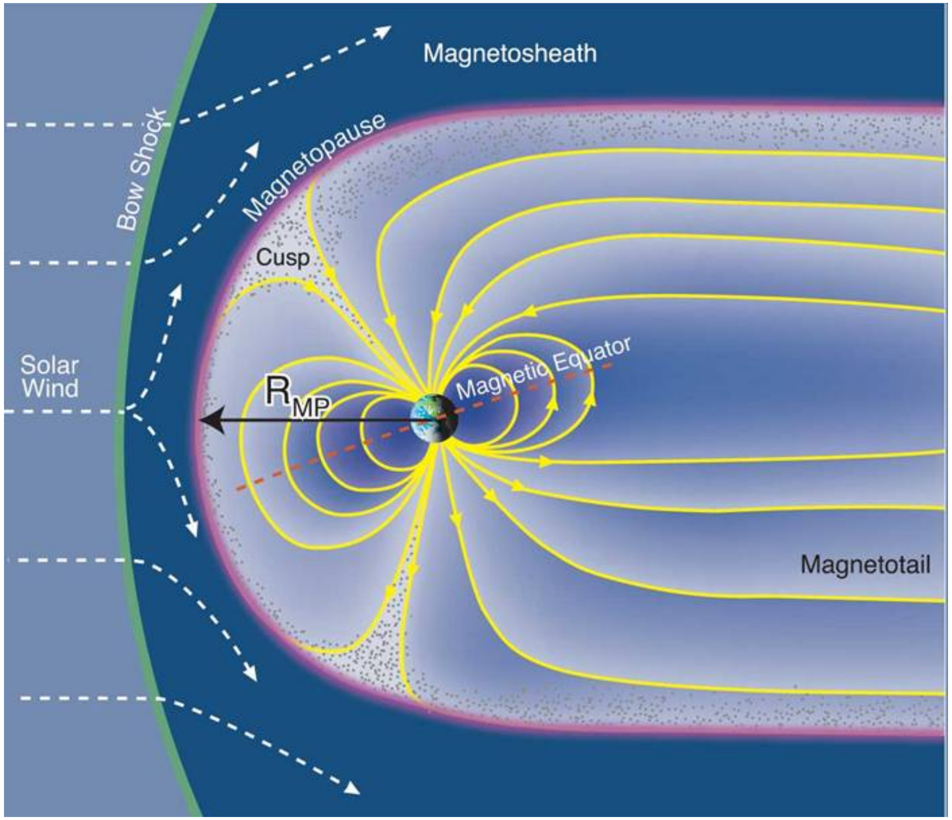
Earth's Magnetosphere



Lasp.colorado.edu

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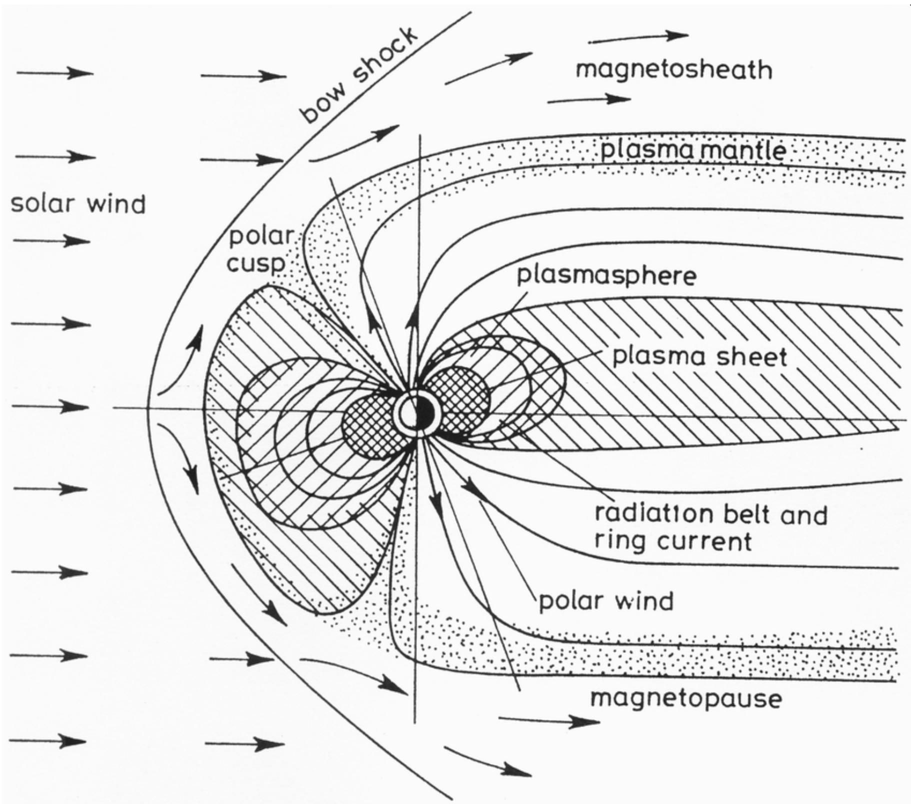
www.skywave-radio.org

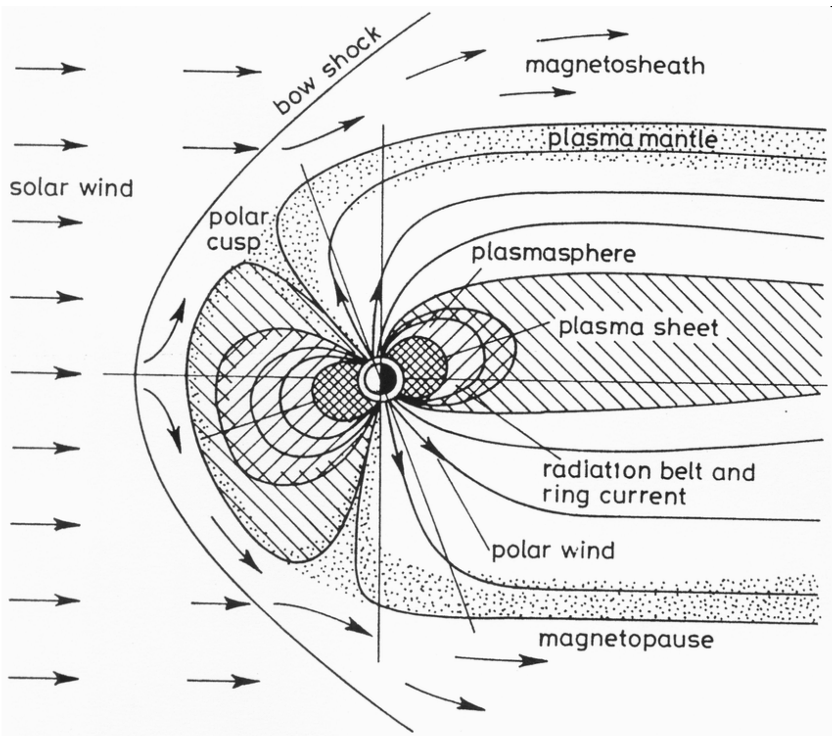
Magnetosphere



Davies

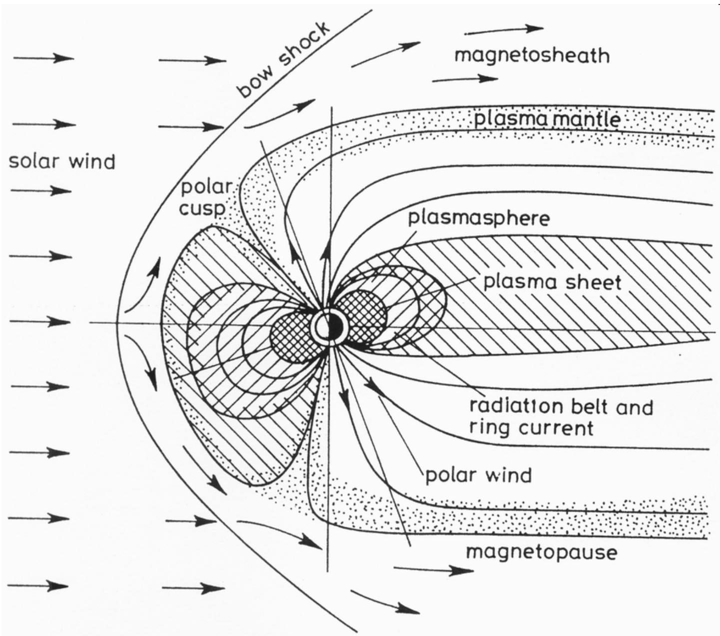
- The magnetosphere is the region of space occupied by Earth's magnetic field.
- It is particularly important in studying the ionosphere at high latitudes.
- As we know, Earth's magnetic field, and thus the magnetosphere, is severely distorted by the solar wind emanating from the Sun.
- The solar wind impacts the magnetosphere along the bow shock about 10 Earth radii (10 R_E) from the Earth.
- The bow shock compresses the magnetosphere on the dayside and stretches it out on the nightside forming a long magnetic tail.

Composition of the Magnetosphere



- The magnetosphere is fixed relative to the Sun while the Earth itself rotates within the stationary magnetosphere.
- The magnetosphere consists of multiple regions including:
  - Magnetosheath
  - Magnetopause
  - Magnetotail
  - Polar cusp
  - Plasma mantle
  - Plasmasphere
  - Plasma sheet
  - Radiation belts and ring currents
- 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.

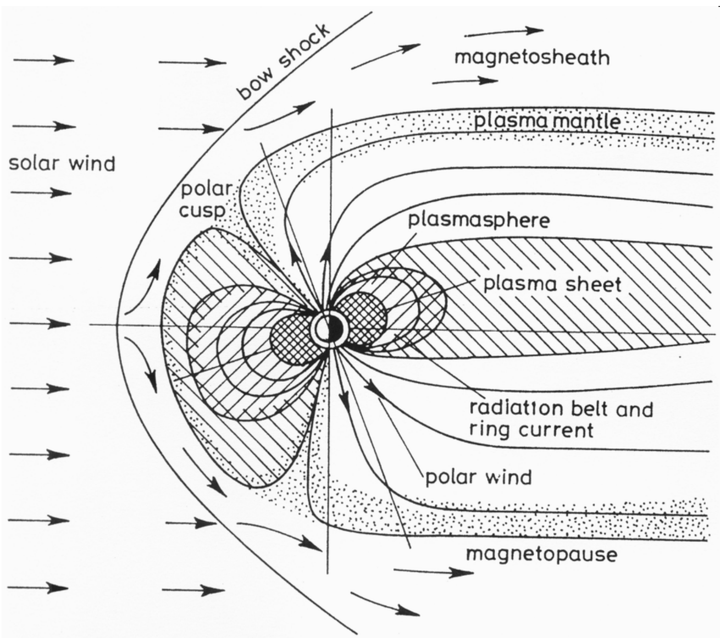
Magnetosheath



Davies

- The solar wind is supersonic as it approaches the bow shock, meaning that its velocity (typically 400 km/sec) exceeds that of any non-electromagnetic wave that can propagate within it.
- Note that the speed of sound at Earth's surface is 0.343 km/sec = 767 mi/hr., so the speed of the solar wind is very fast.
- The solar wind is very tenuous. Its particle density is only around 5 particles per cubic cm. The particles are mostly protons (H^+), with a small percentage (~ 5 %) of a – particles (He^{2+}). The temperature of solar wind is about 10^5 K which is not very hot in terms of solar temperatures.

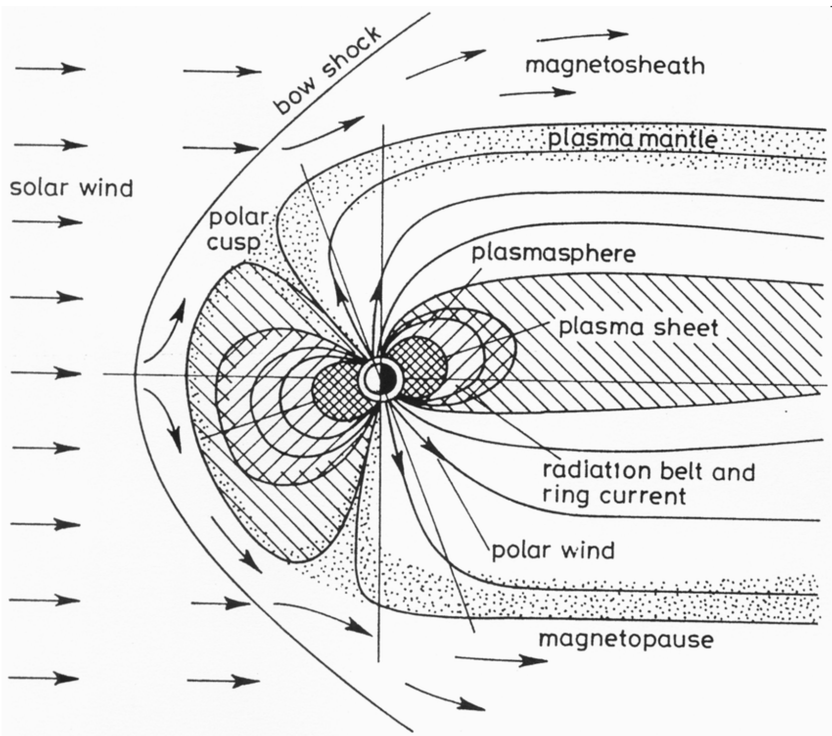
Magnetosheath - continued



Davies

- Most of the solar wind particles are deflected by the bow shock and continue downwind outside the magnetic tail.
- The region between the bow shock and the magnetosphere proper is called the magnetosheath.
- The magnetosheath 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 dissipated as thermal energy, increasing plasma temperature to about 5×10^6 K
- Consequently the magnetosheath plasma is slower and 5 to 10 times hotter than the solar wind.
- Like the solar wind, most of the magnetosheath plasma continues downwind outside the magnetosphere.

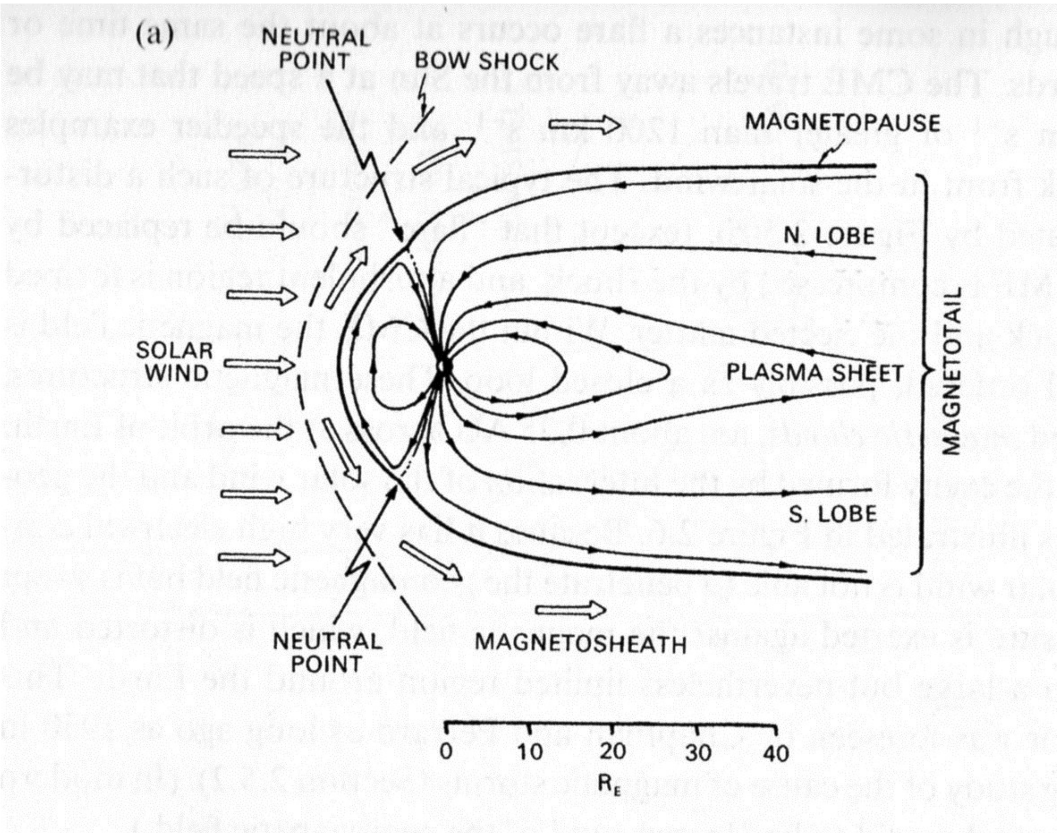
Magnetopause



Davies

- The magnetopause is the boundary between the magnetosheath and the magnetosphere.
- The geomagnetic field vanishes at the magnetopause (field strength decreases to 0 nT).
- It is replaced outside the magnetopause by the Interplanetary Magnetic Field (IMF).
- In addition to its presence within the magnetosheath, the IMF permeates throughout the solar system carried along by the solar wind.
- The IMF is very weak, only a few nT, compared to Earth's geomagnetic field of between 25,000 to 65,000 nT at Earth's surface.

Magnetotail



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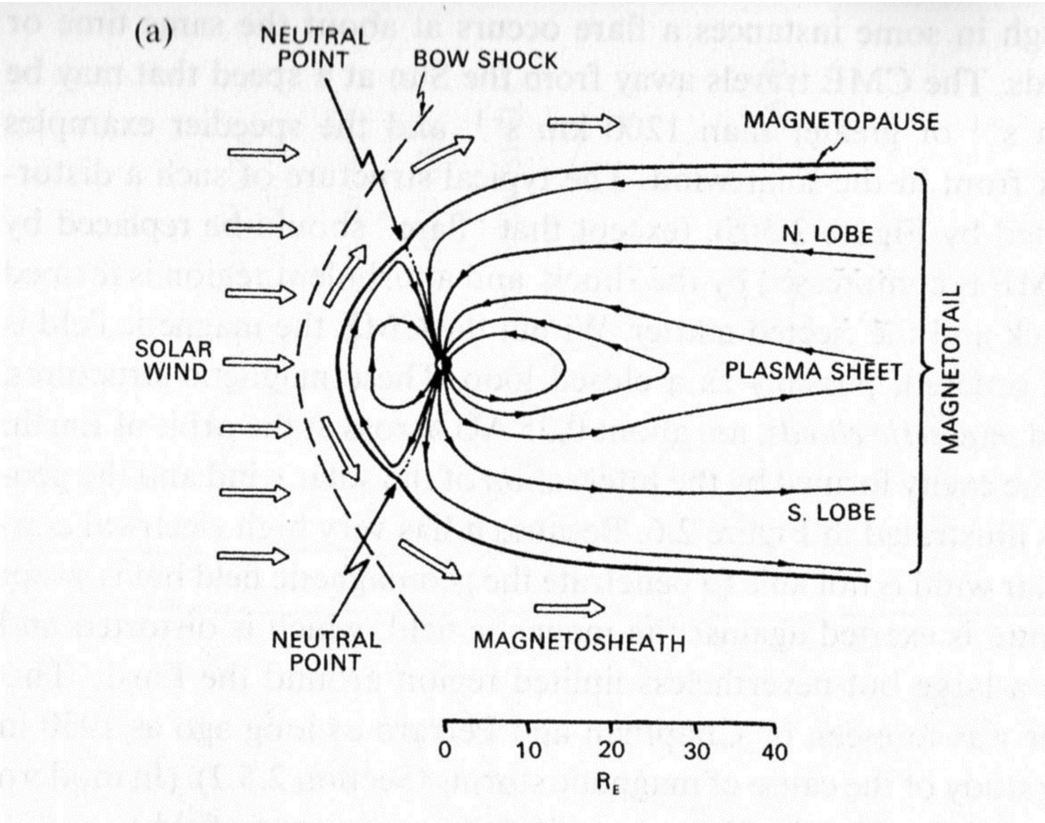
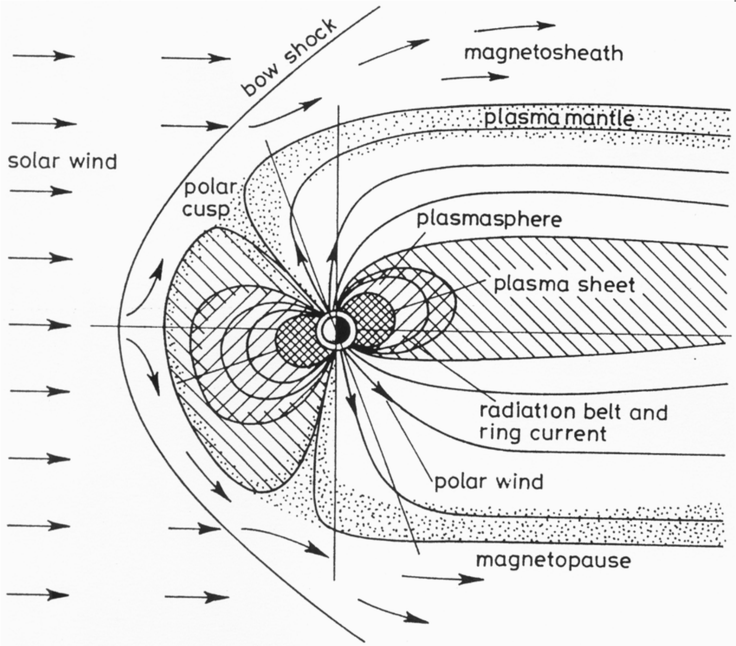
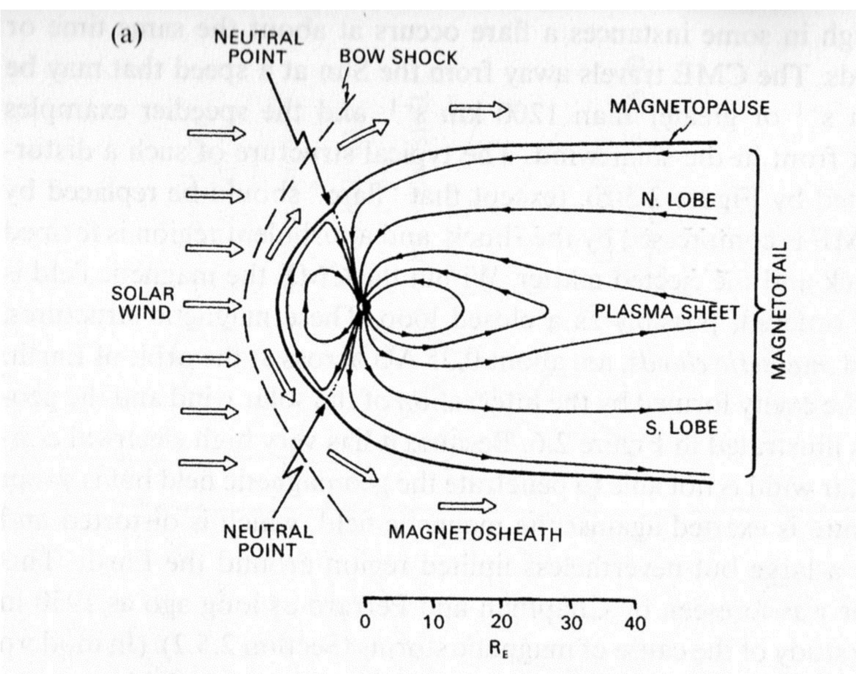
- The magnetotail extends hundreds of thousands of kilometers outward away from Earth's nightside.
- The tail is roughly circular with a diameter of about 30 R_E and at least 10^7 km in length.
- While the tail extends far out into space, the opposite end of the tail is anchored in Earth's polar region.
- Consequently, the polar ionosphere can be significantly affected by events occurring in the tail.

North & South Magnetotail Lobes



- The tail consists of three important regions beyond about 10 R_E. They are the South Lobe, North Lobe, and the Neutral Sheet which runs down the center of the tail between the two lobs.
- The magnetic field points away from Earth in the south lobe and toward the Earth in the northern lobe.
- The Neutral 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 neutral sheet where the reversal occurs.

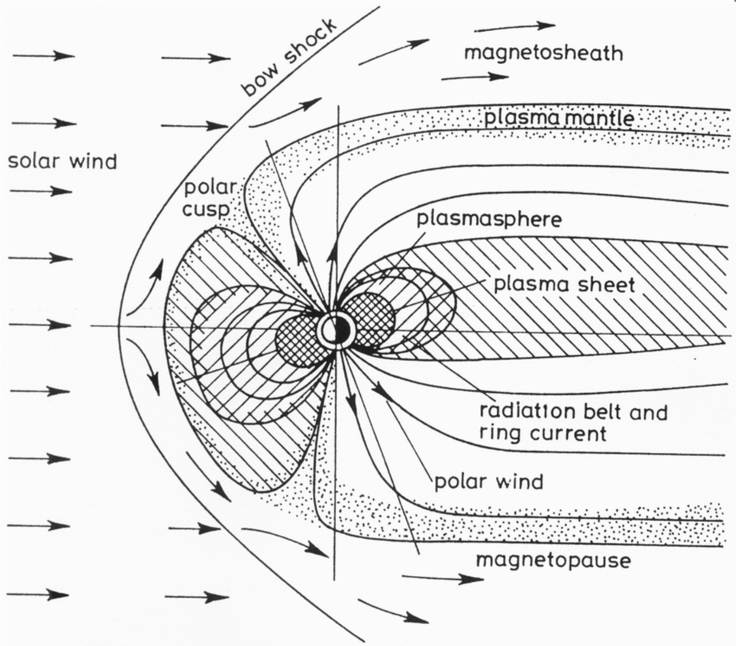


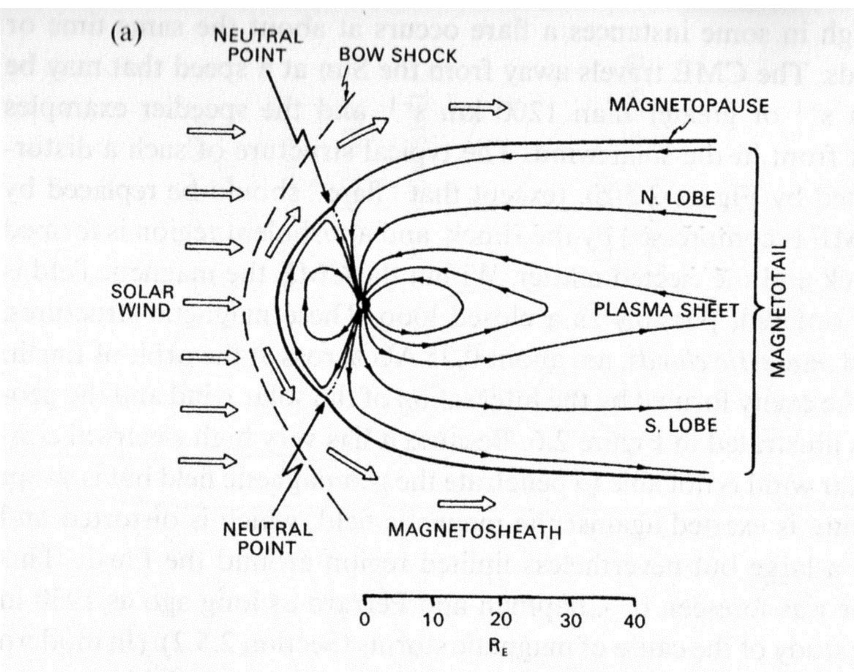


Polar Cusps

- Moving charged particles can travel along magnetic field lines but can not cross them.
- Consequently, high energy particles emanating from the Sun are prevented from entering the atmosphere in the equatorial regions 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 ionosphere.
- In addition, there are two neutral points within the magnetopause, one in each hemisphere, where the total magnetic field is zero.

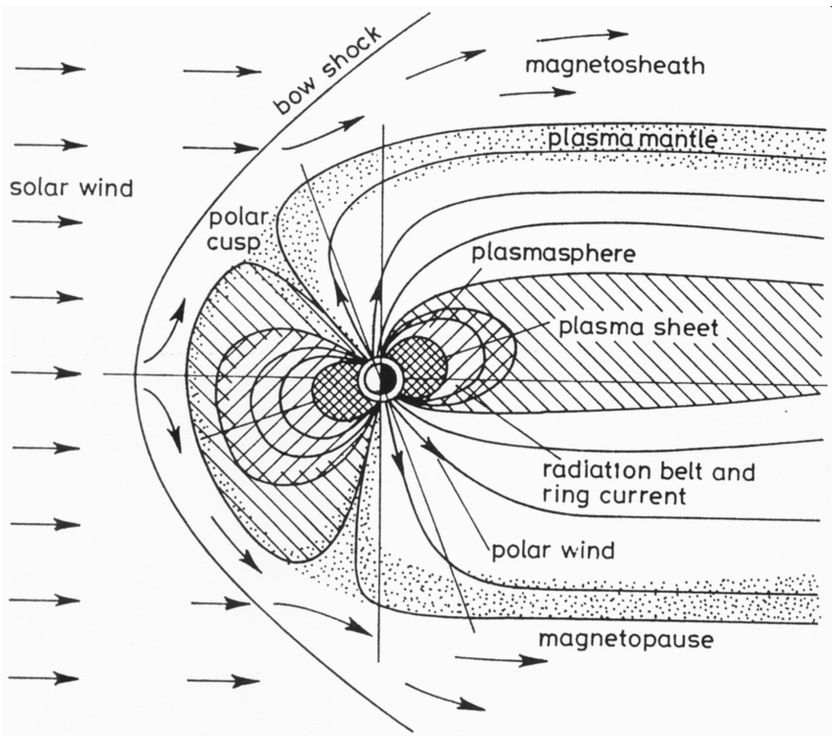
Polar Cusps - continued





- These neutral points (actually two neutral circular ring) are known as the Polar Cusps.
- 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 any magnetic field lines.
- Each polar cusp extends down to Earth's surface forming a ring about 5^o wide in latitude centered at around 77^o magnetic latitude.
- Within the cusps high energy solar wind and magnetosheath particles are funneled directly into Earth's upper atmosphere, unimpeded, significantly affecting the high latitude ionosphere.

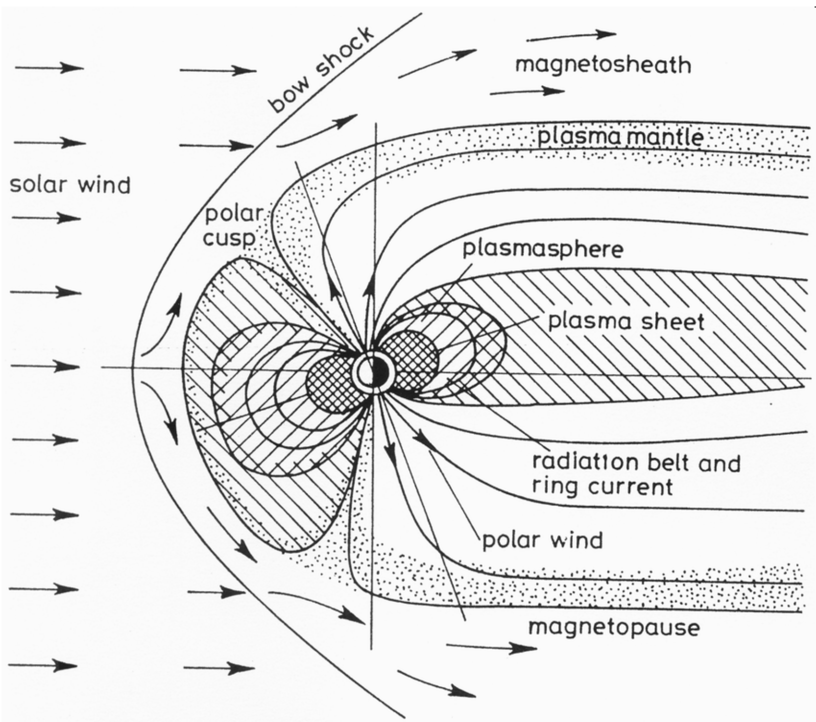
The Plasma Mantle



Davies

- The plasma mantle is the outer ionized region of the magnetosphere consisting of both ionospheric and magnetosheath ions.
- The ionospheric ions 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.

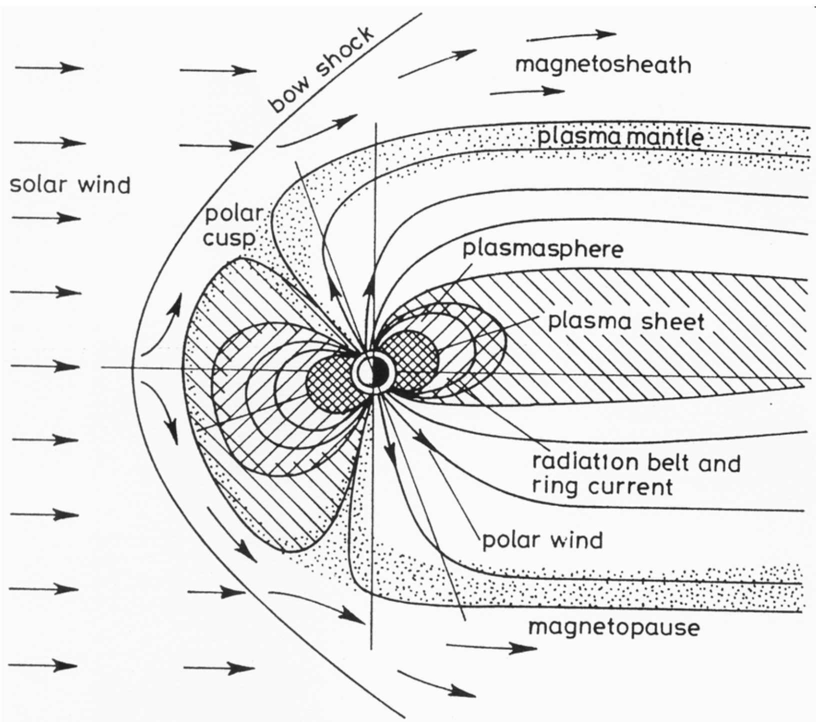
Plasmasphere



Davies

- The plasmasphere is a region of charged particles deep within the magnetosphere.
- It is located 3 – 4 R_E from the Earth, inside the radiation belt and ring current, and is closely linked to the mid-latitude ionosphere.
- It is comprised of electrons, protons, and some heavy ions.
- Some of the particles within the plasmasphere originate in the ionosphere while others come from the magnetosheath and solar wind.
- Electron densities drop by a factor of 10 or more outside the plasmasphere.
- The plasmasphere acts as a reservoir of charged particles for the F region of the ionosphere.

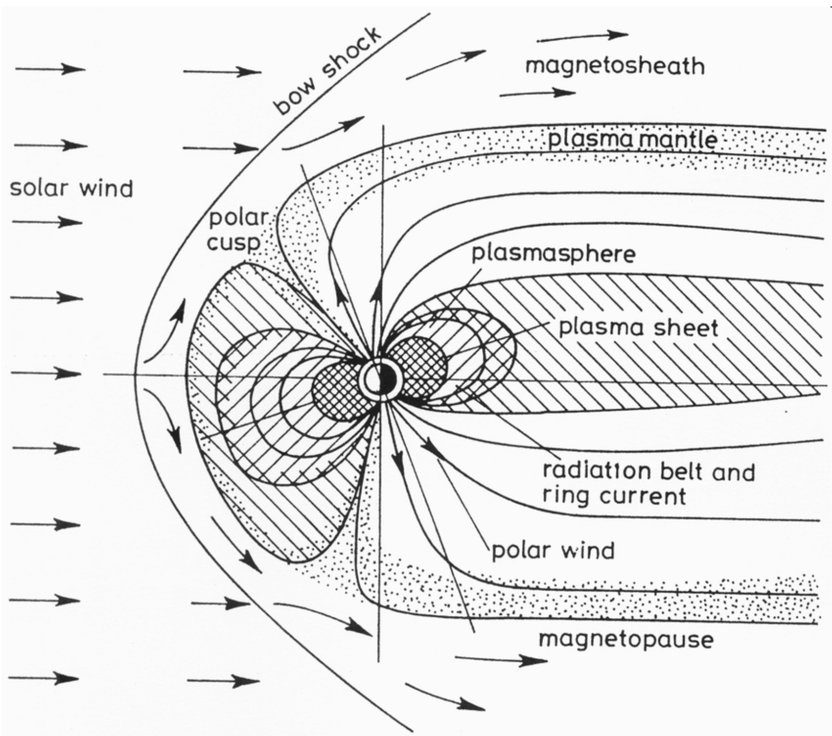
Plasmasphere continued



Davies

- Ionospheric plasma flows upward during the day enhancing the plasmasphere.
- At night some of this plasma flows back to lower levels helping to maintain the night time F region.
- The plasmasphere is doughnut shaped with the maximum extent of the plasmasphere along the equatorial plane.
- The doughnut hole is located over the polar regions.
- It is important to note that the plasmasphere rotates with the Earth while the rest of the magnetosphere (further away from Earth) is stationary with respect to the Sun.
- The plasmasphere is dynamic and variable.
- Its position varies throughout the day and on the night side it bulges out toward the tail.
- During geomagnetic storms the plasmasphere contracts and then gradually recovers over the next few days.

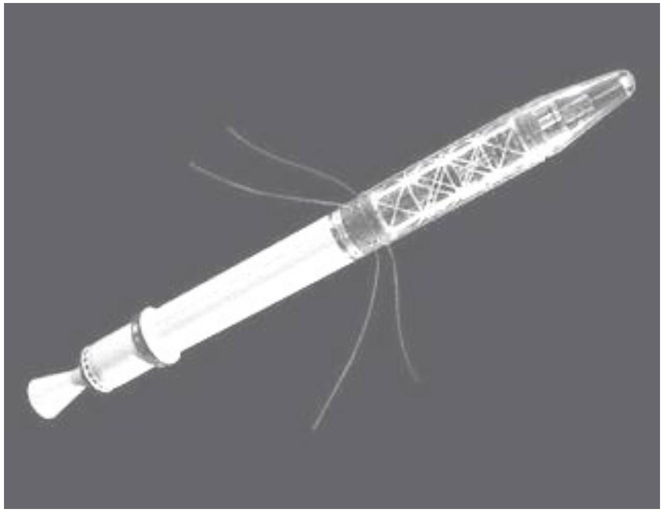
The Plasma Sheet



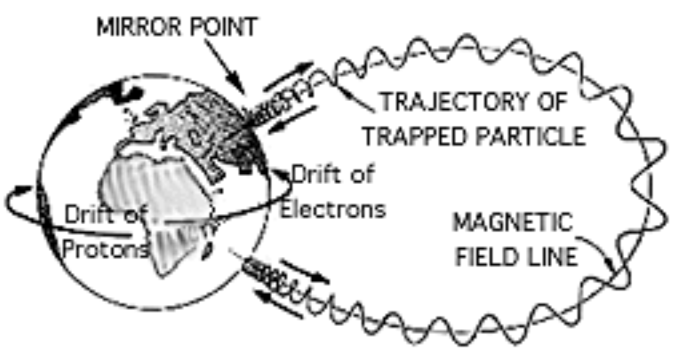
Davies

- An important property of the plasmasphere is its closed magnetic field lines.
- In contrast, magnetic field lines emanating from the polar regions, through the plasmasphere doughnut hole, are open extending outward into the magnetic tail.
- This region of open field lines is called the plasma sheet.
- The plasma sheet extends down the center of the magnetic tail on one end and dips into the Earth's atmosphere in the auroral zone on the other end.
- Disturbances within the plasma sheet produce enhanced auroral activity.
- The plasma sheet thus has important implications for high latitude HF communications.

Trapped Charged Particles - History



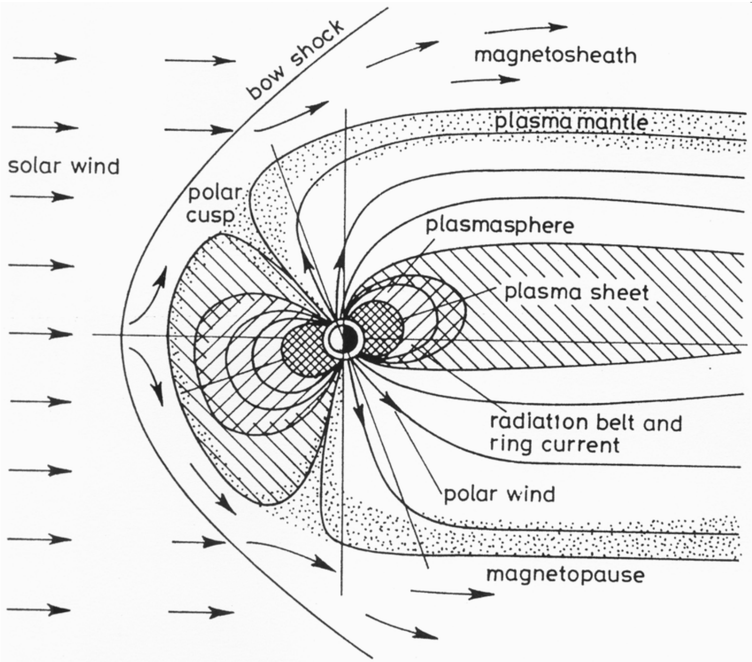
NASA

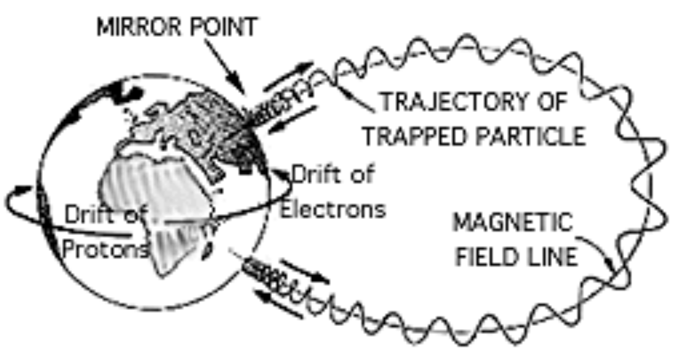


Pwg.gsfc.nasa.gov

- High energy trapped particles in the magnetosphere were not discovered until the beginning of the space age.
- The Explorer 1 satellite launched by the United States on Jan 31, 1958 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 strong radiation from a belt of previously unknown charged particles trapped in Earth's magnetic field.
- The radiation belt was confirmed by another U.S. satellite launched two months later.
- The radiation belt became known as the Van Allen Belts in honor of its discoverer.
- The discovery showed that outer space near the Earth was not empty but contained at least some matter.

Trapped Charged Particles





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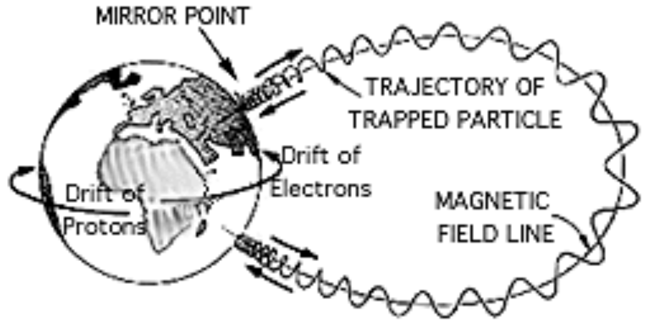
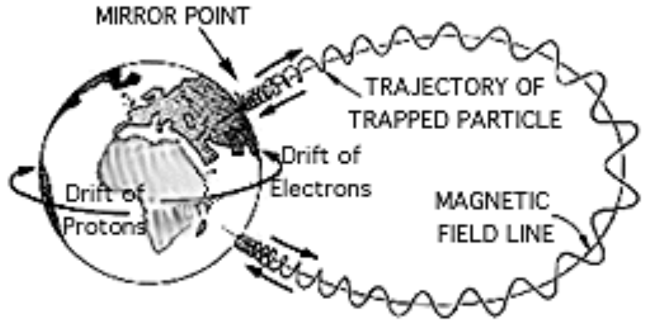
- The charged particles trapped in the Van Allen radiation belt are the most energetic particles in the magnetosphere, with the exception of transient cosmic rays and solar protons.
- The mechanism of their entrapment is interesting.
  - They gyrate around geomagnetic field lines,
  - Bounce back and forth between the north and south hemisphere, and
  - Gradually drift longitudinally around the Earth.
- Gyrating around field lines is the result of electromagnetic dynamics which prevent moving charged particles from crossing magnetic field lines.
- Instead they are forced to spiral around the field lines as they travel toward one magnetic pole or the other.

Trapped Particle Bounce Mechanism



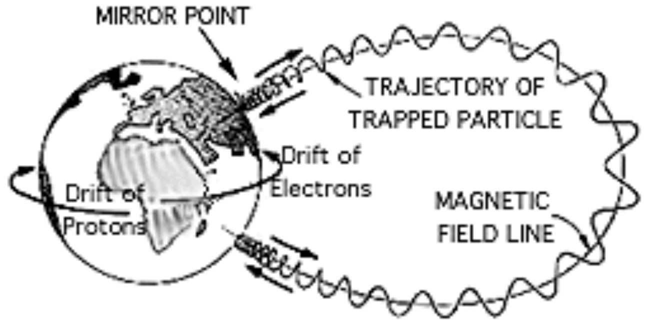
- However magnetic field strength increases as a particle approaches a magnetic pole.
- This directly affects the particle's energy.
- The kinetic energy of a trapped particle consists of two components:
  - A component parallel to the magnetic field line (forward kinetic energy)
  - A component perpendicular to the magnetic field.
- The magnitude of the perpendicular component is proportional to magnetic field strength.
- Field strength increases as the particle moves toward a pole causing its perpendicular component to 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 equator and the opposite magnetic pole.
- The point of reflection is called the mirror point.

Trapped Particle Mirror Point



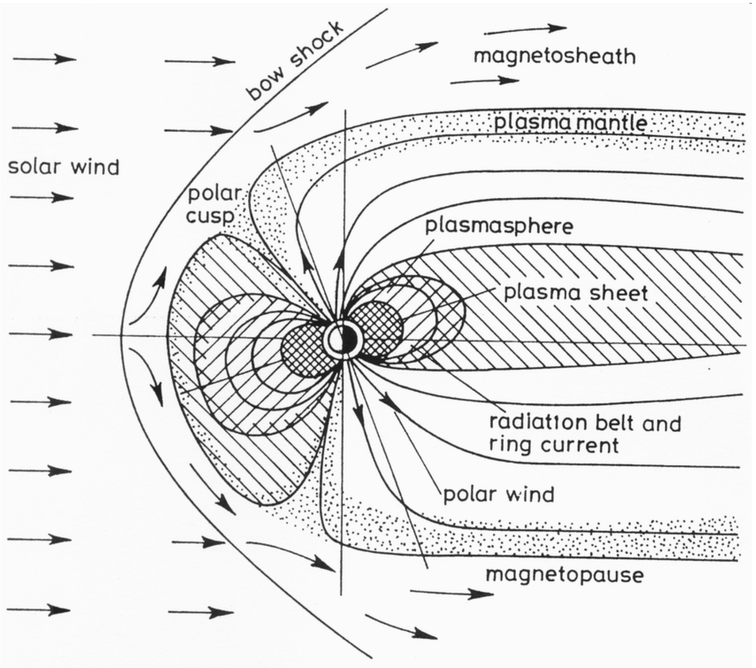
- Since no energy is being lost or gained, the particle can continue to bounce back and forth from one hemisphere to the other as long as nothing happens to the particle.
- One thing that can happen is the particle being absorbed in the ionosphere, through electron – ion recombination, removing it as a trapped particle.
- This can happen if the mirror point is too deep in the atmosphere, below about 100 km.
- The location of the mirror point depends on the particle's direction of travel, called the pitch angle, as it crosses the Earth's equatorial plane.
- Thus the mirror point is unique for each charged particle.
- An event that alters the pitch angle of trapped particles will also change the level of ionospheric ionization as more trapped particles become absorbed in the atmosphere.
- This of course can have a direct affect on HF communications.

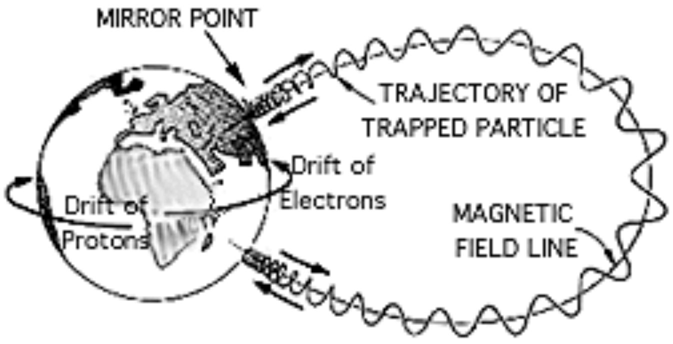
Trapped Particle Longitudinal Motion



- The trapped particles also drift longitudinally as they bounce back and forth from one hemisphere to the other.
- The longitudinal drift is due to radial variations in geomagnetic field strength.
- Electrons drift eastward while protons drift to the west.
- The drift rate is proportional to a particle's energy.

Ring Currents





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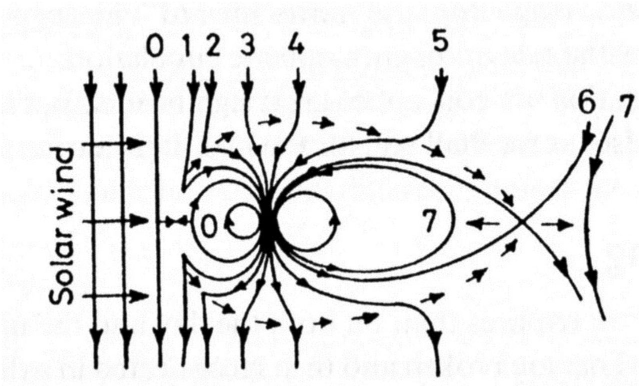
- The longitudinal drift of the charged particles creates a ring current.
- The westward drift of trapped protons and the eastward drift of electrons combine to form a clockwise ring current, as viewed from over the north polar region.
- While the mirror points for the trapped particles is near the Earth, the trajectory of trapped particles extends outward, along the inner edge of the plasma sheet, to a distance of about four to six Earth radii from the Earth.
- The ring current is generally located in this outer region.
- The ring current increase when the geomagnetic field is disturbed.

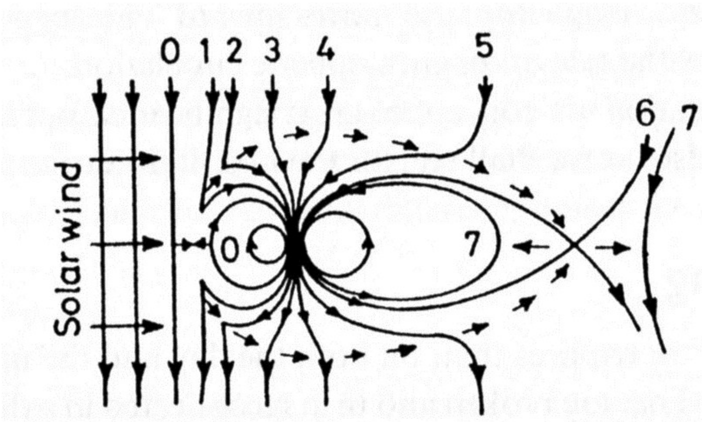
Interconnection Between IMF & Geomagnetic Field



Hunsucker

- When the IMF is pointed southward, with respect to the ecliptic plane, its magnetic field connects to Earth's magnetic field lines which are directed northward.
- A problem arises with this connection.
- 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 opens the geomagnetic field lines preventing them from returning to Earth.
- As they are dragged further, they eventually break away from the IMF and loop back to Earth far out in the magnetosphere tail.

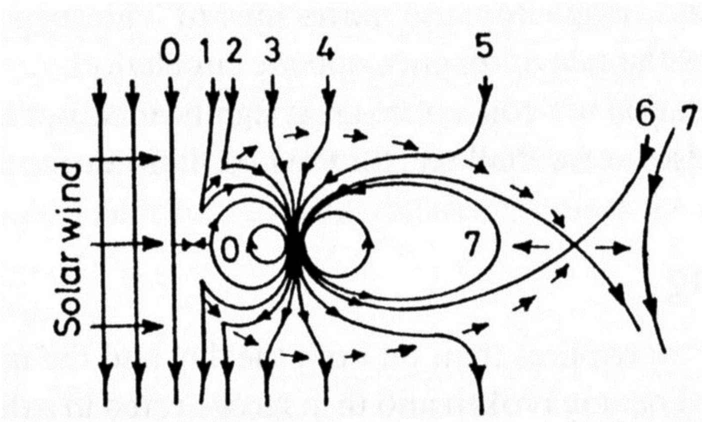
South Directed IMF & Geomagnetic Field



Hunsucker

- 0 through 7 in the figure shows successive position of an IMF field line as it connects with a geomagnetic field line and moves past Earth from the day to night region of the magnetosphere.
- At point 0 the IMF has not yet encountered the geomagnetic field which is closed at point 0 near the Earth.
- The IMF field line connects to a geomagnetic line at position 1. Notice that the geomagnetic field line opens as soon as it connects to the IMF field.
- At points 2 & 3 the geomagnetic/IMF field line becomes progressively straighter as the IMF, embedded in the solar wind, drags the geomagnetic field over the polar cap.
- At points 4 through 6 the geomagnetic/IMF field line becomes more distorted as it is dragged out into the magnetosphere tail.
- At points 7, the geomagnetic field breaks away from the IMF and loops back to Earth while the IMF is carried away from Earth by the solar wind.

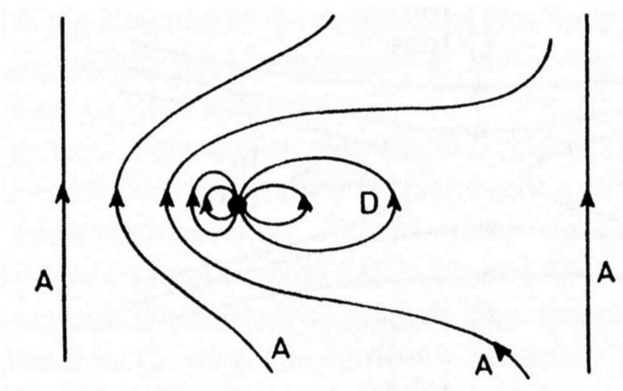
Connected IMF & Geomagnetic Field Disturbances



Hunsucker

- Geophysical activity increases when a south directed IMF connects to Earth's geomagnetic field.
- Magnetic substorms occur more frequently.
- Auroral zones drifts toward the equator.
- Dayside cusps are also displaced equatorward.
- Dayside magnetopause moves inward toward the Earth.
- Magnetic flux in the magnetosphere tail increases.

North Directed IMF & Geomagnetic Field



Hunsucker

- A north directed IMF (A in the figure) does not connect to Earth's geomagnetic field, which is also directed north.
- Since the two fields do not interact, Earth's magnetic field (D in figure) remains primarily a closed field.

The Quiet Geomagnetic Field

- Earth's magnetic field is not constant. Instead its amplitude and phase vary slightly throughout the day, seasonally, and with solar activity.
- The source of Earth's steady state magnetic field are convections currents deep within the Earth.
- Electrical currents flowing primary in the E region of the ionosphere (the equatorial and polar electrojets) cause small diurnal, seasonal, and solar cycle variations in the magnetic field.
- These electrical currents are generally stronger during the day than at night, greater in the summer compared to winter, and about 50% stronger during solar maximum, resulting in corresponding but small changes in Earth's total magnetic field.
- Earth's magnetic field is considered quiet when its amplitude and phase vary smoothly with time in an expected way.
- Under quiet conditions, the solar wind blows calmly along the magnetosheath, the IMF has little or no southward component, the plasma sheet is calm, and the magnetosphere as a whole is undisturbed.

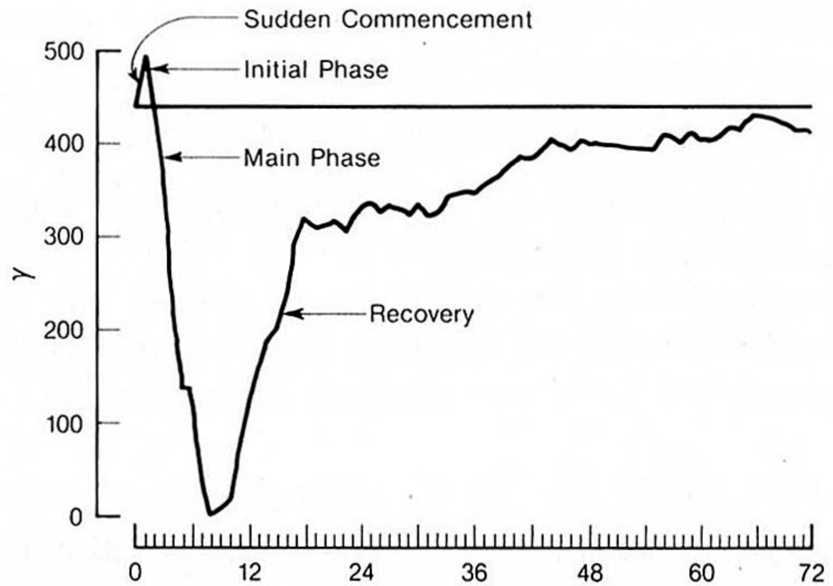
Geomagnetic Storms History

- A geomagnetic storm occurs when changes in field amplitude and phase become erratic.
- Magnetic storms have been known since the eighteenth century, but not by the current name.
- They were first noticed as unexplained fluctuations in compass needles.
- Our current understanding of magnetic storms has come from continuous monitoring of the magnetic field using magnetometers.
- Extensive magnetometer records over the past century clearly shows the sporadic occurrence and intensity of magnetic storms.

Magnetic Storms

- Magnetic storms are caused by fluctuations in the solar wind and in the Interplanetary Magnetic Field (IMF) carried along by the wind.
- The fluctuations are generally the result of high-speed wind streams from solar flares, Coronal Mass Ejections, Coronal Holes, and other solar activity mixing with the ambient solar wind. The mixing significantly increases wind speed and density. These events occur most frequently during solar maximum, but can also occur at other times as well.
- The degree of magnetosphere disruption depends almost entirely on the direction of the Interplanetary Magnetic Field relative to Earth's magnetic field.
- Disruption is greatest when the IMF is directed southward, relative to the ecliptic plane, connecting inside the bow shock with the geomagnetic field which is always in a northward direction.
- A significant south directed IMF is thus required to produce an intense geomagnetic storm.
- In contrast, a northward IMF rarely produces any geomagnetic storms.
- Short duration disturbances also occur in the magnetic field. These are called substorms. They are particularly prominent near the auroral zones. A single isolated substorm last about an hour.

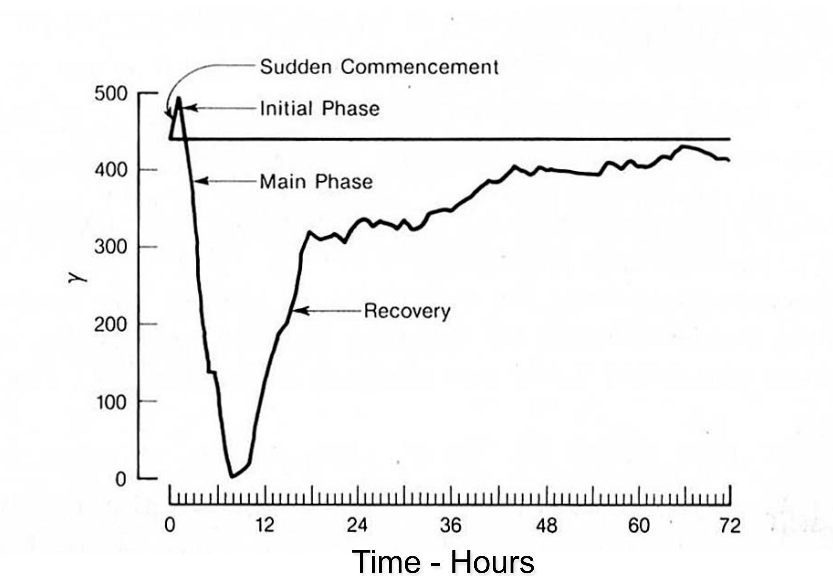
Phases of a Magnetic Storm

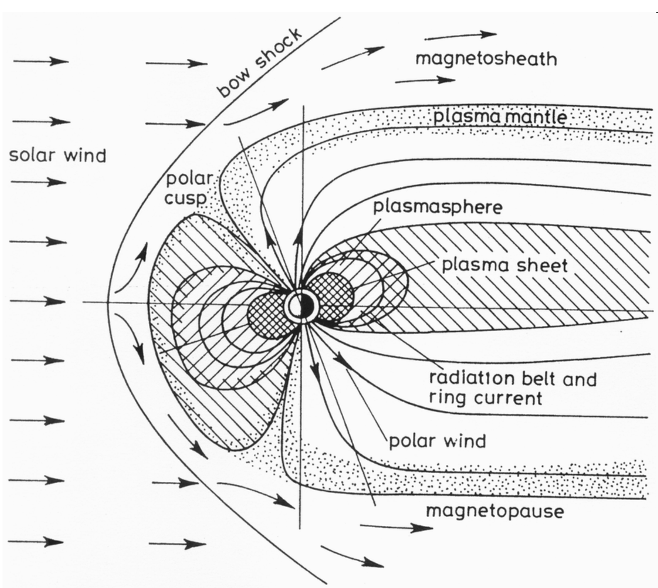


Time - Hours
(source: Davies)

- A typical magnetic storm consists of three phases.
- Initial phase: an increase in the intensity of the magnetic field lasting only a few hours.
- Main phase: a large decrease in magnetic field intensity dropping to its lowest level in several hours to a day.
- Recovery phase: a slow recovery to pre-storm conditions over a period of several days.

Phases of a Magnetic Storm - continued



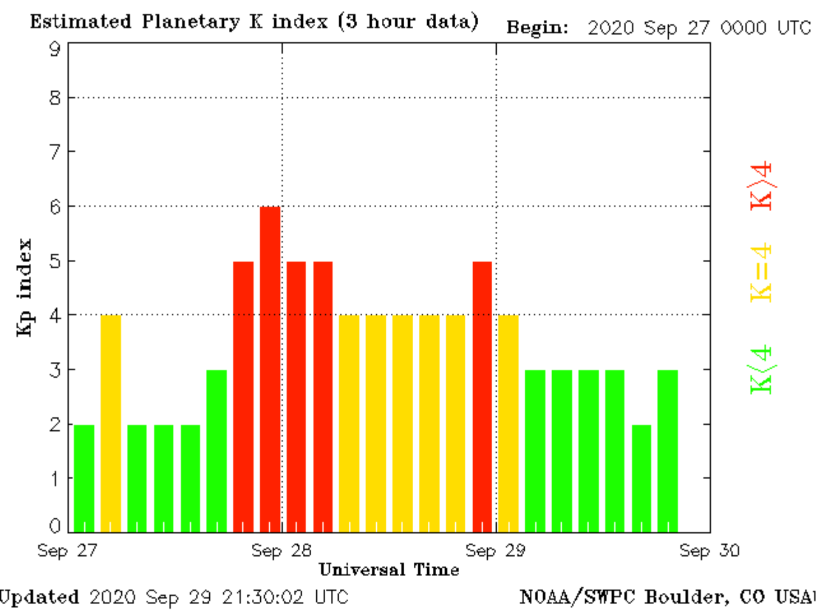


- The initial phase is caused by increased solar wind speed and density compressing the bow shock and the magnetosheath behind it.
- The main phase is due to increased strength of the ring currents.
- An intense southward directed IMF drives plasma sheet ionization from the magnetic tail into the radiation belt.
- The arriving energetic protons and electrons mix with protons and electrons already in the region, greatly increasing the strength of the ring current and its associated magnetic field.
- The enhanced ring current magnetic field partially cancels the geomagnetic field causing a significantly decreases in geomagnetic field strength.
- The recovery phase is simply recovery of the magnetic field to pre-existing conditions as the ring currents decay.

Magnetic Indices

Kp	Ap
0	0
1	3
2	7
3	15
4	27
5	48
6	80
7	140
8	240
9	400

Ap	Geomagnetic Activity
0 - 7	Quiet
8 - 15	Unsettled
16 - 29	Active
30 - 49	Minor Storm
50 - 99	Major Storm
> 100	Severe Storm



- A number of magnetic indices are used to quantify the condition of the geomagnetic field and intensity of magnetic storms.
- Two commonly used indices are K_p and A_p .
- K_p is obtained by measuring and averaging together variations in the magnetic field over a 3 hour period.
- The measurements are performed at about a dozen magnetic observatories around the world.
- The observations from the various observatories are combined together to provide the planetary K_p value.
- The value of K_p for each 3 hour period ranges from 0 (very quiet) to 9 (very disturbed) on a quasi-logarithmic scale.
- A_p is a daily index obtained from the same basic data which is converted to a linear scale and averaged over a full day in Universal Time.

Magnetic Indices – continued

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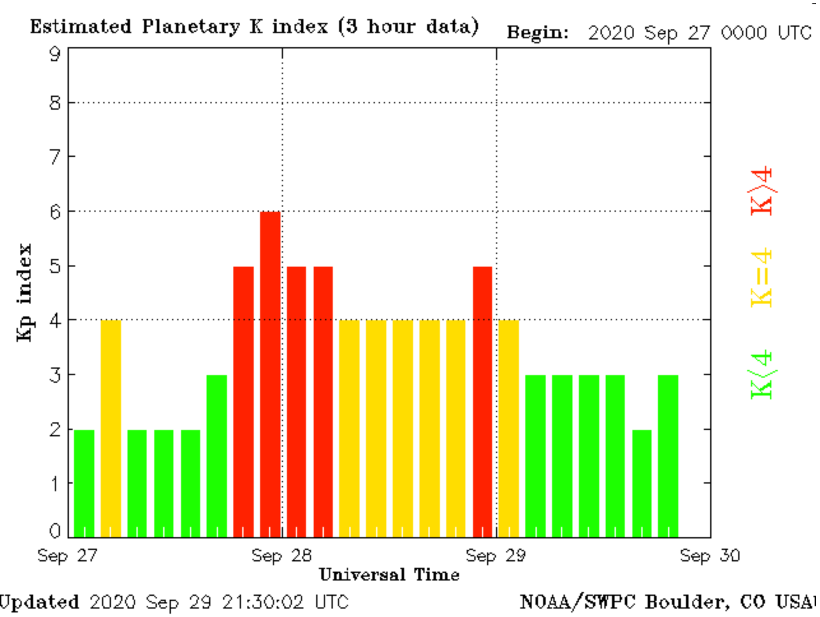
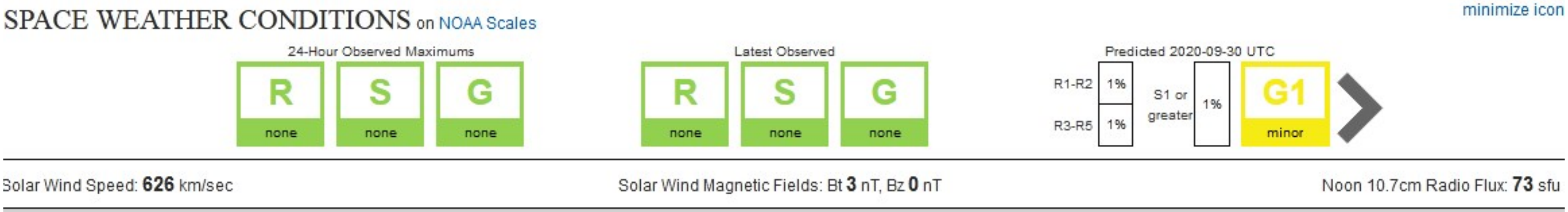
50 - 99	Major Storm
> 100	Severe Storm



- The Sun's rotational period sometimes cause K_p values to recur 27 day later.
- This happens most frequently during the declining phase of a solar cycle.
- The current K_p index value is available under the Current Conditions > K_p Index tab on the website

  www.skywave-radio.org



- NOAA uses three classifications to summarize current Space Weather Conditions.
  - G: Geomagnetic Storms (see next slide for G scale description)
  - S: Solar Radiation
  - R: Radio Blackouts
- These classifications are defined under the Short Articles > NOAA Scales tab of the www.skywave-radio.org website.
- The current space weather conditions are found under the Current Conditions > Space Weather Conditions tab of the same website. The Banner for that tab is shown above.
- On Sept 30, 2020 there was no G, S, or R activity during the previous 24 hours or currently (when the report was issued). However a G1 minor storm was predicted.
- On that date and time:
  - Solar Wind Speed was 626 km/sec
  - Solar Wind Magnetic Field was neither north (positive) or south (negative) since B_z = 0 nT
  - The 10.7 cm Radio Flux was 73

NOAA Classification of Geomagnetic Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

Effect of Magnetic Storms

- So what is the effect of a magnetic storm?
- Large magnetic storms cause auroras to be visible at lower latitudes which is fun.
- During a large storm auroras may be visible in New England, Michigan, and other northern states in the U.S. as well as in central Europe.
- However, more importantly very large magnetic storms can:
  - Seriously disrupt the ionosphere and radio communications,
  - Increase satellite drag, and
  - Seriously disrupt electric power distribution.
- Most of the large magnetic storms occur following solar maximum instead of during or leading up to solar maximum as one might be expected.
- Interestingly, over half of large storms occur around the equinoxes, that is in March through April and September through October.
- The second largest magnetic storm on record occurred on March 13, 1989. This storm was extensively studied by J. A. Joslyn, R. D. Hunsucker, and others.
- The A_p index for the storm was 246, the second largest A_p value in the 57 years since the index began in 1932.
- The storm continued for about two days.
- Toward the end of the storm, the auroral electrojet was flowing south of Fredericksburg, Virginia at a latitude of 49^o N instead of in the auroral zone where it is normally found.

Effects of March 13, 1989 Magnetic Storms

- The aurora produced by the storm was visible as far south as Florida, Mexico, and Grand Cayman Island.
- The intense solar wind, ~30 times greater than normal, compressed the magnetopause from 10 R_e (Earth radii) to 4.7 R_e.
- For a period of time the GOES -6 and GOES-7 satellites in geosynchronous orbits 6.6 R_e from Earth were outside the magnetosphere in the full fury of the solar wind.
- The GOES satellites continuously monitor Earth's magnetic field, solar X-ray and EUV radiation, and a variety of other geophysical parameters.
- In addition to compressing the magnetosphere, the storm also heated Earth's upper atmosphere, increasing air density and in turn the drag on satellites orbiting the Earth
- In general, the increased drag resulting from magnetic storms accelerates the rate of satellite orbital decay causing them to re-enter the atmosphere sooner than expected.
- The storm also seriously disrupted the ionosphere.
- During the day of March 13 mid-latitude electron densities and critical frequencies remained at night time levels.
- The equatorial ionosphere essentially disappeared while the polar ionosphere was considerably disrupted making HF radio communications impossible on many circuits.

Electric Power Disruption

- The most serious impact of the storm, however, was its disruption of electric power distribution in Canada.
- Fluctuations in the geomagnetic field can induce currents in long distance power lines and oil pipelines.
- These fluctuations can cause voltage surges in electrical power distributions systems which saturate power transforms and trip protective relays.
- This occurred on March 13 in the Quebec electric power system which lost power for 9 hour. Users in north-eastern United States were also affected.

Ionization by Energetic Particles

- At mid-latitudes the main source of ionization in the upper atmosphere is X-ray and EUV (Extreme Ultra Violate) radiation from the Sun.
- X-ray and EUV radiation is responsible for ionization at high latitudes as well.
- However, at high latitudes the upper atmosphere is also ionized by high energy particles spirally around magnetic field lines downward deep into the polar region atmosphere.
- At times high energy particles are the primary form of high latitude ionization.
- The high energy particles consists of:
  - High energy electrons, and
  - High energy protons and a – particles (helium nuclei).

Ionization by Energetic Electrons

- In addition to X-ray and EUV radiation, neutral gas particles in the polar region upper atmosphere are also ionized by collisions with energetic electrons.
- Most of the kinetic energy of a fast moving electron is lost when it collides with a neutral gas particle, the energy being absorbed by the particle which is typically 20,000 times more massive than the electron.
- However, a small amount of the energy involved in the collision is converted to X-rays.
- The X-rays penetrate deeper into the atmosphere than do the energetic electrons.
- In the process, the X-rays ionization additional gas particles further down in the atmosphere typically at an altitude of 50 km or less.
- The ionization rate due to the 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.

Ionization by Energetic Protons

- Upon arrival at Earth, high energy protons and a – particles from the Sun spiral downward along magnetic field lines deep into the polar region upper atmosphere.
- As they do so they create high levels of polar region ionization.
- The particles are typically ejected from the Sun by solar flares, Coronal Mass Ejections, and Coronal Holes.
- These particles have significantly more energy than energetic electrons and consequently produce much higher levels of ionization.
- Energetic protons, primarily from flares, are responsible for Polar Cap Absorption events (PCAs).
- During a PCA HF radio signals are absorbed throughout the polar region severely disrupting radio communications for several days.