the equilibrium shape of the boundary - roughly an ellipsoidal shell within about 30 RE of the Earth. The magnetopause surface is shown in the figure. Also shown are the current streamlines within it.

Neem het voorbeeld van de ring current met kruisjes en puntjes

Space Weather - When solar energy meets the Earth’s spheres.



As we go out into space, the atmosphere becomes very thin, until by the time we are in space, it has almost vanished. Almost, but not quite. Even in space there are some atoms which are often moving very quickly. Many forms of energy also move through **space** and it is the **interaction of energy and atoms that produces what we refer to as space weather**. In particular, space weather is the changes that occur in the space environment.

The **sun** is the source of 'normal' terrestrial weather. It is also the **primary (but not the only) source of space weather**. Most aspects of space weather affect us to some extent. The more our society becomes dependent on technology and the more we utilize space, the more we are affected by space weather. Some aspects of space weather are benevolent, and allow activities not otherwise possible such as long range radio communications. Some aspects are benign but fascinating such as the Aurora, and some are malevolent. **Like terrestrial weather, it depends on the situation and the event.**