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Chapter 13

High Latitude Ionosphere

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13 High Latitude Ionosphere

The high latitude ionosphere is very complex. Because of its complexity, it bears little resemblance to the mid latitude ionosphere (Chapter 11) and is vastly different from the equatorial region (Chapter 12). In fact, given its complexity it is amazing that we can transmit HF radio signals through the polar regions. However, we have become proficient at doing so by watching for band openings.

The high latitude ionosphere is the region from roughly 60 to 90° north and south latitudes as illustrated in Figure 1. The Earth's magnetic field is nearly vertical in this region (Figure 2) directly exposing the high latitude ionosphere to solar winds emanating from disturbances on the Sun.

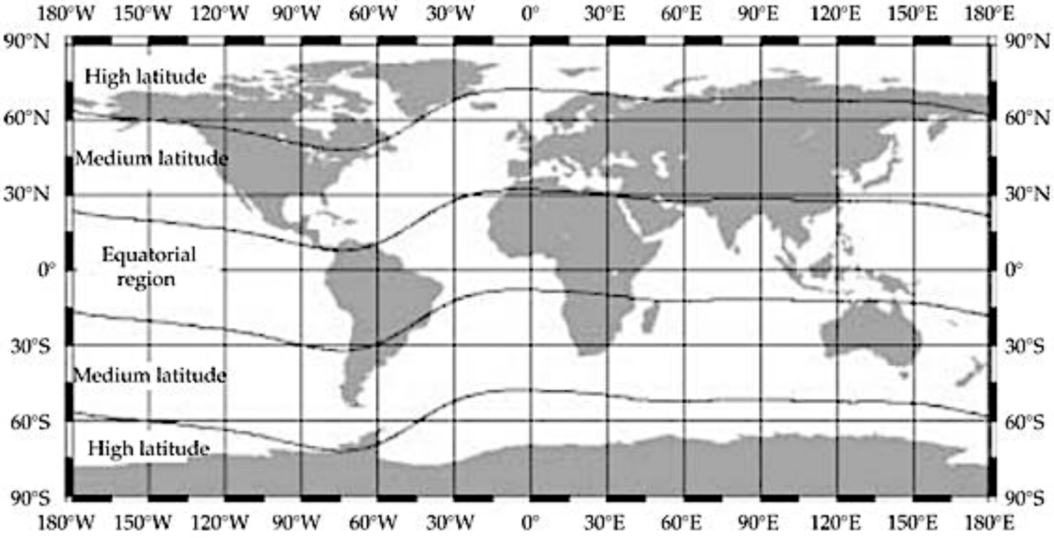

Figure 1 Regions of Earth's Ionosphere (source: ResourceGate.net)

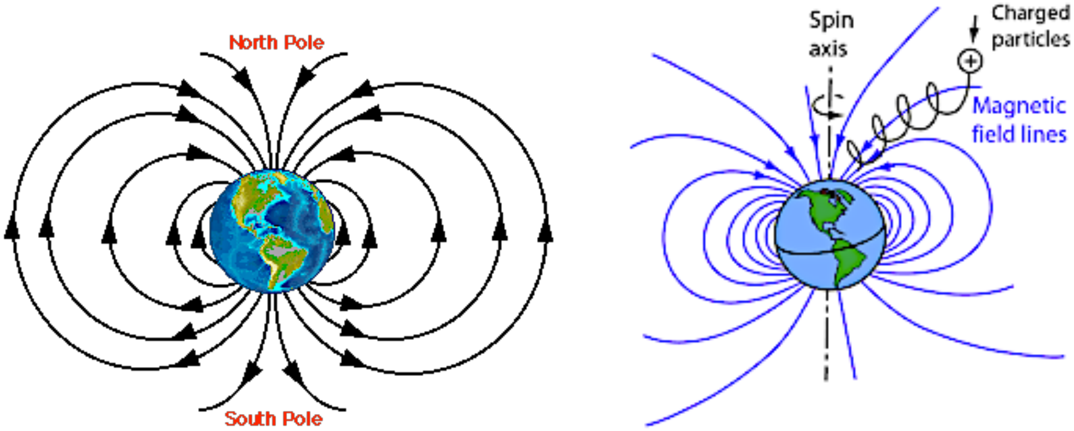

Figure 2 Earth's vertical magnetic field at the poles (source: The Ocean Web and hyperphysics)

In a sense, the north and south polar regions are Earth's garbage pits for all of the junk, hundreds of tons of it, arriving at Earth from turbulent events occurring on the Sun (Figure 3). The junk consists of protons, electrons, and alpha particles; the remains of hydrogen and helium atoms ionized by the intense heat from violent solar events. Hydrogen and helium are, of course, the primary constituents of the Sun.

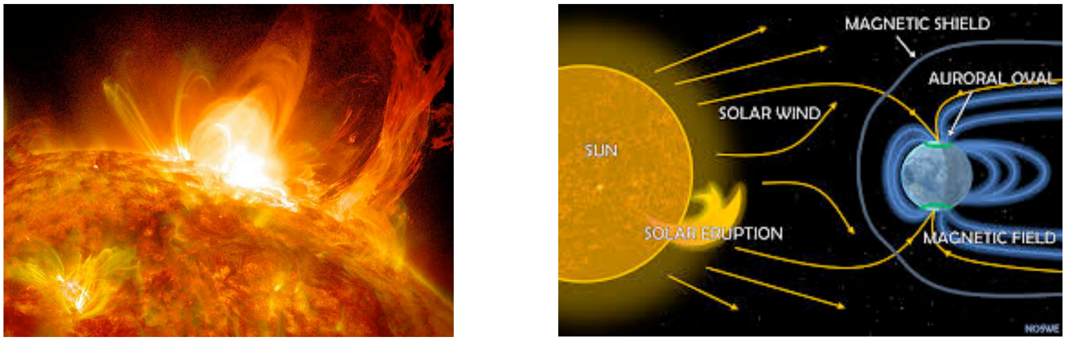

Figure 3 Debris from solar eruptions deposited in Earth's polar zones (source: UiT)

Some of the chaos in the polar regions are of Earth's own making. Nearly 50 tons per day of hydrogen, helium, and oxygen ions escape from the topside of Earth's polar ionosphere into the magnetosphere. Yet, in all of this chaos there is beauty in the polar region aurora light displays (Figure 4). The polar regions are like no other place on Earth.

Figure 4 Auroral Display (source: sciencephoto.net)

13.1 Solar Winds

Solar wind charged particles arriving at Earth from the Sun can not cross Earth's magnetic field lines but are instead diverted, forced to spiral along the field lines as illustrated in Figure 5. Over Earth's equator the field lines are parallel to Earth's surface shielding the equatorial region from the onslaught of solar winds. But in the polar regions the nearly vertical magnetic field lines transport charged particles deep into Earth's upper atmosphere, as illustrated in Figure 5. The charged particles severely disrupt the high latitude ionosphere. In Figure 5, energetic particles (protons in this example) create a Polar Cap Absorption Event knocking out all transpolar radio communications. In this figure the transmitted signal (Tx) is absorbed in the heavily ionized polar D region preventing it from reaching the receiving station (Rx).

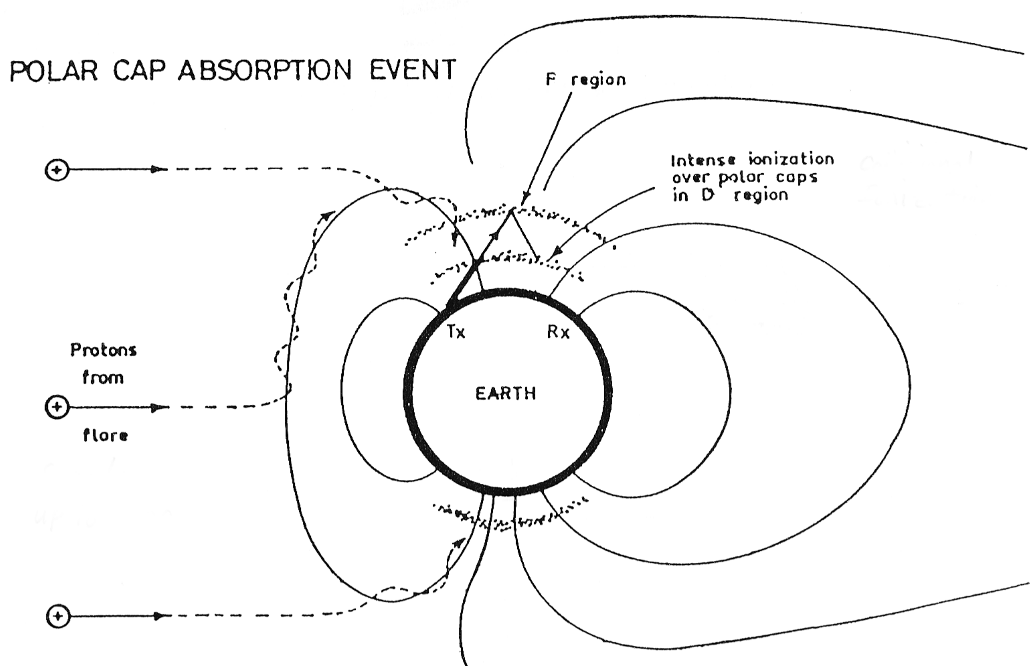

Figure 5 Charged particles follow Earth's magnetic field lines (source: McNamara)

The nearly vertical magnetic field lines not only expose the high latitude ionosphere to the solar winds but also to solar wind driven phenomena occurring throughout Earth's magnetosphere.

As discussed in Chapter 8, the magnetosphere is the region of space occupied by Earth's magnetic field. Earth should have a symmetrical dipolar magnetic field as shown in Figure 2. However, solar wind severely distorts Earth's magnetic field forming the magnetosphere shown in Figure 6. In general, Earth's magnetic field shields Earth from the ravages of the solar wind by defecting the wind past the Earth. As an example, Mars once had rivers, lakes, and possibly an ocean, like Earth. But Mars, which is much smaller than Earth, cooled rapidly and lost its protective magnetic field. Without its magnetic field, the solar winds ravaged the planet, evaporating all its lakes and rivers leaving the planet a barren waste land. Without Earth's magnetic field that would happen to us!

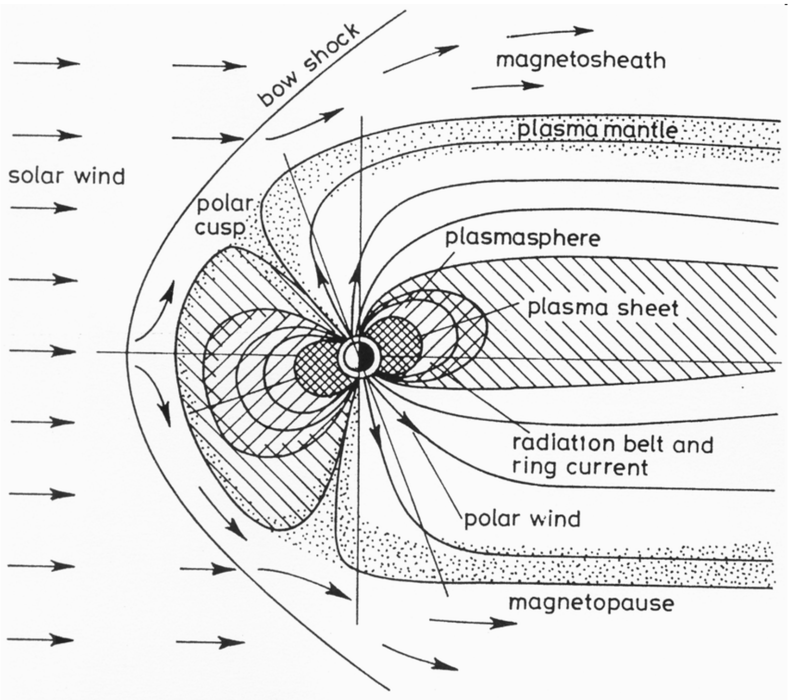

Figure 6 Earth's Magnetosphere (source: Davies)

The solar wind is typically traveling at around 400 km/sec as it approaches Earth. A speed of 400 km/sec is nearly 1 million miles per hour.

The solar wind is tenuous. Its particle density is only around 5 particles per cubic centimeter. Most of these particles are electrons and protons (H^+), with α – particles (He^{2+}) making up about 5% of the particle density. In contrast, the peak electron density in the ionosphere is around 10^6 electrons per cubic cm.

The solar wind impacts Earth's magnetic field in the region of the magnetopause (Figure 6) around 11 Earth radii (11 R_E) from the sunlit side of Earth. (1 R_E = 6,370 km = 3,959 mi). Since the electrically charged solar wind particles can not cross Earth's magnetic field lines, they are forced to travel around the magnetosphere's outer edge. In the process, the solar wind creates a bow shock about 15 R_E from the closest approach to Earth. Despite the tenuous nature of the solar wind, the force that it exerts on Earth's magnetic field compresses the magnetosphere on the dayside and stretches it out on Earth's nightside forming the long comet like magnetic tail illustrated in Figure 7.

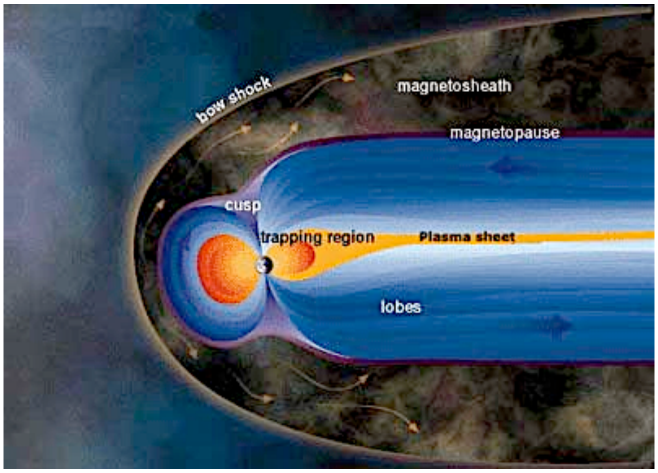

Figure 7 Earth's comet shaped magnetosphere (source: jpl.nasa.gov)

The polar cusps, shown in Figure 6 and Figure 7, form the gap between the day side magnetic field extending out in front of the Earth and the nightside field forming the magnetotail. The polar cusps are extremely important since they are the only locations where charged particles can enter the ionosphere without crossing magnetic field lines. Each polar cusp extends down to Earth's surface forming a funnel which at Earth's surface is about 5° wide centered at around 77° magnetic latitude. Within the cusps high energy solar wind and magnetosheath particles stream down directly into Earth's upper atmosphere, unimpeded, significantly and adversely affecting the high latitude ionosphere.

The magnetosphere is fixed relative to the Sun while the Earth itself rotates within the stationary magnetosphere. That is, the nose of Earth's comet shaped magnetosphere always points toward the Sun while the tail points down stream away from the Sun.

Chapter 8 describes the solar wind's interaction with Earth's magnetic field and the various regions of the magnetosphere.

13.2 Complexity of the High Latitude Region

Earth's high latitude zone is a very complex place with

- Multiple electric fields,
- Electrical currents,
- Particle in flows, and
- Particle out flows

as illustrated in Figure 8. This complexity is due primarily to Earth’s magnetic field being nearly vertical at high latitudes.

To make matters worse, most of the magnetosphere’s various regions (Figure 6) originate or terminate in the high latitudes. 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 area is challenging. The various fields, currents, and particle flows are briefly described next. A more compete discussion is provided in Chapter 8.

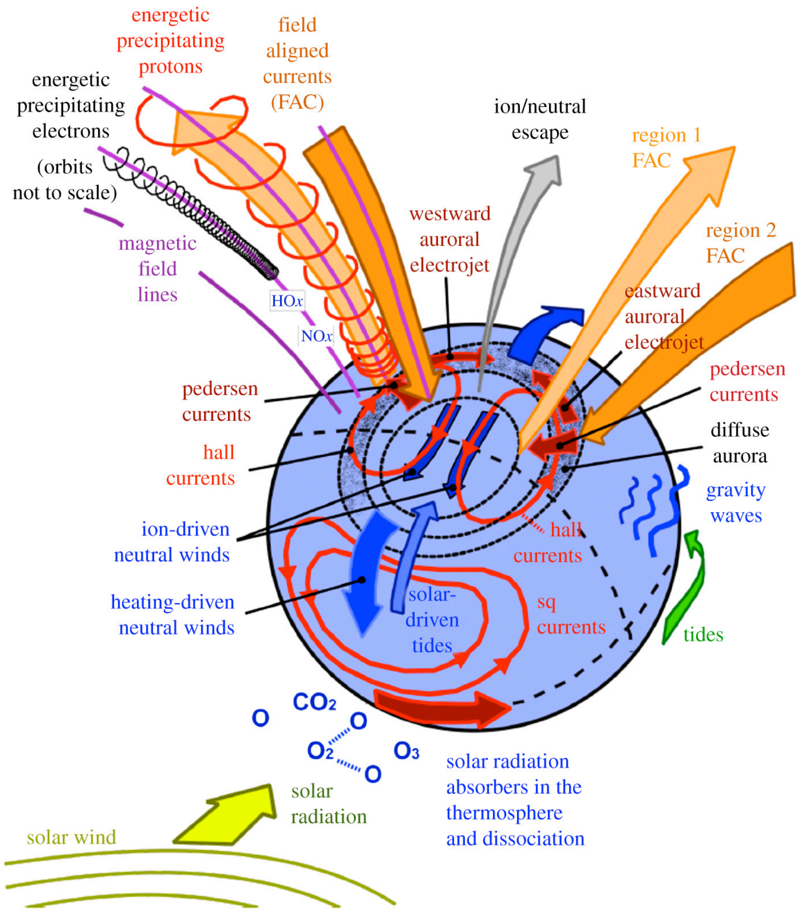

Figure 8 Polar region electrical currents (source: royalsocietypublishing.org)

13.2.1 Field Aligned Currents (FAC)

Prominent in Figure 8 are the field aligned currents shown as the large orange arrows flowing into and out of the high latitude regions. These currents, illustrated in more detail in Figure 9, flow along geomagnetic field lines connecting Earth’s high latitude ionosphere to the magnetosphere. They are important because they are the dominant form of energy exchange between the magnetosphere and ionosphere. Field aligned currents are also known as Birkeland currents.

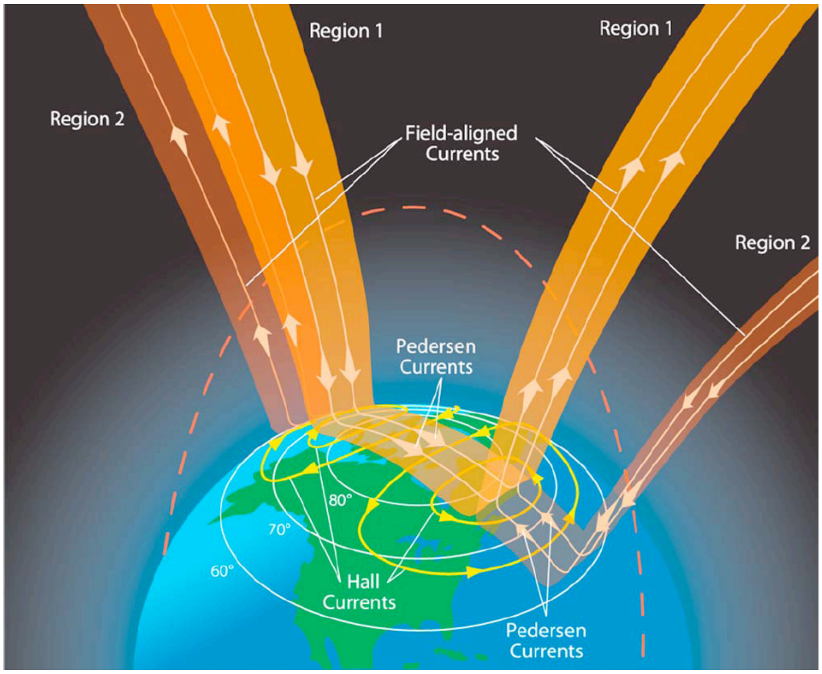

Figure 9 Field Aligned Currents (source: Wikipedia)

There are two sets of concentric field aligned current sheets, one inside the other (Figure 9). The poleward inner current sheet is referred to as Region-1 (R1) while the outer current sheet toward the equator is designated Region-2 (R2). R1 current flows outward from the dusk side of the polar region and downward into the dawn side. R2 current exhibits the opposite flow of R1. R2 current flows upward out of the dawn side and downward into the dusk region as illustrated in Figure 9. Dusk occurs on the right side of this figure.

R1 and R2 currents originate from different parts of the magnetosphere. Diverging currents flowing in the magnetopause are the source for the R1 current, as illustrated in Figure 10. In contrast, R2 current is the result of partial ring currents flowing in the inner magnetosphere. In Figure 10 Region 1 electrical current flows out of the dusk polar region, connects with the Chapman-Ferraro magnetopause current, and then reenters the polar region dawn side. Pedersen currents complete the circuit carrying Region 1 electrical current across the polar cap back to the polar region dusk side. Region 2 electrical current flows out of the dawn region, flows by means of a partial ring current back to the dusk side where it reenters the polar region. Pedersen currents carry the Region 2 current into the outgoing Region 1 current. On its return to the polar region dawn side, part of the Region 1 current is carried by Pedersen currents back to the outgoing Region 2 current completing the Region 2 circuit.

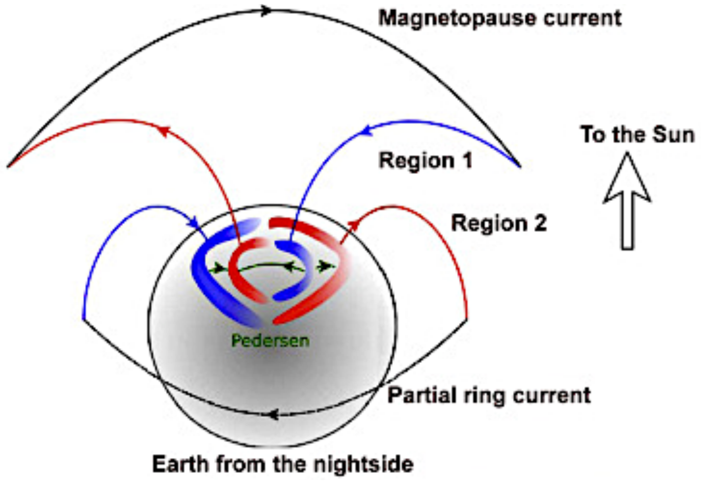

Figure 10 Region 1 and Region 2 Field Aligned Currents (source: ScienceDirect.com)

13.2.2 Hall Currents

The horizontal high latitude Pedersen electric field ($\vec{E}$) in combination with the vertical magnetic field ($\vec{B}$) generate two $\vec{E} \times \vec{B}$ hall current convection cells, illustrated by the yellow arrows in Figure 9. The convection cells carry ionospheric plasma over the poplar cap and then back through the auroral oval, as illustrated in Figures 9.

13.2.3 Polar Wind Outflow

The polar wind is illustrated in Figure 8 by the outward flowing gray arrow.

There are only two possible sources for the charged particles existing throughout the magnetosphere:

- The ionospheric polar wind outflow, and
- The solar wind emanating from the Sun.

The polar wind is a significant and at times the dominate source of charged particles in the magnetosphere. These particles consist of free negatively charged electrons and positive ions composed primarily of hydrogen (H^+), helium (He^+) and oxygen (O^+). These particles flow outward from the polar region topside ionosphere into the magnetosphere forming the polar wind illustrated in Figure 11.

In contrast, the solar wind emanating from the Sun is the other source of magnetospheric charged particles, particularly H^+ and He^{2+} ions.

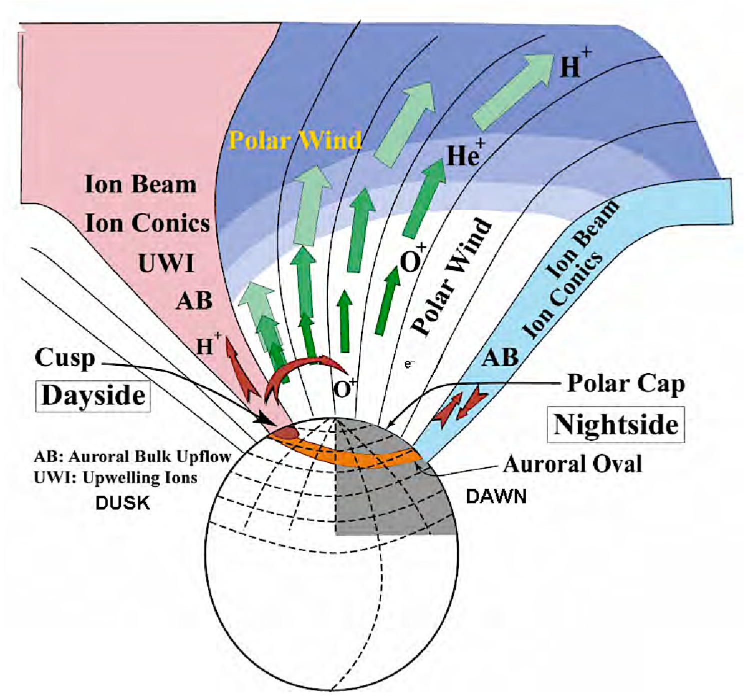

Figure 11 Polar Wind outflow (source: www.semanticscholar.org)

The outflow of light hydrogen (H^+) and helium (He^+) ions along open magnetic field lines into the magnetosphere is due in part to:

- Ionization heating that allows hydrogen H^+ and helium He^+ ions to acquire sufficient energy to escape from the ionosphere into the surrounding magnetosphere.

- Pressure differences between the ionosphere and the magnetosphere. The higher gas pressures present in the ionosphere drive ions outward into the magnetosphere.

- Radially directed electric fields due to the separation of fast electrons from slow heavy oxygen ions. The radial electric fields catapult light hydrogen H^+ and helium He^+ ions into the magnetosphere.

Plasma electrons and ions are linked together by electrostatic forces. An electric field quickly develops if ions and electrons begin to separate. The mass of an electron is nearly 20,000 times less than an oxygen ion O^+, meaning that the pull of gravity on an electron is negligible compared to that on an O^+ ion. In addition, due to its low mass, an electron is much more mobile and incredibly fast compared to an oxygen ion with the same kinetic energy. Because of these differences, fast electrons and slow heavy oxygen ions tend to separate in the topside ionosphere forming a radially directed electric field. The electric field accelerates the outward flow of light hydrogen and helium ions into the magnetosphere, leaving behind the heavy oxygen ions.

In the 1960s spacecraft in Earth orbit began detecting O^+ ions in various regions of the magnetosphere including the plasma sheet, plasmasphere, radiation belts, and far out in the magnetotail. The ionosphere is the only possible source for these oxygen ions since they do not occur in the solar wind.

An energy boost of more than 10 ev (1 ev = 1.602×10^{-19} joules) is needed for O^+ ions to escape the ionosphere. Consequently, other energy sources besides ionization heating, pressure differences and radial electric fields must be operating in the polar wind in order for O^+ ions to be found far out in the magnetosphere. These additional energy sources include:

- Unstable field aligned electrical currents (FAC)
- Interaction of cold ionospheric electrons with hot magnetosphere electrons
- Wave particle interactions (WPI),
- Auroral Bulk Upflows,
- Centrifugal acceleration, and
- Upwelling Ions (UWI).

Basically, all O^+ ions that reach an altitude of 4,000 to 5,000 km have acquired sufficient energy to escape from the ionosphere.

The polar wind spews on the order of 50 tons of plasma per day into the magnetosphere. While 50 tons a day sounds like a lot, it is in fact negligible compare to Earth's total atmosphere.

The polar wind is the second most important mechanism responsible for removing electrons from the high latitude ionosphere, second only to recombination. Consequently, the polar wind tends to decrease electron densities in the polar cap region beyond that normally encountered through recombination.

13.2.4 Precipitating Energetic Particles

Solar wind and magnetosphere charged particles spiraling down magnetic field lines into the polar ionosphere are generally referred to as precipitating electrons and protons. These precipitating particles are illustrated on the top left side of Figure 8.

In addition to EUV and X-ray radiation, neutral gas particles at high latitudes are ionized by collisions with precipitating energetic electrons and high energy ions. The ions are primarily protons and α – particles (helium nuclei).

A collision with an energetic electron can have three consequences:

1. The gas particle with which the incoming electron collides absorbs the electron's kinetic energy converting it to heat which raises the particle's temperature,
2. The energy absorbed from the electron excites the particle to a higher energy state, or
3. The gas particle can actually be ionized by the collision.

In the first case most of the kinetic energy of a fast-moving electron is lost when it collides with a gas particle. A gas particle is huge, typically 20,000 times more massive than an electron. The lost energy is absorbed by the particle heating it to a higher temperature.

In the second case, the energy absorbed from the electron excites the particle to a higher energy level. When excited, a particle typically returns to its normal energy level in a second or two dissipating it excess energy as photons of light. This is the type of collision responsible for auroral light displays.

In the third case the kinetic energy of the incoming electron is high enough to knock an electron out of a gas particle. The collision ionizes the gas particle and doubles the number of free electrons. The free electrons consist of the original incoming electron plus the electron stripped from the gas particle.

Collisions with high energy electrons also has a secondary ionization affect. A small amount of the energy involved in a collision is converted to x-rays. The x-ray radiation penetrates deeper into the atmosphere than does the electrons. In the process, the x-rays ionize additional gas particles further down in the atmosphere typically at an altitude of 50 km or less.

The ionization rate due to secondary x-rays is far less than that produced by the energetic electrons higher up in the atmosphere. However, it is often the primary form of ionization at altitudes below 50 km.

Collisions also occur in the high latitude atmosphere between neutral gas particles and in coming high energy solar wind protons and α – particles. These collisions heat the polar atmosphere. If the collision energy is high enough, the colliding gas particle will be ionized. High energy protons and α – particles ejected from the Sun by solar flares have significantly more energy than energetic electrons and consequently produce much higher levels of ionization.

Ionization by precipitating electrons and protons increases high latitude ionization levels beyond that which would normally occur through EUV radiation.

13.3 Earth's High Latitude Zones

The high latitude region is separated into:

- The polar cap, and
- The auroral oval.

13.3.1 Polar Cap

In Figure 12 the green area is the auroral oval. The yellow region poleward of the oval is the polar cap. Note that the time of day is shown in Figure 12 with 00 being midnight. Also note that the top part of the figure points toward the Sun (local noon).

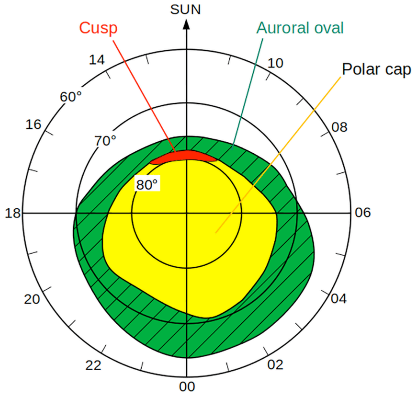

Figure 12 Earth's high latitude zones (source: ResearchGate)

The auroral oval marks the division between Earth's closed and open magnetic field lines illustrated in Figure 13. Both ends of closed magnetic field lines connect back to Earth. Open field lines on the other hand are connected to Earth at only one end. The other end extends out into interplanetary space.

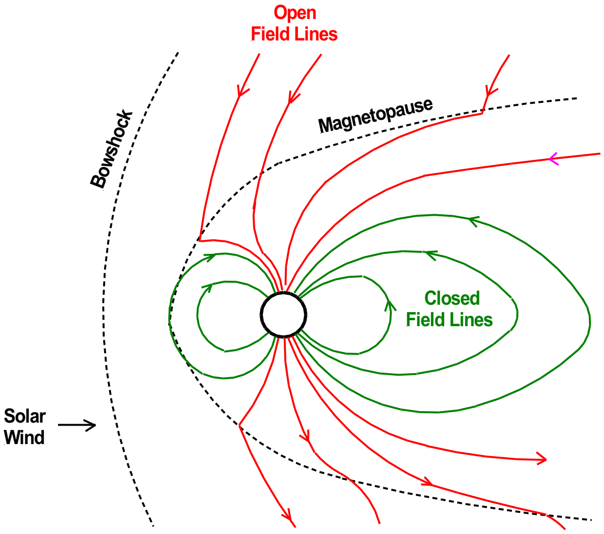

Figure 13 Closed and Open Magnetic Field Lines (source: author)

Magnetic field lines within the polar cap are open, meaning that they flow outward from the polar region eventually connecting with the solar wind Interplanetary Magnetic Field (IMF) far out in the magnetosphere tail. The open field lines provide a conduit for charged particles flowing between the polar cap and the magnetosphere tail, illustrated by the field aligned currents and the polar wind (gray arrow) in Figure 14.

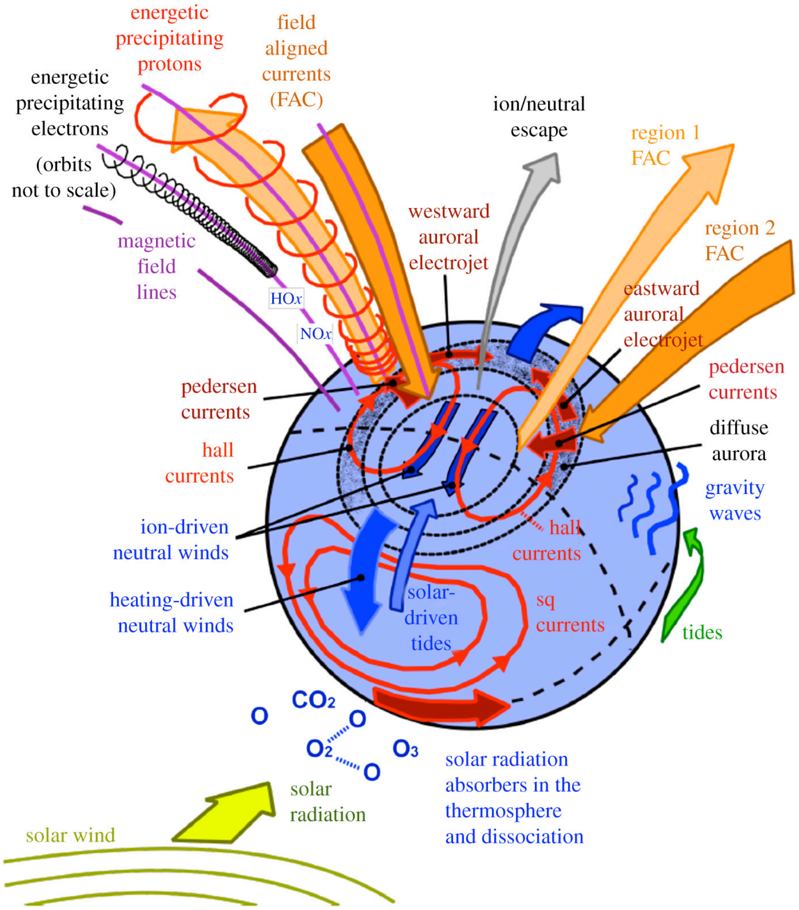

Figure 14 Complexity of high latitude region (source: royalsocietypublishing.org)

13.3.2 Auroral Oval

Beautiful shimmering auroral light displays, like that shown in Figure 15, occur in both the northern and southern high latitude regions. They are known as aurora borealis in the north and aurora australis in the southern hemisphere. Aurora displays frequently include magnificent curtains of light, rays, and arcs that extend across the sky from horizon to horizon. They often appear to pulsate and dance under the influence of ionospheric winds. No two auroral displays are alike. Instead, they vary considerably in shape and brightness over time intervals from seconds to minutes. The patterns and shapes of the aurora are determined by the changing flow of incoming charged particles and varying magnetic fields.

Figure 15 Auroral Display (source: sciencephoto.net)

13.3.2.1 Formation of Auroral Displays

Visual auroras, like that shown in Figure 15, are formed as high energy incoming particles, primarily electrons, collide with neutral atoms and molecules in Earth's upper atmosphere. Far out in the magnetosphere tail, electrons are accelerated by the solar wind's interplanetary magnetic field (IMF) to high energy levels. The accelerated electrons follow Earth's magnetic field lines back toward Earth and down into the polar region, entering Earth's atmosphere in a rough circle called the auroral oval illustrated in Figure 16.

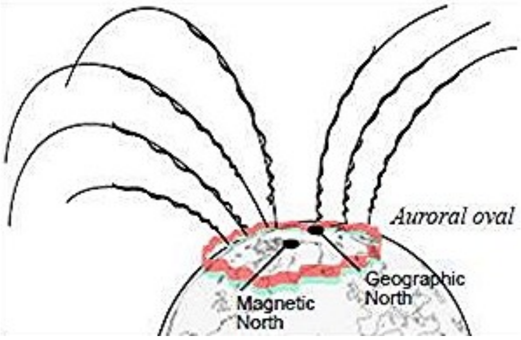

Figure 16 Formation of the auroral oval (source: NOAA space environment center)

13.3.2.2 Color of Auroral Displays

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 the colliding particles. Most auroral features are greenish yellow produced by excited oxygen atoms as illustrated in Figure 17. High altitude oxygen atoms emit a reddish light as do excited nitrogen molecules at lower altitudes, giving the tops and bottoms of tall curtains their reddish color.

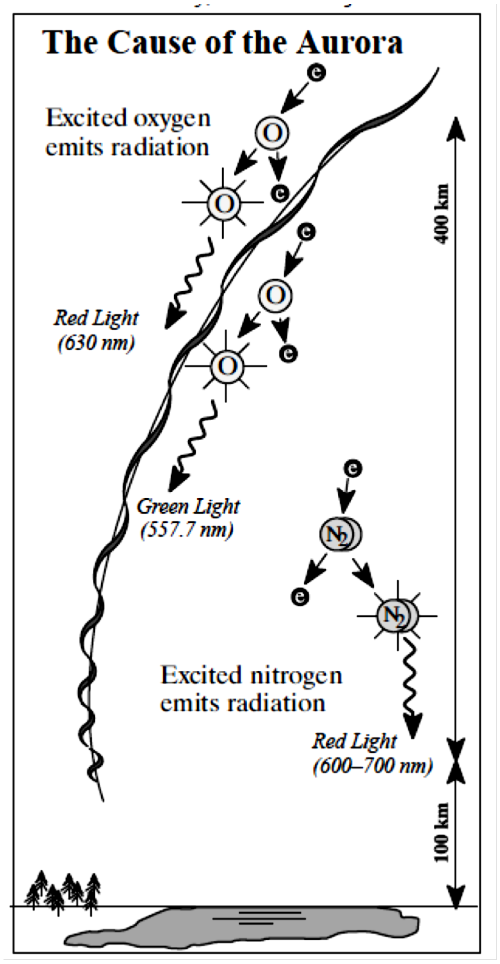

Figure 17 Color of auroral displays (source: NOAA Space Environment Center)

13.3.2.3 Altitude of Auroral Displays

The vast majority of aurora displays form in the high latitude E region of the ionosphere from about 90 to 130 km above Earth's surface. However, aurora can extend down to around 70 km and up to nearly 600 km. The height of individual aurora displays, measured from their lower edge, varies. Most of the bright displays are less than 20 km tall and generally very thin ~ 100 m thick.

13.3.2.4 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 and develop into full displays. 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.

13.3.2.5 Diffused Aurora

In addition to discrete aurora (curtains, arches, rays, etc.) there are also diffused aurora, or auroral glow, such as that shown in Figure 18. 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 diffuse aurora. Discrete forms appear in these images both within the diffuse area and poleward of it. However, discrete forms are seldom seen on the equatorial side of a diffuse aurora. The charged particles forming the discrete and diffused aurora are believed to originate from different sources.

Figure 18 Diffuse Aurora (source: NASA ISS)

13.3.2.6 Size and Location of the Auroral Oval

During quiet geomagnetic conditions the auroral oval is around 3,000 km in diameter centered over the magnetic pole. In general, the oval is located between 64 to 78 degrees latitude. The oval is at its lowest latitude at midnight and highest latitude around noon. The width of the oval also varies. It is greatest at midnight, about 10° wide in latitude, and narrowest at noon. The southern hemisphere auroral oval is similar.

Images from space confirm that the oval is a permanent ring of light around the magnetic pole, as shown in Figure 19, though the intensity of the light varies considerably from one area of the ring to another. During geomagnetic storms the oval grows brighter and larger allowing aurora displays to be observed at lower latitudes, for example in the northern United States and central Europe. The aurora for very large storms can sometimes be seen as far south as Washington D.C. and Virginia.

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

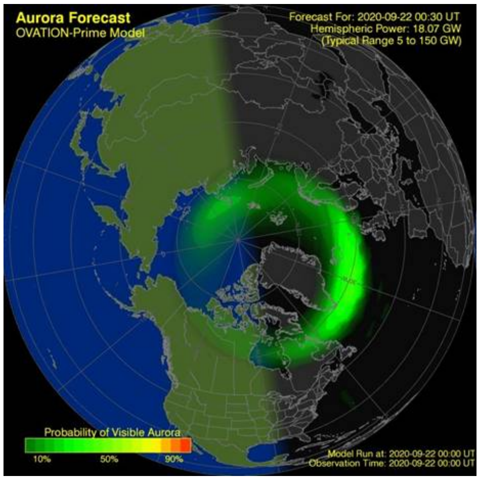

Figure 19 Aural oval (source: Ovation model)

13.3.2.7 Inner and Outer Auroral Ovals

The auroral oval is actually two ovals, an inner (green) and an outer (pink) oval shown in Figure 20.

The inner oval is the visual or luminous oval. Its characteristics include:

- Luminosity,
- Sporadic – E ionized patches
- Spread – F zones, and
- Soft X-ray emissions.

The outer oval is nearly circular. It is situated lower in latitude at approximately 60° to 70°. The characteristics of the outer oval include:

- Diffuse aurora,
- Radio wave absorption,
- Sporadic – E at an altitude of 80 to 90 km, and
- Slow fading of VHF scatter signals.

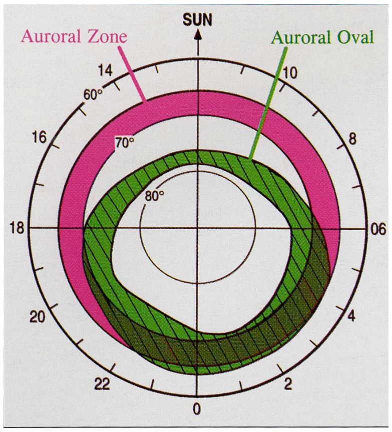

Figure 20 The auroral oval is actually two ovals (source: http://ffden-2.phys.uaf.edu)

Activity in the inner oval is greatest at night. In contrast, the highest level of outer oval activity occurs during the day. Both ovals occupy about the same latitude at midnight (the black region in Figure 20) but become increasingly separated toward noon.

The high energy particles responsible for the inner oval are believed to originate in Earth's geomagnetic tail. High energy particles responsible for the outer oval are thought to originate closer to Earth in the Van Allen radiation belts (Figures 21 and 22), and have higher energy levels than those forming the inner oval.

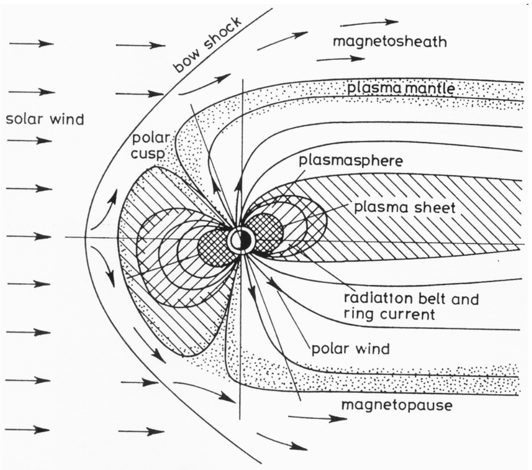

Figure 21 Earth's Magnetosphere (source: Davies)

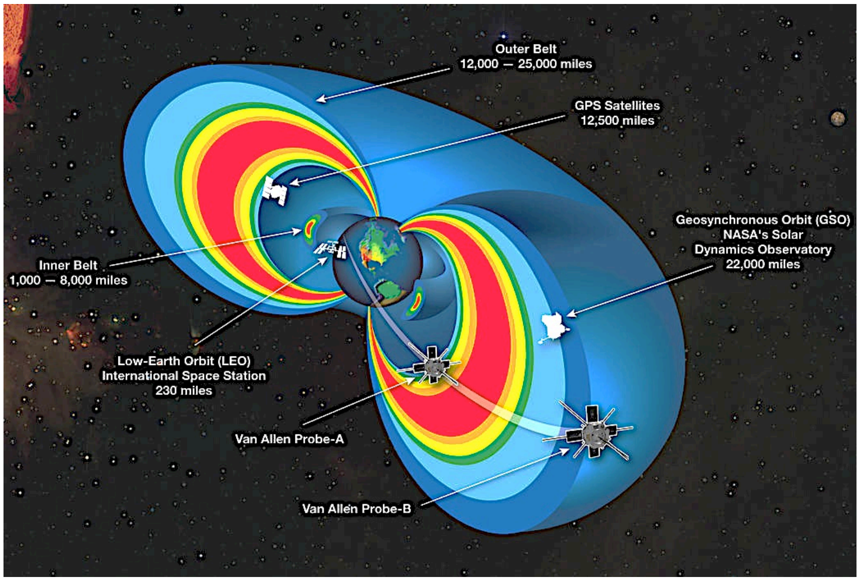

Figure 22 Cutaway model of the radiation belts (source: NASA)

13.3.2.8 Aurora Forecast Model

The OVATION Aurora Forecast Model, Figure 23, predicts the intensity and location of the aurora oval for the time shown at the top of the map. This probability forecast is based on current solar wind conditions measured at the L1 point in space, assuming a 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.

A 30-minute delay corresponds approximately to an 800 km/s solar wind speed as might be encountered during geomagnetic storm conditions. In reality, delay times vary from less than 30 minutes to an hour or so.

In Figure 23 the sunlit side of Earth is indicated by the lighter blue of the 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 lighter edge marks the zone where the Sun is just at the horizon. At the darker edge the Sun is 12 degrees below the horizon. The aurora is not visible during daylight hours; however, the aurora can often be observed about an hour before sunrise or just after sunset.

The current aurora forecast can be viewed by clicking on “Aurora” under “Current Conditions” on the www.skywave-radio.org website.

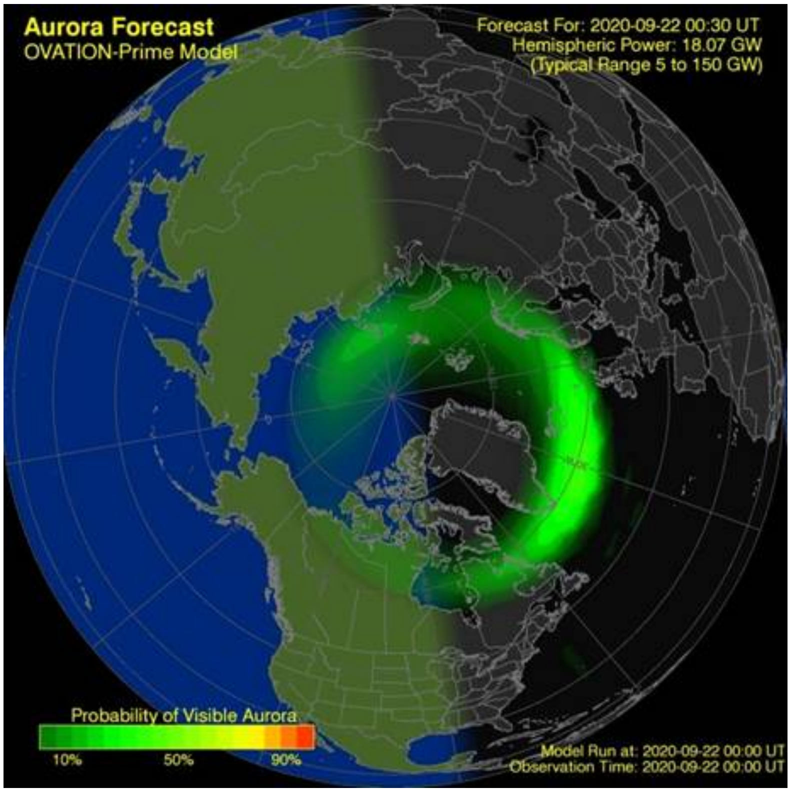

Figure 23 Auroral Oval September 22, 2020

13.4 High Latitude F Region of the Ionosphere

Dynamics in the high latitude F region are very complex. This complexity results from:

- Earth’s nearly vertical magnetic field at high latitudes altering propagation paths,
- The polar cusps directly exposing the high latitude F region to violent disturbances occurring on the Sun,
- Dramatic changes in F region ionization levels caused by charged particles spiraling down magnetic field lines,
- The polar wind transporting charged particles out of the ionosphere,
- Troughs of depleted electron density disrupting communication circuits.

The equatorial and mid-latitude regions of the ionosphere do not encounter these problems.

F region ionosphere plasma in the equatorial and mid-latitude regions is driven by high altitude neutral winds. However, in the polar region, the plasma is driven more by changing electric and magnetic fields than by the neutral winds. The cross-polar electric field, responsible for the Pedersen current shown in Figure 24, coupled with the vertical magnetic field produce plasma speeds of 200 to 1,000 meters per second in accordance with

$$\vec{v} = \frac{\vec{E} \times \vec{B}}{|B|^2}$$

where v is the plasma speed and E and B are the electric and magnetic fields respectively. The direction of the plasma flow is directly over the pole from the polar cap noon to midnight sectors, with a return flow through the auroral oval back to the day sector. This flow is perpendicular to both the polar-cap electric field and the vertical magnetic field, forming two hall current convection cells shown in yellow in Figure 24. Variations in the solar wind and interplanetary magnetic field (IMF) distorts this basic flow pattern.

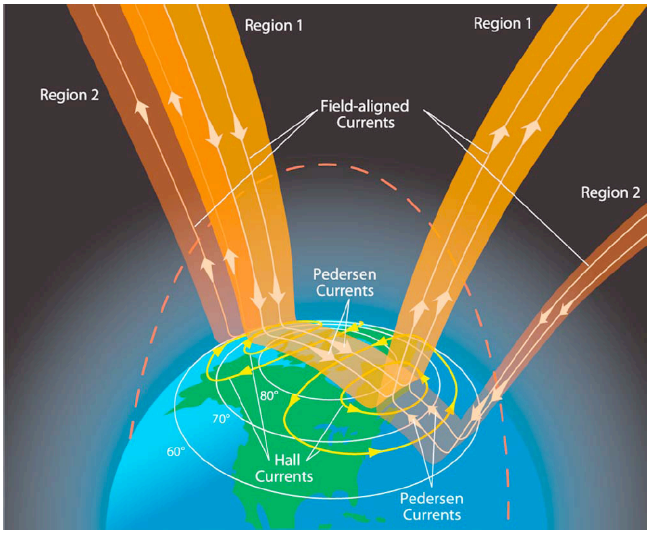

Figure 24 Field Aligned Currents (source: Wikipedia)

13.4.1 F Region in the Polar Cap

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 polar cap ionization resulting in higher than expected critical frequencies.

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 the second most important mechanism responsible for removing electrons from the polar cap ionosphere, second only to recombination. Consequently, the polar wind decreases electron densities in the polar cap region beyond that normally encountered through recombination, resulting in lower than expected critical frequencies.

Variations 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. In the summer during solar maximum polar cap critical frequencies can be as high as 5 to 6 MHz. At times the polar cap F1 region can be stronger than the F2 region.

13.4.2 F Region in the Auroral Oval

The auroral oval F region (the green area in Figure 25) 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 on the poleward side of the oval and extending a few degrees into the polar cap are often enhanced by precipitation of electrons from the solar wind and outer magnetosphere. The polar cap is the yellow part of Figure 25. The enhancements are generally not uniform. Large variations in electron densities can occur over relatively short distances due to irregularities in the precipitation. Ion precipitation is particularly strong in the cusp region highlighted in red in Figure 25. In addition, transport of plasma over the pole contributes significantly to late night ionization levels within the auroral oval. On the equatorial side of the oval, night time depletions in electron and ion densities form F region ionospheric troughs, including the main trough described in the next section.

These factors cause propagation of HF radio signals through the auroral zones to be more erratic than at mid-latitudes.

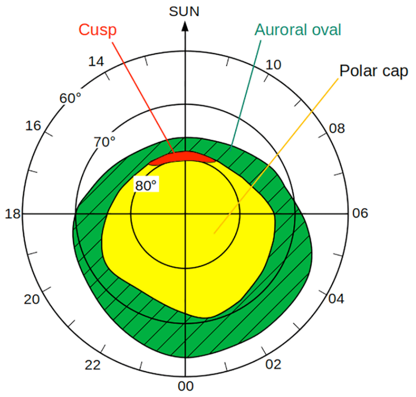

Figure 25 High Latitude Regions (source: ResearchGate)

13.4.3 High Latitude F Region Irregularities

Irregularities in the high latitude F region include:

- Ionospheric troughs,
- High latitude spread F,
- Patches,
- Blobs, and
- Traveling Ionospheric Disturbances.

13.4.3.1 F Region Ionospheric Troughs

An ionospheric trough is a relatively narrow strip of depleted ionization in the high latitude F region of the ionosphere. Within a trough electron densities and O^+ ion concentrations are relatively low compared to regions outside the trough.

A number of troughs exist. The largest and most pronounced trough is the F Region Main Trough shown in Figure 26. It is a narrow ribbon of depleted ionization that stretches east to west near 60^o latitude along the equatorial edge of the auroral oval. It is primarily a night time phenomenon, appearing at dusk and extending through the night to dawn. Typically, the main trough is around 15^o wide in latitude. Originally the main trough was called the mid-latitude trough. Today the term main trough is generally used since there are a number of smaller troughs in both the northern and southern auroral zones.

The main trough is generally considered to mark the boundary between mid and high latitude regions of the ionosphere. However, the main trough is not stationary. It expands and contracts both northward and toward the equator. 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 often in the winter and during the equinoxes. The trough rarely appears in summer. When a summer trough does occur it usually appears only around midnight.

F region troughs that appear in the southern hemisphere are much different from those in the north. Southern hemisphere troughs appear throughout the year and at all times of the day. They tend to occur more often during the day than at night and during the equinoxes and in the summer, the opposite of northern hemisphere troughs. The considerable difference between northern and southern hemisphere troughs is believed to be due to differences in hemispheric polar circulations.

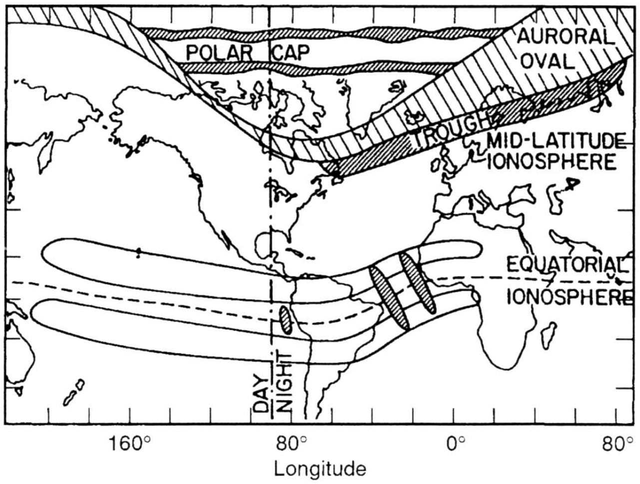

Figure 26 Location of main trough (source: Goodman)

It is generally believed that trough formation is the result of high latitude F region plasma flowing from east to west in the opposite direction of Earth's rotation. The westward flow extends the amount of time that the ionosphere remains in darkness, allowing more time for electron-ion recombination to occur before solar photo-ionization resumes at sunrise. The extended period of darkness results in lower concentrations of electrons and ions in a trough.

Other high latitude troughs occur in the auroral oval. These troughs are typically between 5° to 9° wide and are generally found above 65° latitude. They typically last 4 to 8 hours. Low concentrations of H^+, O^+, and N^+ ions occur in these troughs while, surprisingly, molecular NO^+ and O_2^+ concentrations increase.

Depletions that are not elongated are classified as holes.

A polar hole is a distinct feature of the Antarctic polar cap. The hole is a long-term depletion in ion and electron concentrations that occurs in the winter during years around solar minimum. It hardly ever appears in the summer. The hole develops shortly after midnight at latitudes near 80°. Electron densities within the hole at an altitude of 300 km are around 1×10^2 per cm^3 compared to 10^5 per cm^3 elsewhere in the polar cap. For unknown reasons, a polar hole does not occur in the Artic.

The problem with low electron density in a trough is that it disrupts radio circuits passing through the trough area. Figure 27 illustrates the problem. A signal that would normally propagate through the region without any problem (the red trace in Figure 27) is instead lost to outer space (the black trace) due to the low ionization levels in the trough. The only way to rectify the problem is to switch to a lower operating frequency compatible with the critical frequency within the trough. For example, switching from 40 meters down to 80 meters. Knowledge of trough appearances and locations are thus important for high latitude and transpolar radio communications.

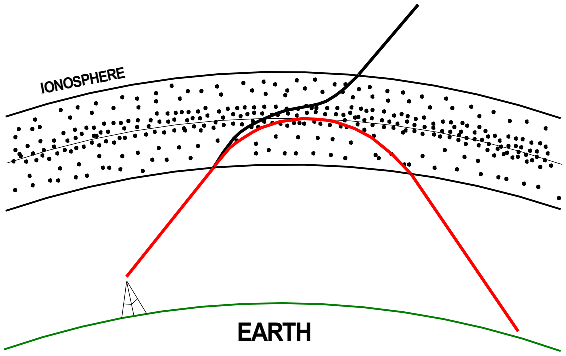

Figure 27 Signal lost to outer space (source: author)

13.4.3.2 High Latitude Spread F

Signal scattering due to field-aligned irregularities results in an F region phenomenon known as spread F. Spread F causes an HF signal to be reflected from various heights within the F layer, as illustrated in Figure 28, stretching out and garbling the transmitted signal. 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. In addition, spread F produces high fading rates.

While the field aligned irregularities producing spread F are highly variable in size, they can range in length from roughly a 100 km to several thousand kilometers and about a kilometer thick. These irregularities drift horizontally at speeds up to about 100 meters per second. At high latitudes, spread F occurrences beginning around 40° 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. In addition, spread F formations, with electron concentrations several orders of magnitude greater than normal, frequently drift into the polar cap from the auroral zones, particularly with elevated solar activity.

During the summer, near the magnetic dip poles, spread F occurs nearly every night and often during the day. In the winter spread F is nearly continuous, both day and night.

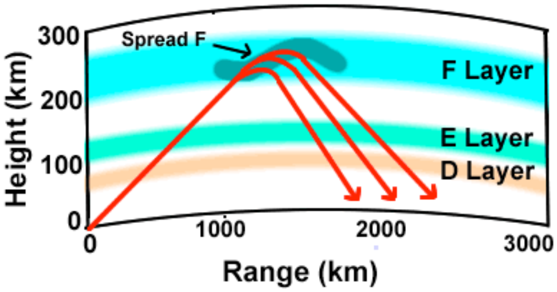

Figure 28 Spread F (source: www.met.nps.edu)

13.4.3.3 Polar Cap Patches

Patches are roughly circular areas of enhanced electron densities, 200 to 1,000 km in size, that generally occur at night in the polar cap. Electron densities within a patch are typically 2 – 10 times higher than in the ambient polar cap ionosphere. For instance, 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. Patches appear under disturbed ionospheric conditions when the IMF is southward. It is believed that a change in polar circulation, due to a sudden increase in solar wind or change in the IMF, can detach plasma from the dayside polar cap. Plasma drift in the polar cap rapidly transports the detached patch over the pole to the night sector. Patches can occur during all seasons of the year but are more frequent during the winter and tend to be stronger at solar maximum.

13.4.3.4 Auroral Zone Blobs

Electron density enhancements in the auroral zone are called blobs. Blobs vary considerably in size. They are smaller than patches, typically tens of kilometers in size instead of hundreds of kilometers. The cause of blobs is uncertain and may be formed by a number of different mechanisms. In some cases, blobs may be formed by particle precipitation. It is also possible that some blobs are formed by patches drifting into the auroral zone from the polar cap and then breaking up into smaller blobs. Why this happens is unknown. In general, blobs seem to move with the auroral F region plasma drift.

13.4.3.5 Traveling Ionospheric Disturbances

Traveling ionospheric disturbances (TIDs), illustrated in Figure 29, are large scale wavelike disturbances with wave periods from a few minutes to more than an hour. They are typically 100 to 1,000 km in size and travel at speeds from 50 to about 1000 meters per second. TIDs have long wave fronts that are tilted forward. Consequently, TIDs appear first at high altitudes and move downward as they pass. Very large TIDs originate in the auroral zone and travel great distances. These disturbances are associated with magnetic storms.

HF radio signals encountering traveling ionospheric disturbances are seriously disrupted. Nearly all aspects of an HF signal are distorted including signal frequency, amplitude, phase, and polarization.

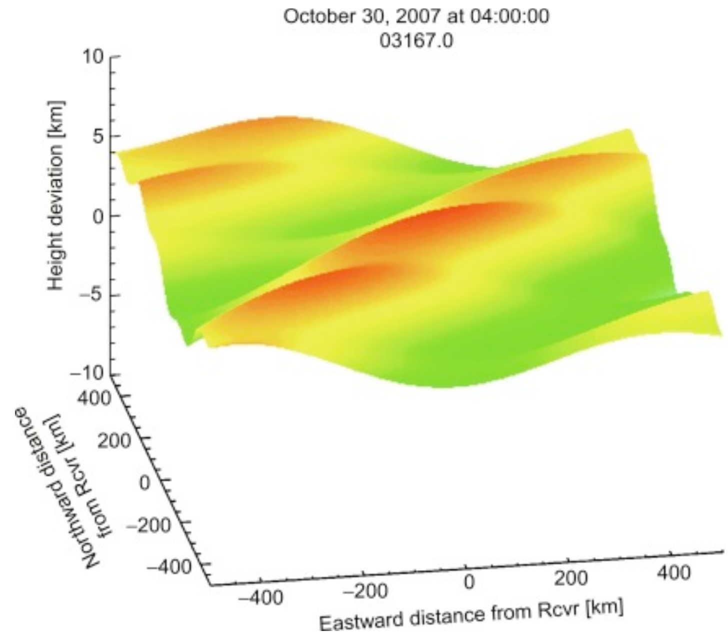

Figure 29 Traveling Ionospheric Disturbance (source: ScienceDirect.com)

13.5 High Latitude E Region

During geomagnetic quite times the high latitude E region is very much like the mid-latitude E region and subject to the same diurnal, seasonal, and solar cycle variations. The E region electron density builds up following sunrise, peaks at local noon, and declines later in the day. However, the Sun is above the horizon most of the time during summer in the high latitudes. For instance, in mid-July, sunrise occurs at 4 AM in Fairbanks, Alaska and sets a few minutes before midnight. Consequently, summer time E Region ionization levels remain relatively high well into the night. In the winter the high latitudes are in darkness a good part of the time leading to low E region ionization.

Geomagnetic storms are the main disturbances affecting the auroral E region. The auroral oval becomes more dynamic during a storm producing visual aurora as well as expanding in size both poleward and toward the equator. Figure 30 shows the aurora (the light blue area) embedded in the E region. Precipitating electrons which create the visual aurora also enhance auroral E region ionization. Collisions between neutral gas particles and energetic electrons doubles the number of free electrons present. The free electrons consist of the original incoming electrons plus the electrons stripped from the ionized gas particles. Ionization by precipitating electrons increases auroral E region ionization levels considerably beyond that which would normally occur through EUV radiation.

It is interesting to note that the E region over the polar cap remains pretty much the same as the mid-latitude E region, even during geomagnetic storms.

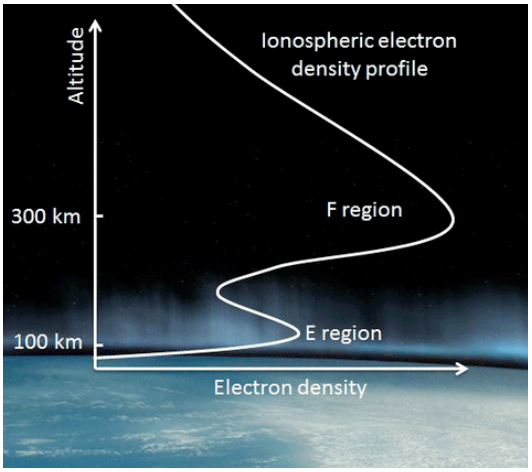

Figure 30 High latitude E region (source: researchgate.net)

13.5.1 Auroral Sporadic E

The appearance of auroral sporadic E zones, particularly at night, is one of the most conspicuous features of a disturbed E region. Auroral sporadic E is formed by energetic electrons streaming down into the auroral ionosphere during a storm, increasing ionization levels. Auroral sporadic E critical frequencies can be as high as 7 MHz.

13.5.2 Auroral E Region Electrojets

Ionization produced by precipitating electrons increases E region conductivity permitting an intense electrical current, known as the auroral electrojet, to flow in the auroral oval E region. The electrojet disrupts the geomagnetic field in the auroral zone causing it to vary in synchronism with the visual auroral display. The electrojet is responsible for the magnetic aspects of an auroral storm while excited atoms and molecules are responsible for the visual part of the storm.

13.6 High Latitude D Region

The high latitude D region of the ionosphere is more complex than the E region above it due to higher atmospheric pressures at D region altitudes. The higher pressure inhibits plasma motion and electrical currents in addition to complicating photochemistry in the region. What the high latitude D and E regions have in common is the importance of precipitating energetic charged particle in ionizing both regions. At times this ionization can be greater than that produced by solar EUV radiation.

There are two absorption phenomena that are unique to the high latitude D region:

- Polar Cap Absorption (PCA), and
- Auroral radio absorption (AA).

Polar cap absorption events are caused by the precipitation of solar energetic protons into the polar cap region, heavily ionizing the ionosphere's D layer following large solar flares. PCAs are relatively infrequent with 8 – 10 occurring per year during solar maximum and only 1 or 2 during solar minimum. However, when a PCA event does occur, it heavily absorbs HF radio signals throughout the polar cap region often creating a radio blackout.

Auroral absorption is caused by sporadic precipitation of energetic electrons into the auroral zone enhancing D region ionization. The energetic electrons generally originate within the magnetosphere during magnetic storms. Auroral absorption is more common than PCA events but not as intense and more sporadic in time and location, often occurring as bursts of absorption within the auroral zone.

13.7 High Latitude HF Radio Communications

Long distance HF radio communications depends on a "smooth" ionosphere from which radio signals can refract back to Earth, as illustrated in Figure 31. At high latitudes unstable levels of ionization, troughs, patches, and blobs are not conducive to a smooth polar ionosphere. Fortunately, these disruptions do not occur all the time. However, their occurrences are frequently predictable. Thus, radio operators must look for propagation openings through the high latitude regions.

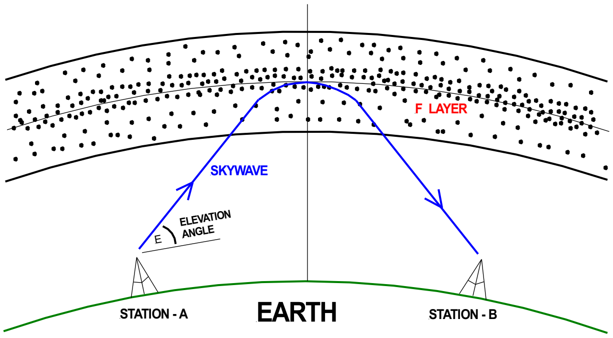

Figure 31 Ionospheric HF radio propagation (source: author)

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