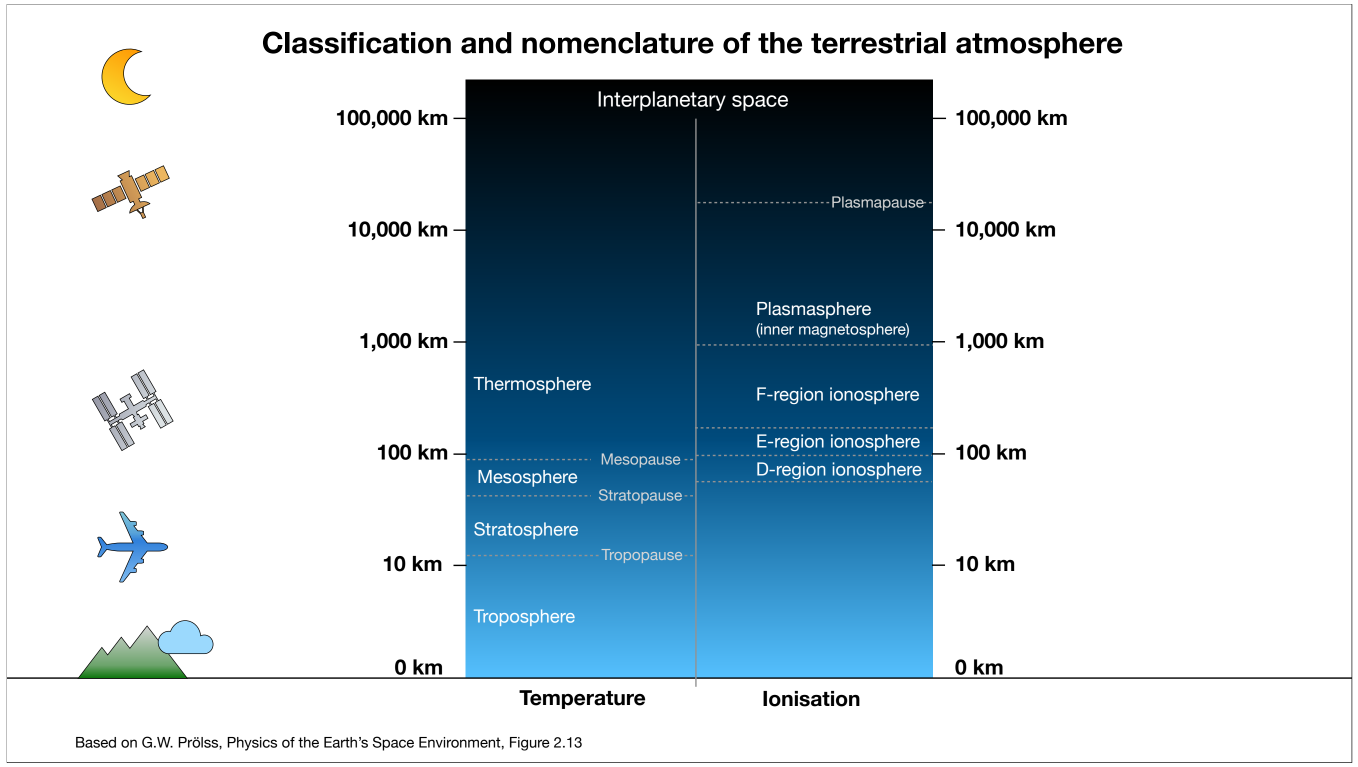
The top atmospheric region with free electrons

Tobias and Jean-Marie
Expertise in Ionosphere and GNSS



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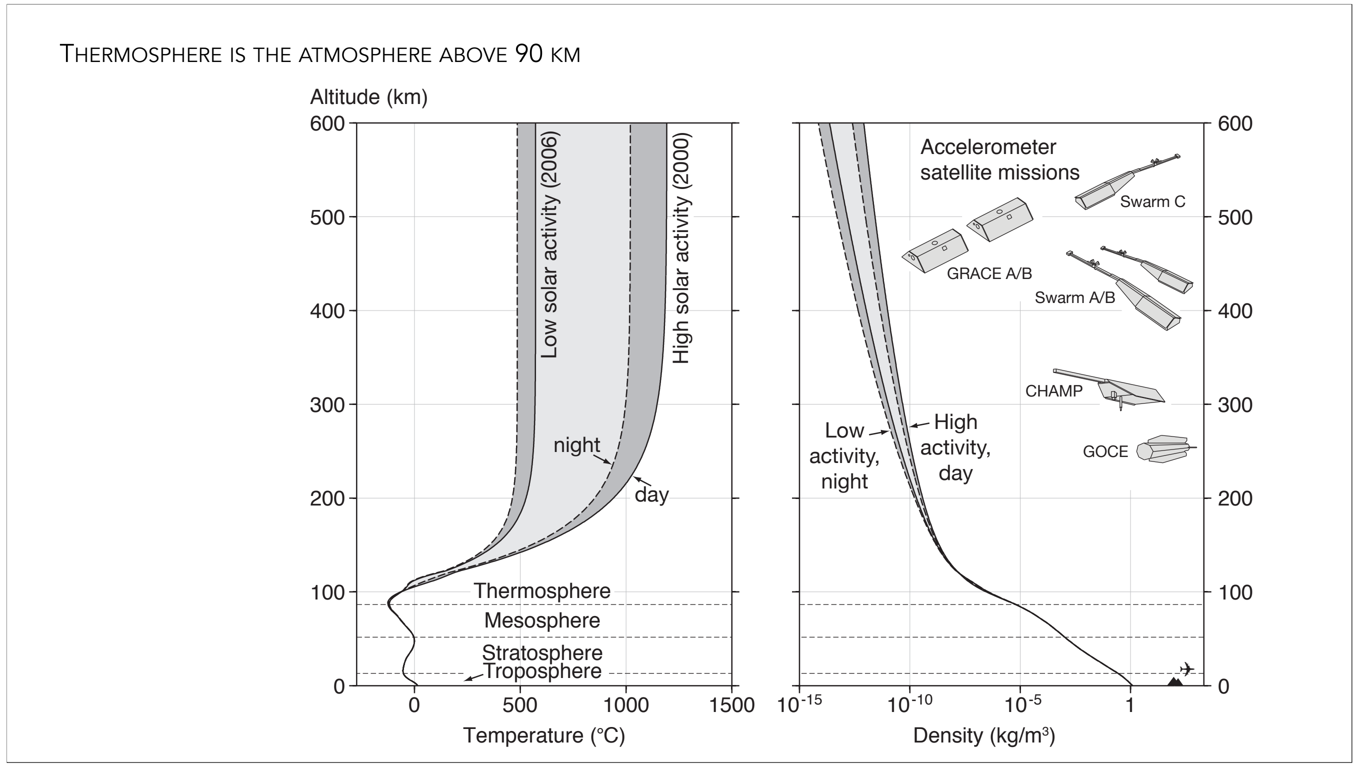


temperature, density, composition all change with varying irradiation

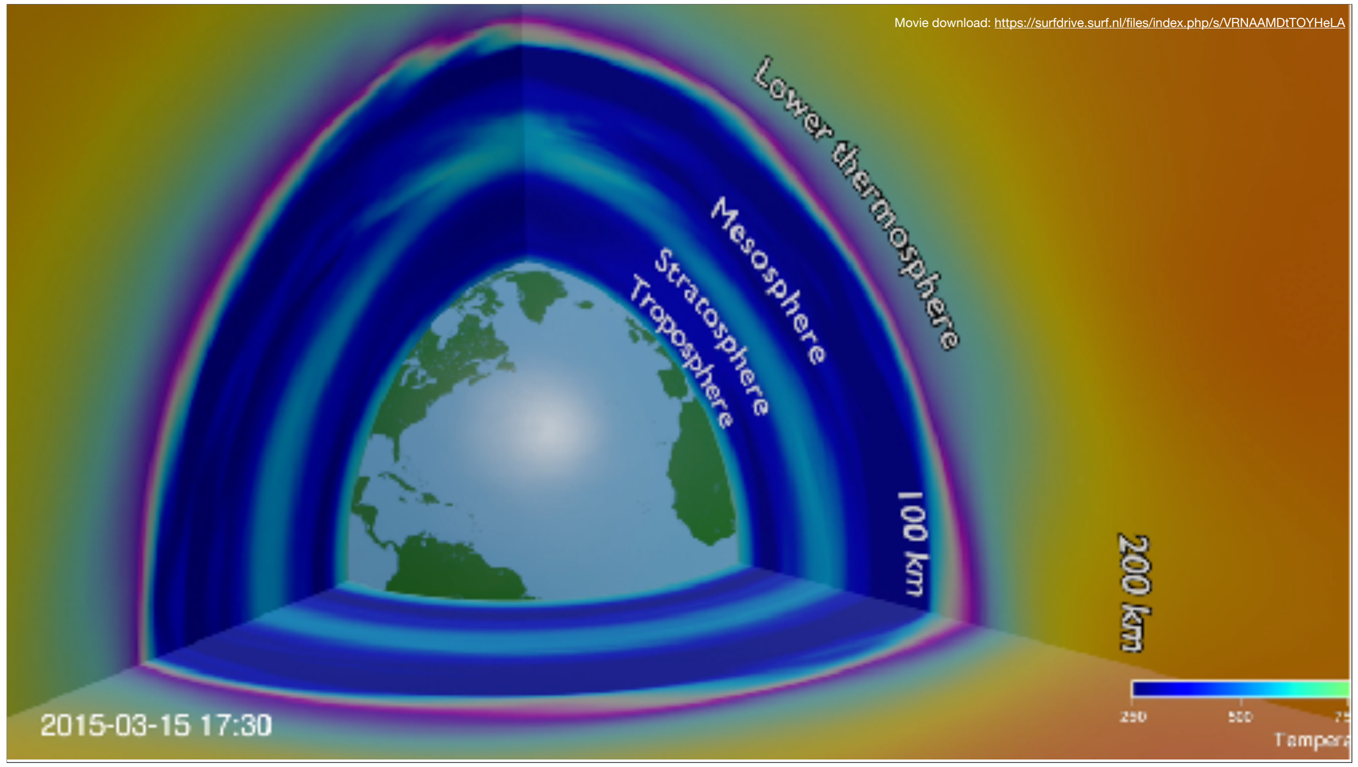
From Doornbos, Eelco & Foerster, Matthias & Fritsche, Bent & Helleputte, Tom & van den IJssel, Jose & Koppenwallner, Georg & Uhr, Hermann & Rees, D. & Visser, Pieter & Kern, Michael. (2023). Air Density Models Derived from Multi-Satellite Drag Observations.

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

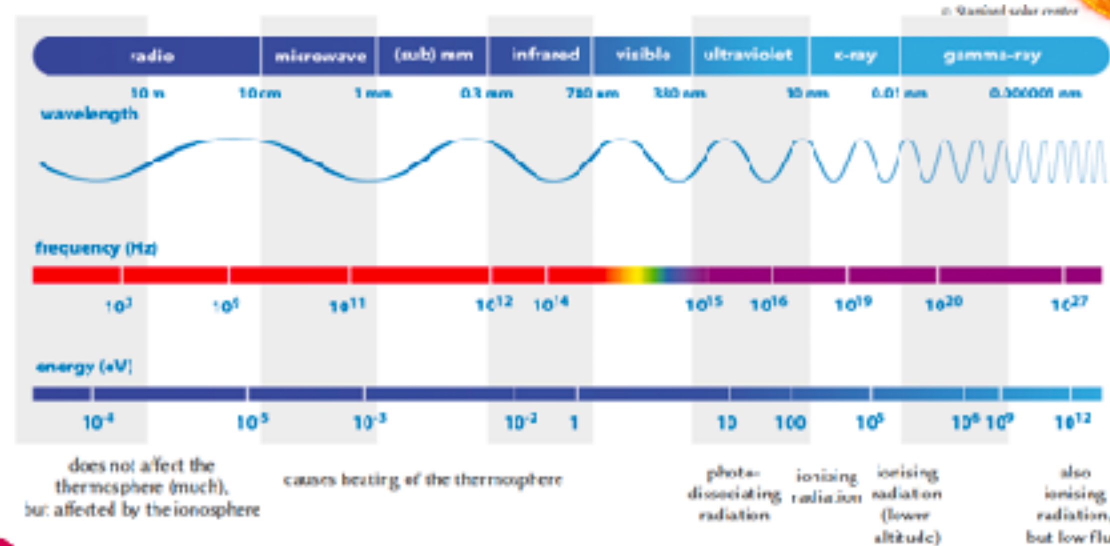
Graph showing how the temperature of the atmosphere changes with altitude. The different atmospheric layers (troposphere, stratosphere, mesosphere and thermosphere) are defined by alternating increases and decreases in temperature. The temperature reaches a maximum value in the thermosphere. The graph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



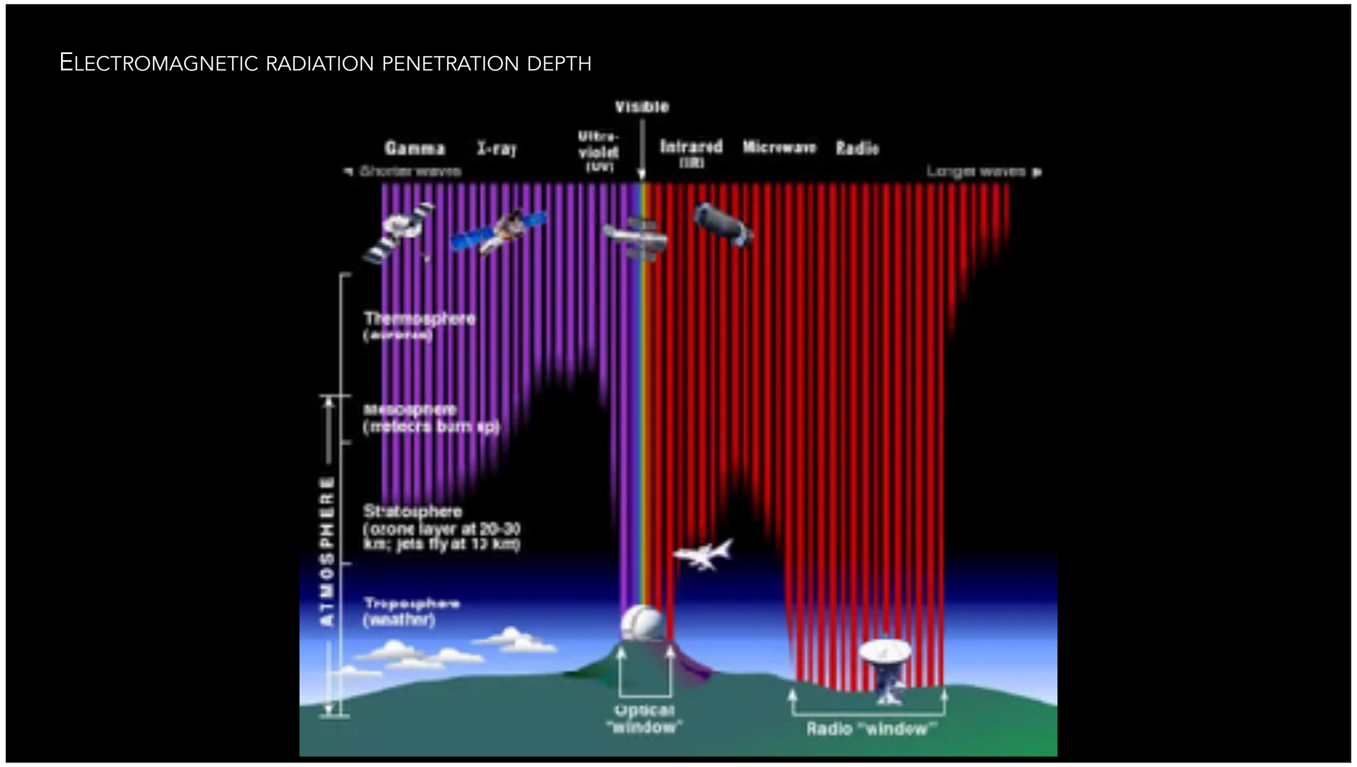
Higher up, you see daily variations in the temperature

THE SOLAR ELECTROMAGNETIC SPECTRUM



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).



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.

Ionisation and recombination in the thermosphere

$$O + \hbar\nu \xrightarrow{\text{Very fast}} O^+ + e^-$$

$$O + \hbar\nu \xleftarrow[\text{Very slow}]{} O^+ + e^-$$

Instead, recombination goes like this (for example)

$$O^+ + N_2 + e^- \longrightarrow NO^+ + N + e^- \longrightarrow NO + N + \text{dissipated energy}$$

- 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.

Ionisation of O is not easily (directly) reversible:
Above: very fast
Second: very slow

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

Consequences:
1 Other ions are usually produced from O+ rather than direct ionisation,
e.g.: (O+) + N2 —> (NO+) + N.
2 Recombination is most effective when catalysed by neutral gas.
The latter point explains a lot of the features of the ionosphere.

Regions in the ionosphere

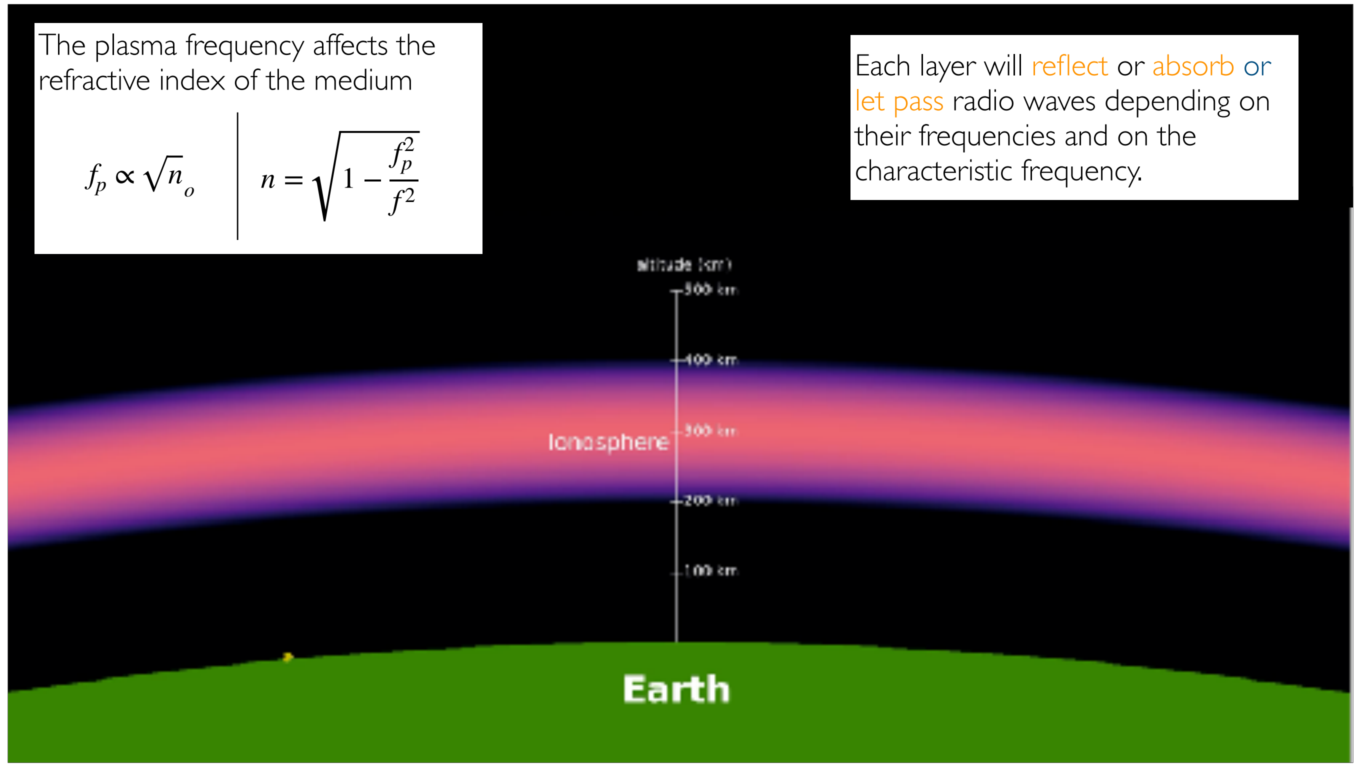
The electron density and the plasma frequency are related

Oscillation of free electrons in the plasma depends on the electron density

Plasma frequency

$$f_p \propto \sqrt{n_o}$$

The plasma frequency is the resonant frequency of the electrons in an ionized medium.
There is a direct relation between the electron density and the plasma frequency, which can be approximated as f ≈ 8.9 Ne^1/2.



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Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium

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n0, electron content —> critical frequency f0F2 or fp or characteristic frequency—> refractive index
n=c/v
v=c —> n=1
V<c —> n>1

A qualitative understanding of how an electromagnetic wave propagates through the ionosphere can be obtained by recalling geometric optics. **Since the ionosphere is a plasma, it can be shown that the refractive index is less than unity.** Hence, the electromagnetic "ray" is bent away from the normal rather than toward the normal as would be indicated when the refractive index is greater than unity. It can also be shown that the refractive index of a plasma, and hence the ionosphere, is frequency-dependent, see Dispersion (optics).[24]

In physics, refraction is the change in direction of a wave passing from one medium to another or from a gradual change in the medium.

f>fp—> passes through ionosphere
f< fp —> reflected by ionosphere —

The ionosphere is the key-layer for HF communication and GNSS performance: or radio waves are reflected at, or pass through the ionosphere. The reflection is used for long distance communications.

The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

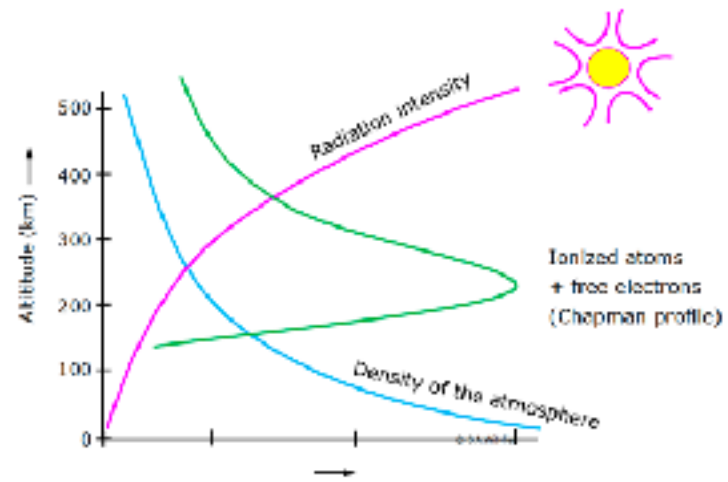
Reflection - binary: or it is being reflected or not
Transmission —> refraction (In physics, refraction is the redirection of a wave as it passes from one medium to another. The redirection can be caused by the wave's change in speed.) For light, refraction follows Snell's law.

Absorption

Ionisation can change over time.
Ionisation is not the same everywhere.

During the night, the ionisation decreases - the skill to reflect drops.
—> also LF goes through —> Maximum Usable Frequency, MUF decreases.

Balance between ionisation and recombination



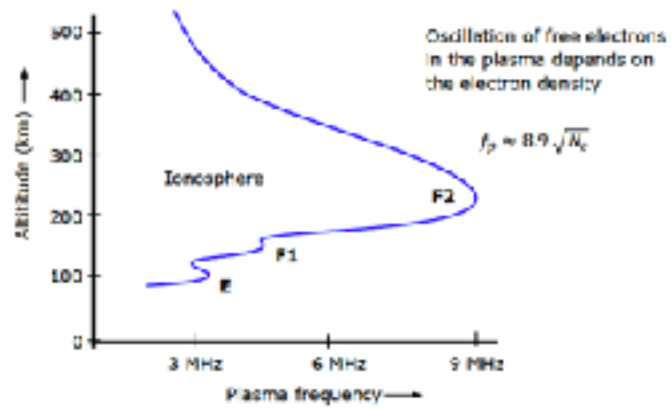
• Equilibrium between photoionisation and recombination (driven by neutral density): maximum free electron density at some altitude.

The electron density varies smoothly with height. It is the radiation of the sun that produces these free electrons.
• The density of atoms in the atmosphere decrease with height.
• The radiation of the sun increases with height.
• Therefore the ionization is maximum at a certain height.
The typical profile of the electron density is described by Sydney Chapman in 1942, and is therefore called the Chapman function.

• Equilibrium between photoionisation and recombination (driven by neutral density): maximum free electron density at some altitude.
• Actually to main maxima: F1-layer around 150 km due to EUV, E-layer around 110 km due to X-rays.
• Hard X-rays can produce an additional, lower D-layer.

Distribution of free electrons

We can calculate the plasma frequency if we know the electron density



So if we know this relationship, we can redraw the Chapman electron density profile to become a plasma frequency profile..
The profile becomes a little 'fatter', but the maximum will remain at the same height.
The horizontal axis of the graph now shows plasma frequency in MHz.

Electron distribution at mid-latitudes (roughly 30°–60°) has a typical layered structure.

- Equilibrium between photoionisation and recombination (driven by neutral density): maximum free electron density at some altitude.
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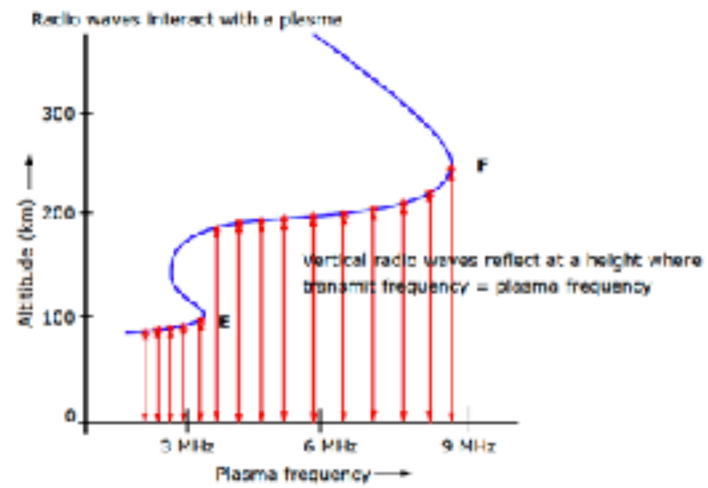
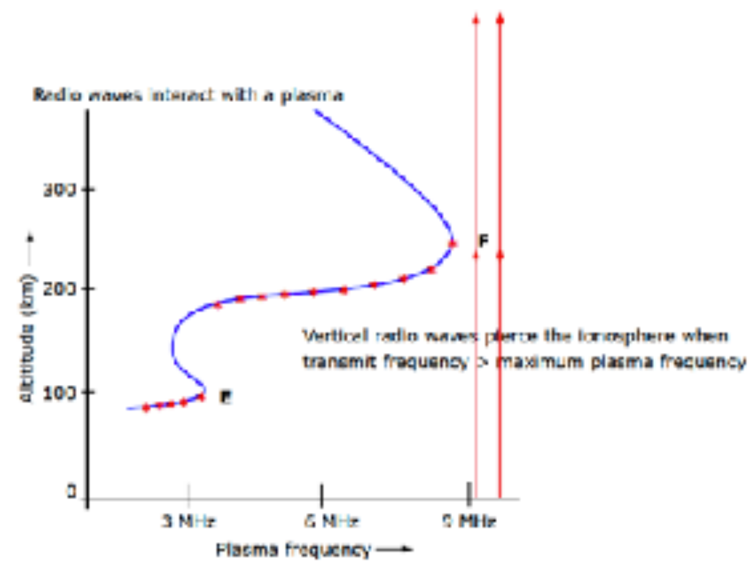
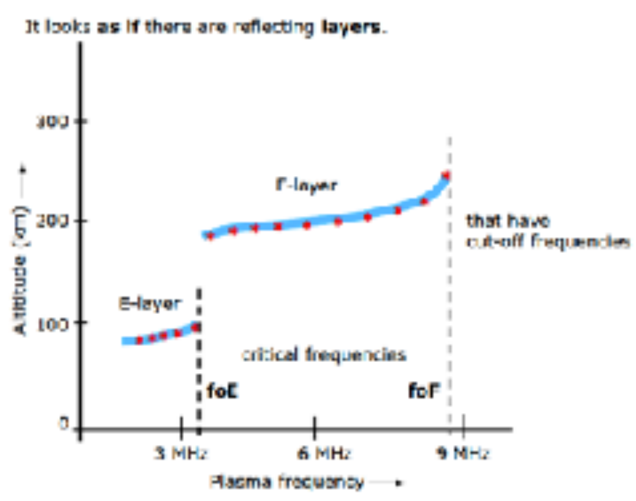


If we send a radio wave of low frequency – let's say 2 MHz - vertically upward, it will be reflected by the ionosphere. If we slowly increase the frequency of the transmitter, we see that the reflection height increases somewhat, but very slowly and gradually.

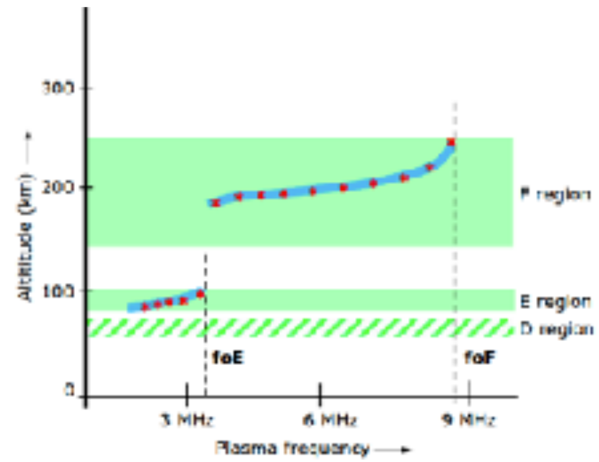
This continues until at some point, a sudden jump in reflection height is seen. This happens when we pass a local maximum in the electron density. After that, the reflection height gradually increases, but now a little bit faster.



Finally, when the transmit frequency becomes greater than the maximum plasma frequency, the waves pierce the ionosphere and travel into space. There will no longer be reflected waves, reflected signals are no longer received.



If we draw lines through the reflection points, it looks as if there are two distinct layers.
The reflecting heights of these layers is frequency dependent, and each layer has a distinct cut-off frequency.



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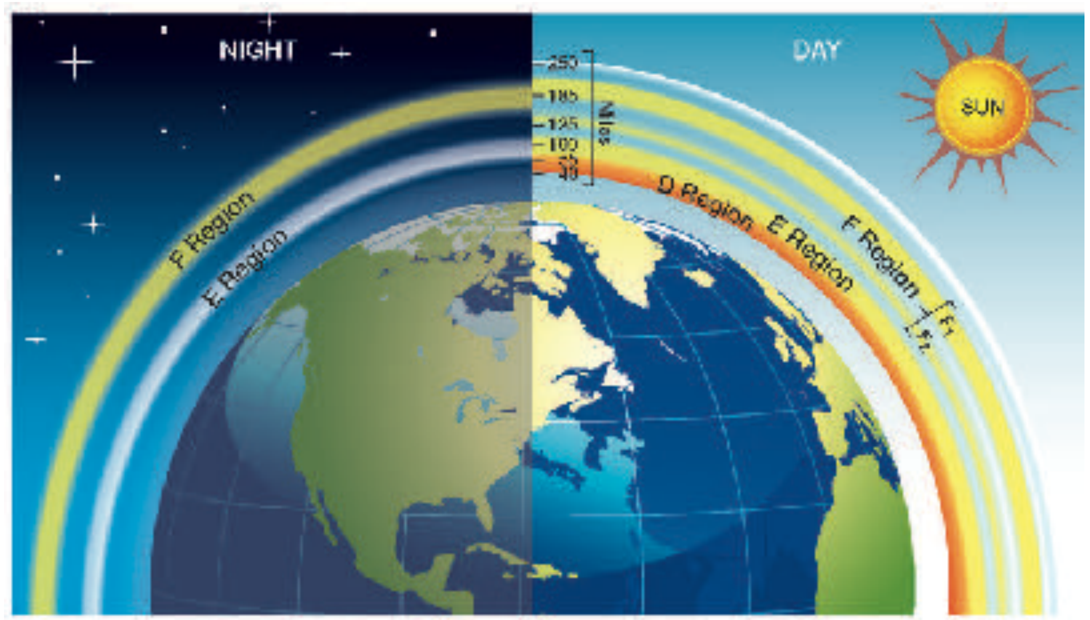
In reality there are no layers, but the expression has stuck.
Scientist rather talk about The D-, E- and F-regions.
But as long as we understand each other, the wording we use is not so critical.

The plasma frequency varies with height. Because of the typical form of the chapman profile, we have layers in the ionosphere and each layer has a critical frequency (foE, for). Radio waves below the critical frequency are reflected in that specific layer, above can pass through that specific layer.

DIURNAL VARIATION

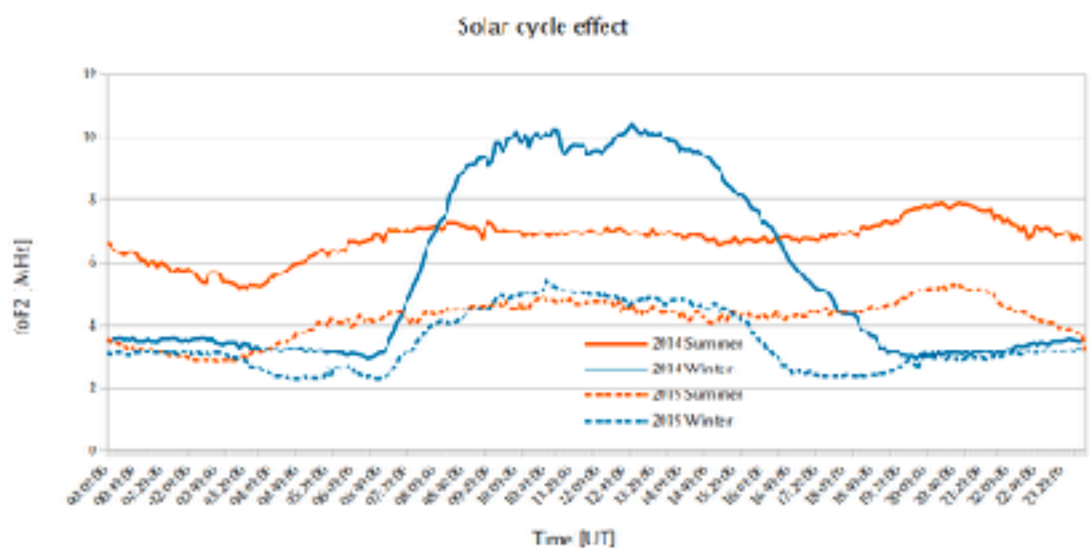


1 The (mid-latitude) ionosphere is stratified into layers: F2, F1, E, D.
2 The lower layers are formed by ionisation/recombination equilibria.
3 The F2 layer persists through the night
Because

- Less neutral gas being present —> slow recombination
- Plasma transport by the neutral wind which drags the plasma (only a few %) with it

The most prominent peak in the mid-latitude ionosphere is the F2, which is above the ionisation/recombination equilibrium heights.
The F2 layer is produced through transport of plasma, rather than direct ionisation.
D layer disappears during the night due to fast recombination because of the neutral gas
Night time ionosphere:
neutral thermospheric winds (drags the plasma with it) are generally from the subsolar point (noon, summer hemisphere) to its antipode (midnight, winter hemisphere).
This leads to generally upward flow of plasma on the day-side, and downward flow on the night side.
The night-time ionosphere is maintained by this inter-hemispheric transport, and the slower recombination rate at high altitude.

Seasonal and solar cycle variation



Critical frequency
During solar max the curves are higher
During solar min the curves are lower

Low and high latitude ionosphere

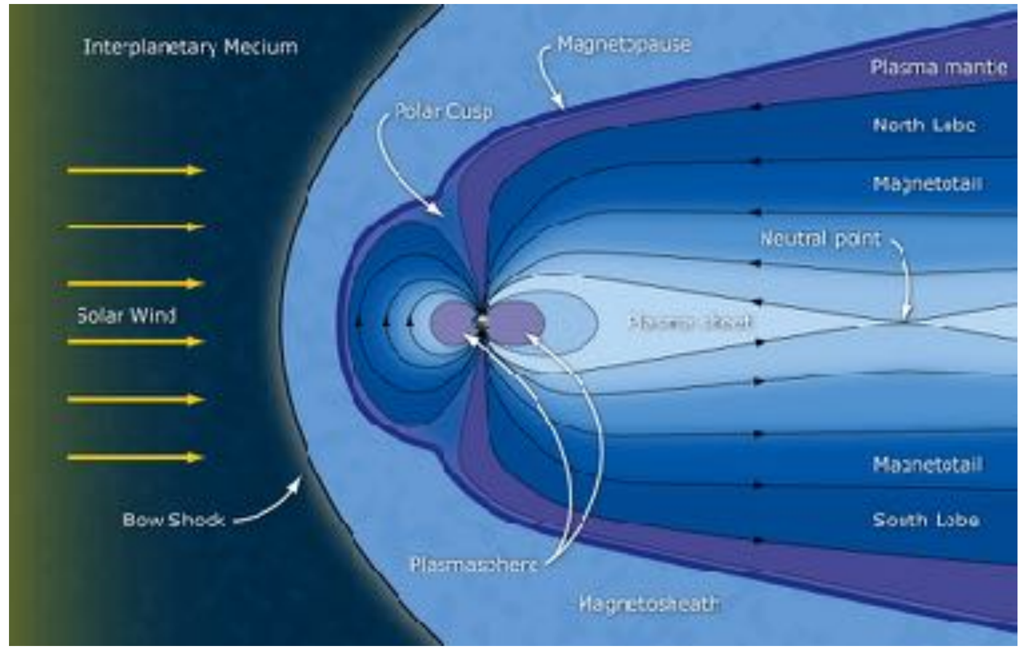
Besides solar irradiation, the ionosphere is strongly influenced by the geomagnetic field.

magnetosphere

magnetosphere-ionosphere coupling

Besides solar irradiation, the ionosphere is strongly influenced by the geomagnetic field.

Magnetosphere - ionosphere coupling



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.)

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.

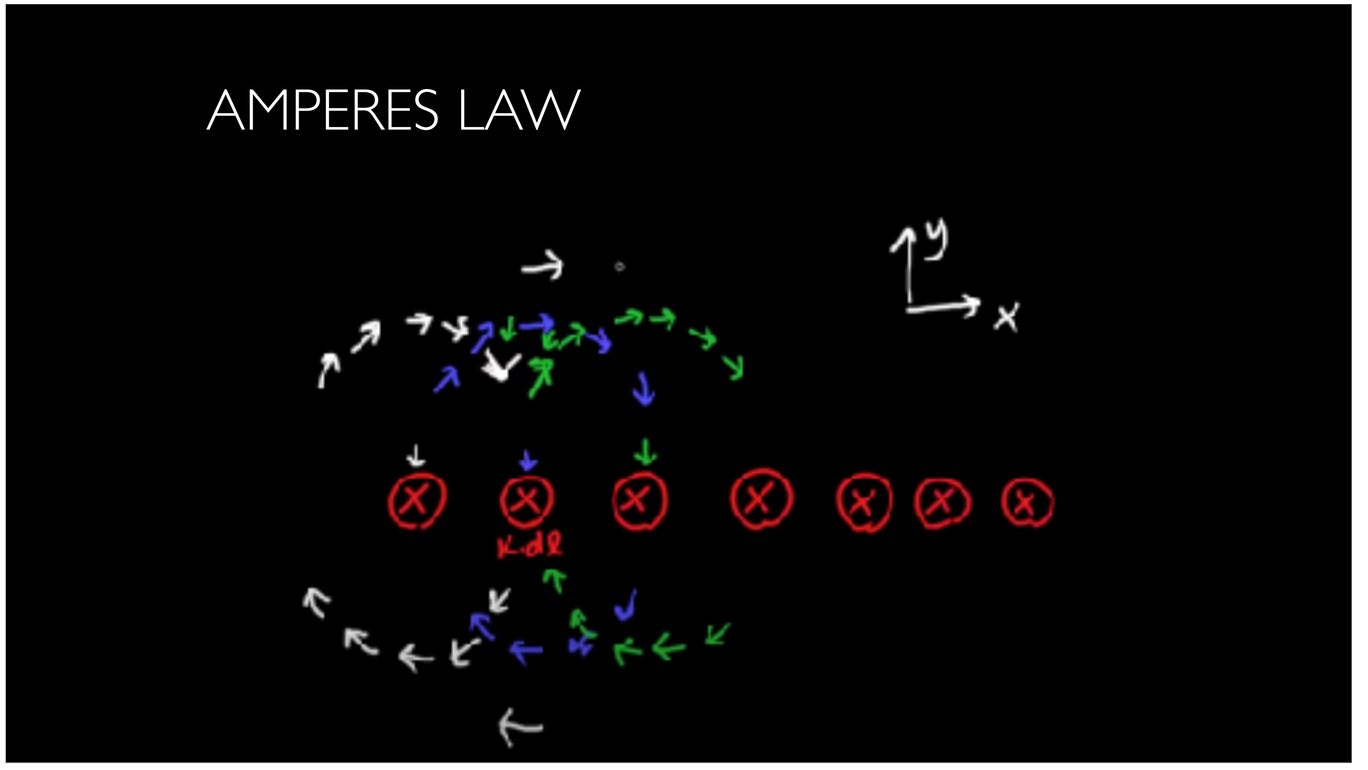
Magnetosphere is a highly dynamical system
https://www.researchgate.net/figure/Structure-of-Earth-magnetosphere-with-magnetopotentials-in-blue-inner-radiation-belt-in_fig3_351130787
Structure of Earth magnetosphere with magnetopotentials in blue, inner radiation belt in green, and outer radiation belt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

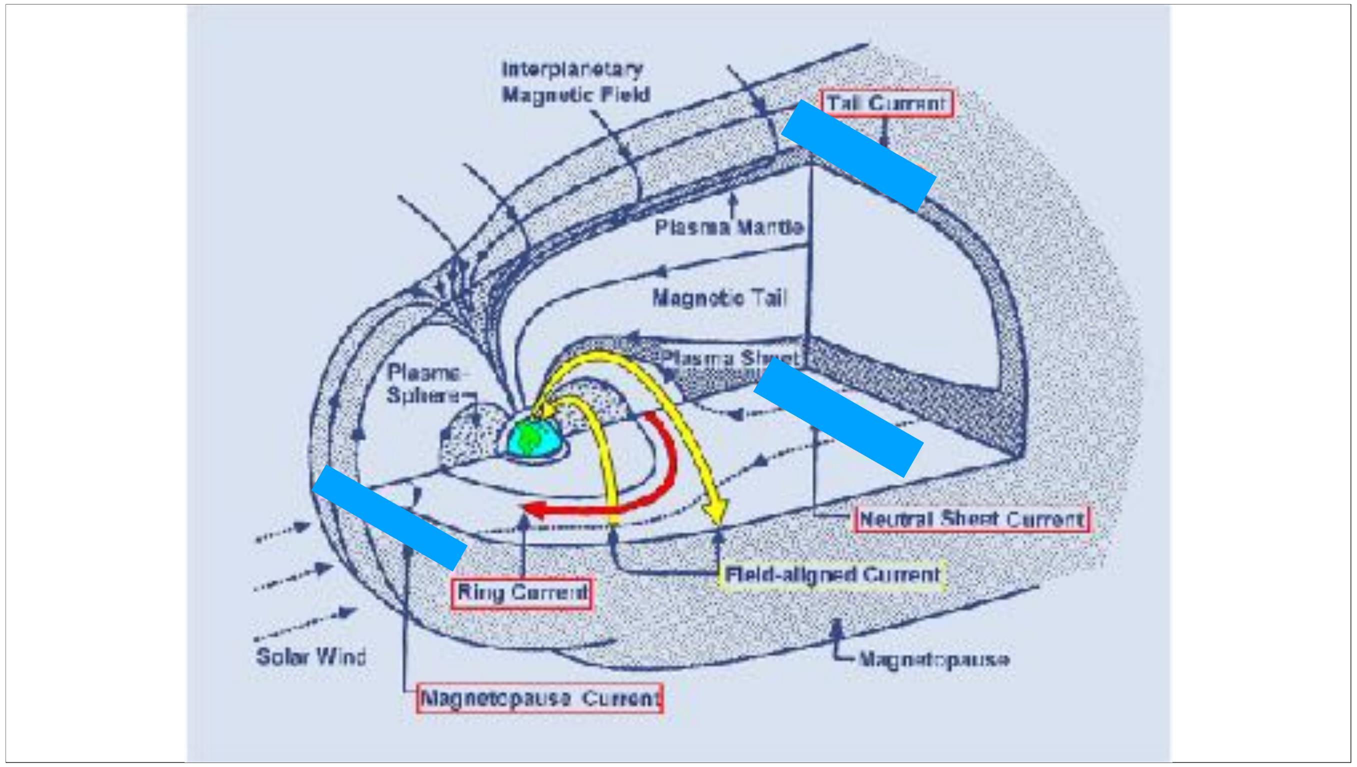
When the plasma up above is caused to move, magnetic field lines communicate this motion down to the ionosphere as if they were pieces of string tying the different plasma regions together.

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



Closed circle B.dl = mu0 . I_enclosed



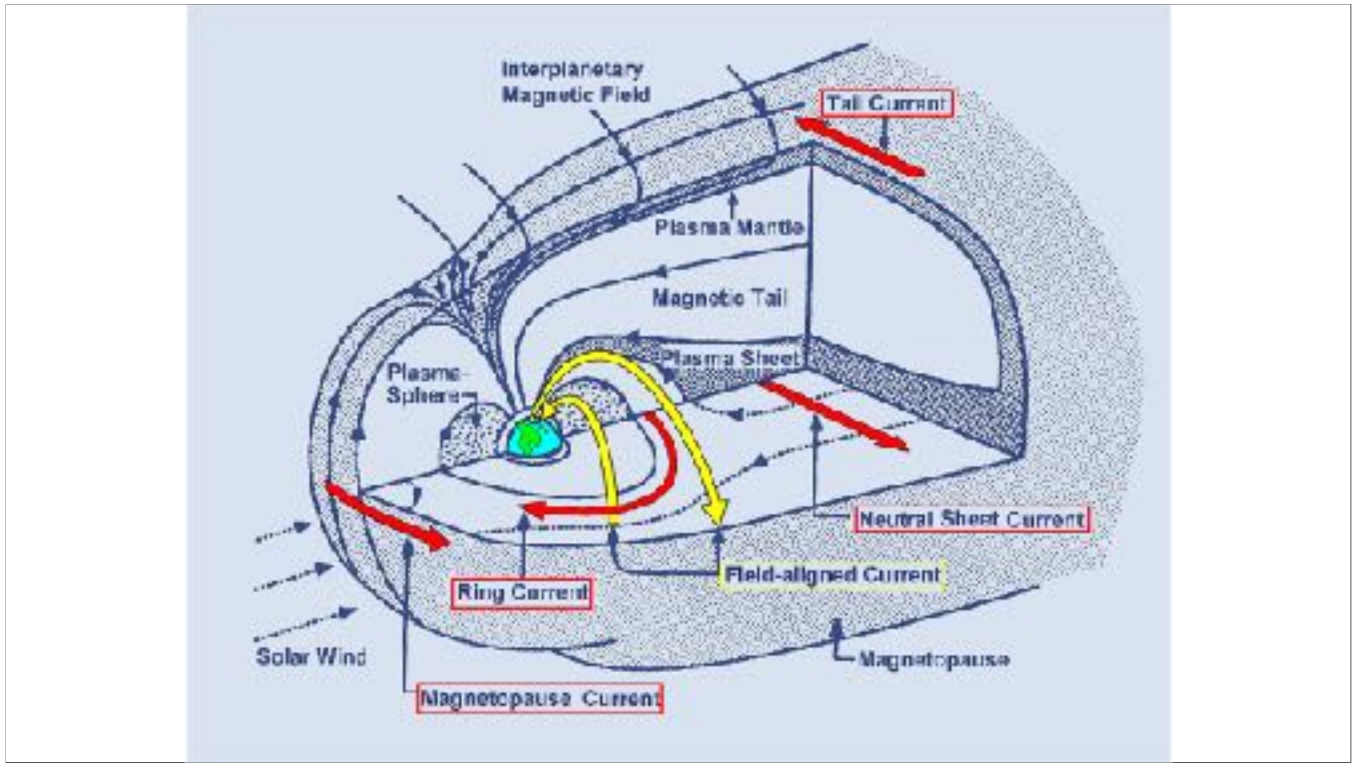
https://www.youtube.com/watch?v=-hTNuJZByDc

The sharp limit of the plasmasphere is called the plasmapause.

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.

Magnetic reconnection

https://www.youtube.com/watch?v=QsGXN8Wf__o



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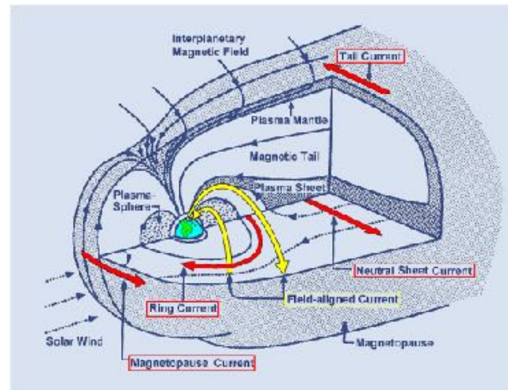
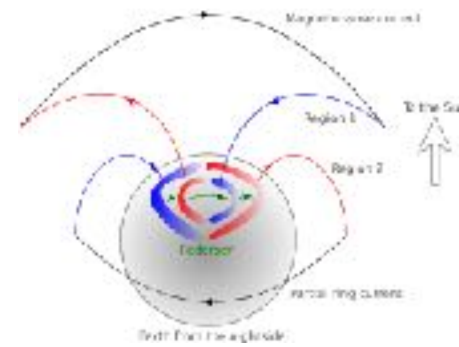
MAGNETOSPHERE - IONOSPHERE COUPLING





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.
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

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

Low-latitude ionosphere

THE EQUATORIAL IONISATION ANOMALY

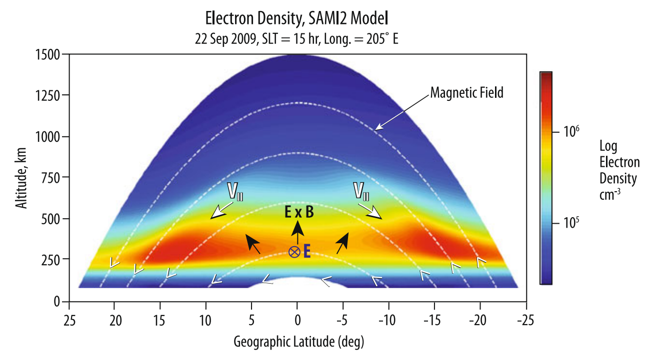
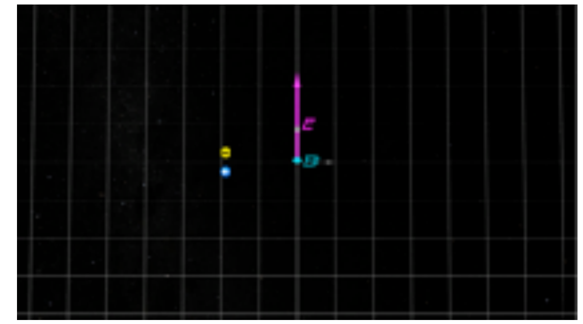


Fig. 19 SAMI2 model calculations versus latitude and altitude of the plasma density for 1500 SLT at 205° East. The upward **E** × **B** drift at the magnetic equator is driven by the eastward electric field, and there is subsequent flow downward along the magnetic field lines

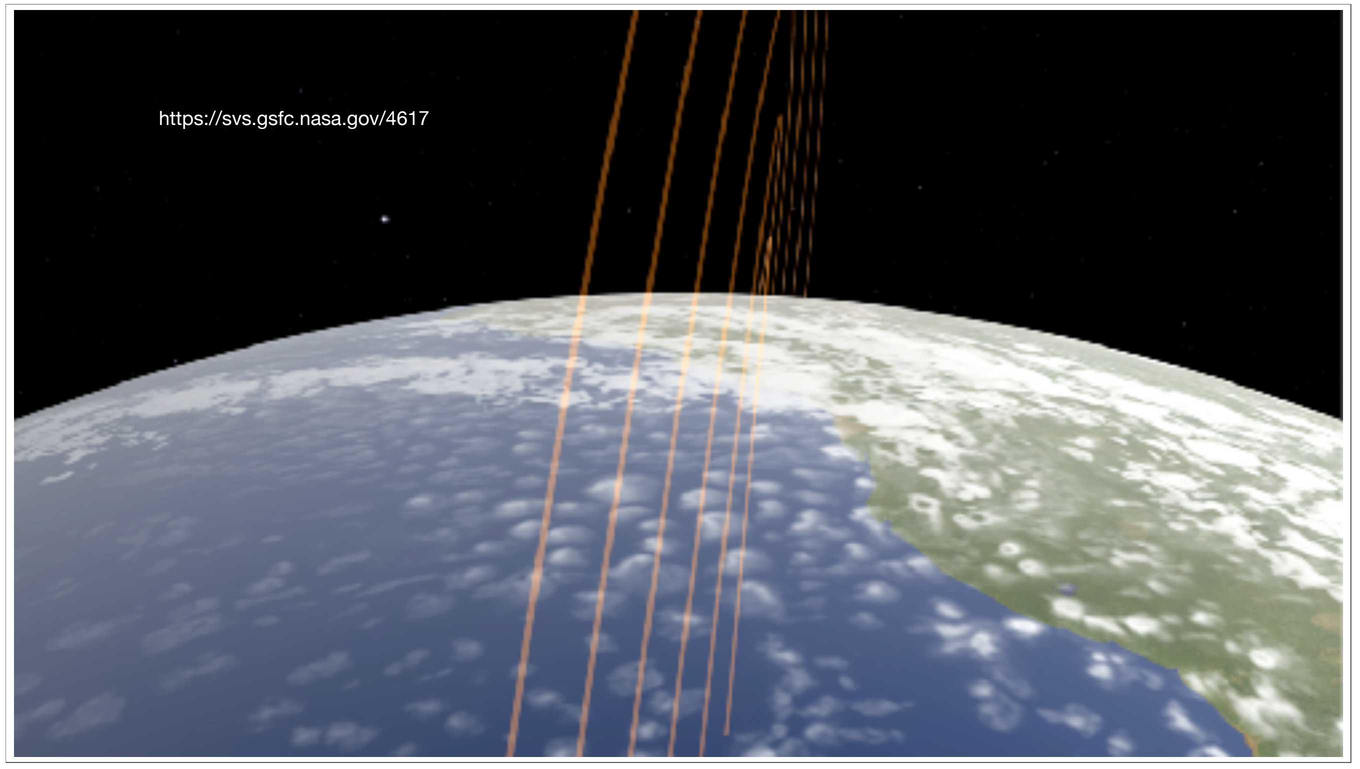


Pfaff, 2012, The Near-Earth Plasma Environment

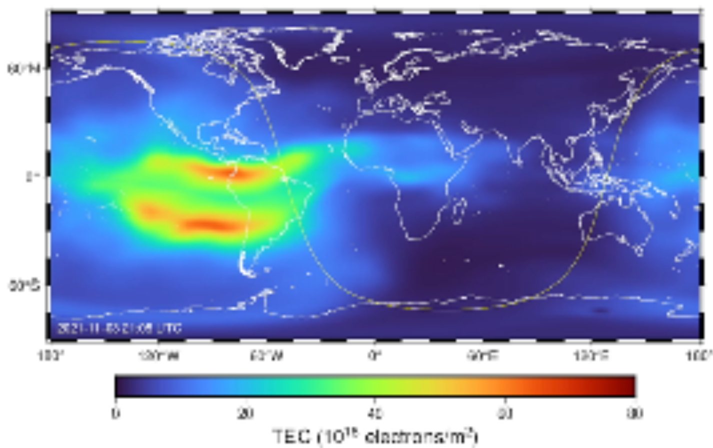
The “Equatorial Ionisation Anomaly” is a permanent feature of the day-time low latitude ionosphere.
“Plasma fountain” close to the magnetic equator, where B is horizontal.

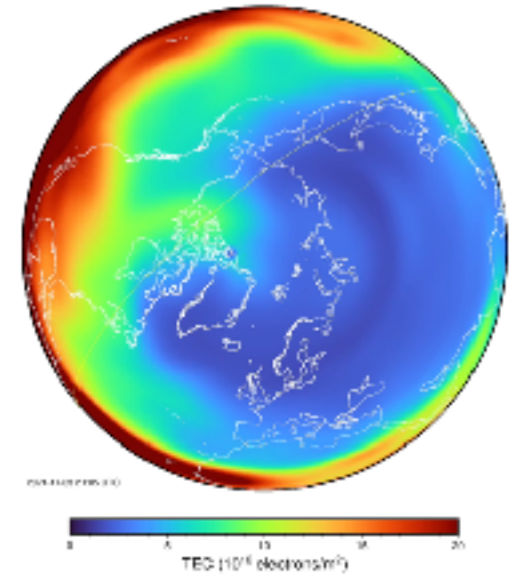
<u>Thermospheric wind creates dynamo E, eastward during day-time.</u>
Thermospheric winds create an electric field by dragging charged particles in the ionosphere through the Earth's magnetic field. This "dynamo" effect occurs because the neutral wind can move ions more easily than the electrons, which are constrained to move along magnetic field lines. This separation of positive and negative charges leads to a buildup of a polarization electric field, particularly in the ionosphere's E-region.

This causes E x B drift upwards (meaning less recombination).

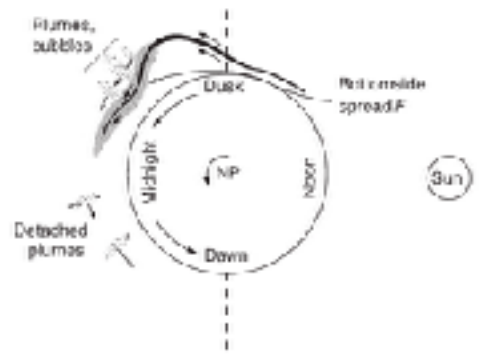

https://svs.gsfc.nasa.gov/4617

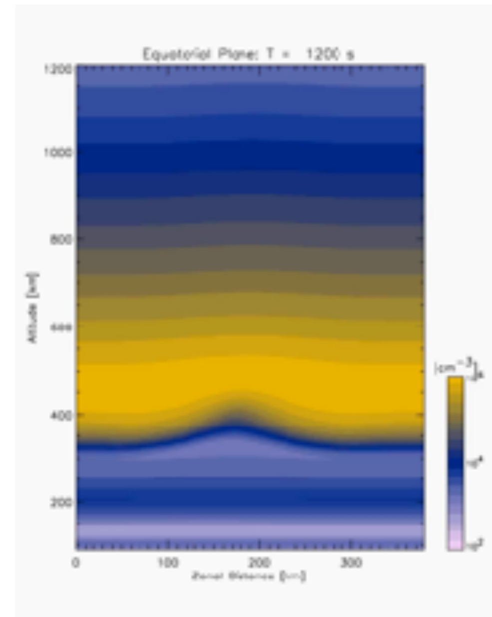
The equatorial ionisation anomaly





EQUATORIAL PLASMA BUBBLES



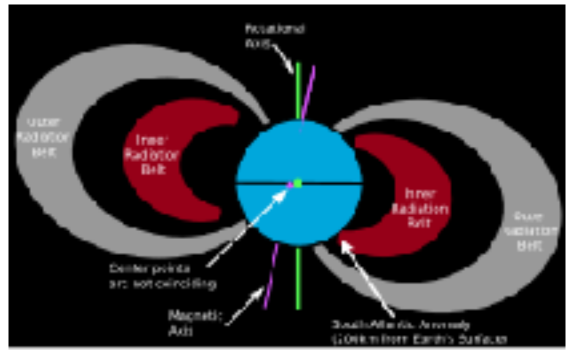


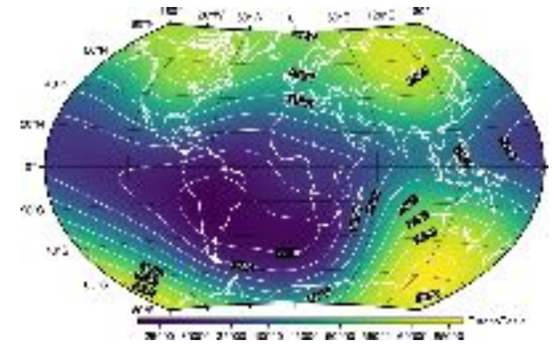
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JA020708

Post sunset - solar cycle dependent

Plasma bubbles are formed at Rayleigh–Taylor instabilities when the lower ionosphere rapidly recombines **after dusk, creating very strong electron density gradients**. They form below hmF2 and **rise to over 700 km, while drifting eastward.**

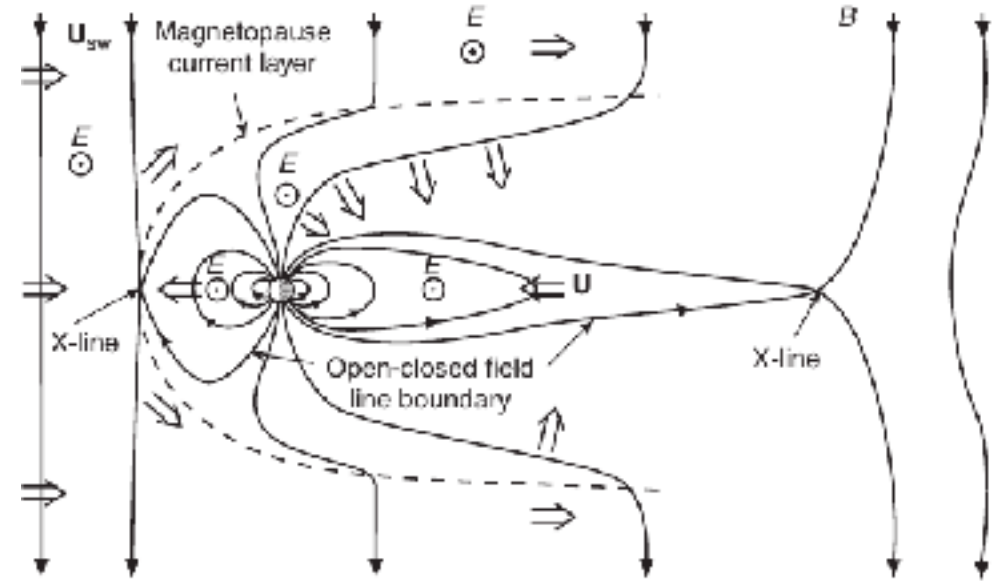
SOUTH ATLANTIC ANOMALY





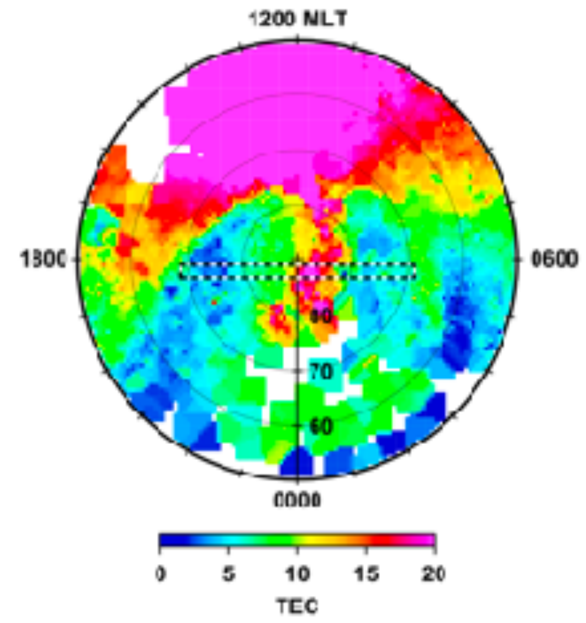
High-latitude ionosphere

POLAR CAP AND AURORAL OVAL



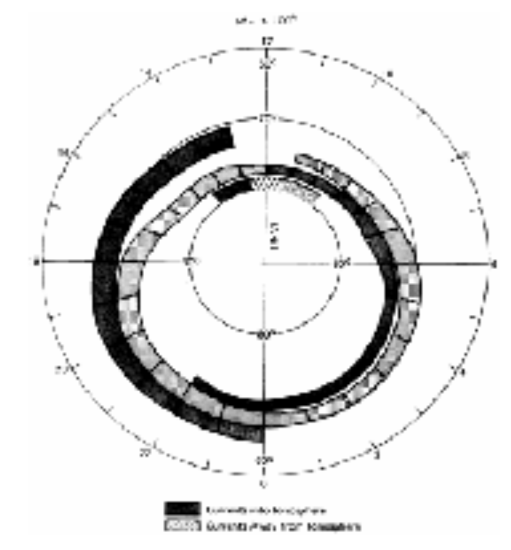
The high-latitude ionosphere is the most complex region, comprising two very different regions: auroral oval and polar cap.
In the polar cap, magnetic field lines are open, connected to the interplanetary field. The auroral oval is the transition region to closed field lines.

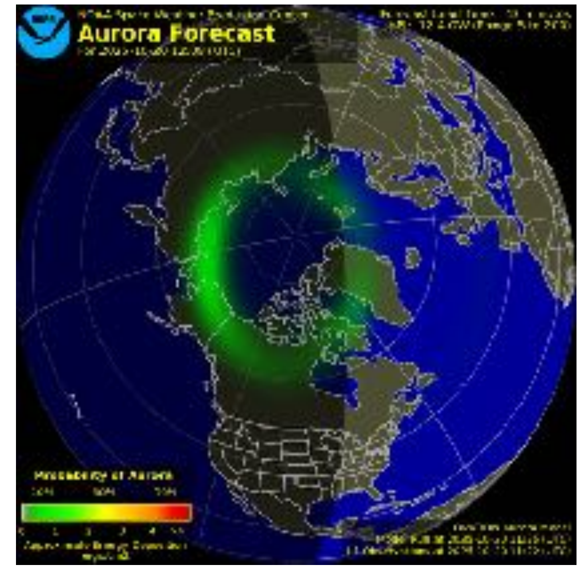
Polar Cap



Plasma flow from noon to midnight over the pole, return around the edges (deformed by Earth rotation & interplanetary field orientation).

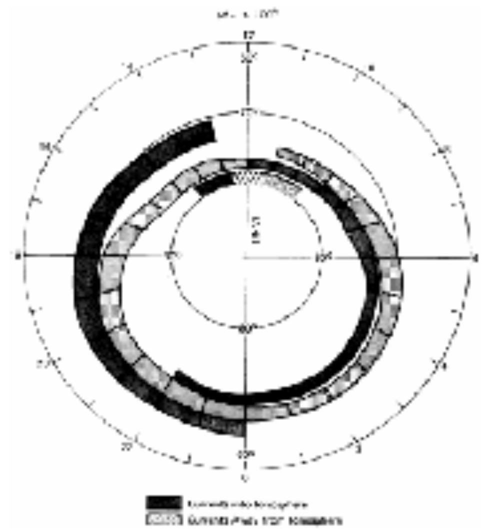
Auroral Oval

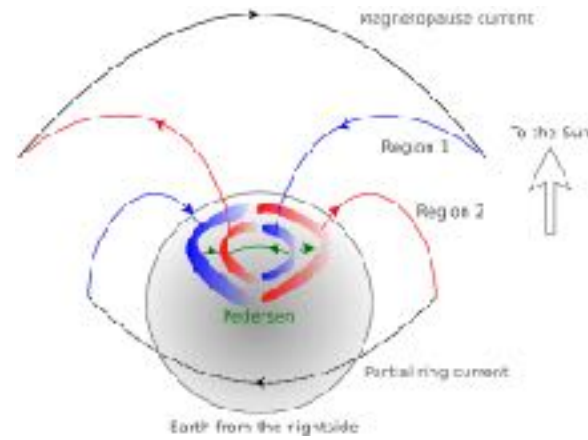




Two regions, one with inflow from, one with outflow to the magnetotail (directly influenced by magnetospheric storms).

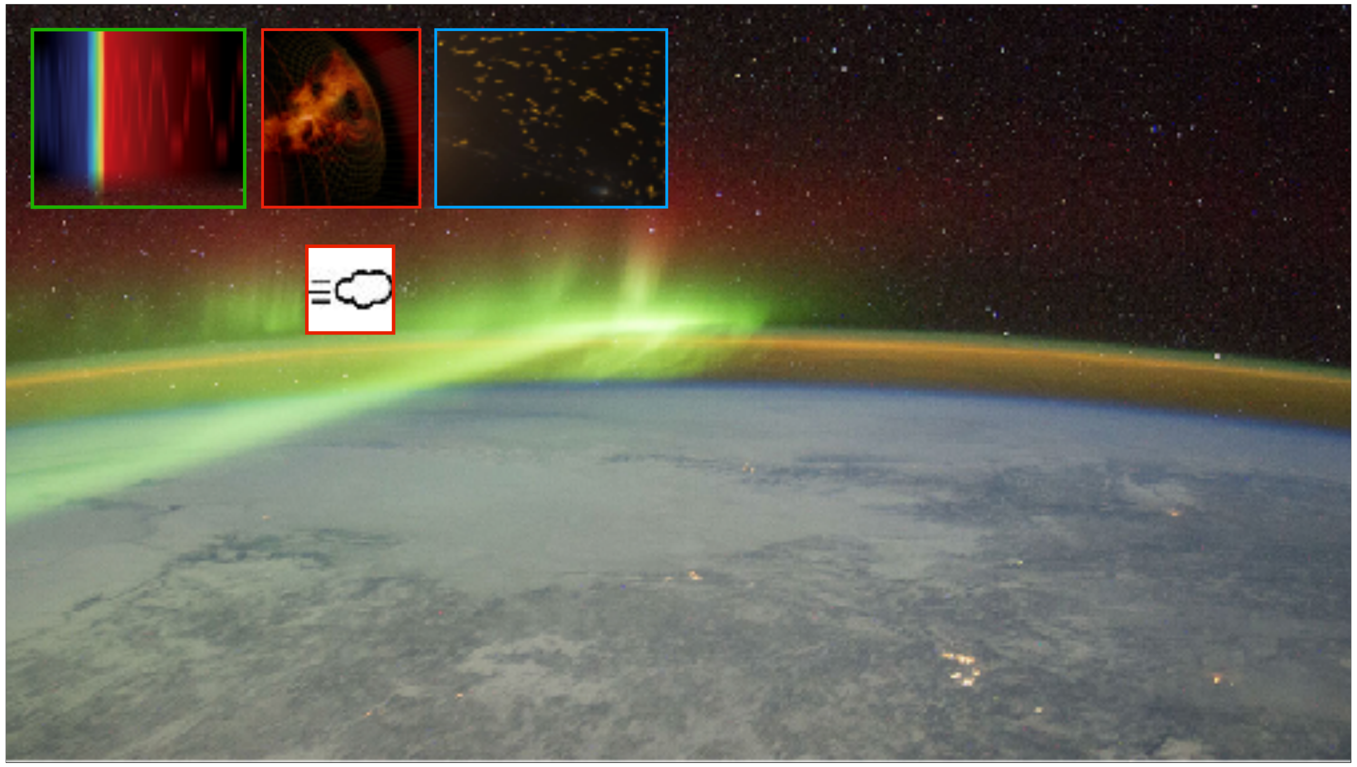
AURORAL OVAL

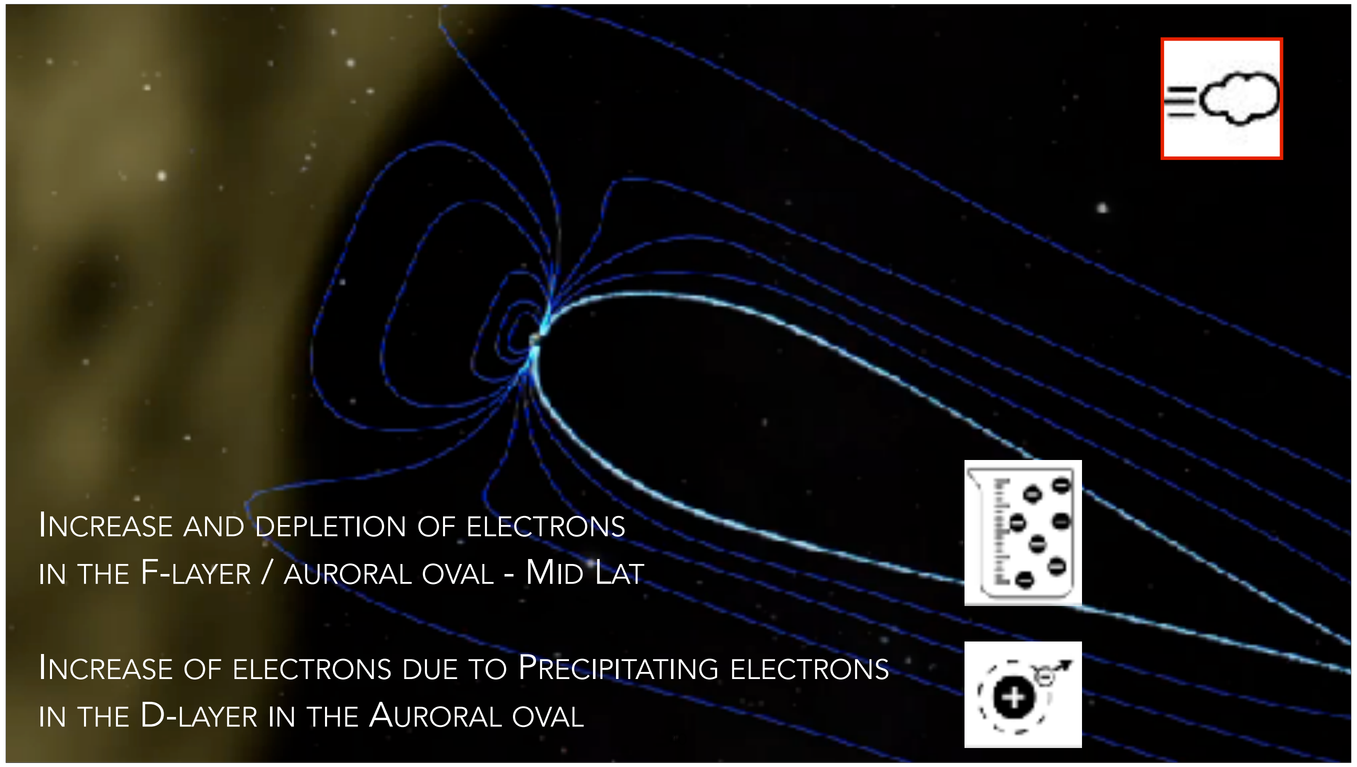




Two regions, one with inflow from, one with outflow to the magnetotail (directly influenced by magnetospheric storms).

Ionospheric irregularities



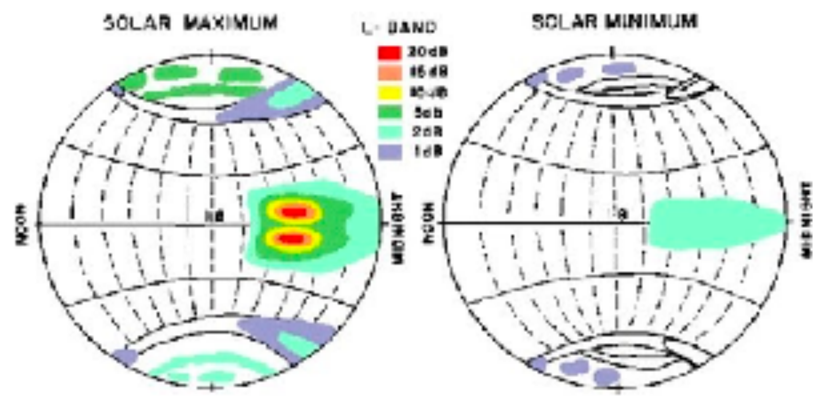


The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the auroral oval expands.
3 This causes large scale movement of plasma towards the equator.
4 Drift along the magnetic field lines cause the ionosphere to move up, which can increase electron density (“positive storm phase”).
5 Finally, upwelling of N2 causes increased recombination, leading to a depletion of ionisation (“negative storm phase”).

The negative phase of a storm is always seen, and lasts for a few days. The positive phase is not always present (this depends among others things on the local time at storm onset).

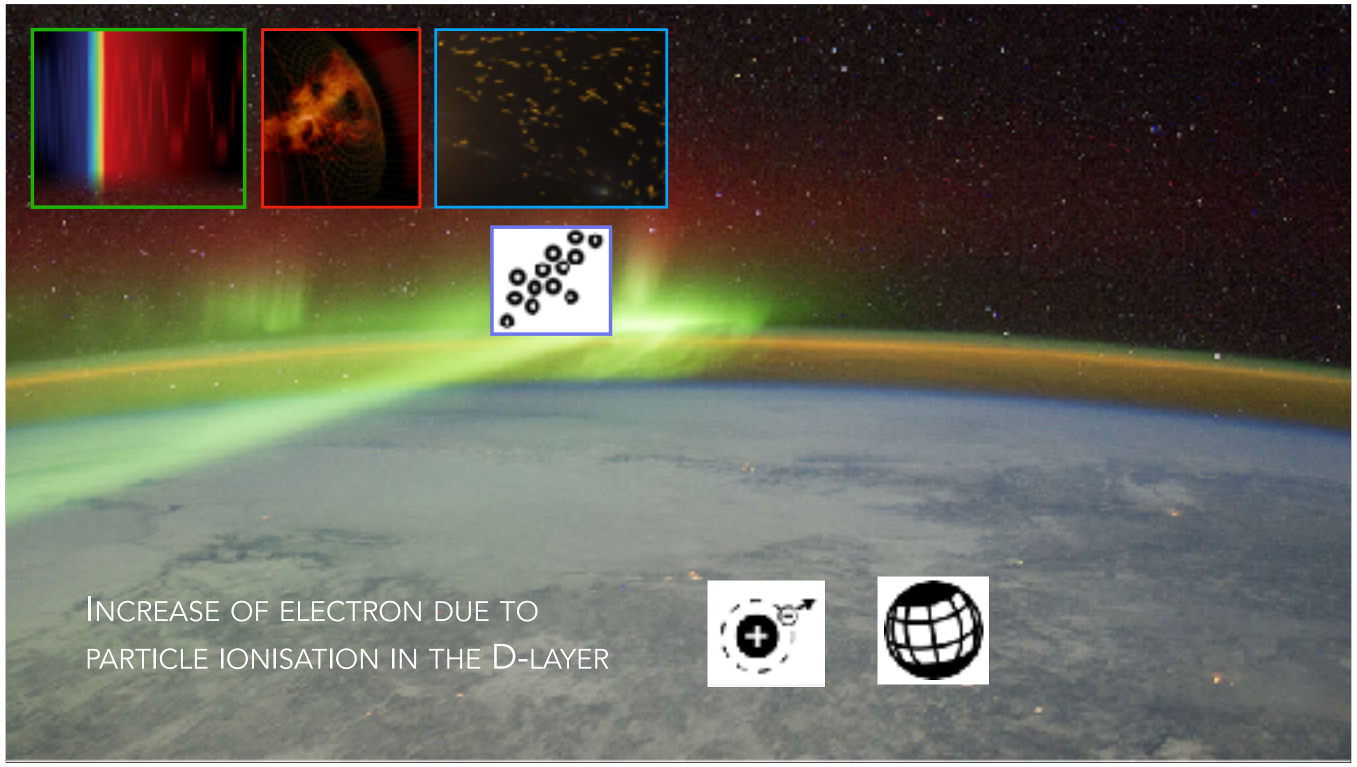
Small Scale Irregularities in the Ionosphere



Global variation of amplitude scintillation fades at L band (after Basu et al. 1988a, b, colored by A.W. Wernik)

In the equatorial region: plasma bubbles (decreased ionisation).
In the auroral regions: Scintillation in the auroral oval is due to small scale structures in the currents patterns associated with inflowing particles
polar cap: arcs and patches of increased ionisation.

Hard X-rays can penetrate the thermosphere to altitudes in the D-region.
The sun only emits significant intensity at these wavelengths during major flares.
The absorption in this case is most severe around the sub-solar point.



Low-altitude ionisation can also be produced by solar energetic particles (mostly high-energy protons), coming in from the solar wind along open field-lines.

These events cause severe absorption in the polar region, but strictly limited to the area of open field lines.