UNIVERSITY OF NAIROBI

SOLAR STORMS AND THEIR EFFECT ON MAN-MADE SATELLITES

BY

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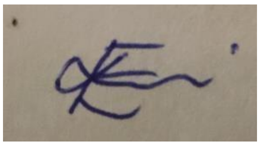
I56/37253/2020

A Thesis Submitted for Examination in Partial Fulfillment of the Requirements for Award of the Degree of Master of Science in Physics of the University of Nairobi

July, 2023

Declaration

I hereby declare that this MSc thesis is my original work and that it has not been submitted to any other university for examination or as a research project. All sources used have been acknowledged by means of proper references.

Signature…  Date… 04-08-2023

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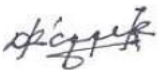
Signature ………  …… Date……04/08/2023……………………

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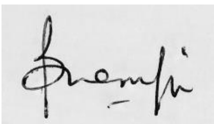
Signature …  Date……August 4, 2023

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Acknowledgements

I would like to thank my family for their support during my studies. The University of Nairobi for the opportunity to pursue my MSc degree. And my supervisors Prof. Collins Mito and Dr. Awuor for their patience.

Abstract

The Sun exists in a cyclical pattern of solar activity. This dynamic nature creates what we refer to as space weather, and a key featured associated with it is a solar storm. These storms create a coupled system joining the Sun, Earth and interplanetary space. Over the past several decades, advancements in technology have allowed for the creation and deployment of multiple satellites into orbit around Earth. These satellites are used for multiple reasons such as communication, navigation, and some even serve as scientific observational equipment for example as telescopes. The Earth's geomagnetic field encompasses the near-Earth space and provides a protective barrier around the Earth. Satellites in orbit are usually within this region. When intense solar storms occur, they release highly energetic particles into space, and some of these particles penetrate the Earth's magnetic field becoming trapped within it. The result of such an interaction is a magnetic storm. Magnetic storms vary in intensity and duration. Intense magnetic storms are capable of affecting ground-based equipment, but pose a significant danger to satellites in orbit. During the Starlink event in February 2022, multiple satellites from the company SpaceX were damaged and destroyed. This project is aimed at analyzing the solar storm that caused this event, to identify the changes it caused to the Earth's atmosphere, the features of this solar storm such as the time it took to reach the Earth, and its Disturbance Storm Time (DST) index.

Key words: Solar storms, geomagnetic field, magnetic storms, Starlink event, DST index

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List of Abbreviations Used

CME – Coronal Mass Ejection

DST Index – Disturbance Storm Index

IMF – Interplanetary Magnetic Field

LASCO – Large Angle and Spectroscopic Coronagraph

NASA – National Aeronautics and Space Administration

ESA – European Space Agency

SECCHI - Sun Earth Connection Coronal and Heliospheric Investigation

SOHO – Solar and Heliospheric Observatory

STEREO – Solar Terrestrial Relations Observatory

UT – Universal Time

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Chapter 1: Introduction

1.1 Background

In 1957, the Russians launched the very first satellite, Sputnik 1. Since then, many countries have become involved in the exploration of space. The results include the formation of organizations dedicated to its study, for example, the European Space Agency (ESA). These organizations have even launched their own satellites into orbit. Satellites have also been deployed to study our neighboring planets such as Mars and Saturn. Private companies, such as SpaceX, have also joined in.

Satellites have become increasingly important in these modern times. They facilitate functions such as navigational through the Global Positioning System (GPS), and scientific observations which include the International Space Station (ISS). Since Sputnik 1, several thousand satellites have been launched, and encompass the Earth.

1.2 Problem statement

Man-made satellites are incredibly useful devices that orbit the Earth. They can serve multiple purposes such as to facilitate communication, they are used for navigation such as Global Positioning System (GPS), and scientific observations. Over the decades, the number of satellites placed in orbit has been on the increase, with the introduction of new and more effective satellites. As technology has improved, the cost for the manufacture of satellites has increased. As of now, the average cost is estimated to be one million dollars, a huge investment. Are they safe in orbit? Unfortunately, no.

The space around the Earth is enclosed by the geomagnetic field. This field is usually capable of shielding the Earth and satellites from the hazards of space such as high energy electromagnetic radiation from the Sun. At times, disturbances on the Sun's surface create solar storms, and when they hit the geomagnetic field, the result may be an intense magnetic storm.

These storms can damage satellites by destroying the sensitive equipment needed for them to function, degrading the solar panel that provide them with power, and even altering their orbits.

Satellites that sustain heavy damage, could be rendered useless or ineffective. This is what happened during the Starlink event of February, 2022, where several satellites belonging to the SpaceX company were damaged by a solar flare. This event not only resulted in a financial loss for the company, but also showed the need for better methods to detect solar storms and how to better protect satellites.

1.3 Objectives

The main objective of this research is to investigate how solar storms interact with the magnetosphere of the Earth with effects that possibly affect the atmosphere as well as satellites in orbit.

The specific objectives are:

- To identify the features of a solar storm.
- To analyze the possibility that a solar storm caused the Starlink event in February, 2022.
- To determine the time it took to reach the Earth.
- To identify the changes the solar storm caused to the Earth's atmosphere.
- To determine the Disturbance Storm Time (DST) Index.
- The effect of the Starlink event on SpaceX's launch procedure.
- To establish better methods of detecting and tracking solar storms.

Chapter 2: Literature Review

2.1 History

The term magnetic storms are what was used to describe what we refer to today as space weather and space storms. It was first used by the German explorer and naturalist Alexander von Humboldt.

Space storms are the key phenomena associated with space weather. Their interactions with the magnetic field of the Earth are capable of producing the following effects in space:

- Accelerating charged particles.
- Intensify electric currents both in space and on the ground.
- Vibrant auroras in the Earth's polar regions.
- Global magnetic disturbances on the surface of the Earth. This is the feature mostly associated with space storms, and hence the origin of the term magnetic storms.

In 1829, von Humboldt conducted an excursion through Russia. After, he encouraged the Czar to set up solar observatories across Russia and Alaska. The Royal Society also established several such observatories in Canada, Africa and Australia. The observations that were made showed that magnetic storms across the world shared a similar structure which results in steep decrease in the horizontal component of the Earth's geomagnetic field and lasts for several hours. After the storm the geomagnetic field would then slowly recover over several days.

Sydney Chapman (1919) explained that during magnetic storms the associated decrease in the geomagnetic field was the result of electric currents flowing to the Earth that were caused by charged particles streaming from the Sun. Later that year, Frederick Alexander Lindemann proposed that electrostatic repulsion could destroy such streams by electric neutralization. This requires the particle stream to contain an equal number of positively and negatively charged particles.

This was an important note that Chapman later used in his work alongside Vincent Ferraro (1930, 1931). They proposed that the stream from the Sun contained both ions and electrons, and was the cause of these magnetic storms. These charged particles were capable of penetrating through the magnetosphere. They then flow around the Earth creating an electric current with a field in the opposite direction to the geomagnetic field. This theory held true for many decades. Only one major aspect has been changed: the stream in Chapman's theory that was thought to be continuous, we now know it only occurs in bursts. Eugene Parker (1958) named these bursts of ionized gas the solar wind. Parker was proved right when the spacecraft Mariner 2 confirmed its existence on its voyage to Venus. Figure 1 (Science Learning Hub New Zealand) illustrates the solar wind with charged particles penetrating the magnetic shield established by the Earth's geomagnetic field.

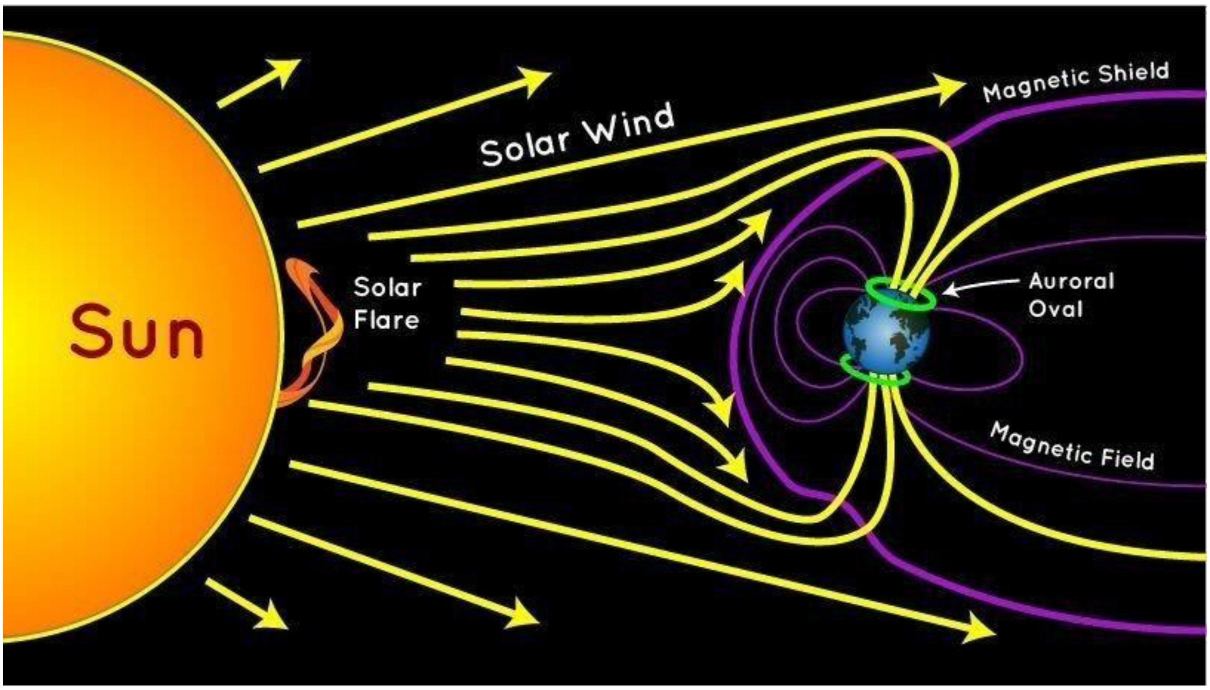

Figure 1: Solar wind interaction with the magnetic field of the Earth.

Some charged particles from the Sun are capable of penetrating the Earth's magnetic field.

Siegfried Fred Singer (1956) proposed that collective motions of charged particles from the Sun can act on the Earth's magnetic field so as to allow some of the particles to pass through and be trapped. The regions where such particles could be trapped had already been identified by Fredrick Carl Mulertz Stromer (1955). Singer's more detailed theory (1957) presents that these energetic particles carry a westward flowing electric current which is responsible for the observed decrease in the horizontal component of the Earth's magnetic field during a storm.

Thanks to an increase in space exploration and observation, we now have a better understanding of solar storms. Often, before solar storms are detected, an interplanetary shock hits the Earth. In order for a storm to occur, an important condition must be met: a long-lasting and intense southward directed Interplanetary Magnetic Field (IMF). It is now considered that coronal mass ejections (CMEs) are responsible for intense solar storms that result in the introduction of energetic particles that increase the westward flowing ring current.

The effect of space storms on the Earth is represented by a time profile called the Disturbance Storm Time (DST) index. Figure 2 (Atmospheric and Environmental Research 2003) is the DST index recorded in November, 2003. It depicts a steep decrease of the horizontal component of the Earth's magnetic field following a magnetic storm.

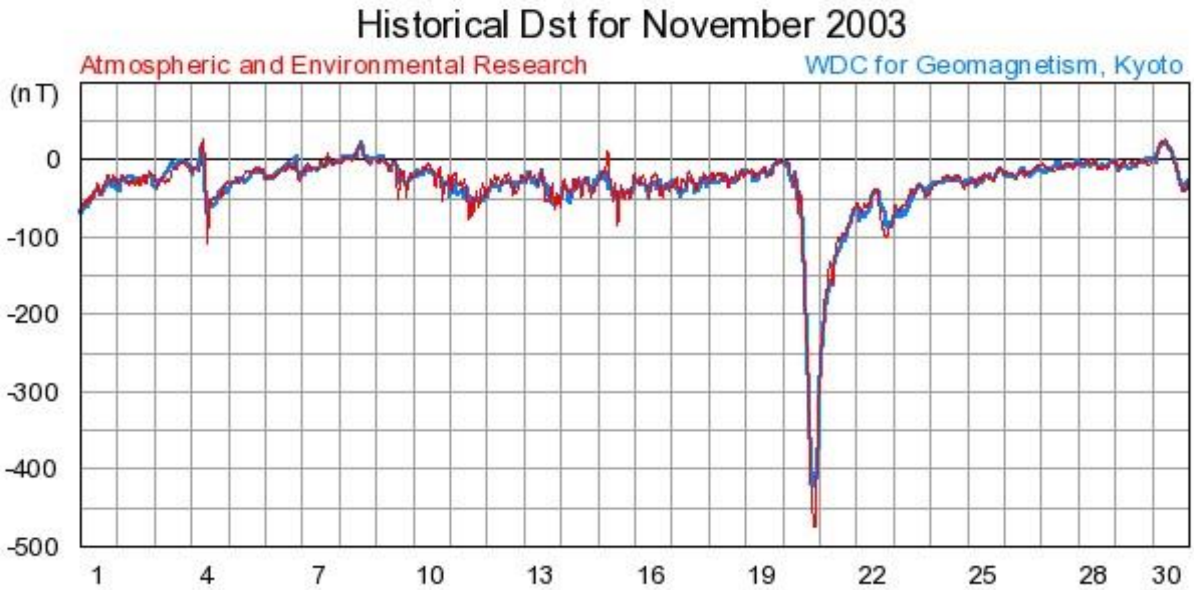

Figure 2: DST index recorded in November, 2003.

The y-axis is the magnetic field in nanoteslas (nT). The x-axis is the time in days.

Based on Chapman's assumption that the decrease in the horizontal component of the Earth's magnetic field is only due to an increase in the westward flowing ring current, the DST index yields a measure of the ring current. But M. Sugiura (1964) defines the DST index as the global change of the low-latitude horizontal component. Ground based magnetometers are used to measure this decrease in low-latitude areas. This data is then used measure the intensity of a magnetic storm.

Today, the DST index is used as a way to monitor and predict solar storms. But, the exact cause of its fluctuations is still a highly contested issue.

2.2 The Van Allen Radiation Belts and Ring Currents

Space storm can cause an observable increase in the intensity of radiation and also of ring currents of the Van Allen Belts.

When ionized particles from the Sun become trapped in the Earth's magnetic field, they drift around the planet. Van Allen (1959) suggested that the radiation was not due to electromagnetism, but rather was caused by microscopic particles such as ions and electrons with energies greater than 1MeV.

Figure 3 (Encyclopedia Britannica, Incorporated) is a representation of the Van Allen radiation belts around the Earth.

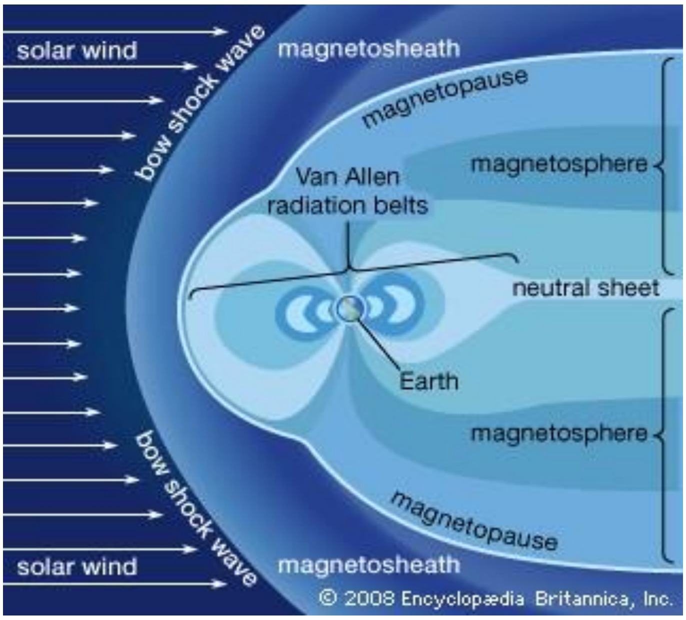

Figure 3: Van Allen radiation belts around the Earth.

These radiation belts also pose serious hazards to spacecrafts, satellites and astronauts.

As was originally introduced by Siegfried Fred Singer in 1957, the ring current that flows westward around the Earth is a toroidal-shaped electric current, and is created by charged particles trapped in the Earth's inner magnetic field that drift around it. These trapped particles exhibit two basic forms of motion:

- Gyration or cyclotron motion (due to Lorentz force).
- Bounce motion along field lines (between mirror points).

Figure 4 presents the cyclotron and bounce motions exhibited by charged particles as they move while trapped between the mirror points in the Earth's magnetic field.

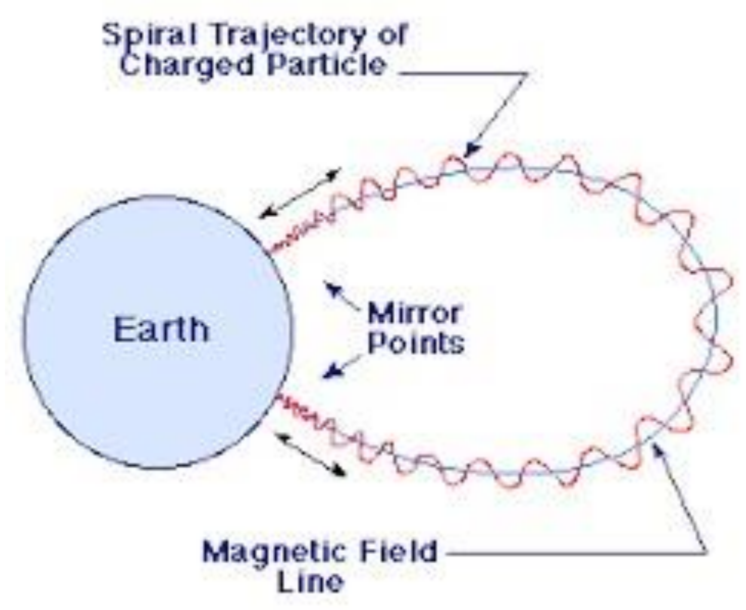

Figure 4: Bounce motion and gyration of trapped charged particles.

Over the decades, advancements in space observations and spacecraft measurements have proved invaluable in our understanding of ring currents. In particular, the Active Magnetospheric Particle Tracer Explorer (AMPTE) mission (1980s) has enabled better understanding of:

- The outline and position of the ring current population.
- The energy and intensity of the particles involved.
- Angular distribution measures of ions on a given magnetic field line.
- The composition of ions responsible for the ring current.

Much about the ring current remains unknown. This is primarily due to insufficient measurements made by a single spacecraft when observing a large and dynamic system.

2.3 Components of Solar Storms

As mentioned earlier, solar storms are the key phenomena associated with space weather. Solar storms are composed of:

- Solar flares.
- Coronal Mass Ejections (CMEs).
- Solar Proton Events (SPEs).

It should be noted that not all solar storms have these three components.

The Sun is not a stationary system. Instead, it undergoes a cyclical period of magnetic pole reversals that lasts for approximately 22 years. This can be observed from the frequency with which sunspots appear. This cyclical period happens in two phases, each lasting approximately 11 years:

- During the first phase, the Sun's magnetic poles reverse their polarity.
- In the second phase, the magnetic poles reverse their polarity and return to their original state.

Sunspots are considered to be the origin of solar storms. When viewed from the Earth, the Sun spins on its axis, and a complete rotation takes approximately 27 days. Sunspot groups are capable of staying active for several solar rotations. As a result, solar storms may exhibit a cyclical 27-day pattern.

Not all solar storms are the same. They may vary in intensity as well as their impact on the Earth. One of the most intense observed solar storms was the Carrington Event in September, 1859.

2.3.1 Solar Flares

These are magnetic explosions that occur on the Sun's surface. Approximately 8 minutes after a solar flare is observed, highly energetic electromagnetic radiation is detected, and includes gamma rays, x-rays, extreme ultraviolet radiation, and radio waves. Some of the effects of solar flares include interfering with satellite communication and radar interference.

Solar flares fall into three groups based on their brightness within the x-ray wavelength. These groups are:

- C-class. These are weak solar flares and they may produce few noticeable effects.
- M-class. These are solar flares within the medium range. Their effects are limited to the polar regions, and include radio blackouts.
- X-class events. These are some of the most intense solar flares that can cause major radiation storms in the upper atmosphere and worldwide radio blackouts.

Table 1 shows the M-class and X-class solar flares with their corresponding intensities.

Table 1: M-class and X-class solar flares and their associated intensities

Class	Intensity (Wm^{-2})
M1	1×10^{-5}
M2	2×10^{-5}
M3	3×10^{-5}
M4	4×10^{-5}
M5	5×10^{-5}
M6	6×10^{-5}

Class	Intensity (Wm^{-2})
X1	1×10^{-4}
X2	2×10^{-4}
X3	3×10^{-4}
X4	4×10^{-4}
X5	5×10^{-4}
X6	6×10^{-4}

2.3.2 Solar Proton Events (SPEs)

During such an event, the Sun produces high energy protons of approximately 10 to 100 MeV. Higher SPEs of approximately 20 GeV can also be produced but such events are rare. On average SPEs arrive at Earth in approximately an hour. The fastest recorded event was on January 20, 2005 taking approximately 15 minutes to reach the Earth. Some of the effects of SPEs include: spacecraft electronic damage, spacecraft solar panel degradation, satellite disorientation, and an extreme radiation hazard to astronauts.

When these high energy protons of SPEs interact with the Earth's atmosphere, the produce ultraviolet auroras, invisible to the human eye. The by-product of such a reaction are nitric oxide compounds, which are detectable in ice cores. SPEs are associated with large Coronal Mass Ejections (CMEs). The larger the CME, the more likely a SPE will occur.

2.3.3 Coronal Mass Ejections (CMEs)

CMEs are massive clouds of plasma with medium to low energies emitted from the solar corona, and are imbued with a magnetic field, ejected into the interplanetary space. When CMEs collide with the Earth's magnetic field, a magnetic storm is created. This causes a noticeable effect worldwide especially in the increase in westward flowing ring current.

The effect of a magnetic storm depends on its orientation to that of the Earth's magnetic field. If the solar storm has a southward magnetic field, it will likely produce a very intense magnetic storm. If the solar storm has a northward magnetic field, the resulting magnetic storm will have a minimal effect. Some of the effects of CMEs are power blackouts, and damages to communication equipment.

Chapter 3: Methodology

3.1 Starlink Satellite Launch

On the 3rd of February, 2022, the SpaceX company launched the spacecraft, Falcon 9, with a payload of 49 Starlink satellites, into orbit. The launch was conducted from National Aeronautics and Space Administration's (NASA) Kennedy Space Center in Florida, USA.

During the launch and initial operation of the satellites, there was a geomagnetic storm caused by the interaction between the Earth's magnetic field and the charged particles from the solar wind following a solar flare. As a result, the Starlink satellites were damaged causing some of them to reenter the Earth's atmosphere on the 7th of February, 2022. Figure 5 (Howell 2022) shows the launch of the rocket Falcon 9.

Figure 5: SpaceX Falcon 9 rocket launch.

Falcon 9 was launched from NASA's Kennedy Space Center in Florida, America. (Image credit: SpaceX)

3.2 The Sun's Active Regions

These are regions of the Sun where its magnetic field is heavily concentrated. As a result, they are the sites where phenomena such as solar flares occur. They exist all over the Sun's surface, but as the Sun rotates, such regions on the far side facing away from the Earth are unobservable. For the case of the February 2022 solar storm, the point of origin identified was the solar active region 12936. Figure 6 (Gopalswamy, Xie, Yashiro, Akiyama 2022) is an extreme ultraviolet image (EUVI) taken by the Solar Terrestrial Relations Observatory (STEREO) Ahead of the active region 12936.

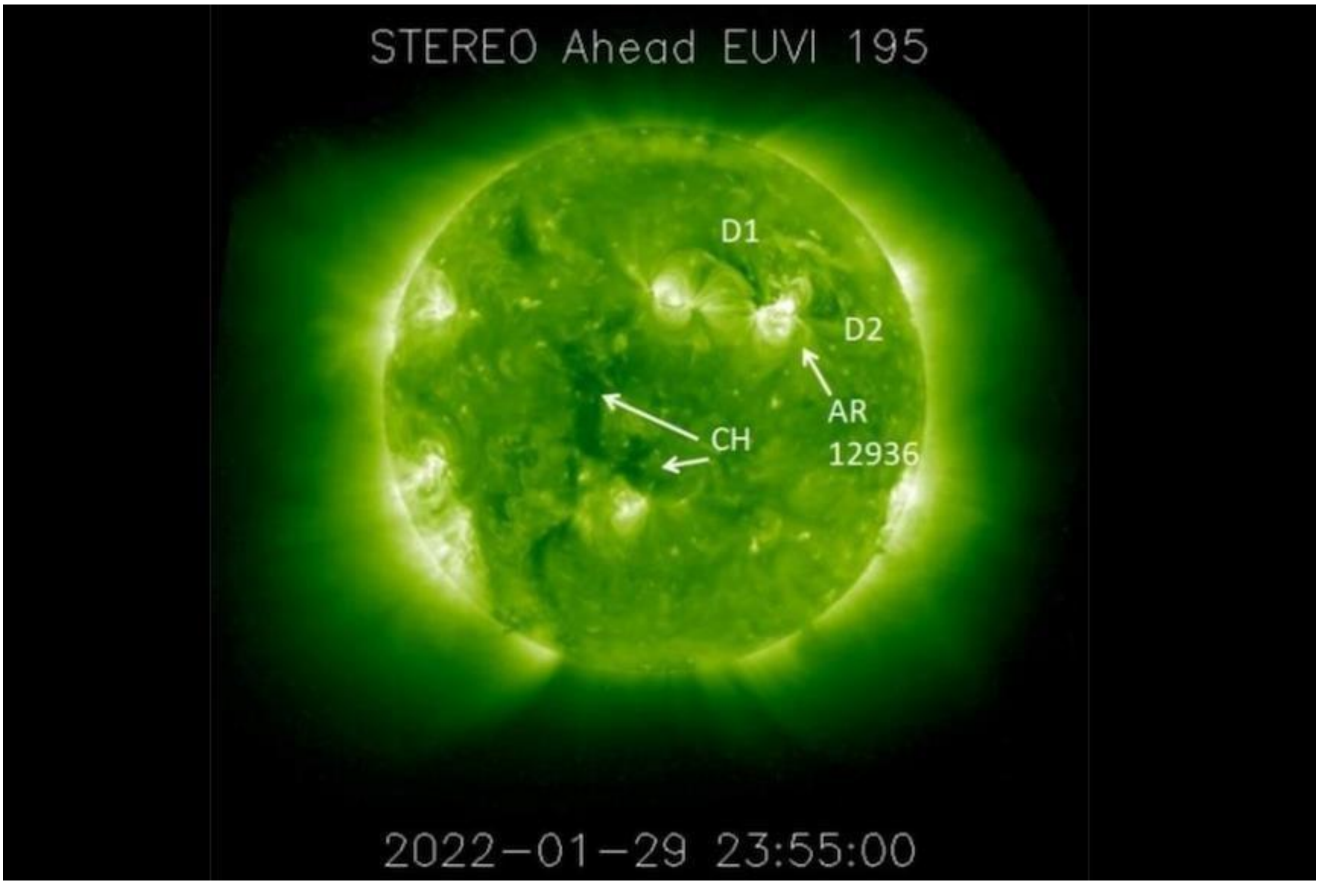

Figure 6: An Extreme Ultra-Violet Image of the Sun.

The image was taken by the Solar Terrestrial Relations Observatory Ahead (STEREO-A) spacecraft that shows the active region 12936.

Figure 6 shows the following key features:

- Coronal holes (CH). These are regions on the Sun where the magnetic field lines are open. As a result, coronal gases are able to escape outwards into the interplanetary space and constitute the solar wind.
- Dimming regions (D1 and D2). These regions are closely associated with coronal mass ejections (CMEs). When strong solar flares occur, they are accompanied by massive CMEs. The areas the CMEs originate from become less bright or dim when compared to their surroundings. As a result, these dimming regions are useful when trying to differentiate solar flares.

3.3 The Solar Corona

The corona is the outermost part of its atmosphere. Although its temperature is several million degrees, it is unobservable under normal circumstances unless viewed during a solar eclipse, or with specialized instruments called coronagraphs or coronameters. This is because the corona is less dense than the Sun's surface, making the surface much brighter.

3.3.1 Coronal Observations

Two important missions to observe the Sun have been conducted by the Solar Heliospheric Observatory (SOHO), and the Solar Terrestrial Relations Observatory (STEREO):

- SOHO is a joint European Space Agency (ESA) and NASA mission. It was launched in 1998, and has proved successful. This mission was extended and has been operational over the past two decades. As a result, it has observed the Sun over several solar cycles. It is equipped with a coronagraph known as Large Angle and Spectroscopic Coronagraph (LASCO).
- STEREO or STA is a NASA mission, that was launched in October, 2006. It consists of two identical observatories that orbit the Sun, with one ahead and the other following it (STEREO-A and STEREO-B). Their purpose was to carry out observations on solar ejections such as CMEs in order to locate their origin and how they evolve as they

traverse the interplanetary space. On the 1st of October, 2014, NASA lost communication with STEREO-B. STEREO-A remains in operation and has provided information on the far side of the Sun. STEREO-A also has a coronagraph onboard known as the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI).

Both SOHO and STEREO have a Sun-centered field of view.

On the 29th of January, 2022, a class M1.0 solar flare occurred. Its point of origin was identified as the active region 12936. The coronagraphs aboard SOHO and STEREO-A were able to capture the associated CME from two different points of view. This CME expanded as it traversed the interplanetary space and reached the Earth on the 2nd of February at 23:03 UT, lasting until the 3rd of February at 10:53 UT. UT means universal time, and is a standard of time that is based on the Earth's rotation. Wind is a spacecraft launched by NASA on the 1st of November, 1994. Its purpose is to study the solar wind. During this period, it observed the solar wind associated with the CME, noting that it had a strong magnetic field, and a low proton number density. The solar wind provided a strong southward flowing interplanetary magnetic field (IMF), with the result being a geomagnetic storm on the 3rd of February, 2022.

On the 4th of February, 2022, the active region 12936 generated another CME which was in the same direction as the first. This new CME arrived at the Earth on the 4th of February 2022, at 02:55 UT and lasted until 20:14 UT. The associated solar wind also provided another strong southward IMF, resulting in another geomagnetic storm.

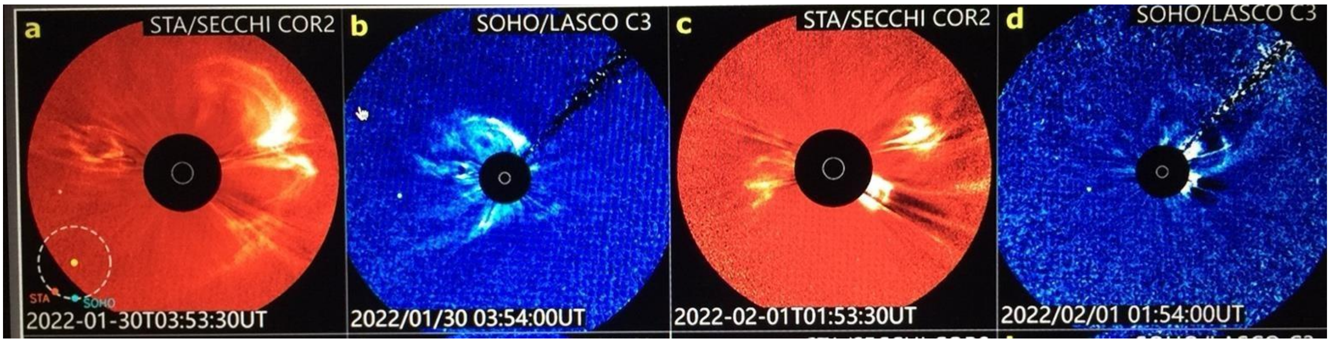

Figure 7: Coronagraph images taken by STEREO-A and SOHO.

Figure 7 (a) and (b) are coronagraph pictures of the first CME directed towards the

Earth taken by the SECCHI coronagraph onboard STEREO- A also known as STA (STA/SECCHI), and the LASCO coronagraph onboard SOHO (SOHO/LASCO) respectively. (c) and (d) are the coronagraph pictures of the second CME that was also directed towards the Earth by STA/SECCHI and SOHO/LASCO respectively.

In Figure 7 (Dang, Li, Luo, Li, Zhang, Pham 2022) (a), the positions of the STA and SOHO observatories have been indicated. Coronagraph pictures such as (a, b, c and d) are analyzed using Graduated Cylindrical model. The model is used to study how three-dimensional CMEs evolve over time with regard to their position and energy, from pictures taken with coronagraphs.

3.4 Swarm Satellites

Swarm is a collection of three identical satellites launched by the European Space Agency (ESA) in November, 2013. Their main purpose is to conduct Earth observations which include gravitational, magnetic and geodynamic measurements. The three satellites are known as Alpha, Bravo and Charlie (A, B and C). Swarm A and C form a pair and orbit the Earth at an altitude of 462 kilometers.

During the geomagnetic storm, the Swarm C satellite was at an altitude of 438 kilometers. It was able to measure the change in atmospheric density between the 3rd and 4th of February, 2022. It detected an increase in the atmospheric density which peaked at $1.5 \times 10^{-12} kg/m^3$, and $1.75 \times 10^{-12} kg/m^3$ on the 3rd and 4th of February, 2022 respectively. This increased the atmospheric drag on the Starlink satellites and caused them to continuously lose altitude. Figure 8 (European Space Agency) is of the three identical Swarm satellites.

Figure 8: The three identical Swarm spacecrafts A, B and C.

3.5 The Disturbance Strom Time (DST) Index

As mentioned earlier, DST is the quantifiable effect that solar storms produce on the horizontal component of the Earth's magnetic field, and is measured by low-latitude ground-based magnetometers. Figure 9 (Dang, Li, Luo, Li, Zhang, Pham 2022) is the DST index recorded between the 2nd and 6th February, 2022. The two shaded regions are of the magnetic storms that occurred during this period.

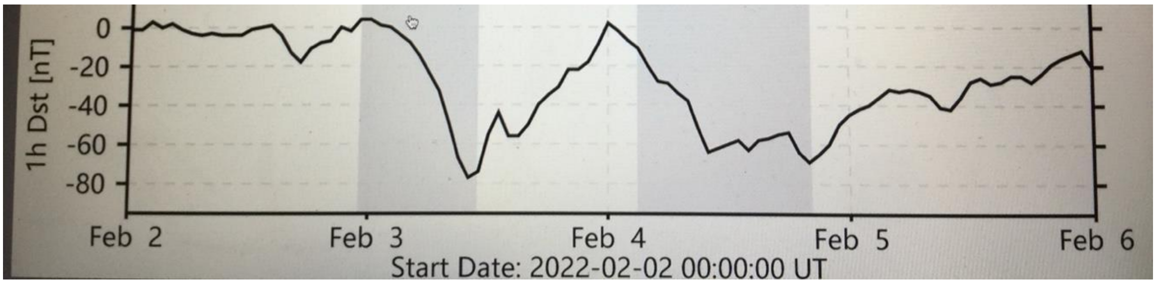

Figure 9: DST Index between the 2nd and 6th February, 2022.

The shaded regions are of the two geomagnetic storms that occurred between the 3rd and 4th of February, 2022.

Chapter 4: Results and Discussion

4.1 Magnetic Reconnection and Atmospheric Drag

The criteria necessary for a magnetic storm to occur is the presence of a strong and southward interplanetary magnetic field (IMF) that interacts with the Earth's magnetic field. During the main phase of the solar storm, this condition was met. As a result, a transfer of energy, mass and momentum occurs between IMF and Earth's magnetosphere, through a process known as magnetic reconnection.

Magnetic reconnection is the connecting of oppositely directed magnetic field lines as in Figure 10 (Hughes 1995). When this phenomenon occurs between the solar wind's IMF and the Earth's magnetosphere, it provides energy to the field lines on the far side of the Earth causing them to reconnect. This creates a stream of plasma in the magnetotail that shoots towards and away from the planet. The plasma is then directed from the magnetotail towards the inner magnetosphere causing auroras in the Earth's polar regions. The auroras first occur on the side of the Earth facing away from the Sun known as the midnight sector. The auroras then move to the longitudes covered by the Earth's magnetosphere. Figure 10 (Hughes 1995) shows the magnetic reconnection between the southward-directed IMF and the Earth's magnetic field, and the field line in the magnetotail. It also depicts the auroral zone in the Earth's northern pole.

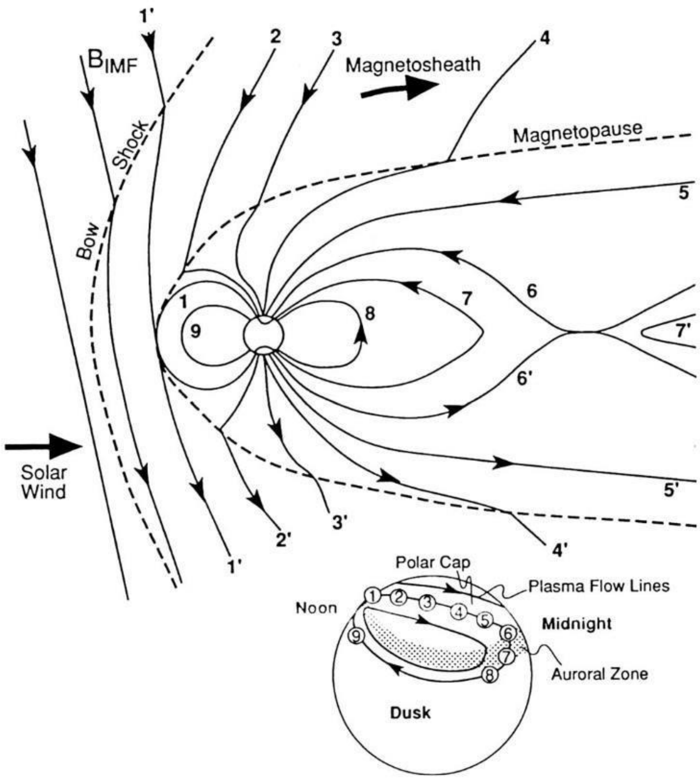

Figure 10: Magnetic reconnection between the southward IMF and the Earth's magnetic field.

Magnetic reconnection also occurs between the antiparallel magnetic fields in the Earth's magnetotail. Figure 10 also contains a depiction of the midnight sector and auroral zone in the Earth's northern pole.

Magnetic reconnection generates a large amount of electromagnetic energy that can affect atmospheric atoms and molecules, causing the upper atmosphere to heat up and expand. When satellites pass through this region during space weather events, they encounter increased atmospheric drag capable of pulling them down to lower altitudes. Evidence in support of this was captured by the Swarm C satellite that observed an increase in the atmospheric density during the solar storm This leads to in atmospheric dragging.

Atmospheric dragging caused the satellites to continuously descend into lower orbits over a period of time. It is possible to estimate the decay time for the Starlink satellites during the solar storm and a relatively calm period without any major space weather. The central gravitational force combined with the atmospheric dragging causes the mechanical energy of the satellites to decay over time.

Figure 11 (Dang, Li, Luo, Li, Zhang, Pham 2022) is the graphical representation of the change in altitude of the Starlink satellites during the magnetic storms with three assumed values of the satellites cross-sectional area, A. The three assumed values of A are:

- A with a maximum value of $25m^2$. This is when the satellites solar panels have been deployed.
- A with a minimum value of either 1 or $2m^2$ without the solar panels deployed.

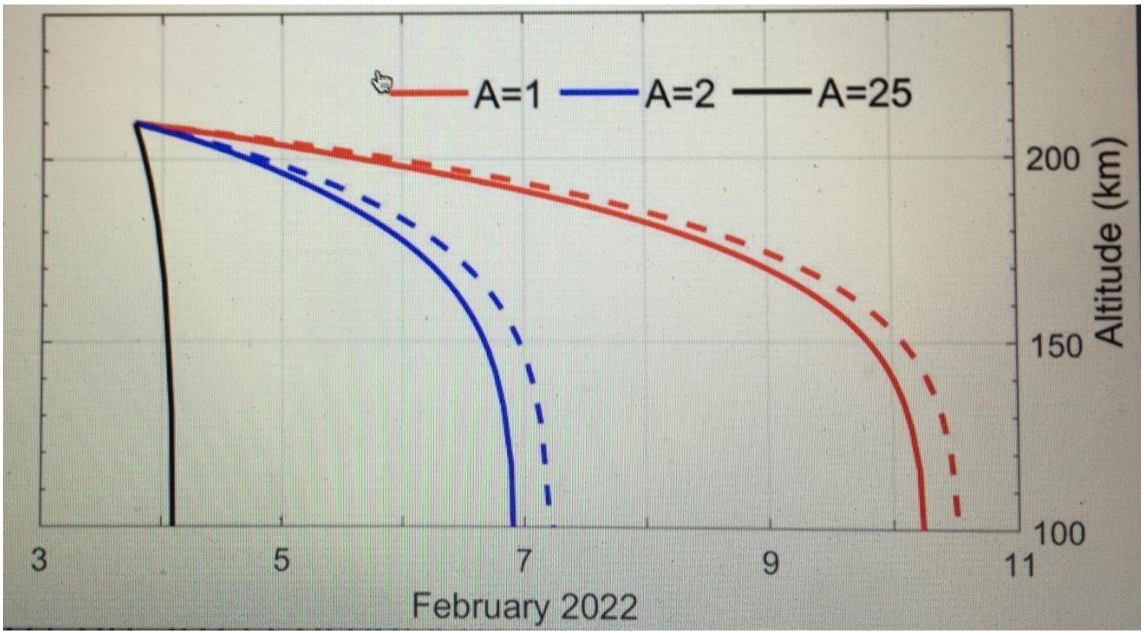

Figure 11: Graph of the change in altitude of the satellites against time.

The three assumed values of the cross-sectional area A of the satellites are used. The dotted lines represent the changing altitude during the relatively calm period.

When A is at its maximum value, the satellite is predicted to fall onto the Earth in a day during a solar storm. However, at its minimum value, the satellites would have remained operational for at least three to seven days. The difference in the lifetime of the satellites during solar storms and the relatively calm period is approximately half a day.

4.2 Financial Implications

Since 2019, SpaceX has been launching satellites to build up their Starlink constellation. Between 2019 and February, 2022, the space weather has been relatively calm. On the 3rd of February, 2022, SpaceX launched 49 Starlink satellites. 38 were destroyed due to the geomagnetic storm that occurred at the same time. Figure 12 (Wall 2022) shows a Starlink satellite breaking up on reentry into the Earth's atmosphere over Puerto Rico.

Figure 12: Starlink satellites reentering the Earth's atmosphere.

The image was taken over Puerto Rico. (Image Credit: Eddie Irizarry, Sociedad de Astronomia del Caribe (SAC))

The standard operating procedure employed by SpaceX is to launch its satellites into initial low orbits at an altitude of approximately 210 km. Then electric thrusters are engaged raising the satellites' altitude to 500 km. This is a good idea because satellites that fail the post-launch checkout would be removed from orbit by the atmospheric drag, reducing the buildup of space debris. Unfortunately, this procedure also renders satellites vulnerable to changes in atmospheric drag caused by space weather. The value of 38 satellites and the cost of launch has been estimated to be a loss amounting to several tens of millions of dollars.

As a result of this loss, SpaceX changed their operating procedure for their next satellite launch. On the 21st of February, 2022, SpaceX conducted another Starlink launch. This new launch had a higher initial altitude of 300 km. The rocket payload was reduced from 49 satellites to 46 satellites.

4.4 Space Debris

Space debris is defined as any man-made junk left in space, and is a direct result of launching objects into space. These objects range in size from tiny pieces to dead satellites no longer in use.

Since the start of the space age in 1957, there have been thousands of rocket launches. Each time a rocket is launched, small pieces of it become detached and set about orbiting the Earth. Some of the space debris in low altitude orbits revolve around the Earth and reenter after a few years. Most of the smaller pieces burn up on reentry. But debris in higher altitude orbits could possibly remain there indefinitely. Such objects include telecommunications and weather satellites. These objects can then collide with each other resulting in even more space debris.

Space debris poses a danger to other satellites in orbit, as a collision can cause damage or even the destruction of a working satellite. Although such collisions are rare, they are possible. In 2021, a Chinese satellite broke up after such a collision. The International Space Station has to perform multiple collision avoidance maneuvers every year. Satellites damage during geomagnetic storms could be rendered inoperable and end up becoming space debris.

Chapter 5: Conclusion

Over the past several decades, interest in space exploration has increased. Because of this more and more satellites have been created and placed in orbit around the Earth. The Starlink event shows that space weather can cause significant changes to the Earth's atmosphere that puts satellites at risk of damage and destruction. It shows the need for more effective methods of predicting solar storm, and a better understanding of the solar cycle.

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