The Polar Ionosphere

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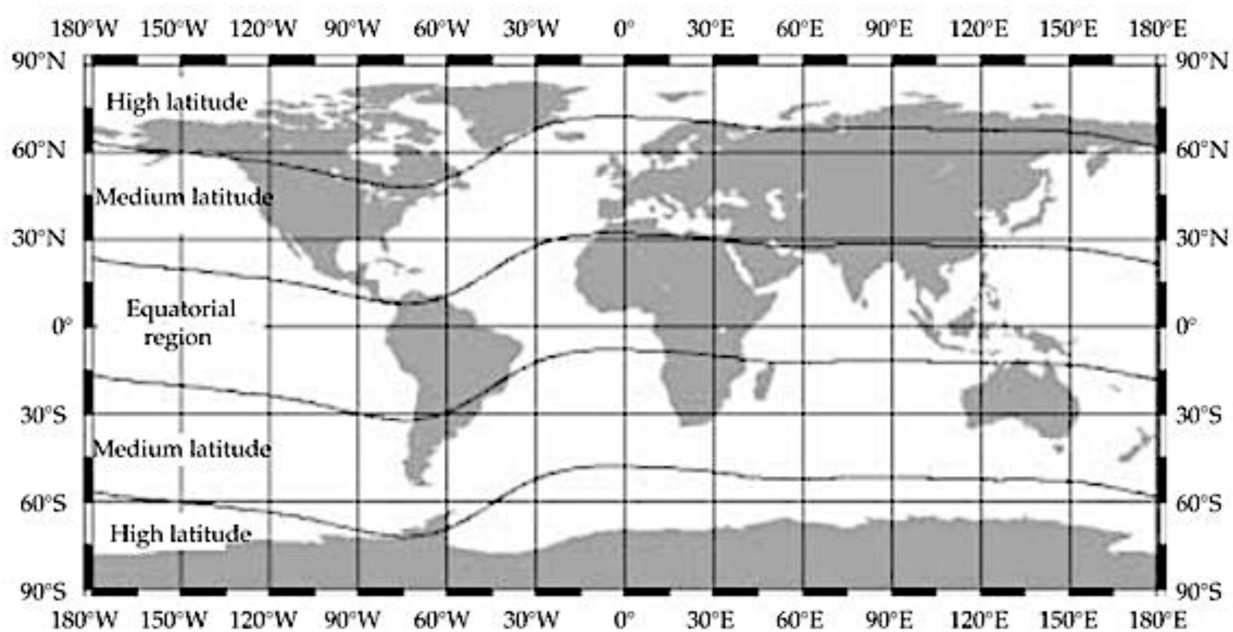
www.skywave-radio.org

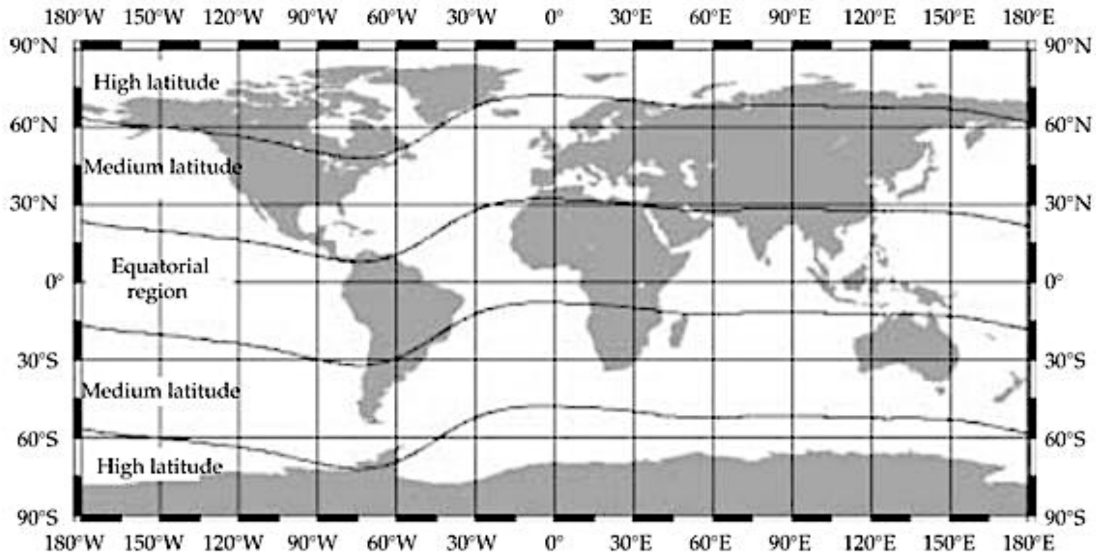
The Ionosphere Changes With Latitude



ResourceGate.net

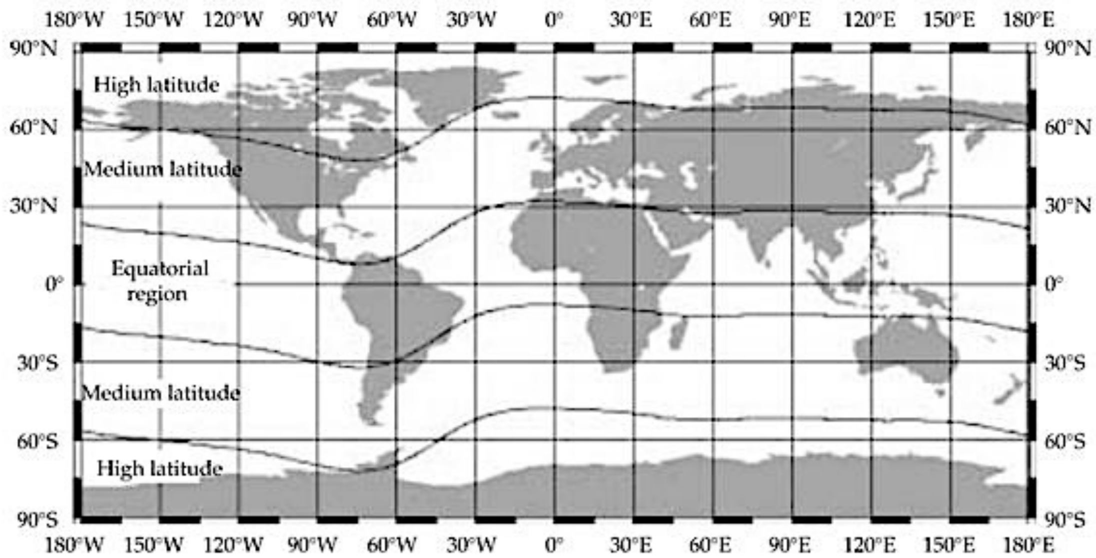
- The Earth's magnetic field exerts a considerable influence over the ionosphere, separating the ionosphere into three broad regions.
  - The low-latitude (equatorial) region,
  - Mid-latitude region (the most studied and well understood), and
  - The high-latitude (polar) region

The Ionosphere Changes With Latitude



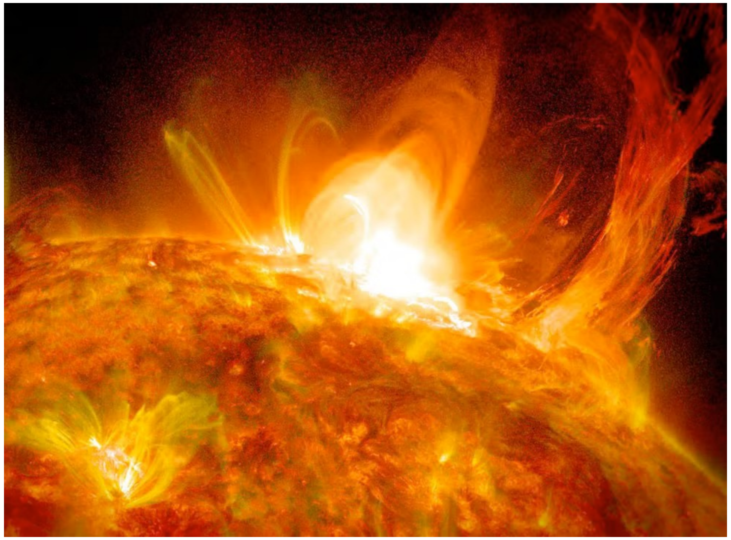
- The phenomena that occur at mid-latitudes also occur at both the high and low latitudes, including:
  - Ionization of the upper atmosphere by solar Extreme Ultra-Violate (EUV) radiation,
  - Diurnal and seasonal variation in the ionosphere
  - Changes in the ionosphere created by the 11 year solar cycle

The Ionosphere Changes With Latitude

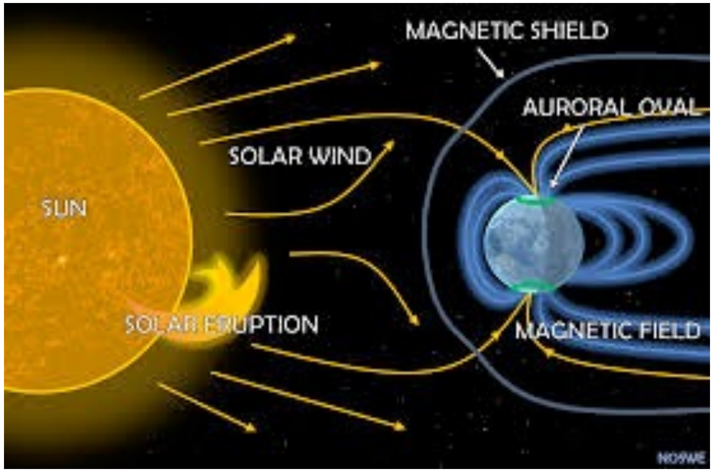


- In addition the low and high latitudes each have phenomena that are unique to their particular regions.
- Consequently, the high-latitude ionosphere bears little resemblance to the low latitude region, and both are considerably different from the mid-latitude ionosphere.

Polar Region Environment



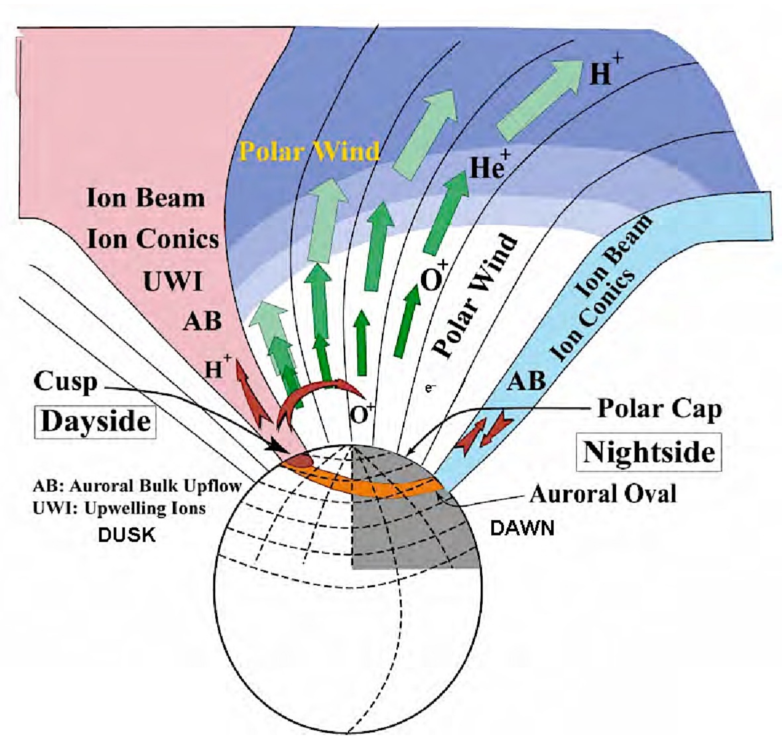
NASA

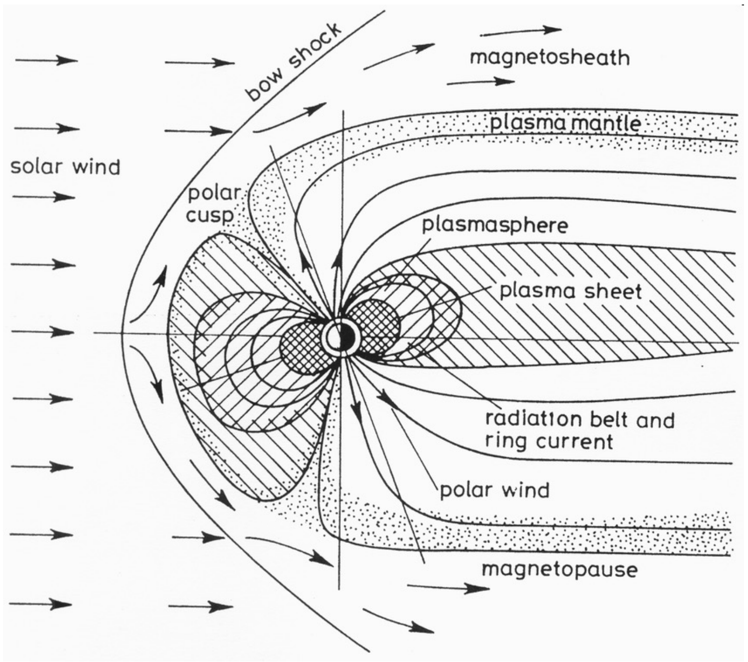


UiT

- In a sense, the two polar regions are Earth's garbage pits for all of the junk, thousands of tons of it, arriving at Earth from turbulent events occurring on the Sun.
- The junk consists of atomic protons, electrons, and alpha particles
- These are the remains of hydrogen & helium atoms ionized by violent events occurring on the Sun.
- Hydrogen and helium, of course, being the primary constituents of the Sun.

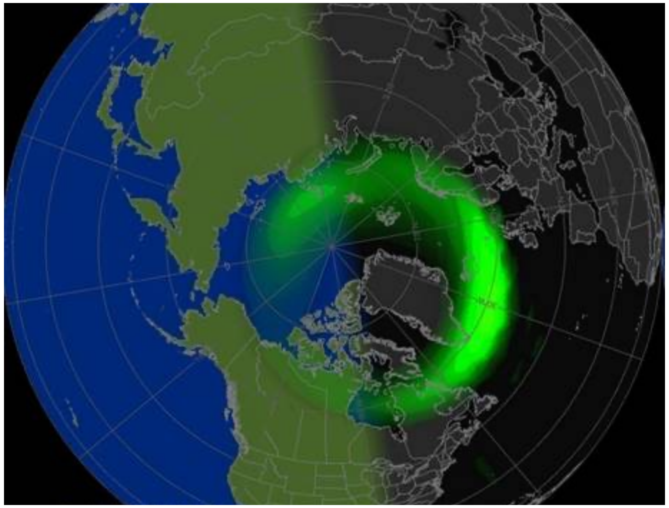
Polar Region Environment





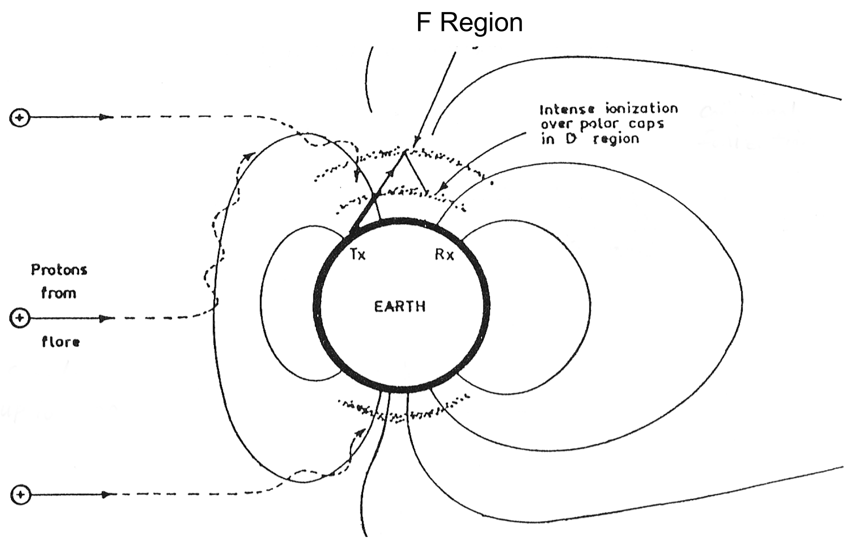
- Some of the chaos in the polar regions are of Earth's own making
- Over 50 tons per day of hydrogen, helium, and oxygen ions escape from Earth's upper polar ionosphere into the magnetosphere

Polar Region Environment



- Yet, in all of this chaos there is beauty in the polar region aurora light displays and in the auroral ovals
- The polar regions are like no other place on Earth
- Within this environment, and because of it, exists the very complex high latitude ionosphere

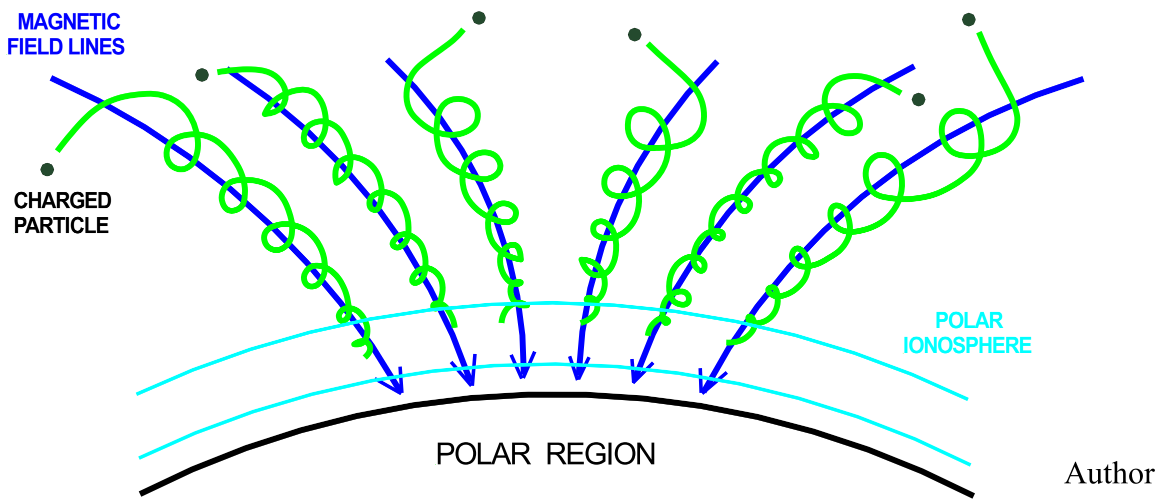
Earth's Magnetic Field Lines



McNamara

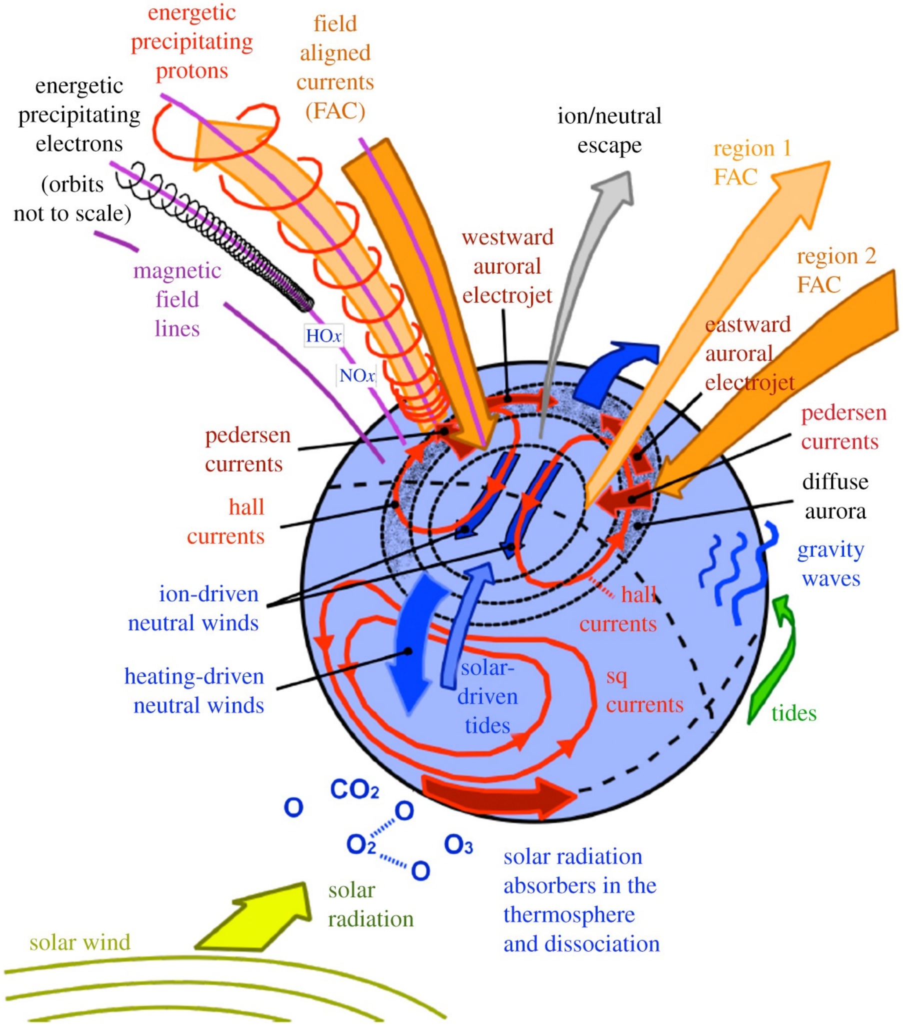
- Charged particles from the Sun can not cross Earth's magnetic field
- Instead they are forced to spiral along the field lines
- Magnetic field lines parallel to Earth's surface shield the equatorial region from the solar winds and energetic charged particles emanating from the Sun.
- This is not the case at high latitudes.
- The magnetic field lines are nearly vertical in the polar regions.

High Latitude Vertical Magnetic Field



- Vertical field lines exposes the high latitude ionosphere to the full fury of the solar wind
- Particles spiral downward around the magnetic field lines deep into the polar atmosphere severely disrupting the high latitude ionosphere
- For this reason the high latitude ionosphere is far more complex than the ionospheres in the mid-latitude and equatorial regions.

High Latitude Region is Very Complex



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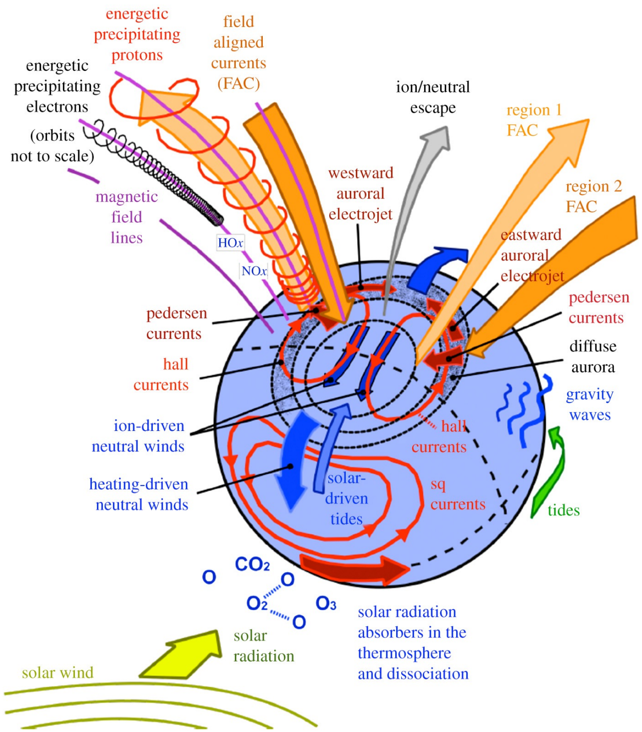
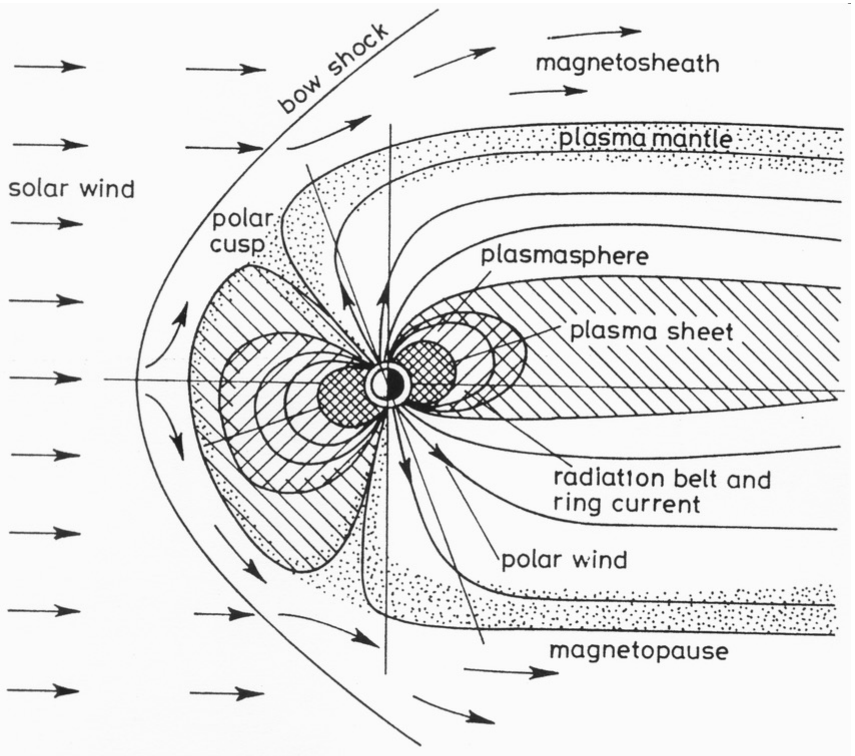
- Earth's high latitude zone is a very complex place with
  - Multiple electric fields,
  - Electrical currents,
  - Particle in flows, and
  - Particle out flows
- This complexity is due entirely to Earth's magnetic field being nearly vertical at high latitudes

Earth's Magnetosphere

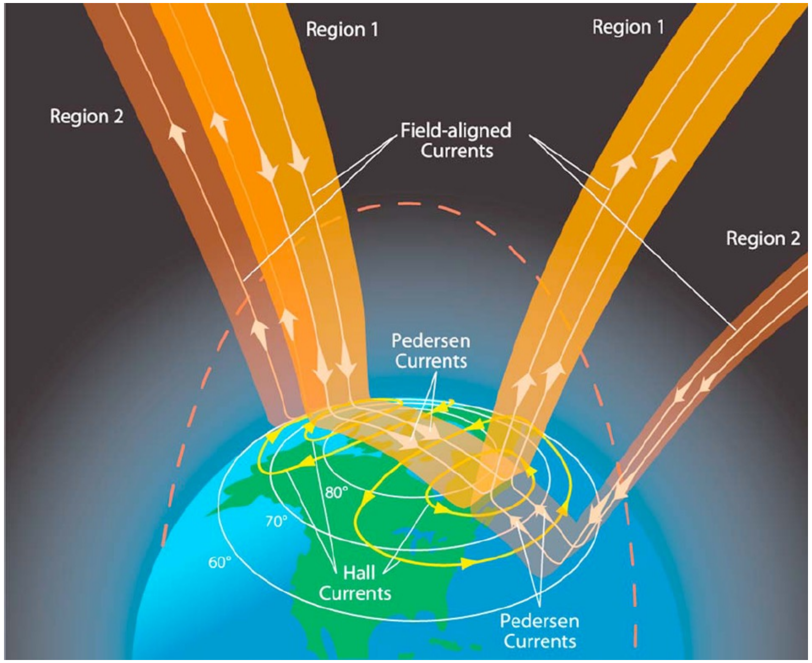




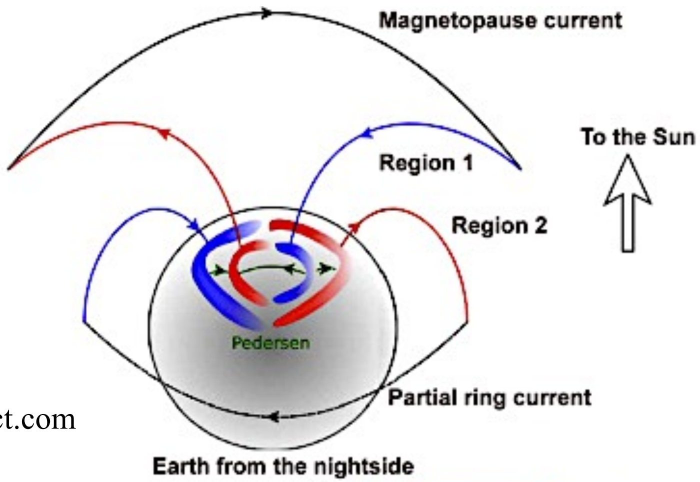
Davies

- Most of Earth's magnetosphere originates or terminates in the polar region
- In addition, the polar cusp provides an unobstructed funnel allowing solar winds particles to stream directly down into the polar region
- It is no wonder that transmitting HF radio signals through the polar regions is challenging
- The various fields, currents, and particle flows are briefly described next

Field Aligned Currents (Birkeland Currents)



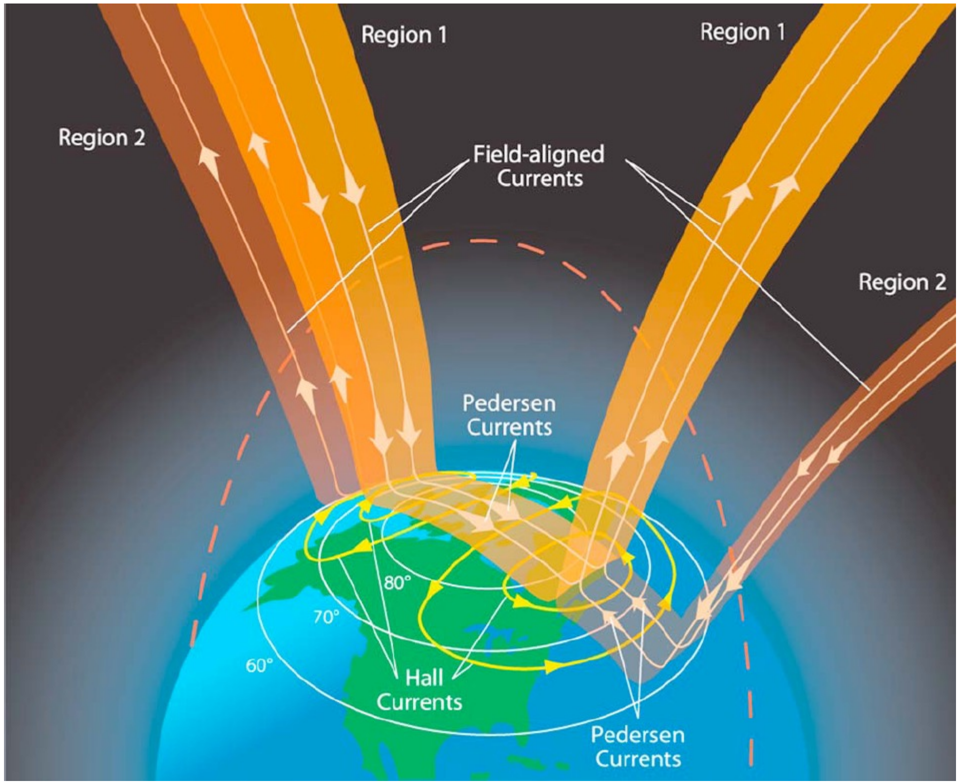
Wikipedia



ScienceDirect.com

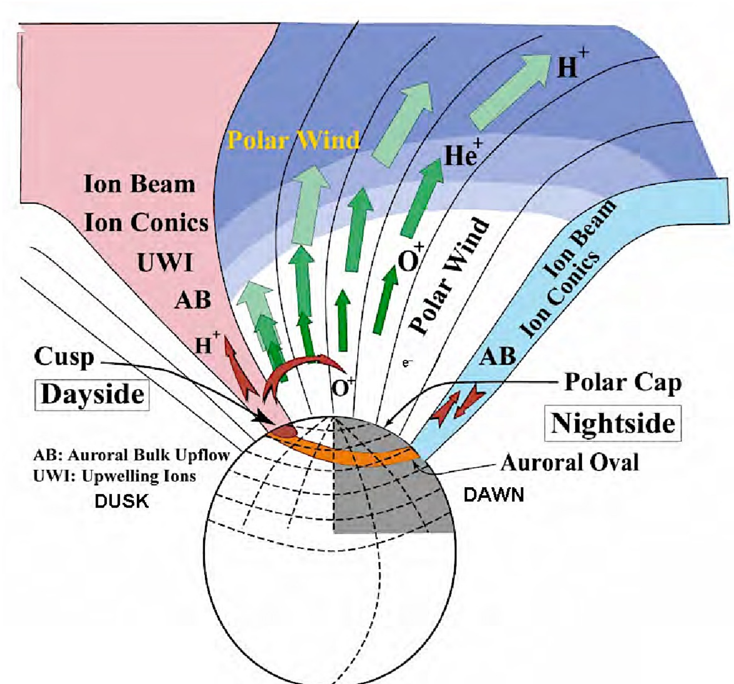
- Field Aligned Currents (FAC) flow along geomagnetic field lines connecting Earth's high latitude ionosphere to the magnetosphere
- They are the dominant form of energy exchange between the magnetosphere and ionosphere
- There are two sets of concentric FAC sheets, one inside the other
- Region 1 (R1) is the inner FAC
- Region 2 (R2) is the outer FAC
- R1 and R2 currents originate from different parts of the magnetosphere

Pedersen and Hall Currents

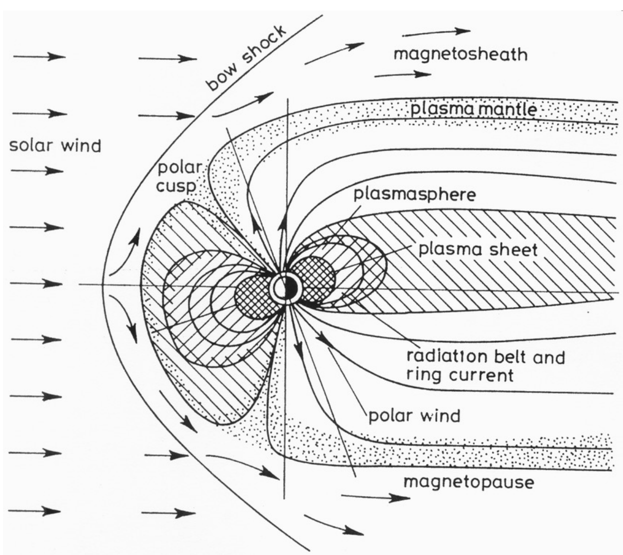


- Polar Cap Pedersen currents interconnect incoming and outgoing R1 and R2 currents
- Polar electric fields perpendicular to the vertical magnetic field generate two hall current convection cells.
- The convection cells carry ionospheric plasma over the poplar cap and then back through the auroral oval

Polar Wind Outflow

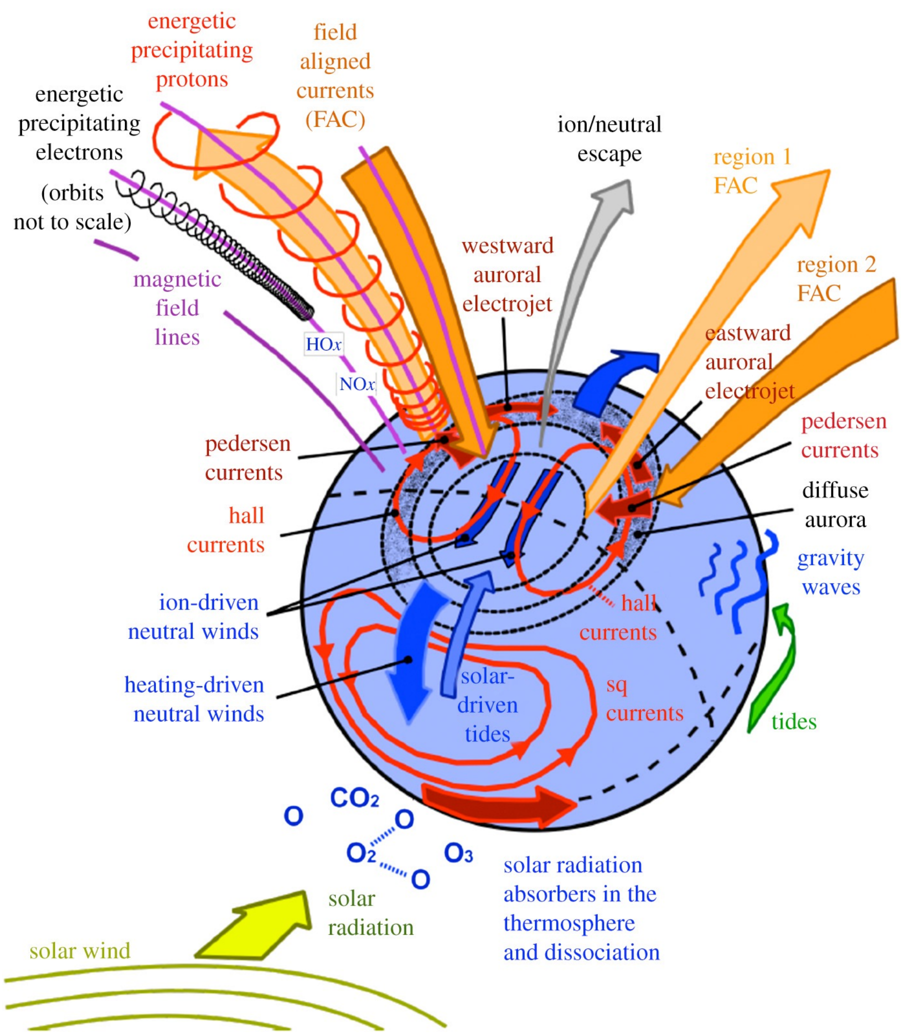


www.semanticscholar.org



- There are only two sources for the charged particles present in Earth's magnetosphere
  - Ionospheric polar wind outflow
  - Solar wind from the Sun
- The polar wind transports electrons and positive ions from the polar region topside ionosphere into the magnetosphere
- The ions are primarily hydrogen (H+), helium (He+) & oxygen (O+)
- The polar wind is at times the dominate source of charged particles in the magnetosphere
- Charged particles from the solar wind are H^+ and He^{2+} ions

Precipitating Charged Particles



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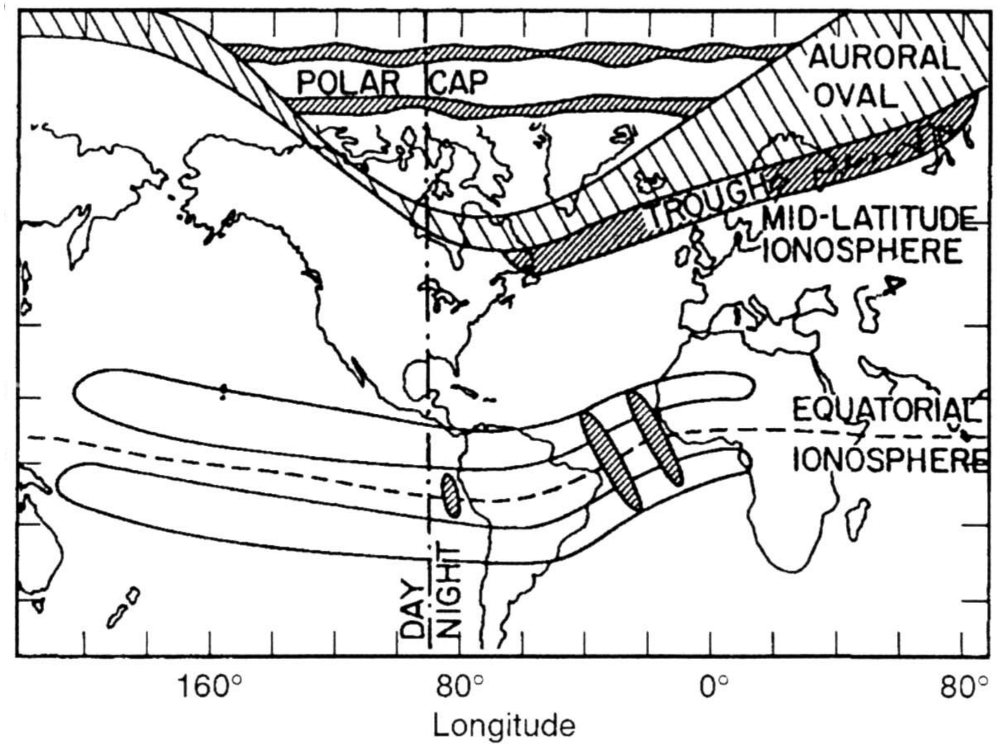
- Charged particles spiraling down magnetic field lines into the polar ionosphere are referred to as precipitating electrons and protons
- In addition to EUV radiation
- Neutral gas particles at high latitudes are ionized by collisions with these precipitating particles
- Ionization is greatest
  - Following solar flares
  - From coronal mass ejections (CMEs)
  - During solar wind storms
- These events dump heavy concentrations of charged particles into the high latitude ionosphere

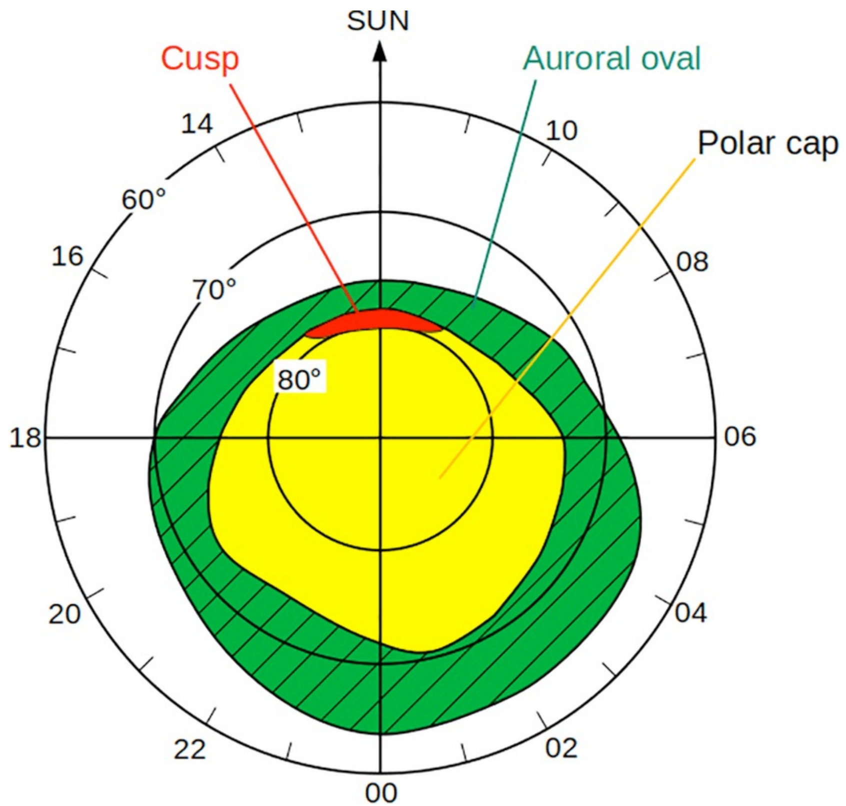
Zones Within the High Latitude Ionosphere

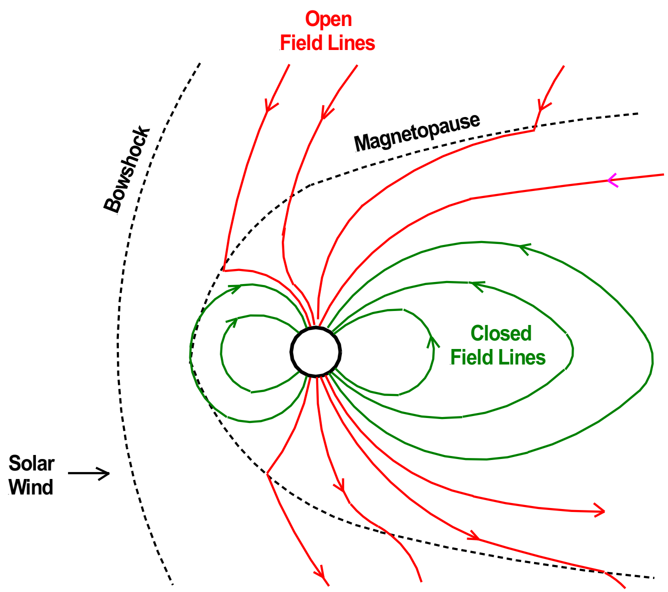


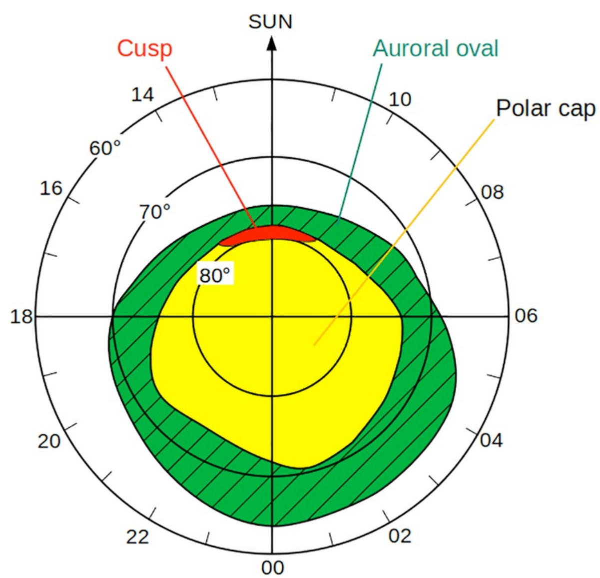
Goodman

- The high latitude region is separated into the:
  - polar cap region
  - auroral oval, and
  - F region ionospheric trough

Polar Cap


SUN
Cusp
Auroral oval
Polar cap
14
10
60°
16
08
70°
80°
18
06
20
04
22
02
00

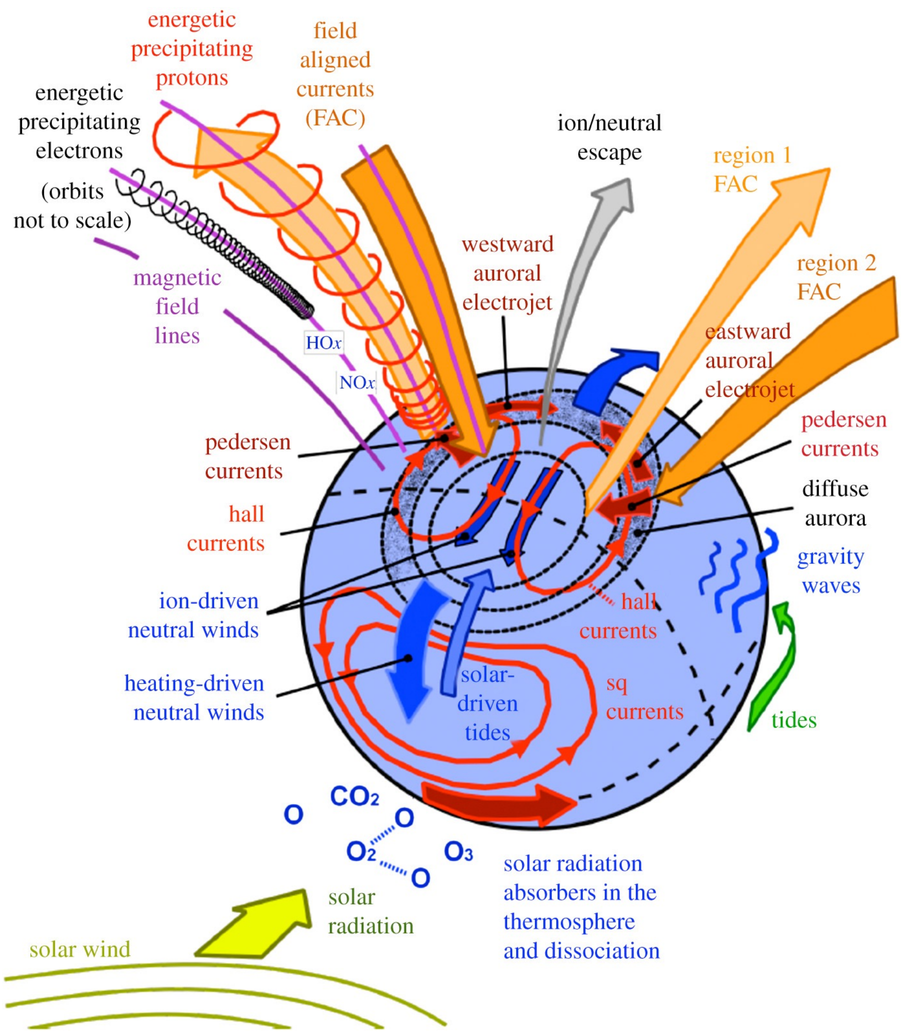




Polar Cap

- The region poleward of the auroral oval is accepted to be the polar cap
- Magnetic field lines within the polar cap are open, meaning that they flow outward from the polar region and connect with the Interplanetary Magnetic Field (IMF) far from Earth.
- Solar wind particles & particles from the magnetosphere flow along open field lines into the polar cap region
- Below the polar cap magnetic field lines are closed, ie, both ends of magnetic field lines connect back to Earth
- The auroral oval marks the division between closed and open magnetic field lines.

Polar Cap Complexity



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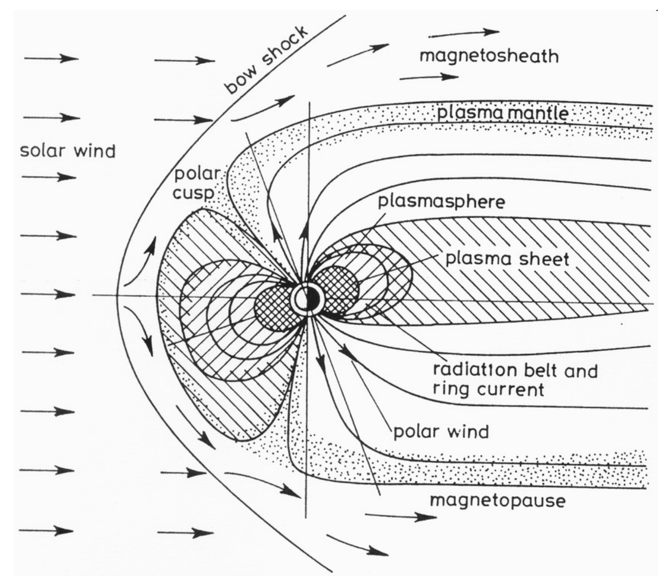
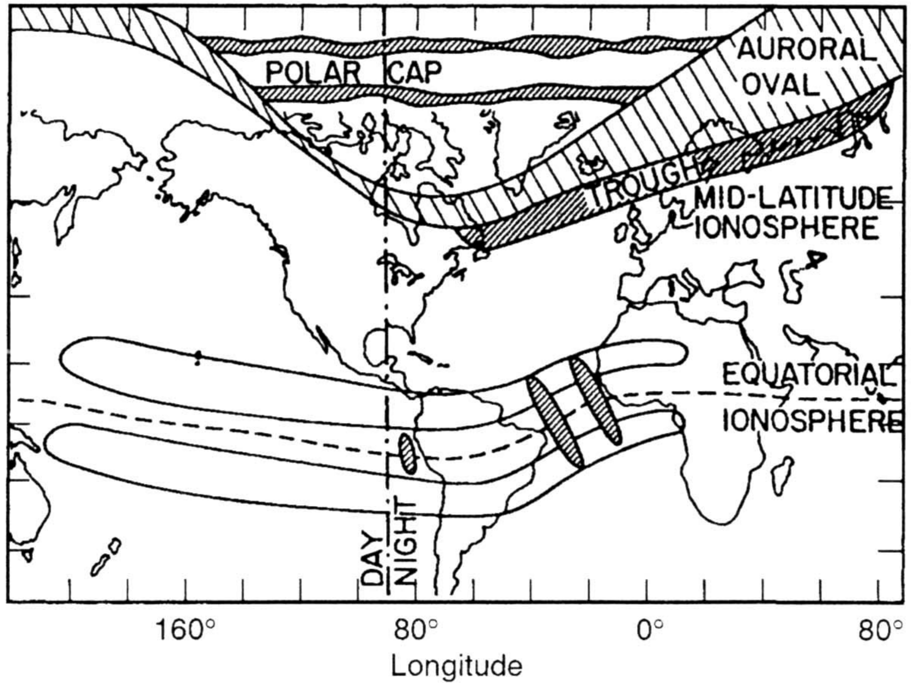
- Most of the high latitude complexity occurs within the polar cap.



The Auroral Zone

The Auroral Zone

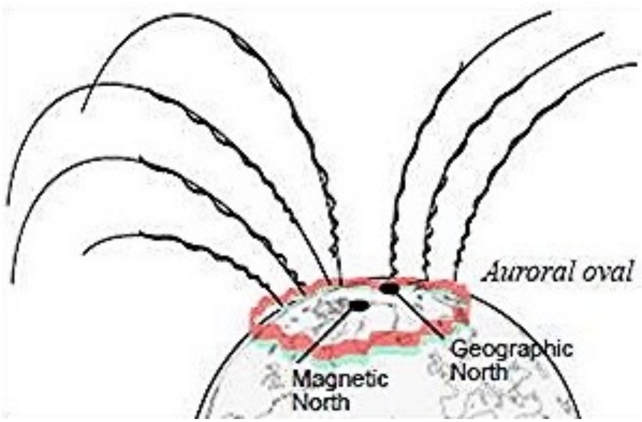


- Beautiful shimmering auroral light displays occur as energetic solar wind particles enter the Earth's atmosphere
- Auroral light displays provide visual evidence of high latitude disturbances that directly affect HF radio communications throughout the polar regions

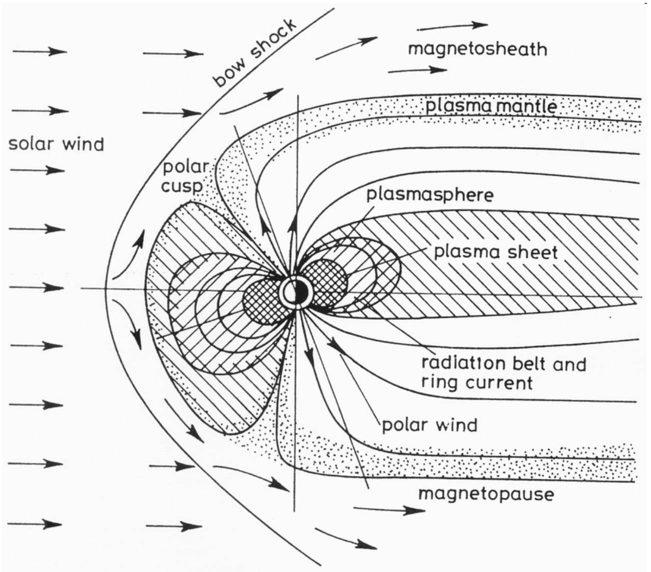
Visual (Luminous) Aspect of Aurora

- Visual auroras occur in both the northern and southern polar regions
  - North aurora borealis
  - South aurora australis
- Aurora displays frequently include
  - Curtains of light,
  - Rays, and
  - Arcs
- Which appear to pulsate and dance under the influence of ionospheric winds.
- The patterns and shapes of the aurora are determined by
  - Changing flow of charged particles and
  - A varying magnetic field.
- No two auroral displays are alike varying
  - In shape and brightness
  - Over timescales of seconds to minutes.

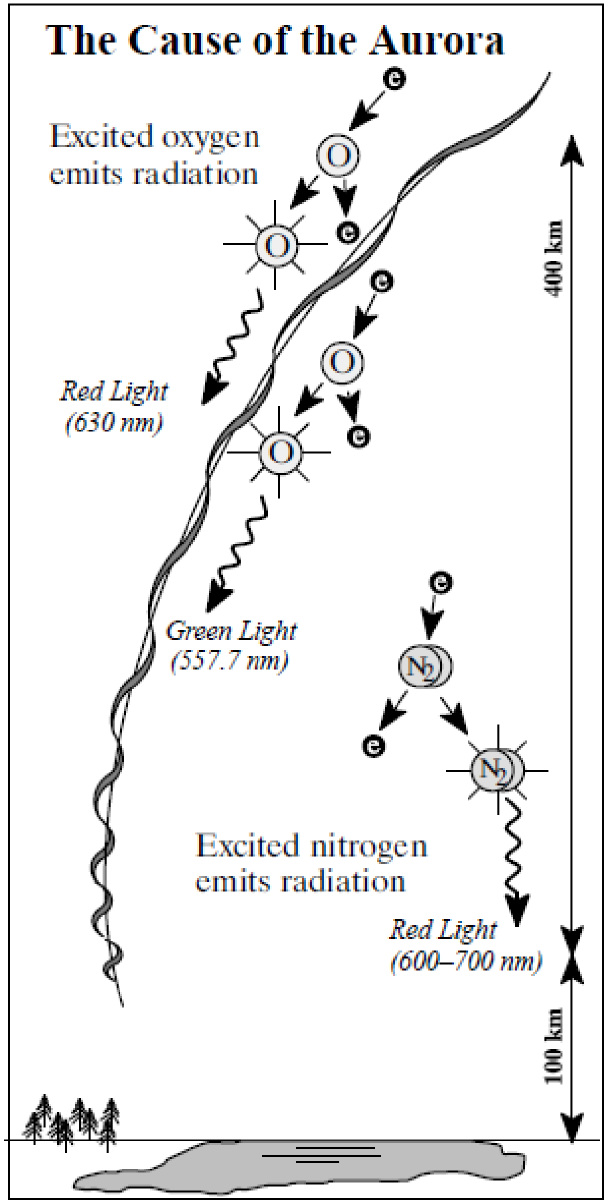
Formation of The Aurora



NOAA Space Environment Center



- The aurora is the result of high energy particles, primarily electrons, colliding with neutral atoms in Earth's atmosphere.
- The electrons are accelerated by solar winds and IMF to high energy levels in the downwind tail (night side) of the magnetosphere.
- The accelerated electrons follow Earth's magnetic field lines down into the polar regions entering Earth's atmosphere in a rough circle called the auroral oval.
- The vast majority of aurora displays form in the E region of the ionosphere from about 90 to 150 km above Earth's surface.
- Most of bright displays less than 20 km tall and generally very thin ~ 100 m thick.



NOAA Space Environment Center

Aurora Colors

- Valence electrons of oxygen and nitrogen atoms in Earth's upper atmosphere are excited to higher energy levels as these atoms collide with the energetic electrons streaming in from the magnetosphere.
- The valence electrons emit photons of light as they drop back to their normal energy levels.
- The color of an aurora depends on the specific atmospheric gas involved and the energy of colliding particle.
- Most auroral features are greenish yellow produced by excited oxygen atoms.
- High altitude oxygen atoms emit a reddish light as do excited nitrogen atoms at low altitudes, giving the tops and bottoms of tall curtains their red color.

Evolution of an Auroral Display

- An auroral display begins as one or more arcs in the auroral oval brighten.
- Auroral formations begin appearing in the bright arcs.
- Auroral formations becomes fully developed
- After 30 minutes to an hour the formations fade and disappear marking the end of the auroral event.
- The sequence is likely to repeat 2 to 3 hours later.

Discrete and Diffused Aurora

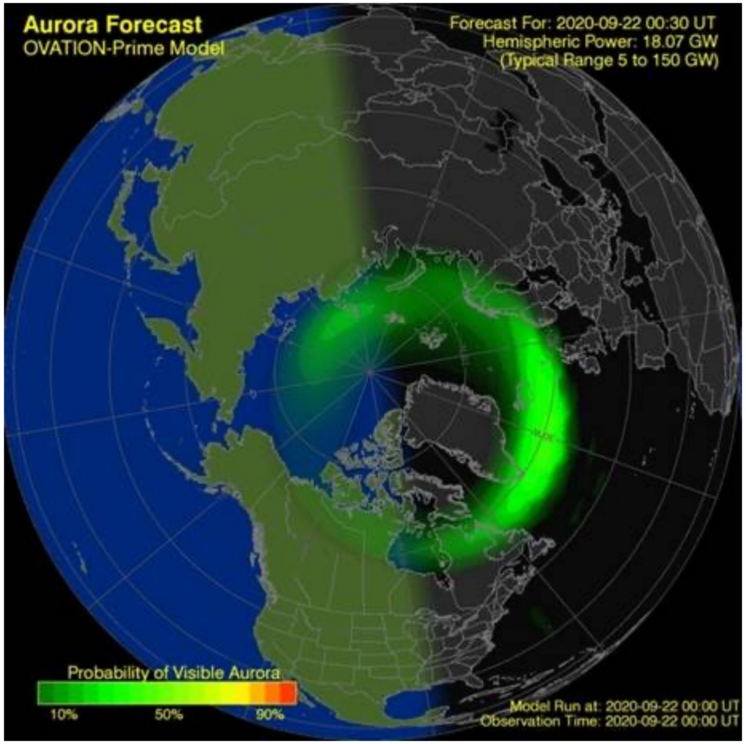
NASA ISS

- In addition to discrete aurora (curtains, arches, rays, etc.)
- There are also diffused aurora
- Diffused aurora are more difficult to see from the ground because of their lower light intensity, although they produce as much total light as discrete aurora.
- Satellite images of the aurora tend to be dominated by the diffuse aurora.
- Discrete forms appear in these images both within the diffuse area and poleward of it.
- However, discrete forms are not seen on the equatorward side of the diffuse aurora.
- The charged particles forming the discrete and diffused aurora are believed to originate from different areas within the magnetosphere tail.

Auroral Oval

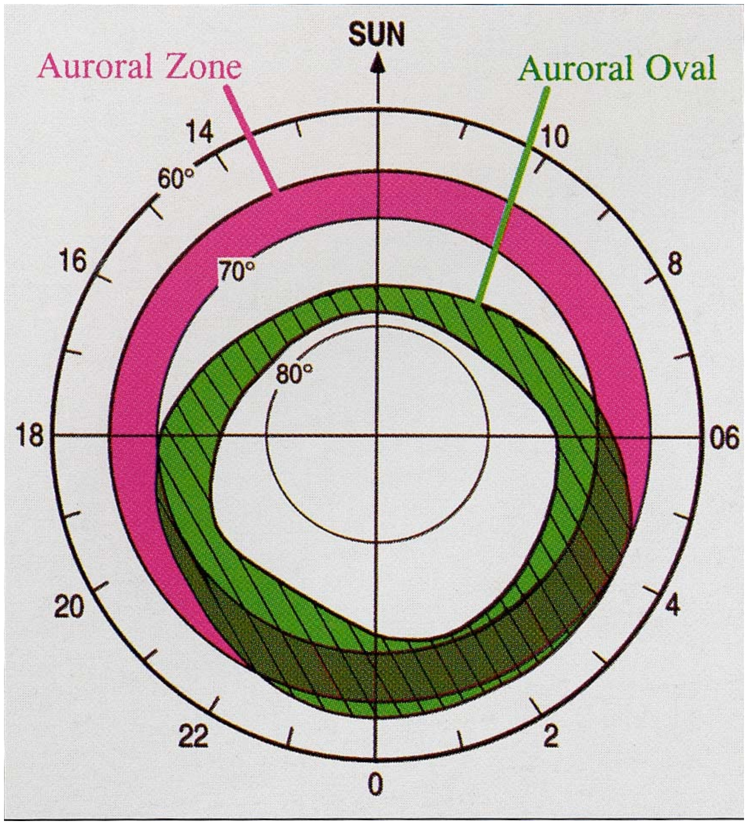
The oval is a permanent ring of light around the magnetic pole

It is important to note that the oval is fixed with respect to the Sun with the Earth rotating beneath it.



- During quiet geomagnetic conditions, the oval is around 3,000 km in diameter centered over the magnetic pole.
- In general, the ovals are located between 60 to 70 degrees latitude in both north and south hemispheres.
- An oval is at its lowest latitude at midnight and highest latitude around noon.
- The width of an oval also varies.
  - It is greatest at midnight, about 10^{o} wide in latitude, and
  - Narrowest at noon.
- During geomagnetic storms the ovals grow larger and brighter, allowing the aurora to be observed at lower latitudes, for example in the northern United States and central Europe.

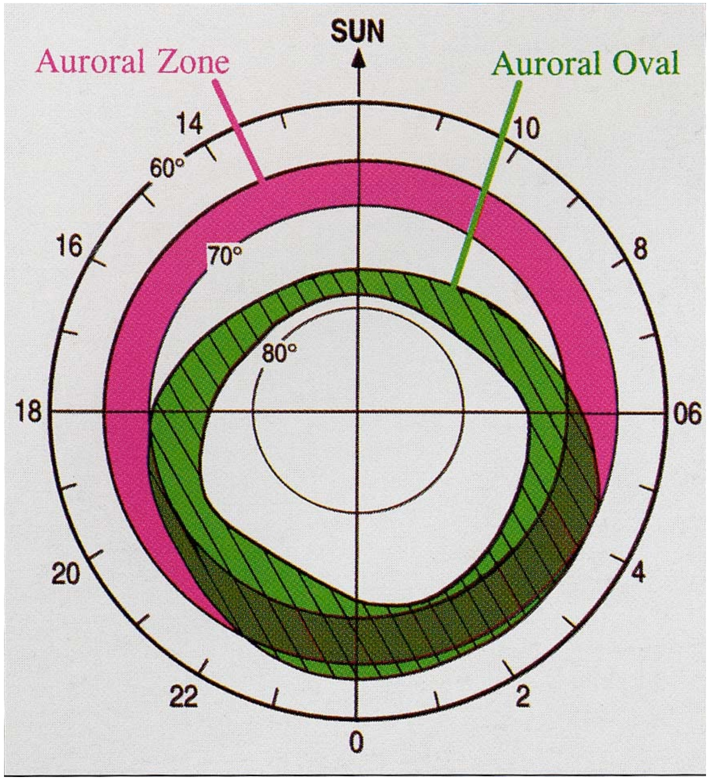
Inner and Outer Ovals



http://ffden-2.phys.uaf.edu

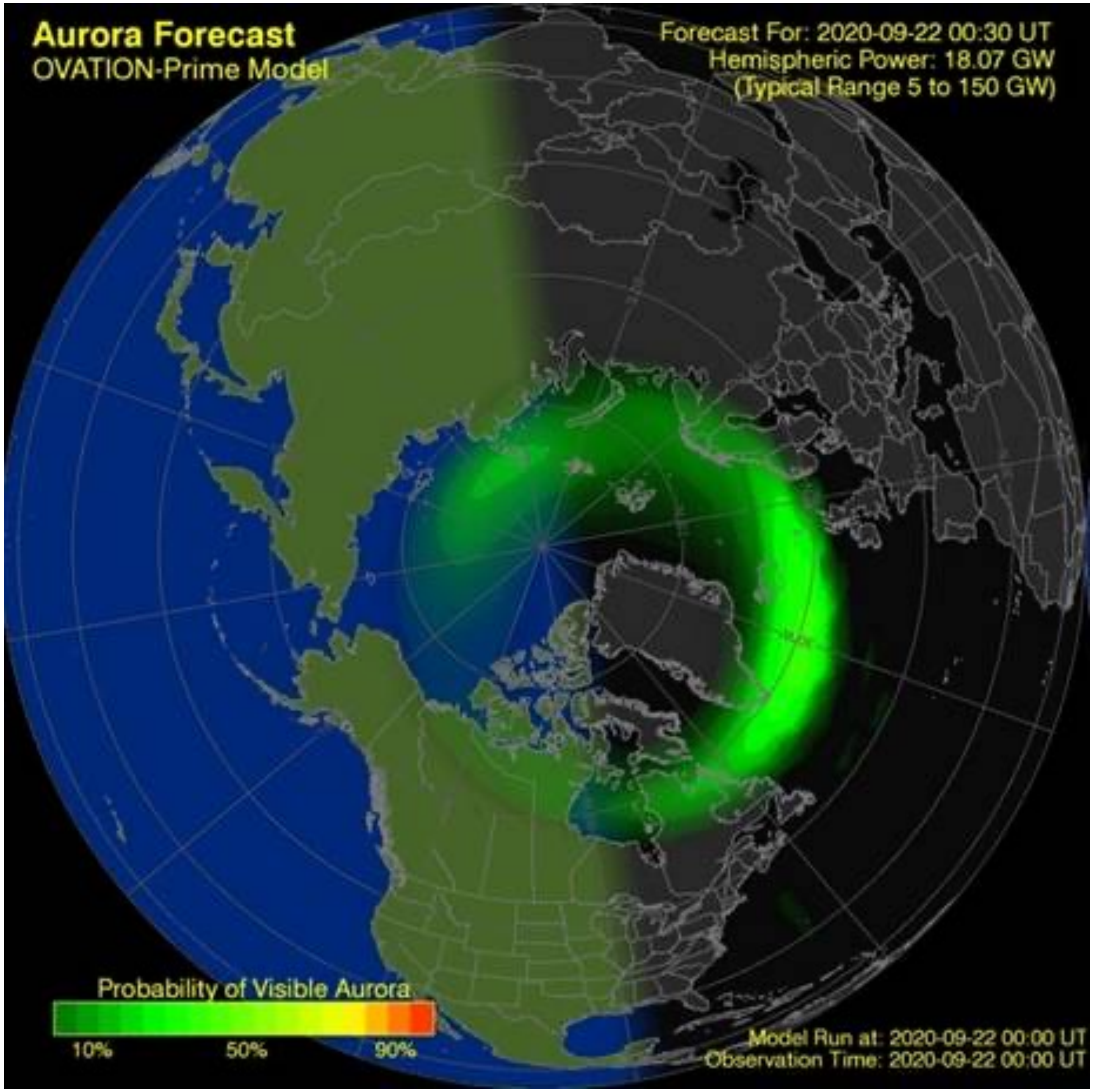
- The auroral oval is actually two ovals, an inner and an outer oval.
- The inner oval is the visual or luminous oval.
- Characteristics of the inner oval include:
  - Luminosity,
  - Sporadic – E
  - Spread – F, and
  - Soft X-rays.
- The highest level of inner oval activity occurs at night.
- The high energy particles forming the inner oval originate far out in the magnetic tail.

Outer Oval



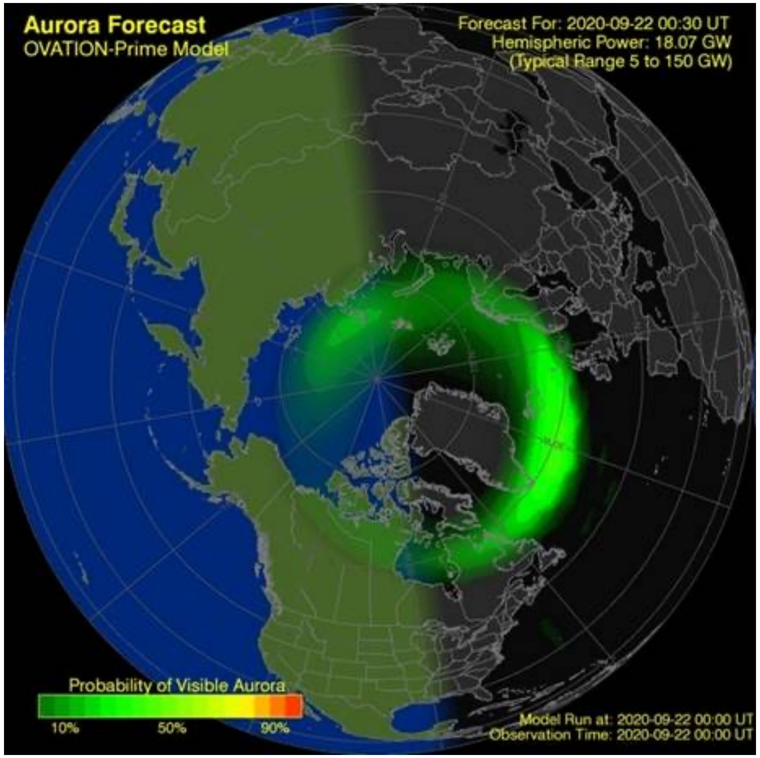
- The outer oval is nearly circular at approximately 60º to 70º with its center at 65º magnetic.
- Characteristics of the outer oval include:
  - Diffuse aurora,
  - Radio wave absorption,
  - Sporadic – E at an altitude of 80 to 90 km
- Outer oval activity is greatest during the day.
- Both inner and outer ovals occupy about the same latitude at midnight but become increasing separated toward noon.
- The high energy particles responsible for the outer oval originate in the Van Allen radiation belts, and have higher energy levels than those forming the inner oval.

Current Aurora Forecast



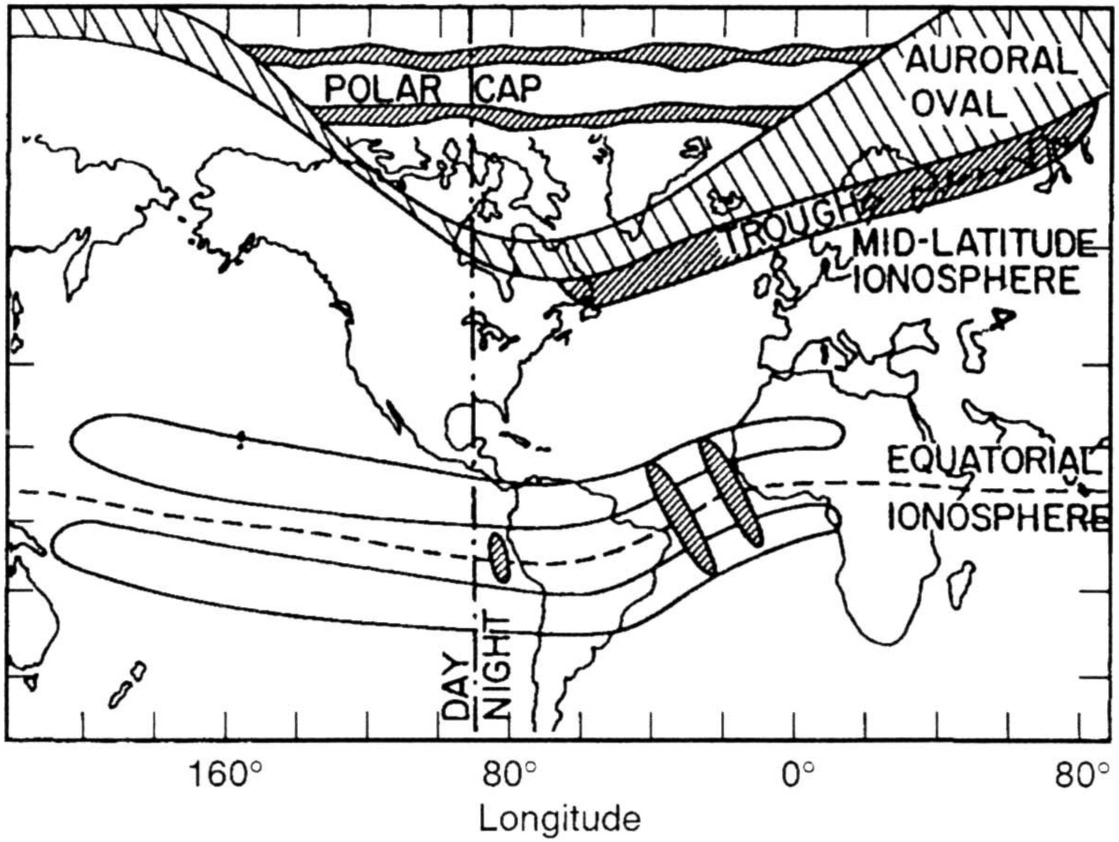
- The OVATION Aurora Forecast Model shows the intensity and location of the aurora predicted for the time shown at the top of the map.
- This probability forecast is based on current solar wind conditions measured at L1, but using a fixed 30-minute delay time between L1 and Earth.
- L1 is a location in space where the gravitational forces of the Earth and Sun are equal creating a point of equilibrium where spacecraft can be "parked" to observe the Sun and solar wind conditions.

Current Auroral Forecast

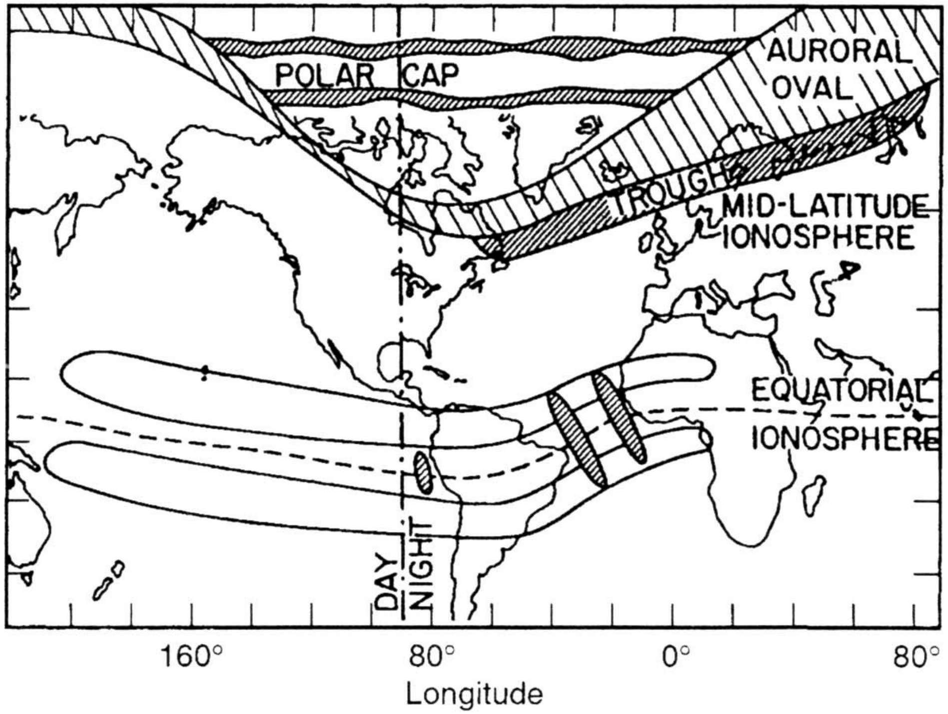


- A 30-minute delay corresponds to approximately 800 km/s solar wind speed (geomagnetic storm)
- Solar wind arrival from L1 orbit varies from less than 30 minutes to an hour or so
- The sunlit side of Earth is the lighter blue ocean and the lighter color of the continents.
- The day-night line, or terminator, is shown as a region that goes from light to dark.
- The aurora can not be seen during daylight hours, but often observed within an hour before sunrise or after sunset.
- Current auroral forecast can be viewed under Current Conditions > Auroral on the www.skywave-radio.org website

F Region Ionospheric Trough

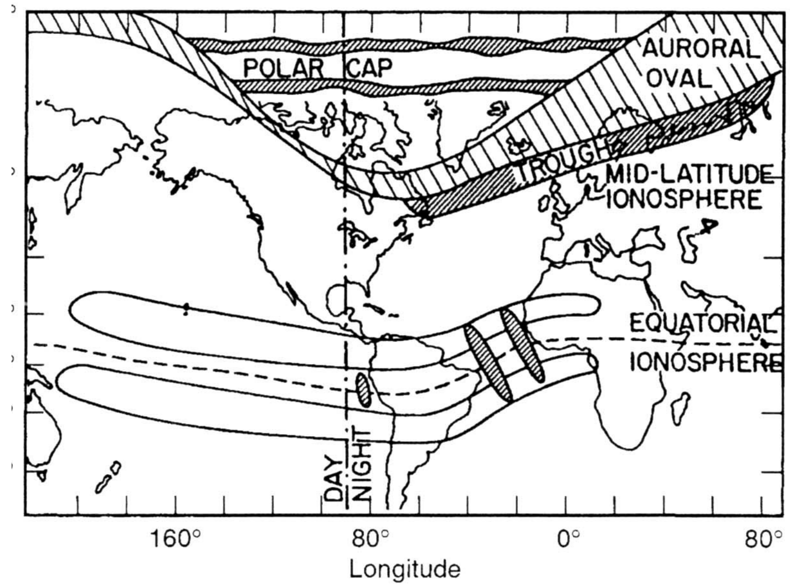


F Region Ionospheric Trough



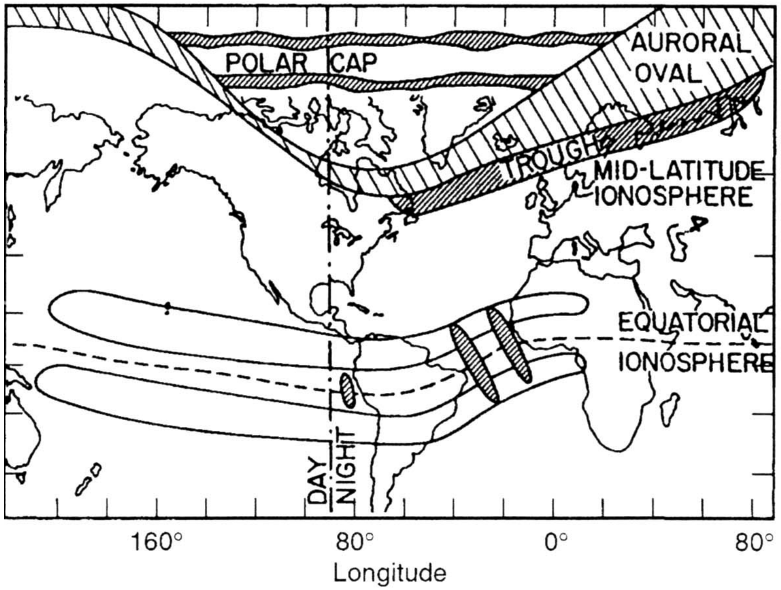
- An ionospheric trough is a relatively narrow ribbon of depleted ionization (primarily depleted O+ ions and electrons) that stretches from east to west.
- Knowledge of trough appearance and location is important for high latitude and trans-polar radio communications.

F Region Ionospheric Trough



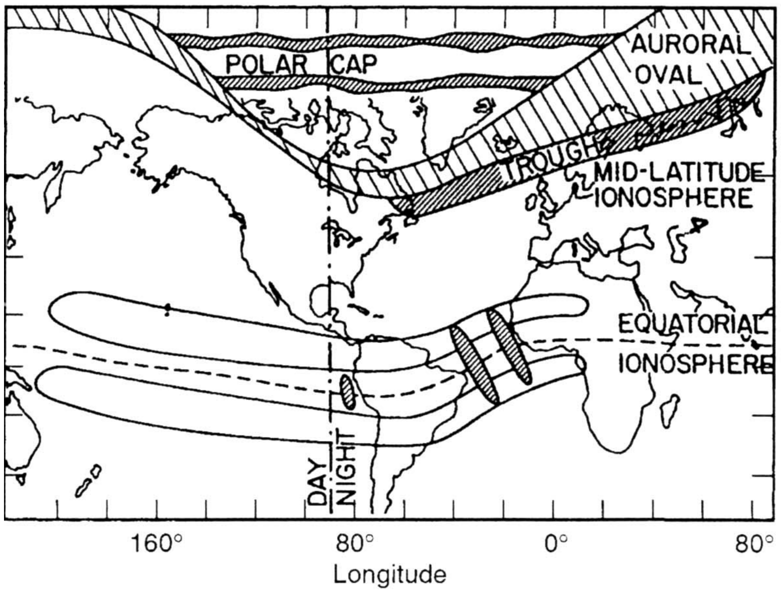
- The F region Main Trough near 60° latitude marks the boundary between the mid and high latitude regions of the ionosphere.
- The main trough is primarily a night time phenomenon, appearing at dusk and extending through the night to dawn.
- During the night the trough often drifts to lower latitudes.
- It can also drift toward lower latitudes during geomagnetic storms.
- The main trough occurs most frequently in the winter and during the equinoxes.
- The trough can disrupt U.S. to Europe radio circuits during winter nights

Southern Hemisphere Ionospheric Trough



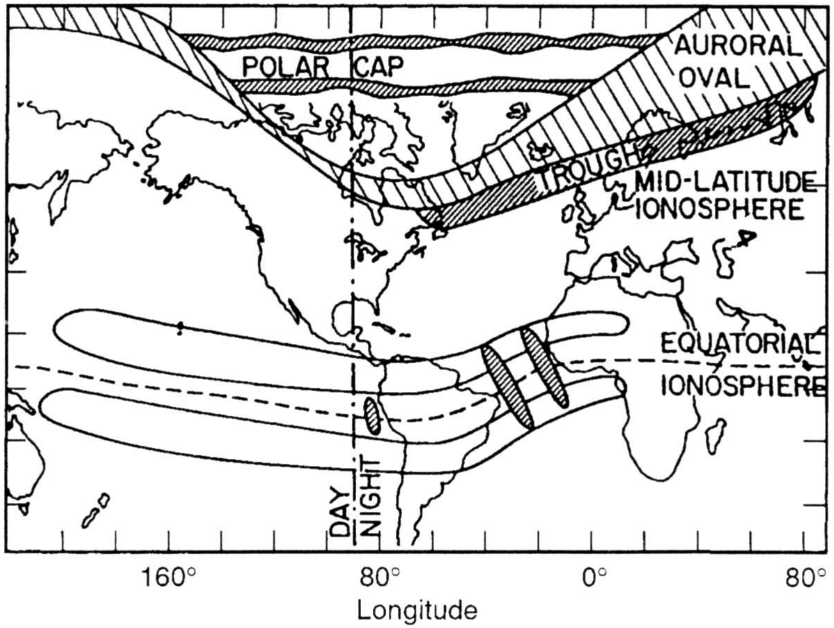
- The appearance of troughs in the southern hemisphere is opposite that in the north.
- Troughs in the southern hemisphere are present in all seasons occurring more often during the summer with more troughs during the day than at night.
- It is assumed that differences between southern and northern troughs are due to hemispheric differences in polar circulation.

Formation of Ionospheric Trough



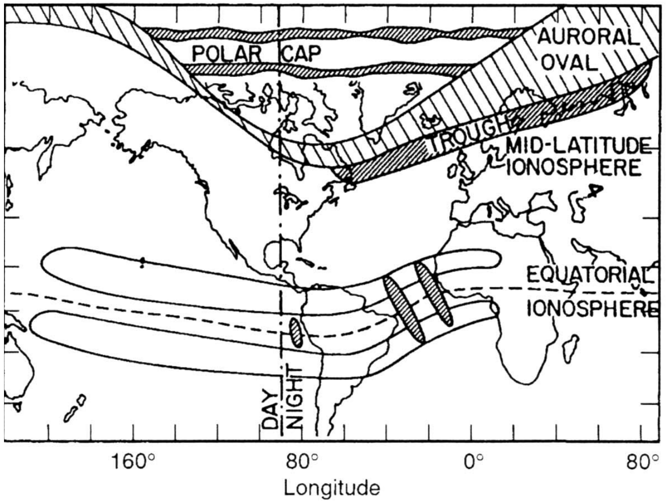
- In general, it is believed that trough formation is the result of east to west plasma flow (in the opposite direction of Earth's rotation) prolonging the time the plasma remains in night time darkness.
- The delay provides a longer period for electron-ion recombination to occur before daylight photo-ionization returns
- The result is fewer ions and a lower electron density in the trough region.

Other High Latitude Troughs



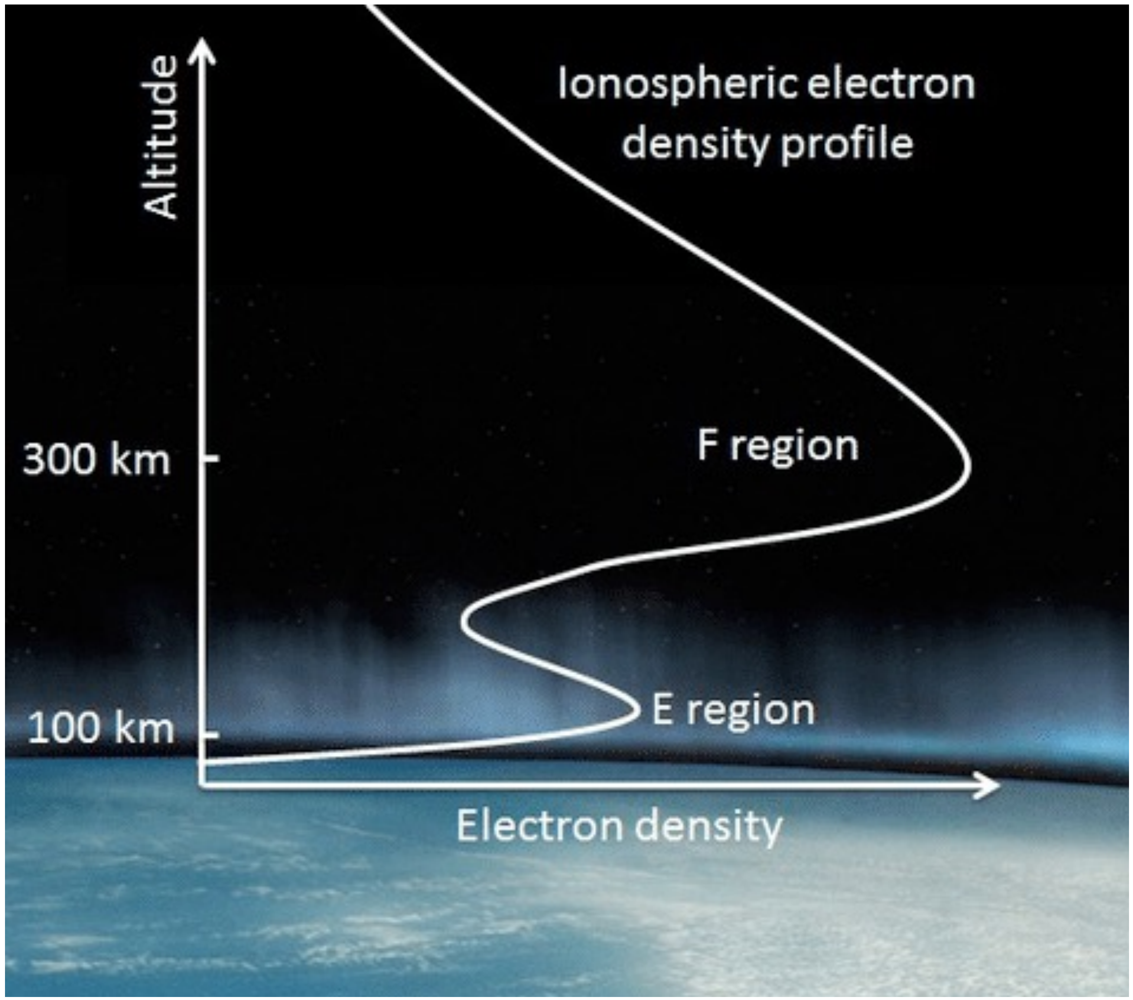
- Other high latitude troughs occur within the auroral oval and polar cap.
- These troughs are between 5^o and 9^o wide ranging from 65^o to 70^o in magnetic latitude
- They last for 4 to 8 hours, gradually moving higher in latitude over this period of time.
- Within these troughs atomic ions of H^+, O^+, and N^+ are reduced in concentration, but surprisingly concentrations of molecular NO^+ and O_2^+ increase.

Antarctic Polar Hole

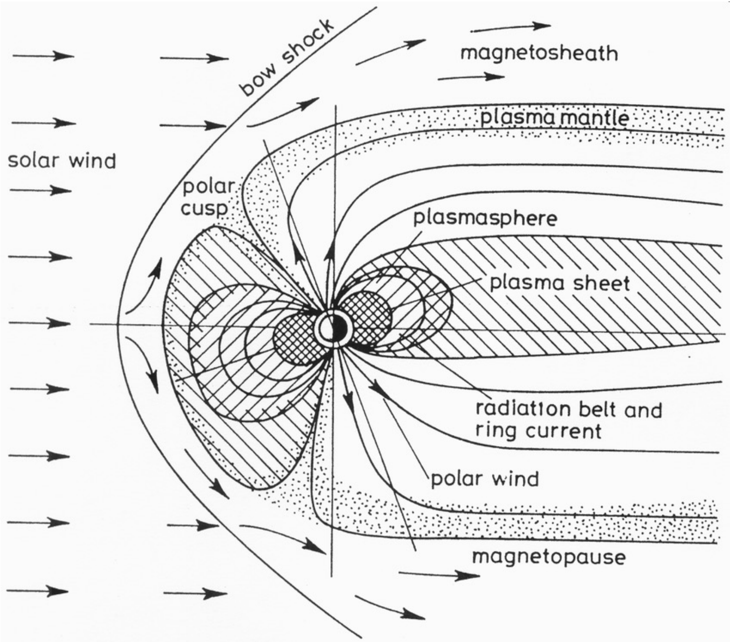


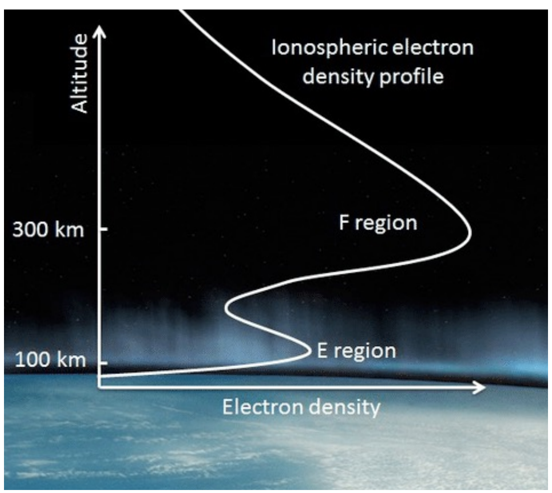
- The polar hole is a distinct feature of the Antarctic polar cap.
- It is a long term depletion that occurs in the winter in years surrounding solar minimum.
- The hole develops shortly after midnight at magnetic latitudes near 80^o.
- Within the hole electron density at an altitude of 300 km can be as low as 1 x 10^2 per cm^3, compared with 10^5 per cm^3 elsewhere in the polar cap.
- A polar hole does not occur in the Arctic for reasons that are still unknown.

High Latitude F Region



High Latitude F Region

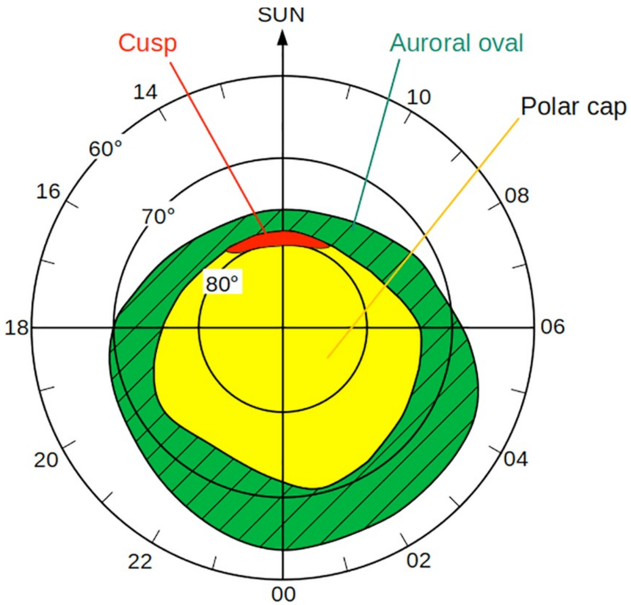




Dynamics of the high latitude F region are very complex due to:

- Earth's nearly vertical magnetic field at high latitudes,
- The polar cusps directly exposing the high latitude F region to violent events occurring on the Sun
- The polar wind transporting charged particles out of the ionosphere
- The F region plasma being driven by constantly changing electric and magnetic fields instead of by high altitude wind
- The equatorial and mid-latitude regions of the ionosphere do not encounter these problems

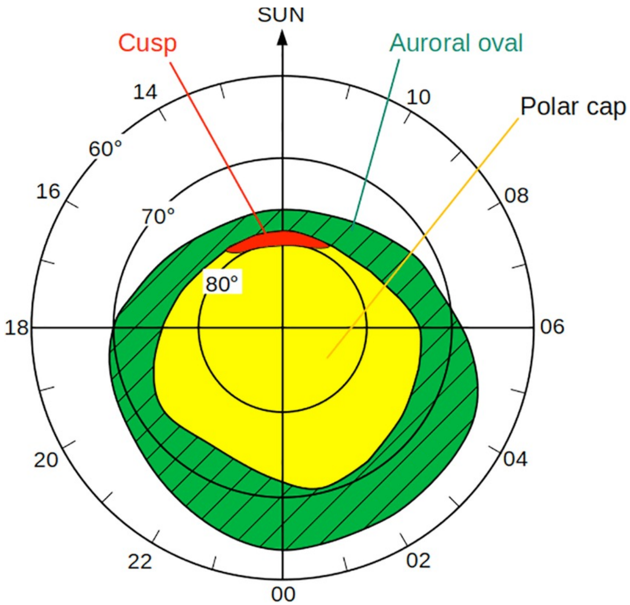
F Region in the Polar Cap



ResearchGate

- Ionization of the polar cap F regions is the result of
  - EUV radiation from the Sun as usual – Plus
  - Energetic electrons and ions precipitating into the polar cap
- At times, precipitating particles are the primary source of high latitude ionization
- Loss of electrons in the polar cap F region is the result of
  - Electron – ion recombination as usual – Plus
  - Polar wind transporting electrons out of the ionosphere
- Polar wind is second only to recombination in removing electrons from the polar ionosphere
- Polar wind decreases polar electron densities below that normally expected, decreasing critical frequencies
- Variation in the polar cap F region are greatest during the winter when the polar cap is darkest.
- Critical frequencies of 2 – 3 MHz are common in the winter and occasionally as low as 1 MHz
- At times the polar cap F1 region can be stronger than the F2 region.

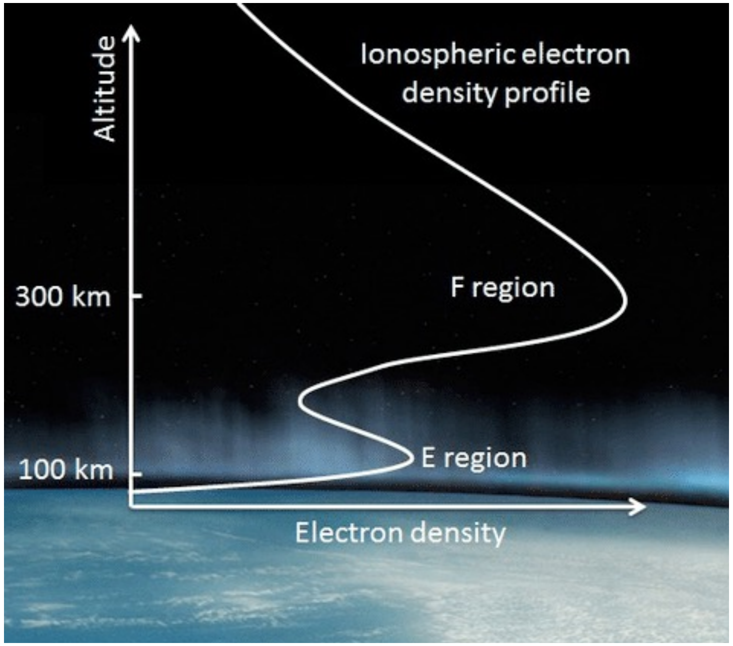
F Region in the Auroral Oval



ResearchGate

- The auroral oval F region is similar to the F region at mid latitudes including
  - Diurnal and seasonal variations,
  - The winter anomaly,
  - Variations with the solar cycle, etc.
- However, electron densities are often enhanced by precipitation of electrons from the solar wind
- The enhancements are generally not uniform
- In addition, transport of plasma from the day side oval over the pole to the night side contributes significantly to late night ionization levels within the auroral oval.
- Erratic ionization within the auroral oval disrupts HF communications through the auroral region

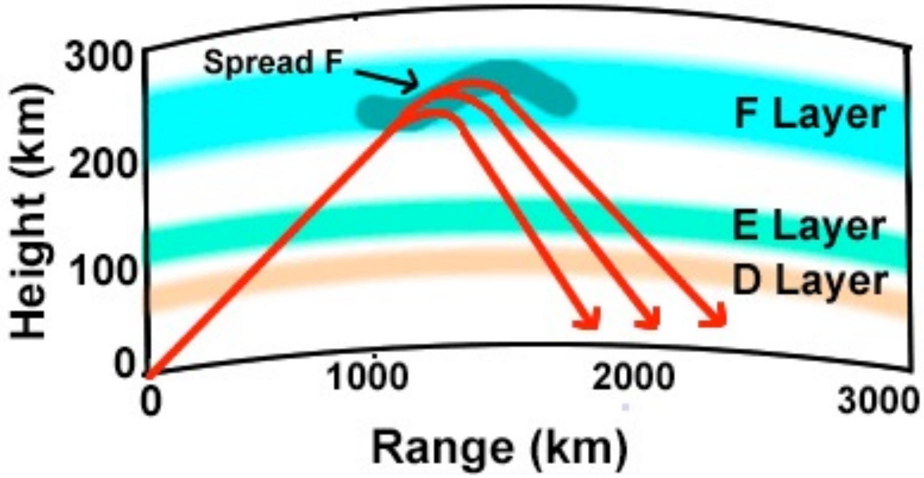
High Latitude F Region Irregularities



researchgate.net

- Electron density irregularities in the high latitude F region include:
  - High latitude spread F,
  - Patches, and
  - Blobs

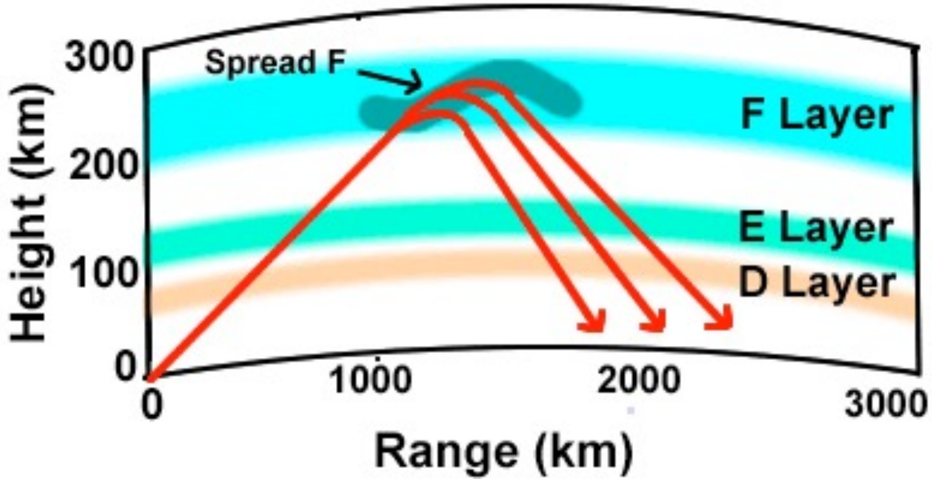
High Latitude Spread F



www.met.nps.edu

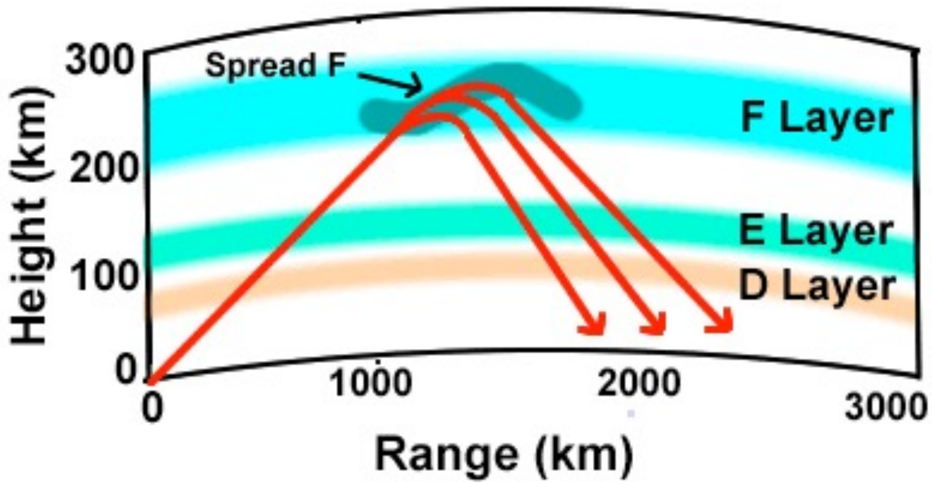
- Signal scattering due to field aligned irregularities results in the spread F phenomena
- Spread F causes an HF signal to be reflected from different heights within the F layer.
- Received HF signals are spread in time and space, making frequency resolution difficult and producing garbled messages
- Received digital data pulses can be up to 10 times wider than the transmitted pulses limiting the data rate of signals that can be successfully transmitted. This type of distortion is known as range spread.
- In addition, spread F produces high fading rates.

High Latitude Spread F



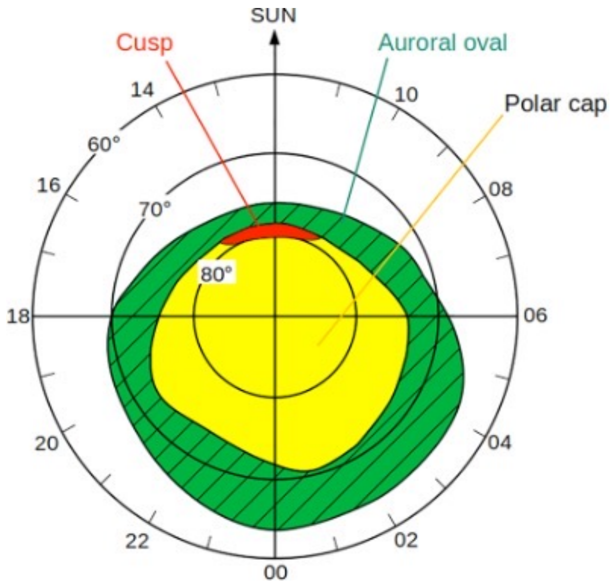
- Field aligned irregularities producing spread F are highly variable in size ranging from roughly a 100 km to several thousand kilometers in length & about a kilometer thick.
- These irregularities drift horizontally at speeds up to about 100 meters per second.
- Spread F occurs most frequently in the equatorial and high latitude regions.
- There is little spread F at geomagnetic latitudes between 20º to 40º.

High Latitude Spread F



- At high latitudes, spread F begins to appear at around 40º and becomes more pronounced with increasing latitude
- In both the auroral and polar cap zones increased geomagnetic activity dramatically increases the appearance and growth of spread F
- Spread F formations can have electron concentrations several orders of magnitude greater than normal
- Spread F is one of the irregularities contributing to the extreme variability of the high latitude F region.

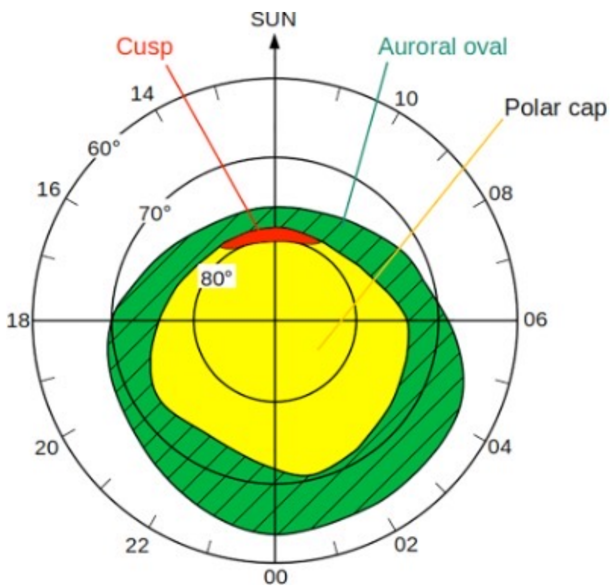
Polar Cap Patches



source: ResearchGate

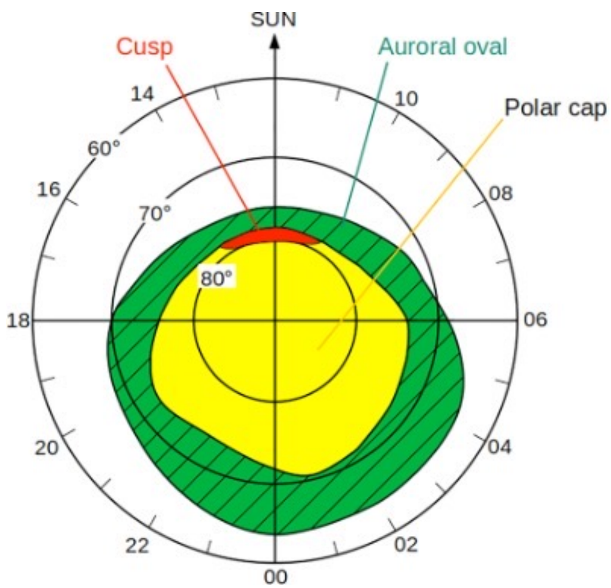
- Patches are roughly circular areas of enhanced electron densities, 200 to 1000 km in size
- They generally occur at night in the polar cap
- Electron densities within a patch are typically 2 – 10 times higher than ambient ionosphere
- A patch may have an electron density of 10^6 electrons per cm^3 compared to 10^5 per cm^3 in the surrounding ionosphere.

Polar Cap Patches



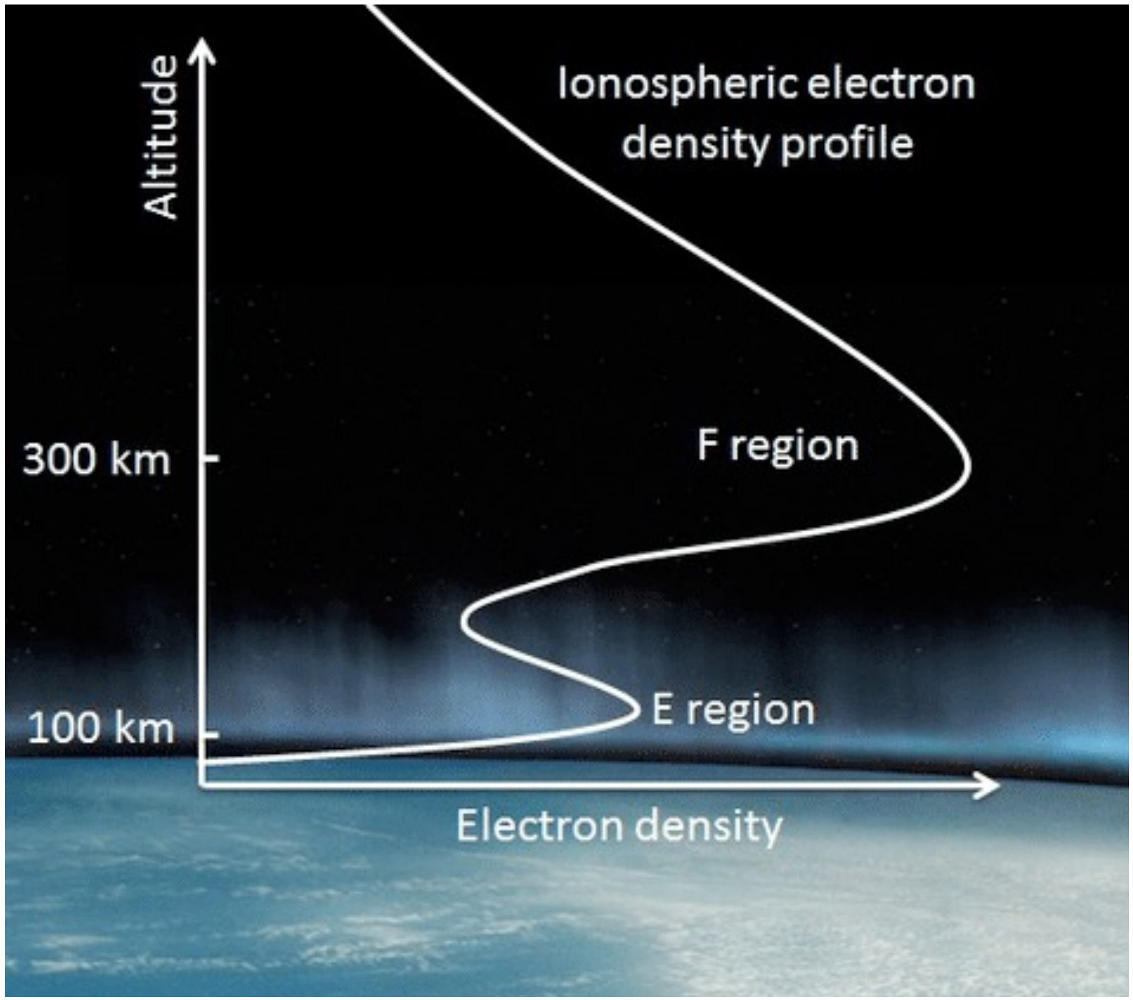
- Patches appear under disturbed ionospheric conditions when the IMF is southward
- A change in polar circulation, due to a sudden increase in solar wind or change in IMF, can detach plasma from the dayside polar cap
- The detached patch drifts over the pole to the night sector at roughly 100 up to 1000 km per second.
- Patches can occur during all seasons of the year but are more frequent during the winter and tend to be stronger at solar maximum.
- Enhanced electron densities within patches coupled with their dynamic behavior produces erratic fading in HF signals propagating through the polar cap region

Auroral Blobs

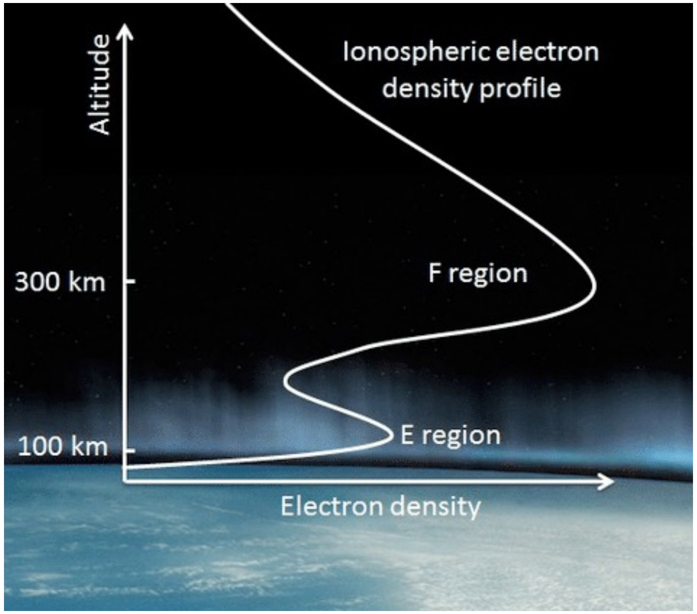


- Blobs are electron density enhancements in the auroral zone
- Blobs vary considerably in size and are smaller than patches
- Blobs are typically tens of kilometers in size instead of hundreds of kilometers for patches
- The cause of blobs is uncertain
- In general, blobs seem to move with the auroral F region plasma drift.
- Blobs also cause erratic fading in HF radio signals

High Latitude E Region

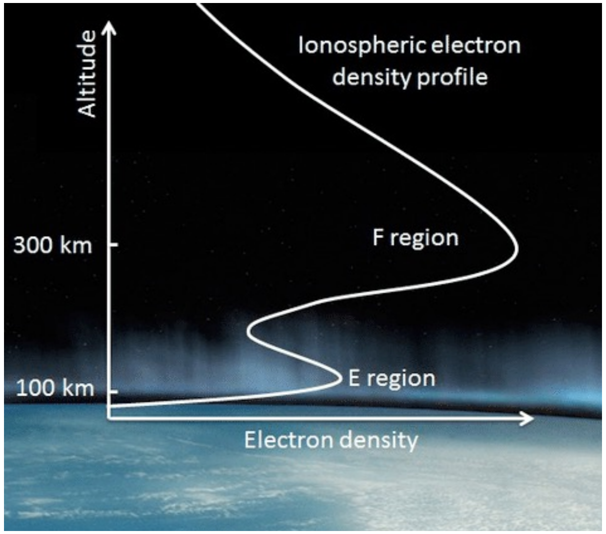


High Latitude E Region



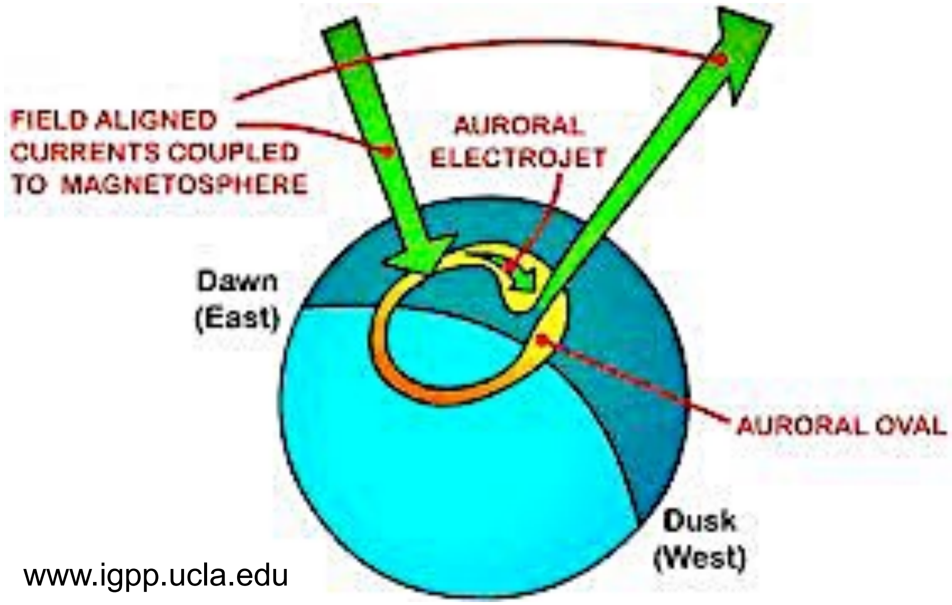
- During geomagnetic quite times the high latitude E region is very much like the mid-latitude E region
- It is subject to the same diurnal, seasonal, and solar cycle variations as the mid-latitude E region
- The E region electron density builds up following sunrise, peaks at local noon, and declines later in the day, same as at mid-latitudes
- During summer the Sun is above the horizon most of the time in the high latitudes
- Consequently, summer time E region ionization levels remain relatively high well into the night
- In winter the high latitudes are in darkness a good part of the time leading to low E region ionization

High Latitude E Region Substorms



- Geomagnetic substorms, associated with the appearance of auroral displays, are the main disturbances affecting the auroral E region
- The auroral oval becomes more dynamic during a storm
  - producing visual aurora
  - expanding oval size
- Precipitating electrons which create the visual aurora also enhance auroral E region ionization.
- Ionization levels considerably exceed that produced solely by EUV radiation
- Substorms often produce auroral sporadic E events particularly at night
- Auroral sporadic E critical frequencies can be as high as 7 MHz

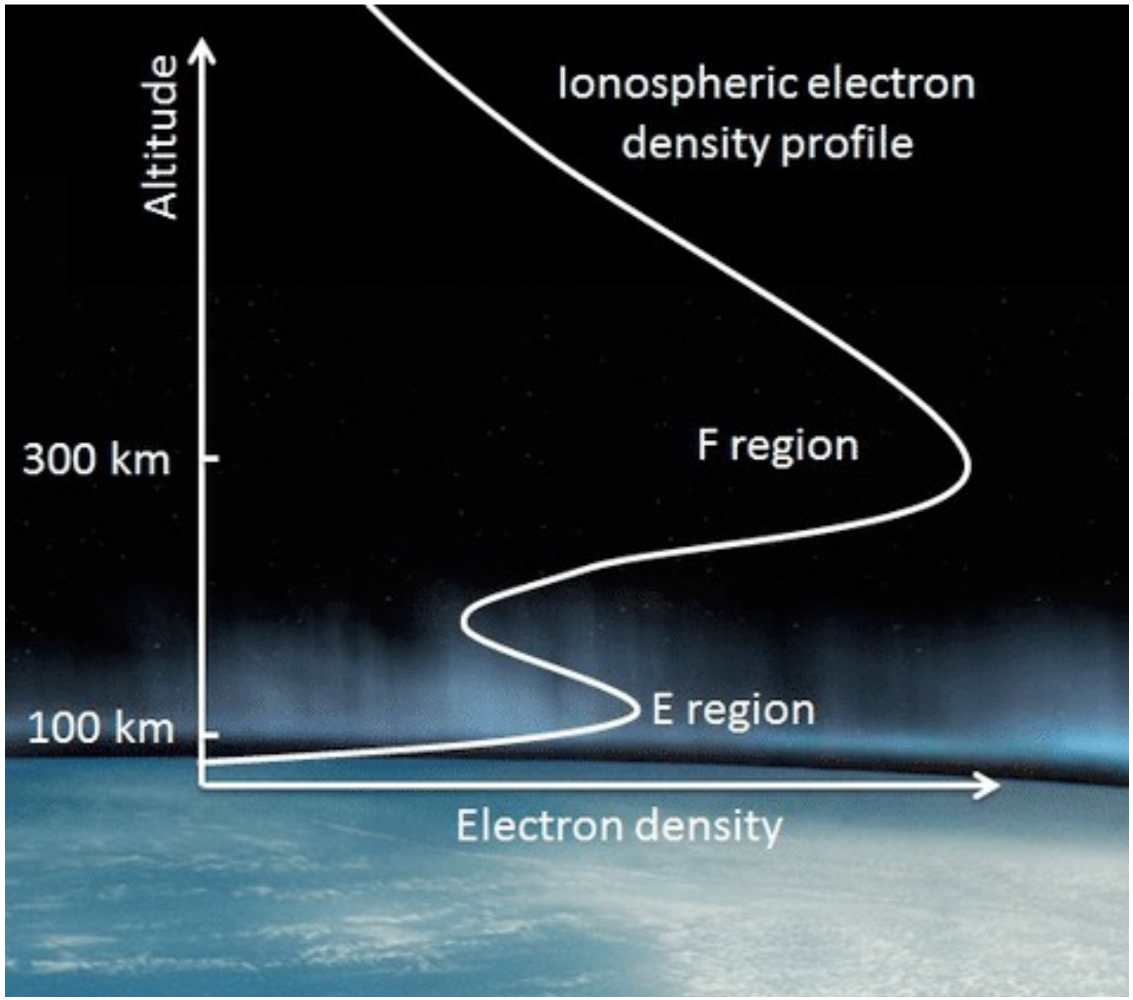
Auroral E Region Electrojet



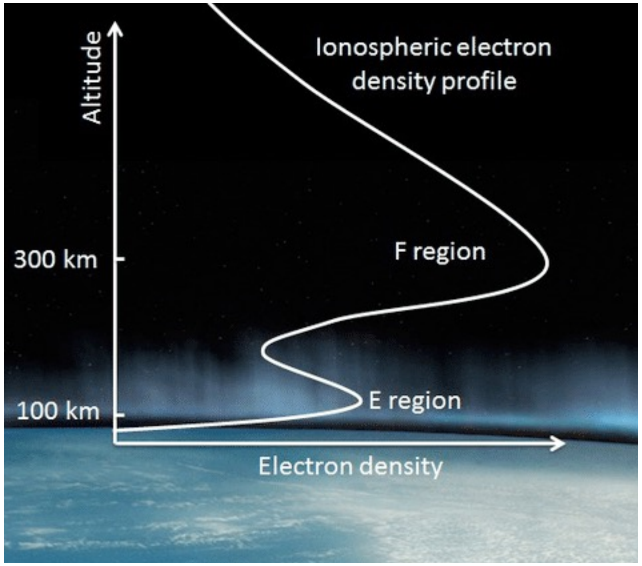
www.igpp.ucla.edu

- Precipitating electrons increases E region electron density and conductivity
- Increased conductivity permits an intense electrical current to flow in the auroral E region
- This is the auroral electrojet
- The electrojet disrupts the auroral geomagnetic field
- The electrojet is responsible for magnetic aspects of an auroral storm
- Excited atoms and molecules are responsible for the visual part of the storm.

High Latitude D Region

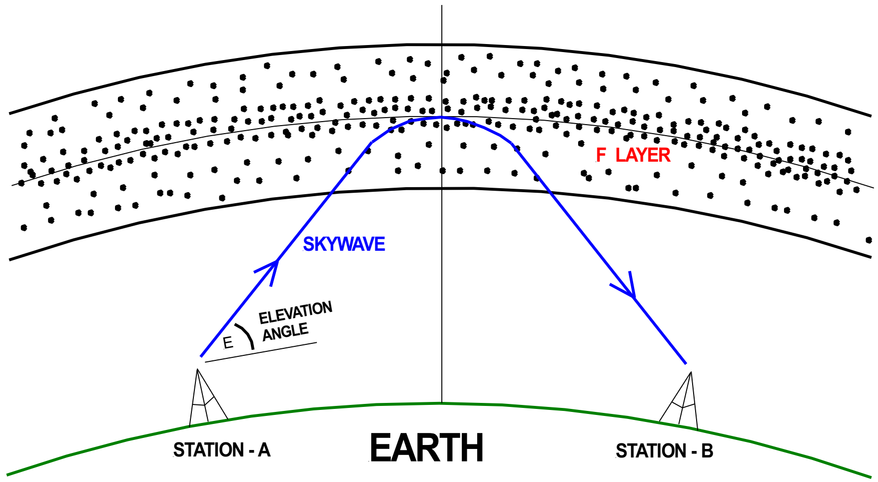


High Latitude D Region



- The high latitude D region lies below the auroral zone E region of the ionosphere
- It is more complex than the E region above it due to higher atmospheric pressures which
  - Inhibit plasma motion
  - Inhibit electrical currents
  - Complicate photochemistry in the region
- Precipitating energetic charged particle ionize the D region similar to the E layer above it
- At times this ionization can be greater than that produced by solar EUV radiation.
- Very high energy particles from solar flares can penetrate down into the high latitude D region
- When they do they heavily ionize the D region creating Polar Cap Absorption (PCA) events
- PCA events absorb HF radio signals throughout the polar cap region often creating radio blackouts

High Latitude Radio Circuits



Author

- Long distance HF radio communications depends on a “smooth” ionosphere from which radio signals can refract back to Earth
- At high latitudes unstable levels of ionization, patches, blobs, and troughs are not conducive to a smooth polar ionosphere
- Fortunately these disruptions do not occur all the time
- However, their occurrences are not always predictable, thus
- Radio operators must look for propagation openings thru the high latitude regions