# DYNAMICS OF INTERPLANETARY MAGNETIC FIELD IN SPACE WEATHER

By
Desta Fekede Geleta

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**Supervisor:** ______________________
**Tolu Biressa (PhD Fellow)**

**Cosupervisor:** ______________________
**Hiwot Tegegn (MSc.)**

**External Examiner:** ______________________
**Solomon Belay (PhD)**

**Internal Examiner:** ______________________

**Chairperson:** ______________________

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**Author:** **Desta Fekede Geleta**

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**Signature of Author**

***TO MY BELOVED FAMILY***

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# Acknowledgements

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# Abstract

The interaction of the solar wind magnetic field with the Earth's magnetosphere has a great effect on the near-Earth space environment. This space weather interaction further affects human life activities and life on earth. So today, there has been growing interest in solar-terrestrial studies as a result of the availability of satellite observations of space, particularly in the near Earth environment. However, as recent literature reviews show that though there is an overall progress in the observational works the theories that fit the observations lack correlation and need further works. One of the key points contributing to the difficulty of theoretical work is exploiting the full Magnetohydrodynamic (MHD) equations. If there is any, most works assume the collision-free system with simplify boundary conditions. Motivated by this scientific background, we did study the solar wind - earth's magnetosphere interactions by working on the magnetohydrodynamic (MHD) equations by setting simplifying boundary equations where both collision and collisionless fluid system is considered in plasma state(cold and hot). The results we derived here is in conformity to conclude the existing models indeed work at large but has limitations to include very fine local effects like magnetic storms and the observed relativistic particle anomalies in ionosphere. Additionally, we come to the conclusion that there is a need of advanced computational works to extract more accurate data from the full MHD equations.

**Key words: IMF, Ionosphere, Magnetosphere, MHD, Space Weather, Sun.**

# Chapter 1

# General Introduction

## I. Background

Studying the Sun is important to understand the various ways in which it affects our terrestrial environment. For more than a century, scholars studying the Sun and Sun-Earth connection have identified different regions within the sun, the solar wind and its mechanism through interplanetary space to the Earth's magnetosphere and regions of the Earth's atmosphere.

Today, we have more sophisticated ground-based and space-based observations to study solar activity and its effect on surrounding environment. And on the other hand, there is a great deal of theoretical works going on with a plethora of models to fit the observations[1]. Yet, there are debates over the theoretical works in matching the observations. One of the key points contributing to the debates is the difficulty of working out the full Magnetohydrodynamic (MHD) equations that includes all effects like collisions and relativistic effects. So motivated with this scientific rationale, we are interested to work on MHD interactions of solar-terrestrial environment from the sun through to the earth's ionosphere which is crucial for how to control, adjust and get ready to live when it comes to life matter on earth. Accordingly we have dynamical equations such as the Interrestrial Magnetic Field (IMF) from MHD system that includes collision effect. Then, the physical contents and implications of the analytically derived equations are being discussed with some setting appropriate boundary conditions.

The outline of the work is organized as follows: In chapter one we introduce the general introduction. In the second chapter we introduce the basic physics and principles of plasma fluid. Here, we do derive the fundamental plasma equations from Boltzmann's Transport Equation (BTE), the MHD equations where it is being used in our system of the solar wind and earh's magnetosphere interaction. In the third chapter we present the solar wind-earth's magnetosphere interaction. Here, the structure and the geometry of the magnetosphere is provided and described. In chapter four we discuss on the the physical contents and implications of the derived MHD equations on the solar wind - magnetosphere coupling with and without collision by setting appropriate boundary conditions. In the fifth final chapter we give the summary and conclusions of our results.

## II. Literature Review

According to current understanding, the earth has an internal dipole magnetic moment created by a magnetic dynamo deep inside the earth in the fluid, electrically conducting core. The sun emits magnetized plasma consisting of mainly protons and electrons to its surrounding terrestrial environment (the solar wind). The pressure exerted by this flowing plasma is counteracted by the earth's magnetic field just at the end of the upper atmosphere (ionosphere)[8]. This coupling layer with the solar wind is commonly known as the magnetosphere.

Currently, ground-based and space-borne solar observations reveal that a geomagnetic storm can be regarded as an event in which disturbances are triggered by solar eruptions. These features, that have their origin in the magnetic activity of the sun, propagate through interplanetary space and interact with the terrestrial magnetosphere subsequently affecting the near-earth space environment and the upper atmosphere.

Consequently, space weather discipline involves different physical scenarios, which are characterized by very different physical conditions, ranging from the sun to the terrestrial magnetosphere and ionosphere[12],[16]. Today, great modeling efforts made during the last years that a few sun-to-ionosphere physics-based numerical codes have been developed. However, the success of the prediction is still far from achieving the desirable results and much more progress is needed. Some aspects involved in this progress concern both the technical progress (developing and validating tools to forecast, selecting the optimal parameters as inputs for the tools, improving accuracy in prediction with short lead time) and the scientific development, i.e., deeper understanding of the energy transfer process from the solar wind to the coupled magnetosphere-ionosphere- system[19].

Generally, in order to understand how the solar wind interacts with the magnetosphere and in turn the magnetosphere reacts needs examining the motion of charged particles in magnetic fields and the creation of the electric and magnetic fields by these same particles. The charged particles moving in a magnetic field experiences Lorentz's forces with complex motion pertaining to the interactions where the particle gyrates around the magnetic fields. On the other hand if the magnetic field varies it causes to induce currents, electric fields and further interactions in the environment[20],[21]

The basic laws of the charges, currents, electromagnetic fields in plasma together with the conservation of mass, momentum and energy are being used to derive the governing equations in the form of waves (in the plasma). Accordingly, to the current understanding there are three propagation speed modes in the magnetized solar wind plasma. The fast mode wave compresses the magnetic field and plasma; the intermediate mode wave bends the flow and magnetic field, but does not compress it; and the slow mode wave rarefies the field while it compresses the plasma and vice versa. The solar wind travels faster than the propagation speed of all three of these waves so when it reaches the Earth's magnetosphere the pressure waves needed to deflect the solar wind plasma cannot propagate upstream into the solar wind without creating a shock front. The geometry of this shock, the deflected flow, called the magnetosheath and the magnetopause, the boundary between the magnetosheath and the magnetosphere can flow. So the interaction of the solar wind with a dipole magnetic field is somewhat complicated. The solar-terrestrial environment comprises fully ionized plasmas, partially ionized plasma (the ionosphere) and Earth's neutral atmosphere. The Sun-Earth interaction depends on chains of coupling processes involving the solar interior, the solar atmosphere, and solar wind-magnetosphere, magnetosphere-ionosphere, and ionosphere atmosphere interactions. These interactions occur through radiative, dynamic and electromagnetic processes. Within the chain of relations, the Sun is the primary driver of change as it continuously emits charged particles and radiation in the solar-terrestrial environment[18]

The Sun and the Earth represent a coupled dynamic system. The space between the Earth and the Sun is filled with the solar wind plasma. This solar wind also carries with it a magnetic field, which allows it to interact strongly with the Earth's magnetosphere due to the so called magnetic field reconnection. The interaction of the solar wind magnetic field with the Earth's magnetosphere has a great effect on the near-Earth space environment. The effect of this interaction is called space weather. Space weather is an important topic of current research. Space weather can pose a danger to trans-polar flights, while geomagnetically induced current can flow through power lines and pipelines near the surface and damage them as a result of auroral disturbances[9]

Extreme space weather situations are called geomagnetic storms, and are defined as periods of intense geomagnetic activity. Geomagnetic activity is primarily driven by magnetic reconnection between the Interplanetary Magnetic Field (IMF) and the terrestrial magnetic field. Coherent solar wind structures containing magnetic fields and high velocities are most efficient drivers of space weather events. We can observe the geomagnetic activity with ground-based magnetometers. Geomagnetic storms have been related to the interaction of the solar wind with the Earth's magnetosphere. Several fundamental points in the problem of magnetic reconnection still remain to be clarified. For example, even if theoretically the main features distinguishing a resistive or a collisionless reconnection layer are fairly well understood, the debate concerning which micro-process drives reconnection is still open. Another outstanding problem of magnetic reconnection is the interplay between the micro and macrophysics during the full evolution of the large scale system. On the other hand, magnetic reconnection has been the focus of extended studies since its first introduction by[18],[9]. To explain the sudden release of energy in solar flares. Nowadays it is considered as the key ingredient for theories of coronal heating, solar flares and jets, and coronal mass ejections in the Sun, of magnetic storms and sub-storms in the Earth magnetosphere.Such attributes made it attractive for high-energy astrophysics to explain, radiation and flares in active galactic nuclei (AGNs) jets or in gamma-ray bursts, the heating of Active Galactic Nuclei (AGN)and micro quasar coronae and associated flares, the flat radio spectra from galactic nuclei and AGNs[22].

## III. Statement of the Problem

Reviewing the current state of scientific models available for solar wind Earth's magnetosphere interaction development is actually extreme ambitious task. It covers a broad range of topics from the sun to the earth and of techniques and methods from the ideal Magnetohydrodynamic equations to particle interaction modeling. In recent years, great effort have been undertaken to understand the solar wind with and interplanetary magnetic field with it, the interactions of solar wind and earth's magnetic field and the effects of this interaction the space weather but, many issues remain unsolved. The ongoing upgrade projects for a direct detection of solar wind are involving new and improved technologies. The physics behind the collision effect of solar wind magnetosphere interaction and the space weather is currently given attention by the scientific community. There is a great scientific collaboration for theoretical modeling and ground based and space based observational events. The mechanism of matching and testing theoretical principles by observation or the converse remains a challenge at any level.

## Research Questions

• How a Solar wind affect atmosphere of the earth?

• How Solar wind and Interplanetary Magnetic Field couple with earth's magnetosphere and produce disturbances on earth?

• What is the significance of collision effect in the coupling shock waves between the solar wind and the magnetosphere?

### IV . Objectives

### I. General objective

The main objective is to study the Dynamics of Interplanetary Magnetic Field in Space Weather

### II. Specific Objectives

• To derive dynamical equations from the MHD equations in plasma state of interacting media (solar-earth).

• To analyze the physical implications of the derived MHD equations in explaining the interactions and effect of solar events including solar-wind on earth.

### V. Methodology

• The general method is to derive dynamical equations from which relevant dynamical parameters such as sound wave, energy and momentum are being derived from appropriate MHD equations in plasma state.

- The analytically derived equations are used to generate numerical values computationally with MATHEMATICA. The results had been discussed and summarized to remark.

# Chapter 2

# Basics of Plasma Physics and Magnetohydrodynamic Equations

The physics of the Sun Earth system is governed by many plasma processes and comprises nuclear reactions in the Suns interior, plasma eruptions from the Sun's surface, a steady-state solar wind, the interaction of the solar wind with the Earth's magnetosphere and the formation of the ionosphere. Therefore, one can not understand the physics in the regions of the Sun, Solar wind- Magnetosphere interaction and Interplanetary magnetic field without the knowledge of Plasma Physics.

## 2.1 Definition of Plasma

Of the four fundamental states of matter, plasma is by far the most abundant in the observable Universe, with estimates suggesting that more than 99 percent of all known matter is in the plasma state [2]. Plasma is a quasi-neutral gas consisting of positively and negatively charged particles (usually ions and electrons) which are subject to electric, magnetic and other forces, and which exhibit collective behavior. i.e., Plasma is a gas of electrically charged particles in which the number of negatively charged particles is roughly equal to the number of positively charged particles. Both positive and negative charge carriers are evenly distributed throughout a plasma resulting in average charge neutrality.

This equality between the density of both negative and positive charge carriers on a large scale, along with possible smaller regions of charge imbalance, is known as quasineutrality.

Plasmas can contain some neutral particles which interact with charged particles via collisions or ionization. Examples include the Earth's ionosphere, upper atmosphere, interstellar medium, molecular clouds. The simplest plasma is formed by ionization of atomic hydrogen, forming plasma of equal numbers of (low mass) electrons and (heavier) protons. Hence, any ionized gas cannot be called plasma, of course; there is always some small degree of ionization in any gas. Three fundamental parameters characterize plasma [7]:

1. The particle density n (measured in particles per cubic meter)

2. The temperature T of each species (usually measured in eV, where 1 eV=11,605 K)

3. The steady state magnetic field B (measured in Tesla).

A host of subsidiary parameters like Debye length, Larmor radius, plasma frequency, cyclotron frequency, thermal velocity can be derived from these three fundamental parameters. the plasma state to exist, three fundamental criteria must be fulfilled. Each of these will now be discussed in turn.

## 2.2 The Debye Shielding

The most important feature of a plasma is its ability to reduce electric fields very effectively [6]. We can discuss this effect of shielding by placing a point-like extra charge +Q into an infinitely large homogeneous plasma, which originally has equal densities of electrons and singly charged positive ions $n_i = n_e$. A single stationary point-like charged particle (e.g. an electron of charge e), in the absence of any other charged particle, produces an electrostatic field (E) as described by the Poisson equation:

$$\nabla.E = \frac{e}{\varepsilon_o}\delta^3(r) \tag{2.2.1}$$

where $\delta(r)$ is the Dirac delta function, $\epsilon_o$ is the vacuum permittivity and r is the radial unit vector. The solution to equation 2.2.1 is well known and is the electric field of a single charge:

$$E_o(r) = \frac{e}{4\pi\epsilon_o}\frac{r}{r^3} \tag{2.2.2}$$

where r is the distance from the charged particle.

Since $\nabla \times E_o = 0$, the electric field vector can be expressed in terms of a scalar potential as $E_o = -\nabla\Phi(r)$ where the scalar potential is:

$$\Phi(r) = \frac{e}{4\pi\epsilon_o r} \tag{2.2.3}$$

This scalar potential is known as the Coulomb Potential and it describes the electric potential field created by a stationary point-like charged particle. The effect of the Coulomb Potential is that particles of the opposite charge to the point-like charged particle are attracted to it whilst particles of a similar charge (e.g. both negatively charged) are repelled from it. In a plasma, where there is an abundance of both negatively and positively charged particles, a cloud of oppositely charged particles forms around a single charged particle. This effect is known as Debye Shielding [10]. Due to the Debye Shielding, the single point charge is no longer in the absence of other charged particles and so the electric potential field differs from $\Phi(r)$ in Eq.2.2.3. The new potential, known as the Debye potential $\Phi_D$, can be expressed as a function of the original potential:

$$\Phi_D = \Phi_o e^{-e\sqrt{\frac{n_o}{\varepsilon_o kT}}r} \tag{2.2.4}$$

$$\Phi_D = \Phi_o e^{-\frac{r}{\lambda_D}} \tag{2.2.5}$$

where $\lambda_D$ is a parameter known as the Debye length and is defined as:

$$\lambda_D = \sqrt{\frac{\varepsilon_o k_B T_e}{n_o e^2}} \tag{2.2.6}$$

where $k_B$ is the Boltzmann constant, T is the effective plasma temperature and $n$ is the electron/ion density. The quantity $\lambda_D$, called the Debye length is a measure of the shielding distance or thickness of the sheath. The electron and ion Debye length measure the contribution of each charged to this shielding and are only equals when $K_BT_i = K_BT_e$, Because of electron temperature is usually higher $K_BT_e \gg K_BT_i$ the electron Debye length is then larger and is often considered as the plasma Debye length. The shielding length increases when the temperature rises, i.e, the size of the perturbed region becomes smaller. The Debye shielding length, equation 2.2.6 is of great importance: in areas smaller than $\lambda_D$ electric fields are too weak to take influence on the motion of particles. Thus quasineutrality is only given beyond a given volume. The result of Debye potential, given in Eq. 2.2.5 is that at distances larger than the Debye length the effective potential of the single point charge diminishes exponentially due to Debye Shielding. At lengths much greater than the Debye length (i.e. $L \gg \lambda_D$), the electro-static force from individual charges is essentially zero and so the plasma is quasineutral. This is the first criterion of a plasma.

## 2.3 The plasma and coupling parameters

The ideal plasma requires a number of electric charges inside an sphere with radius of $\lambda_D$, then the Debye sphere is defined by the volume $V_{Debye}$

$$V_{Debye} = \frac{4}{3}\pi\lambda_{D^3} \tag{2.3.1}$$

In a Debye sphere there are charged particle and there is a number $N_D$ of particles. Several definitions exist for the term plasma parameter, including the ratio of the average potential and kinetic energies in the plasma. Then the plasma parameter ($\Lambda$)is given by:

$$\Lambda = 4\pi n\lambda_D^3 \tag{2.3.2}$$

And this defines the electron plasma parameter as well as the equivalent definition of ion plasma parameter.

Another definition for the plasma parameter is the number of electrons in a plasma contained within a Debye sphere (a sphere with a radius equal to the Debye length) and is given by:

$$N_D = \frac{4}{3}\pi n \lambda_D^3 \tag{2.3.3}$$

The average distance between particles is,

$$r_d \equiv n^{-1/3} \tag{2.3.4}$$

and the distance of closest approach,

$$r_c \equiv \frac{e^2}{4\pi}\epsilon_o T \tag{2.3.5}$$

The states of neutral matter, solid, liquid, gaseous, are determined by the degree of coupling between the atoms, which is described by the coupling parameter. Coupling parameter is the ratio of the potential energy of nearest neighbors $\Gamma = E_{el}/E_{th}$ and the thermal energy $E_{th} \sim k_b T$. Or is the ratio between average distance between particles and the distance of closest approach.

$$\Gamma = \frac{r_d}{r_c} = \frac{e^2 n^{1/3}}{4\pi\epsilon_o k_B T} \sim \frac{< E_{el} >}{< E_{th} >} \tag{2.3.6}$$

Respectively we have,

$$< E_{el} > \sim \frac{e^2}{4\pi}\epsilon_o r_d \qquad \text{and} \qquad < E_{th} > \sim K_b T$$

When the $r_d/r_c$ ratio is small, charged particles are dominated by one anothers electrostatic influence more or less continuously, and their kinetic energies are small compared to the interaction potential energies. Such plasmas are termed strongly coupled. On the other hand, when the ratio is large, strong electrostatic interactions between individual particles are occasional and relatively rare events. Such plasmas are termed weakly coupled. The relation between the plasma parameter and coupling parameter can be found by combining the equations 2.3.2 and 2.3.6.

$$\Lambda = \frac{1}{4\pi}\left[\frac{r_d}{r_c}\right]^{3/2} = \frac{(4\pi)^{1/2}\epsilon_o^{3/2}}{e^3}\frac{T^{3/2}}{n^{1/2}} \tag{2.3.7}$$

It can be seen that the case $\wedge \ll 1$, in which the Debye sphere is sparsely populated, corresponds to a strongly coupled plasma. Likewise, the case $\wedge \gg 1$ in which the Debye sphere is densely populated, corresponds to a weakly coupled plasma. Regardless of the two plasma parameter definition is used, the second plasma criterion is that the plasma parameter of the ionized gas must be large e.g. $\Lambda \gg 1$

## 2.4 Plasma Frequency

When the quasineutrality of a plasma is disturbed by some external force, the electrons (and to a lesser extent the ions) oppose the disturbance to restore charge neutrality. On small scales one expects there to be local breakdowns in charge neutrality. But, since plasmas consist of positive and negative charges, and opposite charges attract, then any departure from charge neutrality leads to a restoring force back towards charge neutrality. Due to their inertia, they oscillate around the equilibrium position and charged particle can leave its neutral position up to a defined length, the Debye length $\lambda_D$. This restoring force leads to a natural oscillation of the plasma, which are called plasma oscillations and occur at a frequency called the plasma frequency ($\omega_p$). Therefore,

$$m\frac{\partial^2\delta}{\partial t^2} + eE = 0 \tag{2.4.1}$$

According to Poisson's equation 2.2.1, a displacement of the charge carriers in a plasma results in a uniform electric field in the direction of the net displacement ($\delta$)

$$E = \frac{ne}{\varepsilon_o}\delta \tag{2.4.2}$$

where $e$ is the standard electrical charge and $n$ is the number density of charge carriers. The equations of motion for the electrons and ions are:

$$m_e\frac{d^2\delta_e}{dt^2} = -eE \tag{2.4.3}$$

$$m_i \frac{d^2\delta_i}{dt^2} = eE \tag{2.4.4}$$

where $m_e$ and $m_i$ are the electron and ion masses, respectively. Combining the equations of motion gives the oscillating relative motion between the ions and electrons:

$$\frac{d^2\delta}{dt^2} = \frac{d^2\delta_e}{dt^2} - \frac{d^2\delta_i}{dt^2}$$

$$= \left( \frac{e^2 n}{\epsilon_o m_e} + \frac{e^2 n}{\delta \epsilon_o m_i} \right) \tag{2.4.5}$$

The frequency of the oscillation, as described in equation 2.4.5 is the plasma frequency and is the sum of the squares of the oscillation frequencies of the electrons ($\omega_{pe}$) and the ions ($\omega_{pi}$):

$$\omega_p^2 = \omega_{pe}^2 + \omega_{pi}^2 \tag{2.4.6}$$

Where $\omega_{pe}$ and $\omega_{pi}$ are given by

$$\omega_{pe} = \sqrt{\frac{e^2 n}{\epsilon_o} m_e} \tag{2.4.7}$$

$$\omega_{pi} = \sqrt{\frac{e^2 n}{\epsilon_o} m_i} \tag{2.4.8}$$

Since the mass of the ions is much greater than the mass of the electrons ($m_e \gg m_i$), the oscillation frequency of the electrons is much higher than that of the ions ($\omega_{pe} \gg \omega_{pi}$). The plasma frequency is therefore approximately equal to the electron plasma frequency ($\omega_p \approx \omega_{pe}$)

It is a characteristic frequency for a system of charged particles and it depends on the particles mass and density. We may also interpret the time scale associated to the plasma frequency $\tau_{pe}$ as proportional to the time that a thermal electron (with velocity

$V_{Te} = \sqrt{2k_bT_e/m_e}$) travels along a Debye length, i.e, is the average time between collisions of charged and neutral particles.

$$\tau_{pe} = \frac{1}{f_{pe}} \simeq \frac{\lambda_D}{VT_e} \simeq (\frac{\epsilon_o m_e}{2n_e e^2})^{1/2} = \frac{1}{\sqrt{2}f_{pe}} \tag{2.4.9}$$

For the plasma state to remain, the time average between two charged-neutral particle collisions ($\tau_n$) must be larger than the reciprocal of the plasma frequency,i.e. $\omega_p\tau_n \gg 1$. This is the third plasma criterion.

## 2.5 Charged Particle Motion

In the solar wind plasma, the mean free path of the charge carriers is so large that they can be considered with collision. The starting point to understanding the behavior is to know that the motion of a charged particle in such a system is governed by the Lorentz force ($F_L$):

$$F_L = q(E + V \times B) \tag{2.5.1}$$

which, in the context of a single particle, can be expressed as:

$$m\frac{dV}{dt} = q(E + V \times B) + F_g \tag{2.5.2}$$

where $m$ is the mass of the particle, $v$ is its total velocity and $q$ is its charge. The term $F_g$ represents non electromagnetic forces, such as the gravitational force. But not much important in this study.

**Particle Gyration**

For a particle in a magnetic field which is both uniform and unchanging, and in the absence of an electric field (i.e.$E = 0$), the charged particle will experience cyclotron gyration. Ignoring none electromagnetic forces and if B is assumed to act in the $\hat{z}$ direction only, i.e. $B = B_{\hat{z}}$, then the equation of motion, given in equation of Lorentz force $m\frac{dv}{dt} = q(E+V\times B)$, becomes:

$$\frac{dv}{dt} = \frac{q}{m} V \times B = \frac{q}{m} \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \\ v_x & v_y & v_z \\ 0 & 0 & B \end{bmatrix} \tag{2.5.3}$$

which gives:

$$\frac{dv_x}{dt} = \frac{qB}{m} v_y \tag{2.5.4}$$

$$\frac{dv_y}{dt} = -\frac{qB}{m} v_x \tag{2.5.5}$$

$$\frac{dv_z}{dt} = 0 \tag{2.5.6}$$

equations 2.5.4 and 2.5.5 imply that the particle has a circular motion perpendicular to B (i.e. in the x/y plane) with angular frequency $\Omega$

$$\Omega = \frac{qB}{m} \tag{2.5.7}$$

This angular frequency is often referred to as the cyclotron frequency or gyrofrequency. The radius of this circular motion, centred about the magnetic field line, is often known as the Larmor radius ($r_L$) or gyroradius and is given by:

$$r_L = \frac{v_\perp}{\Omega} = \frac{m v_\perp}{qB} \tag{2.5.8}$$

where $v_\perp$ is the perpendicular velocity and is constant for all particles of the same species. equations 2.5.7 and 2.5.8 show that heavier particles, of the same charge, will rotate at a lower gryofrequency and at a larger gyroradius and that particles with a faster perpendicular velocity will also rotate at a larger gyroradius. Ions and electrons, owing to their opposite electric charge, will rotate in opposite directions.

## 2.6 Boltzmann and Vlasov Equation

In a plasma, the most important force is the Lorentz force

$$F_i = q_i(E + V_i \times B) \tag{2.6.1}$$

where $q_i$ is the charge of particle i, E the electric field intensity, and B the magnetic flux density, must be evaluated at the time and location of the particle.

$$m_i \frac{dv_i}{dt} = F_i \qquad and \frac{dx_i}{dt} = v_i \tag{2.6.2}$$

As the sun shine, there is out flow energy for the interior of the sun's to the surface region. We now turn to an extremely simple description of how this flow can be quantified; this treatment is due to Ludwig Boltzmann and should not be confused with the Boltzmann formula of Maxwell-Boltzmann statistics. considering the in flow and out flow to and from a differential phase volume dV we have:

$$\text{particle density} \times dV = \frac{N}{V} A dx_i$$

$$\frac{N}{V} \times A \frac{dx_i}{dt} dt = \nu \frac{N}{V} A dt$$

the inflow is

$$= [\frac{dx_i}{dt} f(x_i, t) \frac{dv}{dx_i}] dt \tag{2.6.3}$$

outflow

$$\frac{dx_i}{dt} (f(x_i + dx_i, t) \frac{dv}{dx_i}) dt \tag{2.6.4}$$

the net outflow and inflow

$$\sum_i \frac{dx_i}{dt} [\frac{f(x_i + dx_i - f(x_i, t)}{dx_i}] dv dt \tag{2.6.5}$$

$$= \sum_i v_i \frac{\partial f}{\partial x_i} dvdt$$

The distribution function $f_\alpha(x, v, t)$ describes the density of particles phase space (x, v), it is the solution of the kinetic Boltzmann Vlasov equation and by taking the partial differential of the function.

$$f_\alpha = f_\alpha(x_i, v, t) \tag{2.6.6}$$

$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial x_i}\frac{dx_i}{dt} + \frac{\partial f_\alpha}{\partial v}\frac{dv}{dt} + \frac{\partial f_\alpha}{\partial t}\frac{dt}{dt}$$

$$\sum_i v_i \frac{\partial f}{\partial x_i} + a_i \frac{\partial f}{\partial v_i} + \frac{\partial f}{\partial t} \tag{2.6.7}$$

$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + a.\nabla_v f_\alpha = \frac{df_\alpha(x, v, t)}{dt}|_c \tag{2.6.8}$$

where the total time derivative is

$$|\frac{df_\alpha(x, v, t)}{dt}|_{collision} = \frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + a.\nabla_v f_\alpha,$$

$$a = \frac{q_\alpha}{m_\alpha}(E + v \times B) \tag{2.6.9}$$

In the absence of collision the collision integral is zero, and

$$\frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + \frac{q_\alpha}{m_\alpha}(E + V \times B).\nabla_v f_\alpha = 0 \tag{2.6.10}$$

The Boltzmann equation with the collisional term equal to zero is called collisionless Boltzmann equation or Vlasov equation. Therefore, equation 2.6.7 becomes,

$$\sum_i \frac{\partial f_\alpha}{\partial x_i}\frac{dx_i}{dt} = \frac{df_\alpha}{dt} - \frac{\partial f_\alpha}{\partial t}$$

$$v_i \frac{\partial f_\alpha}{\partial x_i} = -(\frac{\partial f_\alpha}{\partial t} - \frac{df_\alpha}{dt}) \tag{2.6.11}$$

The net outflow is given by

$$\sum_i v_i \frac{\partial f_\alpha}{\partial x_i} dvdt = -(\frac{\partial f_\alpha}{\partial t}) - \frac{df_\alpha}{dt} dvdt \tag{2.6.12}$$

note that $X_i$ represents the spatial and momentum coordinates

$$\frac{df_\alpha}{dt} = \sum_i (\dot{x_i} \frac{\partial f_\alpha}{\partial x_i} + \dot{p_i} \frac{\partial f_\alpha}{\partial p_i}) + \frac{\partial f_\alpha}{\partial t} = \Im \tag{2.6.13}$$

the action considered as the creation rate therefore,

$$\sum_i \frac{dx_i}{dt} \frac{\partial f_\alpha}{\partial x_i} dvdt = -(\frac{\partial f_\alpha}{\partial t} = -(\frac{\partial f_\alpha}{\partial t} - \Im) dvdt \tag{2.6.14}$$

$$\Im = \sum_i [(\dot{x_i} \frac{\partial f_\alpha}{\partial x_i}) + (\dot{p}_i \frac{\partial f_\alpha}{\partial p_i}) + \frac{\partial f_\alpha}{\partial t}] \tag{2.6.15}$$

This is known as the Boltzmann transport equation and can be written in several different ways. In vector notation we get

$$\Im = \frac{\partial f_\alpha}{\partial t} + \vec{v}.\vec{\nabla} f + \vec{F}.\frac{1}{m} \vec{\nabla}_v f \tag{2.6.16}$$

But, $\vec{F} = -\vec{\nabla}\Phi$

$$= \frac{\partial f_\alpha}{\partial t} + \vec{v}.\vec{\nabla} f - \frac{1}{m} \vec{\nabla}\Phi.\vec{\nabla}_v f$$

Here the potential gradient $\nabla\Phi$ has replaced the momentum time derivative while v is a gradient with respect to velocity. The quantity m is the mass of a typical particle. It is also not unusual to find the Boltzmann transport equation written in terms of the total Stokes time derivative

$$\frac{Df}{Dt} = \frac{\partial}{\partial t} + \vec{v}.\vec{\nabla} \tag{2.6.17}$$

equation2.6.17 is total Stoke's time derivation

$$\frac{Df}{Dt} = \Im \tag{2.6.18}$$

If $\Im = 0$, no particle creation and destruction and $\frac{Df}{Dt} = 0$ is called the homogeneous Boltzmann Transport equation

## 2.7 Magnetohydrodynamic Equations

Particle motion in the two-fluid system is described by the individual species mean velocities $u_e$, $u_i$ and by the pressures $P_e$, $P_i$ which give information on the random deviation of the velocity from its mean value. Magnetohydrodynamics is an alternate description of the plasma where instead of using $u_e$, $u_i$ are used. [3]

The current density is given by

$$J = \sum_\alpha n_\alpha u_\alpha q_\alpha \tag{2.7.1}$$

where the center of mass velocity is

$$u = \frac{1}{\rho}\sum_\alpha m_\alpha n_\alpha u_\alpha \qquad \text{where} \quad \rho = \sum_\alpha n_\alpha m_\alpha \tag{2.7.2}$$

### 2.7.1 Continuity Equation

The $n^{th}$ moment of the Boltzmann equation can be represented by

$$\int V^n \left[\frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + a.\nabla_v f_\alpha\right] dv = \int V^n \frac{\partial f_\alpha}{\partial t}|_{\text{collision}} dv \tag{2.7.3}$$

Taking the zeroth moment of Boltzmann equation n = 0 multiplying Eq. 2.7.3 by V raised to the power zero and then integrating over velocity space, then multiplying by the mass of the species $m_\alpha$ and sum over species to obtain.

$$\sum_\alpha m_\alpha \int \left[\frac{\partial f_\alpha}{dt} + v.\nabla f_\alpha + a.\nabla_v f_\alpha\right] dv = \sum_\alpha m_\alpha \int \frac{\partial f_\alpha}{\partial t}|_{collision} dv \tag{2.7.4}$$

The account for the collision term in Boltzmann equation is

$$Q^\rho(x,t) = m \int_{-\infty}^{\infty} \frac{\partial f_\alpha}{\partial t} \;|_c\; dv \tag{2.7.5}$$

$$Q^p(x,t) = m\int_{-\infty}^{\infty}(V-U)\frac{\partial f_\alpha}{\partial t}\mid_c dv \tag{2.7.6}$$

$$Q^E(x,t) = \frac{1}{2}m\int_{-\infty}^{\infty}(V-U)^2\frac{\partial f_\alpha}{\partial t}\mid_c dv \tag{2.7.7}$$

$$\sum_\alpha m_\alpha\int\frac{\partial f_\alpha}{\partial t}dv + \sum_\alpha m_\alpha\int(v.\nabla f_\alpha)dv + \sum_\alpha m_\alpha\int(a.\nabla_v f_\alpha)dv = \sum_\alpha m_\alpha\int\frac{\partial f_\alpha}{\partial t}\mid_c dv \tag{2.7.8}$$

using the definition in equation 2.4.9 the first term of this equation gives

$$\sum_\alpha m_\alpha\int\frac{\partial f_\alpha}{\partial t}dv = m_\alpha\frac{\partial}{\partial t}\sum_\alpha\int f_\alpha dv = \frac{\partial}{\partial t}\sum_\alpha m_\alpha n_\alpha \tag{2.7.9}$$

The time and velocity are independent variables. Here equation 2.7.9 can be given by

$$\sum_\alpha m_\alpha\int\frac{\partial f_\alpha}{\partial t}dv = \frac{\partial\rho}{\partial t} \tag{2.7.10}$$

The zeroth moment of the second term of Eq.2.7.8 gives

$$\sum_\alpha m_\alpha\int(v.\nabla f_\alpha)dv = \sum_\alpha m_\alpha\int\nabla.(f_\alpha v)dv \tag{2.7.11}$$

Using the identity

$$\nabla.(\phi D) = \phi\nabla.D + D.\nabla\phi \tag{2.7.12}$$

we can write Eq.2.7.11

$$\nabla.(f_\alpha v) = f_\alpha\nabla.v + v.\nabla f_\alpha \tag{2.7.13}$$

Since V is independent of the position X in phase space, the first term on the right hand side of Eq.2.7.13 vanishes

$$\sum_\alpha m_\alpha\int(v.\nabla f_\alpha)dv = \sum_\alpha m_\alpha\int\nabla.(vf_\alpha)dv = \nabla.\sum_\alpha m_\alpha\int(vf_\alpha)dv \tag{2.7.14}$$

We define mean velocity flow as

$$\vec{U} = \vec{V} = \frac{\int_{-\infty}^{\infty} \vec{v} f_{\alpha d\vec{v}}}{\int_{-\infty}^{\infty} f_{\alpha}} d\vec{v} \tag{2.7.15}$$

using the definition in Eq.2.6.1 and 2.7.2 gives,

$$\sum_{\alpha} m_{\alpha} \int (v.\nabla f_{\alpha}) dv = \nabla. \sum_{\alpha} m_{\alpha} \int u_{\alpha}(f_{\alpha}) dv$$

$$= \nabla. \sum_{\alpha} m_{\alpha} n_{\alpha} u_{\alpha}$$

$$= \nabla.(\rho U) \tag{2.7.16}$$

Similarly using the identity given in Eq.2.7.12

$$\nabla_v.(a f_{\alpha}) = f_{\alpha} \nabla_v.a + a.\nabla_v f_{\alpha} \tag{2.7.17}$$

Since a is independent of V in phase space, the first term on the right hand side of Eq.2.7.17 vanishes. Then

$$\nabla_v.(a f_{\alpha}) = a.\nabla_v f_{\alpha} \tag{2.7.18}$$

thus, using the result of Eq.2.7.18, we get

$$\int_v \nabla_v.(a f_{\alpha}) dv = \int_s (a f_{\alpha}) ds$$

However, the distribution function, $f_{\alpha}$, vanish as $V \rightarrow \infty$, and this surface integral in velocity space therefore vanishes, as there is no particle with infinite velocity. The collision term of the Boltzmann equation reduces to $Q^{\rho}$ such that in summary the 0th moment of the Boltzmann equation reduces to:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = Q^{\rho} \tag{2.7.19}$$

Thus, the above equation is the continuity equation with collision term $Q^{\rho}$. This equation is noting but the mass conservation equation

### 2.7.2 Equation of Motion

Multiplying Boltzmann equation by $\vec{v}$ and integrating over all velocity space will produce momentum like moments. To obtain an equation of motion we take the first moment of Boltzmann equation then multiplying by $V$, $m_\alpha$ and sum over species to obtain:

$$\sum_\alpha m_\alpha \int v \left[\frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + (a).\nabla_v f_\alpha\right] dv = \sum_\alpha m_\alpha \int \left| v \frac{\partial f_\alpha}{\partial t} dv \right|_c \tag{2.7.20}$$

We now define the velocity $V$ relative to the mean velocity of the species $U$ as $V = V^{'} + U$ where $V^{'}$ is the random velocity of the species. Therefore, Eq.2.7.20 can be written as

$$\sum_\alpha m_\alpha \int (V^{'} + U) \left[\frac{\partial f_\alpha}{\partial t} + v.\nabla f_\alpha + (a).\nabla_v f_\alpha\right] dv = \sum_\alpha m_\alpha \int \left| (V^{'} + U) \frac{\partial f_\alpha}{\partial t} dv \right|_c$$

$$= \sum_\alpha m_\alpha \int (V^{'} + U) \frac{\partial f_\alpha}{\partial t} dv + \sum_\alpha m_\alpha \int (V^{'} + U)(v.\nabla f_\alpha) dv + \sum_\alpha m_\alpha \int (V^{'} + U)(a.\nabla_\alpha f_\alpha) dv$$

$$= \sum_\alpha m_\alpha \int \left| (V^{'} + U) \frac{\partial f_\alpha}{\partial t} dv \right|_c$$

$$= \frac{\partial}{\partial t} \sum_\alpha m_\alpha \int (V^{'} + U) f_\alpha dv + \frac{\partial}{\partial x}. \sum_\alpha m_\alpha \int (V^{'} + U)(V^{'} + U) f_\alpha dv$$

$$+ \sum_\alpha m_\alpha \int V \frac{\partial}{\partial v}.(a) f_\alpha dv = \sum_\alpha m_\alpha \int \left| V \frac{\partial f_\alpha}{\partial t} dv \right|_c$$

$$= \frac{\partial}{\partial t} \sum_\alpha m_\alpha \int (V^{'} + U) f_\alpha dv + \frac{\partial}{\partial x}. \sum_\alpha m_\alpha \int (V^{'} V^{'} + V^{'} U + U V^{'} + UU) f_\alpha dv$$

$$+ \sum_\alpha m_\alpha \int V \frac{\partial}{\partial v}.(a) f_\alpha dv = \sum_\alpha m_\alpha \int \left| V \frac{\partial f_\alpha}{\partial t} dv \right|_c \tag{2.7.21}$$

Expanding Eq.2.7.21 gives

$$\frac{\partial}{\partial t}\sum_{\alpha} m_{\alpha}\int V^{'}f_{\alpha}dV+\frac{\partial}{\partial t}\sum_{\alpha} m_{\alpha}\int Uf_{\alpha}dv+\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int V^{'}V^{'}f_{\alpha}dv+\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int V^{'}Uf_{\alpha}dv+$$

$$\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int UV^{'}f_{\alpha}dv+\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int UUf_{\alpha}dv+\sum_{\alpha} m_{\alpha}\int V\frac{\partial}{\partial v}.(a)f_{\alpha}dv=\sum_{\alpha} m_{\alpha}\int \left|V\frac{\partial f_{\alpha}}{\partial t}dv\right|_{c} \quad (2.7.22)$$

The average of the fluctuation vanishes. That is,

$$< V^{'} >=\int V^{'}f_{\alpha}dV=0 \quad (2.7.23)$$

making use of Eq.2.7.23 the first, fourth and fifth terms on the left hand side of Eq.2.7.22 vanishes. Therefore, Eq.2.7.22 reduced to

$$\frac{\partial}{\partial t}\sum_{\alpha} m_{\alpha}\int uf_{\alpha}dv+\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int V^{'}V^{'}dv+\frac{\partial}{\partial x}\sum_{\alpha} m_{\alpha}\int UUf_{\alpha}dv+$$

$$\sum_{\alpha} m_{\alpha}\int V\frac{\partial}{\partial v}.(a)f_{\alpha}dv=\sum_{\alpha} m_{\alpha}\int \left|V\frac{\partial f_{\alpha}}{\partial t}dv\right|_{c} \quad (2.7.24)$$

using Eq.2.7.2, the first term on the left-hand side of Eq.2.7.24 can be written as

$$\frac{\partial}{\partial t}\sum_{\alpha} m_{\alpha}\int Uf_{\alpha}dv=\frac{\partial}{\partial t}(\rho U) \quad (2.7.25)$$

The second integral can be evaluated by using the definition of the pressure tensor. The MHD pressure tensor is now defined in terms of the random velocities relative to u as

$$P=\sum_{\alpha} m_{\alpha}\int V^{'}V^{'}f_{\alpha}dv \quad (2.7.26)$$

Using this definition, the second term on the left hand-side of Eq.2.7.24 can be written as

$$\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha}\int V^{'}V^{'}f_{\alpha}dv=\frac{\partial}{\partial x}P \quad (2.7.27)$$

Similarly the third term on the left hand-side of Eq.2.7.24 becomes

$$\frac{\partial}{\partial x}.\sum_{\alpha} m_{\alpha} \int UUf_{\alpha}dv = \frac{\partial}{\partial x}(\rho UU) \tag{2.7.28}$$

In order to simplify the acceleration

$$\sum_{\alpha} m_{\alpha} \int V\frac{\partial}{\partial v}.(af_{\alpha})dv = 0$$

first let us solve the first integral

$$\sum_{\alpha} m_{\alpha} \int V\frac{\partial}{\partial v}.(af_{\alpha})dv = 0 \tag{2.7.29}$$

In order to simplify the equation first let us reduce the integral to its lowest form, i.e.,

$$\sum_{\alpha} m_{\alpha} \int V\frac{\partial}{\partial v}.(af_{\alpha})dv = \sum_{\alpha} m_{\alpha} \left[\int \frac{\partial}{\partial v}.(aVf_{\alpha})dv - \int af_{\alpha}\frac{dv}{dv}dv\right] \tag{2.7.30}$$

Since $f_{\alpha} \to 0$ as $V \to \infty$, this integral in velocity space vanishes. Therefore the integral becomes,

$$\sum_{\alpha} m_{\alpha} \int v\frac{\partial}{\partial V}.(af_{\alpha})dv = -\sum_{\alpha} m_{\alpha} \int af_{\alpha}\frac{dv}{dv}dv \tag{2.7.31}$$

Thus, using the definition of the tensor $\frac{\partial v}{\partial v} = 1$ and substituting the value of Eq. 2.7.31 Eq.2.7.30becomes

$$\sum_{\alpha} m_{\alpha} \int v\frac{\partial}{\partial v}.(af_{\alpha})dv = -\sum_{\alpha} m_{\alpha} \int q_{\alpha}(E + V \times B)f_{\alpha}dv$$

$$\sum_{\alpha} m_{\alpha} \int v\frac{\partial}{\partial v}.(af_{\alpha})dv = -\sum_{\alpha} m_{\alpha}q_{\alpha}(E + V \times B) \int f_{\alpha}dv$$

$$= -\sum_{\alpha} m_{\alpha}q_{\alpha}E \int f_{\alpha}dv - \sum_{\alpha} m_{\alpha} \int q_{\alpha}(V \times B)f_{\alpha}dv$$

using the definition of $n_{\alpha} = \int f_{\alpha}dv$ this equation becomes

$$-\sum_{\alpha} q_{\alpha}n_{\alpha}E - \sum_{\alpha} q_{\alpha}n_{\alpha}(v \times B) \tag{2.7.32}$$

making use of Eq.2.7.1 we can use J instead of $\sum_\alpha q_\alpha n_\alpha V$. Therefore Eq.2.7.32 becomes

$$-\sum_\alpha q_\alpha n_\alpha E - \sum_\alpha q_\alpha n_\alpha (V \times B) = -\sum_\alpha q_\alpha n_\alpha E - J \times B \tag{2.7.33}$$

Substituting Eq.2.7.2, 2.7.27, 2.7.28 and 2.7.32 into equation 2.7.24 gives

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho U U) - \sum_\alpha q_\alpha n_\alpha E - J \times B + \nabla.P = \sum_\alpha m_\alpha \int \left| V \frac{\partial f_\alpha}{\partial t} dv \right|_c \tag{2.7.34}$$

MHD is typically used to describe phenomena with large spacial scales where the plasma is essentially neutral, so that $\sum_\alpha q_\alpha n_\alpha \approx 0$. Thus, Eq.2.7.34 reduces to

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho U U) - J \times B + \nabla.P = \sum_\alpha m_\alpha \int \left| V \frac{\partial f_\alpha}{\partial t} dv \right|_c \tag{2.7.35}$$

The first two terms of left hand-side of Eq.2.7.35 can be simplified as

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho U U) = \rho \frac{\partial U}{\partial t} + U \frac{\partial \rho}{\partial t} + \rho U.\nabla U + U \nabla.\rho U$$

Or

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho U U) = \rho \left( \frac{\partial}{\partial t} + U.\nabla \right) U + U \left[ \frac{\partial \rho}{\partial t} + \nabla.(\rho U) \right] \tag{2.7.36}$$

But the second term inside the bracket of right hand-side of Eq.2.7.36 is a continuity equation which has the value of $Q^\rho = m \int \frac{\partial f_\alpha}{\partial t}|_c$ Hence Eq.2.7.35 reduces to

$$\rho \left( \frac{\partial}{\partial t} + U.\nabla \right) U - J \times B + \nabla.P = \sum_\alpha m_\alpha \int \left| V \frac{\partial f_\alpha}{\partial t} dv \right|_c \tag{2.7.37}$$

Then by comparing Eqs. 2.7.37 and 2.7.36

$$\rho \left( \frac{\partial}{\partial t} + U.\rho \right) U + m \int U \frac{\partial f}{\partial t} dv = J \times B - \nabla.P + m \int V \frac{\partial f}{\partial t} dv$$

$$\rho \left( \frac{\partial}{\partial t} + U.\rho \right) U - J \times B + \nabla.P = m \int (V - U) \frac{\partial f}{\partial t} dv \tag{2.7.38}$$

$$\rho \left( \frac{\partial}{\partial t} + U.\rho \right) U - J \times B + \nabla.P = Q^p \tag{2.7.39}$$

$$\rho \left( \frac{\partial}{\partial t} + U.\rho \right) U = J \times B - \nabla.P + Q^p$$

Or

$$\rho \frac{DU}{Dt} = J \times B - \nabla.P + Q^p \tag{2.7.40}$$

Where

$$\frac{DU}{Dt} = \left( \frac{\partial}{\partial t} + U.\rho \right) U$$

This equation, 2.7.40, is the standard form of the MHD equation of motion with the collision term $Q^p$

### 2.7.3 Momentum Equation

In the presence of strong magnetic field the pressure tensor of an inviscid fluid is anisotropic. When the cyclotron frequency is much larger than the collision frequency, a charged particle gyrates many times around a magnetic force line during the time between collisions, so that there is equipartition between the particle kinetic energy in the two independent direction normal to B but not, in general, in the direction along B. If we denote by $P_{\|}$ and $P_{\perp}$ the scalar pressures in the plane normal to B, and along B, respectively, and consider a local coordinate system in which the third axis is in the direction of B, we can write the pressure tensor of an inviscid fluid as

$$P = \begin{pmatrix} P_{\perp} & 0 & 0 \\ 0 & P_{\perp} & 0 \\ 0 & 0 & P_{\perp} \end{pmatrix} \tag{2.7.41}$$

Note that the parallel and perpendicular indexes used here do not refer to vector components but only indicate that the part of the scalar pressures associated with the kinetic energy densities of the particle motion along B and in the plane perpendicular to B, respectively. When the magnetic field is not constant, the orientation of the axes of the local coordinate system changes from point to point and this change in direction must be taken into account when evaluating the divergence of the pressure tensor. We can express P, in Eq. 2.7.37 as the sum of a hydrostatic scalar pressure $P_\perp$ and another tensor refereed to the local coordinate system as:

$$P = P_\perp I + (P_\parallel - P_\perp \hat{B}\hat{B}) \tag{2.7.42}$$

where I is the unit dyad given by

$$I = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and $\hat{B}\hat{B} = \frac{BB}{B^2}$

$$\hat{B}\hat{B} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The momentum equation must be modified to include the anisotropic of the pressure dyad. Thus, we write

$$\rho\frac{DU}{Dt} = Q^p + J \times B - \nabla.P$$

To evaluate $\nabla.P$ with P as given by Eq.2.7.42, we note that

$$\nabla.P_\perp I = \nabla.P_\perp, \tag{2.7.43}$$

where the second term in the right-hand side vanishes in virtue of $\nabla.B = 0$ we obtain

$$\nabla.P = \nabla.P_\perp + (B.\nabla)\left[(P_\perp - P_\parallel \frac{B}{b^2})\right] \tag{2.7.44}$$

Using maxwells equations, we can write the magnetic force per unit volume as

$$J \times B = \frac{1}{4\pi}(\nabla \times B) \times B \tag{2.7.45}$$

using the identity $(\nabla \times B) \times B$ can be written as

$$\nabla(A.B) = A \times (\nabla \times B) + B \times (\nabla \times A) + (A.\nabla)B + (B.\nabla)A \tag{2.7.46}$$

where $A = B$, B=B

$$(B.\nabla)B - \frac{\nabla(B^2)}{2} = (\nabla \times B) \times B$$

So Eq.2.7.45 can be written as

$$J \times B = \frac{1}{4\pi}\left[(\nabla.B)B - \frac{\nabla(B^2)}{2}\right] \tag{2.7.47}$$

Substituting expression Eqs.2.7.44 and 2.7.47 into the momentum equation we obtain,

$$\rho\frac{DU}{Dt} = Q^p - \nabla.\left(P_\perp + \frac{B^2}{8\pi}\right) + (B.\nabla)\left[\frac{B}{4\pi} - \frac{(P_\parallel - P_\perp)}{B^2}B\right],$$

or

$$\rho\frac{DU}{Dt} + \nabla\left(P_\perp + \frac{B^2}{8\pi}\right) - (B.\nabla)\left[\frac{(P_\perp - P_\parallel + \frac{B^2}{4\pi})}{B^2}B\right] = Q^p \tag{2.7.48}$$

### 2.7.4 Energy Equation

Taking the second moment of the Boltzmann equation we derive the energy equation for homogeneous collision plasma as follows. We multiply the Boltzmann equation by $(m_\alpha V^2/2)$ and integrating it by parts with respect to the volume in space velocity, dv to get

$$\sum_\alpha \frac{m_\alpha}{2}\int V^2\left[\frac{\partial f}{\partial t} + v.\nabla f_\alpha + \vec{a}.\nabla_v f\right]dv = \sum_\alpha \frac{m_\alpha}{2}\int V^2\left|\frac{\partial f_\alpha}{\partial t}dv\right|_c \tag{2.7.49}$$

$$\sum_\alpha \frac{m_\alpha}{2}\int V^2\frac{\partial f_\alpha}{\partial t}dv + \sum_\alpha \frac{m_\alpha}{2}\int V^2(v.\nabla f_\alpha)dv + \sum_\alpha \frac{m_\alpha}{2}\int V^(a.\nabla_v f_\alpha)dv = \sum_\alpha \frac{m_\alpha}{2}\int V^2\left|\frac{\partial f_\alpha}{\partial t}dv\right|_c$$

$$\frac{\partial}{\partial t}\int \frac{m_\alpha}{2}V^2 f_\alpha dv + \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}V^2(vf_\alpha)dv + \int \frac{m_\alpha}{2}V^2\frac{\partial}{\partial v}(af_\alpha)dv = \int \frac{m_\alpha}{2}V^2\frac{\partial f_\alpha}{\partial t}dv|_c \tag{2.7.50}$$

By using the definition $V = V' + U$ the more general definition of the pressure P for N dimensions as

$$P = \frac{m_\alpha}{N}\int V'V' f_\alpha dv \tag{2.7.51}$$

Each term of Eq.2.7.50 can be simplified separately as follow. The first time derivative term becomes

$$\frac{\partial}{\partial t}\int \frac{m_\alpha}{2}V^2 f_\alpha dv = \frac{\partial}{\partial t}\int \frac{m_\alpha}{2}(V^{'}+U)^2 f_\alpha dv$$

$$= \frac{\partial}{\partial t}\int \frac{m_\alpha}{2}(V^{'}V^{'}+2V^{'}U+UU)f_\alpha dv$$

$$= \frac{\partial}{\partial t}\int \frac{m_\alpha}{2}V^{'}V^{'}f_\alpha dv + \frac{\partial}{\partial t}\int \frac{m_\alpha}{2}U^2 f_\alpha dv + \frac{\partial}{\partial t}\int m_\alpha V^{'}U f_\alpha dv \tag{2.7.52}$$

The third term of this equation can be ignored

$$\frac{\partial}{\partial t}\int \frac{m_\alpha}{2}V^{'}V^{'}f_\alpha dv + \frac{\partial}{\partial t}\int \frac{m_\alpha}{2}U^2 f_\alpha dv$$

$$\frac{\partial}{\partial t}\int \frac{m_\alpha V^2}{2}f_\alpha dv = \frac{\partial}{\partial t}\left(\frac{NP}{2}+\frac{m_\alpha n_\alpha U_\alpha^2}{2}\right) \tag{2.7.53}$$

Again using $V = V^{'}+U$ the space derivative term become

$$\frac{\partial}{\partial x}.\int \frac{1}{2}m_\alpha V^2(Vf_\alpha)dv = \frac{\partial}{\partial x}.\int^{'} \frac{m_\alpha}{2}(V^{'}+U)^2(V^{'}+U)f_\alpha dv, \tag{2.7.54}$$

$$= \frac{\partial}{\partial x}\int \left[\frac{m_\alpha}{2}(V^{'}V^{'}+2V^{'}U+UU)(V^{'}U)f_\alpha dv\right]dv$$

$$\frac{\partial}{\partial x}\int \frac{m_\alpha}{2}\left[V^{'}V^{'}V^{'}+2V^{'}V^{'}U+U^2V^{'}+2V^{'}U^2+V^{'}V^{'}U+U^2U\right]f_\alpha dv$$

$$= \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}V^{'}V^{'}V^{'}f_\alpha dv + \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}2V^{'}V^{'}Uf_\alpha dv + \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}U^2V^{'}f_\alpha dv +$$

$$\frac{\partial}{\partial x}\int \frac{m_\alpha}{2}2V^{'}U^2 f_\alpha dv + \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}V^{'}V^{'}Uf_\alpha dv + \frac{\partial}{\partial x}\int \frac{m_\alpha}{2}U^2Uf_\alpha dv \tag{2.7.55}$$

From Eq.2.7.55 the 3rd and 4th terms from the right hand side vanishes, because of the average of fluctuation is zero. Then defining the heat flux as

$$Q = \frac{m_\alpha}{2} \int V^{'} V^{'} V^{'} f_\alpha dv$$

Eq.2.7.54 yields

$$\frac{\partial}{\partial x} \int \frac{1}{2} m_\alpha v^2 (V f_\alpha) dv = \frac{\partial}{\partial x} \left[ Q + \frac{2+N}{2} PU + \frac{m_\alpha n_\alpha u^2}{2} \right] \tag{2.7.56}$$

Lastly, from Eq.2.7.50 the $3^{rd}$ term gives

$$m_\alpha \int \frac{1}{2} V^2 .a \frac{\partial}{\partial v} f_\alpha dV = m_\alpha \int \frac{\partial}{\partial v} . \left( \frac{1}{2} a V^2 f_\alpha dv \right) - \int \frac{1}{2} f_\alpha V^2 \frac{\partial}{\partial v} .adV - \int \frac{1}{2} f_\alpha a. \frac{\partial v^2}{\partial v} dv \tag{2.7.57}$$

But the first integral on the right hand-side of Eq.2.7.57 is the volume integral of a divergence in velocity space. Therefore Gausss theorem gives $f_\alpha$ evaluated on a surface at $V = \infty$ because $f_\alpha \to 0$ as $V \to \infty$ this surface integral in velocity space vanishes. Thus, using the expression for the acceleration and simplifying it this equation reduces to

$$\int \frac{m_\alpha}{2} V^2 a \frac{\partial}{\partial v} f_\alpha dv = -m_\alpha \int \frac{1}{2} f_\alpha a. \frac{\partial v^2}{\partial v} dv$$

$$= -m_\alpha \int a f_\alpha .v dv$$

$$= -m_\alpha \int q(E + U \times B) f_\alpha dv$$

$$\int \frac{m_\alpha}{2} V^2 a \frac{\partial}{\partial v} f_\alpha dv = -q m_\alpha n_\alpha E.U \tag{2.7.58}$$

now conbinning Eqs. 2.7.53, 2.7.56, and 2.7.58 we have

$$\frac{\partial}{\partial t} \left[ \frac{N}{2} P + \frac{m_\alpha n_\alpha u^2}{2} \right] + \nabla . \left[ Q + \frac{2+N}{2} PU + \frac{m_\alpha n_\alpha u^2}{2} U \right] - q n_\alpha E.U = \int \frac{m_\alpha}{2} V^2 \frac{\partial f_\alpha}{\partial t} |_c dv \tag{2.7.59}$$

The plasma is assumed to be perfect conductor and the heat flux, Q is neglected and taking some mathematical identities on Eq.2.7.59, we have

$$\frac{\partial}{\partial t}\frac{N}{2}P+\nabla.\left[\frac{2+N}{2}PU\right]+\frac{\partial}{\partial t}\left(\frac{m_\alpha n_\alpha u^2}{2}\right)+\nabla.\left(\frac{m_\alpha n_\alpha u^2}{2}U\right)-qn_\alpha E.U=\int\left|\frac{mV^2}{2}\frac{\partial f}{\partial t}dv\right|_c$$

$$\left(\frac{\partial}{\partial t}+U.\nabla\right)\frac{N}{2}P+\frac{N}{2}P\nabla.U+\nabla.(PU)+\left(\frac{\partial}{\partial t}+U.\nabla\right)\frac{m_\alpha n_\alpha u^2}{2}-qn_\alpha E.U=\int\left|\frac{mV^2}{2}\frac{\partial f}{\partial t}dv\right|_c$$

$$\frac{D}{Dt}\left(\frac{N}{2}P\right)+\frac{N}{2}P\nabla.U+\nabla.(PU)+n_\alpha m_\alpha\frac{D}{Dt}\left(\frac{U^2}{2}\right)-qn_\alpha E.U=\int\left|\frac{mV^2}{2}\frac{\partial f}{\partial t}dv\right|_c \quad (2.7.60)$$

To simplify Eq. 2.7.60 further, let us take the dot product of Eq. 2.7.39 with the velocity u we get

$$\frac{\partial}{\partial t}(\rho U).U+\nabla.(\rho UU).U+(\nabla.P).U-\left[\sum_\alpha q_\alpha n_\alpha E-J\times B\right].U=\int U(V-U)\frac{\partial f_\alpha}{\partial t} \quad (2.7.61)$$

Now using some identities as before we arrive at

$$\frac{n_\alpha m_\alpha}{2}\frac{DU^2}{Dt}+U.\nabla P=qn_\alpha E.U+\frac{1}{2}m_\alpha\int(V-U)^2\frac{\partial f_\alpha}{\partial t}dv \quad (2.7.62)$$

Then substituting Eq. 2.7.62 into Eq. 2.7.60 yields

$$\frac{D}{Dt}\left(\frac{N}{2}P\right)+\frac{N}{2}P\nabla.U+\nabla.(PU)+n_\alpha m_\alpha\frac{D}{Dt}\left(\frac{u^2}{2}\right)-n_\alpha m_\alpha\frac{D}{Dt}\left(\frac{u^2}{2}\right)+U.\nabla P=\frac{1}{2}m_\alpha\int(V-U)^2\frac{\partial f_\alpha}{\partial t}dv$$

$$\frac{D}{Dt}\left(\frac{N}{2}\right)+\frac{N}{2}P\nabla.U+\nabla.(PU)-U.\nabla P=\frac{1}{2}m_\alpha\int(V-U)^2\frac{\partial f_\alpha}{\partial t}dv \quad (2.7.63)$$

For

$$\nabla.(PU)-u.(\nabla P)=(P\nabla).U$$

But here, P is the tensorial pressure

$$(P\nabla).U=(P.\nabla)U \quad (2.7.64)$$

Finally from the preceding two equations, Eq.2.7.64 is written as

$$\frac{D}{Dt}\left(\frac{N}{2}P\right)+\frac{N}{2}P\nabla.U+(P.\nabla)U=Q^{E}$$

For N=3

$$\frac{D}{Dt}\left(\frac{3}{2}P\right)+\frac{3}{2}P\nabla.U+(P.\nabla)U=Q^{E} \tag{2.7.65}$$

This is the MHD energy equation with collision term $Q^E$

# Chapter 3

# The Solar Wind Earth's Magnetosphere Interaction

## 3.1 The sun

The Sun is a yellow dwarf star of spectral type G2V. It is our nearest star and lies a distance of $\sim 1.5 \times 10^8$ km (1 AU from the Earth). The Sun is a massive ball of gas composed of approximately ninety percent hydrogen, ten percent Helium, and 0.1 percent heavier elements [17], and is held together and compressed by its own gravitational attraction. The radius of the Sun (the distance from its center to the bottom of its atmosphere) is $\sim 6.97 \times 10^5$ km. The Suns core extends radially to one quarter of the total radius and here the temperature and pressure are so high, $\sim 1.5 \times 10^7$ K and $10^{16}$ pa respectively, that nuclear fusion reactions take place. Hydrogen nuclei combine to produce helium nuclei, and energy is released in the form of photons, which then radiate outwards. These nuclear reactions are the source of the Suns energy. A thick radiative zone surrounds the core. Here, thermal radiation transfers the intense heat of the core outward. The density and temperature decrease rapidly outside the core such that the outer layer of the Suns interior is a turbulent convection zone, with an average temperature of $5 \times 10^5$ K. After the radiative zone, the convection zone is the outermost interior layer of the Sun and has a depth of about 200,000 km up to the visible surface. The Suns atmosphere lies above the convection zone,

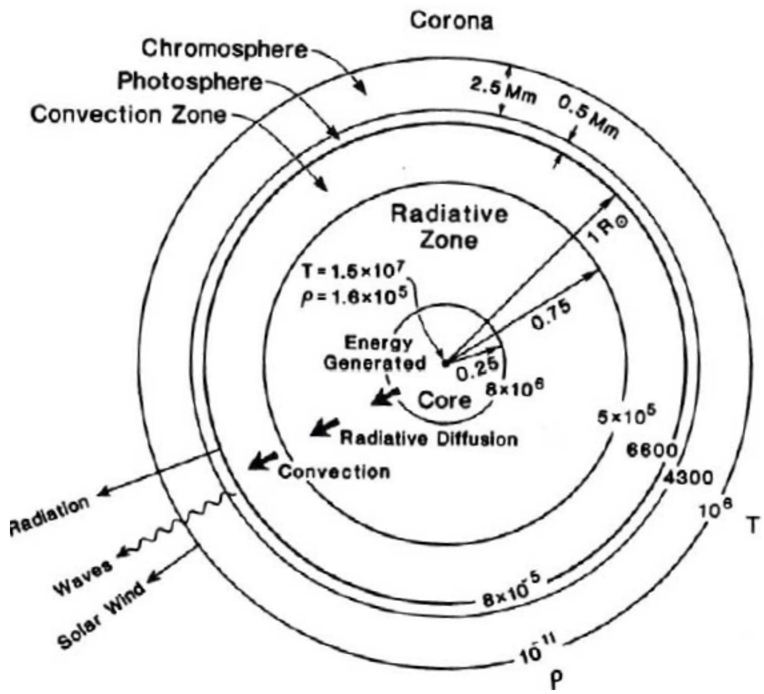


Figure 3.1: Cross section of the Sun showing the overall structure of the solar interior (the core, the radiative zone, and the convection zone) and the solar atmosphere (the photosphere, chromosphere, and corona).
[17]

and is comprised of three layers. The bottom layer, the photosphere, is 500 km thick and is at a temperature of $\sim 6600$ K. This layer emits most of the Suns visible light and called the visible surface of the sun. Above the photosphere lies the chromosphere. This layer is $\sim 2.5 \times 10^3$ km thick and here the temperature drops to $\sim 4300$ K. The chromosphere is relatively thin middle layer of the Sun's atmosphere and usually invisible to the naked eye because of the brightness of the photosphere below. The temperature then increases to reach $10^6$ K at the base of the corona, the outermost region of the Suns atmosphere. This is a high enough temperature to strip atoms of their electrons and form ions, thus producing a charge-neutral plasma. The corona extends away from the Sun in all directions forming the solar wind, a low density plasma that fills the solar system.

## 3.2 Solar Activities

### 3.2.1 The Sun's Magnetic Field

Many astrophysical bodies, including galaxies, stars, and planets, have an internally generated magnetic field. Solar magnetic energy is continually being created, annihilated, and ejected [4]. The Sun's magnetic field is at the heart of its activity and is an integral part of the solar system. At the interface between the uniformly-rotating radiative zone and the differentially-rotating convective zone, known as the tachocline, the large-scale shear in plasma flow is thought to cause a dynamo effect which continuously generates the Suns magnetic field. This basic principle is also believed to be responsible for the terrestrial magnetic field. However, the Sun's magnetic field bears little resemblance to the smooth, well-behaved dipolar field of the Earth. Instead the Sun's field varies wildly from dipolar, to quadrupolar and back to dipolar over the course of 11 years called the solar cycle. The Sun has an 11-year activity magnetic field cycle, which can be tracked by measuring the number of sunspots visible on the Suns surface. At solar minimum (the start of the cycle) the sunspot number is low and the solar magnetic field is approximately dipolar. Approaching solar maximum, the sunspot number increases and the magnetic field becomes disordered. After 11 years the magnetic polarity of the Sun's global magnetic field has been switched, the sunspot number again reaches a minimum and the magnetic field is ordered again, but with the opposite polarity. The cycle begins again and the process repeats itself and the original orientation is restored it takes another 11 years for the Suns magnetic field to return to its original polarity. This reveals that there is also an approximate 22-year magnetic solar cycle. The frequency of many forms of solar activity, including solar flares and Coronal Mass Ejections (CMEs), also follow the 11-year solar cycle [5]

### 3.2.2 Sunspots and Active regions

Active Regions (ARs) are locations where intense magnetic fields emerge through the photosphere and into the solar atmosphere [6]. They are important for space weather because complexes of magnetic activity out of which events such as Solar Flares (SF), Coronal Mass Ejections (CMEs) and other solar phenomena emerge and tend to erupt from this locations. They are form when the tops of loops of magnetic flux emerge into the solar atmosphere. These regions tend to be bipolar, i.e. they come in pairs of opposite polarity and are roughly aligned with the eastwest direction. Active regions are characterized by high magnetic field fluxes and often complicated field configurations, i.e the effects of the magnetic field on the temperature and density structure of an active region depend on its strength, the relative fraction of the active region it fills and its topology. These zones are footpoints of emerging flux tubes because of their buoyancy and the nearly vertical density (and pressure) gradient of the transition region into the Corona to form the loops. At one footpoint of each loop the magnetic field comes out of the Sun (north polarity), and at the other footpoint it goes back into the Sun (south polarity). Active regions are formed of many such bipolar pairs of footpoints connected by coronal loops at the site where the active region appears. The high density at which magnetic loops are packed together at their photospheric footpoints and the coronas low plasma- $\beta$ i.e plasma in the loops remains relatively confined and can be at different temperatures compared to the surrounding atmosphere is the distinctive feature that makes active regions different from the surrounding quiet atmosphere. Sunspots always appear within larger regions of emergent flux, the Active region. But, not all active regions contain sunspots. These emergent flux regions often manifest as sunspots, which are magnetic structures and visible as dark regions on the solar disk. The sunspots have two distinct regions, the dark central umbra and the lighter outer penumbra. These sunspots are formed because the intense magnetic fields suppress convection resulting in the umbra having a cooler temperature ($\sim 4,000K$) and corresponds to the inner region of the magnetic field at photospheric level. Mean while, the Penumbra has an intermediate temperature ($\sim 5,000K$) and corresponds to the outer part of magnetic field.

## 3.3 The Solar Wind

Space between the Sun and its planets is not empty. It is filled by a tenuous magnetized plasma, which is a mixture of ions and electrons flowing away from the Sun, the solar wind. The Suns outer atmosphere is so hot that not even the Suns enormous gravity can prevent it from continually evaporating. The solar wind is a high-speed plasma out flow which originates from the Sun's corona and terminates at the boundary of interstellar space (some 160 AU from the Sun). The medium which permeates the heliosphere is known as the solar wind consists of a gas of charged particles i.e plasma flowing radially out ward from the Sun. These escaping plasma carries the solar magnetic field along, out to the border of the heliosphere where its dominance finally ends. The solar wind being under the control of the magnetic field of the sun is ejected from the sun in all directions. That is, being constraints to move along the magnetic lines of force, the solar wind has no fixed directions. It moves through space in a most complex manner filling up the whole interplanetary space with the interplanetary magnetic field (IMF).

### 3.3.1 The Origin of the Solar Wind

The magnetic field of the Sun can be considered as having two distinct components: Open magnetic flux in which the field lines remain attached to the Sun and are dragged outward into the heliosphere with the solar wind and Closed magnetic flux in which the field remains entirely attached to the Sun, and forms loops and active regions in the solar corona. The solar wind is in fact the outward extension of the million degree hot upper atmosphere of the Sun, called the corona because of its crown-like shape which can be seen during eclipses. Close to the Sun, this atmosphere is strongly bound since the mean gravitational energy per ion is roughly ten times the thermal energy. However, because this medium is ionized and very hot, it conducts heat very efficiently hence the temperature decreases very slowly with altitude so that the thermal energy becomes greater than the gravitational energy beyond about ten solar radii. In static fluid equilibrium, the pressure would not decrease very much beyond this point, and since it is many times higher than that of the tenuous interstellar medium, the corona expands away into space, i.e solar wind blows from this region.

### 3.3.2 Types of solar wind and Compositions

The solar wind is a stream of charged particles released from the upper atmosphere of the Sun and is a collection of streams of energetic particles and escapes through the coronal holes at supersonic speeds. This plasma consists of mostly electrons, protons and alpha particles with thermal energies between 1.5 and 10 keV. Embedded within the solar-wind plasma is the interplanetary magnetic field. The composition of the solar wind is a mixture of materials found in the solar plasma, composed of ionized hydrogen (electrons and protons) with an eight percent component of helium (alpha particles) and trace amount of heavy ions and atomic nuclei: Carbon, Nitrogen, Neon, magnesium, Silicon, Sulphur and Iron ripped apart by heating of the sun's outer atmosphere, that is the corona [14]. Although the solar wind is electrically balanced, and consists almost exclusively of charged particles and is an excellent electrical conductor, i.e plasma. By exploring the sun in a distance of 1 AU, at present there are known three different kinds of solar wind, each having unique properties respectively termed the slow solar wind, fast solar wind and transient wind [13]. The slow solar wind has an average velocity of about 400 km/s, a temperature of about $1.2 - 1.6 \times 10^6 K$ and a very high density of $11 \times 10^6 kg/m^3$ at a distance of r=1 AU from the sun. Its composition closely matches that of the corona and it represents an unsteady flow and strongly depends on the solar cycle. The origin of the slow solar wind involves magnetic reconnection, which leads to transient openings of coronal loops and feeds plasma to the slow wind. By contrast, The source of the fast solar wind is located at the coronal holes. It is stable for long periods and is therefore accredited to the quiet sun. It has a typical velocity of about 800 Km/s (varying between 600-800 km/s), a temperature of $8 \times 10^5$ K, the density in a distance of 1 AU is very low $\approx 3 \times 10^6 kg/m^3$ and the fraction of helium is about 3-4 percent. The third type-the transient wind is related primarily to big flares and coronal mass ejections (CMEs) that may in the interplanetary space later evolve into magnetic clouds.

## 3.4 Properties and Origin of the Earth's Magnetic Field

Our planet is surrounded by a magnetic field. Due to the motion of molten iron inside Earth, a relatively strong magnetic field surrounds it. Like the magnetic field in sunspot pairs or magnets, Earths magnetic field emerges from one hemisphere with a certain direction and points towards the opposite hemisphere[15]. Earth's magnetic field, also known as the geomagnetic field is the magnetic field that extends from the earth's interior out into space and it is a super position of magnetic fields generated by different sources. The field generated by a magnetic dynamo in the Earths liquid core by a geodynamo mechanism is called the main field and is by far the most dominant one. It represents more than 90 percent of the geomagnetic field measured at the earth's surface. It ranges in magnitude from some 30000 nT at the equator up to more than 60000 nT in polar regions. The crustal field or Lithosphere, is also an associated magnetic field. This field is some 400 times smaller that the core contributions and generally ranges from $0 to \pm 1000$ nT. The physical processes originating the lithospheric field are completely different from those generating the core field since generated by magnetized rocks in the Earths crust. The external field, produced by electric currents flowing in the ionosphere and in the magnetosphere, owing to the interaction of the solar electromagnetic radiation and the solar wind with the Earths magnetic field. Because ultraviolet light from the sun ionizes the atoms in the upper atmosphere, the sunlit hemisphere and strong electric currents circulate in the sunlit hemisphere generating their own magnetic fields, with intensities up to 80 nT. There is also a magnetic field resulting from an electromagnetic induction process generated by electric currents induced in the crust and the upper mantle by the external magnetic field time variations which adds to the total geomagnetic field. Generally the geomagnetic field components which make up the total geomagnetic field are: The main field, the external field and the induced field[11].

## 3.5 The Structure of the Magnetosphere

The earths magnetic field would resemble a simple magnetic dipole, much like a big bar magnet, except that the solar wind distorts its shape. The solar wind stretches the earths magnetic field into a bullet shape, forming the large cavity known as the magnetosphere. The magnetosphere is that region dominated by the Earths magnetic field. The magnetosphere is a large plasma cavity generated by the interaction of Earths magnetic field and the solar wind plasma. Close to the earths surface the magnetic field approximates a dipole field, but further out the field becomes increasingly distorted. The magnetosphere is blunt on the sunward side, extending out 10 to 12 RE, earth radii (64,000-75,000 km), toward the sun and also has a long tail on the anti-sunward side, extending thousands of Earth radii (millions of kilometers) in the direction away from the sun.

Although much of the magnetosphere is nearly a perfect vacuum, its huge size allows energy in the solar wind to drive electric currents and set plasma in motion within the magnetosphere and earths upper atmosphere. Since all space operations occur in the magnetosphere, it is important to recognize how the magnetospheric activity impacts various operations in space. The structure of the magnetosphere is best described in the frame of reference with a fixed Sun-Earth axis. The magnetosphere than stays fixed in space while

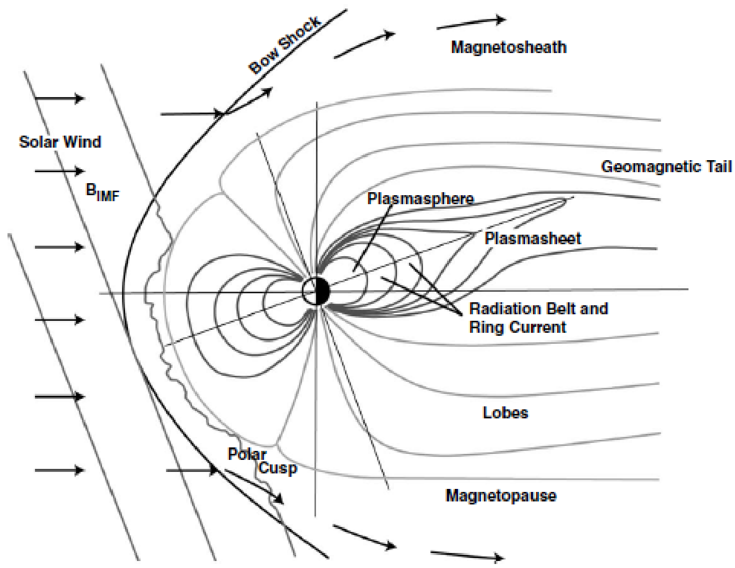


Figure 3.2: Sketch of the structure of the magnetosphere.
[17]

the Earth rotates inside it. This system divides the magnetosphere into two parts, a day side directed towards the Sun and a night side facing the magnetotail.

## 3.6 Interaction of Solar Wind with the Earth's Magnetosphere

The size of the terrestrial magnetosphere is determined by the balance between the solar wind dynamic pressure and the pressure exerted by the magnetosphere, principally that of its magnetic field. The shape of the magnetosphere is additionally influenced by the drag of the solar wind, or tangential stress, on the magnetosphere. This drag is predominantly caused by the mechanism known as reconnection in which the magnetic field of the solar wind links with the magnetic field of the magnetosphere. Within the magnetosphere the dynamics of charged particles (the plasma) are determined by the configuration of Earths magnetic field, which looks like a dipole farther from Earth because of its interaction with the magnetized solar wind.

### 3.6.1 The Bow Shock and the Magnetosheath

The solar wind plasma travels usually at super-fast speeds relative to the magnetosphere. Therefore a standing shock wave forms around the magnetosphere. The bow shock is prominent feature in front of the magnetosphere where the supersonic solar wind speed is slowed down to subsonic sped. The solar wind plasma and magnetic field carries with it, i.e, interplanetary magnetic field cannot cross into the earths magnetic field because of this Bow shock, but it can distort it. The bow shock slows the solar wind and begins to divert it around the magnetosphere. So that, the size, shape and location of the bow shock are not constant and are affected by changes in the solar wind. Some times the supersonic solar wind passes through the bow shock where it is then slowed and this passed plasma is the shocked solar wind plasma. The bow shock is the shock in front of the magnetosphere and the magnetosheath is the shocked solar wind plasma. This shocked plasma is diverted around the magnetosphere due to the frozen in magnetic field not allowing it pass through the Earth's magnetic field. Therefore it is not directly the solar wind plasma which constitutes the boundary of the magnetosphere but the strongly heated and compressed plasma behind the bow shock. The region is rich in various wave phenomena, boundaries and shocks are often treated as discontinuities.

### 3.6.2 The Magnetopause

The magnetospheric cavity is separated from the interplanetary magnetic field by the magnetopause. The magnetopause is the actual boundary between the shocked solar wind and the magnetospheric plasma and it is defined by an equilibrium between the solar wind kinetic pressure and the pressure of the terrestrial magnetic field. In other word, The magnetopause is a discontinuity separating both fields forming a cavity in the solar wind. However, the magnetosphere is not closed in terms of the magnetic field but there is considerable magnetic flux crossing the magnetopause. Also the boundary does permit a certain amount of solar wind plasma entry and entry is easier along magnetic field lines. The magnetopause is an highly important region because the physical processes at this boundary control the entry of plasma, momentum, energy and the redistribution of geomagnetic flux.

The position of magnetopause depends on the strength of the solar wind pressure, which is primarily due to solar wind density and velocity and balance between the solar wind pressure and the magnetic pressure of the magnetosphere. As solar wind pressure increases, it moves the magnetopause earthward. When solar wind pressure decreases, the entire magnetosphere expands.

### 3.6.3 Cusps and Mantle

The cusp and mantle regions are directly adjacent and inward of the magnetopause. Are two small regions where the earths magnetic field is perpendicular to the magnetopause. The cusp is a region where highly energetic particle can be produced and it is very active in terms of turbulence and wave energy because the boundary field lines converge in the cusp and all waves which travel along the magnetic field are channeled into this region. Cusps exists above the magnetic poles of the earth. This geometry allows to go slowly or gradually of charged solar wind protons and alpha particles to directly enter the magnetosphere. Therefore these cusp regions are one of the main routes for solar wind plasma to enter into the Earth's magnetosphere and hence contain both magnetosheath plasma and magnetospheric plasma. The magnetospheric plasma is a mixed distribution since the magnetic field lines in the cusps connect to all regions of the magnetosphere. The solar wind particles that enter the polar cusps are funneled along magnetic field lines straight to the earths atmosphere where they ionize atoms and emit light. This steady stream of particles causes a weak, diffuse glow extending over a large part of the polar cap the aurora.

The mantle region represents a boundary to the magnetotail usually filled with solar wind plasma but with a stretched magnetospheric magnetic field.

### 3.6.4 The Magnetotail

The interaction of Earths magnetic field with the magnetized solar wind produces a long magnetotail. The magnetotail is the long tail-like extension of the magnetosphere on anti-sunward side of the magnetosphere. The magnetotail is divided into two lobes. Magnetic field lines in the northern lobe are directed toward the earth, and those in the southern lobe are directed away from the earth. Since the magnetic field points toward the Earth in the northern lobe and away in the southern lobe, there is a current in the westward direction. Because of its structure there is considerable energy stored in the magnetic field in the magnetotail. During magnetically quiet times convection is typically low and energy in the plasma flow is only a tiny fraction of the overall energy density. In the magnetotail the earths magnetic field lines are drawn back in the antisolar direction by the motion of the solar plasma attempting to pass around the magnetopause. The solar plasma draws the tail backward for millions of kilometers where it eventually becomes indistinguishable from the interplanetary magnetic field. Beyond about 10 RE the magnetic field lines of the earths field are essentially parallel to those of the IMF.

### 3.6.5 The plasma sheet and Radiation Belts.

Since the magnetic field resembles a dipole close to Earth, The dipole region of Earths magnetosphere is called the inner magnetosphere. The plasma sheet is a region of concentrated hot plasma that extends from down the magnetotail. Plasma sheet has two regions; The distant plasma sheet (neutral sheet) and the inner plasma sheet. At a time of interaction plasma concentration which stretches down the magnetotail from about 30 RE, is called the neutral sheet. Protons and electrons from the solar wind diffuse across the magnetopause in the magnetotail, drift toward the plasma sheet, and accelerate earthward. Electric current flows from dawn to dusk in the neutral sheet in order to keep the magnetic lobes separated. The energy of electrons in the neutral sheet range from 200 eV to more than 12 keV. The inner plasma sheet is the plasma sheet region extending inward from about 30 RE to about 8 RE (in the antisolar direction) and further inward as it tapers north and south toward the geomagnetic poles. The magnetic field lines of the inner plasma sheet are closed. Within the earthward edge of the inner plasma sheet (1-8 RE), magnetic field lines are less distended and more dipole-shaped in the radiation belts. Here high-energy charged particles are trapped. Charged particles spiral around magnetic field lines, reflecting from the magnetic mirror points near the magnetic poles. The radiation belt consist of two distinct regions of energetic particles. The outer belt, composed mostly of energetic electrons, has its inner edge around 3 rE and its highly variable outer edge. It contains low-energy protons ( 200 keV to 1 MeV) of solar wind origin. Protons and electrons from the solar wind diffuse across the magnetopause in the magnetotail, drift toward the plasma sheet and on arrival from the plasmasheet, these particles are ejected into the outer radiation belt. The protons are deflected westward by the earths magnetic field, and the electrons are deflected eastward.

The inner belt, which consists of energetic electrons and protons, extends out to about 2.5 rE. It is composed high-energy protons (up to hundreds of MeV) primarily of terrestrial origin. The inner belt is more dipole-shaped than the outer belt and particles can be trapped for long time. The region between the belts (called the slot) is generally kept clear of energetic particles by mechanisms that enhance the loss of the particles into the ionosphere. The radiation belts contain intense radiation that can kill astronauts and damage or destroy sensitive electronics on spacecraft[15], [12]

### 3.6.6 The Ring Current

Because of the shape and strength of Earths dipole magnetic field region, energetic ions flow from midnight to the dusk side, and energetic electrons flow in the opposite direction. This difference in flow directions of positively charged ions and negatively charged electrons gives rise to an electric current, a ring current that circles Earth. The ring current consists of the current due to the eastward (electron) and westward (proton) drift in the radiation belts and causes a net decrease in the magnetic field on the surface of the Earth. This ring current in turn gives rise to a magnetic field that points in the opposite direction to the dipole field at Earths surface. Therefore, the ring current decreases the strength of Earths magnetic field as measured on the surface. When the ring current some times suddenly changes its intensity, there is a rapid decrease in magnetic field strength of the earth .

### 3.6.7 Magnetic reconnection

Magnetic reconnection is a fundamental process which violates the concept of frozen in flow. A direct consequence of the frozen-in theorem is that when two different plasma regimes meet (such as the solar wind and magnetosphere), a boundary layer must be formed between them (e.g. the magnetopause). This is because plasma can only flow along field lines (not across them) and so the two distinct plasma regimes cannot mix. The magnetic field topology on either side of the boundary layer can be completely different, with differing field direction and strength, but, close to the boundary, the fields will be antiparallel and tangential to the boundary. Solar wind plasma is magnetized fluid, which makes interaction between the solar wind flow and Earths magnetosphere. When two magnetic fields are brought together, the fields combine. So if we bring two magnets close to each other and measure the strength of the field at some point, we would measure contributions from both. When this occurs in a magnetized plasma, such as in the solar wind and magnetosphere, the fields can interact in a new way to form new field lines. In this process, called magnetic reconnection, energy is taken from the magnetic field and put into particle motion (magnetic energy is converted to particle kinetic energy). Magnetic reconnection is reconfiguration of two different magnetic field topologies in which plasma elements that are initially connected to one magnetic field become attached to another magnetic field. Note that there are two distinct field lines when solar wind plasma interact with the earth's magnetosphere, one that has both ends in the solar wind and one connected to both poles of Earth. When they come together, they can reconnect, and in addition to converting some of the magnetic energy into particle kinetic energy, the two original field lines topologies are converted into two new field line topologies. Field lines with both ends connected to Earth are called closed, and those with one end connected to Earth and the other in the solar wind are called open.

## 3.7 Magnetosphere-Ionosphere Coupling

The ionosphere is the region where the atmosphere is partially ionized plasma and neutrals strongly interact and often is described as the base of the magnetosphere. This interaction exerts a drag on the plasma. The plasma density can be very high but also strongly variable such that the ionospheric conductance can vary by orders of magnitude. Magnetospheric plasma motion is transmitted into the ionosphere and forces ionospheric convection. This also implies the existence of strong currents along magnetic field lines which close through the ionosphere. In particular at high latitudes these currents lead to magnetic perturbations during times of strong magnetospheric activity (fast convection and changes of the magnetospheric configuration). Currents and solar wind plasma flows couple the ionosphere and the magnetosphere. The motion of particles, plasmas, and magnetic fields gives rise to currents and currents in the magnetosphere associated with its large-scale structure current inside the magnetopause and the tail current separating the southern and northern lobes. In addition, the drift of charged particles trapped in the radiation belts gives rise to a ring current. These currents are perpendicular to the magnetic field and another kind of current flows parallel to the magnetic field and therefore can provide coupling between the ionosphere and the magnetosphere. The entire configuration then can be interpreted as a circuit with the solar wind-magnetosphere interaction working as a dynamo and the ionosphere being a load with dissipative losses.

## 3.8 Solar Wind-Magnetosphere-Ionosphere Coupling

As discussed in the previous sections, the solar wind is a plasma out flow which constantly bombards the near-Earth system. Protecting the Earth from this bombardment is the terrestrial magnetic field which, due to the frozen-in acts as a shield preventing the plasma from stripping away the Earth's atmosphere. However, the frozen-in can, and does, break down. In cases where the magnetic field approaches unity, such as at the boundary between the magnetosheath and the magnetosphere, the frozen-in no longer holds and magnetic reconnection takes place. Magnetic reconnection couples field lines from the interplanetary magnetic field to the terrestrial magnetic field and allows solar wind particles, who would not normally be able to cross magnetic field lines, to enter into the near-Earth environment. Reconnection at the dayside magnetosphere causes open magnetic field lines, traveled at the Earth's pole, to stretch out into interplanetary space. The solar wind flow drags these open field lines anti-sunward towards the magnetotail region of the magnetosphere. In this region open field lines reconnect with those from the opposite pole to form a new geomagnetic field line and a new interplanetary field line. The geomagnetic field line travels earthward whilst the interplanetary field line flows off into interplanetary space. In addition to creating plasma flow, reconnection at the magnetopause causes an in flux of solar wind particles to populate the terrestrial magnetic field lines. This increase in charged particles enhances magnetospheric currents, such as the ring current, and can modify the magnetic field strength on the Earth's surface. Additionally, Energetic particles like electrons, protons and alpha particles from the solar wind and the magnetosphere can penetrate the Ionosphere and contribute to an extraordinary production of ions and electrons in the ionosphere. Such particle precipitation is closely related to the northern light phenomenon, and the layers of the ionosphere vary, therefore, often very irregularly, in the auroral zone.

# Chapter 4

# Result and Discussion

The part of the Suns magnetic field that is pulled out into the heliosphere by the solar wind is called the interplanetary magnetic field (IMF). The magnetized solar wind expands radially (directly away from the Sun), pulling the solar magnetic field along with it. As the Sun rotates, the position or footpoint of where the solar wind stream leaves its surface moves counter-clockwise when viewed from above the Sun. This causes the magnetic field to start to spiral as it moves farther from the Sun with respect to the original footpoint position. Because the Suns rotation rate is essentially constant in time, the angle the spiral makes with respect to the Sun-Earth line (an imaginary line connecting the Sun and Earth) is due to the speed of the solar wind alone. The set of summarized resistive (collision inclusive) MHD equations used in the solar wind-earth's magnetosphere interaction are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0; \quad \text{continuity equation} \tag{4.0.1}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \mathbf{J} \times \mathbf{B} \quad \text{motion equation} \tag{4.0.2}$$

$$\frac{1}{\gamma - 1}\left(\frac{\partial p}{\partial t} + \nabla \cdot (p\mathbf{u})\right) = -p\nabla \cdot \mathbf{u} + \eta \mathbf{J}^2 \quad \text{energy equation} \tag{4.0.3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \quad \text{dynamo equation} \tag{4.0.4}$$

The coupling of the flowing plasma (the solar wind plasma), earth's magnetic field including its ionosphere particle distribution play key role in the earth's magnetosphere geometrical structure where the expected dipole configuration is being disturbed with the like of drifts, drags, diffusion, etc. So we discuss on how the summarized MHD equations inform the IMF dynamics in magnetosphere during the solar wind interaction with the earth's atmosphere.

**i) The dynamo equation**

The ratio of the second term (commonly known as the inertial force) to the first term (known as the viscous force) of the right hand side of equation 4.0.4 called the Lundquist of magnetic Reynolds number is used to measure and analyse magnetic diffusion through the fluid.

Considering small changes to apply linearization, the Reynolds number $R$ is given by

$$R_m = \frac{uL}{\eta} \text{ or } R = \mu_0 \sigma u L \tag{4.0.5}$$

where $L$ is the characteristic length over which the field change.

Equation 4.0.4 implies that in a highly conducting ($\sigma \rightarrow \infty$ or $\eta \rightarrow 0$) fluid the diffusion is negligible and thus the second term vanishes. Then, the total magnetic flux crossing a surface $S$ bounded by a closed curve at some initial time, will remain constant in time as the plasma fluid moves through the system and the location of $S$ and or its shape change in agreement with the work of Alfven and Falthammar (1963). All plasma elements initially connected by a magnetic flux tube of cross section $S$ then remain linked by the same flux tube in time as the plasma drifts through space, a consequence of the frozen-in magnetic field. Here, we observe that the plasma regimes of different properties can mix easily along $\mathbf{B}$, but not perpendicularly. The magnetic field is then tangential on either side of the boundary, but will in general be of different magnitude and direction with a current sheet at the boundary according to Ampre's law.

On the other hand if the plasma flow on either side is negligible, the dynamo equation is dominated by the diffusion component. In this case, in particular if $\mathbf{B}$ is oppositely directed on either side of an infinite plane, but of same magnitude and locally parallel to the plane the magnetic flux will then diffuse toward the current sheet where it annihilates and magnetic field energy is converted into heat. In time, the gradient in the field decreases, results to reduce diffusion rate as the local plasma pressure builds up; a self-limiting process of balancing pressure.

Finally, when the magnetic Reynold's number $\simeq 1$ the current sheet then equals unity, which means that the MHD frozen-in flux condition breaks down. However, the continuity equation requires that there must be an outflow as long as there is a plasma inflow and a second dimension gets introduced that sets a limit to the extension of the diffusion region. where the magnetic reconnection come into picture. But it is difficult to describe when and where exactly the reconnection will occur. However, literature reviews point out the possible factors believed to influence the probability of the reconnection onset and the rate by which reconnection takes place.

**ii ) The conservation law of MHD equations, discontinuity layers, shocks and structures of the magnetosphere**

According to the current understanding, beyond being the source of energy for life on earth, the sun streams out hot charged particle (plasma) called the solar wind. The Earth is to a large extent protected against this plasma flow by its magnetic field, which is generated by the thermal convection of its liquid interior. The geomagnetic field deflects most of the solar wind around the Earth, and creates a cavity in the solar wind that we call the magnetosphere.

Because of the magnetic field geometry of the earth at higher and lower latitudes, due to day-side and night-side temperature distributions, atmospheric particle density distribution variation: ion with altitude, orientation (facing) of the earth with respect to the sun and the solar wind distributions and variations there are set of magnetosphere layers classified based on mean characteristic parameters. For example, the first boundary layer that first interacts with the solar wind is characterized by collisionless plasma by the similar reason as described under case **(i)**. At this boundary, conservation of mass, conservation of momentum, conservation of energy are all being considered to derive the appropriate dynamical parameters like **B** both along the direction of the wind and tangential to the shock bow at the interface of the solar wind and the magnetosphere.

# Chapter 5

# Summary and Conclusion

The work in this thesis has been undertaken to investigate the interaction between the solar wind and the Earth's magnetosphere, particularly, it was of interest to determine whether one could predict the near-Earth magnetic field conditions using MHD equations. The solar wind carries a frozen-in magnetic field. Its convection to the earth's atmosphere provides inside into configurational changes in the magnetic topology, distribution of magnetic energy, mixing of plasma and connection of different region of the magnetosphere. Energy, momentum, and plasma enter the magnetosphere both via magnetic reconnection at the magnetospheric boundaries in regions where the interplanetary and terrestrial fields are antiparallel and via viscous interactions along the boundary. Energy transfer is most efficient when the reconnection process takes place at the dayside magnetopause, which occurs during periods when the interplanetary field points southward and is thus antiparallel to the intrinsic geomagnetic field. Variability in the north-south orientation of the interplanetary magnetic field causes episodic energy loading-dissipation cycles termed magnetospheric substorms one of the effects of space weather.Substorms typically occur at a rate of four to five per day, each lasting typically two to three hours. They are initiated by enhanced dayside reconnection and hence increased energy input to the magnetosphere. This causes a configuration change in the magnetosphere including enhancement of the magnetospheric current systems and formation of a thin and intense current sheet from near-geostationary distance outward which is another consequence of space weather, the aurora.

The dynamic processes associated with the solar wind-magnetosphere-ionosphere coupling processes can have significant effects in the near-Earth space environment, in the atmosphere, and on the Earths surface. This space weather interaction further affects human life activities and life on earth. Solar energetic particles arising from active events on the Sun cause degradation and failure of space-borne systems. High-energy electrons in the outer Van Allen radiation belts can penetrate through spacecraft walls and through electronics boxes and become buried in dielectric materials. Besides being a threat to technological systems, energetic particles pose a hazard to astronauts on space missions. The ionosphere is heavily utilized as a transmitter of radio-frequency communication signals and the radio wave communication is significantly influenced by the ionospheric properties and especially the auroral currents. High frequency (HF) radio wave communications are most affected, as they utilize reflection from the ionosphere to carry the signal to distances beyond the local horizon. At times of high auroral activity, the signal can be even completely absorbed making the high frequency radio propagation impossible. Space weather effects are seen even on ground, as strong currents in the magnetosphere can induce currents in long baseline conductor systems on ground. Affected systems include electric power transmission networks, oil and gas pipelines, telecommunication cables and railways systems. In power grids, these geomagnetically induced currents cause saturation of transformers, which tends to distort and increase the excitation current which the result of permanent damage of transformers. As a result, today there are enormous studies and interest in solar-terrestrial environments and interactions due to the availability of satellite observations of space, particularly in the near Earth environment. However, though, there is an overall progress in the observational works the theories that fit the observations lack correlation and need further works pertaining to the difficulty of exploiting the full Magnetohydrodynamic (MHD) equations. If there is any, most works assume the collision-free system with simplify boundary conditions.

In this thesis we did work on the MHD equations with simple boundary conditions and were able to conclude that they indeed work within limitations such as over mean global characteristic parameters including the steady solar wind etc. But has limitations to determine exactly eventful observations like coronary mass ejections and their interaction with the magnetosphere and the local magnetic storms.

We also observe that it is important to develop more advanced computational works to extract more accurate data from the full MHD equations.

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**Desta Fekede Geleta have read and evaluated his thesis entitled "Dynamics of Interplanetary Magnetic Field in Space Weather" and examined the candidate. This is therefore to certify that the thesis has been recommended to the school of graduate studies for acceptance in partial fulfilment of the requirements for the degree of Master of Science in Physics (Astrophysics).**

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# Declaration

**This is my original work, the thesis has not been presented for a degree in any other university and that all sources or materials used for the thesis have been duly acknowledged.**

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**email: desta.fekede@gmail.com**

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**This thesis has been submitted for examination with our approval as University advisor and Co-advisor.**

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**Date: ____________________**

**Co-advisor: Miss. Hiwot Tegegn**

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