CHAPTER ONE

REEVIEW OF SPACE PLASMA

(1-1) Definition of a Plasma

A plasma is a gas of charged particles, which consists of equal numbers of free positive and negative charge carriers. Having roughly the same number of charges with different signs in the same volume element guarantees that the plasma behaves quasineutral in the stationary state. On average a plasma looks electrically neutral to the outside, since the randomly distributed particle electric charge fields mutually cancel.

For a particle to be considered a free particle, its typical potential energy due to its nearest neighbor must be much smaller than its random kinetic (thermal) energy. Only then the particle's motion is practically free from the influence by other charged particles in its neighborhood as long as no direct collisions take place.

Since the particles in a plasma have to overcome the coupling with their neighbors, they must have thermal energies above some electron volts. Thus a typical plasma is a hot and highly ionized gas. While only a few natural plasmas, such as flames or lightning strokes, can be found near the Earth's surface, plasmas are abundant in the universe.

More than 99% of all known matter is in the plasma state. (Wolfgang Baumjohann, 1996)

(1-1-1) Debye Shielding

For the plasma to behave quasineutral in the stationary state, it is necessary to have about equal numbers of positive and negative charges per volume element. Such a volume element must be large enough to contain a sufficient number of particles, yet small enough compared with the *characteristic lengths for variations of macroscopic parameters such as density and temperature. In each volume element the microscopic space charge fields of the individual charge carriers must cancel each other to provide macroscopic charge neutrality.*

To let the plasma appear electrically neutral, the electric Coulomb potential field of every charge, q

$$\theta_c = \frac{q}{4\pi\epsilon_o r} \qquad (1.1)$$

With ϵ_0 *being the free space permittivity, is shielded by other charges in the plasma and assumes the Debye potential form*

$$\theta_D = \frac{q}{4\pi\epsilon_o r}\ e^{-\frac{r}{\lambda_D}} \qquad (1.2)$$

In which the exponential function cuts off the potential at distances r > AD. The characteristic length scale, AD, is called Debye length and is the distance, over which a balance is obtained between the thermal particle energy, which tends to perturb the electrical neutrality, and the electrostatic potential energy resulting from any charge separation, which tends to restore charge neutrality. Figure 1.1 shows the shielding effect.

In Sec. 9.1 we will show that the Debye length is a function of the electron and ion temperatures, T_i *and* T_e*, and the plasma density,* $n_i \approx n_e$ *(assuming singly charged ions)*

$$\lambda_D = \left(\frac{\epsilon_o k_B T_e}{n_e e^2}\right) \qquad (1.3)$$

Where we have assumed $T_i \approx T_e$*and where ks the Boltzmann constant and e the electron charge. We will give the exact definition for the temperature in Sec. 6.5. Until then we will use the terms temperature and average energy, (W) =* k_B *T, as synonyms. In order for a plasma to be quasineutral, the physical dimension of the system, L, must be large compared to AD*

$$AD << L \qquad (1.4)$$

Otherwise there is not enough space for the collective shielding effect to occur, and we have a simple ionized gas. This requirement is often called the first plasma criterion. (Wolfgang Baumjohann, 1996)

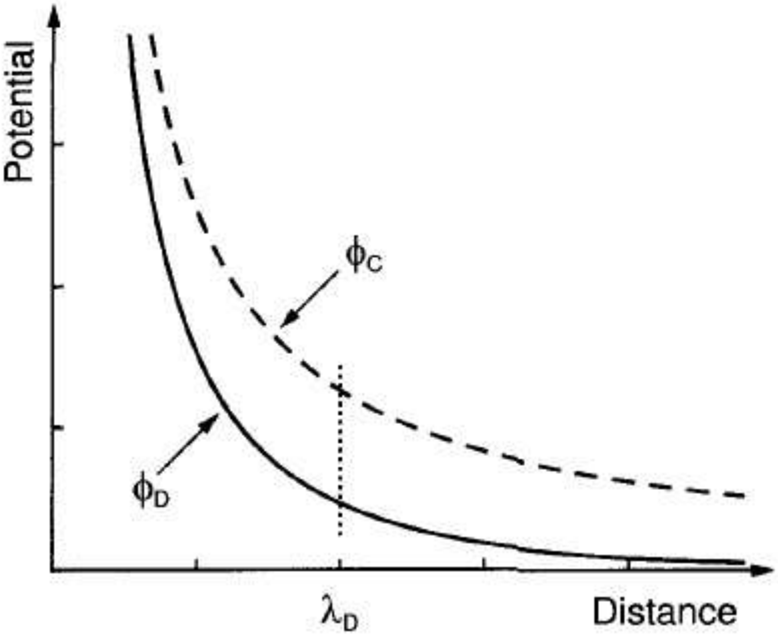


Fig. ***1.1.*** *Comparison of Debye and Coulomb potential; All Figure from (1.1) – (1.5) after (Wolfgang Baumjohann, 1996)*

(1-1-2) Plasma Parameter

Since the shielding effect is the result of the collective behavior inside a Debye sphere of radiusλ_D , it is necessary that this sphere contains enough particles. The number of particles inside a Debye sphere is $\frac{4\pi}{3} n_e \lambda_D^3$.The term $n_e \lambda_D^3$ is often called the plasma parameter,Λ and the second criterion for a plasma reads

$$\Lambda = n_e \lambda_D^3 \gg 1 \qquad (1.5)$$

By substituting AD by the expression given in Eq. (1.3) and raising each side of Eq. (1.5) to the 213 power, it becomes apparent that the second criterion quantifies what is meant by free *particles. The mean potential energy of a particle due to its nearest neighbor, which is inversely proportional to the mean interparticle distance and thus proportional to* $n_e^{1/3}$ *must be much smaller than its mean energy, ke Te.* (Wolfgang Baumjohann, 1996)

(1-1-3) Plasma Frequency

The typical oscillation frequency in a fully ionized plasma is the electron plasma frequency, $w_{pe.}$ *If the quasineutrality of the plasma is disturbed by some external force, the electrons, being more mobile than the much heavier ions, are accelerated in an attempt to restore the charge neutrality. Due to their inertia they will move back and forth around the equilibrium position, resulting in fast collective oscillations around the more massive ions. The plasma frequency depends on the square root of the plasma density. With me as electron mass, wpe can be written as*

$$\omega_{pe} = \left(\frac{n_e e^2}{m_e \epsilon_o}\right)^{\frac{1}{2}} \qquad (1.6)$$

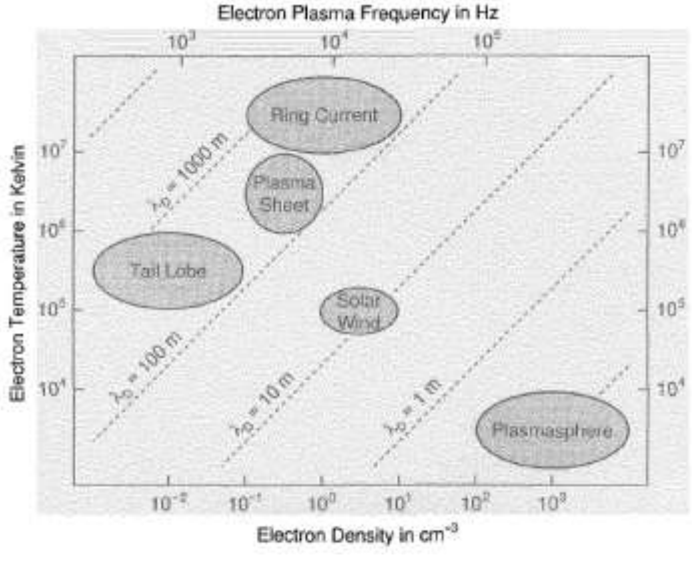


Fig. 1.2. Ranges of typical parameters for several geophysical plasmas.

Some plasmas, like the Earth's ionosphere, are not fully ionized. Here we have a substantial number of neutral particles and if the charged particles collide too often with neutrals, the electrons will be forced into equilibrium with the neutrals, and the medium does not behave as a plasma anymore, but simply like a neutral gas. For the electrons to remain unaffected by collisions with neutrals, the average time between two electron-neutral collisions, τ_n *must be larger than the reciprocal of the plasma frequency*

$$\omega_{pe}\tau_n \gg 1 \qquad (1.7)$$

This is the third criterion for an ionized medium to behave as a plasma. (Wolfgang Baumjohann, 1996)

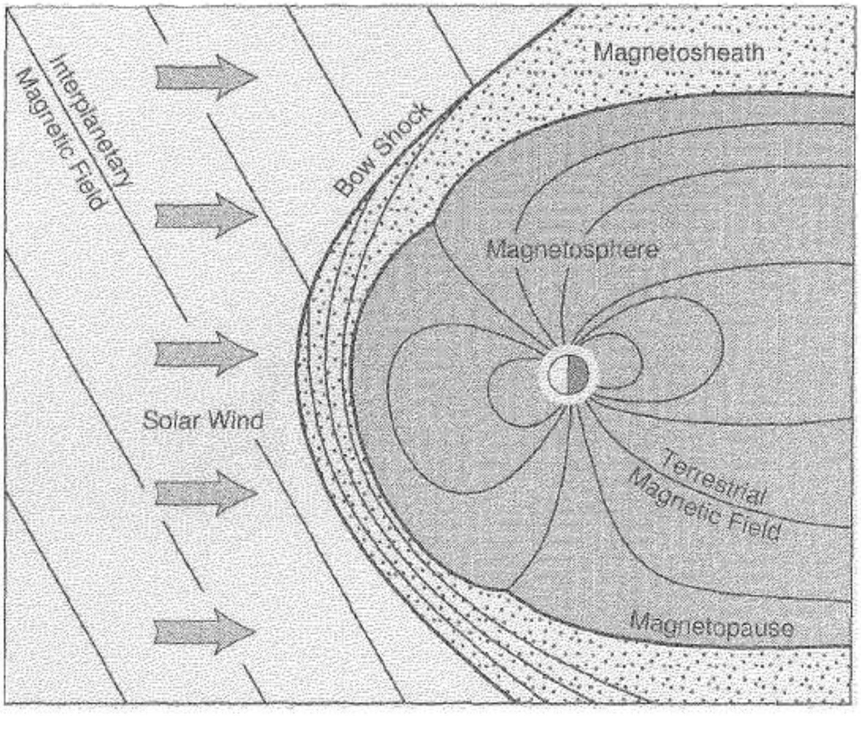


Fig. 1.3. Topography of the solar-terrestrial environment.

(1-2) Geophysical Plasmas

Plasmas are not only abundant in the universe, but also in our solar system. Even in the immediate neighborhood of the Earth, all matter above about 100 km altitude, within and above *the ionosphere, has to be treated using plasma physical methods. There are quite a number of different geophysical plasmas, with a wide spread in their characteristic parameters like density and temperature (see Fig. 1.2).* (Wolfgang Baumjohann, 1996)

(1-2-1) Solar Wind

The sun emits a highly conducting plasma at supersonic speeds of about 500 km/s into the interplanetary space as a result of the supersonic expansion of the solar corona. This plasma is called the solar wind and consists mainly of electrons and protons, with an admixture of 5% Helium ions. Because of the high conductivity, the solar magnetic field is frozen in the plasma (like in a superconductor) and drawn outward by the expanding solar wind. Typical values for the electron density and temperature in the solar wind near the Earth are $n_e = 5cm^{-3}$ *and* $T_e = 10^5$ *K (1 eV = 11,600 K). The interplanetary magnetic field is of the order of 5 nT.*

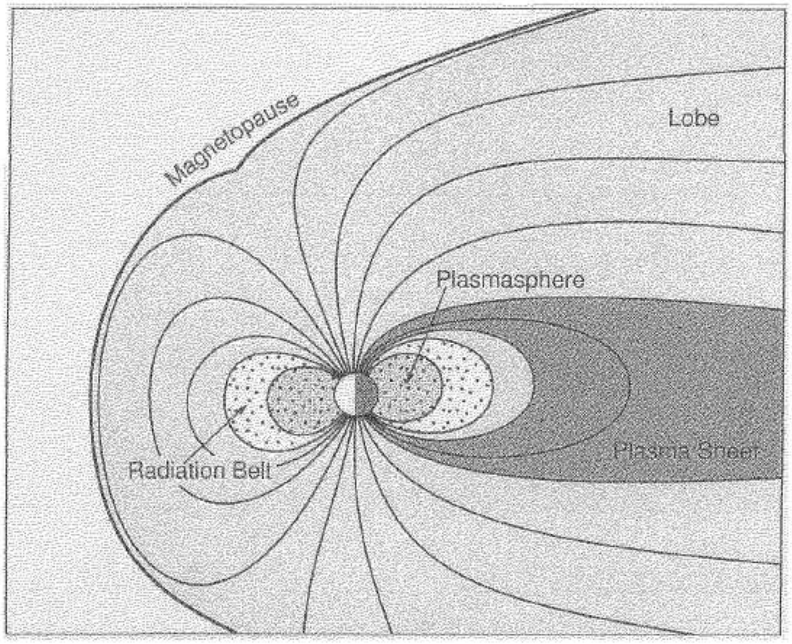


Fig. 1.4. Plasma structure of the Earth's magnetosphere.

When the solar wind hits on the Earth's dipolar magnetic field, it cannot simply penetrate it but rather is slowed down and, to a large extent, deflected around it. Since the solar wind hits the obstacle with supersonic speed, a bow shock wave is generated (see Fig. 1.3), where the plasma is slowed down and a substantial fraction of the particles' kinetic energy is converted into thermal energy. The region of thermalized subsonic plasma behind the bow shock is called the magnetosheath (see Fig. 1.3). Its plasma is denser and hotter than the solar wind plasma and the magnetic field strength has higher values in this region. (Wolfgang Baumjohann, 1996)

(1-2-2) Magnetosphere

The shocked solar wind plasma in the magnetosheath cannot easily penetrate the terrestrial magnetic field but is mostly deflected around it. This is a consequence of the fact that the interplanetary magnetic field lines cannot penetrate the terrestrial field lines and that the solar wind particles cannot leave the interplanetary field lines due to the aforementioned frozen-in characteristic of a highly conducting plasma. The boundary separating the two different regions is called magnetopause and the cavity generated by the terrestrial field has been named magnetosphere (see Figs. 1.3 and 1.4). The kinetic pressure of the solar wind plasma distorts the outer part of the terrestrial dipolar field. At the frontside it compresses the field, while the nightside magnetic field is stretched out into a long magnetotail which reaches far beyond lunar orbit. The plasma in the magnetosphere consists mainly of electrons and protons. The sources of these particles are the solar wind and the terrestrial ionosphere. In addition there are small fractions of He^+ *and* O^+ *ions of ionospheric origin and some* He^{++} *ions originating from the solar wind. However, the plasma inside the magnetosphere is not evenly distributed, but is grouped into different regions with quite different densities and temperatures. Figure 1.4 depicts the topography of some of these regions.*

*The radiation belt lies on dipolar field lines between about 2 and 6*R_E *(1 Earth radius = 6371 km). It consists of energetic electrons and ions which move along the field lines and oscillate back and forth between the two hemispheres .Typical electron densities and temperatures in the radiation belt are* $n_e \approx 1cm^{-3}$*and* $T_e \approx 5.10^7K$. *The magnetic field strength ranges between about 100 and 1000 nT.*

Most of the magnetotail plasma is concentrated around the tail midplane in an about 10 R_E *thick plasma sheet. Near the Earth, it reaches down to the high-latitude auroral ionosphere along the field lines. Average electron densities and temperatures in the plasma sheet are* $n_e = .5cm^{-3}$ $, T_e \approx 5 . 10^6K, with\ B \approx 10\ nT.$

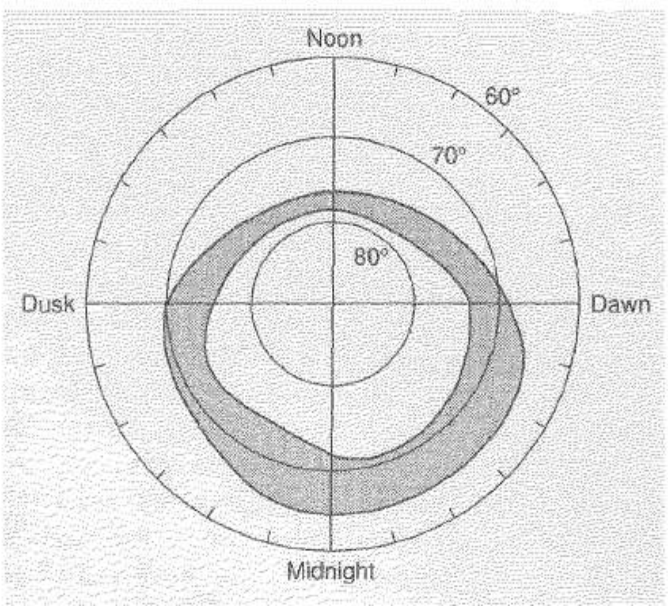
The outer part of the magnetotail is called the magnetotail lobe. It contains a highly rarified plasma with typical values for the electron density and temperature and the magnetic field strength of $n_e = 10^{-2}cm^{-3}$ $, T_e \approx 5 . 10^5K, and\ B \approx 30\ nT,$ *respectively.* (Wolfgang Baumjohann, 1996)

(1-2-3) Ionosphere

The solar ultraviolet light impinging on the Earth's atmosphere ionizes a fraction of the neutral atmosphere. At altitudes above 8Okm collisions are too infrequent to result in rapid recombination and a permanent ionized population called the ionosphere is formed. Typical electron densities and temperatures in the mid-latitude ionosphere are $n_e = 10^5cm^{-3}$ $, T_e \approx 10^3K$ *the magnetic field strength is of the order of* 10^4 *nT.*

The ionosphere extends to rather high altitudes and, at low- and mid-latitudes, gradually merges into the plasmasphere. As depicted in Fig. 1.4, the plasmasphere is a torus shaped volume inside the radiation belt. It contains a cool but dense plasma of ionospheric origin ($n_e = 5. 10^2cm^{-3}$ $, T_e \approx 5 . 10^3K$*), which corotates with the Earth. In the equatorial plane, the* *plasmasphere extends out to about 4 R_E, where the density drops down sharply to about 1cm^{-3}. This boundary is called the plasmapause.*

At high latitudes plasma sheet electrons can precipitate along magnetic field lines down to ionospheric altitudes, where they collide with and ionize neutral atmosphere particles. As a by-product, photons emitted by this process create the polar light, the aurora. These auroras are typically observed inside the auroral oval (see Fig. 1.5), which contains the footprints of those field lines which thread the plasma sheet. Inside of the auroral oval lies the polar cap, which is threaded by field lines connected to the tail lobe. (Wolfgang Baumjohann, 1996)



Figure, 1.5. Average auroral oval and polar cap.

CHAPTER TWO

NEAR EARTH PLASMA CONFIGURATION

(2-1) Earth's Magnetosphere:

A magnetosphere is the region surrounding a planet where the planet's magnetic field dominates. Because the ions in the solar plasma are charged, they interact with these magnetic fields, and solar wind particles are swept around planetary magnetospheres. Life on Earth has developed under the protection of this magnetosphere.

The shape of the Earth's magnetosphere is the direct result of being blasted by solar wind. Solar wind compresses its sunward side to a distance of only 6 to 10 times the radius of the Earth. A supersonic shock wave is created sunward of Earth somewhat like a sonic boom. This shock wave is called the bow shock. Most of the solar wind particles are heated and slowed at the bow shock and detour around the Earth. Solar wind drags out the night-side magnetosphere to possibly 1000 times Earth's radius; its exact length is not known. This extension of the magnetosphere is known as the magnetotail. Many other planets in our solar system have magnetospheres of similar, solar wind-influenced shapes. (Dr Eric R. Christian, 2012,)

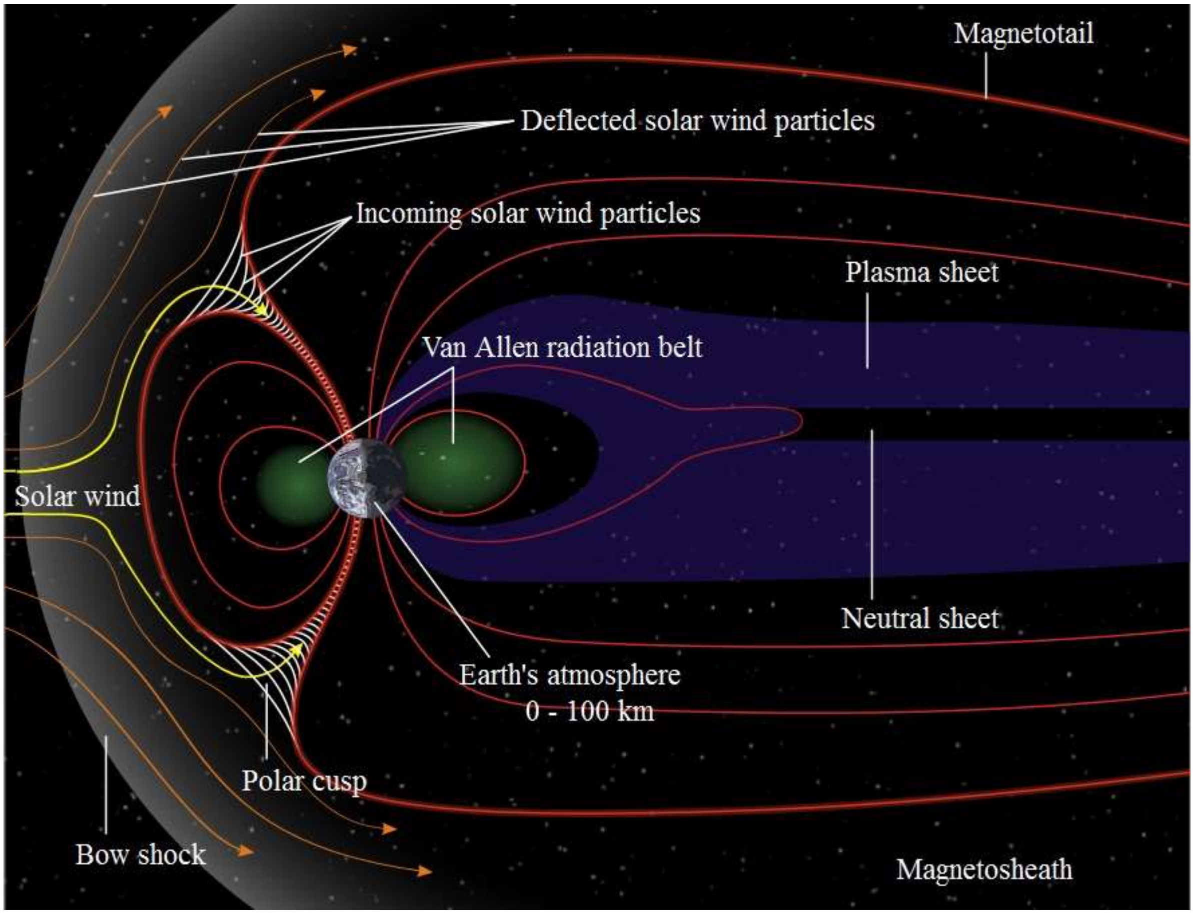


Figure (2.1): Show Earth’s Magnetosphere Structure; *after:* (Aaron, 2008)

(2-1-1) Bow Shock:

When the supersonic flow of the solar wind first encounters the earth’s magnetic field it creates a shock wave. This interaction compresses the magnetosphere on the dayside and shapes it into an elongated teardrop on the nightside. The ultimate consequences of this interaction are far-reaching disturbances in our atmosphere, such as magnetic substorms that interfere with power transmission and communications and produce the spectacle of the polar auroras. The wave is called the bow shock, in analogy to the bow wave of a boat, and is a jump in plasma density, temperature, and magnetic field associated with the transition from supersonic to subsonic flow.

So turbulent is the shock that we have been unable to model the highly nonlinear processes that determine its structure. But progress has been made in modeling the foreshock region (upstream of the bow shock) where energetic protons reflected from the shock back toward the sun may help to heat, decelerate, and deflect the solar wind. Earth's bow shock is about 17 kilometers (11 mi) thick and located about 90,000 kilometers (56,000 mi) from the planet. (Stand & Formisanoceds, 1975)

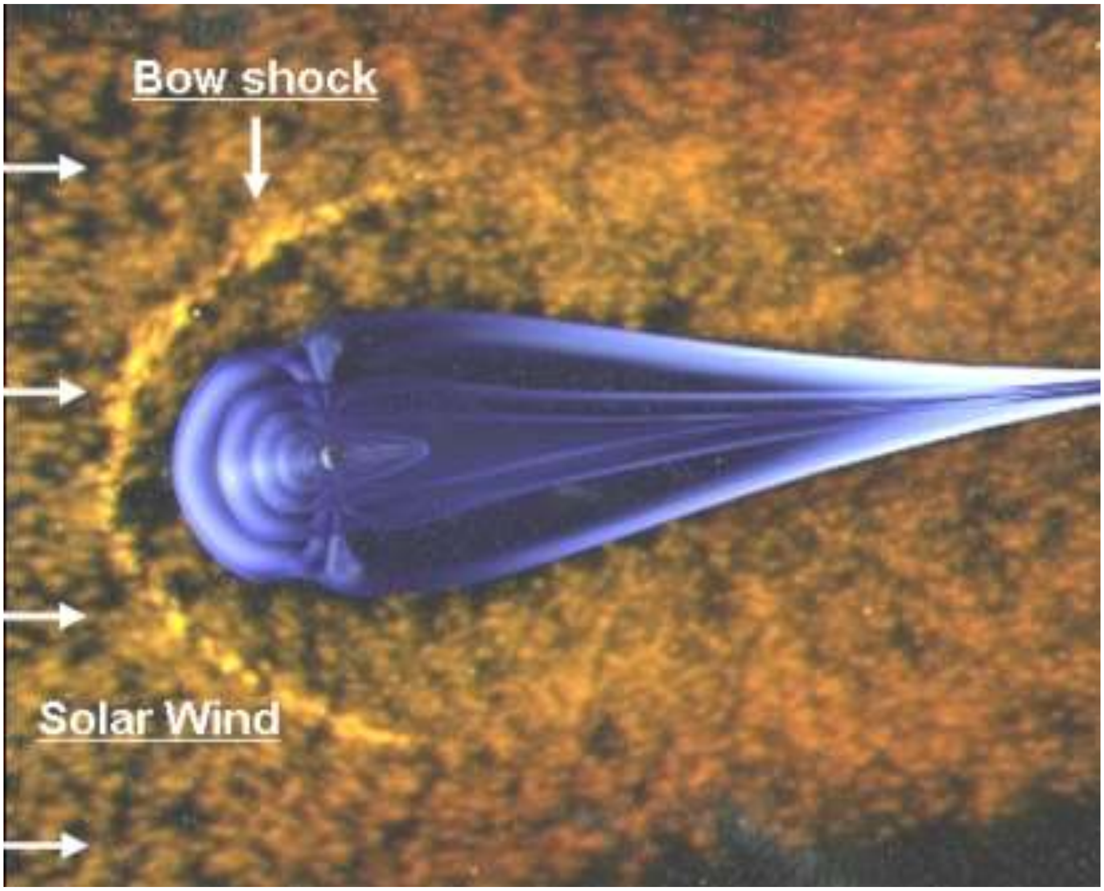


Figure (2.2) Earth's Bow Shock; After: (Noordwijk, 2009)

(2-1-2) Magnetosheath:

The magnetosheath is the region of space between the magnetopause and the bow shock of a planet's magnetosphere. The regularly organized magnetic field generated by the planet becomes weak and irregular in the Magnetosheath due to interaction with the incoming solar wind, and is *incapable of fully deflecting the highly charged particles. The density of the particles in this region is considerably lower than what is found beyond the bow shock, but greater than within the magnetopause, and can be considered a transitory state. Scientific research into the exact nature of the magnetosheath has been limited due to a longstanding misconception that it was a simple byproduct of the bow shock/magnetopause interaction and had no inherently important properties of its own. Recent studies indicate, however, that the magnetosheath is a dynamic region of turbulent plasma flow that may play an important role in the structure of the bow shock and the magnetopause, and may help to dictate the flow of energetic particles across those boundaries. The Earth's magnetosheath typically occupies the region of space approximately 10 Earth radii on the upwind (Sun-facing) side of the earth, extending significantly farther out on the downwind side due to the pressure of the solar wind. The exact location and width of the magnetosheath does depend on variables such as solar activity.* (Cairns, 1999)

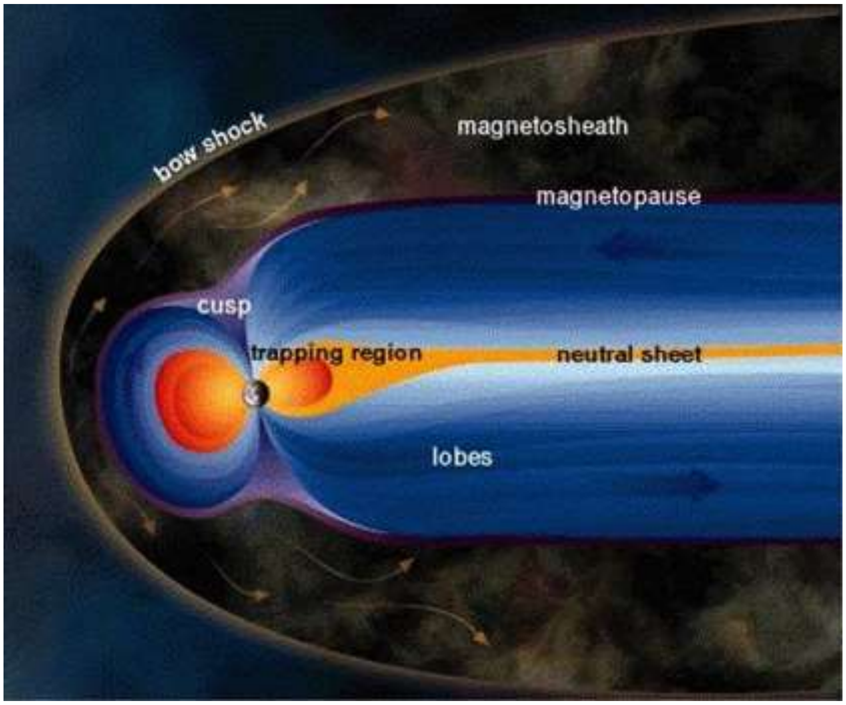


Figure (2.3) Magnetosheath of earth; after: (MICHEL, 2010)

(2-1-3) Magnetopause:

The magnetopause is the abrupt boundary between a magnetosphere and the surrounding plasma. For planetary science, the magnetopause is the boundary between the planet's magnetic field and the solar wind. The location of the magnetopause is determined by the balance between the pressure of the dynamic planetary magnetic field and the dynamic pressure of the solar wind. As the solar wind pressure increases and decreases, the magnetopause moves inward and outward in response. Waves (ripples and flapping motion) along the magnetopause move in the direction of the solar wind flow in response to small scale variations in the solar wind pressure and to Kelvin-Helmholtz instability. The magnetic boundary between the Earth's field and the solar wind, named the magnetopause, has a bullet-shaped front, gradually changing into a cylinder. Its cross-section is approximately circular. Distances in the magnetosphere are often measured in Earth radii (RE), with one Earth radius amounting to 6371 km or 3960 miles. In these units, the distance from the Earth's center to the "nose" of the magnetosphere is about 10.5 RE and to the flanks abreast of the Earth about 15 RE, while the radius of the distant tail is 25-30 RE. By way of comparison, the moon's average distance is about 60 RE. These, though, are just averages: the pressure of the solar wind rises and falls, and as it does, the magnetopause shrinks or expands. For instance, when the boundary is hit by a fast flow from a coronal mass ejection, the "nose" is pushed in, occasionally (a few times a year, usually) even past the synchronous orbit at 6.6 RE. (Chao, 2002)

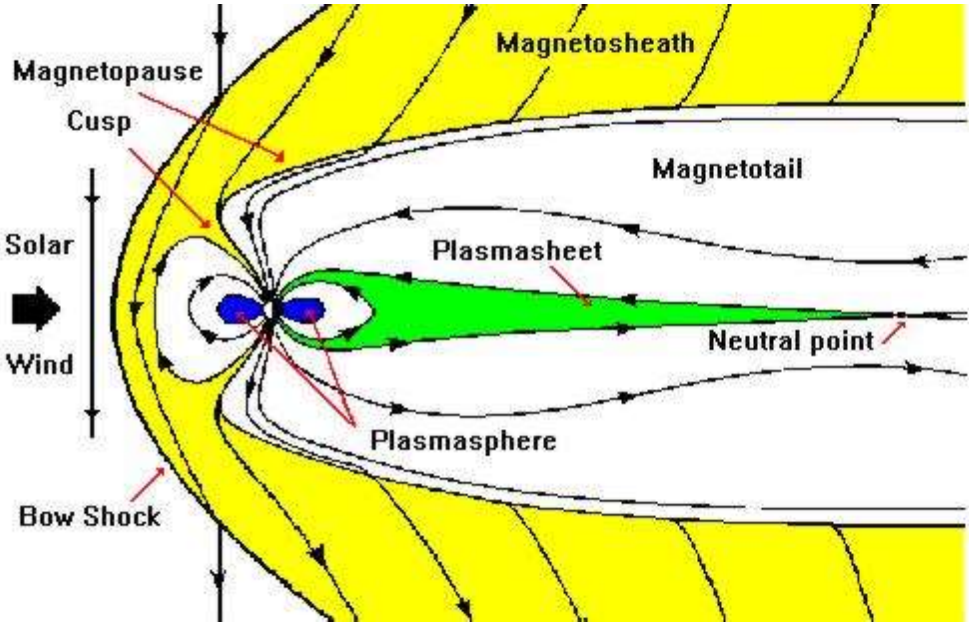


Figure (2.4)Earth's Magnetopause

(2-1-4) The Tail of the Magnetosphere:

In contrast to the dayside magnetosphere, compressed and confined by the solar wind, the nightside is stretched out into a long "magnetotail". This part of the magnetosphere is quite dynamic, large changes can take place there and ions and electrons are often energized.

The magnetotail is also the main source of the polar aurora. Even before the space age observers noted that in the arctic winter, when the sky was dark much of the time, the brightest auroras were seen in the hours around midnight. It was widely believed then that auroral electrons came from the Sun, and the fact that aurora seemed concentrated on the side facing away from the Sun puzzled everyone. Those observations made much more sense after satellites discovered and mapped the magnetosphere's long tail. (Stern, 2006)

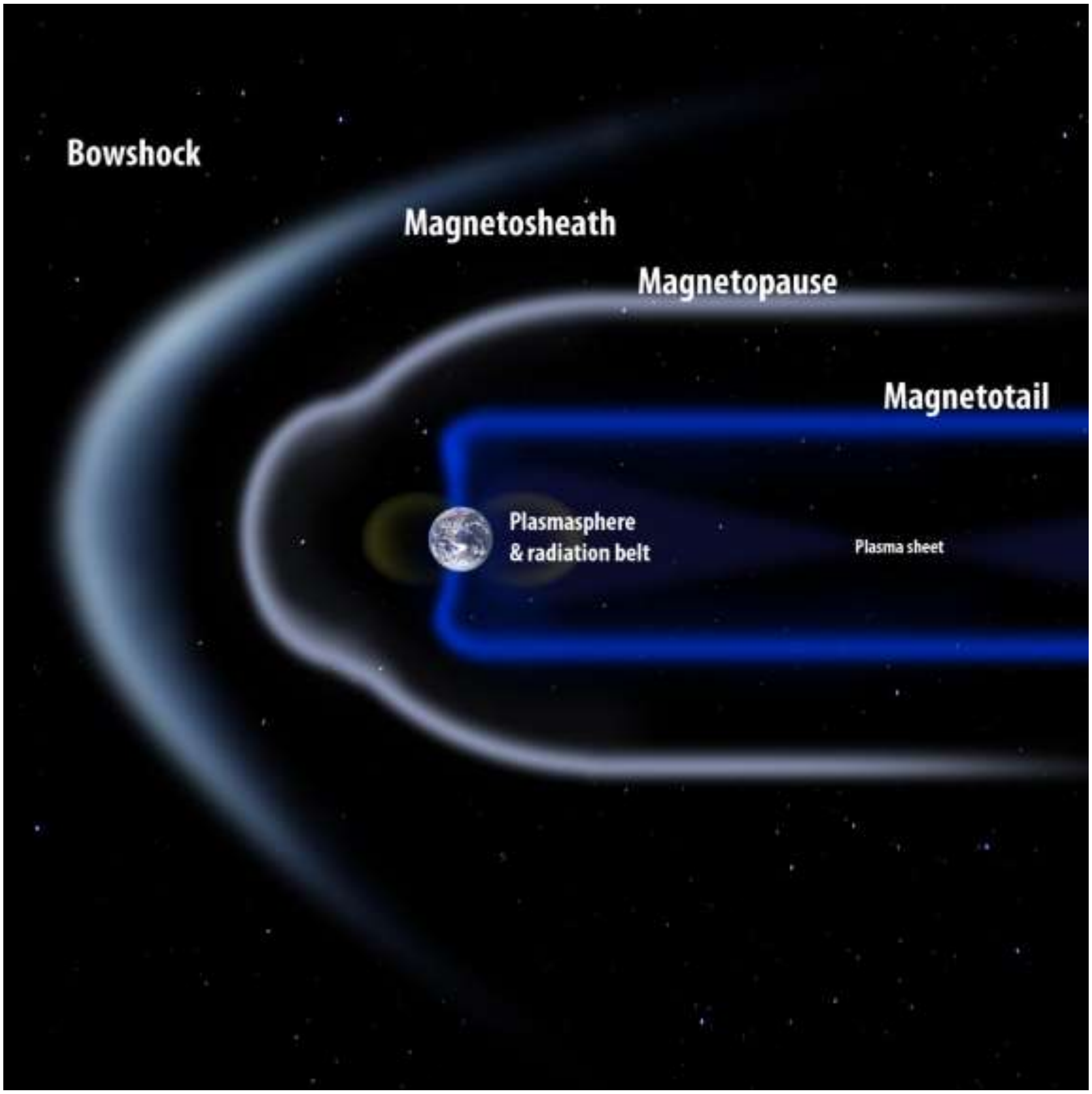


Figure (2.5) The Tail of the Magnetosphere

(2-1-5) The Tail Lobes:

Most of the volume of the tail is taken up by two large bundles of nearly parallel magnetic field 9lines. The bundle north of the equator points earthwards and leads to a roughly circular region including the northern magnetic pole, while the southern bundle points away from Earth and is linked to the southern polar region.

These two bundles, known as the "tail lobes", extend far from Earth: ISEE-3 and Geotail found them well-defined even at 200-220 RE (Earth radii) from Earth. At those distances the lobes are already penetrated by some solar wind plasma, but near Earth they are almost empty. One may compare typical plasma densities:

Table (2-1) Comparing between plasma density in differ region (Stern, 2006)

Plasma Region	**Density**
Solar wind near Earth	6 ions/cm^3
Dayside outer magnetosphere	1 ion/cm^3
"Plasma sheet" separating tail lobes	0.3– 0.5 ions/cm^3
Tail lobes	0.01 ion/cm^3

This extremely low density suggests that field lines of the lobe ultimately connect to the solar wind, somewhere far downstream from Earth. Ions and electrons then can easily flow away along lobe field lines, until they are swept up by the solar wind; but very, very few solar wind ions can oppose the wind's general flow and head upstream, towards Earth. With such a one-way traffic, rather little plasma remains in the lobes. (Stern, 2006)

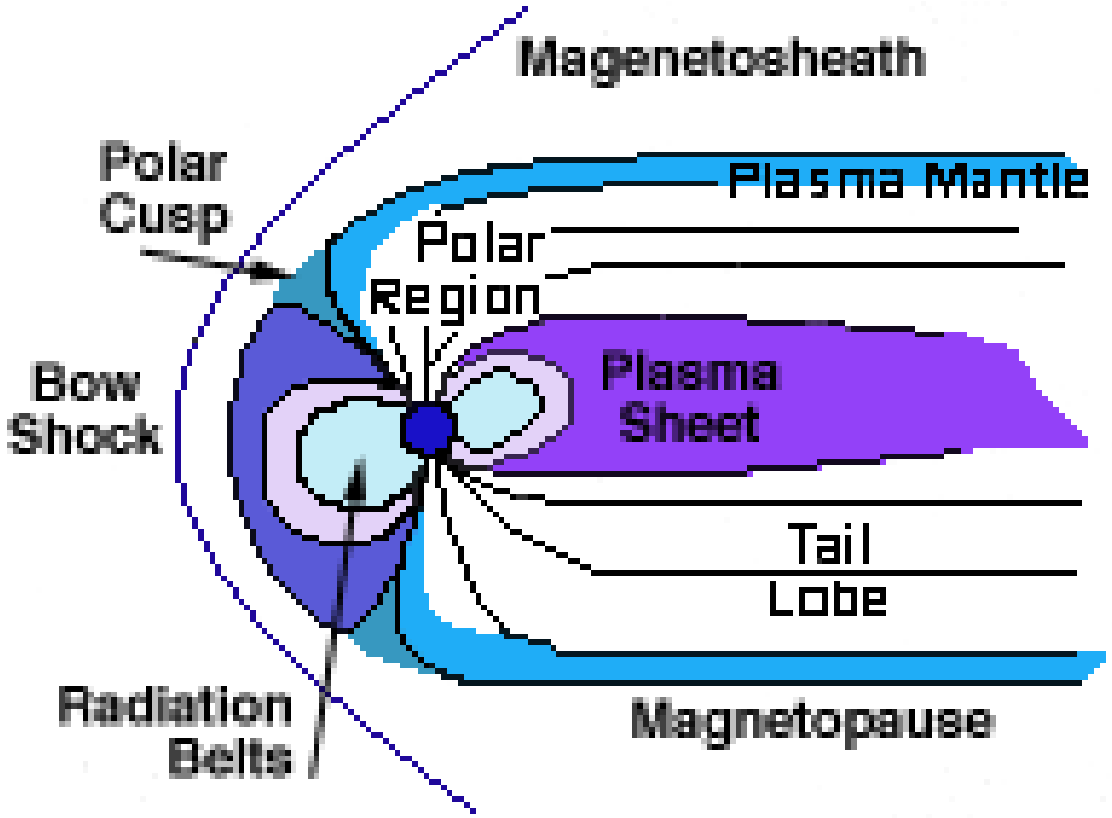


Figure (2.6) The tail lobes of earth; after (Stern, 2006)

(2-1-6) The Plasma Sheet:

A magnetosphere is produced by the interaction of a stream of charged particles, such as solar wind, with a planet's (or similar body's) magnetic field. All planets with intrinsic magnetic fields, including Earth, are surrounded by a magnetosphere. The plasma sheet is just that, a sheet of plasma that extends down the magnetotail dividing the two lobes of the Earth's magnetic field. This outer plasma is hotter than the plasma in the Plasmasphere, but is considered low energy when compared to the particles in the Van Allen radiation belts. In the magnetosphere, the plasma sheet is a sheet-like region of denser (0.3-0.5 ions/cm3 versus 0.01-0.02 in the lobes) hot plasma *and lower magnetic field near the equatorial plane, between the magnetosphere's north and south lobes.* (C.E.I, 1972)

(2-1-7) Plasmasphere:

The Plasmasphere, or inner magnetosphere, is a region of the Earth's magnetosphere consisting of low energy (cool) plasma. It is located above the ionosphere. The outer boundary of the Plasmasphere is known as the plasma pause, which is defined by an order of magnitude drop in plasma density. The Plasmasphere has been regarded as a well behaved cold plasma with particle motion dominated entirely by the geomagnetic field and hence co rotating with the Earth. In contrast, recent satellite observations have shown that density irregularities such as plumes or bite outs may form. It has also been shown that the Plasmasphere does not always co-rotate with the Earth. The plasma of the magnetosphere has many different levels of temperature and concentration. The coldest magnetosphere plasma is most often found in the Plasmasphere, a donut-shaped region surrounding the Earth's middle. But plasma from the Plasmasphere can be detected throughout the magnetosphere because it gets blown around by electric and magnetic field. Data gathered by the twin Van Allen Probes show that the plasmasphere also limits highly energetic ultrarelativistic electrons from cosmic and solar origin from reaching low earth orbits and the surface of the planet (C.E.I, 1972)

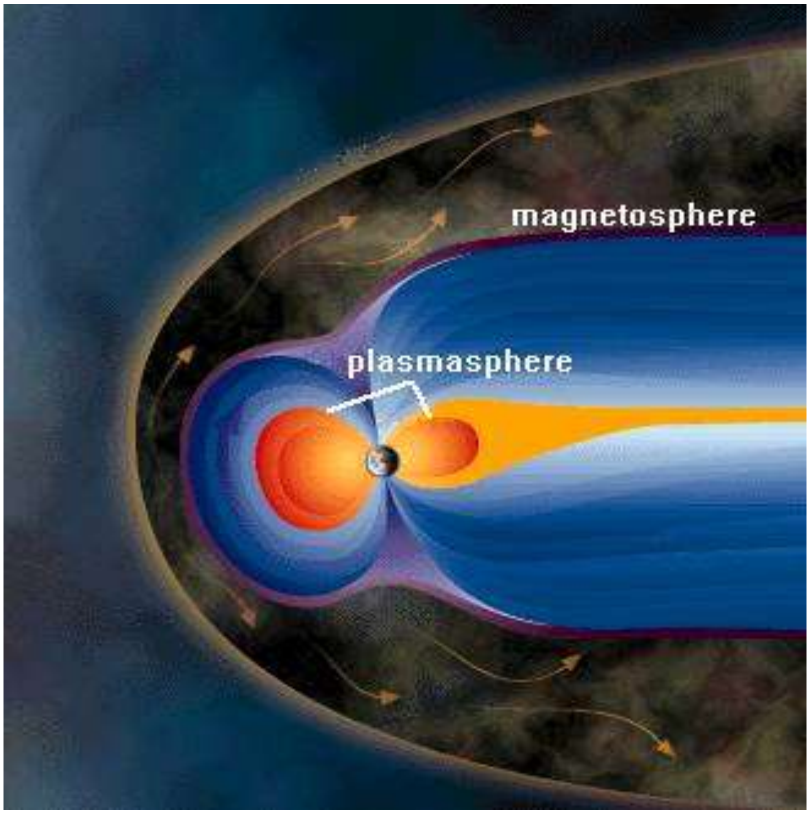


Figure (2.7) Earth's plasmasphere; after: (Russel.C, 2008)

(2-1-8) Van Allen radiation belt:

Doughnut-shaped zones of highly energetic charged particles trapped at high altitudes in the magnetic field of Earth. The zones were named for James A. Van Allen, the American physicist who discovered them in 1958, using data transmitted by the U.S. Explorer satellite.

The Van Allen belts are most intense over the Equator and are effectively absent above the poles. No real gap exists between the two zones; they actually merge gradually, with the flux of charged particles showing two regions of maximum density. The inner region is centered approximately 3,000 km (1,860 miles) above the terrestrial surface. The outer region of maximum density is centered at an altitude of about 15,000 to 20,000 km (9,300 to 12,400 miles), though some estimates place it as far above the surface as six Earth radii (about 38,000 km [23,700 miles]).

The inner Van Allen belt consists largely of highly energetic protons, with energy exceeding 30,000,000 electron volts. The peak intensity of these protons is approximately 20,000 particles per second crossing a spherical area of one square cm in all directions. It is believed that the protons of the inner belt originate from the decay of neutrons produced when high-energy cosmic rays from outside the solar system collide with atoms and molecules of Earth's atmosphere. Some of the neutrons are ejected back from the atmosphere; as they travel through the region of the belt, a small percentage of them decay into protons and electrons. These particles move in spiral paths along the lines of force of Earth's magnetic field. As the particles approach either of the magnetic poles, the increase in the strength of the field causes them to be reflected. Because of this so-called magnetic mirror effect, the particles bounce back and forth between the magnetic poles. Over time, they collide with atoms in the thin atmosphere, resulting in their removal from the belt.

The outer Van Allen belt contains charged particles of both atmospheric and solar origin, the latter consisting largely of helium ions from the solar wind (steady stream of particles emanating from the Sun). The protons of the outer belt have much lower energies than those of the inner belt, and their fluxes are much higher. The most energetic particles of the outer belt are electrons, whose energies reach up to several hundred million electron volts. (Danny Summers, 2013)

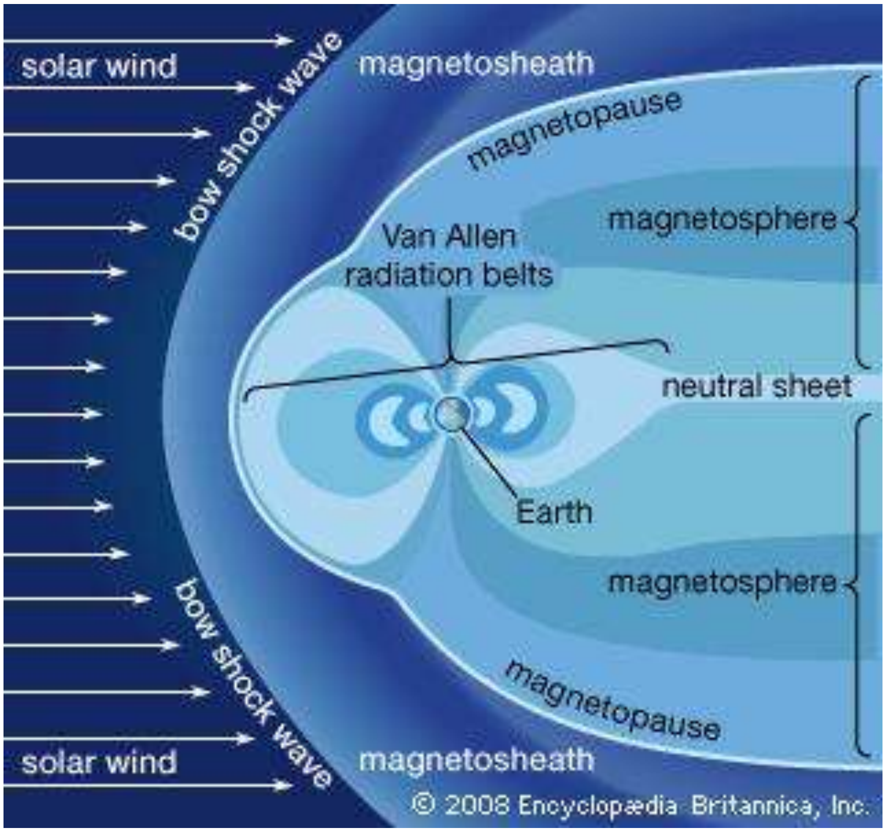


Figure (2.8) Van Allen Radiation Belts;

CHAPTER THREE

REEVIEW OF SPACE WEATHER IMPACT

(3-1) Space Weather:

Space weather is a branch of space physics and aeronomy concerned with the time varying conditions within the Solar System, including the solar wind, emphasizing the space surrounding the Earth, including conditions in the magnetosphere, ionosphere and thermosphere. Space weather is distinct from the terrestrial weather of the Earth's atmosphere (troposphere and stratosphere). The science of space weather is focused on fundamental research and practical applications. The term space weather was first used in the 1950s and came into common usage in the 1990s. (Cade III & Chan-Park, 2015)

(3-1-1) Introduction:

In the last 50 years, we have become a space faring civilization. With robotic and manned spacecraft, we have started to survey our Solar System. We have learned that we live in the atmosphere of a dynamic, violent Sun that provides energy for life on Earth, but also can cause havoc among its fleet of satellite and communications systems. Space weather is the emerging field within the space sciences that studies how the Sun influences Earth's space environment and the technological and societal impacts of that interaction – damage to or destruction of Earth-orbiting satellites and threats to both astronaut safety during long-duration missions to the Moon and Mars and to the reliability and accuracy of global communications and navigation systems. (Moldwin, 2008)

Modern society depends on accurate forecasts of weather (day-today variability of temperature, humidity, rain, etc.) and understanding of climate (long-term weather trends) for commerce, agriculture, transportation, energy policy, and natural disaster mitigation. The science of understanding weather, meteorology, is one of the oldest human endeavors to make sense of our natural environment. Like meteorology, the field of space weather seeks to understand and predict climate and weather, but of outer space. For millennia, space storms have raged above our heads unknown to us. But with the advent of the space age, we have begun to notice the destructive power of severe space weather.

Like weather, space weather has its roots in the Sun. The main distinctions between the two types of weather are where it takes place and the type of energy from the Sun that influences it. For weather, we are most concerned with the troposphere, which extends from Earth's surface to the top of the highest clouds at about 10 km. Space weather science is interested in the space environment around Earth all the way to the Sun. Space begins in a region of Earth's atmosphere called the thermosphere, which starts at roughly 100 km. The space shuttle and space station fly at an altitude of about 350 km. Figure (3.1) shows a picture of Earth's atmosphere from the space shuttle. The sharp on trast between the blue of Earth's atmosphere and the blackness of pace is at approximately 100 km.

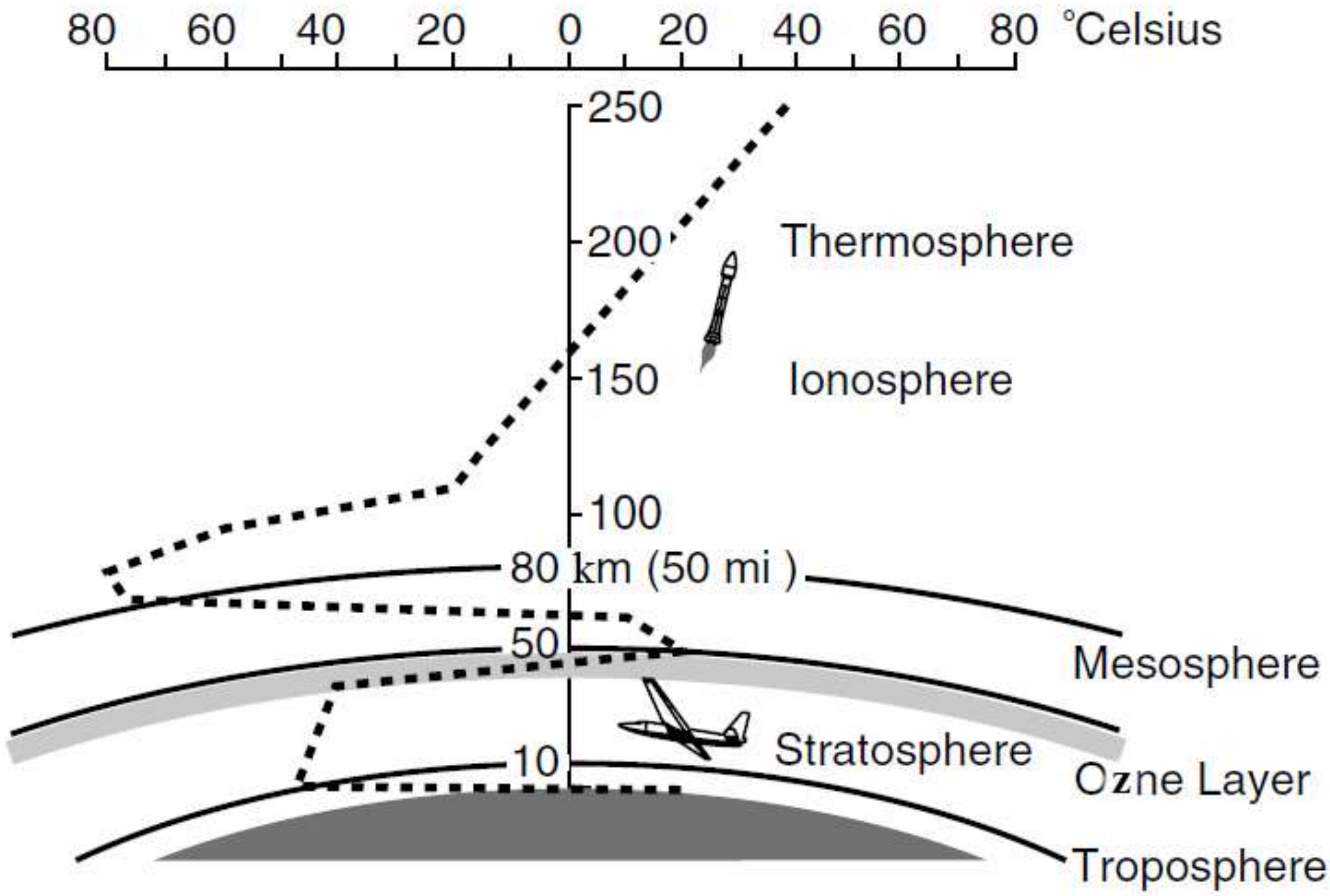


Figure (3.1) the vertical temperature scale of Earth's atmosphere. The dashed line represents the temperature as a function of height. Each region is defined by how the temperature changes with height (courtesy of Cislunar Aerospace, Inc.).

The second difference between weather and space weather is the type of solar energy that influences the two regions. The Sun continuously emits two main types of energy into space – electromagnetic (EM) radiation and corpuscular radiation. Visible light, radio waves, microwaves, infrared, ultraviolet, X-rays, and gamma rays are forms of EM radiation. The Sun's EM radiation bathes the top of Earth's atmosphere with about 1400 watts of power per square meter and heats the lower atmosphere, surface and oceans unevenly. Winds are driven by these differences in atmospheric temperature.

The Sun also continuously emits corpuscular (minute particle) radiation, charged atoms and sub-atomic particles (mostly protons and electrons) in what is called the solar wind. Like winds on Earth, the solar wind is driven by temperature differences, but those differences are between the Sun's upper atmosphere and interplanetary space. The solar wind, which expands out into the Solar System carrying with it the Sun's magnetic field, carves out a region of interstellar space called the heliosphere.

The solar wind is not steady or uniform, but changes constantly. These changes affect Earth's space environment in a number of ways, including creation of new corpuscular radiation that bombards Earth's upper atmosphere, causing aurorae (northern and southern lights) and large electrical currents that can disrupt communication, power grids, and satellite navigation.

Occasionally the Sun's surface erupts and sends a large part of the solar atmosphere streaming away at high speeds. These events, called coronal mass ejections (CMEs), can contain 1012 (or 1 000 000 000 000) kg of material (equivalent to a quarter of a million aircraft carriers) and can move away from the Sun at over 1000 km s−1 (over several million miles per hour). If CMEs are directed towards Earth, a great space storm can develop far above our heads, crippling satellites, causing increased radiation exposure for airline crews and passengers, blacking out some forms of radio communication, and disrupting power systems on Earth.

These space storms, like weather storms such as Hurricane Katrina in 2005, have caused severe damage to technological systems in the past. In March 1989, a large CMEs slammed into Earth causing massive power outages in eastern Canada. The emerging science of space weather is attempting to understand the causes of space storms and their impact on Earth's technological *infrastructure with the hope that we can forecast space weather and mitigate damage.* (Moldwin, 2008)

(3-2) Space Weather impact on Earth:

Space weather has broad, everyday impacts on humans and technology. Spacecraft and astronauts are directly exposed to intense radiation that can damage or disable systems and sicken or kill astronauts. Radio signals from satellites to ground communication and navigation systems, such as the Global Positioning System (GPS), are directly affected by changing space environment conditions. What may be surprising is that many ground systems, such as power transmission grids and pipelines, and landline communication networks, such as transoceanic fiber-optic cables, are also susceptible to space weather impacts. Figure (3.2) shows the wide variety of systems that are affected by space weather, including astronauts and commercial airline crew and passengers as well as a host of satellite and radio communication devices. This chapter will describe how space weather affects these systems and describe the impacts space weather-related failures can have on technology and society. (Moldwin, 2008)

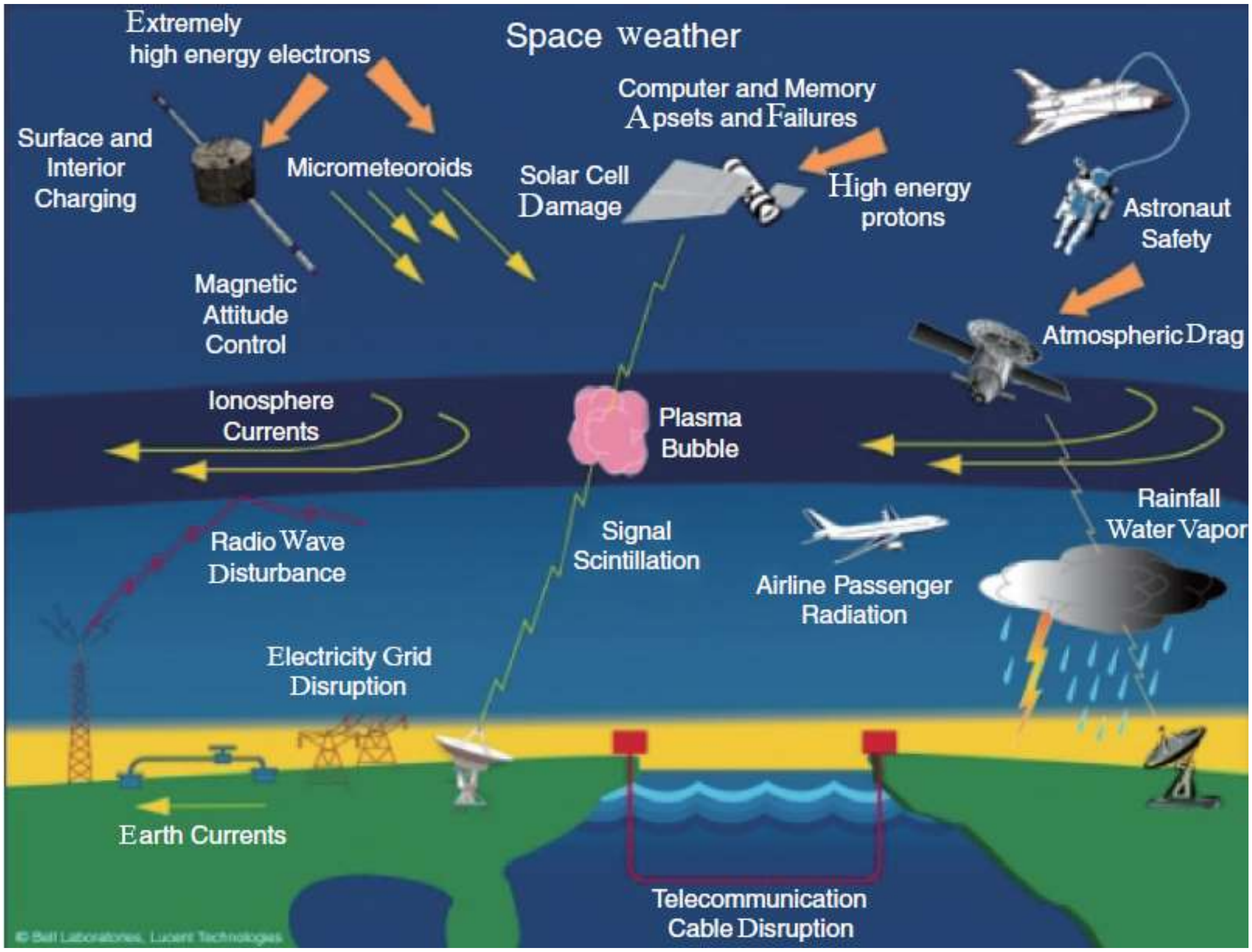


Figure (3.2): Different systems affected by space weather include satellites, astronauts, radio communication, and electric power grids

(Courtesy of Bell Laboratories, Lucent Technologies).

(3-2-1) Radiation impacts on satellites

Medium-Earth orbit (MEO), high-Earth orbit (HEO) and geosynchronous (GEO) satellites do not have significant satellite drag effects but they have their own unique space weather concerns. *These include spacecraft charging and high-energy radiation dose effects. Satellites in these orbits spend at least part of their orbit traversing the Van Allen radiation belts (discussed in*

Section 4.4), which contain trapped energetic particles that can severely damage or destroy sensitive electronic components.

There are a wide variety of radiation effects on satellites. These include surface charging, deep dielectric charging, single event upsets, and UV degradation of solar arrays. The next section describes each of these effects in detail. (Moldwin, 2008)

(3-2-1-1) Radio communication and navigation impacts

Space weather storms modify the density distribution of the ionosphere. Because radio wave propagation depends on the medium the waves move through, a time variable and spatially inhomogeneous ionosphere can severely perturb and degrade ground-to-satellite and satellite-to-ground communication. This can have serious impacts on different systems, but is particularly important for high frequency (HF) radio communication and Global Positioning System (GPS) navigation systems. (Moldwin, 2008)

(3-2-1-2) HF radio blackouts

High-frequency (HF) radio is used for ship-to-shore and ship-to-ship communication as well as by commercial airlines for air-to-ground and ground-to-air communication. This radio band is also popular with amateur radio operators. HF radio frequencies are between 3 and 30 MHz. The ionosphere can reflect these frequencies, and therefore long-range communication is possible by bouncing your signal off the ionosphere several hundred kilometers above Earth. This phenomenon, called "skywave", allows for over-the-horizon communication and is how Marconi was able to make the first trans-Atlantic radio communication in 1901 (see Figure 3.3). The benefit of this frequency band – that it can interact with the ionosphere to permit long-range radio communication – is also its problem. Because the ionosphere is highly variable in space and time, HF radio communication can be severely degraded or even made inoperable depending on a wide variety of factors. Many of these factors are related to space weather and include the amount of *solar activity (and hence sunspot cycle) and geomagnetic activity (particularly aurorae).* (Moldwin, 2008)

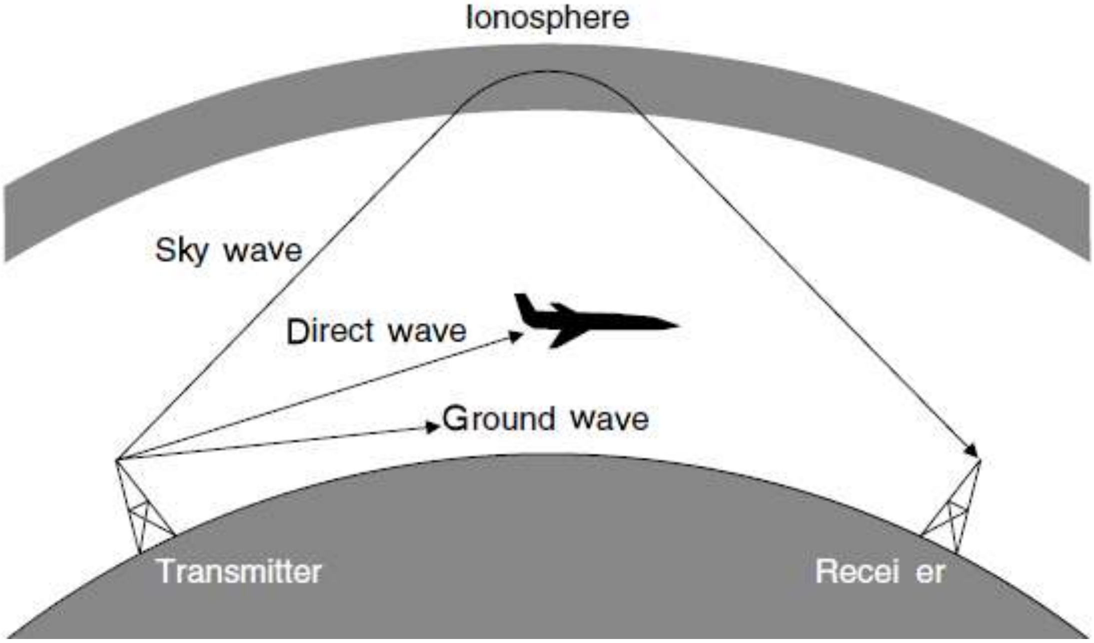


Figure (3.3) the ionosphere can refract and reflect radio waves. Long distance radio communication is possible due to "bouncing" radio waves off the ionosphere

(Adapted from Radtel HF Radio Network).

HF radio propagation depends on ionospheric density, which is controlled by sunlight and geomagnetic activity. Space weather degradation of HF radio has a particularly big impact on trans-polar airline flights. During large geomagnetic storms, HF radio communication can be rendered inoperable over the poles. Therefore, commercial airlines, which rely on HF radio communication, must base their flight schedules on space weather forecasts. Airlines will re-route trans-polar flights during large geomagnetic storms because of the impact on their HF radio communication ability.

Because of potentially serious impacts on HF radio communication, many users are switching to satellite phone communication (which uses much higher-frequency radio waves) and using HF as a backup system. However, since the cost of satellite communication is still relatively high, a significant number of industrial and government (maritime, aviation, and military) employees use HF radios, which are subject to space weather impacts. (Moldwin, 2008)

(3-2-1-3) GPS satellites errors

The Global Positioning System (GPS) allows users to accurately locate their position on Earth. The system consists of over 28 satellites in medium-Earth orbit arranged in such a way that at any given point on Earth at least four satellites are in view of an observer with an unobstructed view of the sky. These satellites have atomic clocks on board and continuously broadcast the time. A user on the ground with a GPS receiver can get this signal. By comparing the time broadcast by the satellite with the time at which the signal arrived, a distance (distance equals speed of radio signal divided by time for the signal to go from satellite to ground-user) to the satellite can be estimated. By triangulation (the process of determining the position of an object using three independent distance determinations), the exact location of the user can be estimated. Because the user does not have an atomic clock, a fourth satellite is used to acquire accurate time and the three other satellites are used to triangulate position. The speed at which a radio signal propagates through a vacuum is the speed of light (given as "c" in Einstein's famous equation). However, the speed at which an electromagnetic signal like a radio wave propagates through matter is less than the speed of light. This is called diffraction and has the effect of slowing down and bending the signal. The amount of bending and how much slowing occurs depend on the frequency of the signal and the properties of the medium. We experience this phenomenon when we look into water and see a rainbow. For a plasma, the property that determines electromagnetic propagation effects is *the density. Therefore, because of ionospheric density, the radio signal from a GPS is slowed down. GPS systems attempt to account for this delay by using estimates or models of ionospheric density. For typical handheld single-frequency GPS measurements, positional errors on the order of 50 meters are common due to differences between the model ionosphere and the real ionosphere. This doesn't sound like much, but if GPS is used to fly an airplane, being 50 meters off the runway can make a big difference. (Moldwin, 2008)*

(3-2-2) Ground system impacts

A number of technological systems on the ground are susceptible to space weather. During a large geomagnetic storm, large time-varying currents flow into and through the ionosphere. These currents can induce currents in long conductors on the ground, such as electric power lines, telephone lines, and pipelines. Induced currents in these systems can overload electrical components, causing failure, or can decrease the lifetime of the infrastructure by enhancing corrosion. The main principle behind these induced currents is called Faraday's2 law of induction. This is a physical relationship that describes how a time-changing magnetic field can induce current and voltage in a conductor. Electricity can be described in terms of current or voltage. They are related through Ohm's law. In space, electrical currents flow into and through the ionosphere. These currents intensify and move to lower latitudes during geomagnetic storms. The time-changing and spatially varying currents create a time-changing magnetic field. According to Faraday's law, this time changing magnetic field then can induce a voltage in long conductors. A wire is a good conductor designed to carry electrical signals long distances. On Earth, we have millions of kilometers of wire connecting buildings and houses with power plants and phone companies. These electric and communication grids are therefore susceptible to space weather effects. (Moldwin, 2008)

(3-2-2-1) Power grids

In the last few decades, power generation and distribution have become an interconnected continental-sized industry. Electricity produced by hydroelectric systems in Washington State in the United States is shipped to California. Power generated by Hydro Quebec in eastern Canada can be shipped across the border to power homes in New York. Because of deregulation and this new interconnectivity, system vulnerabilities have increased. A power outage in one part of the grid can quickly propagate to other regions. Overgrown tree branches crossing a high voltage line in Ohio triggered the power outage of 2003 that stretched from Detroit to New York City and left 50 million people in the dark. In March of 1989 a major geomagnetic storm caused an overload of a transformer in Quebec that quickly caused the collapse of the whole system. The transformer had been exposed to induced currents from the geomagnetic storm that exceeded its design capacity and it melted. Transformers can convert high-voltage–low-current electricity into low-voltage–high-current electricity. It is more efficient to run high-voltage electricity long distances, but household appliances need high-current. Therefore the electrical system ships the electricity from the power plant to the user at high voltage, and transformers located near the user convert the electricity into useful household or industrial high-current electricity. If the transformer gets more voltage than it is designed for (like induced voltage from enhanced ionospheric currents during a geomagnetic storm), it can fail. Power grid operators therefore must watch the geomagnetic or space weather forecasts and reduce the load on their systems during geomagnetic storms. Of course, if a storm occurs during a heat wave or cold snap when electricity usage is high, the operators may not have the flexibility to handle the situation 6.7 Supplements 89 and then must institute planned rolling "brownouts" or potentially suffer catastrophic blackouts. It is estimated that if a perfect storm occurs during the next solar maximum (a large geomagnetic storm *during a heavy electrical usage interval due to a cold or heat wave), hundreds of transformers could be damaged or destroyed. Replacement could take years because transformer manufacturing is expensive and fairly limited. (Moldwin, 2008)*

(3-2-2-2) Pipelines:

Metal will corrode when exposed to a variety of environmental conditions (like moisture and air). Corrosion is enhanced if there is an electrical current flowing through the metal. Along pipeline can be susceptible to enhanced corrosion if electrical currents are allowed to flow across it. Pipelines carry natural gas and oil throughout the arctic region from their source region to terminals at lower latitudes. For example, the trans- Alaskan pipeline carries crude oil from Prudhoe Bay on the north slope of Alaska to the town of Valdez on the south coast of Alaska, traversing a distance of nearly 1300 km (800 miles). In Valdez the oil is loaded onto super-tankers for shipment to California and refineries elsewhere. The pipeline sits underneath the auroral oval, which is coincident with the largest ionospheric currents usually seen due to geomagnetic activity. These time-changing ionospheric currents can induce large currents in the pipeline. The Alaskan pipeline is especially electrically grounded to minimize this impact, but many pipes throughout the arctic region are not, and therefore their lifetime and potential for leaks is increased because of space weather. The major disruption of oil production in Prudhoe Bay in 2006 was due to severe pipeline corrosion that may have been exacerbated by currents induced by auroral activity. (Moldwin, 2008)

Chapter Four

SOME COLLECTED EVIDENCES FOR SPACE WEATHER IMPACT

(4-1) Impact Evidence:

Here, we have reported some evidences showing the impact of space weather on local electrical grid as well as the impact on GPS satellites of the Russian GLONASS satellites; these evidences were being collected from different sources.

(4-1-1) Blackout records in the national grid that synchronized with storm time:

As being described in **CHAPTER THREE** *the space weather has impact on electric power grids in a way such that the geomagnetically induced currents can leak into high power transformers making failure on the power supply and blackouts hence will occur; in a previous study by* (ABAKAR, 2015) *he showed that in the national grid of electric power in Sudan a good number of blackouts could be possibly caused by geomagnetic disturbances, i.e. he showed that 17 out of 37 blackout events were correspond to time of occurrence of geomagnetic storms. The following table shows some of these events.*

Table (4.1) show the DST observation and blackout times (causes are reported by (Electricity, 2001-2013)) and other information; after: (ABAKAR, 2015)

Year	DATE	TIME	Gen.before B.O (MW)	Restoration time (H)	Losses)MWH(	Causes	DST Observation
2009	4/2/2009	/13:46	637		1936	Due to sudden loss of bulk generation (all Gar units&Khn ST4) which is happen after cct1&cct2 ros—senj tripped by B/B Prot. Side senj due to mal operation causing a loss of 183	storm
	11/7/2009	6:38	556		8000	Due to loss of bulk generation all MWP units	Non storm
	10/4/2009	14:55	1113		5200	all MWP (7 units) tripped out due to loss of control(loss of UBS)	Non storm
	26/11/2009	15:37	539		3000	MWP-MRK Cct opened at MWP due to mal operation result in complete isolation of MWP.	Non storm
	30/11/2009	15:21	887		1500	Loss of the controller at MWP led to trip of all units in MWP	Non storm

Another studies by (اللطيف, 2014) *showed that in the national electric power in Sudan there was a blackout on 4/2/2009, that happened mean while a disturbance taking place in the space, see figure 4.1 down here.*

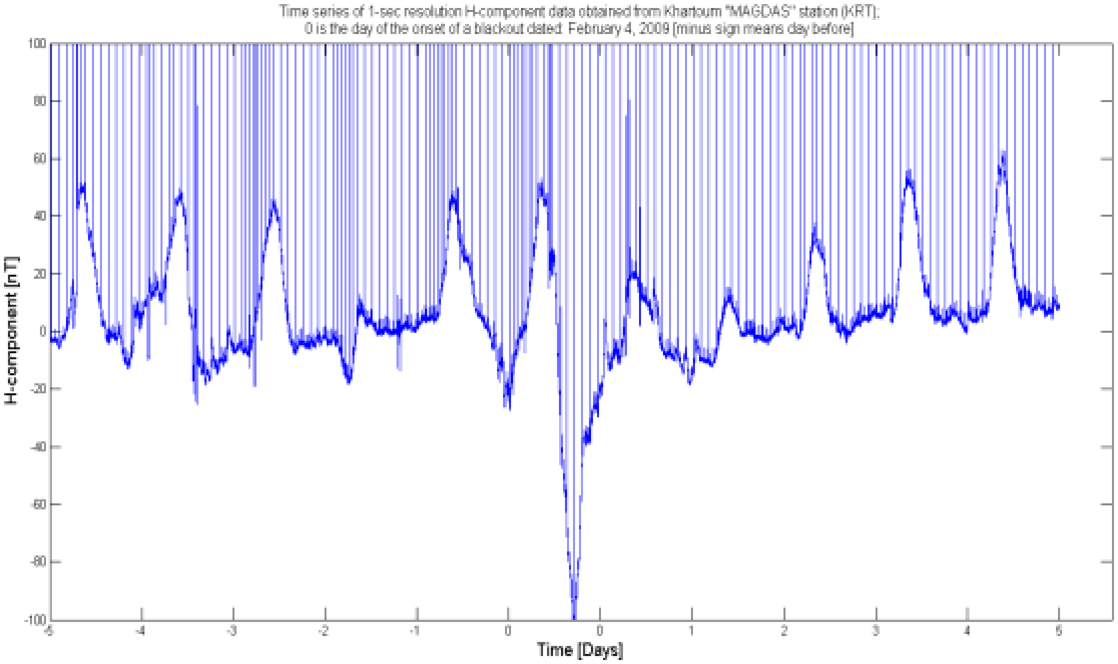


Figure (4.1) Show time series of data that obtained at "MAGDAS" station in Khartoum (KRT) on 4/2/2009 the number (0) indicates the onset day out of blackout. Negative sign means day before positive means day after; after: (اللطيف, 2014)

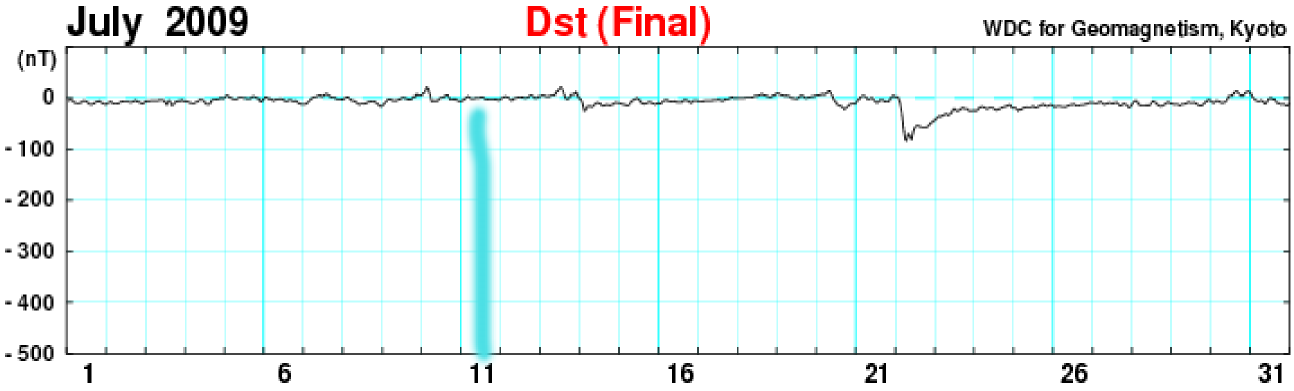


Figure (4.3) show Final and Professional Dst for the Months when blackout occurred, the red lines show corresponding times of blackouts on DST scaled disturbed days, while the cyan lines show the corresponding times of blackouts on relatively DST scaled quiet days. (ABAKAR, 2015)

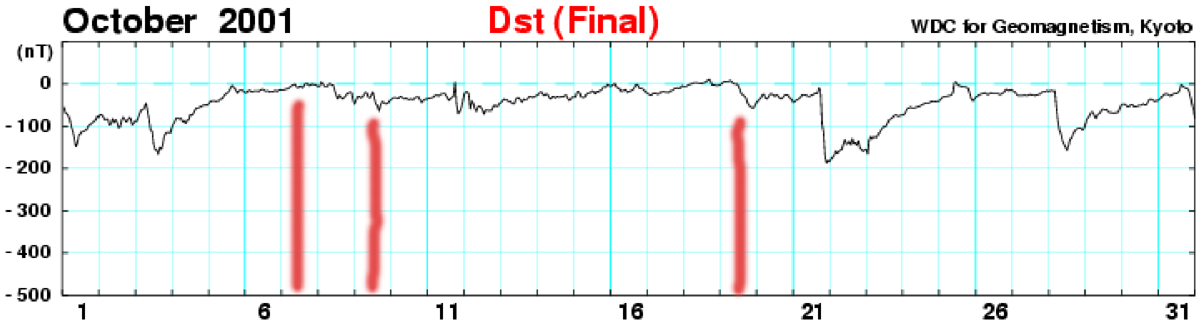


Figure (4.4) show Final and Professional Dst for the Months when blackout occurred, the red lines show corresponding times of blackouts on DST scaled disturbed days, (ABAKAR, 2015)

(4-1-2) GPS Satellites outage:

*As we discussed in **CHAPTER THREE** space weather also had an impact on satellites, positional errors are common due to differences between the model ionosphere and the real ionosphere, in previous study by (Rayne, 2014) he showed that between 1030 and 0400 UTC on April 2, 2014, most of Russia's GLONASS satellites reported "illegal" or "failure" status. They do not appear to be back online. It's possible that the outage is related to either a new M-class solar storm the start of which was reported about 48 hours ago. (Rayne, 2014)*

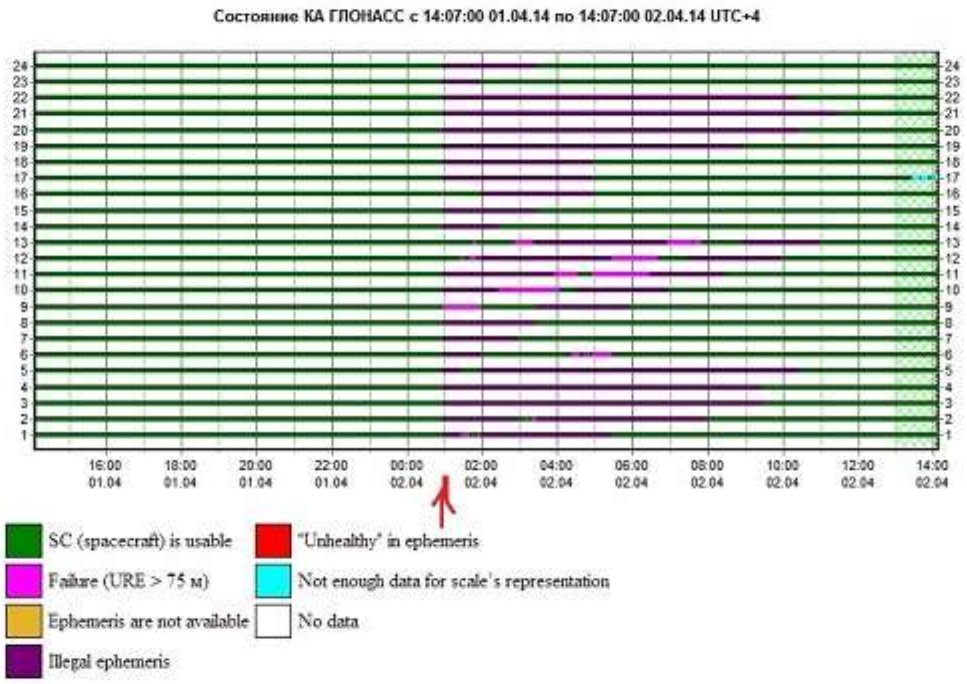


Figure (4.5) show the Russian GLONASS satellites, and the pink color show the satellites outages.

(4-2) Conclusion

Space weather impact on Earth was been configured long time ago since the first outages of power and telegraph systems was reported during space disturbances observed via different observatories on both in situ and the ground. Therefore, blackouts in power grids and degradations and malfunctions in satellite systems were found to be the most outstanding impact of space weather in both Earth and in situ. Our review revealed important feature of one of those direct and outstanding impacts of space weather, i.e. the blackouts in a low latitude region, this feature was attracted the attention of scientists for long time, because this space weather impact on Earth was deduced to be a main feature of Aurora to high-latitude region, but its presence in a low-latitude region was raised as an important question.

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