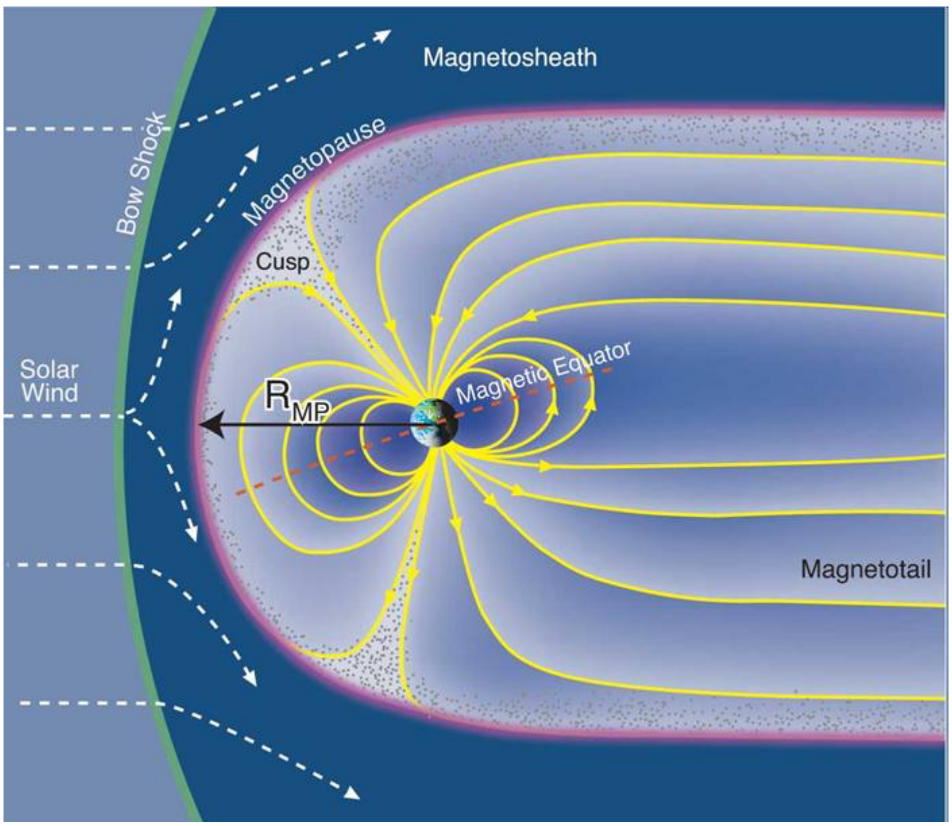
Chapter 8

Earth's Magnetosphere



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8 Magnetosphere

Most of what is presented in this chapter has been learned since the beginning of the space age in 1958. Prior to that we had no knowledge, certainly no proof, that any of this existed.

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 1. However, solar wind emanating from the Sun severely distorts Earth's magnetic field forming the magnetosphere shown in Figure 2. Earth's magnetic field shields the Earth from the ravages of the solar wind by defecting the wind past the Earth. Mars once had rivers, lakes, and even an ocean much like the Earth. However, when Mars cooled and lost its magnetic field, its atmosphere was ripped away by the solar wind which also evaporated its rivers, lakes, and ocean turning Mars into a barren desert.

Interaction of the solar wind with the magnetosphere create geomagnetic storms here on Earth that can seriously disrupt electrical power distribution grids causing millions of people to lose electrical power for several hours to a few weeks. Geomagnetic storms also disrupt the ionosphere and radio communications, affect airline travel on routes over the polar regions, increase satellite drag accelerating satellite end of life , and affect many other aspects of our technological world. The most severe geomagnetic storm on record occurred in 1859 seriously disrupting telegraph communication. It is estimated that a storm of that magnitude occurring today would cause over $2 trillion in damages.

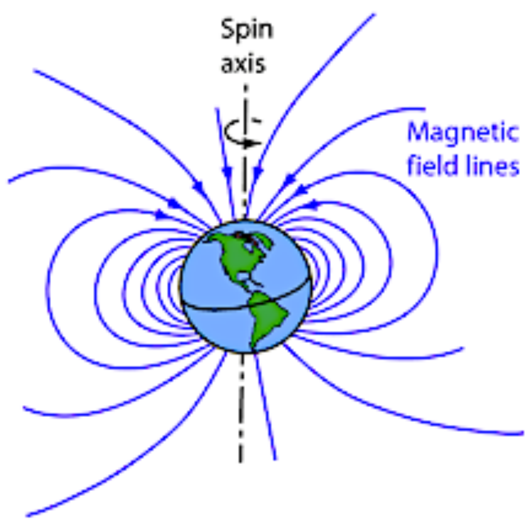


Figure 1 Earth's dipolar magnetic field (source: Hyperphysics)

Solar wind particles (mostly electrons, protons [H^+], and some α-particles [He^{2+}]) impact Earth's magnetic field in the region of the magnetopause around 11 Earth radii (11 R_E) from the sunlight side of the Earth. (1 R_E = 6,370 km = 3,959 mi). In general, the electrically charged solar wind particles can not cross magnetic field lines into the magnetosphere and so are forced to travel around the magnetosphere outer edge creating a bow shock about 15 R_E from closest approach to the Earth. The force exerted by the solar wind on Earth's magnetic field compresses the magnetosphere on the dayside and stretches it out on the nightside forming a long comet like magnetic tail that extends out past the Moon (Figure 3). Notice that during a full moon the moon is within the magnetic tail. However, during a new moon the moon, at a distance of 384,400 km (238,900 mi ~ 60 R_E), is outside the magnetosphere subjecting it to the ravages of the solar wind.

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.

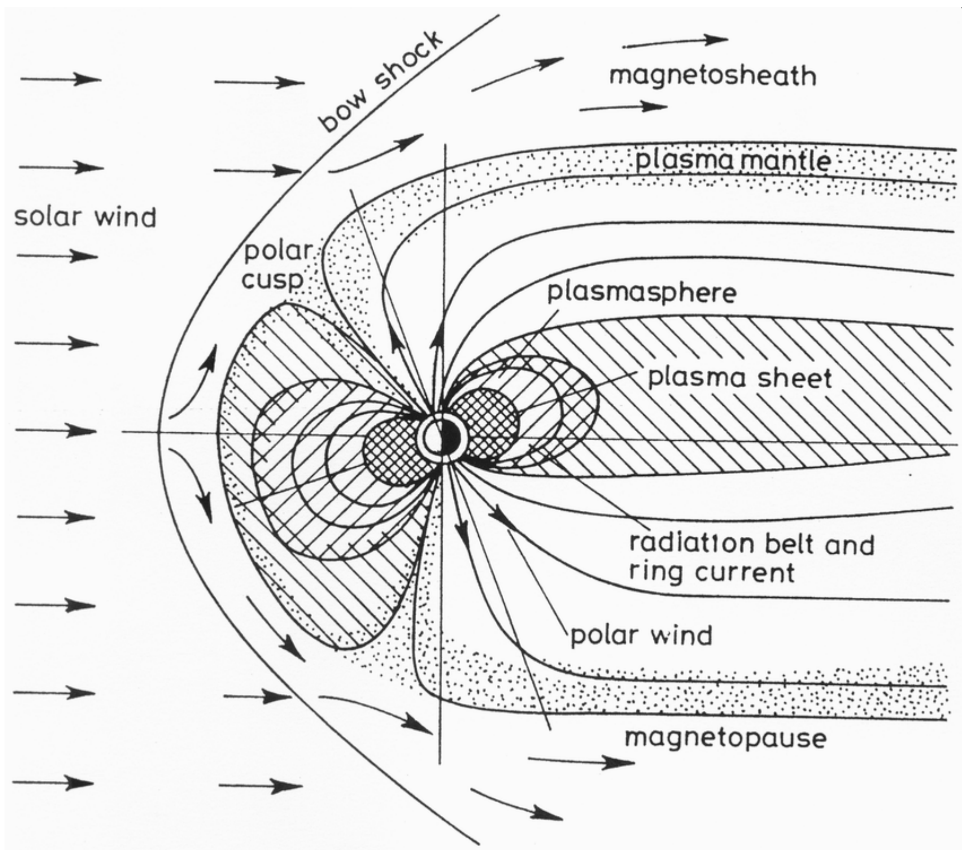


Figure 2 Earth's Magnetosphere (source: Davies)

8.1 Magnetospheric Regions

The magnetosphere consists of multiple regions including:

- Magnetosheath
- Magnetopause

- Plasma Mantle
- Magnetotail
- Polar Cusp
- Radiation Belts
- Plasmasphere
- Plasma Sheet

Note that, with the exception of the Magnetosheath and Magnetopause, All of the magnetospheric regions begin or terminate in the Earth's polar region. It is no wonder that the high latitude (polar) ionosphere is so complex.

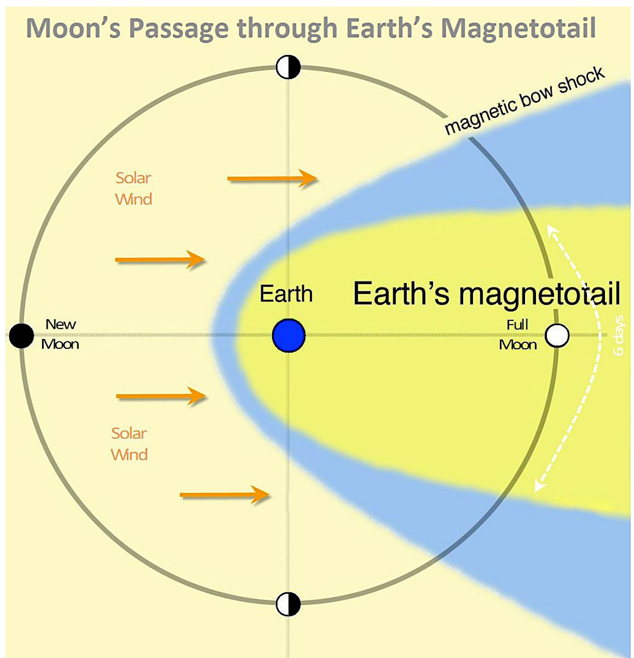


Figure 3 Earth's magnetic field tail stretches out past the moon (source: Time-Price-Research)

8.2 Magnetosheath

The solar wind is supersonic as it approaches the bow shock, meaning that its velocity, typically 400 km/sec, exceeds (out runs) that of Alfven and pressure (sound) waves that propagate in the solar wind plasma. A solar wind 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 cm. Most of these 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 temperature of solar wind is about 100,000 – 150,000 ^oK. In comparison, the Sun's photosphere is about 5,000 ^oK while the corona is over a million degrees K.

Most of the solar wind particles are deflected by the bow shock and continue downwind outside the magnetic tail.

The magnetosheath (Figure 2) is not actually part of the magnetosphere. It is instead a transition region between the magnetosphere and the bow shock. It consists mainly of solar material, but its composition is generally different than the solar wind. The speed of the solar wind plasma that does cross the bow shock is slowed to about 250 km/sec. The loss in kinetic energy is converted into thermal energy, increasing plasma temperature to about 5 $x10^6$ K. Consequently, the magnetosheath plasma is slower and about 30 times hotter than the solar wind. Like the solar wind, most of the magnetosheath plasma continues downwind outside the magnetosphere.

Even though the magnetosheath plasma is extreme hot, you would not experience that temperature if you were there because the plasma particle density is so very low. From our human perspective, the magnetosheath is part of the vacuum of outer space. However, we have learned from the discoveries of the early space age that the magnetosheath, and the magnetosphere within it, are not a vacuum. There is matter there in the form of charged particles which, driven by the solar wind, have serious consequences here on Earth.

8.3 Magnetopause

The magnetopause is the boundary between the magnetosheath and the magnetosphere, as shown in Figure 2. At its closest approach, the magnetopause is around 11 R_E from the sunlight side of the Earth and is only about 1 km thick.

The geomagnetic field vanishes at the magnetopause. It is replaced outside the magnetopause by the Interplanetary Magnetic Field (IMF) that is carried by “frozen into” the solar wind. The IMF permeates throughout the solar system carried along by the solar wind. The IMF is very weak, only a few nT (nano - Teslas), compared to Earth’s geomagnetic field of between 25,000 to 65,000 nT at Earth’s surface. However, at the magnetopause the strength of Earth’s magnetic field drops to 0 nT, that is, at the magnetopause Earth’s magnetic field ends and the IMF begins.

8.4 Plasma Mantle

The plasma mantle, shown in Figure 2, is the outer ionized region of the magnetosphere. It consists of ions from both the magnetosheath and Earth’s ionosphere. The ionospheric particles are predominately energetic oxygen O^+ ions that have escaped from the polar regions of the ionosphere. The escaping ions flow outward away from Earth along magnetic field lines. The outward flow of ions is known as the polar wind described in more detail later.

8.5 Magnetotail

The magnetotail extends over ten million kilometers outward away from Earth's nightside, about a tenth of the way to Mars. The tail is roughly circular with a diameter of about 30 R_E (1 R_E = 6,370 km). In comparison the Moon is 60 R_E (384,400 km) from Earth (Figure 3). While the tail extends far out into space, the opposite end of the tail is anchored in Earth's polar region. Consequently, the polar ionosphere can be significantly affected by events occurring in the tail.

The magnetotail is quite dynamic. Large changes can take place there including energizing ions and electrons. The magnetotail is the main source of ions and electrons entering Earth's polar regions producing the aurora.

The tail, shown in Figure 4, consists of three important regions. They are the South Lobe, North Lobe, and the Plasma Sheet. The plasma sheet runs down the center of the tail between the two lobes. The plasma sheet, in the direction perpendicular to that shown in Figure 4, literally cuts the magnetotail in half stretching from the magnetopause on one side of the magnetosphere to the magnetopause on the opposite side of the magnetosphere. The north lobe exists above the plasma sheet while the south lobe is below the plasma sheet. The magnetic field points away from Earth in the south lobe which is linked to Earth's southern polar region. The northern lobe magnetic field points towards the Earth and is linked to Earth's northern polar region. The plasma sheet is the region where the magnetic field reverses direction from outward to inward. The magnetic field strength in the lobes is about 20 nT and much weaker in the plasma sheet where the reversal occurs.

Densities in the tail are very low as shown in the following table.

Region	Ion Density
Solar wind near Earth	5 ions/cubic centimeter
Dayside outer magnetosphere	1 ions/cubic centimeter
Plasma sheet separating tail lobes	0.3 – 0.5 ions/cubic centimeter
Tail lobes	0.01 ions/cubic centimeter

The extremely low ion density in the tail suggests that lobe field lines ultimately connect to the solar wind far downstream from Earth. Ions and electrons can easily flow along the field lines away from Earth until they are eventually swept up the solar wind. However, very few solar wind ions can oppose the wind's general flow past the Earth and flow upstream toward Earth. Consequently, little plasma remains in the lobes. What is there tends to be sucked out into the polar wind far downstream from Earth.

8.6 Polar Cusps

Moving charged particles can travel along magnetic field lines but can not cross them. As a result, high energy particles emanating from the Sun are prevented from entering the atmosphere in the Earth's equatorial region where the magnetic field is parallel to Earth's surface.

However, the magnetic field lines are nearly vertical in the polar regions. Consequently, high energy solar wind and magnetosheath particles spiral downward along these magnetic lines directly into the polar atmosphere.

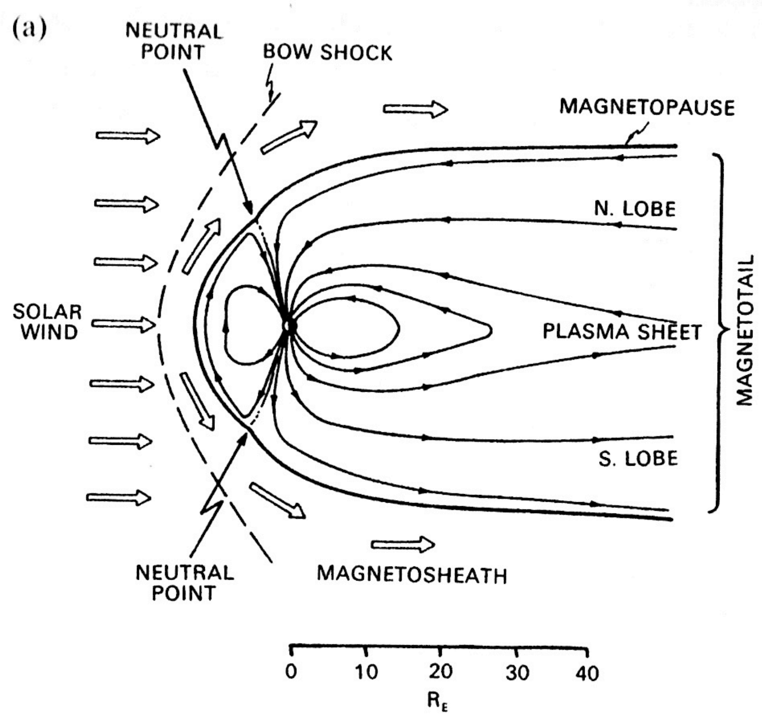


Figure 4 Magnetotail (source: Hunsucker)

In addition, there are two neutral points within the magnetopause, one in each hemisphere, where the total magnetic field is nearly zero. These neutral points (actually two neutral funnels) are known as the Polar Cusps. As shown in Figures 4 and 5, the polar cusps 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 magnetosphere 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 in latitude 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 affecting the high latitude ionosphere.

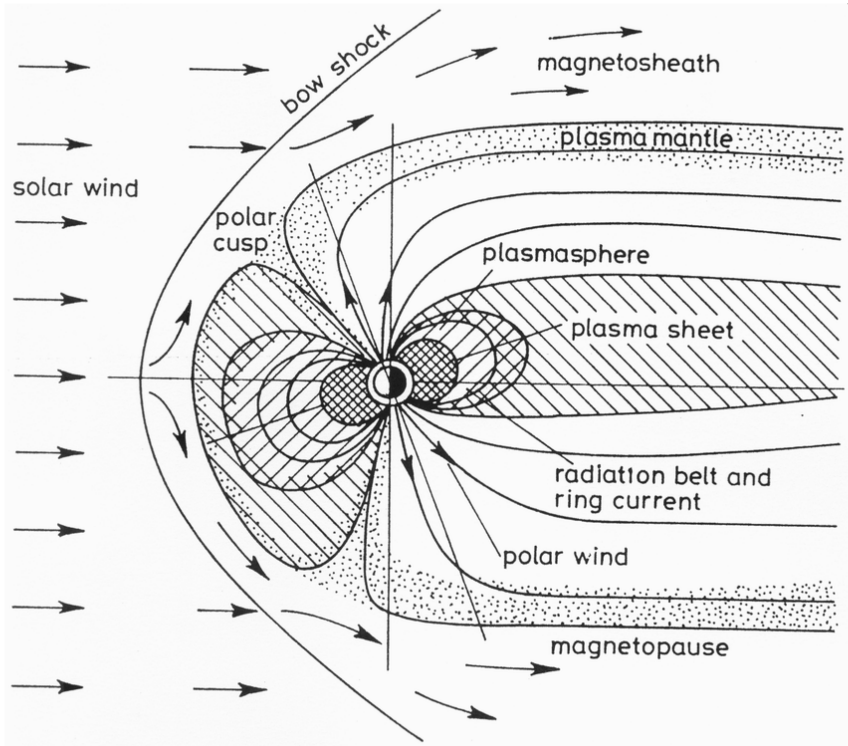


Figure 5 Earth's Magnetosphere (source: Davies)

8.7 Polar Wind

Charged particles are present throughout the magnetosphere in varying degrees of concentrations from essentially none to small but yet very significant concentrations. Small meaning low particle densities compared to the high density of neutral atoms in Earth's upper atmosphere. The particles consist of free negatively charged electrons and positive ions composed primarily of hydrogen (H^+), helium (He^+) and oxygen (O^+) ions.

There are only two sources for the charged particles present in the magnetosphere:

- Direct and indirect injection of solar wind charged particles (electrons, H^+ and He^{2+}) into the magnetosphere, and

- Ion (H^+, He^+, and O^+) plus electron outflows from the Earth's polar ionosphere.

The polar ionosphere is a significant and at times the dominate source of magnetospheric charged particles. These particles are primarily transported from the polar region topside ionosphere into the magnetosphere by the polar wind illustrated in Figure 6. Looking very closely at Figure 6 you will see the symbol e^- indicating that the polar wind includes free electrons as well as positive ions.

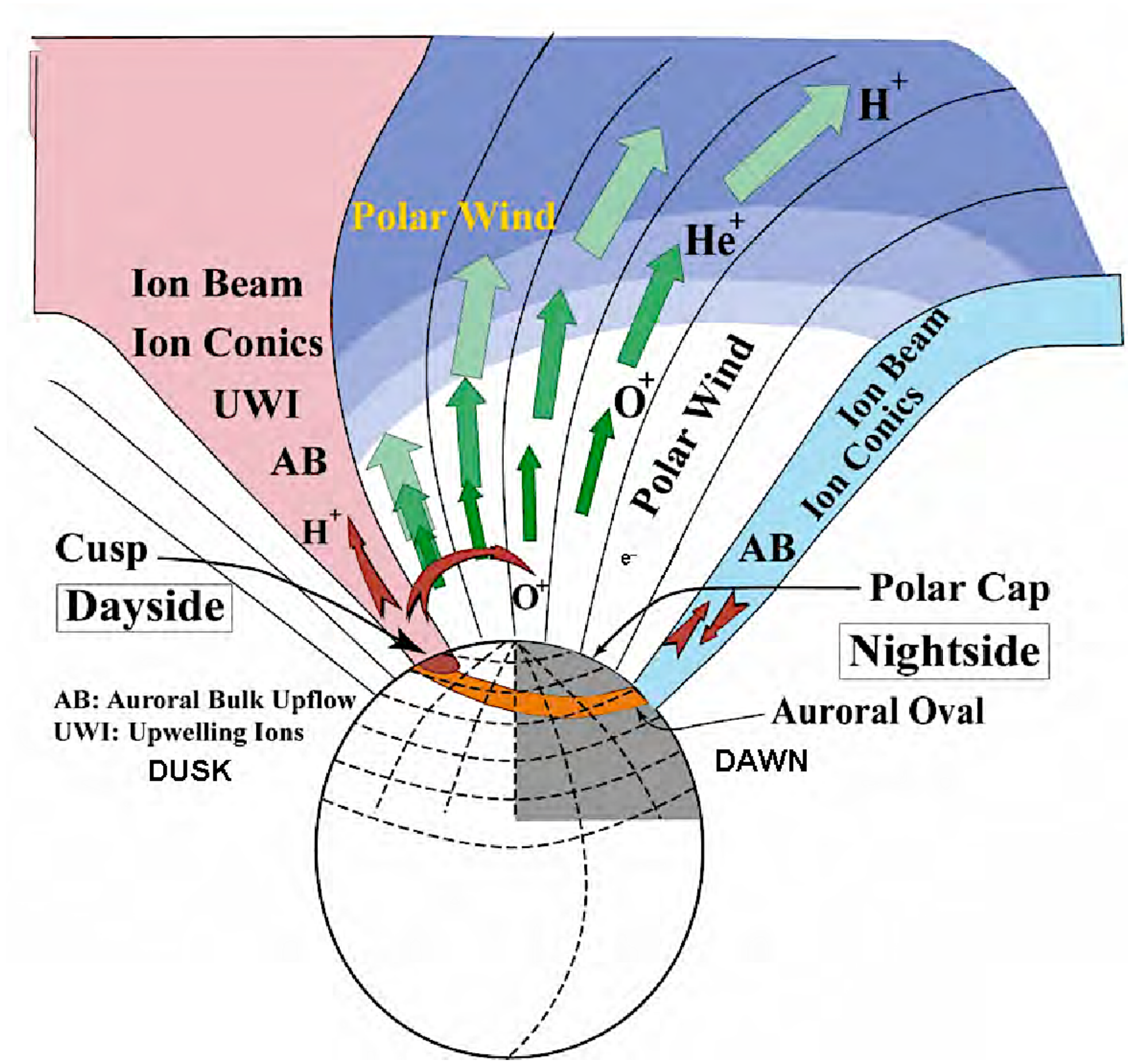


Figure 6 Polar Wind outflow (source: www.semanticscholar.org)

The ionosphere is created by extreme ultraviolet (EUV) and x-ray radiation from the Sun which partially ionizes the dayside of Earth's upper atmosphere forming free negatively charge electrons and an equal number of positive ions (Figure 7). The daytime electron density of the ionosphere at an altitude of 300 km is around 10^6 electrons per cubic centimeter. The ion density is similar. These densities compared to 10^9 neutral atoms per cubic centimeter at the same altitude (Figure 8). The ionosphere is thus very thin and wispy compared to Earth's upper atmosphere in which it resides!

The ionization process raises the temperature of the ionosphere plasma to a few thousand degrees kelvin (K), substantially warmer than the neutral parent gases from which it is created. This heating allows significant numbers of lighter ions, particularly hydrogen H^+ and helium He^+, to acquire sufficient energy to escape from the ionosphere into the surrounding magnetosphere.

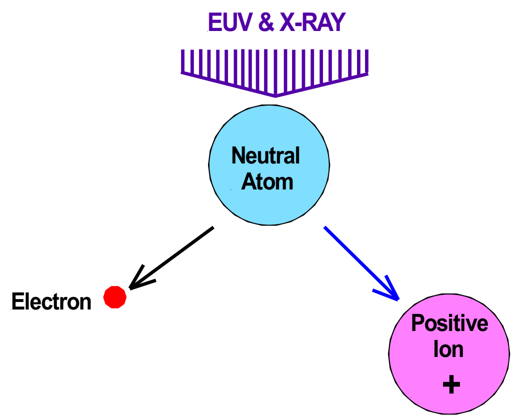


Figure 7 Photoionization process (source: author)

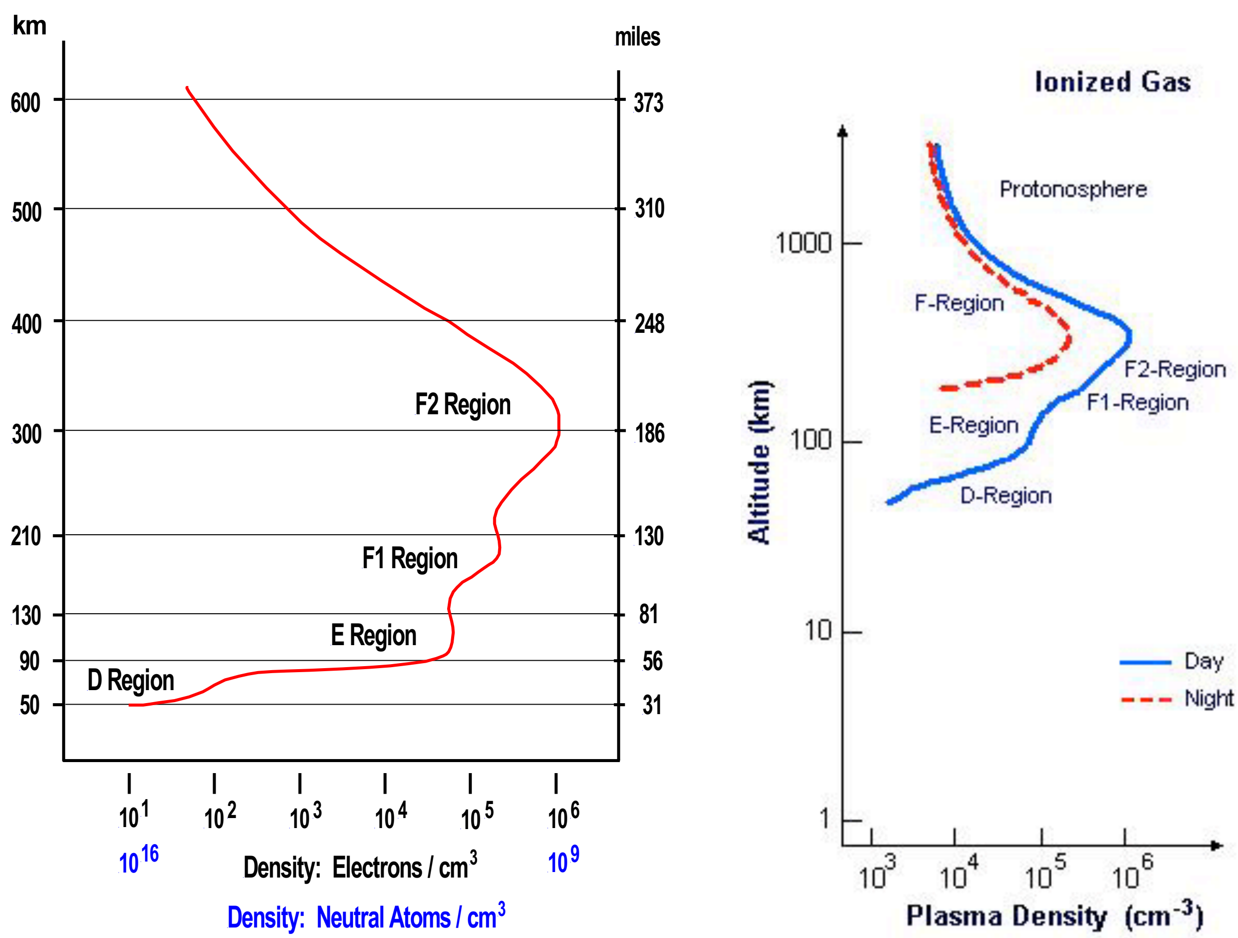


Figure 8 Electron density of Earth’s ionosphere (source: author)

8.7.1 Classical Polar Wind Theory

The magnetic field lines in Earth's two polar regions are predominately open flowing outward into the magnetotail instead of looping back to Earth's surface (Figure 5). Notice in Figure 5 that magnetic field lines at lower latitudes, toward the Earth's magnetic equator, do loop back to Earth's surface. These equatorial ward field lines are closed.

According to the initial (classical) polar wind theory, the polar wind consists of light hydrogen (H^+) and helium (He^+) ions that flow outward from the polar regions along the open field lines into the magnetosphere. The outflow of ions 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 that 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 electric field pulls electrons and ions back together, keeping them in close proximity with equal electron and ion concentrations. However, the mass of an electron is nearly 15,000 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.

The outflow of hydrogen ions H^+ begins above the F-region peak ionization altitude at around 400 km (Figure 8). The H^+ outward drift velocity increases with altitude becoming supersonic above 800 to 1,200 km (supersonic meaning faster than the speed of sound at that altitude in Earth's atmosphere). The supersonic nature of the hydrogen ion outflow prompted W. I. Axford in 1968 to name the outflow Polar Wind, conceptually similar to the supersonic solar wind.

The polar wind ion flux is limited by the rate at which outflowing ions are produced and the rate at which they are lost due to coulomb (electrostatic) collisions with other ions.

The electron exchange reaction between EUV ionized oxygen atoms (O^+) and neutral hydrogen is the dominant source of polar wind H^+ ions at low altitudes (below a few thousand km), in accordance with the equilibrium equation.

$$O^+ + H \leftrightarrow O + H^+$$

The maximum H^+ outflow that can be achieved is thus determined by how much H^+ can be created from O^+.

For typical topside ionospheric densities and temperatures, the maximum H^+ flux at an altitude of 1,000 km during solar minimum is roughly 3 x 10^8 ions per square centimeter per second. The flux decreases to about 1 x 10^8 ion per square centimeter per second at solar maximum. The decrease in flux during solar maximum is due to increased exospheric temperature and a corresponding increase in neutral hydrogen density at high altitudes (Figure 15).

In comparison, helium He^+ flux is dependent primarily on the density of neutral atmospheric He and nitrogen N_2 molecules. The density of helium atoms affects its photoionization rate (its ionization due to extreme ultra-violate radiation from the Sun). High concentrations of helium result in higher photoionization rates increasing the number of He^+ ions available. On the other hand, the density of nitrogen molecules determines the loss rate of He^+ ions due to He^+ and nitrogen charge exchange in accordance with the equation

$$He^+ + N_2 \leftrightarrow He + N_2^+$$

The maximum He^+ flux rate varies from around 1 to 3 x 10^5 ions per square centimeter per second during solar minimum summer months to about 0.5 to 1.5 x 10^7 ions per square centimeter per second in the winter months of solar maximum. Unlike H^+, the He^+ flux rate is greater during solar maximum when He photoionization rates are highest.

Based on above mechanisms, the solar wind was originally thought to consist only of hydrogen and helium ions flowing outward into the magnetosphere along open field lines. Oxygen ions O^+, prevalent in the topside ionosphere, were considered too massive (gravitationally bound) to escape from the ionosphere. Instead, it was believed that oxygen ions propelled outward quickly fell back into the ionosphere due to gravitational forces.

8.7.2 Non-classical Polar Wind Theory

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 x 10^{-19} joules) is needed for O^+ ions to escape the ionosphere. Consequently, other energy sources must be operating in the polar wind, other than those identified in classical theory, 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 from nonclassical processes to escape from the ionosphere.

Unstable field-aligned electrical currents (FACs) in the region of the auroral oval (Figure 9) can excite electromagnetic waves which accelerate a portion of the ion population to much higher energy levels. These accelerated ions, including O^+ oxygen ions, form ion beams and conics with sufficient energy to escape the ionosphere (Figure 9).

The interaction of cold (low energy) outward flowing polar wind electrons with hot (high energy) magnetospheric electrons results in a field-aligned outward directed polar cap electric field that separates the hot and cold electron populations. The hot magnetospheric downward flowing electrons are known as polar rain. The electric field energizes H^+ and O^+ ions above 4,000 km allowing them to escape from the ionosphere. The interaction of the cold polar wind and hot magnetospheric electrons also has a direct effect on the underlying ionosphere. The cold polar wind electrons gain energy from the hot magnetospheric electrons. This energy is conducted downward into the underlying ionosphere raising the temperature of the electrons and ion which form the ionosphere. Increasing electron and ion temperatures causes them to drift further apart decreasing ionosphere density. In some regions of the polar cap the peak density in the F-region can change by a factor of 10.

Wave Particle Interaction (WPI) operates over a wide range of altitudes and is important in the cusp, nocturnal auroral oval, and polar cap. WPIs heat ions causing them to move in a direction perpendicular to the geomagnetic field. Gradient magnetic field forces then drive the ions upward while magnetospheric electric fields drive the ions in an anti-sunward direction across the polar cap.

Auroral Bulk Upflows (Figure 9) are capable of moving large amounts of O^+ ions to high altitudes. The outflows are produced by a combination of physical processes including plasma heating by electric fields in the auroral zone. Once at high altitudes, transverse ion energization by plasma waves can give O^+ ions sufficient energy to escape into the magnetosphere.

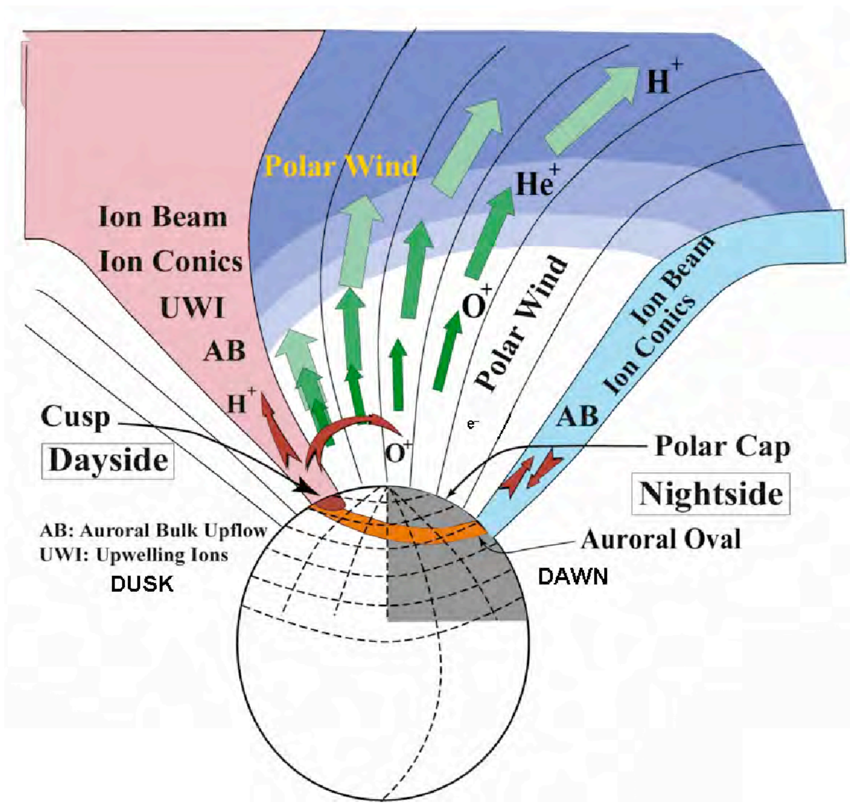


Figure 9 Polar Wind outflows (source: www.semanticscholar.org)

Centrifugal acceleration from Earth's rotation increases ion outflow velocities as plasma flows across the polar cap.

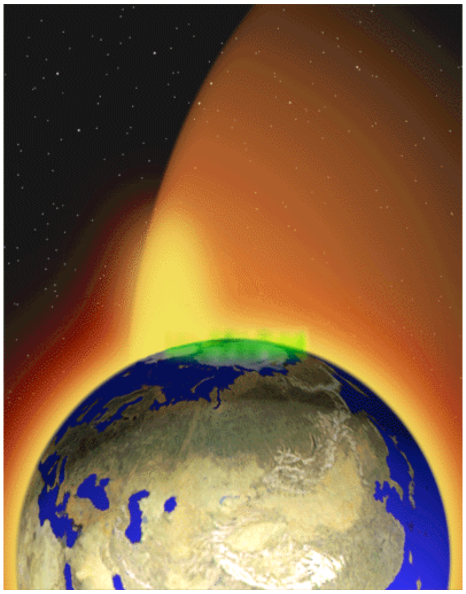
Upwelling ions (UWI) originating in the auroral oval can form an ion fountain (Figures 9 and 10). The ion fountain consists of oxygen, helium, and hydrogen ions that gush into the magnetosphere from Earth's polar regions. Lower energy heavy ions fall back into the polar atmosphere while more energetic ions escape to the plasma sheet. In Figure 10 the faint yellow gas shown above the auroral oval represents gas lost from Earth's upper atmosphere. The green gas is aurora borealis plasma pouring back into the polar region.

The ion fountain is Earth's most prolific leak of atmospheric gas spewing 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.

8.7.3 Seasonal Variation of the Polar Wind

The polar wind outflow varies with season, solar cycle, and geomagnetic activity. The O^+ flux exhibits a summer maximum, while the H^+ flux reaches a maximum in the spring. The He^+ flux increases by a factor of 10 from summer to winter. At both magnetically quiet and active times the

H^+ ion flux is largest at noon and smallest at midnight. More H^+ flux is produced during solar minimum while the reverse is true for He^+ flux.



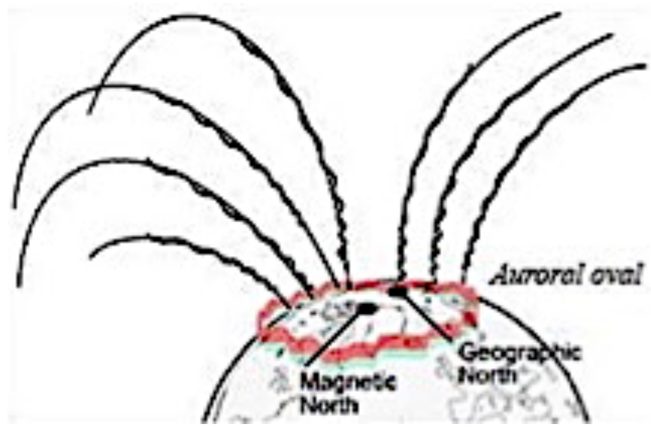


Figure 10 Ion fountrain (source: Wikipedia)

8.8 Radiation Belts

The radiation belts, illustrated in Figure 11, are two concentric donut shaped regions consisting of high energy particles which are trapped in Earth's magnetic field. The region between the two belts, called the "slot", contains very few energetic particles. However, the slot is populated by a substantial number of low energy electrons.

The inner belt extends from about 2 – 4 Earth radii (1 R_E = 6,378 km = 3,963 mi) measured from the center of the Earth at the geomagnetic equator. The outer belt is located roughly 4 – 10 Earth radii measured from the center of the Earth. (The altitudes shown in Figure 11 are measured from Earth's surface.) Note that the two belts each begin and terminate in the polar regions of the Earth.

The two belts expand and contract over time. The belts expand as increased solar winds pump more ions and electrons into the belts through the polar cusps. A strong electrical current (the equatorial ring current discussed later) is produced as the injected particles are accelerated to nearly the speed of light (to relativistic energy levels) producing intense geomagnetic storms in the process. The belts contract as electrons and ions escape from the radiation belts either along field lines down into Earth's atmosphere or back out into interplanetary space.

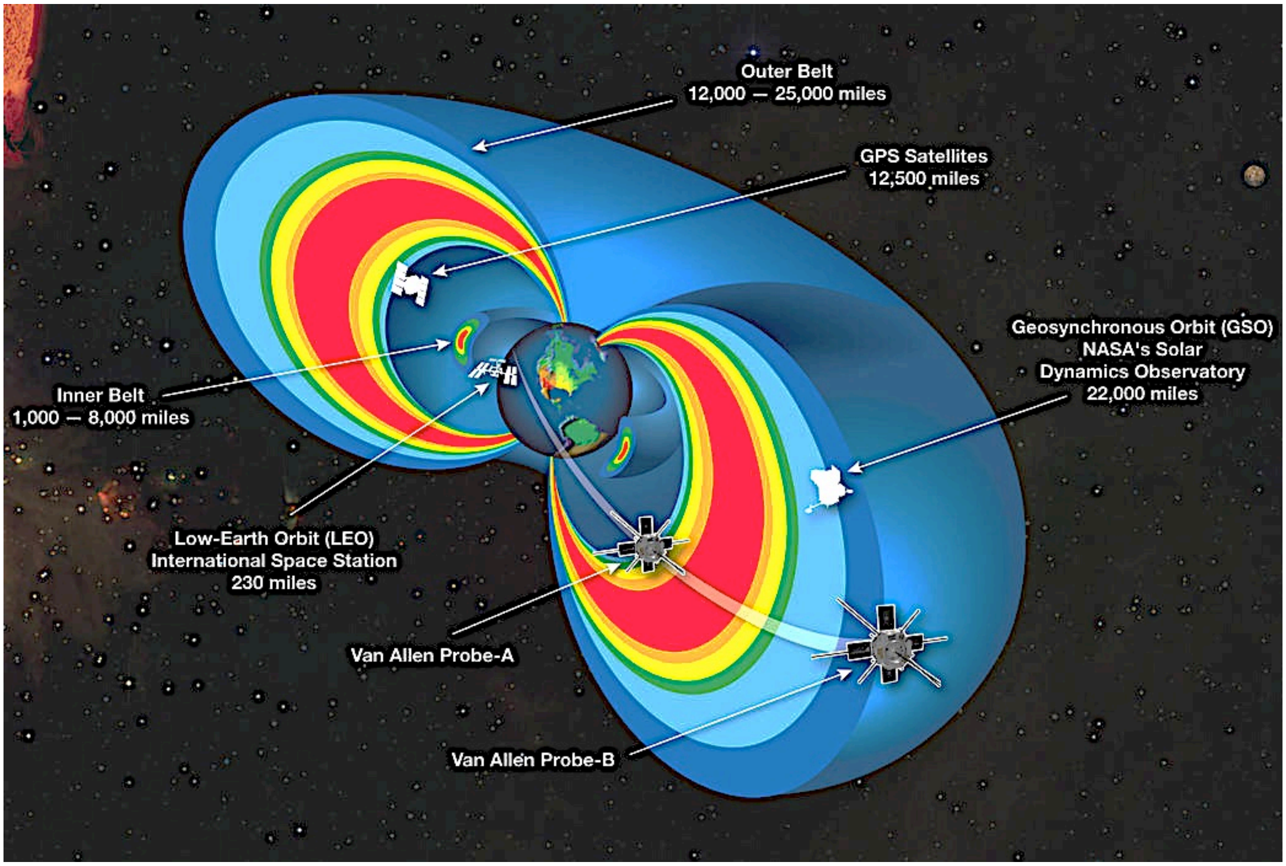


Figure 11 Cutaway model of the radiation belts (source: NASA)

The charged particles trapped in the two radiation belts are the most energetic particles in the magnetosphere, with the exception of transient cosmic rays and solar protons.

Figure 11 shows the positions of various representative spacecraft in Earth orbit. Most of the spacecraft with long duration missions, including commercial, scientific, communication, and military spacecraft, are positioned in geosynchronous orbit 22,000 miles over the Earth's equator. These spacecraft, represented in Figure 11 by NASA's Solar Dynamic Observatory, orbit in the outer belt close to the belt's upper boundary. The constellation of global positioning satellites (GPS) orbit at the lower edge of the outer belt. Finally, satellites in low earth orbit (LEOs), including the International Space Station orbiting at 230 miles, orbit in a region below the inner belt. Consequently, the structure and dynamics of the radiation belts have a direct effect on operation of spacecraft in Earth orbit.

8.8.1 Discovery of the Radiation Belts

Existence of the radiation belts was the first major discovery of the space age. Until then the radiation belts, and most of the magnetosphere structure, were unknown.

The Explorer 1 satellite, shown in Figure 12, was launched by the United States on Jan 31, 1958. It was the first U.S. satellite launched into Earth orbit and followed launch of the Soviet Union's Sputnik 1 on October 4, 1957.

Explorer 1 carried a Geiger counter to study cosmic rays. The instrument was built by Dr. James Van Allen and his team at the University of Iowa. The instrument encountered far fewer cosmic rays than expected. But in its elongated looping orbit 354 x 2,515 km the satellite passed through regions of strong radiation. The radiation belts were confirmed by another U.S. satellite launched two months later. The radiation belts are known as the Van Allen Radiation Belts in honor of Dr. Van Allen and his team who discovered the them.

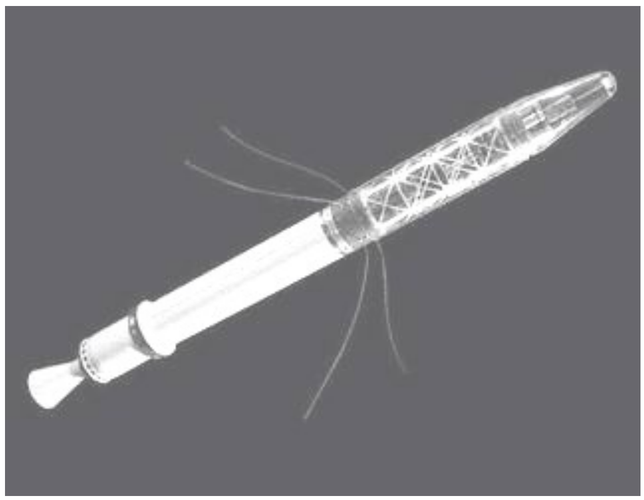


Figure 12 Explorer 1 Satellite (source: NASA)

The discovery showed that what was presumed to be the vacuum of outer space, at least near the Earth, was not empty at all but contained matter in the form of charged particles.

Since then a number of satellites, including the SAMPEX satellite launched in July 1992 and Polar satellites in 1995, made significant contributions to the study of the radiation belts. However, these studies provided an incomplete understanding of the belts. It became evident that a mission dedicated exclusively to studying the radiation belts was needed. This led to the concept and eventual realization of the Van Allen Probes, initially known as the Radiation Belt Storm Probes (RBSP).

On August 30, 2012, NASA launched two identical Van Allen Probe spacecraft into highly eccentric orbits that covered the entire radiation belt region. A pair of spacecraft with identical instruments was needed. By making simultaneous measurements from two spacecraft located in different regions of the radiation belts scientists could determine if observations were measuring disturbances in the radiation belts as a whole or only in the immediate vicinity of one spacecraft.

The highly elliptical orbits of the probes, shown in Figure 13, were tilted 10 degrees from Earth's equator. The orbits ranged from a 600 kilometer perigee to an apogee of 30,000 kilometers, almost to geosynchronous orbit where most long duration satellites operate. The probes traversed the distance from perigee to apogee and back again in 9 hours. The local time at which apogee occurred drifted slowly sweeping through 360 degrees over a period of about a year and a half.

After 7 years in orbit, operation of Van Allen Probe -A ended on October 18, 2019 just prior to running out of fuel needed to maintain control of the spacecraft. The orbit of the spacecraft was allowed to decay until it eventually re-entered and burned up in Earth's atmosphere. Operation of Van Allen Probe-B ended four months earlier.

Figure 13 Van Allen Probe Spacecraft (source: NASA)

8.8.2 Inner Radiation Belt

The inner radiation belt consists of high energy protons (H^+ ions) and electrons originating primarily from two sources, the interaction of cosmic rays with Earth's atmosphere and solar energetic particles (SEPs).

Cosmic rays are extremely high-speed protons (H^+) and alpha particles (He^{+2}) traveling at nearly the speed of light. Some of these rays are galactic in origin while others originate from solar flares. Free neutrons are produced when cosmic rays collide with nitrogen and oxygen nuclei in Earth's upper atmosphere. Some of these neutrons escape outward into the radiation belts. However, free neutrons are unstable and quickly decay. When a free neutron decays it breaks up into a proton, an electron, plus neutrinos in a process called cosmic ray albedo neutron decay (CRAND). The neutrinos escape into outer space while the protons and electrons become trapped in the inner radiation belt by Earth's magnetic field.

Solar energetic particles (SEPs) are created by strong interplanetary (IP) shocks, solar flares, and coronal mass ejections (CMEs). Only about 1% of CMEs produce strong SEP events. SEPs consist of high energy protons (H^+ ions) and electrons with energy levels ranging from a few tens of keV to many GeV. Some of these SEPs enter the magnetosphere via the open field lines over the polar regions and become trapped in the inner radiation belt.

Interplanetary shocks occur when fast moving solar wind overtakes slower moving solar wind creating disruptions that ripple outward through the solar system.

In addition to energetic cosmic ray protons and SEPs, polar wind O^+ oxygen ions drifting outward from Earth's ionosphere also become trapped in the inner radiation belt.

Some of the inner belt energetic particles eventually escape due to collisions with neutral atoms in the polar regions of Earth's upper atmosphere. However, such collisions are sufficiently rare that particles typically remain in the inner belt anywhere from a few hours to 8 years or more. With such a low loss rate only a small input of protons, SEPs, and O^+ ions is required to maintain the population of high energy particles in the inner belt. Consequently, the inner belt is fairly stable.

8.8.3 Outer Radiation Belt

The outer radiation belt is composed primarily of energetic electrons ranging in energies from a few hundred keV to several MeV. Generally the energy of these electrons is below 10 MeV. Consequently, outer belt energy levels are less than those encountered in the inner belt.

The outer belt is very dynamic. Electron concentrations in the outer belt can change by several orders of magnitude in minutes as well as over longer time periods ranging from hours, days, seasons, and years.

Energetic electrons result from a multitude of energizing processes within the magnetosphere. These processes act on low energy electrons, on the order of 100s of keV, injected into the outer belt from the magnetosphere tail.

The energizing processes include wave-particle interaction involving a variety of electromagnetic waves present in the magnetosphere. These electromagnetic waves accelerate the trapped electrons to nearly the speed of light (to relativistic energy levels) in a matter of a few days. Electric fields generated by the rapid compression of the magnetosphere by interplanetary shocks also drive outer belt electrons to high energy levels. In this case the energizing process is very quick and dramatic. Solar wind high speed streams (HSS), prevalent during the descending part of the 11 year solar cycle, and coronal mass ejections (CMEs) common during the solar cycle ascending phase are also responsible for accelerating electrons to relativistic energy levels. In all of these cases a southward directed interplanetary magnetic field (IMF) considerably enhances the energizing processes. The impact of the south directed IMF is greatest during the spring and fall of the year when the tilt of

Earth's axis is conducive for coupling of the IMF with Earth's magnetic field. This phenomena is commonly known as the Russell-McPherron effect.

Injection and energizing processes increase the number of high energy electrons in the outer belt while loss process decrease the number. The concentration of energetic electrons depends on the balance between the two processes. The loss processes include escape of energetic electrons through the magnetopause into interplanetary space, and scattering of energetic electrons into the upper atmosphere in Earth's polar regions.

8.9 Plasmasphere

The plasmasphere, illustrated in Figure 14, is doughnut shaped region of cold dense plasma trapped by closed magnetic field lines in the inner part of the magnetosphere. Cold means low energy. The plasmasphere is positioned between the radiation belts and Earth's upper atmosphere, in the region just above the Earth's exosphere (Figure 15). The outer boundary of the plasmasphere is called the plasmapause. The plasmapause separates the relatively high density plasmasphere (10 – 100 particles per cm^3) from the low density (1 – 10 particles per cm^3) background plasma of the magnetosphere. The plasmasphere doughnut hole is located over the Earth's polar regions with the maximum extent of the plasmasphere along the equatorial plane. The lower part of the plasmasphere is closely linked to the mid-latitude ionosphere as shown in Figure 14. The plasmasphere rotates in the same direction as the Earth but takes 27 hours to complete one revolution compared to 24 hours for the Earth. The rotation of the plasmasphere is important since the rest of the magnetosphere (further away from Earth) is stationary with respect to the Sun.

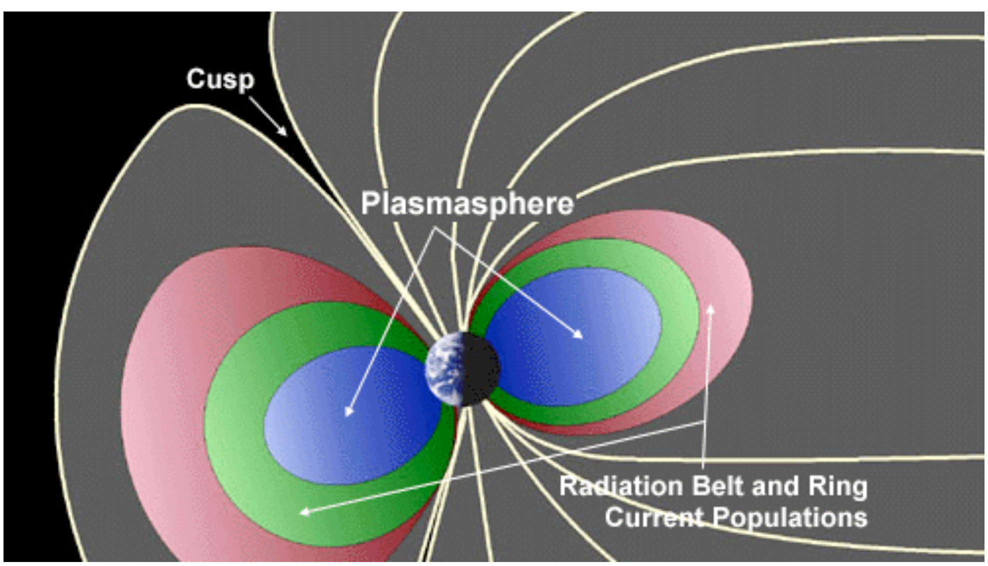


Figure 14 Plasmasphere (source: Alchetron)

Although plasma is found throughout the magnetosphere, the plasmasphere usually contains the coldest (lowest energy) plasma.

The plasmasphere is formed by electrons and ions escaping from the polar ionosphere that quickly become trapped by Earth's strong magnetic field present in the lower part of the magnetosphere. The escaping ions consist primarily of hydrogen H^+ and oxygen O^+ ions. Over a short time period of hours to days the trapped plasma increases in concentration until an equilibrium is reached with as much plasma flowing outward into the plasmasphere as flows inward back into the ionosphere.

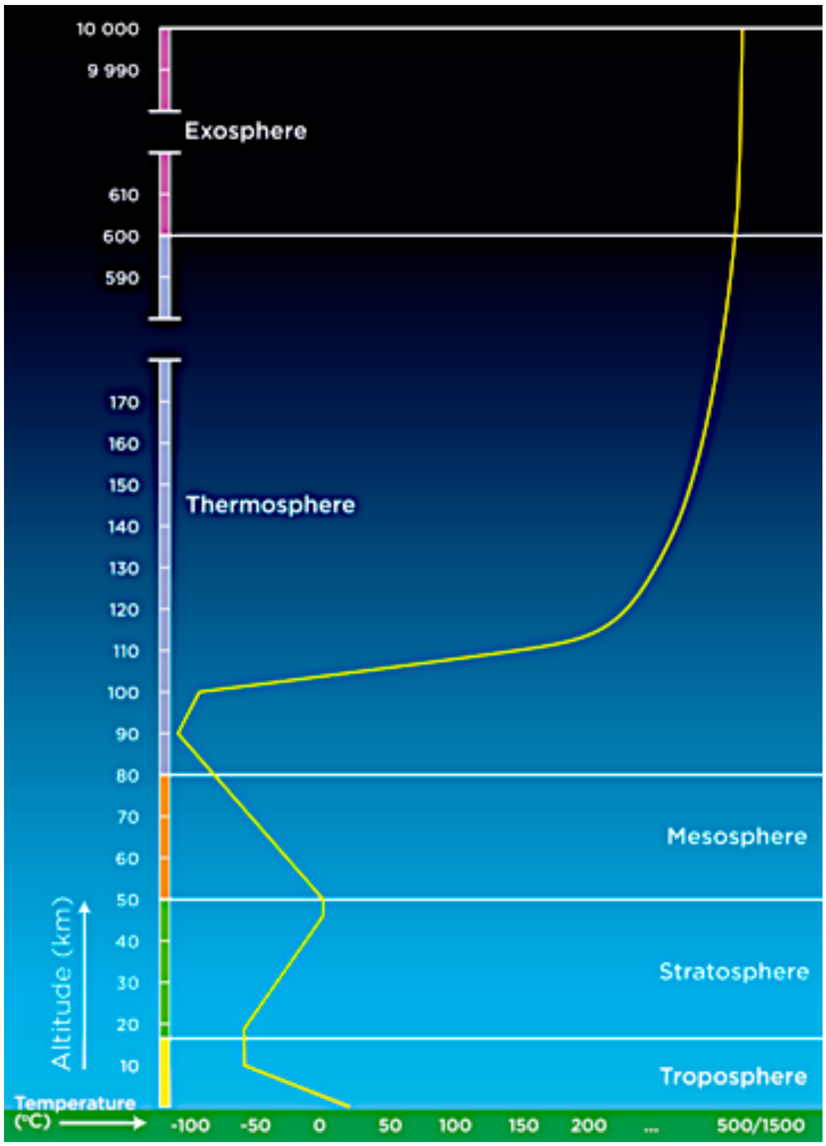
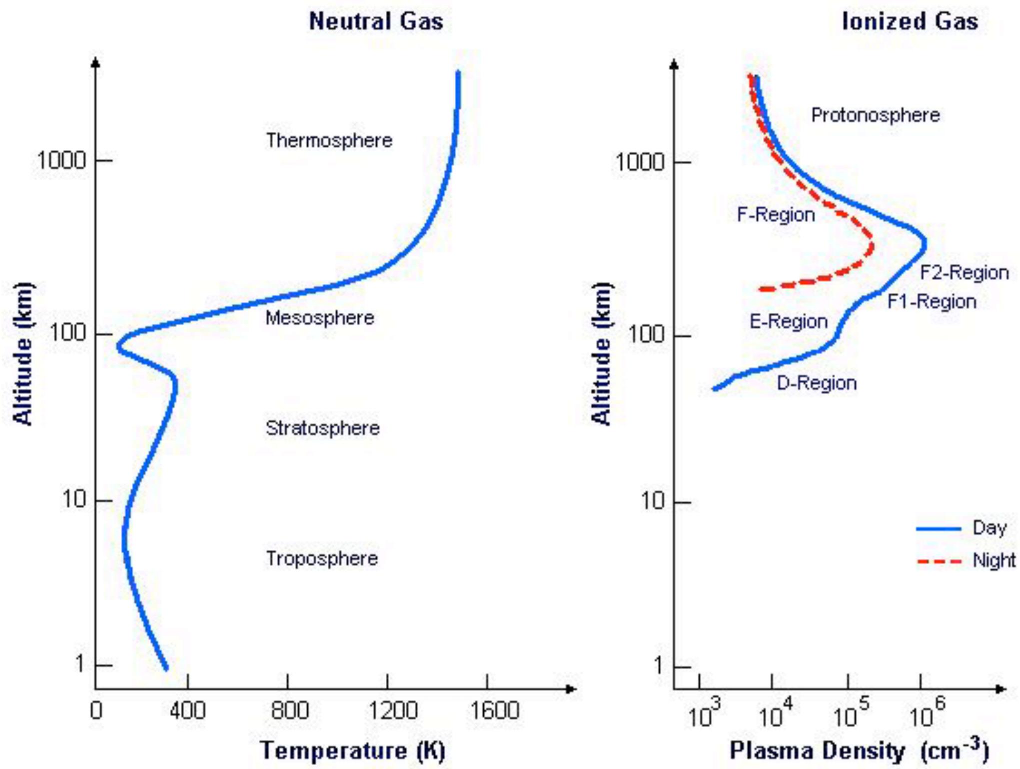


Figure 15 Layers of Earth's atmosphere (source: siyavula.com)

The plasmasphere acts as a reservoir of charged particles for the F region of the ionosphere (Figure 16). Ionospheric plasma flows upward along magnetic field lines during the day enhancing the plasmasphere. At night some of this plasma flows back down to lower levels helping to maintain the night time F region.



Neutral part of the atmosphere The Ionosphere

Figure 16 Structure of Earth's atmosphere and ionosphere (source: ResearchGate)

In addition to the ionosphere, plasmasphere charged particles also originate from the magnetosheath and solar wind, entering the plasmasphere through the cusps.

The plasmasphere is dynamic. Its position and size vary throughout the day and on the nightside it bulges out toward the tail. During geomagnetic storms the plasmasphere shrinks and moves inward toward the Earth. The radiation belts follow the plasmasphere, also moving inward toward the Earth. Following a storm, the plasmasphere gradually refills with ions over several days to a week or so until equilibrium is again reached.

8.10 Plasma Sheet

An important property of the plasmasphere are the closed magnetic field lines that surround and contain the plasmasphere. That is, both ends of these magnetic field lines connect to the Earth.

In contrast, magnetic field lines emanating from Earth's polar regions, through the plasmasphere doughnut hole, are open extending outward into the magnetic tail without returning to Earth. As discussed earlier the magnetotail, shown in Figure 17, consists of three important regions. They are the South Lobe, North Lobe, and the Plasma Sheet. The plasma sheet extends down the center of the magnetic tail between the two lobes. The plasma sheet is anchored in Earth's polar region on one end and extending far out into the tail on the other end.

The plasma sheet, in the direction perpendicular to that shown in Figure 17, literally cuts the magnetotail in half. It stretches across the tail from the magnetopause on the dawn side of the magnetosphere to the magnetopause on the opposite dusk side of the magnetosphere. The north lobe exists above the plasma sheet while the south lobe is below the sheet. The magnetic field points away from Earth in the south lobe which is linked to Earth's southern polar region. The northern lobe magnetic field points toward the Earth and is linked to Earth's northern polar region. The plasma sheet is the region where the magnetic field reverses direction from outward to inward. The magnetic field strength in the lobes is about 20 nT and much weaker in the plasma sheet where the reversal occurs.

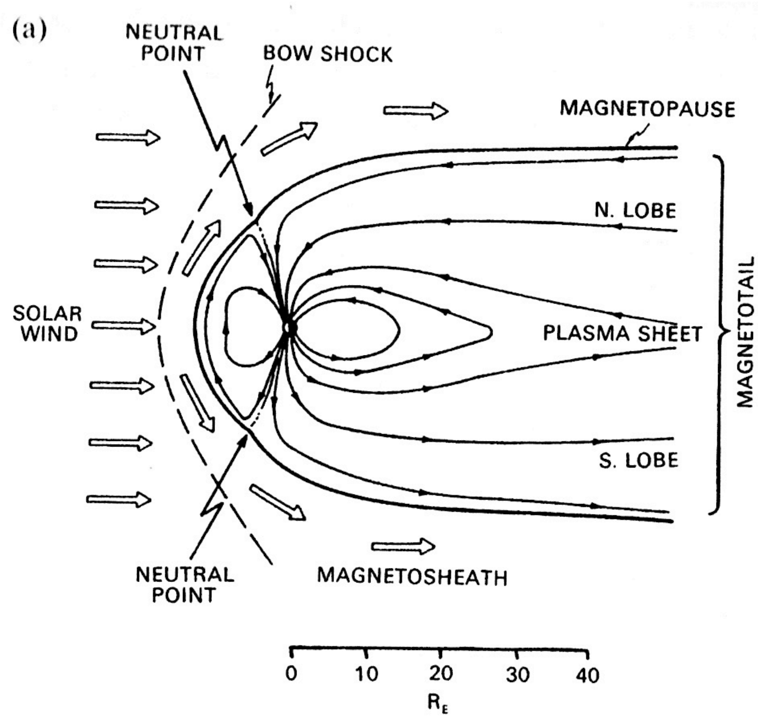


Figure 17 Magnetotail (source: Hunsucker)

The plasma sheet is several Earth-radii thick, although its thickness varies. Electron and ion densities in the plasma sheet are each only about 0.5 particles per cubic centimeter. The average energy for an electron in the plasma sheet is about 0.6 keV while that of a proton is around 5 keV, although these values vary as well.

A neutral point forms about 50 R_E down the tail (Figure 18). Here the magnetic field collapses within a local region and then reforms further down the tail. At the neutral point plasma is accelerated in the plasma sheet both toward and away from the Earth.

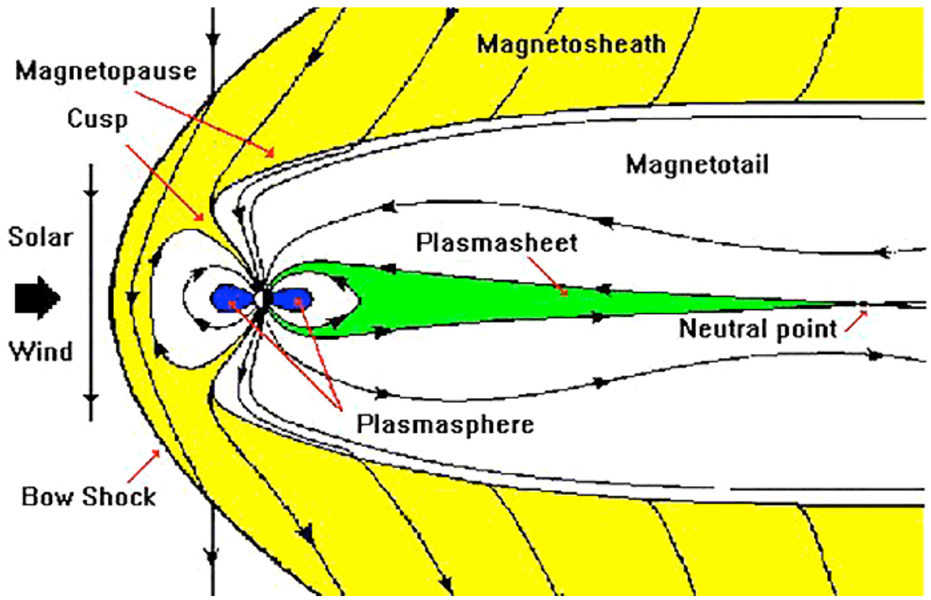


Figure 18 Plasmasheet (source: ResearchGate)

The importance of the plasma sheet, among other things, is that disturbances within the sheet produce enhanced auroral activity and disruptions in the polar ionosphere. The plasma sheet thus has important implications for high latitude HF communications.

8.11 Trapped Energetic Charged Particles

Charged particles (ions and electrons) are prevented by electromagnetic forces from crossing magnetic field lines. They can, however, easily move along field lines. As they do so the charged particles can become trapped in Earth's magnetic field, bouncing back and forth along field lines between Earth's northern and southern hemispheres. These trapped particles form the two radiation belts.

Electromagnetic forces cause a charged particle to gyrate around a field line as illustrated in Figure 19.

The frequency of gyration is equal to

$$f = \frac{e}{2\pi m} B \quad Hz$$

where

f = frequency in Hertz

e = the particle's electrical charge

m = the particle's mass

B = magnetic field strength

Consequently, the frequency of gyration increases as the magnetic field strength increases.

The distance at which a charged particle spirals around a magnetic field line is given by

$$r = \frac{mv}{Bq}$$

where

r = distance of the charged particle from the magnetic field line about which it is gyrating

m = mass of the particle in kilograms

v = velocity of the charged particle in meters per second

B = magnetic field strength in Teslas

q = electrical charge of the particle in coulombs.

Notice that the distance r, or radius, at which a particle spirals around a field line decreases with increasing magnetic field strength. This is important because magnetic field strength increases as a particle approach a magnetic pole causing the particle to spiral closer to the field line and at a higher frequency as shown in Figure 19.

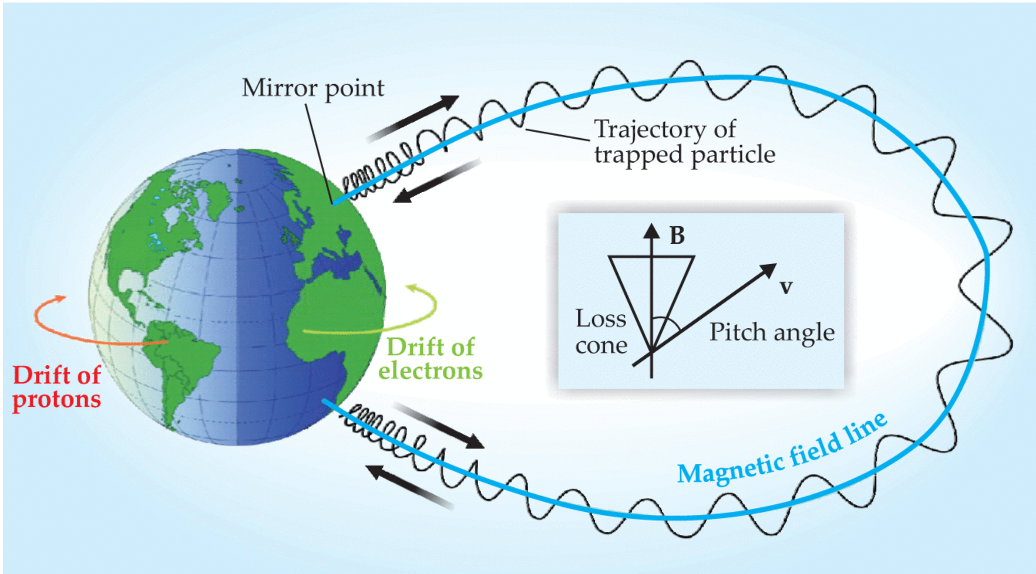


Figure 19 Trapped Charged Particles (source: Physics Today – Scitation)

Increasing field strength also directly affects a particle's energy. The kinetic energy of a trapped particle consists of two components:

- A component parallel to the magnetic field line (forward kinetic energy), and
- A component perpendicular to the magnetic field.

The magnitude of the perpendicular component is proportional to magnetic field strength. Since field strength increases as a particle moves toward a pole, its perpendicular component also increases while its forward kinetic energy decreases by the same amount. At some point its forward kinetic energy goes to zero, it stops, and is reflected back toward the equatorial plane and the opposite magnetic pole. The points of reflection, which occurs just above the Earth's magnetic poles, are called the mirror points. There are obviously two mirror points, one in the northern hemisphere and the other in the southern hemisphere. Only the northern hemisphere mirror point is labeled in Figure 19.

Since kinetic energy

$$K = \frac{1}{2}mv^2$$

the parallel ($v_\parallel$) and perpendicular ($v_\perp$) components of a particle's velocity change in the same manner. At the mirror points a particle's parallel velocity goes to zero ($v_\parallel = 0$), the particle stops, and then is accelerated back along the field line in the opposite direction.

8.11.1 Pitch Angle

The location of a mirror point depends on a particle's direction of travel as it crosses above Earth's magnetic equator. This direction of travel is called the equatorial pitch angle (α_{eq}). The pitch angle, illustrated in Figure 19, is the angle of a particle's velocity vector relative to the magnetic field line around which it is gyrating and is defined as

$$\alpha = \tan^{-1}\left[\frac{v_{\perp}}{v_{\parallel}}\right]$$

where

$v_{\perp}$ = a particle's velocity perpendicular to a magnetic field line

$v_{\parallel}$ = a particle's velocity parallel to the magnetic field line.

The pitch angle of a particle increases as it travels toward a magnetic pole. That is, the particle's parallel velocity ($v_{\parallel}$) decreases while a corresponding increase occurs in its perpendicular velocity ($v_{\perp}$). At the mirror points

$$\alpha = 90^0 \qquad i.e.\ v_{\parallel} = 0$$

The ratio of the magnetic field line strength over the magnetic equator (B_{eq}) to its strength (B_m) at the mirror points is given by the following expression

$$\frac{B_{eq}}{B_m} = \left(\sin\alpha_{eq}\right)^2 = \frac{(\cos\mathcal{L}_m)^6}{[1 + 3(\sin\mathcal{L}_m)^2]^{1/2}}$$

where

$\mathcal{L}_m$ = Earth's magnetic latitude of a mirror point.

Consequently, the magnetic latitude of a particle's mirror point ($\mathcal{L}_m$) depends only on its equatorial pitch angle (α_{eq}). A charged particle with a large pitch angle at the equator has a small parallel velocity ($v_{\parallel}$) resulting in its mirror points being located at relatively low geomagnetic latitudes. In contrast, a charged particle with a small equatorial pitch angle has a large parallel velocity ($v_{\parallel}$) causing its mirror points to be located at high latitudes.

Since no energy is being lost or gained, a charged particle (a highly energized ion or electron) continues to bounce back and forth from one hemisphere to the other until it eventually, perhaps after years, escapes from the radiation belt. A particle can escape in one of two ways. First, a particle can escape along an open magnetic field line further out into the magnetosphere. Second, a particle can be absorbed in the ionosphere, through various forms of electron – ion recombination, removing it as a trapped particle. This can happen if the mirror point is too deep in the atmosphere, below about 100 km.

8.11.2 Loss Cone

This leads to the concept of a loss cone illustrated in Figure 20. In this figure $\vec{V}$ is the velocity vector of a particle gyrating around a field line. $\overrightarrow{B_{eq}}$ is the vector of the magnetic field line over the equator while $\overrightarrow{B_m}$ is the vector for the field line at the mirror point. α_{eq} is the pitch angle of the particle as it passes through the magnetic equatorial plane. Finally, α_0 is loss pitch angle.

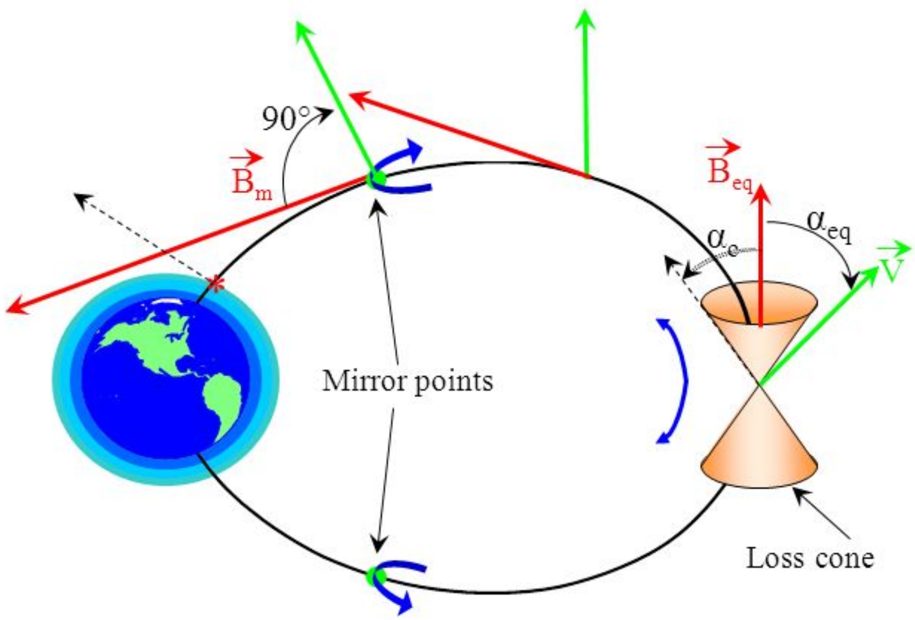


Figure 20 Loss Cone (source: Slideplayer.com)

If the pitch angle α_{eq} of the particle is too small, the mirror points will be in Earth's upper atmosphere, causing the trapped particle to be lost due to collisions with upper atmosphere atoms. The approximate angle α_0 of the loss cone, illustrated in Figure 20, is

$$(\sin \alpha_0)^2 = \frac{(\cos \mathcal{L}_E)^6}{[1 + 3\,(\sin \mathcal{L}_E)^2]^{1/2}}$$

where

α_0 = loss pitch angle

$\mathcal{L}_E$ = the latitude for the point at which the magnetic field line enters the Earth's upper atmosphere.

Solving the above equation for the loss pitch angle (α_0) gives

$$\alpha_0 = \sin^{-1}\sqrt{\frac{(\cos\mathcal{L}_E)^6}{[1+3\,(\sin\mathcal{L}_E)^2]^{1/2}}}$$

All particles with

$$|\alpha_{eq}| < \alpha_0 \quad and \quad |\pi - \alpha_{eq}| < \alpha_0$$

lie in the loss cone and are lost due to collisions with upper atmosphere atoms.

8.11.3 L - Shells

The distance of a magnetic field line above the Earth is often given in terms of its "L – shell" number. L is the distance of a magnetic field line above Earth's magnetic equator measured in Earth radii (R_E) from the center of the Earth. In equation form

$$L = \frac{r_{eq}}{R_E}$$

where

R_E = Earth's equatorial radius = 6,378 km

r_{eq} = distance of a magnetic field line above Earth's magnetic equator measured in km from the center of the Earth

Various L – shells from 1.5 to 5 are shown in Figure 21. Notice that L – shells, representing magnetic field lines, enter the Earth at progressively lower latitudes as L decreases in number.

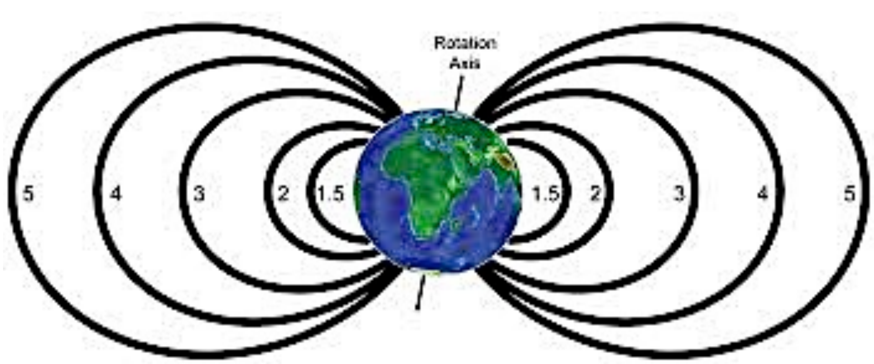


Figure 21 Various L – shells (source: Wikipedia)

As an example the inner radiation belt corresponds to L = 1.25 to 3.0 while the outer radiation belt is at roughly L = 4 to 7.

In terms of L – shell values the loss pitch angle (α_0) is equal to

$$\alpha_0 = \sin^{-1}\sqrt{\frac{1}{\sqrt{4L^6 - 3L^5}}}$$

Thus, the loss pitch angle is independent of charge, mass, or energy of a particle traveling along a given field line. It is only a function of the field line's distance above the magnetic equator.

As an example, the loss pitch angle for a field line in the inner radiation belt at L = 2 is approximately

$$\alpha_0 = 16.3°$$

The loss pitch angle for a field line in the outer radiation belt at L = 5 is roughly

$$\alpha_0 = 3.78°$$

Consequently, the loss pitch angles are quite small.

In the outer radiation belt the loss pitch angle is only about 4 degrees. Thus, only those particles in the outer radiation belt with pitch angles (α_{eq}) equal to or less than 4° will be lost in Earth's upper atmosphere. Particles with pitch angles greater than 4° will continue to bounce back and forth from one hemisphere to the other

8.12 Equatorial Ring Current

The Equatorial Ring Current, enhanced by the injection of solar wind particles, is the primary cause of geomagnetic storms. The ring current circles the Earth above the magnetic equator in the region of the van Allen radiation belts 2 to 6 Earth radii from the center of the Earth.

As described earlier, charged particles trapped in Earth's magnetic field gyrate around magnetic field lines as they bouncing back and forth between Earth's northern and southern hemispheres (Figure 22). The distance r at which a charged particle spirals around a magnetic field line is given by

$$r = \frac{mv}{Bq}$$

where

r = distance of the charged particle from the magnetic field line about which it is gyrating

m = mass of the particle in kilograms

v = velocity of the charged particle in meters per second

B = magnetic field strength in Tesla

q = electrical charge of the particle in coulombs.

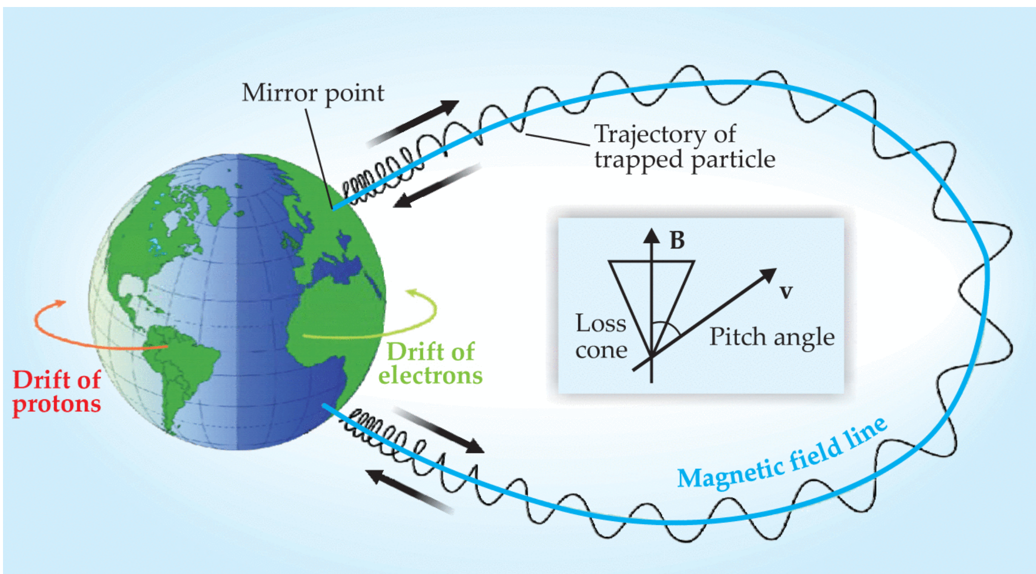


Figure 22 Formation of Ring Currents (source: Physics Today – Scitation)

After reflecting from the polar mirror points, the trapped particles fan out along the field lines as they travel back toward the equatorial plane. Magnetic field strength continuously weakens as the particles approach the magnetic equator, causing the particles to gyrated further and further away from their respective field lines (r becomes large). Near the equatorial plane the particles begin to feel perpendicular gradient forces in the magnetic field created by adjacent field lines. The gradient force cause positively charged particles to slowly diffuse westward and negatively charged electrons to diffuse to the east. The combined motion of the electrons and ions produces an electrical current that circulates westward around the Earth (Figure 22). This current is known as the Equatorial Ring Current since it only exists over the magnetic equator.

The ring current produces its own magnetic field. This magnetic field opposes Earth's core magnetic field causing a drop in Earth's magnetic field strength, particularly in the horizontal direction. The strength of the core field in the equatorial region is around 40,000 nT. In comparison, the strength of the ring current magnetic field during a strong magnetic storm is on the order of -200 nT. While the ring current magnetic field strength is only a small percentage of the core magnetic field, the fluctuations that it causes in the total magnetic field create a significant and adverse impact on our high tech society (electrical power grids, radio communications, GPS navigation systems, etc.). The ring current is important.

The ion content of the ring current consists primary of protons H^+. In addition, alpha particles He^{2+} and oxygen ions O^+ are also found in the ring current. Protons and alpha particles are plentiful in the solar wind, but oxygen ions are not. Consequently, oxygen ions and a certain percentage of protons come from Earth's polar ionosphere. The remaining protons and alpha particles originate in the solar wind.

Solar wind high speed streams, interplanetary shocks, coronal mass ejections and other solar related events inject large quantities of charged particles through the polar cusps down into the radiation belts increase ring current strength. This in turn causes a significant drop in the terrestrial magnetic field producing a geomagnetic storm. A storm subsides as some of these particles escape outward along magnetic field lines to the outer regions of the magnetosphere. Other particles precipitate out of the radiation belts into Earth's upper atmosphere at high latitudes creating intense auroral activity.

The Disturbance Storm Time (Dst) index measures the magnetic field strength of the equatorial ring current. An increase in the ring current produces a worldwide depression in the horizontal component of Earth's magnetic field causing a geomagnetic storm. The Dst index is compiled from hourly averages of the horizontal component of Earth's magnetic field recorded at four low latitude observatories. The observatories are located at Kakioka Japan, Honolulu Hawaii, San Juan Puerto Rico, and Hermanus South Africa. The Dst index is zero on geomagnetic quiet days. An index of -50 or greater indicates a storm-level disturbance in the magnetic field. An index of -200 or deeper is associated with a severe storm that can produce aurorae visible as far south as Washington D. C. Notice that a negative Dst number, for example -50, when added to Earth's positive core magnetic field intensity results in a decrease in total magnetic field strength. The Dst index is used by government agencies, satellite operators, power grid engineers, and others to analyze the strength and duration of geomagnetic storms.

Figure 23 shows the Dst index for March 1989. March 13th of that year was one of the most severe geomagnetic storms experienced in recent decades. The storm was so intense that it knocked out the Hydro Quebec electric power distribution system causing over 6 million people to lose electricity. Notice in this figure that the magnetic field spiked down -600 nT on the 13th of March.

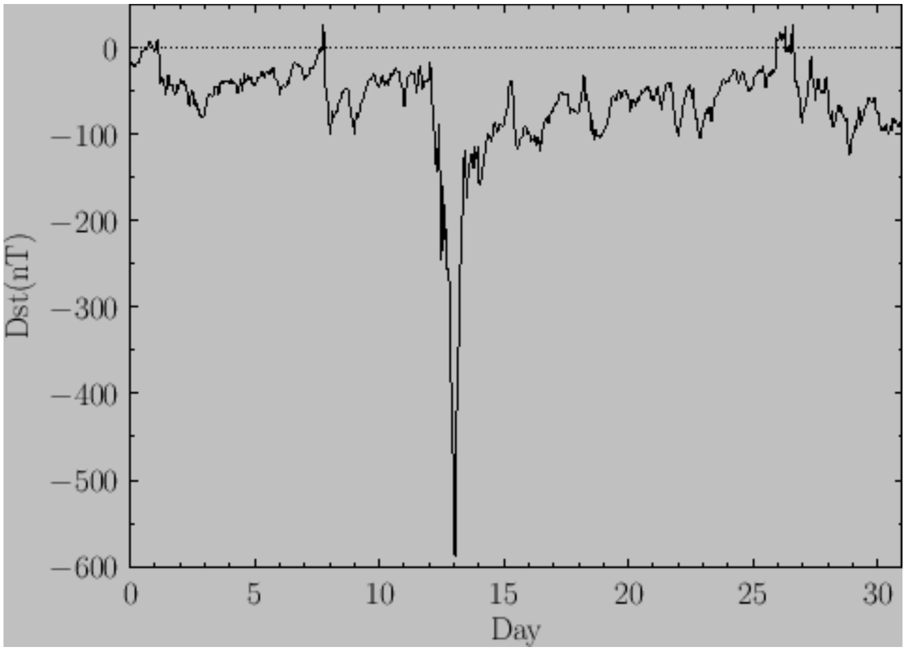


Figure 23 Dst index for the month of March 1989 (source: Farside.ph.utexas.edu)

The current Dst level can be obtained by clicking on Dst Index under the Current Conditions tab of the www.skywave-radio.org website.

8.13 Other Electrical Currents

A number of other electrical current systems circulate within the magnetosphere in addition to the equatorial ring current. These other currents system include the

- Chapman-Ferraro magnetopause current,
- Cross-tail current.
- Polar field aligned currents, and
- Pedersen currents

as illustrated in Figure 24

These electric current systems are very dynamic. Each system undergoes significant changes in size, magnetospheric location, and intensity due to variations in the solar wind and IMF impacting Earth's magnetic field. In addition, these electrical currents each produce their own magnetic field which, taken together, adversely effect Earth's core magnetic field producing potentially damaging geomagnetic storms. Space weather predictions critical to power grid operators, the safety of orbital spacecraft, communication systems, and many other technology based systems depend heavily on understanding the real time dynamics of these electrical current systems and their current state.

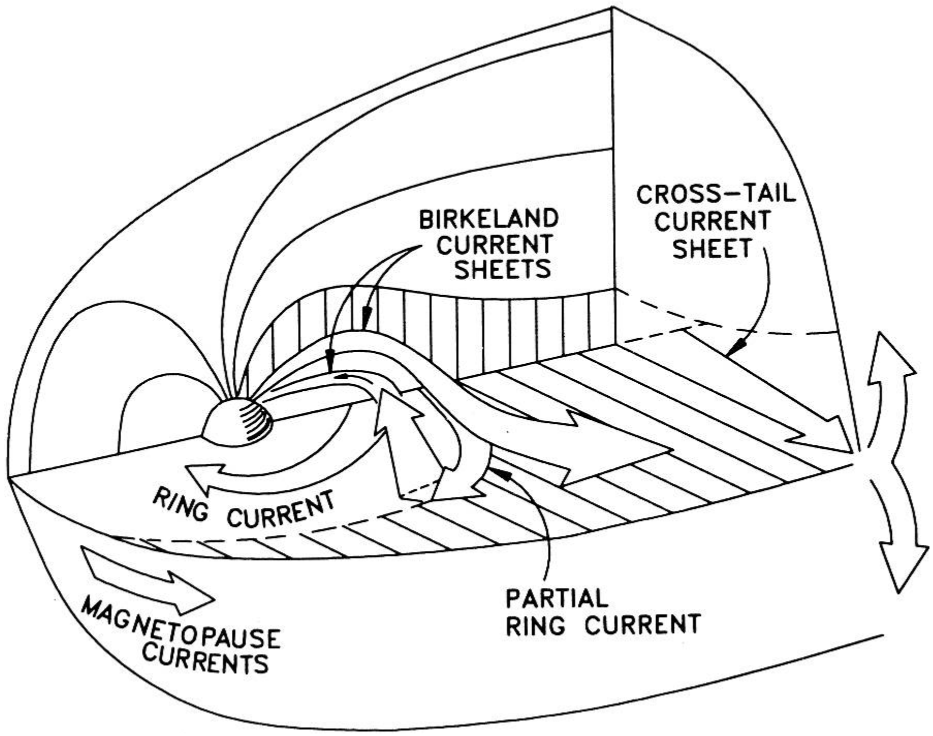


Figure 24 Magnetosphere Electrical Currents (source: Wikipedia)

8.13.1 Chapman-Ferraro Magnetopause Current

The Chapman-Ferraro electrical current is an extensive current system located in Earth's magnetopause that circulates around the polar cusps, as illustrated in Figure 25. The current is produced by time varying compression of Earth's dayside magnetosphere resulting from the constantly changing solar wind impacting Earth's magnetic field.

The Chapman-Ferraro electrical current is not an isolated system. It interacts extensively with the Region 1 Field Aligned Current (FAC) discussed below.

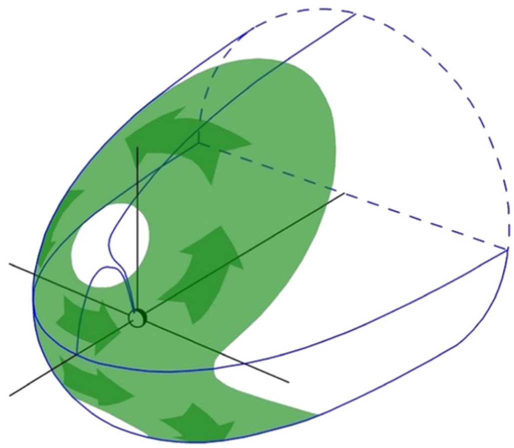


Figure 25 Chapman-Ferraro magnetopause electrical current (source: Ganushkina et al)

8.13.2 Cross-Tail Current

As discussed earlier, the magnetotail, Figure 26, consists of three important regions, the South Lobe, North Lobe, and the Plasma Sheet. The plasma sheet runs down the center of the tail between the two lobes. The Earth's magnetic field points away from Earth in the south lobe which is linked to Earth's southern polar region. The northern lobe magnetic field points towards the Earth and is linked to Earth's northern polar region. The plasma sheet is the region between the two lobes where the magnetic field reverses direction from outward to inward. The magnetic field strength in the lobes is about 20 nT and much weaker in the plasma sheet where the reversal occurs.

The plasma sheet literally cuts the magnetotail in half extending from the magnetopause on one side of the tail to the magnetopause on the opposite side of the tail as illustrated in Figure 27.

An electrical current, known as the cross-tail current, flows in the plasma sheet across the magnetotail perpendicular to the tail axis as shown in Figure 27. The current flow splits when it reaches the magnetopause. Part of the current flows through the magnetopause above the plasma sheet while the other part flows through the magnetopause below the plasma sheet. The two flows combine again at the edge of the plasma sheet on the opposite side of the tail, completing the electrical circuit.

The cross-tail electrical current is consistent with the right-hand rule. If the fingers of your righthand curve in the direction of the electrical current flow, then the thumb of your righthand points in the direction of the magnetic field. In the case of the magnetotail, the electrical current flowing across the plasma sheet and returning through the magnetopause above the plasma sheet is consistent with the inward directed magnetic field (toward the Earth) in the north lobe. Similarly, the cross-tail electrical current returning through the magnetopause below the plasma sheet is consistent with the outward directed magnetic field (away from the Earth) in the south lobe.

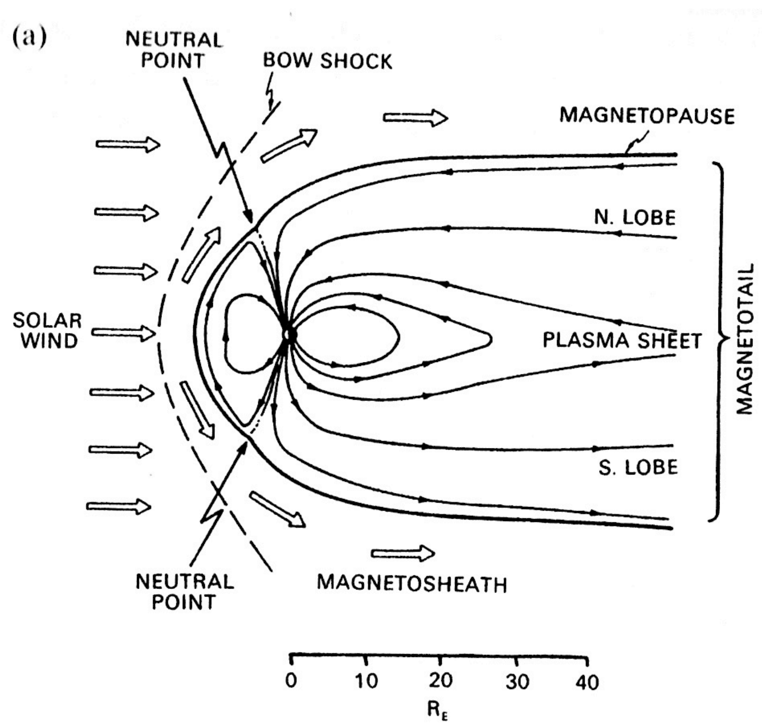


Figure 26 Magnetotail (source: Hunsucker)

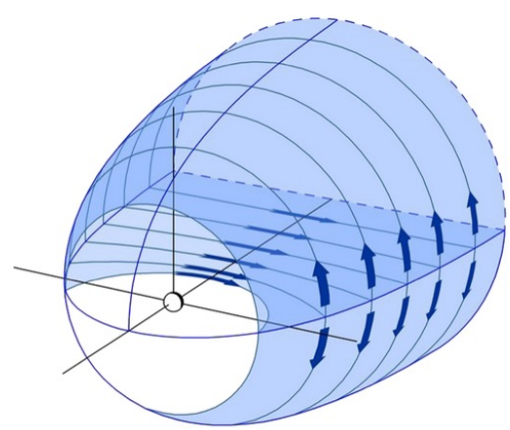


Figure 27 Magnetosphere cross-tail electrical current (source: Ganushkina et al) Polar Field

During a geomagnetic storm the magnetotail can collapse in a limited region forming the near-Earth neutral line shown in Figure 28. The cross-tail current from that region becomes diverted along field lines forming a field aligned current wedge that flows into the ionosphere as illustrated in Figure 29. The electrical circuit is completed by an electrojet flowing in the E-region of the ionosphere.

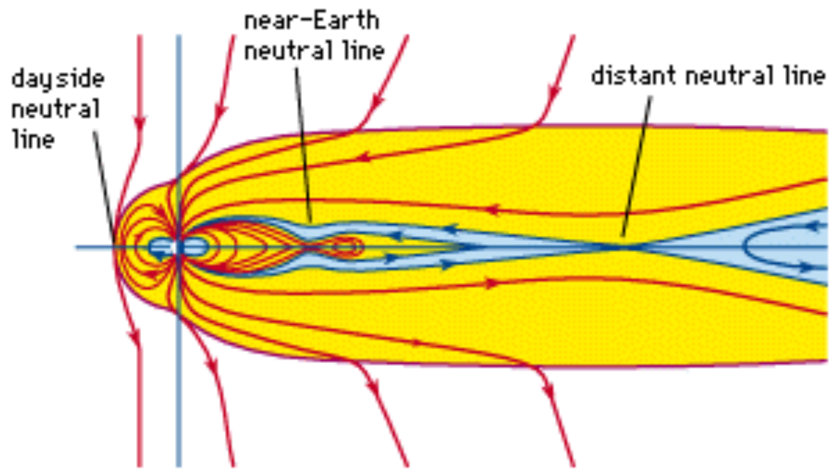


Figure 28 Magnetotail neutral lines (source: Encyclopaedia Britannica)

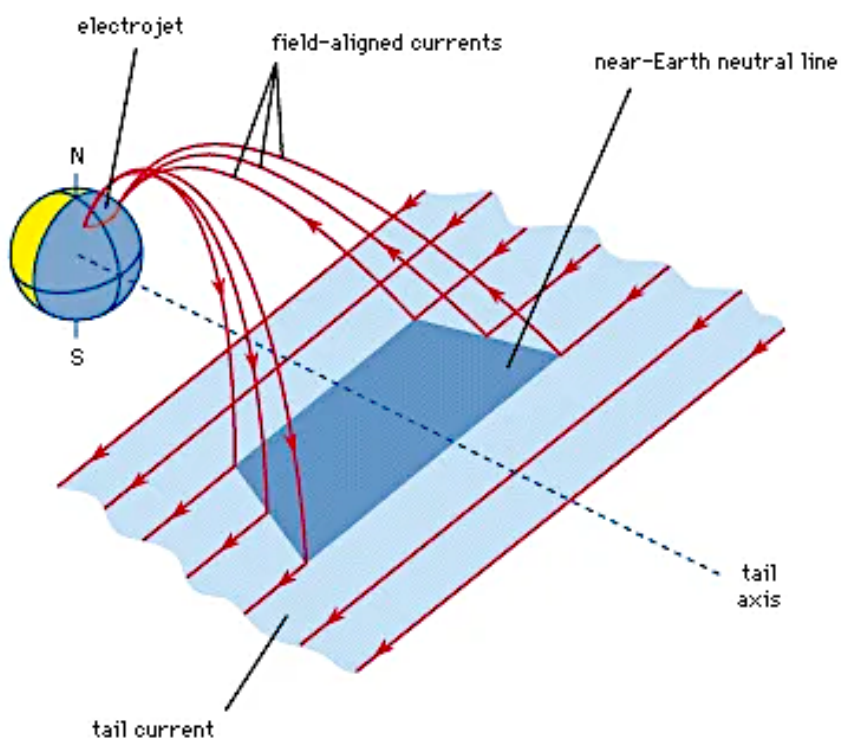


Figure 29 Magnetotail current wedge (source: Encyclopaedia Britannica)

The downward field aligned current occurs on the dawn side of the polar region and the upward current on the dusk side. The direction of these field aligned currents is the same as the Region 1 field aligned current discussed in the next section. The location of upward and downward currents coincides approximately with the west and east boundaries of the auroral bulge that forms in the nightside auroral oval during the onset of a substorm. The wedge current fades away with the substorm recovery.

8.13.3 Polar Field Aligned and Pedersen Currents

Field aligned currents (Figure 30) 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.

There are two sets of concentric polar field aligned current sheets, one inside the other. The poleward inner current sheet is classified as Region 1 (R1) while the outer current sheet toward the equator is designated Region 2 (R2). R1 current flows outward from the dusk region of the polar ionosphere and downward into the dawn ionosphere. R2 currents exhibit the opposite flow of R1 currents. R2 current flows upward out of the ionosphere dawn region and downward into the dusk polar region as illustrated in Figure 30. In this figure dusk occurs on the right side of the figure.

R1 and R2 currents originate from different parts of the magnetosphere. R1 currents originate from the divergence of the Chapman-Ferraro current flowing in the magnetopause. In contrast, R2 currents are the result of partial ring currents flowing in the inner magnetosphere as illustrated in Figure 31. In Figure 31 Region 1 electrical current flows out of the dusk ionosphere, connect with the Chapman-Ferraro magnetopause current, and then reenters the dawn side of ionosphere. Pedersen currents complete the circuit carrying Region 1 electrical currents across the polar cap back to the dusk side of the ionosphere. Region 2 electrical current flows out of the dawn ionosphere, flows by means of a partial ring current back to the dusk side of the polar region where it reenters the ionosphere. Pedersen currents carry the Region 2 current into the outgoing Region 1 current. On its return to the dawn side ionosphere, part of the Region 1 current is carried by Pedersen currents back to the outgoing Region 2 current completing the Region 2 circuit.

When the IMF turns southward, the dayside magnetopause is eroded by magnetic reconnection between the IMF and Earth's northward directed magnetic field (see Section 13.14). Stripping away part of the dayside magnetic flux brings the magnetopause closer to Earth and causes the cusps to shift slightly toward the equator. As the solar wind flows past the Earth, the IMF and Earth's reconnected magnetic field are dragged across Earth's polar region transporting magnetic flux from the dayside magnetosphere to the nightside, in addition to increasing plasma flows in the polar region ionosphere. All of this disruption causes the Region 1 FAC to increase in size while decreasing the Chapman-Ferraro current system.

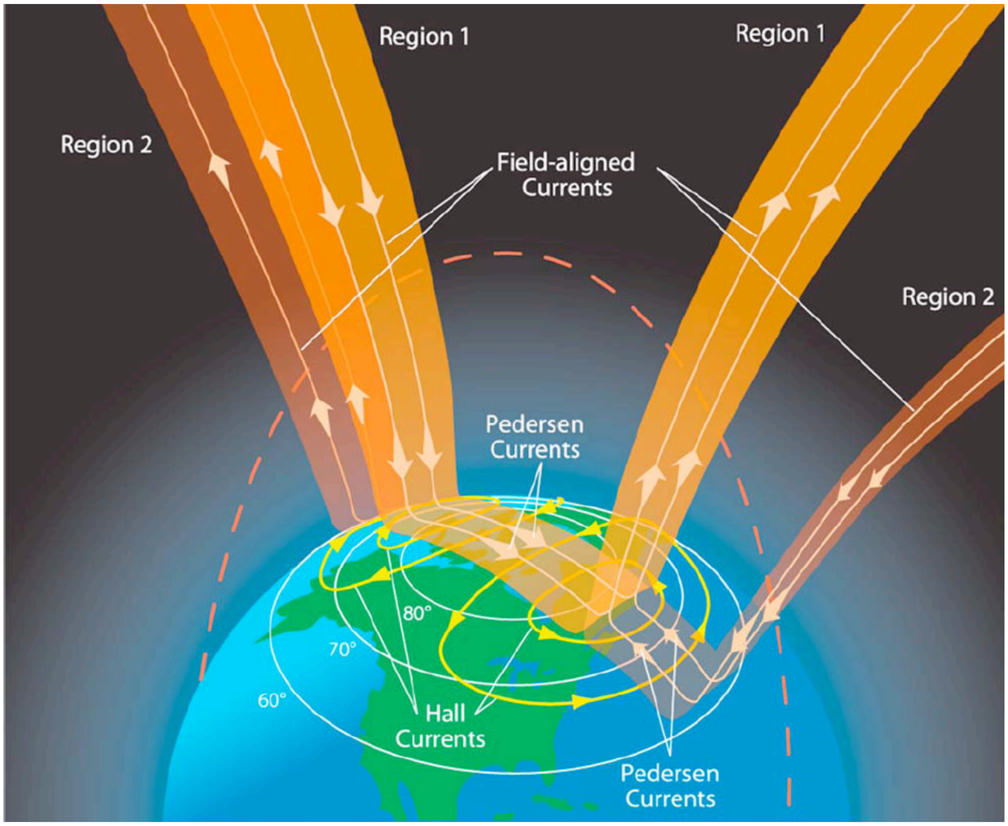


Figure 30 Field Aligned Currents (source: Wikipedia)

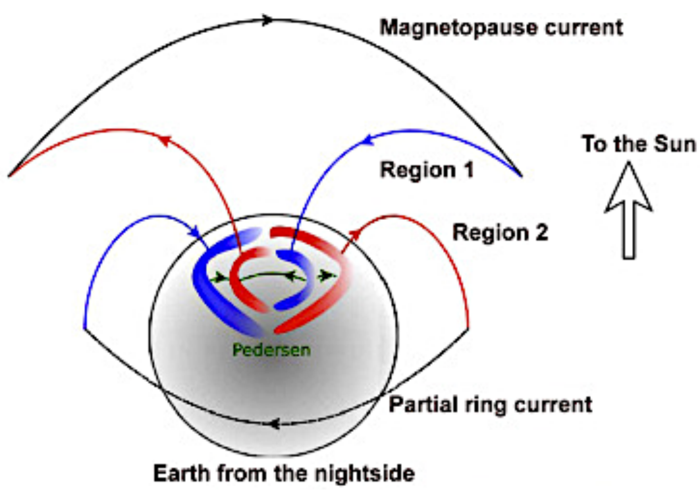


Figure 31 Region 1 and Region FAC (source: ScienceDirect.com)

8.13.4 Field Aligned Currents vs Polar Wind

What is the difference between field aligned currents and the polar wind?

The polar wind is the mechanism by which charged particles flow out of the ionosphere into the magnetosphere at an astonishing rate of around 50 tons of plasma per day. The out flow from the ionosphere in combination with the inflow from the solar wind are the only two mechanisms available for populating the magnetosphere with ions and free electrons.

The ring, partial ring, Chapman-Ferraro, cross-tail, field aligned and other electrical currents present in the magnetosphere are the result of Earth's magnetic field, in combination with dynamic solar wind and IMF forces, acting upon the charged particles present in the magnetosphere.

8.14 Interaction of the IMF with Earth's Geomagnetic Field

The Geocentric Solar Magnetospheric (GSM) coordinate system, shown in Figure 32, is considered the best system to use when studying the effects of solar wind IMF on Earth's magnetosphere. The GSM coordinate system, centered on the Earth (geocentric), is defined relative to Earth's magnetic field axis. The radial x-axis (X_{GSM}) points from the center of the Earth to the center of the Sun. The z-axis (Z_{GSM}) is aligned with Earth's magnetic field axis and the y-axis (Y_{GSM}) is perpendicular to both the x and z axis.

In Figure 33 a southward directed ($-Z_{GSM}$) Interplanetary Magnetic Field (IMF) encounters Earth's northward ($+Z_{GSM}$) magnetic field on the sunward side of the magnetopause. The oppositely directed magnetic field lines cancel each other forming a magnetic neutral point, the red rectangle adjacent to the bow shock in Figure 33. Neither field exists within the neutral point. Consequently, each field line is broken as it enters the neutral region. Above and below the neutral point the "broken" IMF and geomagnetic field lines reconnect, but this time to each other as illustrated in Figure 34. In this figure the field line marked 1' is an IMF field line just as it is about to cancel with geomagnetic field line 1. Field line 2 represent the two broken field lines after they have reconnected forming a single combined line.

However, a problem arises with this reconnection. The IMF is "frozen in" the solar wind and thus moves with the wind. As it does so it drags Earth's connected magnetic field lines along with it over the poles from the day to night side of the magnetosphere. In addition, connection to the IMF peels open the geomagnetic field lines over the polar regions allowing a flood of solar wind charged particles to flow down the field lines into Earth's inner magnetosphere. The inflow of charged particles increase the strength of the equatorial ring current leading directly to a geomagnetic storm. How strong the storm is depends on the speed and particle density of the solar wind at the time. High speed solar wind streams created by coronal holes, coronal mass ejections, solar flares, solar energetic particles (SEPs), in addition to corotating wind interaction regions near the Earth can all increase the speed and density of the solar wind, increasing the severity of a geomagnetic storm.

After being dragged over the polar region, the geomagnetic field finally break away from the IMF far out in the magnetosphere tail, reconnects to itself (field line 6) and loops back to Earth (field line

7). The reconnection occurs in the magnetotail neutral zone illustrated in Figure 33 by the red rectangle in the night side magnetosphere. The IMF part of the field lines (field line 7') is carried away from Earth out into the far reaches of the magnetotail where it eventually rejoins the main part of the IMF.

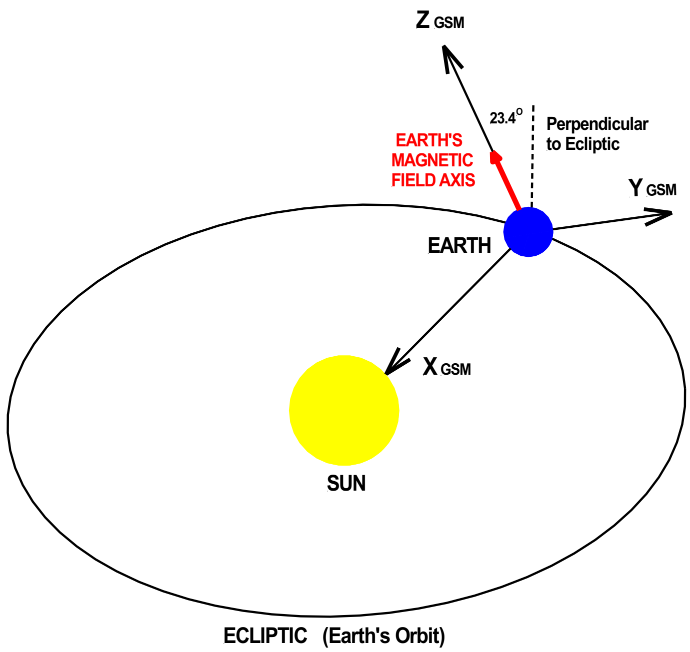


Figure 32 Geocentric Solar Magnetospheric (GSM) Coordinates (source: author)

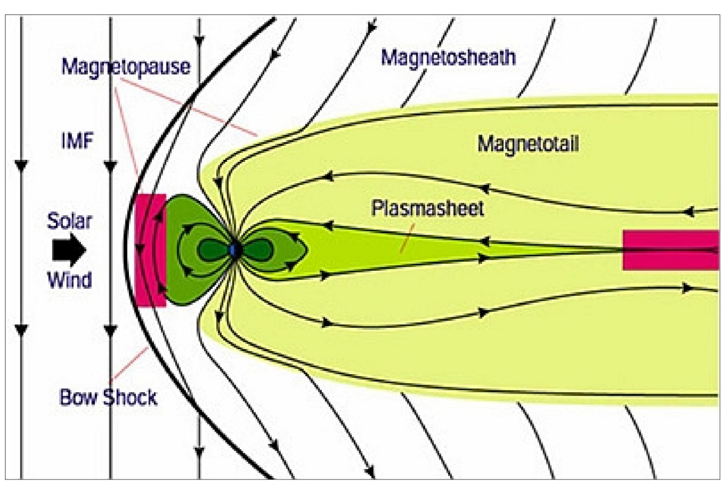


Figure 33 Magnetic neutral points (source: Satellite Missions)

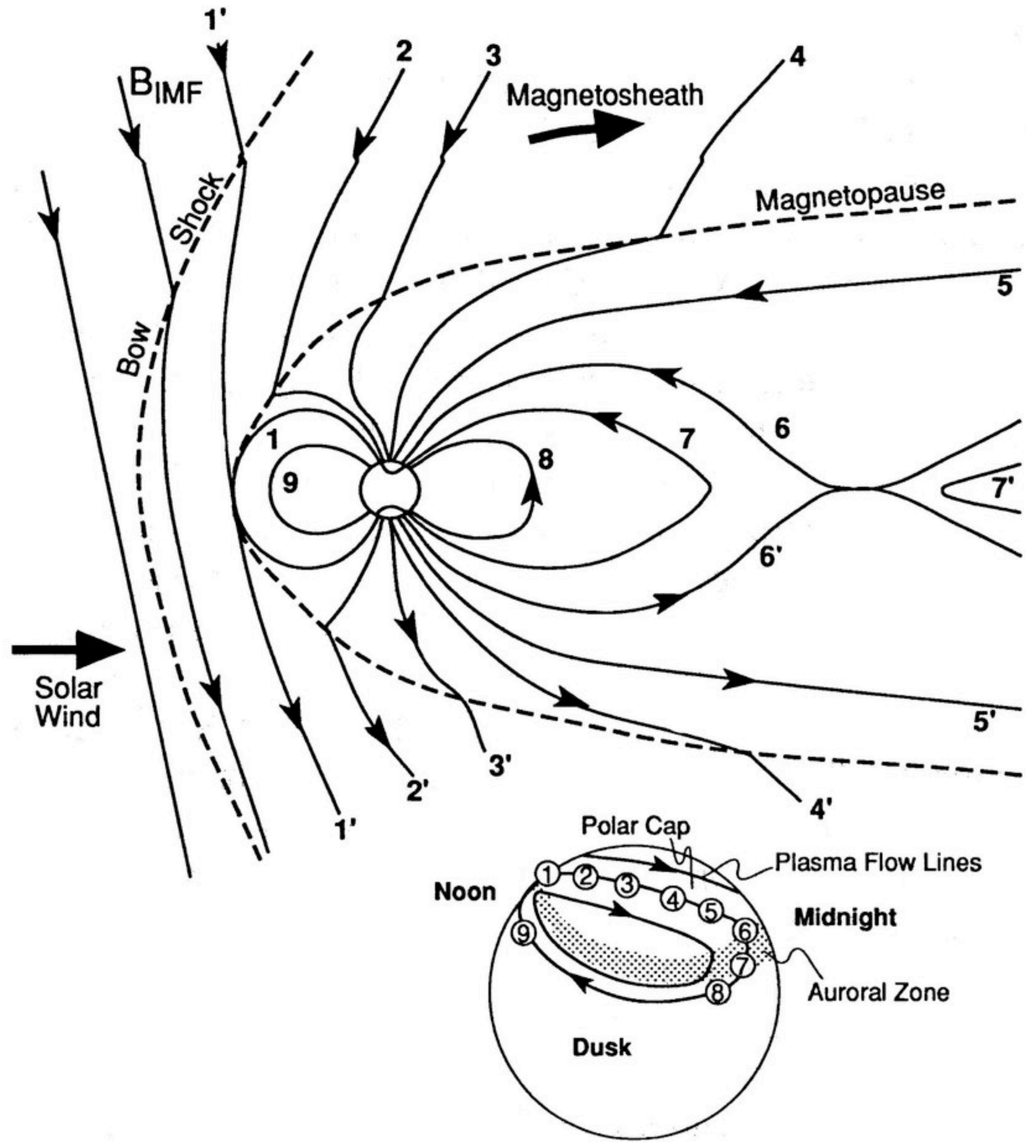


Figure 34 Dungey convection cycle (source: ResearchGate)

In the process plasma in Earth's ionosphere is dragged across Earth's polar region from the day to night side of the Earth (1 through 6 shown in the Figure 34 insert). The plasma flows back toward the day side of the Earth at latitudes below the auroral zone as the geomagnetic field breaks away from the IMF and loops back to Earth (7 through 9 in Figure 34).

Dragging of the geomagnetic field across the polar regions of the Earth combined with the associated plasma flows is known as the Dungey convection cycle. British scientist James Dungey proposed the cycle in 1961 to explain the interaction between Earth's magnetosphere and the solar wind.

The Dungey convection cycle does not occur with a north directed IMF. A north directed IMF (Figure 35) is parallel to the geomagnetic field. Consequently, a magnetic neutral point on the day side of the magnetosphere, with its corresponding magnetic reconnections, does not occur. Since the two fields do not break and reconnect, Earth's magnetic field (D in Figure 35) remains primarily a closed field.

Geomagnetic storms can occur during a north directed IMF if the speed and density of the solar wind is great enough. However, the magnitude of such storms is generally small since the geomagnetic field lines remain closed minimizing the inflow of solar wind particles into the inner magnetosphere.

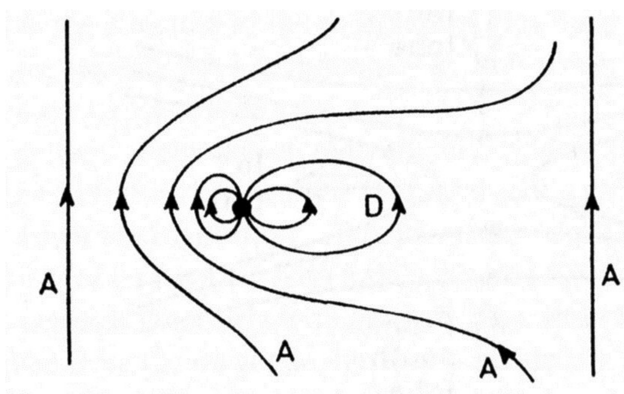


Figure 35 North Directed IMF (source Hunsucker)

Geophysical activity increases when a south directed IMF reconnects to Earth's magnetic field.

- Magnetic storms occur more frequently,
- Auroral zones drift toward the equator,
- Dayside cusps are also displaced toward the equator,
- The dayside magnetopause moves inward toward the Earth, and
- Magnetic flux in the magnetosphere tail increases.

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