ON THE TOPIC OF SUDDEN STORM COMMENCEMENTS RELATED TO THE EARTH'S GEOMAGNETIC FIELD WITH AN EMPHASIS ON THE PRECURSOR SIGNATURE

by

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ABSTRACT

ON THE TOPIC OF SUDDEN STORM COMMENCEMENTS RELATED TO THE EARTH'S GEOMAGNETIC FIELD WITH AN ON THE PRECURSOR SIGNATURE

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Much of space physics deals with the relationship between the sun and the earth. The type of interaction—solar winds, flares, particles, mass ejections, radiations, plasma, and magnetic fields—determine the phenomenon observed on earth. Sudden Storm Commencements (SSCs) are unique high impulse disturbances in the Earth's magnetosphere characterized by an anomalous rise in the Dst index. Both hourly and minute time resolutions would be utilized to compare deviations in value ranging from 10nT to 50nT. The goal will be to study SSCs by analyzing satellite data and constructing simulations in order to be able to predict future such storms on Earth. The proper identification of a hypothesized 'precursor signature' of SSCs is predicted to increase accuracy of space weather forecasting. Methodology will include both magnetohydrodynamical and magneto-statistical equations to analyze and infer the

existence of the precursor signature. Accurate mapping of space storms will improve GPS connectivity, prevent widespread power failures and improve satellite communications system.

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CHAPTER 1

INTRODUCTION

1.1 A Brief Summary

Humans have encountered geomagnetic storms since the last 200 years. However, it is in the last sixty to seventy years or so, have we been able to attain technological prowess required to study them. Due to advancements in space technology, satellite launches, and instrumentation analysis, studying geomagnetic storms have become easier and more accurate, although data is still sparse. Space scientists today are trying to understand this unique relationship between the Sun and Earth which makes geomagnetic storms possible. In the following pages, this research project will give a brief history of geomagnetic space storms, their origins, and the physics behind their occurrence.

Since the nineteenth century, a new field of physics has emerged, coined – Space Weather. It means exactly what it sounds like, concerning itself with the Sun, the Earth and its atmosphere, other planets (in the Solar System) and their magnetospheres, interplanetary space, etc. It is now well known information that the solar wind, sunspots, or Coronal Mass Ejections (CMEs) of the Sun are responsible for disturbances in the Earth's geomagnetic field.

Magnetic field of the Earth is a vector quantity and thus, one has some reasonable degree of freedom in labelling the three different axis (or components) of the magnetic field by indicating length and angle of the corresponding vector (where length corresponds to the strength of the magnetic field and the angle to the direction).

They can be:

1. three orthogonal strength components (X, Y, and Z)
2. the total field strength and two angles (F, D, I) or
3. two strength components and an angle (H, D, Z) [2]

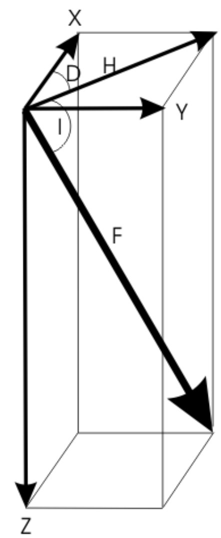

Figure 1.1: Pictorial representation of all the different vector quantities [2]

Component	Description
F	Total intensity of magnetic field vector
H	Horizontal intensity of magnetic field vector
Z	vertical component of the magnetic field vector; by convention Z is positive downward
X	the north component of the magnetic field. X is positive northward
Y	the east component of the magnetic field. Y is positive eastward
D	magnetic declination, defined as the angle between true north (geographic north) and the magnetic north (the horizontal component of the field). D is positive eastward of true North.
I	magnetic inclination, defined as the angle measured from the horizontal plane to the magnetic field vector; downward is positive

Table 1.1: Different magnetic components and their description [2]

Today, by definition, a geomagnetic storm is characterized by a main phase during which the horizontal component of the Earth's low latitude magnetic fields are significantly depressed over a time span of one to a few hours followed by its recovery, which may extend over several days [1]. One can have two different types of disturbances at the beginning of the event – Sudden Commencement (SC) or the Gradual Commencement (GC). In SCs, dynamic pressure of the solar wind is accelerated by the interplanetary shock. Once the shockwave reaches the Earth, it compresses the Earth's field (on SC or GC). Then it energizes a diamagnetic current system causing rapid depression in the H component of the Earth's magnetic field.

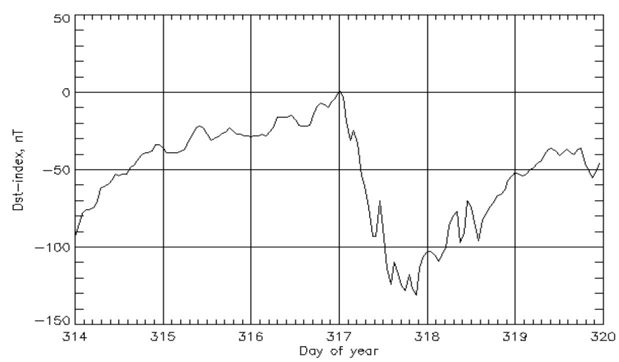

Figure 1.2: Example of a Gradual Commencement and a geomagnetic storm – 10 Nov 1998 to 15 Nov 1998

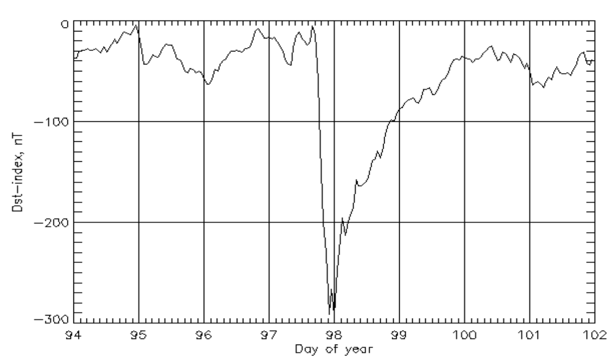

Figure 1.3: Example of Sudden Commencement and a geomagnetic storm – 04 April 2000 to 12 April 2000

The Interplanetary Magnetic Field (IMF) is a part of the sun's magnetic field, which is drifted in space (by solar wind) towards the earth and is detected by our satellites, which are in orbit around at the distance where $E_g = S_g$. Because the sun rotates once roughly every 27 days, the IMF creates a spiral pattern, like a water sprinkler on a lawn. Thus, depending on the orientation of the IMF, the solar wind interacts with the Earth's magnetosphere, creating storms, auroras, and other phenomenon.

CHAPTER 2

OVERVIEW OF SUDDEN STORM COMMENCEMENTS

2.1 Storm Indices

From the many different units of measurement, intensity of a geomagnetic storm is measured by the Dst (Disturbance Storm Time) Index. To understand Dst, we must first understand the Ring Current (RC) circulating at a distance of 3 – 8 Earth radii. Imagine a charged particle of plasma in the Earth's atmosphere with a velocity *v* in magnetic field *B*. By Lorentz force, we get:

$$F = q\vec{v} \times \vec{B} = qvB \sin\theta$$

Where *F* is the force experienced by the charged particle and *q* is the charge. Due to the sine relation, maximum Lorentz force experienced will be at 90° or, when *v* is orthogonal to *B*. Thus, particle travels in circular path, exhibiting gyro motion, where centripetal force equals the Lorentz force *F*:

$$\frac{mv^2}{r} = q\vec{v} \times \vec{B}$$

And $$r = \frac{mv^2}{q\vec{v}\times\vec{B}} = \frac{mv}{q\vec{B}}$$

By the above equations, we can draw the conclusion that the velocity of the charged particle is directly proportional to its gyrating radius. Similarly, such abovementioned charged particles in the Earth's atmosphere (protons, electrons, [O^+], and others) exhibit other types of motion as well, like bouncing motion and drift motion

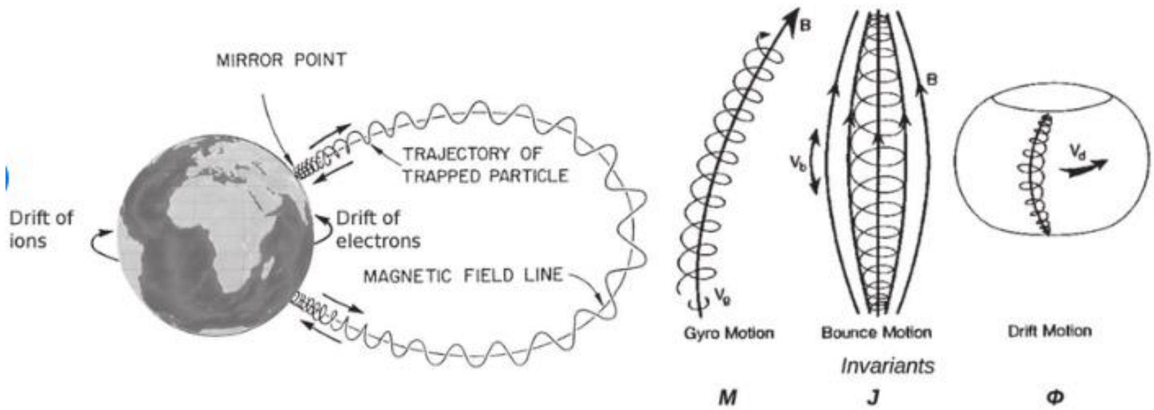

Figure 2.1: Schematic of different types of particle motion in magnetic field [3]

However, a combination of both the gradient and curvature effects experience a combined drift, referred to as a gradient-curvature drift, which is primarily responsible for the ring current and is described by the following equation:

$$v_{GC} = \frac{m}{q}\frac{v_{||}^2 + \frac{1}{2}v_{\perp}^2}{B_0}\frac{B_0 \times \nabla B_0}{B_0^2}$$

A few things to note in this equation is that gradient curvature velocity is inversely proportional to not only the amount of charge but also the type of charge, whether positive or negative. This means that in the ring current, positive and negative ions drift in opposite directions, away from each other, leading to a quasi-neutral ring current. These ions in the ring current are responsible in producing a magnetic field opposite to the Earth's magnetic field. Thus, this potential decrease in the Earth's magnetic field at the equator is measured by Dst index.

The Dst (Disturbance storm time) index is a measurement of earth geomagnetic activity and is widely used to characterize the geomagnetic storm. It is calculated on the basis of the average value of the horizontal component of the earth's magnetic field at four observatories, namely, Hermanus (33.3° south, 80.3° in magnetic dipole latitude and longitude), Kakioka (26.0° north, 206.0°), Honolulu (21.0° north, 266.4°), and San Juan (29.9° north, 3.2°) and is expressed in nano-Teslas. The strength of the low-latitude surface magnetic field is inversely proportional to the energy content of the ring current around earth caused by solar protons and electrons, which increases during geomagnetic storms. Thus, a negative Dst index value indicates that the earth's magnetic field is weakened, which is specifically the case during solar storms. Predicting Dst index is a difficult task due to its structural complexity involving a variety of underlying plasma mechanism. [4]

Dst measures undergo radical changes during geomagnetic storms. After the sun's activities transfer energy via the IMF to the ring current, there is a change in the ring current densities. A Sudden Commencement (SC) showcases a sudden rise in Dst, followed by the recovery period, where the Dst recovers slowly back to normal ranging from 5 - 15 days. It is important to keep in mind the Dst measures at its peak when it is at its most negative, corresponding to the abnormally low Earth's magnetic field at the equator. Dst is nothing but a measure of the deflection of Earth's magnetic field which indirectly indicates the strength of the particle flux density of the ring current.

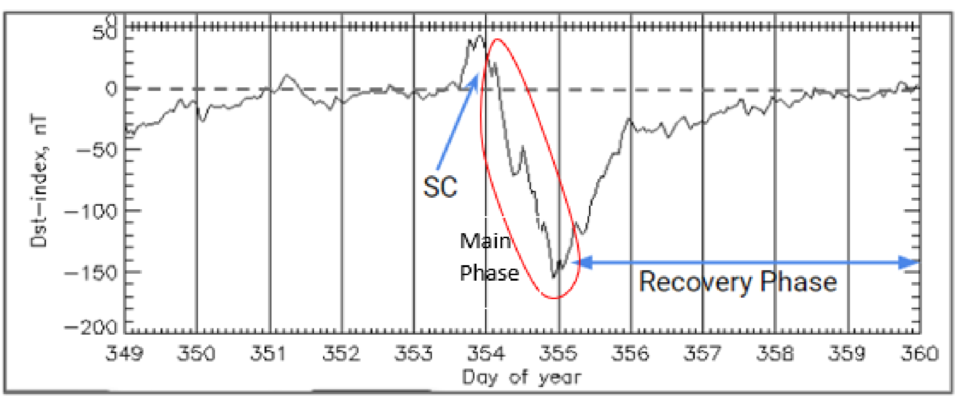

Figure 2.2: Dst measure of Dec 15, 2015 to Dec 25, 2015

Dst is measured hourly and a minimum of -50nT must be reached for a perturbation in the magnetic field to be qualified as a geomagnetic storm. Major storms can sometimes cross the -300nT barrier. [5] In figure 2.2, one can observe the “main phase”, which comes after the SC, where the primary exchange of energy from the solar wind to the magnetosphere takes place, increasing the RC, and thus, producing a strong decrease in Dst. The recovery phase acts just as the opposite where the magnetosphere falls back to its initial value, with a speed depending on the rate of decay of the RC.

2.1.1 SYM-H

Although similar indices, there is a difference in the time resolution where SYM-H gives a one minute time resolution compared to one hour time resolution of Dst. Dst combines measurements of four magnetometers, whereas SYM-H includes six or more. Both Dst and SYM-H are quite interchangeable, but a minute time resolution is preferred for small storm deviations typically around 10 nT - 50 nT. Since the Earth’s magnetic field is a vector quantity, we describe it using various coordinate systems (depending on our requirements). The most familiar coordinate system being the (X, Y, Z). Others are (F, D, I) or (H, Z, D). The (H, Z, D) is used for Dst or SYM-H, where H is the horizontal intensity, Z is the vertical component (by convention, positive downwards) and D is the magnetic declination angle (Figure 1.1). In SYM-H, we primarily are more interested in the change in the Horizontal intensity of the ring current. The effects of the dynamic pressure variations are more clearly seen in the SYM-H than the hourly Dst index.

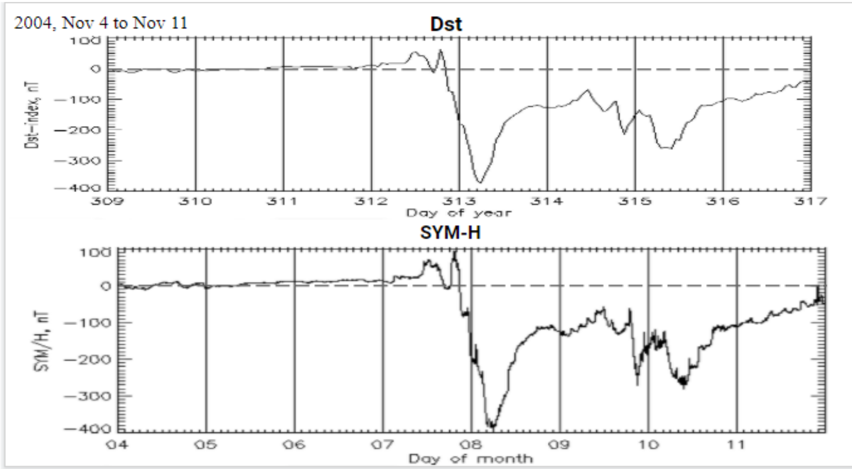

Figure 2.3: Comparison of Dst Vs SYM-H for s specific same date

Clearly, one can see more minor deviations of the magnetic field in SYM-H whereas the Dst graph appears smoother due to lower resolution. Furthermore, using SYM-H, one can zoom in further towards the SSC for added detail as now one has the advantage of minute resolution. For example, considering the same date as above, we get:

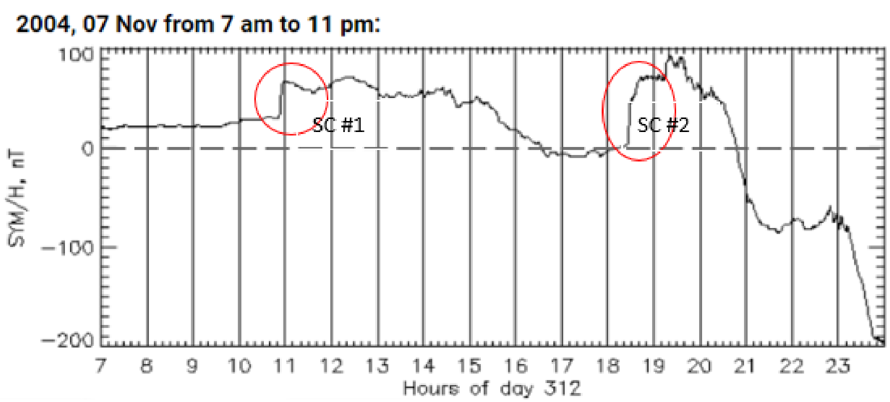

Figure 2.4: SYM-H zoomed in for a specific date and time period

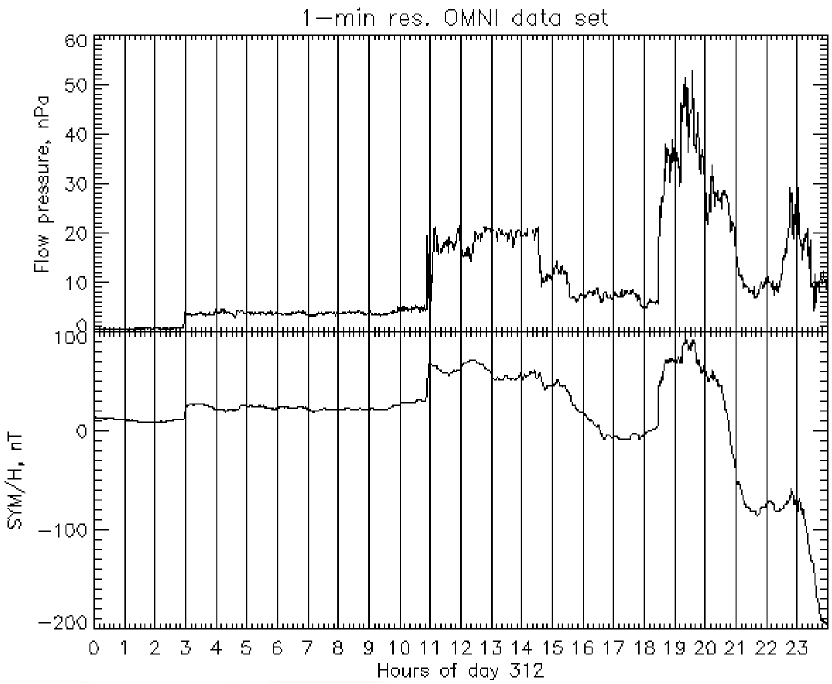

Figure 2.5: Confirmation of correspondence of dynamic pressure from solar wind to SYM-H at hour 11 and hour 18.5

CHAPTER 3

METHODOLOGY

3.1. Precursor Signature

A much needed analysis of predicting geomagnetic storms would be useful in protecting communication satellites, GPS systems and preventing costly power blackouts. Using Dst as a measure, a hypothesis is held up about a precursor signature just before Dst starts depressing rapidly. A good candidate date of a Sudden Storm Commencement (SSC) needs to be selected, and for the purposes of this project, Dec 15, 2015 to Dec 25, 2015 (Figure 2.1) has been selected.

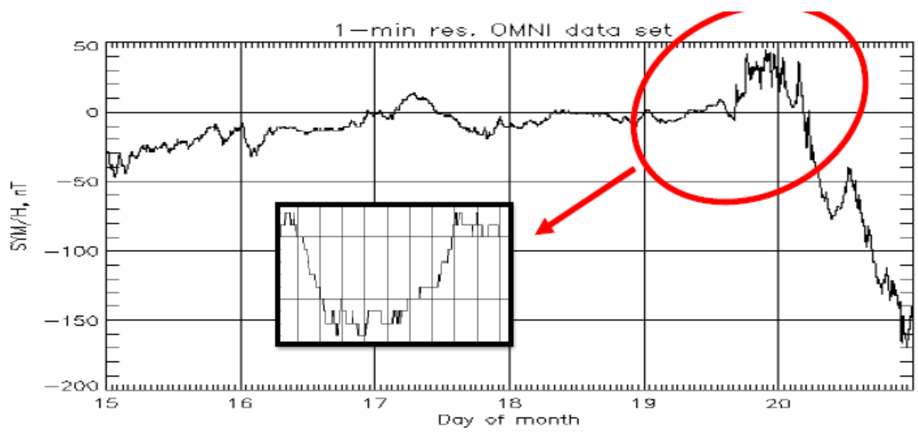

Figure 3.1: Hypothesized Precursor Signature of SSC

3.1.1 Existence of Precursor Signature

The problem to address would be to predict whether a precursor signature actually exists observationally or not. In figure 3.2 one can see that the simulated ICME contacts the bow shock, a precursor signature is observed in Dst. These signatures arise from the intense current sheet that forms at the IMF discontinuity as it jumps from−5nT to ±127nT. Because the virtual Dst is the result of a Biot-Savart integral covering the entire MHD domain, the ICME current sheet begins to drive pre-arrival signatures as soon as it enters the MHD model's upstream boundary at $+32R_E$. This signal is a result of the magnetostatic assumption implicit in the Biot-Savart integral. [6]

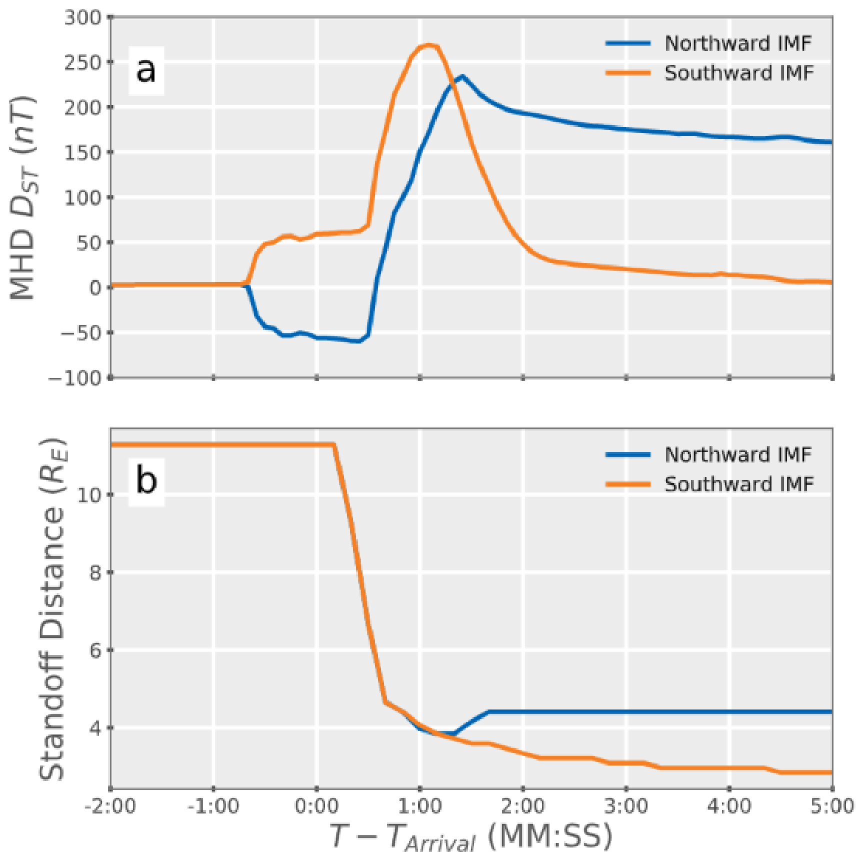

Figure 3.2: Summary of the northward IMF (blue) and southward IMF (orange) simulated sudden impulse in terms of the Dst index (frame a) and the magnetopause standoff distance (frame b) [6]

3.1.2 Discretization

The precursor signature can be found out whether it exists observationally by using various different techniques, one of which is discretization (for additional details on numerical discretization, check appendix A). It is a process of converting continuous functions into discrete parts for easier numerical analysis. For the concerned SSC, one needs to be able to discretize the magnetic field of the heliospheric current sheet travelling through interplanetary space. Neglecting any thickness, we have a sheet of charge, which store energy and while moving forward, is primarily responsible for releasing this energy near the Earth – the term called *Reconnection*. Using the Biot-Savart's law, one can calculate magnetic field of a constant current thus so:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{d\vec{l} \times \vec{r}}{|r|^3}$$

Where $d\vec{B}$ is the infinitesimal magnetic field generated by infinitesimal length $d\vec{l}$ at point of interest P (Figure 3.2), $\vec{r}$ is the distance from the current to the point of interest and $\frac{\mu_0}{4\pi}$ is a constant.

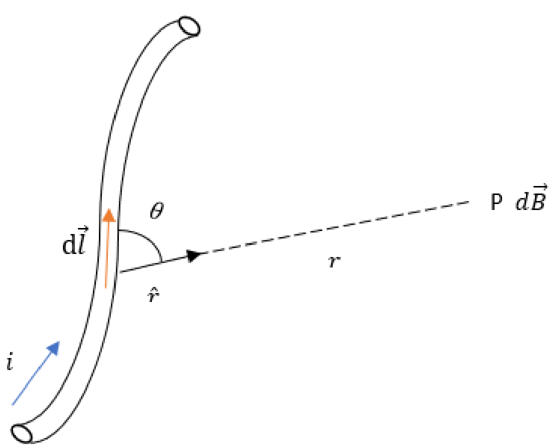

Figure 3.3: Biot Savart's Law

To find magnetic field *B*, integrate both sides to get:

$$\mathrm{B} = \frac{\mu_0}{4\pi} \int \frac{\vec{dl} \times \vec{r}}{|r|^3}$$

Which can be discretized to:

$$\Delta \vec{B} = \frac{\mu_0}{4\pi} \frac{\Delta \vec{l} \times \vec{r}}{|r|^3}$$

And thus,

$$\vec{B} = \sum_{i=1}^{N} \Delta \vec{B}_i$$

Such a technique is equally valid for our 2 dimensional current sheet:

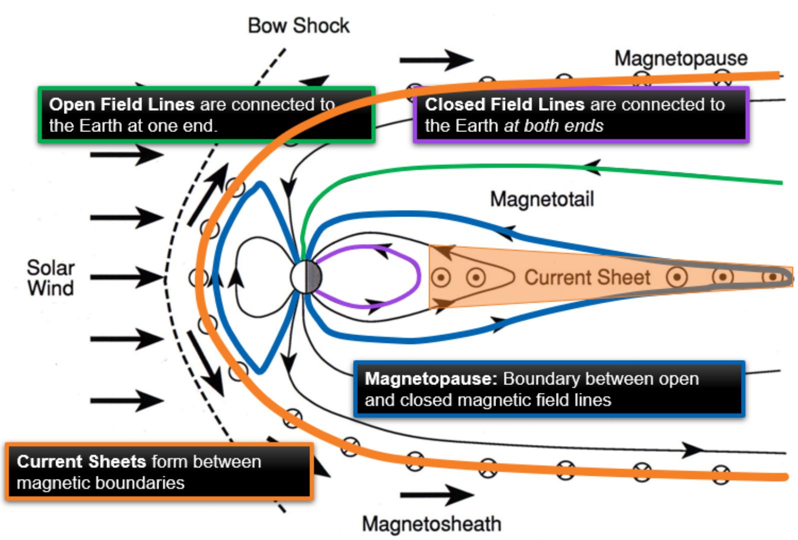

Figure 3.4: A typical magnetosphere (adapted from a talk given by Dr. Welling)

3.1.3 Setup

Let there exist a current sheet travelling towards Earth with a velocity *v*. The dimensions of the current sheet be 10 by 10 Earth radii with the distance between current sheet and Earth being 100 Earth radii and let current density be *K*.

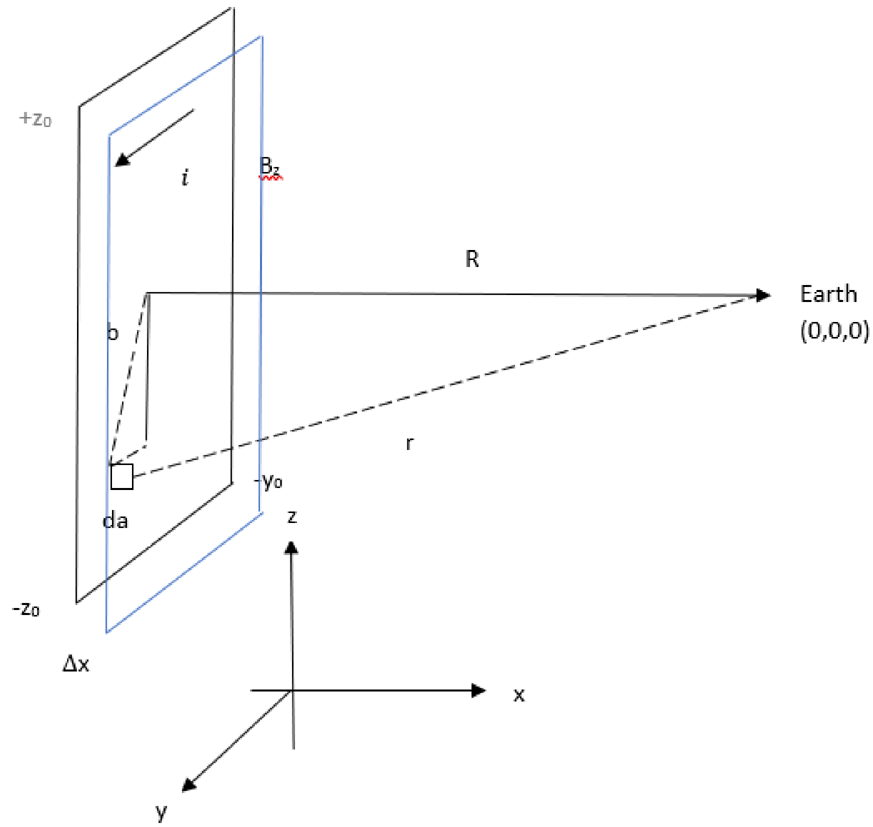

Figure 3.5: Setup required for numerical calculation

From Biot Savart Law in 2 dimensions, we have:

$$B_{earth} = \frac{\mu_0}{4\pi}\iint f(y,z)\,dy\,dz$$

Where, $f(y,z) = \frac{|\overrightarrow{K}\times\overrightarrow{r}|\hat{z}}{r^2}$

$$= \frac{K_x r_y - K_y r_x}{\sqrt{\sqrt{y^2+z^2}+R^2}}$$

Finally, after discretization, we get the following equation, ready for numerical analysis:

$$B_{Earth} = \frac{\mu_0}{4\pi}\sum_{-y_0}^{y_0}\sum_{-z_0}^{z_0}\frac{K_x r_y - K_y r_x}{\sqrt{\sqrt{y^2+z^2}+R^2}}\Delta y\ \Delta z$$

CHAPTER 4

RESULTS

4.1 Code in Python

Following is the code adopted to calculate the numerical discretized formula of the magnetic field:

```
'''
A module for calculating the proposed ground perturbation
due to an interplanetary current sheet before it comes in
contact with the Earth's upstream bow shock.
'''

import numpy as np

### Some useful constants:
mu0 = 4*np.pi*1E-7
Re = 6371000 # Earth radius in meters.


def midpoint (f, a, b, c, d, nx, ny):

    '''
    f is the function needed to discretize
    a, b, c, and d are the bounds of your summation
    function
    nx and ny are our step size
    '''

    hx = (b - a)/float(nx)
    hy = (d - c)/float(ny)
    I = 0
    for i in range(nx):
        for j in range(ny):
            xi = a + hx/2 + i*hx
            yj = c + hy/2 + j*hy
            I += hx*hy*f (xi, yj)
    return I
```

```
def test_midpoint(tol = 1E-5):

    '''
    Test our midpoint problem using an ideal function
    '''

    f = lambda x, y: 2*x + y
    result = midpoint (f, 0, 2, 2, 3, 5, 5)

    expected = 9.0 # This should be what we get!

    # If result is different than expected answer more than
    # a set tolerance removes extra decimal accuracies.

    if np.abs(result-expected) > tol:
        print ('Result = {}, Expected = {}’.format (result,
              expected))
        raise ValueError ('Did not return correct
                          result!!!')

def gen_kernal(R, ky, kz):

    '''
    Create functions that represent the kernal for the
    integral, both for by and bz.

    The function that is the integral kernal for the biot-
     savart function.

    "R" is the distance of the center of the sheet from
     Earth (r-x) and y, z are the coordinates along the
     sheet where we are currently integrating.

    Kx, Ky are the strength of the current sheet.

    Returns: Bz portion of integral kernal.

    UNITS: Use meters and amp/meters.  SI units.

    '''

    by = lambda y,z: 0
    bz = lambda y,z: (kx*y-ky*R)/np.sqrt(
np.sqrt(y**2+z**2) + R**2 )

    return by, bz
```

```
def biot_savart(R, ky, kz, width=128, dX=.1):

    '''
    Using the midpoint integrator, calculate the surface
magnetic field perturbation from a uniform interplanetary
current sheet.

    Parameters:
    ==========
    R  : float
         Distance from Earth in Earth radii
    ky : float
         Current sheet strength in the GSM Y-direction
         (amps/m)
    kz : float
         Current sheet strength in the GSM Y-direction
         (amps/m)


    Other parameters:
    =================
    width : float
            Width of current sheet in both Y and Z
            directions in Re.
            Defaults to 128 earth radii.
    dx    : float
            Size of spatial step for integration in Earth
           radii.
            Defaults to .1Re.

    Returns:
    ===========
    by, bz: float, float
        Perturbation as measured by ground at center of
        Earth in the Y, Z directions (GSM).

    '''

    # Convert units!
    R      *=Re #earth radii to meters.
    #width *=Re #earth radii to meters.
    #dX    *=Re #earth radii to meters.

    # Get number of steps required to finish integral:
    nx = int(width/dX)

    # Create integral kernals:
```

```
    kern_y, kern_z = gen_kernal(R, ky, kz)

    # Integrate!
    by = 0 # Hey fix this in the future.
    bz = midpoint (_biot_kernal_z, width/2, width/2,
          width/2, width/2, nx, nx)

    return(bz)

def calc_K(b1, b2):

    '''
    For *b1* (downstream magnetic field, or field closer to
     the Earth)and *b2* (upstream magnetic field, or further
     from the Earth), calculate the current sheet required
     to sustain the change between the fields.
    Return current density in amperes/meter.

    Magnetic field should be given in nanotesla!

    '''

    return 1E-9*(b1-b2)/mu0

if __name__ == '__main__':
    # This is the default action if you run this code!
    print ('Testing against Extreme SSI simulation!')

   # Get our current sheet strength using values from
   # simulation:
    Ky = calc_K (-5, 127)
    Kz = 0

    # Set distance from Earth:
    R = 20 * Re # 20 RE from Earth!

    # Integrate!
    bz = biot_savart (R, Ky, Kz)

    # To get time series, loop over an array of R-values:
    x_all = np.arange(150, 15, -1)
    b_all = np.zeros(x.size)

    for i, x in enumerate(x_all):
        b_all[i] = biot_savart(x, Ky, Kz)
```

4.2 Future Work

Future research goals upon this topic will be (but not limited to):

1. Make use of the following simulation (Figure 4.1) to calculate K_x and K_y components of the current density K.

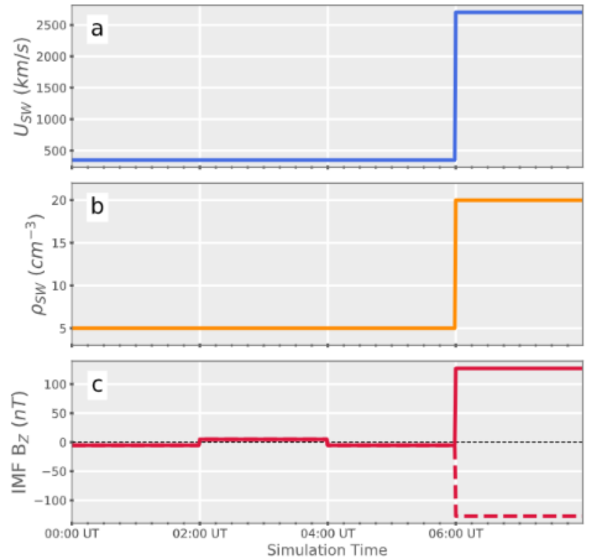

Figure 4.1: Hypothetical Solar Drives

2. Using MHD equations instead of discretization

3. Writing, compiling and executing code from MHD

APPENDIX A

DISCRETIZATION METHOD

Let there be a function $f = f(x)$ represented by the following figure:

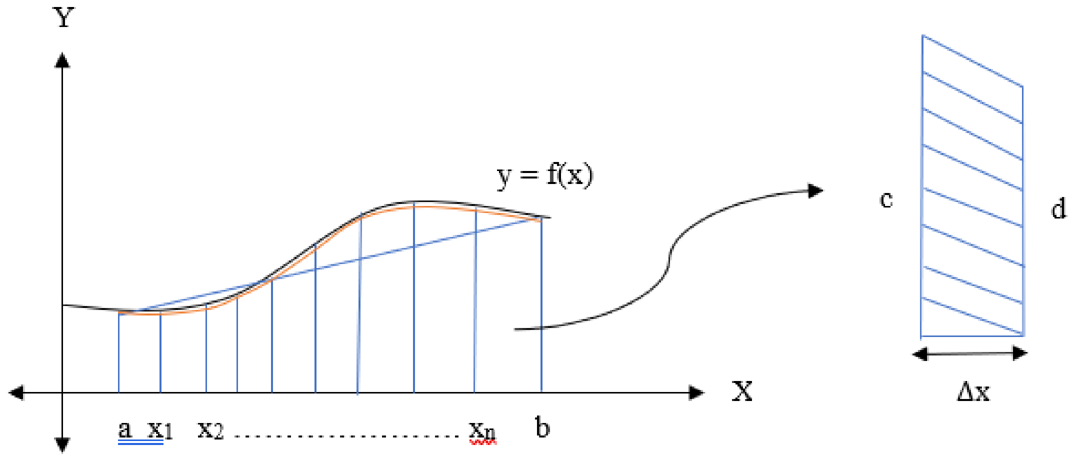

Figure A.1: Sample function to test Trapezoidal Rule

By Trapezoidal Approximation Technique, to calculate area under the curve of f(x), we divide the area into many different trapezoids of length Δx, calculate area of each trapezoid and sum it over from a (the lower bound) to b (the upper bound). The smaller the length of the trapezoid greater the accuracy of the area under the curve.

Area of trapezoid is = $\frac{c+d}{2}\Delta x$ and thus, total area is:

$$\int_a^b f(x) \approx \frac{1}{2}[f(a) + f(x_1)]\Delta x + \frac{1}{2}[f(x_1) + f(x_2)]\Delta x + \cdots + \frac{1}{2}[f(x_i)$$

$$+ f(x_{i+1})]\Delta x + \ldots + \frac{1}{2}[f(x_{n-1}) + f(b)]\Delta x$$

$$\approx [\sum_{i=1}^{n-1} f(x_i) + \frac{1}{2} f(a) + f(b)]\Delta x$$

APPENDIX B

SAMPLE CODE FOR DISCRETIZATION METHOD

```
import math
import matplotlib.pyplot as plt
import numpy
import time
#####################################
# TRAPEZOIDAL APPROXIMATION PACKAGE
def trapezoidal (f, a, b, n):
    h = float(b-a)/n
    result = 0.5*f(a) + 0.5*f(b)
    for i in range (1, n):
        result += f (a + i*h)
    result *= h
    return result
#######################################

xlist= [] # list for x values of graph
ylist= [] # list for values of the function (y values)
sum=0

for i in range (-50,50): # For loop for creating array of
domain and range of the function
    sum+=1
    xlist.append(sum)
    f=i**2 # basic function of y=x^2
    ylist.append(f)

print(xlist)
print(ylist)

plt.plot(xlist, ylist) # Plotting Values
plt.xlabel('x values') # labelling
plt.ylabel('f(x)')     # labelling
plt.show()

from trapezoidal import trapezoidal # Importing the
#Trapezoidal Approximation package

from math import exp
v = lambda x: (x**2) # Inputting the function whose
#integral sum is to be calculated. Here f = x^2

n =100 # determining step size
numerical = trapezoidal (v, -1, 1.1, n) # Calling the
#function with bounds from -1 to 1.1
```

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