Chapter 2

The Earth’s Magnetosphere and Ionosphere

2.1 Introduction

2.1.1 The Earth’s Magnetosphere

The Earth’s magnetosphere is a *magnetic* cavity around the Earth created by the interaction of the solar wind with the Earth’s magnetic field. In this cavity, the terrestrial magnetic field is dominant and the shape is distorted from that of a perfect dipole, due to the solar wind pressure. When the supersonic solar wind encounters the sun-facing side of the Earth’s magnetic field, it exerts a pressure on the dayside of the Earth’s magnetic field and is compressed towards Earth forming a head-like structure, having a radius of curvature of about 10 $R_E$. The night side of the field is stretched out to form a long magnetic tail whose cylindrical diameter is about 50 $R_E$. A schematic diagram of the magnetosphere showing the large-scale structure is shown in figure 2.1.
All of the solar wind particles incident on the Earth’s magnetosphere cannot penetrate into the magnetosphere because the charged particles are deflected by the geomagnetic field. Thus, the Earth’s magnetosphere shields the Earth from the harmful high-energy particles emitted by the Sun. But there are times when a small fraction of the incident energy enters into the magnetosphere. The amount of solar wind particles entering into the Earth’s magnetosphere depends on various factors such as the direction of the IMF and solar wind parameters like density and velocity. At the times when the direction of the IMF is antiparallel to the geomagnetic field, the two fields merge to some extent through a process called magnetic reconnection and open the magnetosphere for the transfer of energy. When these field lines are parallel to one another, there is no magnetic field merging. At such times, the magnetosphere is closed and the terrestrial magnetic pressure deflects the solar wind flow, preventing the transfer of energy. Thus, the transfer of energy into the magnetosphere is not
continuous but increases and decreases almost at random depending on the IMF directions and the solar activity.

2.2 Structure of the Magnetosphere

The plasma present inside the Earth’s magnetosphere originates partly from the solar wind and partly from the Earth’s ionosphere. This plasma distribution inside the magnetosphere is not uniform and can be grouped into different regions with different densities and temperatures. Figure 2.1 shows a global view of the different plasma regions found in the magnetosphere. Approximate values of the field and plasma parameters for the solar wind plasma is given in table 2.1. These different regions are interconnected by the magnetic fields and different current systems flowing inside the magnetosphere. The shape and size of the different regions of the magnetosphere undergo significant changes in response to different solar wind conditions. The Earth’s magnetosphere on the large scale is roughly divided into two regions - inner and outer magnetosphere. The region of the magnetosphere, where the geomagnetic field lines are closed, is called the inner magnetosphere. This inner magnetosphere is again subdivided into different regions which include ionosphere, plasmasphere, Van Allen radiation belts etc. It extends upto about 8 R_E from Earth. On the other hand, the region of the magnetosphere where the geomagnetic field lines are either deviated to a great extent from a perfect dipole shape or open to the solar wind in the far downstream tail region, is called the outer magnetosphere. The two tail lobes, the plasma sheet boundary layer (PSBL) and the current sheet are the major regions that forms the outer magnetosphere.


<table>
<thead>
<tr>
<th>Plasma</th>
<th>( n(\text{cm}^{-3}) )</th>
<th>T (eV)</th>
<th>B (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstellar</td>
<td>1</td>
<td>(10^{-2})</td>
<td>1</td>
</tr>
<tr>
<td>Solar wind (1AU)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>(10^6)</td>
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<td>(10^4)</td>
</tr>
<tr>
<td>Solar corona</td>
<td>(10^6)</td>
<td>(10^2)</td>
<td>(10^6)</td>
</tr>
<tr>
<td>Lobe</td>
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<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PSBL</td>
<td>0.1</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>Plasma sheet</td>
<td>0.5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Neutral sheet</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2.1: Approximate plasma and field parameters across the plasma universe and in the Earth’s magnetosphere.

2.2.1 Bow shock

When the supersonic solar wind approaches the Sun-facing near-Earth region, the solar wind and IMF undergoes an abrupt transition in its properties such as the change in density, temperature, flow speed and field strength. This is a standing shock wave produced as a result of the supersonic solar wind encountering the Earth as an obstacle in its flow. It is called the Bow shock. It is roughly at a distance of about 15 R\(_E\) (1R\(_E\)=6384 km) along the Sun-Earth line. This shock allows the high speed solar wind, which flows faster than the speed of the compressional waves in a plasma, to be slowed down to subsonic speed, heated and deflected. Since the bow-shock is associated with changes in plasma parameters and field strength, it is often treated as a discontinuity.

2.2.2 Magnetopause and Magnetosheath

The upper boundary of the Earth’s magnetosphere is called the magnetopause. This boundary separates the geomagnetic field and plasma of terrestrial origin from solar-wind plasma. It is at a distance of about 10 R\(_E\) from the Earth.
along the Sun-Earth line. Such a boundary was first proposed by Chapman and Ferraro [1931].

**Magnetosheath** is the region of space between the bow-shock and the magnetopause. This region is filled with plasma which has been slowed down at the bow shock. The particle density in this region is lower than what is found beyond the bow shock but greater than within the magnetopause. The plasma in this region is a very turbulent medium which is mainly due to the large influx of energy from the solar wind. Kinetic flow energy is converted into thermal energy, heating the plasma to about 5 to 10 times the solar wind temperature.

### 2.2.3 Plasmasphere and Van Allen radiation belts

The plasmasphere is a donut-shaped region of dense ($\sim 10^3$ cm$^{-3}$) and low energy ($\sim 1$eV) plasma encircling the Earth which is located just above the upper ionosphere inside the Earth’s magnetosphere. It is formed by trapping the ionospheric plasma upflows on the dipolar field lines extending upto 4–5 R$_E$ in the equatorial plane. The plasma in this region is the coldest plasma found inside the magnetosphere and corotates with the Earth as it is associated with the Earth’s strong magnetic field region. This region is dominated by particles originating from ionosphere since it contains high O$^+/H^+$ ratio and the existence of other ion species such as He$^+$, O$^{2+}$, N$^+$ and N$^{2+}$ which cannot be found in the solar wind. The outer boundary of the plasmasphere (approximately at 5 R$_E$ from the centre of the Earth) which is characterized by a drop in density is called the plasmapause. The plasmasphere was discovered in 1963 by Don Carpenter [Carpenter, 1963] from the analysis of VLF whistler wave data.
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The Van Allen radiation belts are two layers of energetic charged particles (plasma) around the Earth, trapped by dipole magnetic field lines. These particles move along the field lines and oscillate back and forth between the two hemispheres. These radiation belts partially overlap the plasmasphere but they are mostly populated by highly energetic charged particles (upto tens of MeV) and extends up to about $7 \, \text{R}_\text{E}$. These belts are named after their discoverer, James Van Allen. Typical plasma densities in this region are $\sim 1\, \text{cm}^{-3}$. The existence of the belts was confirmed by the Explorer 1 and Explorer 3 missions in early 1958, under Dr. James Van Allen at the University of Iowa.

The **inner radiation belt** extends from an altitude of about 1 to 3 $\text{R}_\text{E}$ in the equatorial region around the Earth. This region is dominated by highly energetic protons with energies exceeding 10 MeV, trapped by the strong (relative to the outer belt) magnetic fields in the region. This belt also contains high concentrations of electrons in the energy range of hundreds of keV and lesser amounts of other nuclei, such as alpha particles, oxygen ions, etc. The energetic protons are produced by the beta decay of neutrons created by cosmic ray collisions with nuclei of the upper atmosphere.

The **outer radiation belt** extends from an altitude of about 3 to 7 $\text{R}_\text{E}$ with the greatest intensity at around 4–5 $\text{R}_\text{E}$. This belt is dominated by electrons with energies in the range of 0.1 to 10 MeV, trapped by the Earth’s dipole magnetic field lines. Typical ion density is of the order of 50 keV. The outer electron radiation belt is mostly produced by the inward radial diffusion and local acceleration due to transfer of energy from the whistler mode plasma waves to radiation belt electrons. Radiation belt electrons are also constantly
removed by collisions with atmospheric neutrals, losses to magnetopause, and the outward radial diffusion.

The outer belt is larger than the inner belt and its particle population fluctuates widely. Energetic (radiation) particle fluxes can increase and decrease dramatically depending on the geomagnetic conditions, which are themselves triggered by magnetic field and plasma disturbances produced by the Sun. The increases are due to storm-related injections and acceleration of particles from the tail of the magnetosphere.

### 2.2.4 Tail lobes and Plasma sheet

The tail lobes are the two regions of relatively smooth and nearly parallel magnetic field lines, north and south of the plasma sheet. The field lines in each lobe region maintain roughly the same direction until they converge above the poles. The lobe with magnetic field lines pointing towards the north pole is called the northern tail lobe whereas the lobe with field lines pointing away from the south pole is called the southern tail lobe. The magnetic field lines in these two lobe regions are open to the solar wind in the far downstream tail region from the Earth, so that electrons and ions can easily flow away along lobe field lines later to join the solar wind. Because of this, the plasma density and temperature are extremely low with typical values of about 0.01 cm\(^{-3}\) and 20 eV respectively, but the magnetic field strength is relatively strong (\(\sim 30\) nT) compared to the plasma sheet region. Thus in this region the magnetic field pressure is large and the plasma pressure is small. The position of the lobe boundaries is quite variable and, under some circumstances (usually active geomagnetic conditions),
the lobe plasma can be observed even on the geosynchronous orbit [Moldwin et al., 1995].

The plasma sheet is the region with hot (\( \sim 1 \text{keV} \)), relatively dense plasma (\( \sim 0.1 - 1 \text{cm}^{-3} \)) that is found at the center of the magnetotail surrounding the neutral sheet. This plasma sheet region separates the northern and southern tail lobes. The plasma sheet is typically \( 4-8 \, \text{R}_E \) thick. In this region, the magnetic field pressure is dominated by the plasma pressure often with \( \beta \) values greater than 0.5. The magnetic field is relatively weak (\( \sim 10 \, \text{nT} \)) with very small nearly 0 nT in the field reversal region at the center of the current sheet. The plasmasheet is primarily connected to closed magnetic field lines. The plasma sheet region is a very complex and dynamic region. The thickness, density and energy of the particles vary greatly during different geomagnetic conditions. The onset of various geomagnetic phenomena such as substorms, storms, etc takes place in this region. Plasma convection in this region is primarily due to \( \mathbf{E} \times \mathbf{B} \) motion. During ‘substorm’ occurrences some parts of the plasma sheet may get “squeezed out” both earthwards and tailwards: earthward flowing ions gain energy and penetrate the inner magnetosphere, while the outward moving sections (‘plasmoids’) stream away from Earth and lost into the solar wind.

The plasmasheet has its associated electric current, flowing across the tail’s equator from flank to flank, from east to west (dawn to dusk). The current flowing from dawn to dusk is called the cross-tail current. This current then closes along the magnetopause and the magnetic field created by this circuit helps stretch out the tail lobes.
2.2.5 Polar Cusps and Auroral Zone

The polar cusps are two magnetic funnel-shaped regions, one north and one south of the magnetic equator, which on the dayside the magnetic field lines leaving the cusps are closed, compressed, whereas on the nightside, they are almost all open stretched out magnetic field lines reaching deep into the magnetospheric tail. In this cusp region, solar wind plasma from the magnetosheath can enter deep inside of the magnetosphere along the magnetic field lines. This converging field allows the mixing of plasma from two different origins i.e., the solar wind and the ionosphere. This results in auroral displays and enhanced fluxes of energetic particles.

The auroral zone is an oval shaped region above the ionosphere in each hemisphere whose field lines extend into the plasma sheet and boundary layer. This is the region where visible auroras takes place. This oval shaped region has a radius of about 20° around the geomagnetic pole and extends towards the equator during the intense magnetic storms. This auroral zone is created by the precipitation of particles in the atmosphere. The cusp and boundary layers on the dayside and the plasma sheet and plasma sheet boundary layer on the nightside are the sources of these precipitations.

2.3 Ionosphere

The ionosphere is the interface between the ionized plasma of the magnetosphere and the neutral atmosphere, where the concentration of free electrons is
so large that it affects radio waves. This region starts in a height of approximately 50 km above the surface of the earth and extends up to \( \sim 500 \) km. The concentration of electrons varies from \( 10^7 \) particles m\(^{-3}\) at \( \sim 60 \) km to a maximum of \( 10^{12} \) particles m\(^{-3}\) at 250–300 km. Because of the high density of the ionosphere and the existence of a large neutral component, the particle motion is not determined by the magnetic field only. The ionosphere differs from the magnetosphere in so far as collisions of charged particles with the neutrals of the atmosphere occur frequently, the ionosphere therefore is characterized by a collision-dominated plasma. Thus the conductivity is finite and the frozen-in flux approximation is no longer valid. The ionosphere is formed by the ionization of atmospheric constituents by particles coming from different sources. Sources of ionization include photons undergoing photoionization and energetic particle ‘precipitation’ undergoing impact ionization. In the impact ionization process, energetic charged particles collide with atmospheric neutral atoms, ionizing them and creating free electrons. In the process of photoionization due the UV radiation coming from the Sun, solar photons incident on the atmosphere are absorbed by neutral atoms, and then the atom is dissociated into charged particles. At higher altitudes the plasma becomes collisionless and can move freely along magnetic field lines and escapes the gravitational potential of the Earth. As a result, the loss of plasma from the ionosphere is a major source of particles for processes operating in the magnetosphere.
2.3.1 Density variation of the Ionosphere

The ionosphere is composed of a series of overlapping layers. The three major layers of the ionosphere are the D region, the E region and the F region. The F region is further divided into F1 and F2 layers. In each layer, there is an altitude of maximum density. Since UV radiation coming from the Sun is the main source of ionization, the heights and densities of ionization greatly depends on the hour of the day, season of the year and sunspots of a solar cycle i.e, rate of ionization is more in the daytime than at night, more in summertime than in wintertime, and more at solar maxima than at minima. The ionization profile of the various layers is shown in figure 2.2.

The D region is the closest layer to the Earth and is located between 50–90 km above the surface of the Earth with peak density at ~90 km. This layer is primarily caused when solar radiation ionizes nitric oxide (NO). Primary sources of ionization are x-rays and very intense Lyman–α radiation from the sun with a small fraction of ionization by cosmic ray particles. Since solar radiation is the main source of ionization in this region, the ionized particles...
are largely reduced at nighttime because of high recombination rates. The E region is located between 90–150 km above the surface of the earth \( \sim 110 \) km. The ionization is mainly produced by Ultraviolet radiation and solar x-rays. \( \text{O}^2+ \) and \( \text{NO}^+ \) dominates this layer. The plasma in this region is strongly collisional, which makes it a primary site for the closure of field–aligned currents in the ionosphere. At sunset, the E region electron density drops by a factor of 10 or more in a short period (tens of minutes) before reaching a night time equilibrium density. The F1 and F2 layers are located at 150–200 km and 200–higher above the surface of the Earth. This F layer mainly consists of \( \text{O}^+ \) ions. Solar ultraviolet radiation is the primary source of ionization. The F1 region has an altitude peak near 200 km, but is absent at night. The F2 region has a peak near 300 km during the day time and at higher altitudes at night. The two layers combine into one F-region on the nightside but are separated in the presence of sunlight due different ionization and recombination rates.

2.3.2 Magnetosphere - Ionosphere Coupling

The ionosphere has free electric charges that result in an electrical conductance, because of which it actively interacts with the magnetosphere through electromagnetic and kinetic processes. Part of this interaction involves the flow of charged particles along the magnetic fields as field-aligned currents (FAC) (also called Birkeland currents) between the ionosphere and magnetosphere. Closure of this currents occur in ionospheric regions where the collision among the plasma particles is the greatest, typically near 130 km above the Earth. And in the magnetosperic region, closure of these currents occur through the dawn-dusk cross-tail currents.
As the geomagnetic field lines convect from sunward to tailward through the magnetosphere, the associated plasma flows in the magnetosphere and ionosphere ultimately influence one another. As the antisunward convecting plasma moves across the magnetospheric geomagnetic field lines, it gives rise to a dawn-dusk electric field in the equatorial plane, given by the expression $E_M = -v \times B_0$, where $v$ is the convection velocity of the magnetospheric plasma, and $B_0$ is the local magnetic field. The penetration of the dawn-dusk electric field into the high-latitude ionosphere drives an electric current across the magnetic field in the strongly collisional regions of the ionosphere. Field-aligned currents develop wherever the perpendicular currents and the convection electric field has a non-zero divergence. The currents are diverted into field-aligned currents in regions where they have a non-zero divergence, as illustrated in figure 2.3. The region 1
field-aligned currents are the high-latitude currents typically observed between 67° and 75° latitude in the ionosphere. This current is out of the ionosphere in the dusk region and into the ionosphere in the dawn region. The lower latitude channels of field-aligned current, the region 2 currents, are observed between 63° and 68° latitude in the ionosphere. Their direction is opposite to the region 1 currents - into the ionosphere in the dusk region and out of the ionosphere in the dawn region.

The Region 1 current originates in the region of the interface between field lines dragged tailward by the solar wind and field lines returning to the dayside of the Earth. This interface is electrically charged, positive on the dayside of the Earth and negative on the nightside. The charge on this interface is a consequence of the Lorentz force. Positive charges attached to field lines moving tailward on the dawn side of the Earth are deflected earthward toward the interface. In contrast, positive charges moving sunward just inside the interface are deflected away from the Earth (because their velocity is opposite to those on the other side of the interface). This is again toward the interface; hence, a positive charge accumulates. On the dusk side the deflections are the same, but a negative charge accumulates at the interface. Because of this charge, the centres of the loops become charged like the terminals of a battery. Because the ionosphere conducts current, current can flow from the positive to negative terminals. Thus, current leaves the positive terminal of the magnetospheric “battery” and flows down field lines on the dawn side, then across the polar ionosphere, and finally out on the dusk side.
2.4 Geomagnetic substorm

A geomagnetic substorm is a process in which solar wind energy is first stored in the magnetotail lobes through the magnetic reconnection on the dayside magnetopause and then the stored energy grows until at some instant, the magnetosphere becomes unstable and releases explosively the stored energy in the form of particle energization, particle precipitation, and Joule heating causing most dramatic phenomena in various regions of the magnetosphere and ionosphere. A southward turning of the IMF initiates the dayside reconnection. The aurora, a natural light display in the sky usually observed during night time in the polar regions, in the northern and southern hemispheres is one of the phenomena occurring as a result of such large scale disturbances in the magnetosphere. The typical timescale of a substorm process is approximately 1–3 hours.

A typical substorm is considered to consist of three distinct phases: i. Growth phase, ii. Expansion phase, and iii. Recovery phase. Different signatures characterizes each of these phases. During the growth phase, solar wind energy is accumulated in the Earth’s magnetotail lobes due to the southward IMF and subsequent reconnection on the dayside magnetopause as is evidenced by an increase in the size of the polar caps [Sigwarth, 1–02; Frank, T–1]. The stretching of the near-Earth magnetic field from a dipolar to a more tail like geometry, which in other words, plasma sheet thinning as well as increase in tail field magnitude occurs [Aubry and McPherron, 1971] and the peak current density in the cross-tail current becomes very large. The entire auroral oval expands toward lower latitudes [McPherron, 1972]. The duration of the growth phase is about 30 to 60 minutes.
The expansion phase lasts for about 30–60 minutes. During this phase, the stored magnetotail energy is released leading to a more dipolar shape of the magnetic field lines which had been very stretched and tail-like at the end of the growth phase. The aurora suddenly brightens, and the ionospheric current flows, particularly the westward electrojet, intensify greatly.

The substorm sequence completes during the recovery phase which may lasts for about 1–2 hours. During this phase, the magnetosphere returns to its original configuration. The intense ionospheric currents and auroral activity gradually die out with the aurora retreating to higher latitudes. Also the current sheet and plasma sheet returns to its original size.

2.4.1 Substorm models

Substorms start at a small region in space but within minutes cover an immense region of the magnetosphere. The mechanism that triggers substorm onset remains an unsolved issue. Several substorm models have been proposed by many investigators. Two most popular models are the Current Sheet Disruption model (CSD) and the Near-Earth Neutral Line model (NENL). These two models involve identical processes but proposes different substorm onset locations and a different sequence of events.

In the current sheet disruption model, the neutral sheet stability is first disrupted by local kinetic instabilities at about 10 Re from the Earth leading to a cross-tail current disruption, substorm current wedge and geostationary injection. The tail current disruption is quickly followed by the auroral break up [Birn et al., 1999; Lui et al., 1990, 1991]. In the tailward direction, this CSD
launches a rarefaction wave which may or may not trigger a tailward secondary NENL formation.

The Near-Earth neutral line (NENL) model assumes that first magnetic reconnection takes place between the oppositely directed field lines above and below the current sheet at a distance of about 20–30 $R_E$ [Baker et al., 1996]. This leads to plasma convection towards the inner edge of the plasma sheet. The plasma flow is decelerated because the background magnetic field increases as it gets closer to the Earth, and as a consequence, the magnetic flux is piled up in the transition region between the dipolar and stretched magnetic configurations, causing dipolarization there. The associated change in the plasma distribution and the magnetic configuration results in the divergence of the tail current, which has the sense of region 1 current and therefore can be interpreted as the formation of the substorm wedge current system. In this model, the auroral break up occurs later than in the CSD model.

### 2.4.2 Substorm Indices

The strength of geomagnetic substorms is usually measured in terms of the auroral electrojet indices (AE, AU, AL). These indices are designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. The auroral electrojet index was defined and developed by Davis and Sugiura [1966] and later modified by Mayaud [1980]. It is constructed from magnetic records obtained by a chain of magnetometers located throughout the auroral zone. The monthly mean value for each station is first calculated by averaging all
the data and then subtracted from each value of the data recorded at the station during that month. The resulting magnetic records from all the stations are superimposed and two traces are drawn creating an envelop of positive and negative variations. The maximum positive disturbance level defined by the upper envelop defines the Auroral Upper (AU) index and it expresses the strongest current intensity of the eastward auroral electrojet. Similarly, the minimum disturbance level defined by the lower envelop gives the auroral lower (AL) index and it expresses the strongest current intensity of the westward auroral electrojet. The difference of AU and AL indices gives the AE index which expresses the overall activity of the auroral electrojet.

These indices closely reflect the features of magnetospheric substorms. During periods of enhanced geomagnetic activity the westward electrojet, monitored by the AL index, increases abruptly due to currents driven by plasma processes in the magnetotail. On the other hand, the eastward electrojet, which is monitored by the AU index increases due to processes such as the partial ring current closure via the ionosphere in the evening sector [Felstein et al., 2006]. Therefore, the analysis of the AL and AU indices can yield insights into the dynamics of different aspects of the magnetosphere. The AL index reflects the variability of the magnetospheric substorms and is widely used in the studies of the dynamical behaviour.

2.5 Geomagnetic Storm

A geomagnetic storm is a large and long duration (~1–5 days), low–latitude magnetic disturbances occurring as a result of the ring current enhancement
This ring current enhancement occurs when the coupling of the solar wind to the magnetosphere becomes strong and prolonged which in turn leads to increased energy transfer from the solar wind to the magnetosphere.

The solar and interplanetary structures that are mainly responsible for the geomagnetic storms are the Earthward directed Coronal Mass Ejections (CMEs) and the stream-stream interaction regions formed by interaction of high speed wind streams with streams of low speed called Corotating Interaction Regions (CIR) [Gonzalez et al., 1999]. Magnetic storms are relatively rare in comparison to the occurrence rate of substorms. The frequency of geomagnetic storms increases and decreases with the sunspot cycle. CME driven storms are more common during the maximum of the solar cycle and CIR driven storms are more common during the solar minimum.

Storms and substorms are related to some extent. Substorms occurring during storms are generally more intense than substorms occurring during the non-storm times. There are various space weather phenomena that are caused by the storms. They include: Solar Energetic Particle (SEP) events, geomagnetically induced currents (GIC), ionospheric disturbances which cause radio and radar scintillation, disruption of navigation by magnetic compass and auroral displays at much lower latitude than normal. The most commonly used index to measure the strength the magnetic storms is the Disturbance Storm time index (Dst), which is calculated on an hourly basis from measurements made by a network of four ground based magnetometer stations at low and middle latitudes. They are at Honolulu (Hawaii Islands), San Juan (Puerto Rico), Hermanus (South Africa) and Kakioka (Japan). This quantity was derived and introduced by
Sugiura [1964]. Geomagnetic storms with Dst index < -100 nT are generally considered as intense storms.

Phases of a storm:

A magnetic storm, like the substorms, consists of three distinct phases: initial, main, and recovery phase. The initial phase of a storm is characterized by a sudden worldwide increase in the Earth’s magnetic field by tens of nT. This is caused by an increased solar wind dynamic pressure acting on the magnetosphere. The increased pressure compresses the dayside magnetosphere, forcing the magnetopause current closer to the Earth, and at the same time increasing it. The magnitude of the initial phase has been shown to be proportional to the square root of the solar wind dynamic pressure, $\sqrt{nV^2}$, where $n$ is the solar wind density and $V$, the solar wind speed [Ogilvie et al., 1968; Siscoe et al., 1968]. The initial phase may not be present in some of the storms. This phase may take time from minutes to hours.

The main phase, which may last for days, is characterized by a large reduction in the horizontal component of the Earth’s magnetic field by about 100s of nT. This is due to an increase in energetic ions and electrons in the inner magnetosphere, where they become trapped on closed magnetic field lines and drift around the Earth, thus creating the ring current.

The recovery phase is characterized by the magnetosphere returning to its pre-storm stage. This may last for days. Charge exchange and Coulomb scattering have both been identified as major loss processes responsible for the decay of the ring current during this phase [Fok et al., 1991; Smith and Bewtra, 1978].
2.5.1 **Dst Index**

The characteristic signature of a magnetic storm is a depression in the horizontal-component of the magnetic field, which is caused by the ring current encircling the Earth in the westward direction. The *Dst* index represents the most commonly used measure of the state of the ring current. It is constructed by averaging the horizontal component of the Earth’s magnetic field measured hourly at four near equatorial geomagnetic observatories. Negative *Dst* values indicate a storm is in progress. These negative deflections are caused by the storm time ring current which flows around the Earth in the equatorial plane. This is because the strength of the surface magnetic field at low latitudes is inversely proportional to the energy content of the ring current. It was for the first time modelled by Burton et al. [1975] which was later modified by many researchers for a more accurate prediction eg. [Fenrich and Lujmann, 1998; O’Brien and McPherron, 2000].

2.5.2 **K and K_{p} indices**

*K* and *K_{p}* are magnetic indices used to measure the midlatitudinal geomagnetic disturbances. The *K*-index quantifies the maximum fluctuations of horizontal component of Earth’s magnetic field observed on a magnetometer relative to a quite day, during a three-hour interval. It was first introduced by Julius Bartels in 1938. The conversion table from maximum fluctuation (nT) to *K*-index, varies from observatory to observatory in such a way that the historical rate of occurrence of certain levels of *K* are about the same at all observatories. In practice this means that observatories at higher geomagnetic latitude require
higher levels of fluctuation for a given $K$-index. Given below is the conversion table 2.2:

The planetary $K_p$ index is derived by calculating a weighted average of $K$-indices from a network of 13 subauroral geomagnetic observatories. It is designed to measure solar particle radiation by its magnetic effects. It was introduced by [Bartels, 1949].

### 2.5.3 Some Prominent Geomagnetic Storms in History

Most of the geomagnetic storms occur during the maximum years of the solar cycle. Several geomagnetic storms of quite strong intensities have been recorded since nineteenth century. Some of the severe storm events are described here. The first storm event observed by humans was that occurred on September 2, 1959. This storm event was the result of a great solar flare that occurred on September 1 which was observed independently by Carrington and Hodgson.
Another severe storm event occurred on November 1, 1903. Telegraph systems of Western Union were affected by this storm. Transatlantic cables were also affected.

In March 13 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 has been exposed to induced currents from the geomagnetic storm that exceeded its design capacity and it melted. This was the result of a great CME that occurred 3 days before i.e., on March 9, 1989. This storm affected six million people with no lights for completely 9 hours. This storm also caused thousands of space objects (including hundreds of operational satellites) to lose many kilometers of altitude which led to the reduction of orbital lifetime.

Another great storm called the halloween storm occurred on October 29, 2003. During this storm event, intense auroral displays were observed over most of north America. Extensive satellite problems were reported, including the loss of the $ 450 million Midori–2 research satellite. This was the result of a strong solar flare that occurred just 19 hours ahead.
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