Introduction to Plasma Physics

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Terrestrial plasmas

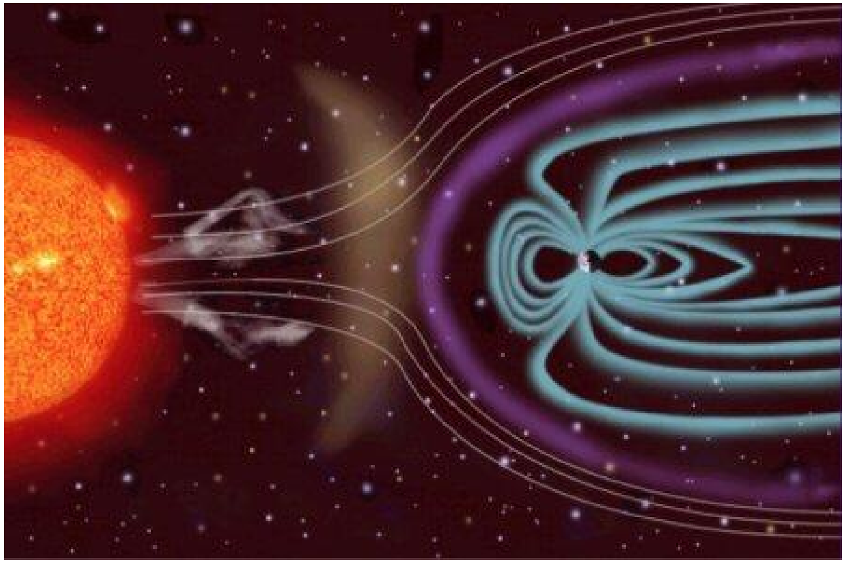
- Magnetosphere
- Radiation belts
- Ionosphere
- Polar lights (aurorae)
- Sprites, elves, jets
- Lightning
- Ball lightning

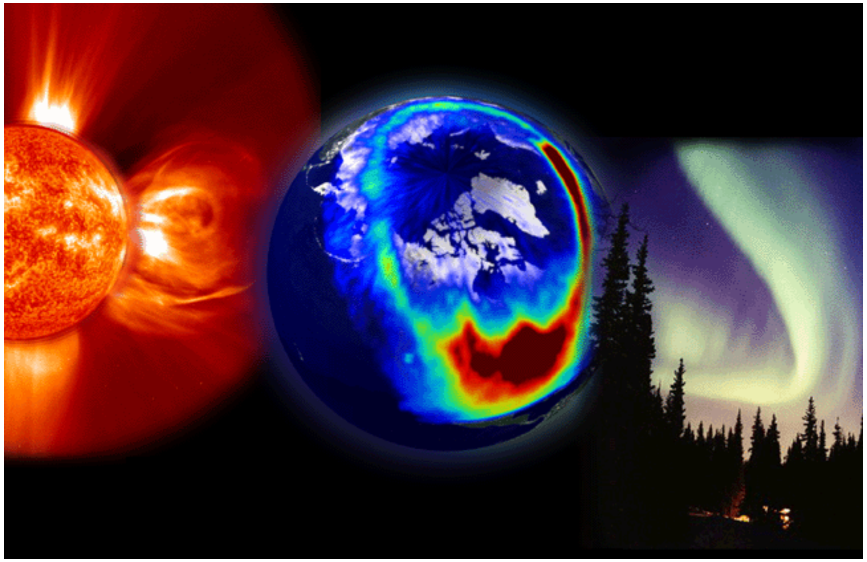
Plasmas

- Astrophysical Plasmas
- Terrestrial Plasmas
- Laboratory Plasmas

Sun-Earth connection

Sun-Earth connection through
- Solar wind, the embedded
- Interplanetary (solar) magnetic field, and
- Violent solar events like
    - Solar proton events and
    - Coronal mass ejections /CMEs).



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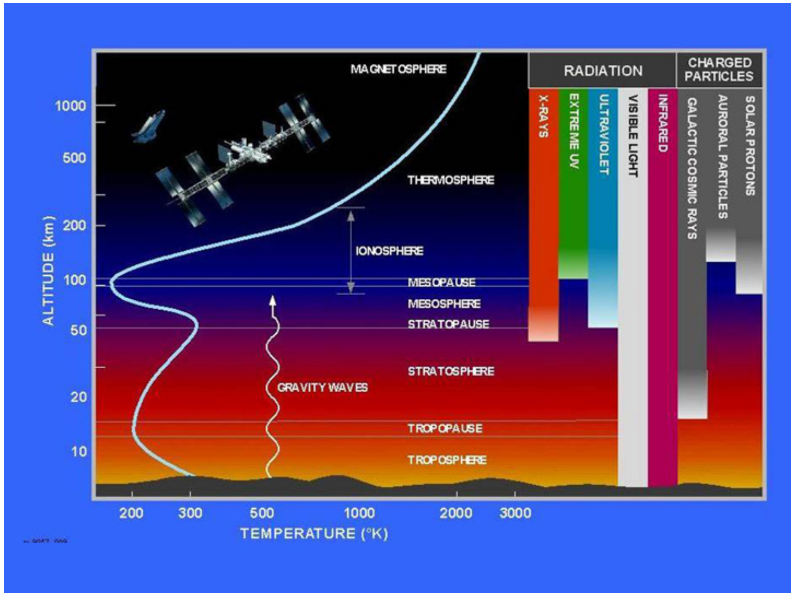
Magnetosphere, Ionosphere and Atmosphere

Life on Earth depends on energy from the Sun. The higher frequency parts of the energy spectrum from the Sun are extremely energetic and would create a hostile environment for life. However, we can enjoy the Sun because we are protected by the Earth's magnetosphere, ionosphere, and atmosphere.



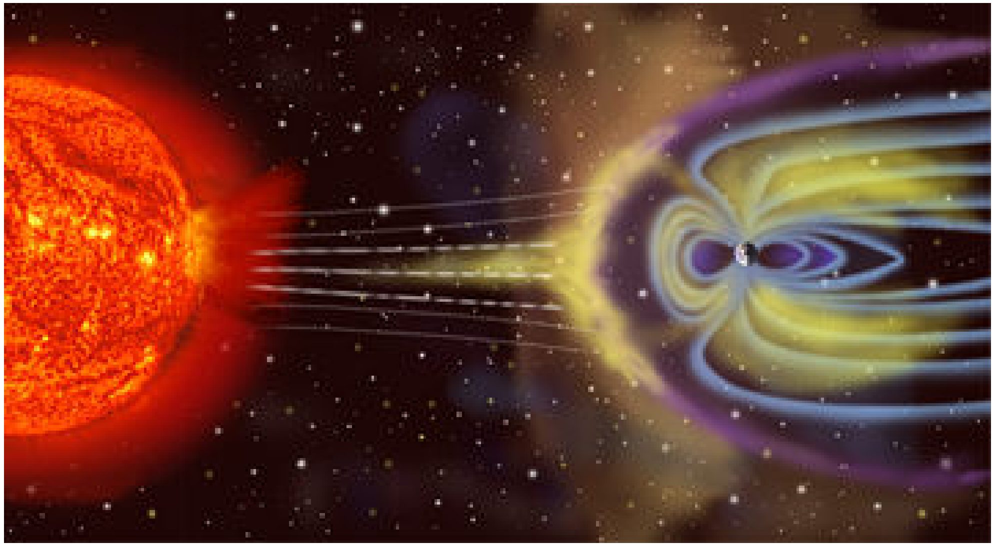
The dense atmosphere protects us by absorbing ultra violet solar radiation and reducing temperature extremes between day and night. The upper atmosphere, at heights of above 80 km, is ionized by extreme ultra violet radiation and is called the ionosphere.

Magnetosphere

A magnetosphere is the region around an astronomical object in which phenomena and processes are dominated by its magnetic field.

- Earth is surrounded by a magnetosphere,
- as are the magnetized planets Mercury, Jupiter, Saturn, Uranus and Neptune.
- Jupiter's moon Ganymede is magnetized, but too weakly to trap solar wind plasma.
- Mars has a patchy surface magnetization.

The term "magnetosphere" has also been used to describe regions dominated by the magnetic fields of celestial objects, e.g. pulsar magnetospheres.



Magnetosphere

Our planet Earth is a big magnet and the magnetic field extends far out into space - called the magnetosphere. The magnetosphere protects the atmosphere and us from the stream of the magnetized gas from the Sun - called the solar wind - by stopping and deflecting the solar wind around the Earth. The Earth's magnetosphere was discovered in 1958 by Explorer 1 during the research performed for the International Geophysical Year.

Thomas Gold proposed the name *magnetosphere* for "The region above the ionosphere in which the magnetic field of the earth has a dominant control over the motions of gas and fast charged particles is known to extend out to a distance of the order of 10 earth radii.“

Two factors determine the structure and behavior of the magnetosphere:

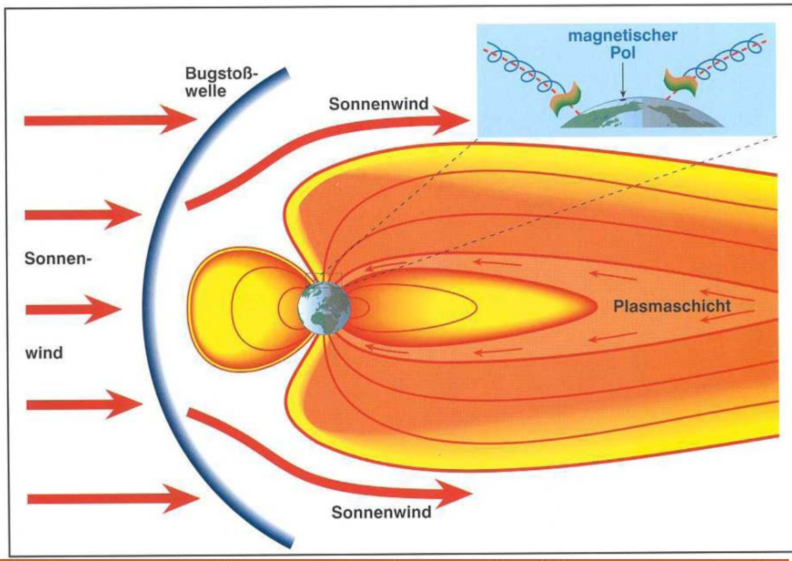
1. The internal magnetic field of the Earth, and
2. The solar wind.

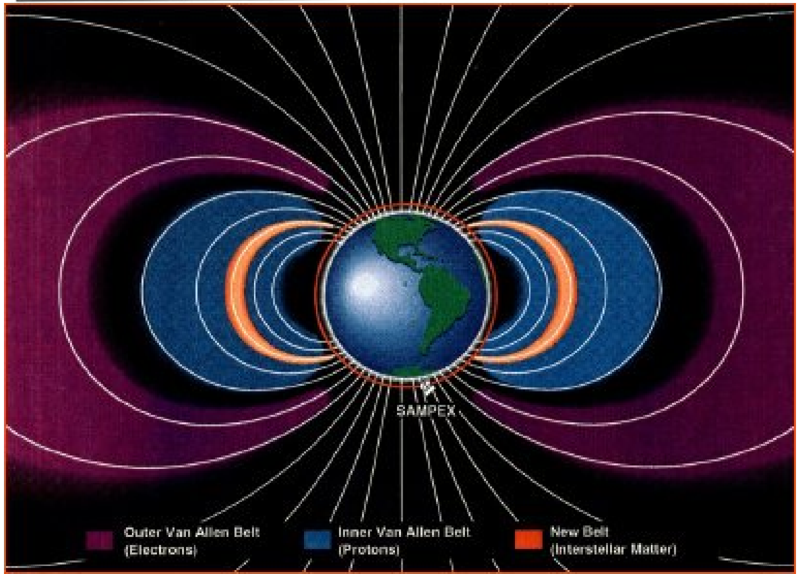
Magnetosphere

The internal magnetic field of the Earth appears to be generated in the Earth's core by a dynamo process, associated with the circulation of liquid metal in the core, driven by internal heat sources.

Its major part resembles the field of a bar magnet ("dipole field") inclined by about 10° to the rotation axis of Earth. The dipole field has an intensity of about 30,000-60,000 nanoteslas (nT) at the Earth's surface.

Its intensity diminishes like the inverse of the cube of the distance, i.e. at a distance of *R* Earth radii it only amounts to $1/R^3$ of the surface field in the same direction.



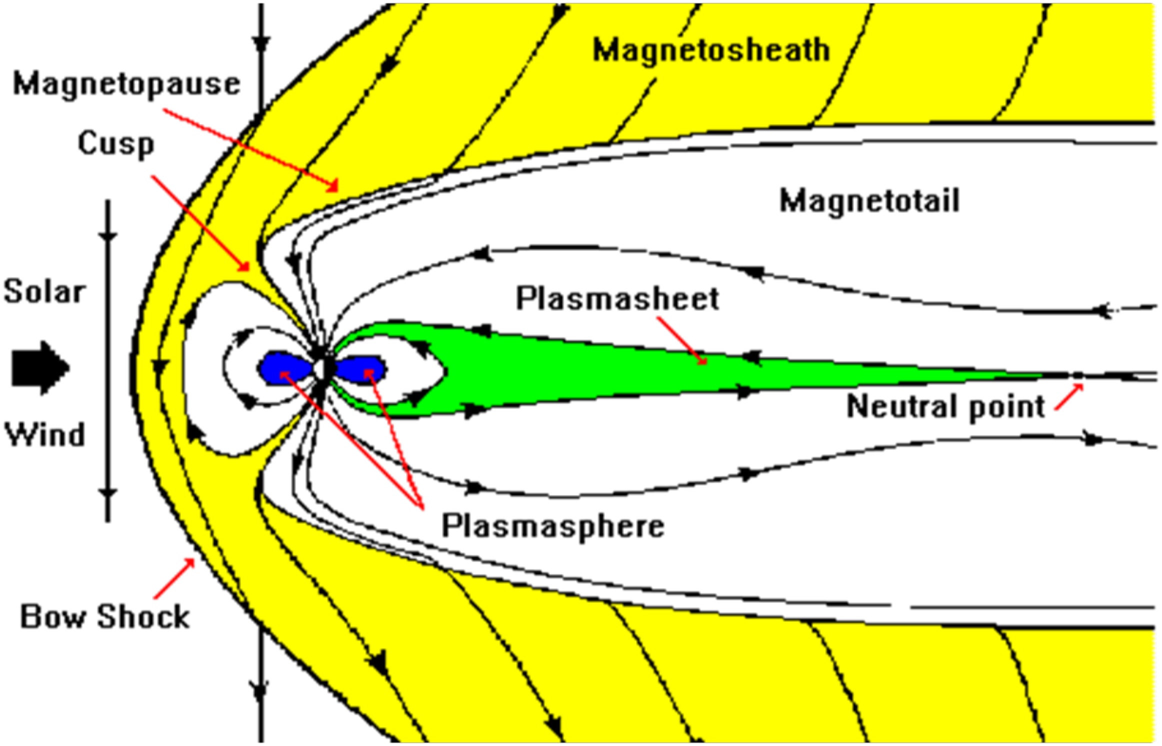


Magnetosphere

In the absence of any external drivers, the geomagnetic field can be approximated by a dipole field with an axis tilted about 11 degrees from the spin axis.

The forcing by the solar wind modifies this field, creating the cavity called the magnetosphere. This cavity shelters the surface of the planet from the high energy particles of the solar wind.

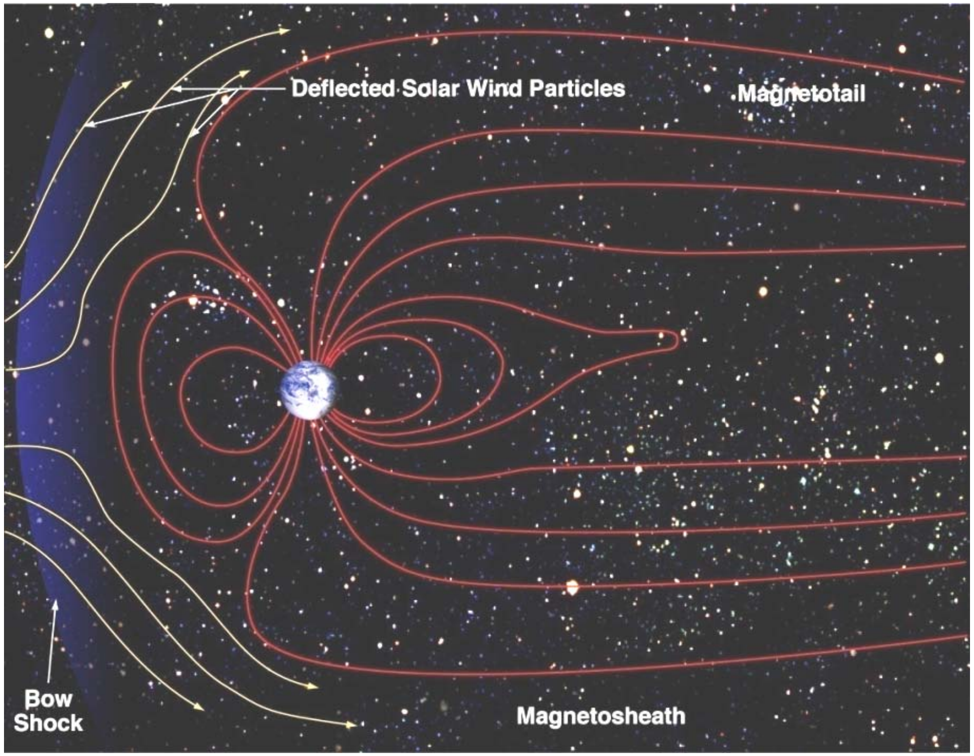
The magnetosphere is filled with plasma that originates both from the ionosphere and the solar wind.



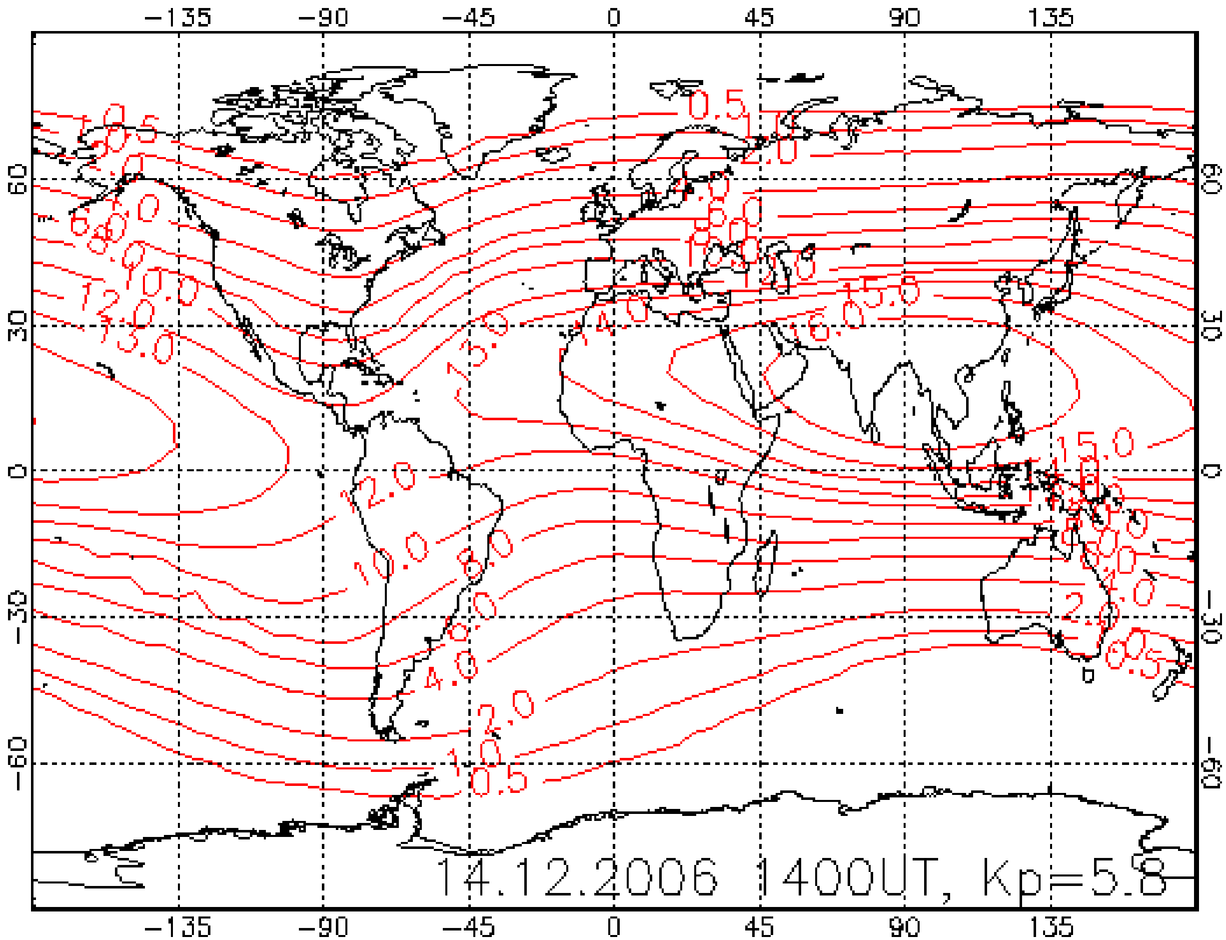
Magnetosphere

In the magnetosphere, a mix of free ions and electrons from both the solar wind and the Earth's ionosphere is confined by magnetic and electric forces. In spite of its name, the magnetosphere is distinctly non-spherical.

Particles from the solar wind and from cosmic rays are deflected by the magnetoshpere away from Earth. The magnetosphere thus provides a shielding from incoming energetic particles.



Cut-off rigidities (in GV)



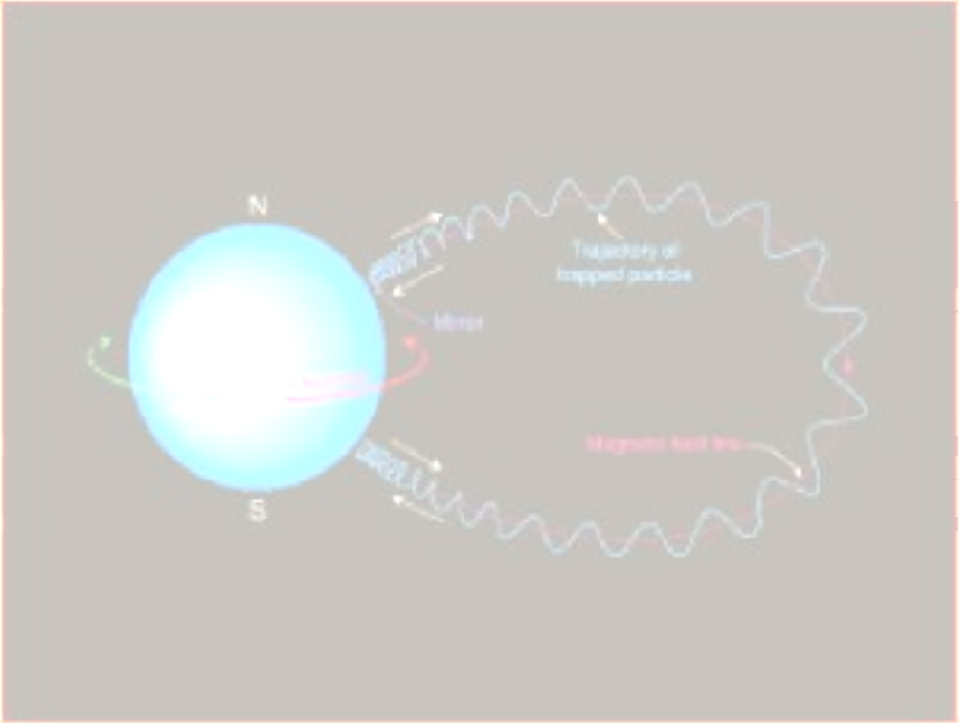
Cut-off rigidity is the energy a vertically incoming proton must have to reach ground.

Cut-off rigidities decrease towards the poles and are largest near-by the equator.

The Ring Current

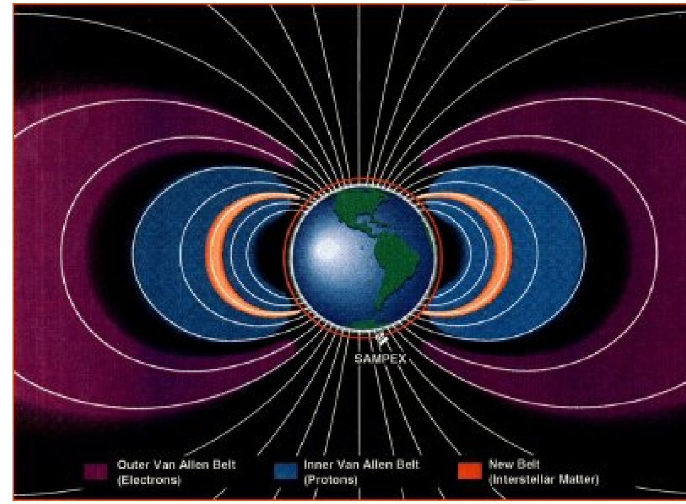
At heights below about 6 Earth radii, the Earth's magnetic field has a dipolar shape. This dipolar configuration means that the magnetic field strength will be lowest at the equator and highest near the north and south poles where magnetic field lines converge.

Charged particles are trapped by this magnetic field configuration.   This means, that particles gyrate around the magnetic field, bounce between the northern and southern hemisphere and drift around the Earth, with electrons and ions drifting in opposite directions. The electric current associated with this drift motion is called the ring current.

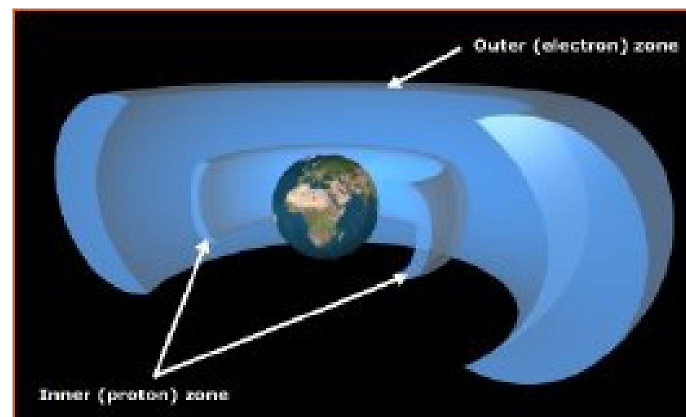


The Radiation Belts of the Earth

The radiation belts (also called the Van Allen belts) are layers of intense particle fluxes trapped by the Earth's magnetic field. These particles are brought to Earth by the solar wind or are produced by the interaction of high-energy galactic cosmic rays with the atmosphere of the Earth. There is an inner and outer radiation belt.



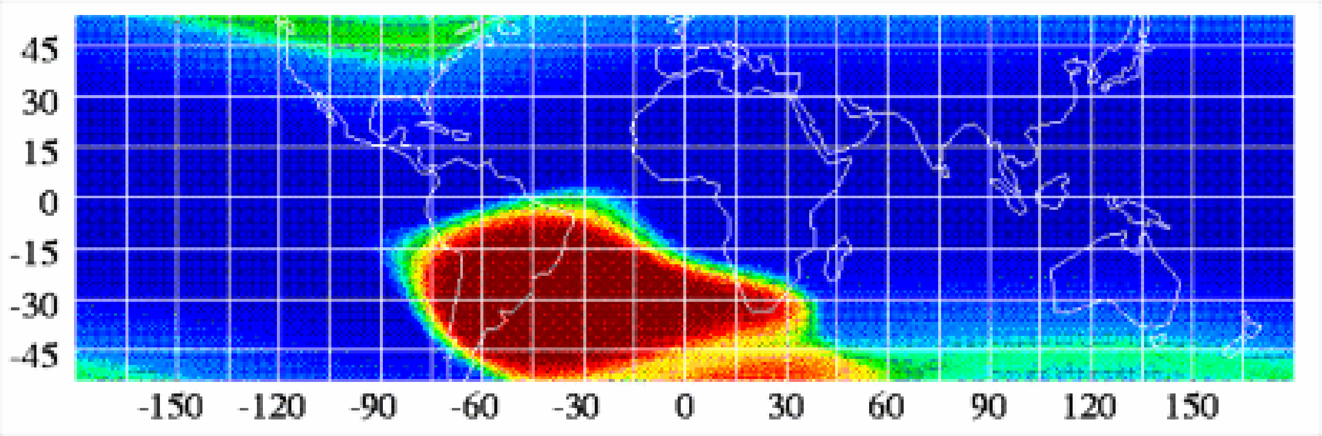
The inner belt (blue) contains predominantly high-energy protons and extends from the equator, up to 30° latitude at an altitude of about 1,000 - 10,000 km.



The outer belt, which contains high-energy electrons (purple), lies at an altitude of about 20,000 - 30,000 km and reaches 60° latitude. The intense particle fluxes in the radiation belts are hazardous to satellites, astronauts, and their equipment.

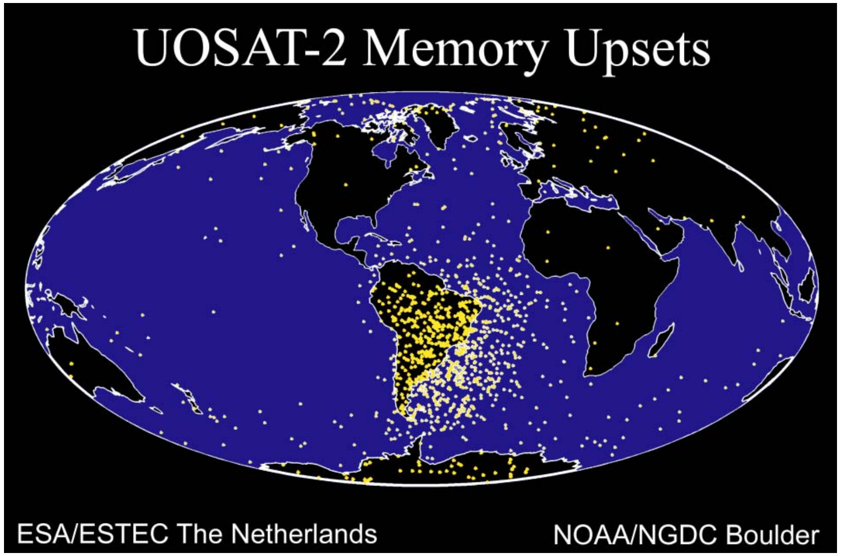
South Atlantic Anomaly

The Earth’s radiation belts are aligned with the magnetic axis of the Earth, which is tilted by 11 degrees from the rotation axis of the Earth, and are thus not symmetrically placed with respect to the Earth's surface. While the inner surface is 1200 - 1300 kilometers from the Earth's surface on one side of the Earth, on the other it dips down to 200 - 800 kilometers. Above South America, about 200 - 300 kilometers off the coast of Brazil, and extending over much of South America, the close portion of the Van Allen Belt forms what is called the South Atlantic Anomaly.



South Atlantic Anomaly

Satellites and other spacecraft passing through this region of space actually enter the Van Allen radiation belt and are bombarded by protons exceeding energies of 10 million electron volts at a rate of 3000 'hits' per square centimeter per second. This can produce 'glitches' in astronomical data, problems with the operation of on-board electronic systems, and premature aging of computer, detector and other spacecraft components.

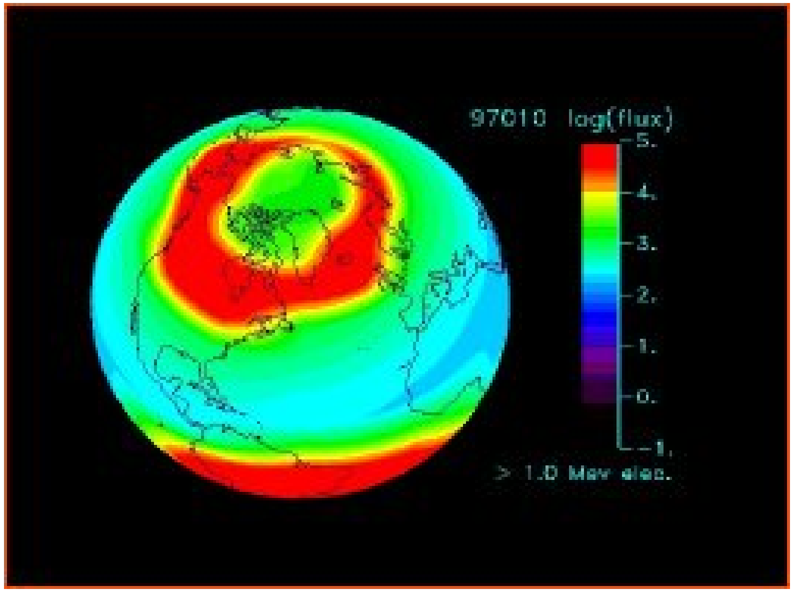


The Hubble Space Telescope passes through the 'SAA' for 10 successive orbits each day, and spends nearly 15 percent of its time in this hostile region. Astronauts are also affected by this region which is said to be the cause of peculiar 'shooting stars' seen in the visual field of astronauts.

High-Energy (Killer) Electrons

Termed "killer electrons" because of the damage they have been causing to spacecraft, these are trapped electrons accelerated to unusually high energies (more than 1 MeV). These electrons populate the outer radiation belt. Their concentration is highly variable and so prediction of the number and location of these particles is a major challenge for space weather research.

Sudden, thousand fold increases in the number of killer electrons in the outer radiation belt are sometimes observed during large geomagnetic storms. In these cases, killer electrons are the major environmental hazard for Earth orbiting spacecraft.



Killer electron intensity in the northern hemisphere measured by the satellite SAMPEX at 600 km altitude. The electrons are accelerated shortly after an interplanetary shock hits the magnetosphere and then propagate to low altitudes along the magnetic field.

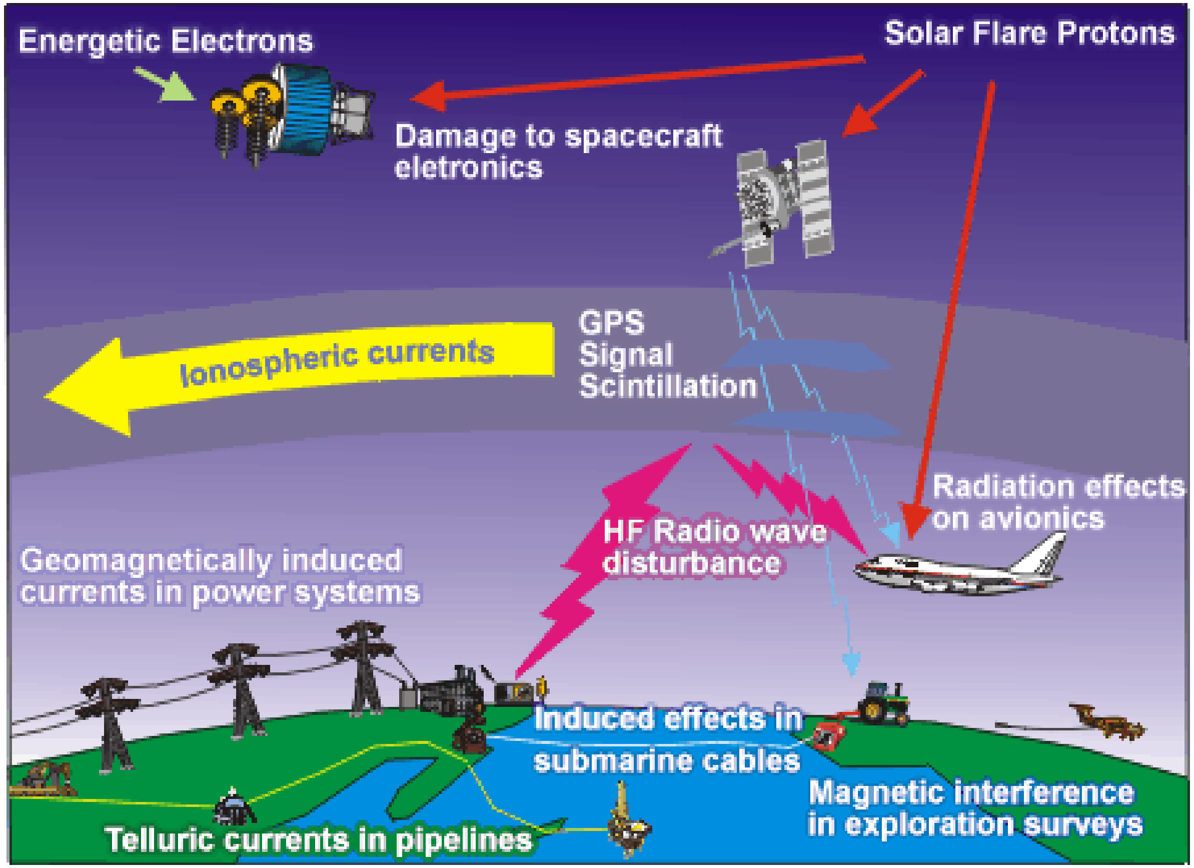
Geomagnetic Storms

When the dynamic pressure of the solar wind is enhanced, for example during the passage of an interplanetary shock, and the interplanetary magnetic field (IMF) is turned southward, a geomagnetic storm is likely to be triggered.

A magnetic storm changes the structure of the whole magnetosphere, from the radiation belts down to the ionosphere and upper atmosphere.

The visible signatures of geomagnetic storms are the aurora borealis and aurora australis. These phenomena may become visible at mid latitudes during large geomagnetic storms. Usually only visible close to the magnetic poles, large magnetic storms sometimes cause aurora over southern Europe or the United States.

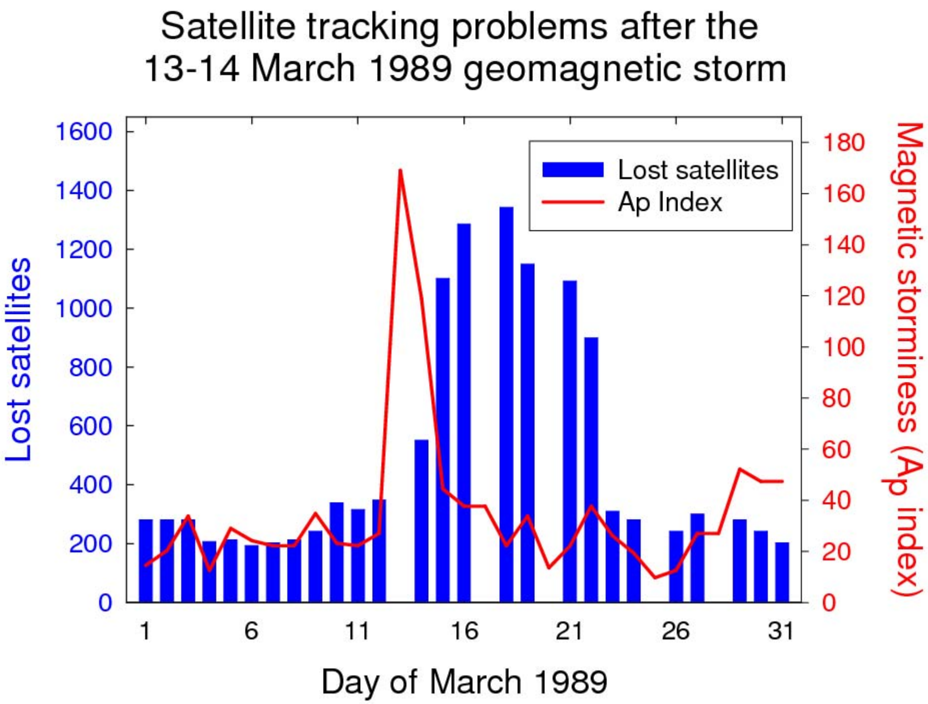
Geomagnetic storms



Geomagnetic storms often cause strong variations in the local space environment that operators must take into account in order to ensure that these systems continue to operate and provide us with the services and data we rely on.

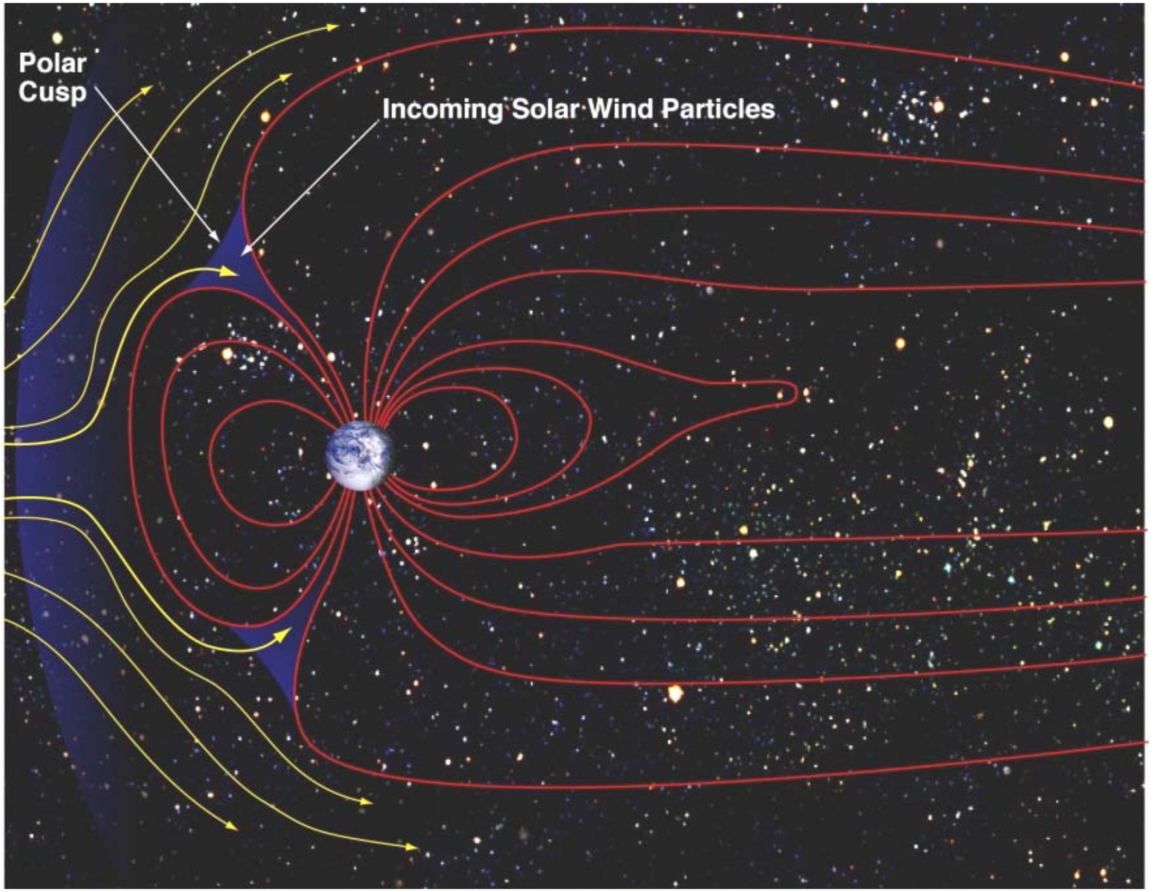
Interplanetary shock waves and geomagnetic storms

Fast, interplanetary shock waves literally shake up the whole heliosphere! As they travel away from the Sun, they disrupt the spiral pattern of the background interplanetary magnetic field. CMEs travelling with speeds above 400 km/s produce a shock wave in front of the ejected material. Energetic particles can be produced both by solar flares and by interaction with interplanetary shocks. These particles, made up of atomic nuclei, protons and electrons, arrive at the Earth with velocities of the order of 1/3 of the speed of light.

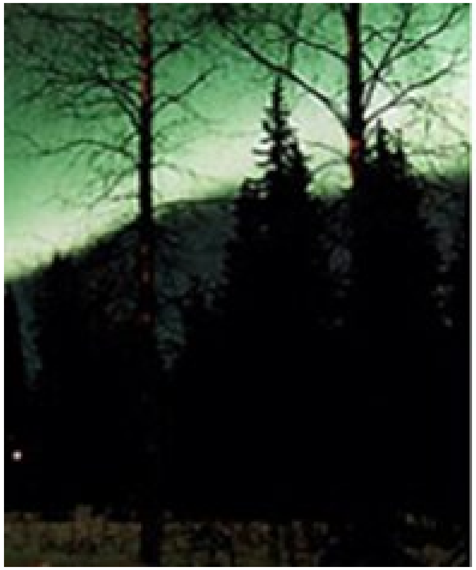


Magnetosphere

A small fraction of solar particles enters the Earth‘s magnetosphere through what is called the Polar Cusp region. These particles give rise to polar lights which are most frequently observed in the ionosphere around the so-called aurora oval.

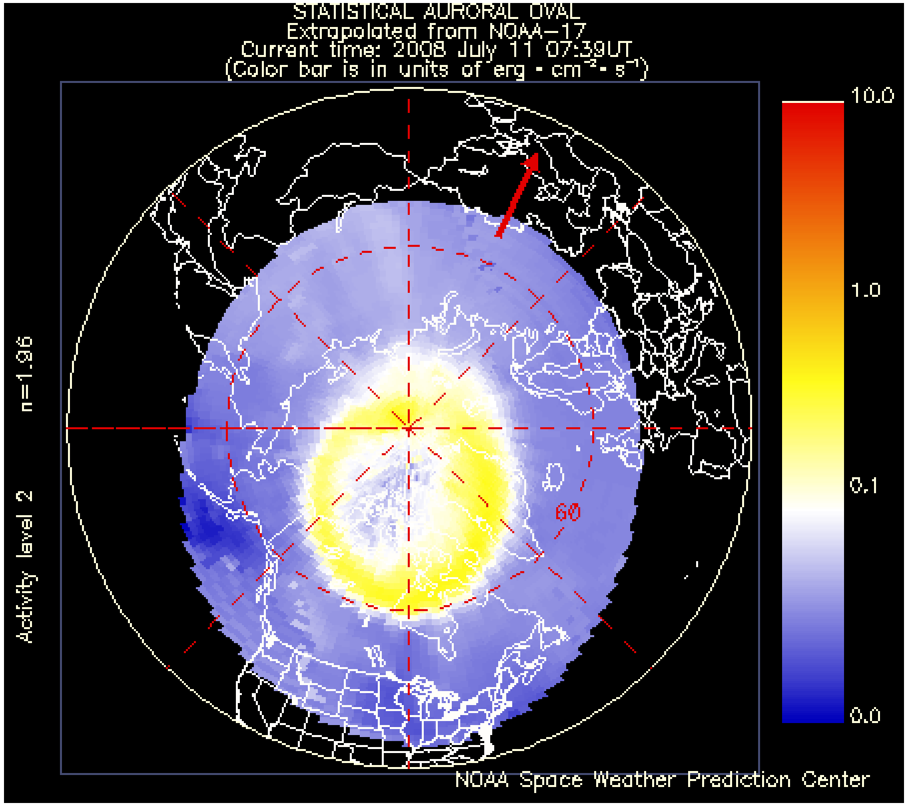


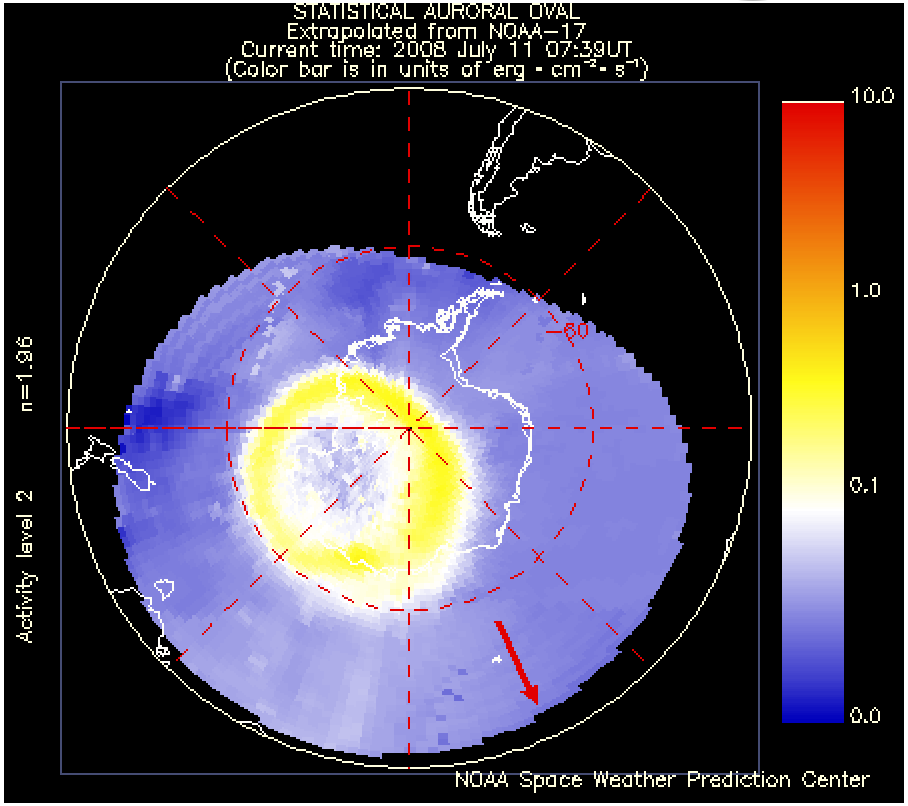
Magnetosphere, Ionosphere and Atmosphere



A small part of the solar wind energy enters the magnetosphere, is stored temporarily and is released in sudden surges. This energy release can be observed in the ionosphere as polar lights, which are caused by charged particles accelerated along the magnetic field lines into the atmosphere and exciting atmospheric molecules and atoms near local midnight.

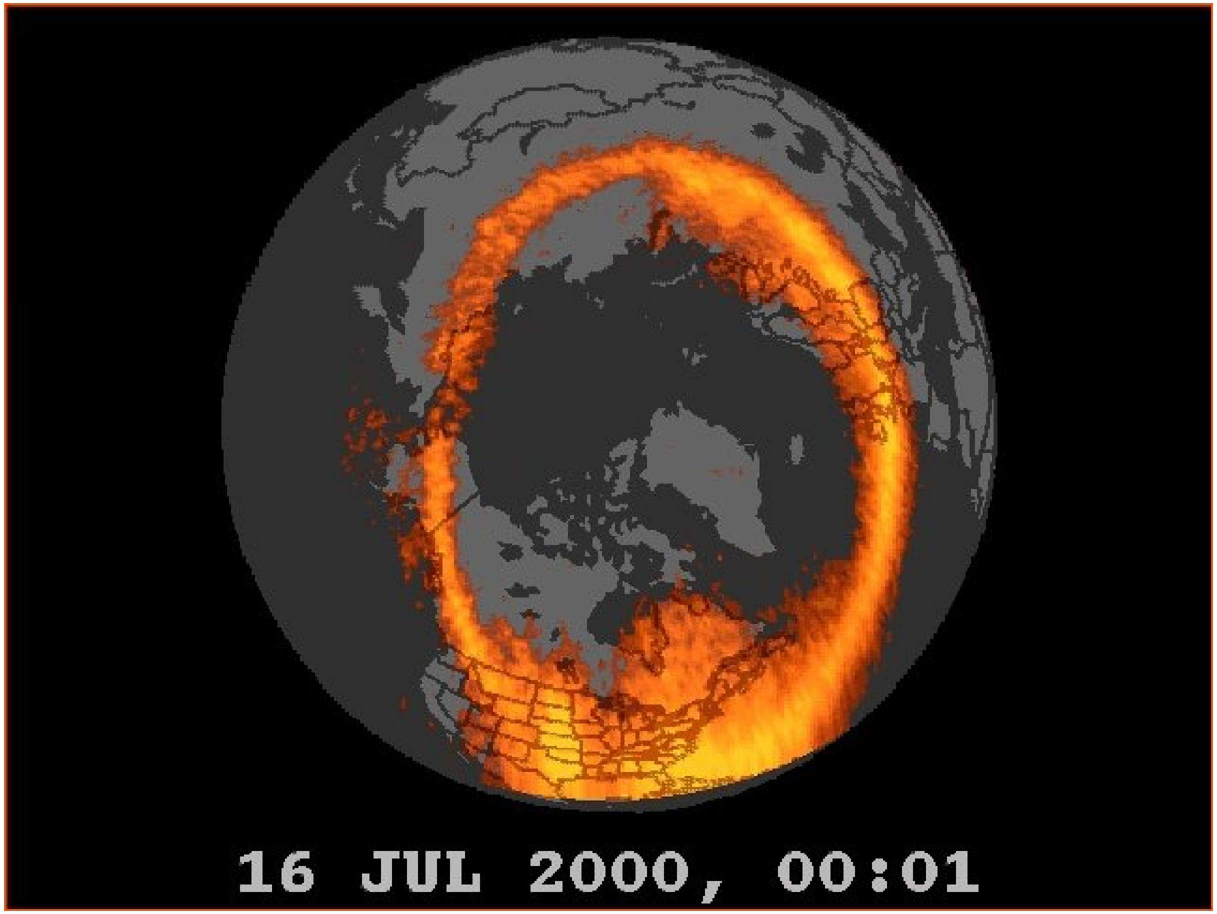
Aurora oval





The plots shows the extent and position of the auroral oval in the northern and in the southern hemisphere, extrapolated from measurements taken during the polar pass of the NOAA POES satellite.

Bastille day aurora on the northern hemisphere.

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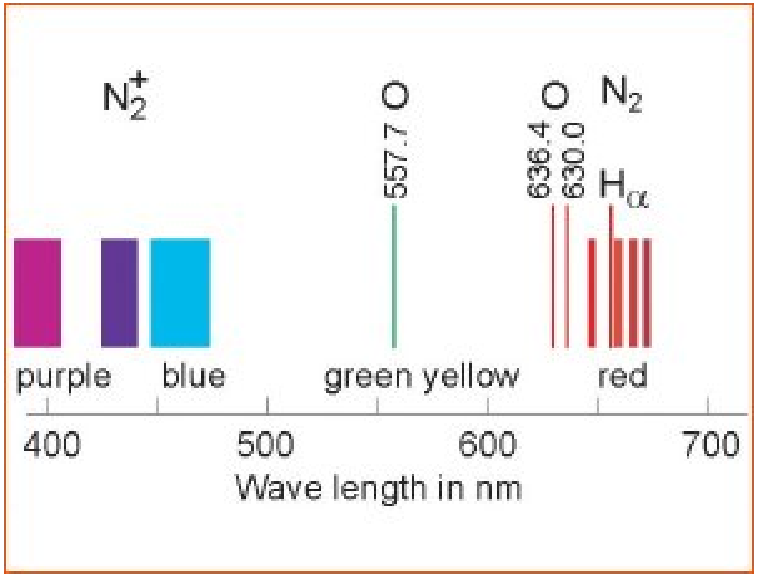
What causes polar lights?

Electrons precipate from the magnetosphere into the upper atmosphere (ionosphere) by spiralling around the geomagnetic field lines.

At altitudes between 500 and 90 km precipitating electrons will hit atmospheric molecules and atoms. These atmospheric constituents gain energy in the collision and subsequently emit light in a similar way to the gas in a flourescent lamp.

The colour of the light depends on the chemical nature of the atmospheric atom or molecule involved in the collision:

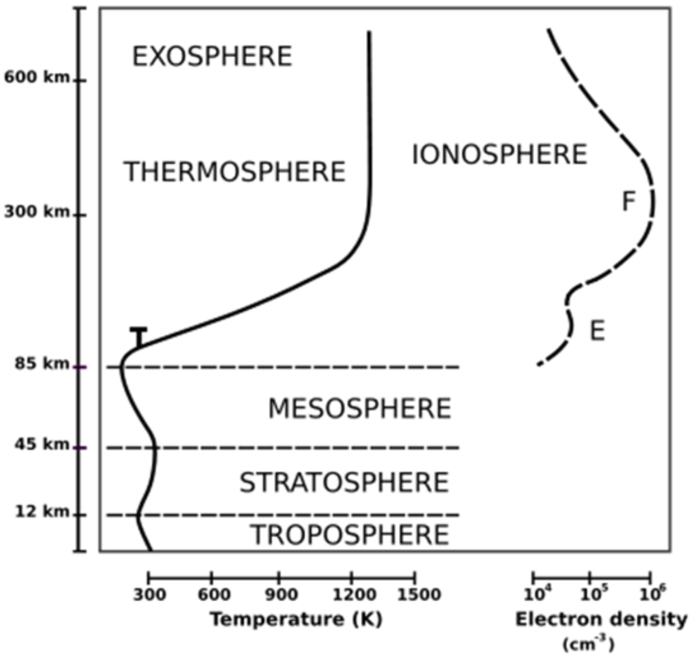
- oxygen emits green and red light
- hydrogen emitts red light
- nitrogen emits violet and blue light.



Ionosphere

At heights above 80 km, in the thermosphere, the atmosphere is so thin that free electrons can exist for short periods of time before they are captured by a nearby positive ion.

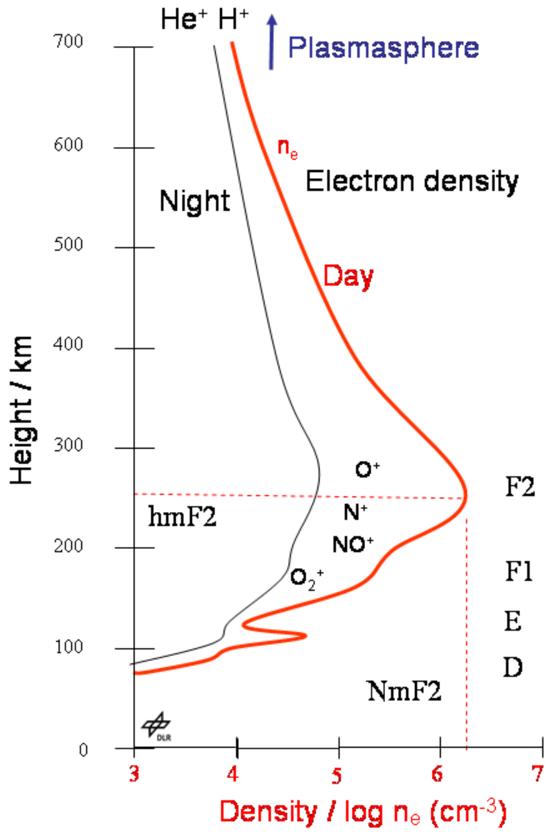
The number of these free electrons is sufficient to affect radio propagation. This portion of the atmosphere is *ionized* and referred to as the ionosphere.



Ionosphere

The vertical structure of the electron density in the ionosphere forms several distinct layers. In analogy to terrestrial weather, the ionosphere is highly dynamic and variable. The most important variation is due to the diurnal variation of solar radiation. This causes a peak in ionisation shortly after noon and a minimum just before sunrise. Since solar illumination also depends on the season, and the geographic location, the same variation is seen in ionospheric density.

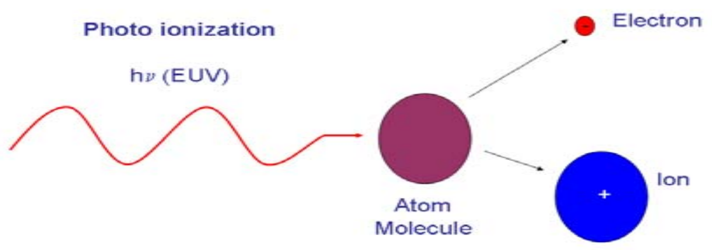
The most important ions are also indicated.



Ionosphere

The ionization depends primarily on the Sun and its activity. The amount of ionization in the ionosphere thus varies greatly with the amount of radiation received from the sun.

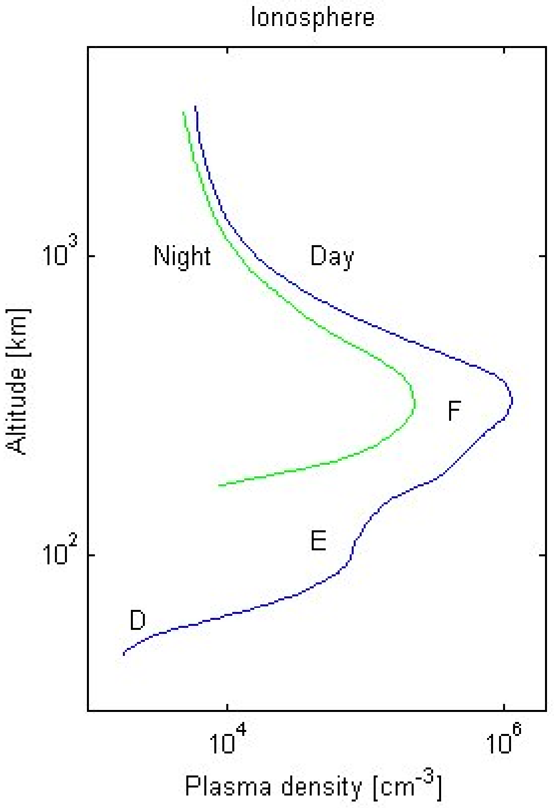
Solar radiation at ultraviolet (UV) and shorter X-Ray wavelengths are *ionizing* atoms and moelcues since photons at these frequencies are capable of dislodging an electron from a neutral gas atom or molecule during a collision.



At the same time, however, an opposing process called recombination takes place in which a free electron is "captured" by a positive ion. As the gas density increases at lower altitudes, the recombination process accelerates since the gas molecules and ions are closer together. The point of balance between these two processes determines the degree of ionization present at any given time.

Ionospheric layers

Solar radiation, acting on the different compositions of the atmosphere with height, generates layers of ionization called D, E, and F layers.



D layer

The D layer is the innermost layer, 50 km to 90 km above the surface of the Earth. Ionization here is due to hydrogen Lyman-α radiation at a wavelength of 121.5 nm ionizing nitric oxide (NO). In addition, when the sun is very active with hard X-rays (wavelength < 1 nm) it can ionize the air molecules (N_2, O_2).

Recombination is high in the D-layer. During the night, cosmic rays produce a residual amount of ionization.

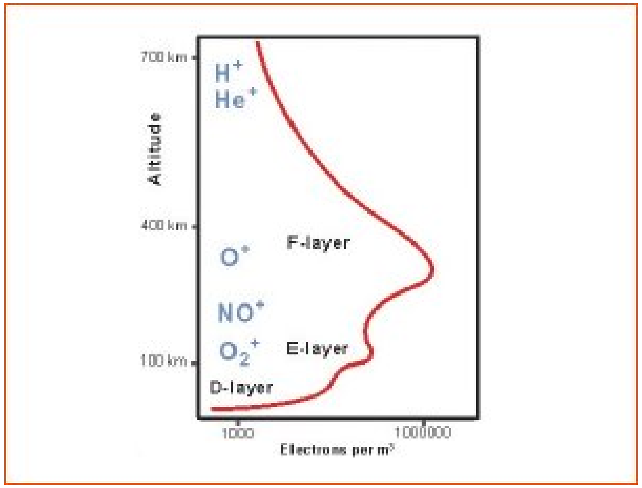
Ionospheric E layer

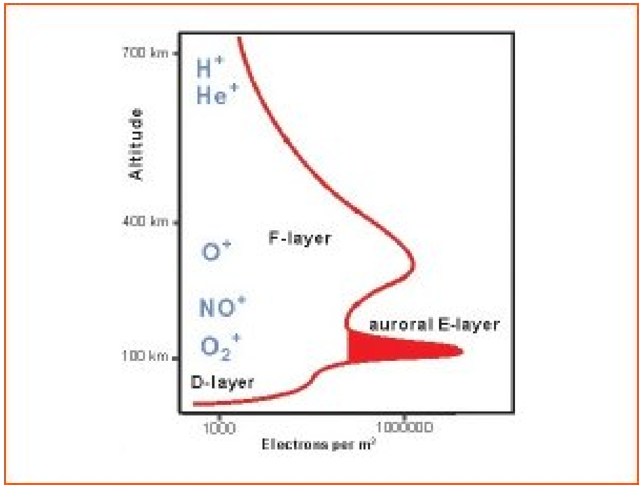
The E layer is the middle layer, 90 km to 120 km above the surface of the Earth. Ionization is due to soft X-rays (1-10 nm) and far ultraviolet (UV) solar radiation. This layer can only reflect radio waves having frequencies less than about 10 MHz. It has a negative effect on frequencies above 10 MHz due to its partial absorption of these waves.

The vertical structure of the E layer is primarily determined by the competing effects of ionization and recombination. At night the E layer begins to disappear because the primary source of ionization is no longer present. This results in an increase in the height where the layer maximizes because recombination is faster in the lower layers. Diurnal changes in the high altitude neutral winds also play a role. The increase in the height of the E layer maximum increases the range to which radio waves can travel by reflection from the layer.

The Ionosphere during Aurora

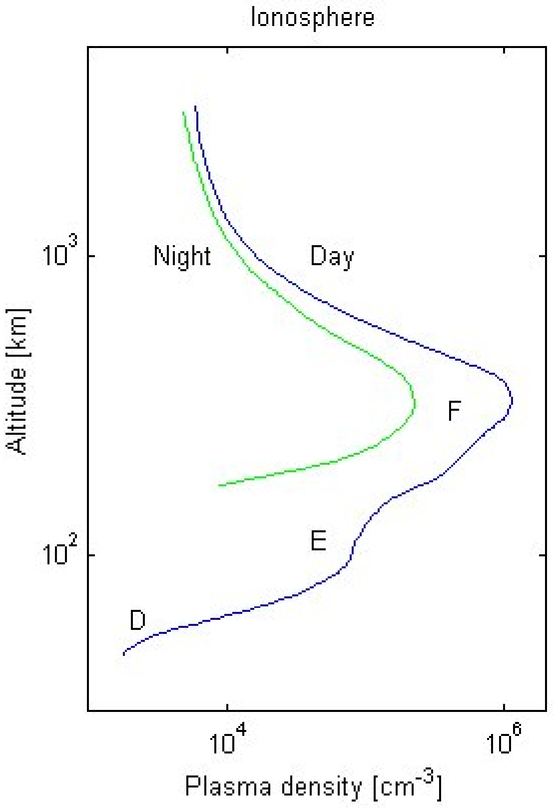
During geomagnetic storms, energetic electrons penetrate down to altitudes between 130 and 90 km at high latitudes. There they hit atmospheric gas molecules and ionise them in a similar way to the solar UV radiation. A strong increase in the ionospheric electron density is the consequence: an auroral E-layer is formed.





Ionospheric F layer

The F layer or region, also known as the Appleton layer, is 120 km to 400 km above the surface of the Earth. It is the top most layer of the ionosphere. Here extreme ultraviolet (UV) (10-100 nm) solar radiation ionizes atomic oxygen (O). The F region is the most important part of the ionosphere in terms of HF communications. The F layer combines into one layer at night, and in the presence of sunlight (during daytime), it divides into two layers, the F_1 and F_2. The F layers are responsible for most skywave propagation of radio waves, and are thickest and most reflective of radio on the side of the Earth facing the sun.



Ionosphere

Thus there is a diurnal (time of day) effect and a seasonal effect. The local winter hemisphere is tipped away from the Sun, thus there is less received solar radiation. Radiation received also varies with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions).

The activity of the sun is associated with the sunspot cycle, with more radiation occurring with more sunspots.

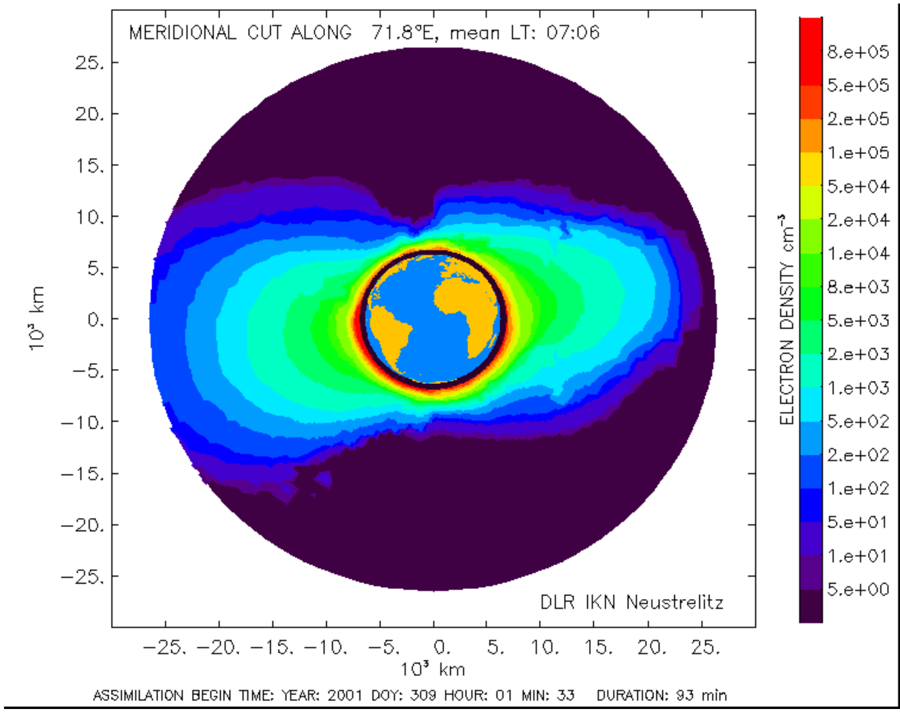
Additionally, charged particles of solar origin, travelling with the solar wind, can precipitate into the atmosphere causing polar lights and ionization in the lower ionosphere.

There are also mechanisms that disturb the ionosphere and decrease the ionization. There are disturbances such as solar flares and the associated release of energetic charged particles which reach the Earth and interact with its geomagnetic field.

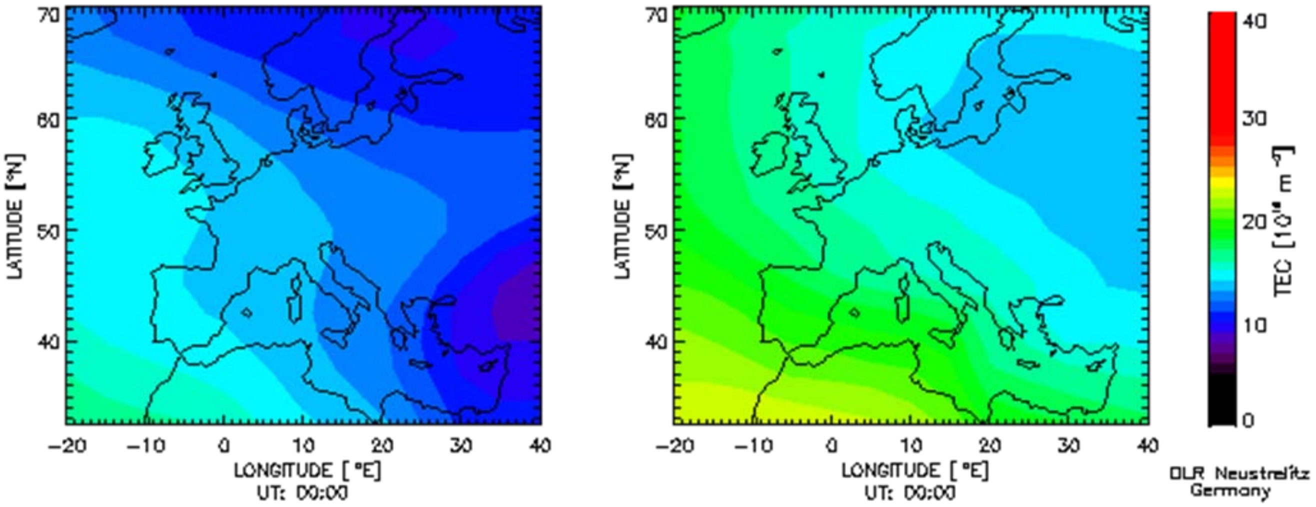
Total electron content (TEC)

The total electron content (TEC) is an important descriptive quantity for the ionosphere of the Earth. TEC is the total number of electrons present along a path between two points, with units of electrons per square meter, where 10^{16} electrons/m^2 = 1 TEC unit (TECU).

TEC is significant in determining scintillation and group delay of a radio wave through a medium. Ionospheric TEC is characterized by observing carrier phase delays of received radio signals transmitted from satellites located above the ionosphere, often using Global Positioning System satellites. TEC is strongly affected by solar activity.



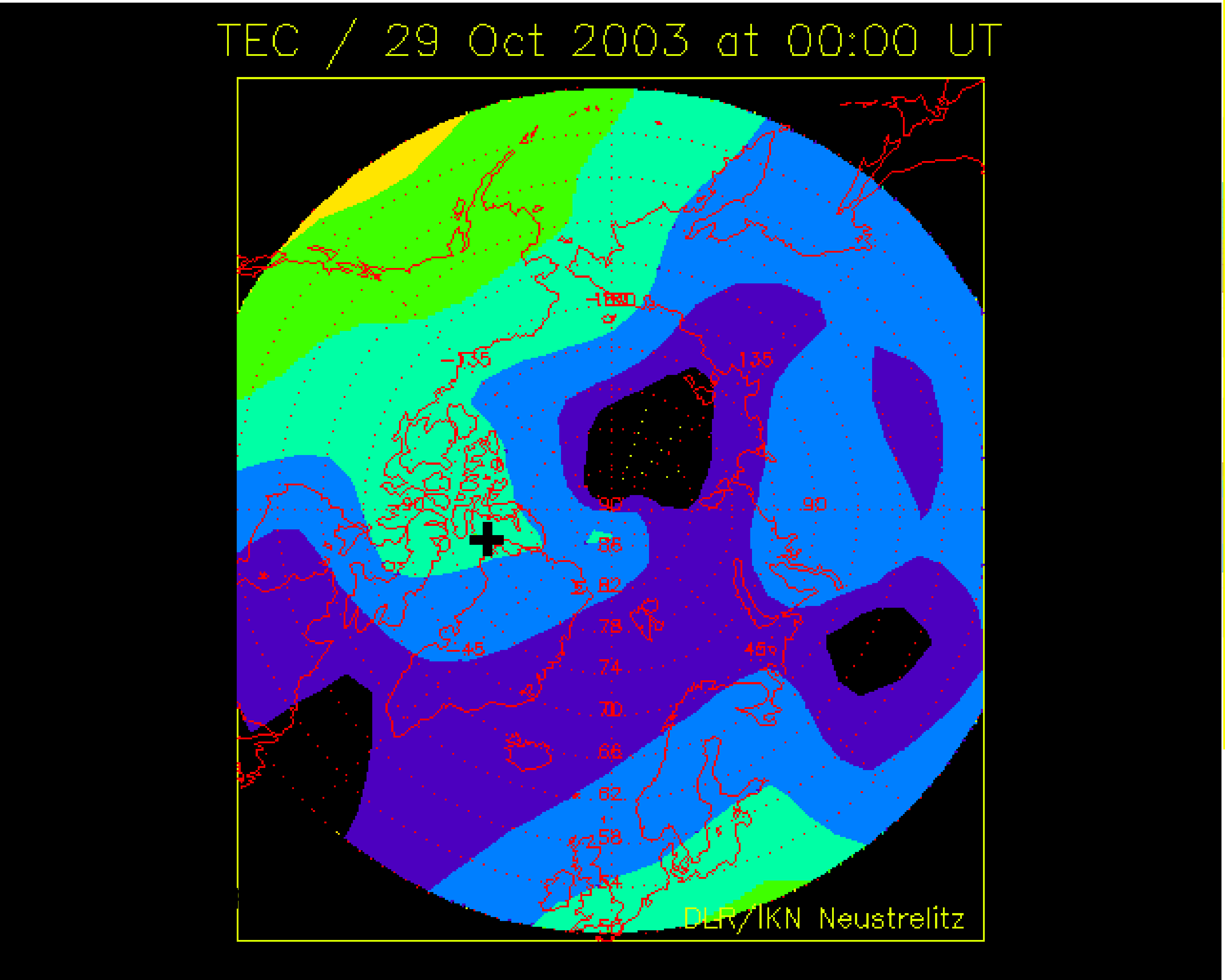
Total electron content (TEC)



The strong solar radiation control of the formation of the ionosphere is illustrated by the ionosphere response on the solar eclipse on 11 August 1999.

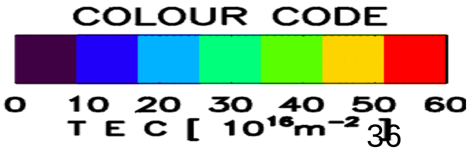
Since the solar radiation is switched off or reduced for a while, the total ionisation is strongly reduced during the eclipse that moved across Europe around about 10-11 UT. The movie is deduced from ground-based GPS measurements of the Total Electron Content (TEC) of the ionosphere. Source: DLR/ Institute of Communications and Navigation, © DLR

Polar TEC during geomagnetic Storm

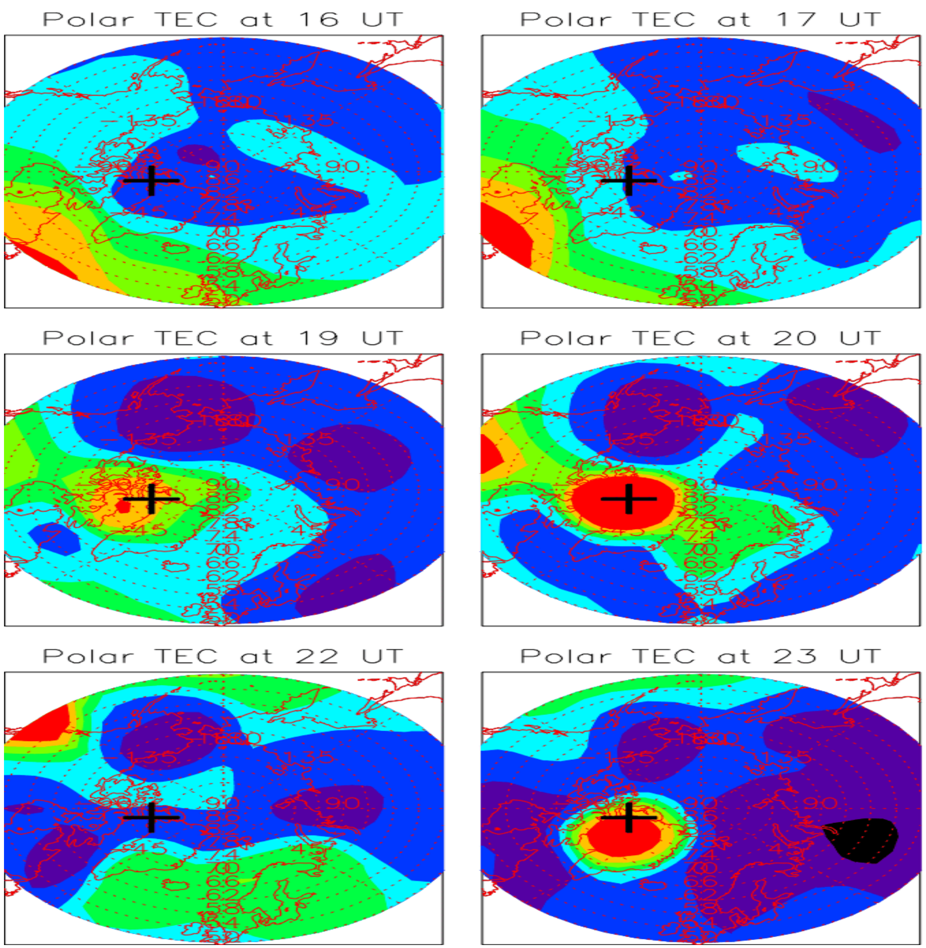


Polar TEC on 29 October 2003 derived from IGS ground based measurements

Map resolution
Time: 10 min
Latitude: 2.5 deg
Longitude: 7.5 deg



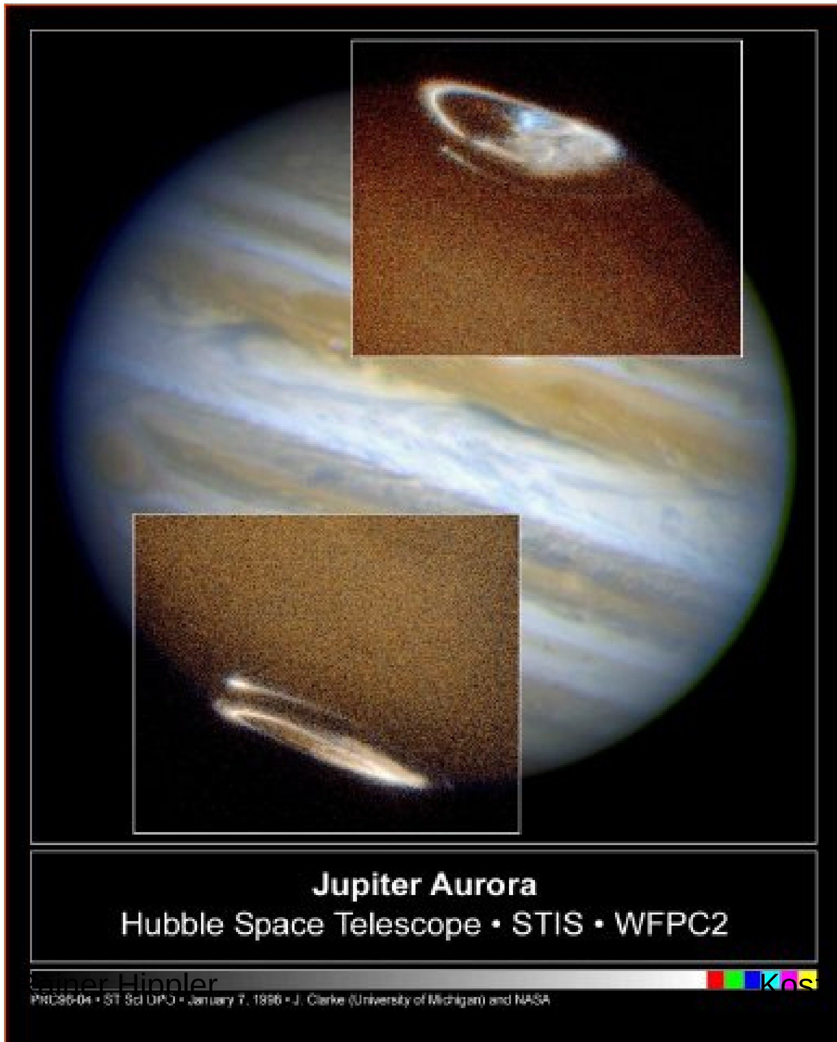
Storm on 29 October 2003 / Polar TEC

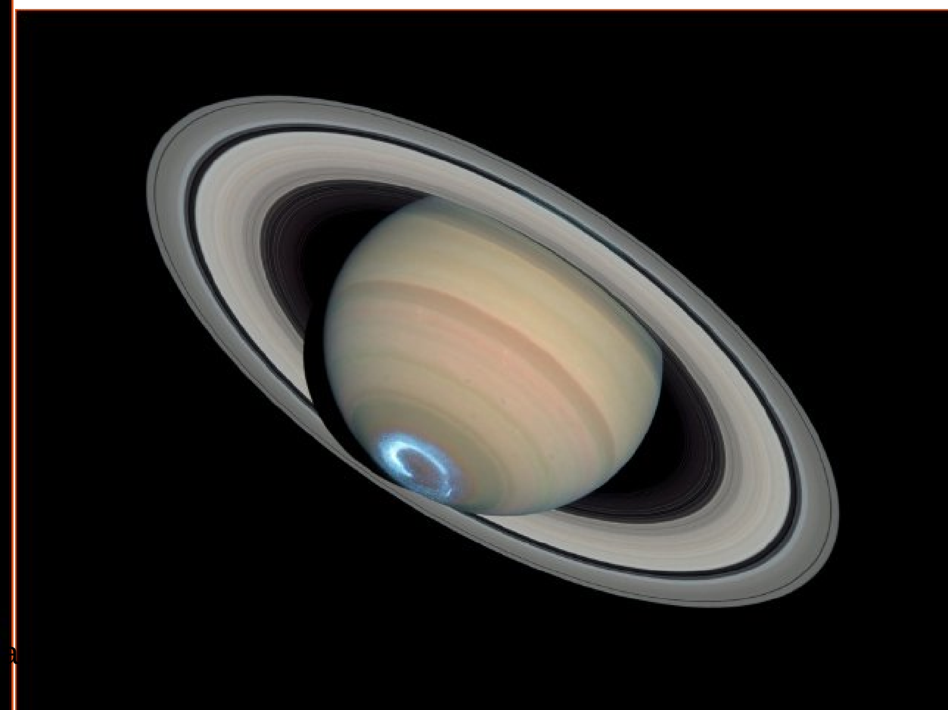


Polar TEC on 29 October 2003 derived from IGS ground based measurements

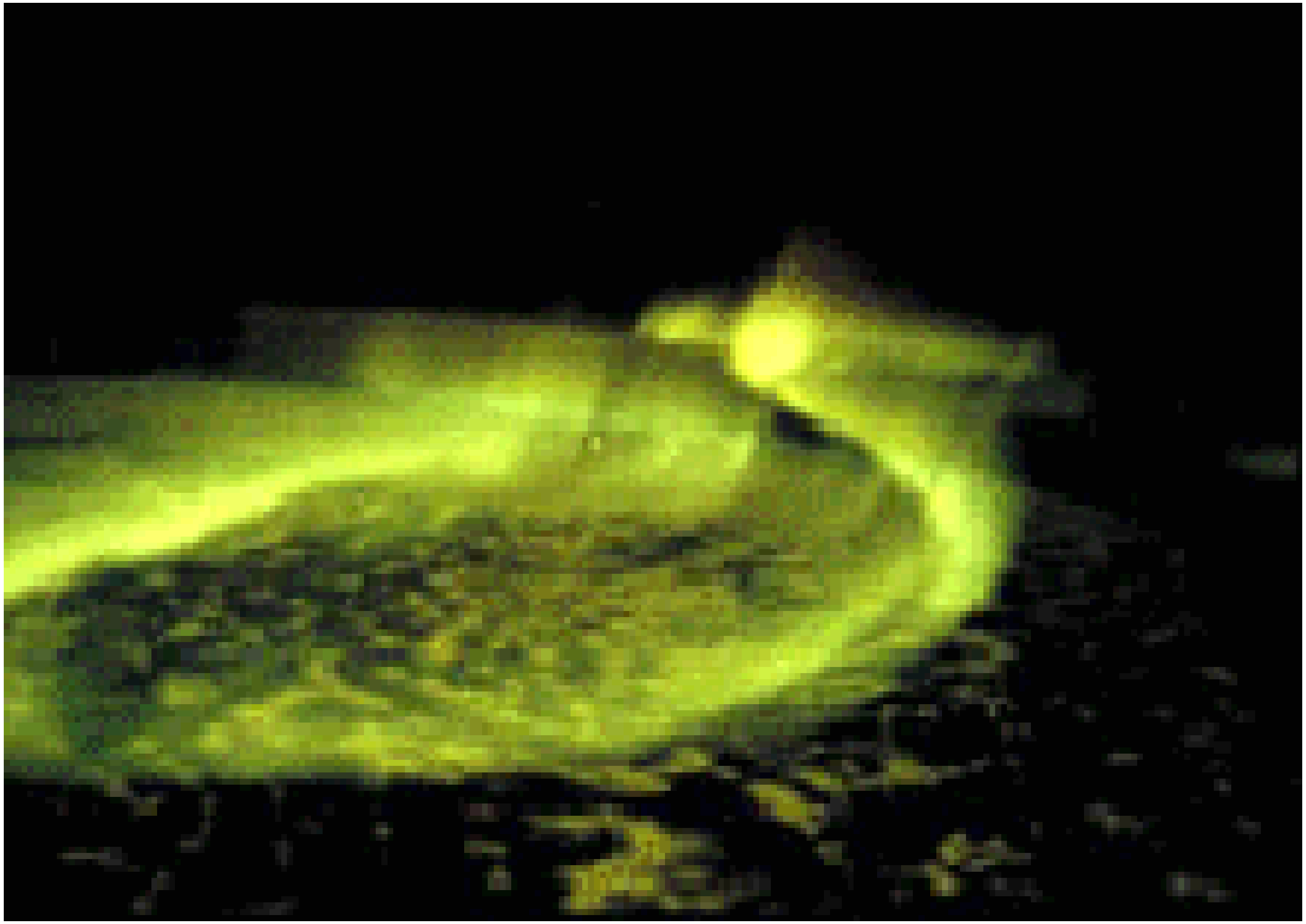
Map resolution
Time: 10 min
Latitude: 2.5 deg
Longitude: 7.5 deg

Aurorae on the planets Jupiter (left) and Saturn (right).





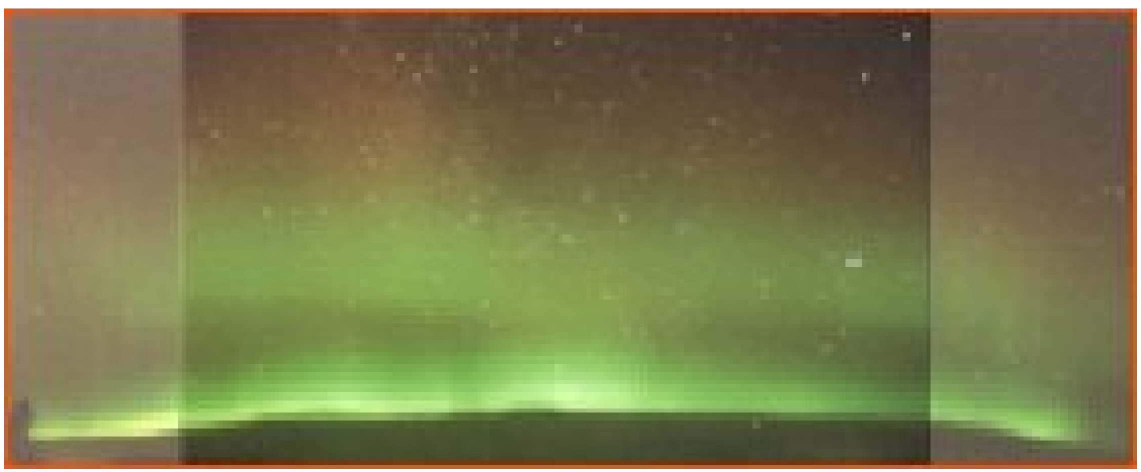
Aurora borealis
(as observed from the space)



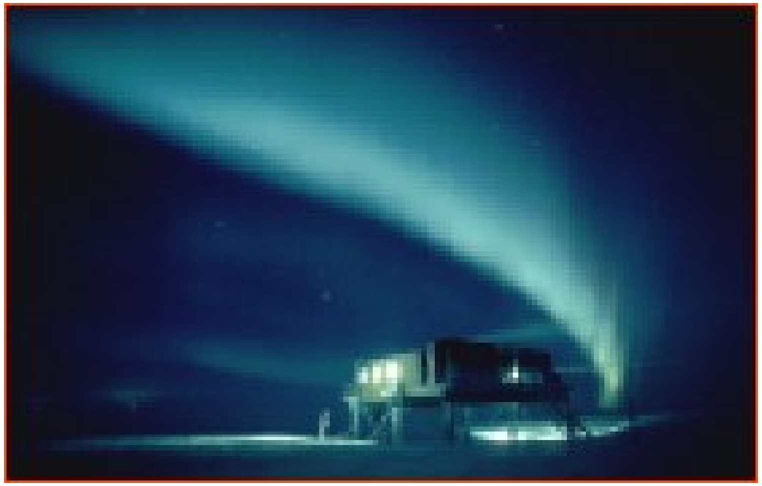
Aurora above an astronomical observatory.

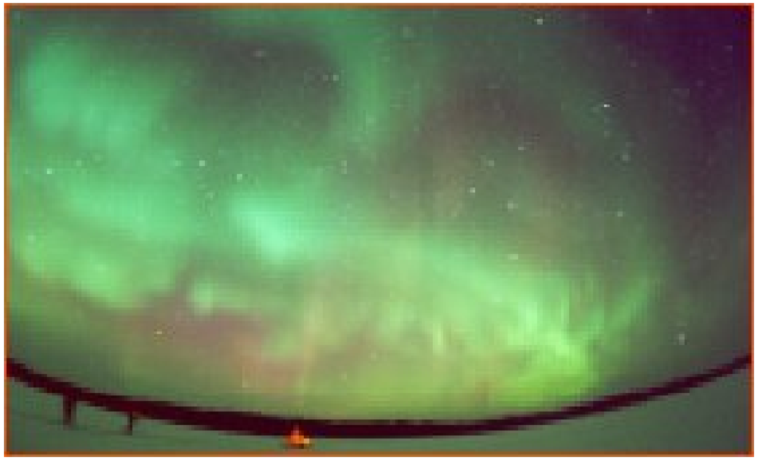
Aurora in Alaska observed during March 2007.

Auroral Gallery - Forms



Auroral Gallery - Forms





Auroral Gallery - Colors

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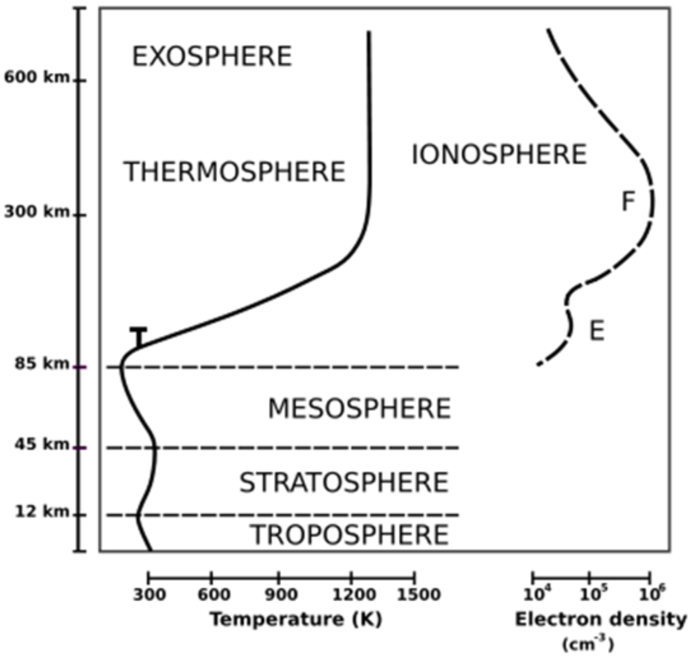
Aurora – Historic art work

Atmosphere

The lowest part of the Earth's atmosphere is called the troposphere and it extends from the surface up to about 10 km.

The atmosphere above 10 km is called the stratosphere, followed by the mesosphere. It is in the stratosphere that incoming solar radiation creates the ozone layer.

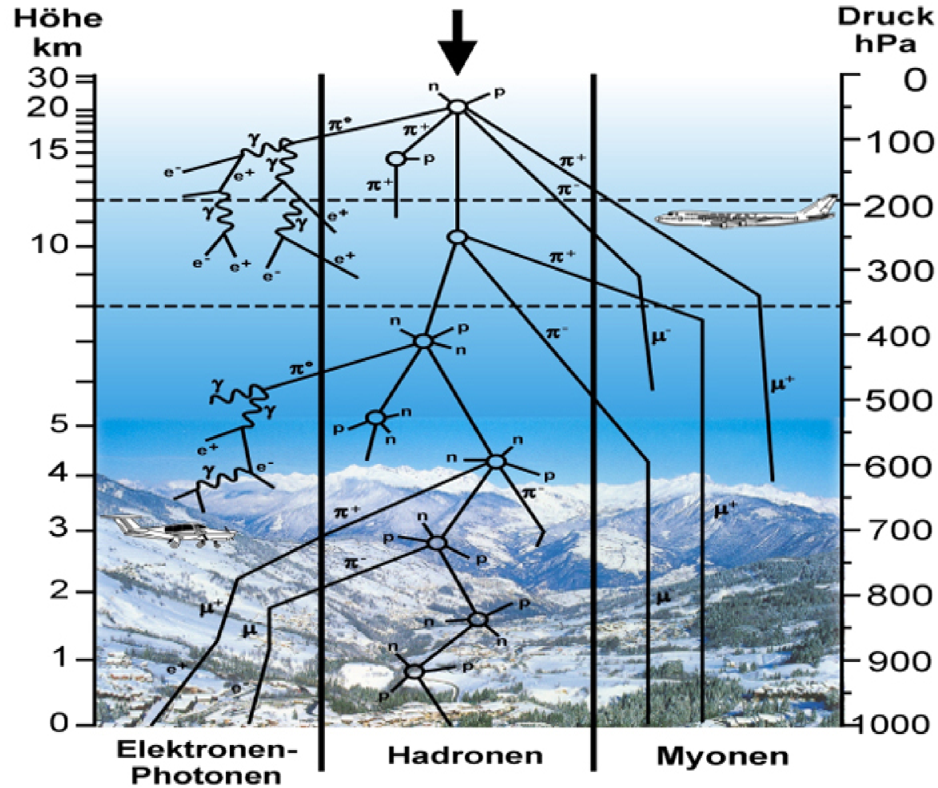


Earth under Air-Shower Attacks

Galactic cosmic rays collide with constituents of the Earth's atmosphere, generating many new highly energetic particles. These particles can pass through the Earth's atmosphere, eventually reaching the ground in a so-called "cosmic ray air-shower".

At the cruising altitudes of passenger aircraft (10-12 km), the number of these energetic particles is about 1000 times higher than at an altitude of 25 km.

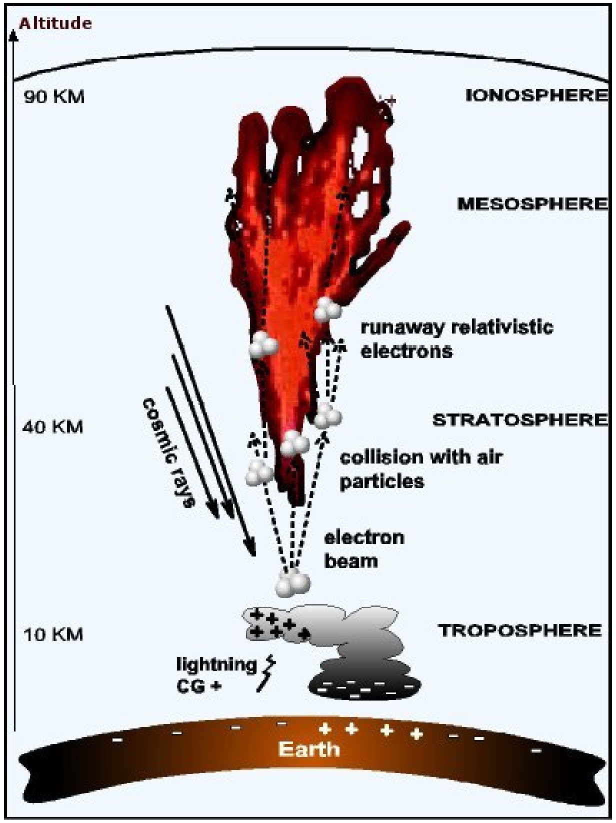
As these particles carry high energies they are able to penetrate many types of material. These might include electronic systems both onboard aircraft and on the ground. Passengers and crew onboard aircraft may also come into contact with these particles. Recent research has also shown that terrestrial climate might be influenced by cosmic rays.



Natural discharge (lightning)

Red Sprite

Upwards directed discharge



Ball Lightning


Thank you
Plasma Physics for Applications