UNDERSTANDING GEOMAGNETIC STORM IN RELATION TO THE SUNSPOT NUMBER DURING SOLAR CYCLE 24 AND 25

By
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To Adriana and the Stones.

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Abstract

Geomagnetic storms, caused by disturbances in Earth's magnetosphere due to solar activity, are significant drivers of space weather and have profound effects on technological systems and infrastructure. This study investigates the relationship between geomagnetic storms and sunspot numbers, a primary indicator of solar activity, during solar cycles 24 and 25. Solar cycle 24, marked by historically low sunspot numbers and subdued solar activity, contrasts with solar cycle 25, which is projected to exhibit increased solar intensity. The research employs a multi-faceted approach, analyzing data from solar wind parameters, interplanetary magnetic fields, and geomagnetic indices such as Dst and Kp. Through statistical analysis and correlation studies, it examines the influence of sunspot number variations on the frequency, intensity, and duration of geomagnetic storms. Additionally, the study explores the distinct characteristics of geomagnetic activity during these two solar cycles, identifying key patterns and trends. By establishing a clearer understanding of the connection between sunspot numbers and geomagnetic storms, this research contributes to the development of more accurate predictive models for space weather events. These findings hold significant implications for improving preparedness and mitigation strategies to safeguard satellite operations, communication systems, and power grid stability against space weather impacts.

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Chapter 1

Introduction

1.1 Background of the study

Sunspots appear to play main role in major solar and geomagnetic disturbances. The sunspot may divide or merge in a single spot or bipolar pair may rotate; such motion may produce a large flare. The solar output in term of particle and field ejected out into interplanetary medium influences the geomagnetic field conditions. It has been observed that the coronal mass ejections (CMEs) play an important role in interplay disturbances and may be responsible for non-recurrent geomagnetic storms. Occurrence of GMSs (recurrent and non-recurrent) varies with 11 year sunspot cycle. During solar activity maximum, major, or GMSs tend to non-recurrent and are predominantly associated with transient disturbances in solar wind arising from active regions of the sun; whereas, during solar minimum activity period, most of the large GMSs are of recurrent type and are commonly associated with co-rotating flows in solar wind streams. Recently, it is observed that geomagnetic activity during the declining phase of solar activity is highly related to high value of the product of solar wind velocity (V) and interplanetary magnetic field (IMF) strength B i.e.,VxB leading to geomagnetic disturbances causing GMSs[14]. It has been investigated the yearly occurrences of geomagnetic storms are not a mirror reflection of yearly variation of sunspots, but yearly occurrence of geomagnetic storms exactly follows the yearly occurrence of Halo CMEs[2]. The occurrence of geomagnetic storms is well associated with Earth-directed coronal mass ejections (CMEs), which appear in coronagraph images as bright halos around the occulting disk. Geomagnetic storms depend upon the orientation of the magnetic field in CME; the Earth-directed CME may or may not have an intense southward Bz field. Hence, the origin of CME, the structure of their source regions and their signatures in the solar wind near the Earth, are the fundamental interest in the physics of the Sun, space plasma and space weather research. When CME enters into the interplanetary medium it is known as ICME and this ICME produced interplanetary shock (IP shock)in flowing plasma. Magnetic field frozen into plasma coming out from sun is called interplanetary magnetic field (IMF) in interplanetary medium. The southward field of IMF causes magnetic reconnection of the day side magnetopause, rapidly injecting energetic particles into the Earth's night side magnetosphere, which are also subjected to forces due to the magnetic field curvature and gradient as well as forces due to gyration effects. For charges of the same sign these forces act in unison, with the net effect of the protons drifting from midnight toward dusk and the electron drifting from midnight toward dawn. This oppositely directed drift comprises a ring of current around the Earth [15]. An enhanced ring current is the prime indicator of a magnetic storm. The initial feature of a geomagnetic disturbance is a sudden increase in the horizontal component of the geomagnetic field H observed in many stations. The geo- magnetic index Ds is used to monitor the worldwide magnetic storm level. It is constructed by averaging H from mid-latitude and equatorial. The diversity of the observable parameters that can be linked to solar activity is very large and they are all related at least in the sense that their variations follow the nearly 11-year periodicity and therefore they are all cross-correlated to a greater or smaller extent. However, the correlations do not imply causal relationships, but are only indicative of the underlying driver of the variability that is the solar mag- netic field. The parameters have been chosen to illustrate that the variations in the parameters are correlated, despite the lack of known physical relationships between them. Even though the physical causal relationship among the indicators are largely unknown, and in fact in many cases may not even exist, there are undoubtedly some dominant causal chains that may act in parallel. This means that the observed phenomena are driven by the yet to be established physical processes, some of which operate independently, but eventually all of them originate in a single, central driving mechanism which can only be the generation mechanism of the Sun's magnetic field. The study is important because the bigger group of sunspots trigger flares and CMEs. The solar flares and CMEs send enormous amounts of energy and charged particles into the Earth's upper atmosphere where they can cause GMSs. GMSs produce numerous effects such as disruption in Satellite, radio, Disruption of Electrical system and cellular communication.

Geomagnetic storms can be categorized, in terms of geomagnetic activity index (Dst), into three categories: (1) major (intense or great) storms, minimum Dst (Dstmin) of -100 nT or less; (2) moderate storms, Dstmin falls between $-50.$ and -100 nT; and (3) weak storms, -30 nT Dstmin -50 nT . Major geomagnetic storms that occurred in solar cycle 23 have been studied comprehensively . It was found that of major geomagnetic storms were associated with interplanetary (IP) coronal mass ejections (ICMEs) and the average storm intensity was typically larger for magnetic cloud (MC) events and smaller for non-cloud ICME or corotating fast flow events. The definition of a super-storm varies in the science community. Here we call a geomagnetic storm a superstorm when Dstmin drops below $-200nT$. Geomagnetic storms are major space weather events. A geomagnetic storm can affect space vehicle operation, interrupt radio communication, and disrupt power grids. During the last solar minimum,20072009, the sunspot number (SSN) was extremely low and no major geomagnetic storm was recorded [12]. Sunspots appear to play main role in major solar and geomagnetic disturbances. The sunspot may divide or merge in a single spot or bipolar pair may rotate; such motion may produce a large flare. The solar output in term of particle and field ejected out into interplanetary medium influences the geomagnetic field conditions. It has been observed that the coronal mass ejections (CMEs) play an important role in interplay disturbances and may be responsible for non-recurrent geomagnetic storms [12]. Occurrence of GMSs (recurrent and non-recurrent) varies with 11 year sunspot cycle. During solar activity maximum, major, or GMSs tend to non-recurrent and are predominantly associated with transient disturbances in solar wind arising from active regions of the sun; whereas, during solar minimum activity period, most of the large GMSs are of recurrent type and are commonly associated with co-rotating flows in solar wind streams.As the current solar cycle 24 comes to a close, a new cycle with a maximum amplitude R 25 weaker than the previous few solar cycles has been predicted. This would continue the decline of the solar activity over the last few solar cycles. The maximum 13-month smoothed sunspot number in the last solar cycle was R 24 = 116.4 in April 2014,The solar activity peak, RN, found in the 13-month smoothed sunspot numbers over the full cycle of the solar cycle having a designated number N, is often considered a representative of the strength of the solar cycle [**?**]. The solar wind is a stream of charged particles ejected from the upper atmosphere of the Sun. It mostly consists of electrons and protons and varies in temperature and speed over time. Solar Energetic Particles (SEPs) are high-energy charged particles originating from energized solar-flare sites or shock waves associated with CMEs. SEPs consist of protons, electrons and heavy ions with energy ranging from afew tens of keV to GeV the fastest particles can reach speed up to They are of particular interest and importance as they can endanger life in outer space. CMEs and SEPs together generate magnetic disturbances and auroras, which are natural bright light displays seen in the vicinity of the magnetic poles of the southern and northern hemispheres. Aurora Borealis refers to auroras found in the north, while Aurora Australis are found in the south. The Sun is a sphere of hot gas (plasma) with loop-like structures on the solar surface which are associated with the magnetic field of the Sun. When one of these loops becomes unstable, it breaks off from the surface of the Sun and creates a solar flare. The biggest flares can be hundreds of times the size of the Earth. Usually, solar flashes associated with solar flares are ranked based on their intensity five categories (A, B, C, M and X). A-class flashes are the weakest, while X-class flashes are the most energetic. Solar flares are seen by the photons (or light) released across the spectrum. X-rays are the primary wavelength monitored in the classification of solar flares. Flares also contribute to the acceleration of protons and other charged particles that may accompany a significant event [5]. The solar cycle 24 could produced intense geomagnetic storm and solar energetic particle (SEP) events are associated with solar phenomenon. Earth directed CMEs are the main factor of generating major geomagnetic storm.Space weather predictions of various agencies are given the disturbance arrivals the Earth. The Earth directed CMEs that containing southward magnetic field component is capable to start geomagnetic storms. Gosling et al. (1990)studied the causes geomagnetic storms have generated that by mostly caused by CMEs phenomena. Hence, best tool of CMEs and shock arrival time at the Earth is desired for prediction of space weather conditions. CME takes the time,arrival to the Earth about minimum in hour and maximum in 1 to 6 days [7].The study is important because the bigger group of sunspots trigger flares and CMEs. The solar flares and CMEs send enormous amounts of energy and charged particles into the Earth's upper atmosphere where they can cause GMSs. GMSs produce numerous effects such as disruption in Satellite, radio, Disruption of Electrical system and cellular communication.

1.2 Statement of the problem

Geometric storm are disturbances in the earth magnetosphere caused by solar wind and coronal mass ejections (CMEs) from the sun.it driven by solar activity, can have significant impacts on earth technological system, including satellite communications, power grids, and navigation system. The sunspot number, a key inductor of solar activity, is known to correlate with the occurrence of geometric storms. However, the specific relationship between sunspot numbers and the frequency and intensity of geometric storms during the upcoming solar cycle (2024-2025) remain underexpolored.as we enter this new solar cycle, there is a critical need to understand how variation in sunspot numbers might influence geometric storm activity. This understanding is essential for improving space weather forecasting, mitigating the risks to technological infrastructure, and enhancing our broader knowledge of solar-terrestrial interactions. Thus, this study seeks to invest the correlation between sunspot numbers and geometric storms during this period, aiming to identify patterns that could inform future predictive models.

1.3 Research question

1. What is the relationship between sunspot numbers and geomagnetic storm activity during the solar cycles of 24and 25?
2. How do fluctuations in sunspot numbers correlation with the frequency and severity of geomagnetic storms in the specified solar cycle period?

1.4 Objective

1.4.1 General objective

To determine the correlation between sunspot numbers and geomagnetic storm activity during the solar cycle of 24 and 25, with an emphasis on understanding how solar activity influences geomagnetic phenomena.

1.4.2 Specific objective

1. To compare the solar activity pattern in 24 and 25 with historical data identify any significant deviation in geometric storm behavior.

2. To analysis the correlation between sunspot numbers and the frequency of geometric storms in 24 and 25.

3. To assess the impact of varying sunspot number on the intensity of geometric storms during the same period.

1.5 Significant of the study

This study is significant because it will provide deeper insights in to the dynamics between solar activity and geomagnetic storm, which are critical for understanding space weather phenomena.by analyzing the relationship between sunspot numbers and geomagnetic storm occurrence; this research will contribute to improve space weather forecasting and mitigation strategist, benefiting satellite operators, communication infrastructure, and power systems to space weather impacts. Additionally the findings could enhance our scientific understanding of solar-terrestrial interactions and aid in the development of more accurate predictive models for future solar cycles

Chapter 2

Solar Activity: Concept and Observations

2.1 The concept of solar activity

Where as the concept of solar activity is quite a common term nowadays, it is not straightforwardly interpreted nor unambiguously defined. For instance, solar-surface magnetic variability, eruption phenomena, coronal activity, radiation of the sun as a star or even interplanetary transients and geomagnetic disturbances can be related to the concept of solar activity. The Sun is magnetically active with an 11-year cycle of activity. During one 11 year cycle it reverses its magnetic field polarity. A full cycle is roughly 22 years in duration with two magnetic reversals. A full solar cycle is known as the Hale cycle. Sunspots have been used to monitor the Sun's activity level due to their high visibility. During the 11-year cycle the sunspots number reaches a maximum before Dropping to a minimum. During solar maximum, solar phenomena such as sunspots are seen in the photosphere. Solar prominence, solar flares, coronal mass ejections, and co-rotating interaction regions are also common. During this time the Sun is considered as active [2].

2.1.1 The Sun

The Sun is the closest star to Earth and is the center of our solar system. A giant, spinning ball of very hot plasma (electrically charged gas), the Sun is fueled by nuclear fusion reactions. The amount of light emitted by the Sun is surprisingly steady, varying by less than of one percent over periods spanning decades. The Sun is said to have a diameter of 1.4 million kilometers, about 109 times the diameter of Earth. Powerful magnetic disturbances within the Sun produce exotic features such as solar prominence and coronal loops. Explosive solar storms, called solar flares and coronal mass ejections (CME), are more common when the Sun's magnetic field is most disturbed at the peak of the sunspot cycle when the spots are plentiful. The structure of the Sun is divided into three domains: the interior, the sun's atmosphere, and the corona [2].

2.1.2 The Sun's Interior

The radioactive layer has an insulating effect that helps maintain the high temperature of the core. The gamma photons produced by fusion in the core are absorbed. The Sun's interior structure includes the core, the radioactive layer, and the convective layer. The core is the source of the Sun's energy, the site of thermonuclear fusion And remitted repeatedly by nuclei in the radioactive layer, with the re-emitted photons having successively lower energies and longer wavelengths. Above the radioactive layer is the convective layer where the temperature is lower, and radiation is less significant. Energy is transported outward mostly by convection. Hot regions at the bottom of this layer become buoyant and rise. At the same time, cooler material from above descends, and giant convective cells are formed. This convection is widespread throughout the Sun, except in the core and radioactive layer where the temperature is too high.

2.1.3 The Sun's Atmosphere

The sun's atmospheres are composed of the layers photosphere the chromosphere and the corona.

1.The Photosphere

The photosphere is the part of the Sun that we see with our eyes. It produces most of the visible (white) light. The photosphere is one of the coolest and darker regions of the Sun. its temperature are about 6,000k,in the photosphere the temperature as well as the density decreases.

2. The Chromosphere

It is a thin layer of gases. The chromosphere lies just above the photosphere, and is slightly cooler at its base. It is called chromo because of its color, which can only be seen when the much brighter light from the photosphere is eliminated. The chromosphere extends for about 2000kms above the visible surface of the sun. The plasma (electrically charged gas) in the chromosphere has a very low density. It is about ten thousand times less dense than the underlying photosphere and more than a million times dense than the Earth's atmosphere. Because it is such a thin layer and made of such tenuous plasma, the chromosphere is normally hidden from our view. The temperature of the chromosphere varies substantially with height above the photosphere. At first, the temperature decreases with height - from roughly 6, 000oC (11, 000oF) at the photosphere to about 4, 000oC (7, 200oF) a couple hundred kilometers higher up. Strangely, temperatures begin to climb in the upper reaches of the chromosphere, reaching a few tens of thousands of degrees.

3. The Corona

The corona is the outer atmosphere of the Sun. It extends many thousands of kilometers (miles) above the visible surface of the Sun, gradually transforming into the solar wind that flows outward through our solar system. The material in the corona is extremely hot but very tenuous plasma. The temperature in the corona is more than a million degrees, surprisingly much hotter than the temperature at the Sun's surface which is around 5, 500oC (9, 940oF or 5,780 kelvins). The pressure and density in the corona is much, much lower than in Earth's atmosphere. The corona is above the Sun's lower atmosphere, which is called the chromosphere [8]. A relatively narrow area called the transition region separates the corona from the chromosphere. Temperatures rise sharply in the transition region, from thousands of degrees in the chromosphere to more than a million degrees in the corona. The density of plasma falls rapidly through the transition region moving upward from the chromosphere to the corona. We normally cannot see the solar atmosphere, including the corona. The surface of the Sun is far too bright to allow a glimpse of the much fainter corona. A special instrument called a coronagraph allows astronomers to view the corona at other times. Some coronagraphs are used with ground-based telescopes.

2.1.4 Features of the Sun

Numerous features, with lifetimes of seconds to months, appear on the sun's surface and in the solar atmospheres. Some of the sun's features includes: sunspots, solar flares, coronal mass ejection, Solar Prominence, and solar wind.

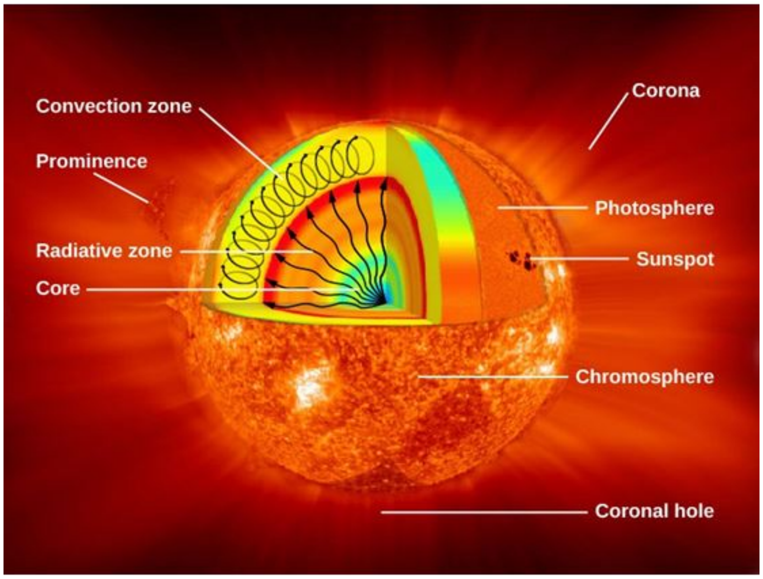

Figure 2.1: the structures and atmospheres of sun

2.1.5 Sunspot

These are regions at the Sun's surface (photosphere) of intense magnetic field and lower temperature (3700K) than the rest of the photosphere (5700K). They appear darker because the higher magnetic field inhibits the rise of heat from the solar interior. Each sunspot has a dark core (umbra), where the magnetic field is stronger and a less dark halo (penumbra), where magnetic field is weaker. Typically they subsist for periods of days until weeks, with a bipolar magnetic structure and are mainly restricted to the activity belts reaching up to 30o - 40o on each side of solar equator. Their number varies over solar cycles. At solar minimum activity no sunspots are observed along several days and at solar maximum activity, ten or more sunspots are common. Near minimum, sunspots appear at high latitudes, at 50o from equator, appearing at increasingly lower latitudes until reaching close to the equator [9]. The common structures are seen the clearest in the largest one. The dark central area is called the umbra, while the area looking like fuzzy radially inclined fibers is called the penumbra.

2.1.6 Solar Flares

Flares are our solar system's largest explosive events. They are seen as bright areas on the sun and they can last from minutes to hours. We typically see a solar flare by the light it releases, at most every wave wavelength of the spectrum. Flares are closely associated with the ejection of plasmas and particles through the sun's corona into outer space; flares also copiously emit radio waves. If the ejection is in the direction of the Earth, particles associated with this disturbance.

2.1.7 Coronal Mass Ejection

a massive burst of high-energy plasma emerges from the solar corona into the interplanetary space. This eruption of high-energy plasma is called Coronal Mass Ejection (CME). Coronal mass ejections are often associated with other forms of solar activity, but a broadly accepted theoretical understanding of these relationships has not been established. Most CMEs originate from the active regions of the Sun's surface, such as groupings of sunspots associated with frequent flares. Coronal mass ejections release huge quantities of matter and electromagnetic radiation into space above the Sun's surface, either near the corona (sometimes called a solar prominence), or farther into the planetary system, or beyond (interplanetary CME). The ejected material is plasma consisting primarily of electrons and protons [11].

2.1.8 The solar wind

Solar wind is the continuous flow of charged particles from the Sun. Many properties of the solar wind change as the Sun's activity changes, especially during the solar cycle. In addition to the electromagnetic radiation, also the solar wind acts as a transporter of energy from the Sun to the Earth, in the form of energetic charged particles carried by the flow. Solar wind is also the main driver in shaping the magnetic field of the Earth into the highly elongated shape which is known as the magnetosphere. In other words, magnetosphere is the region around the Earth (or any other planetary object with a magnetic field) where the motion of charged particles is controlled by the said magnetic field, and not by the solar wind and the hemispheric magnetic [11].

2.1.9 High-speed solar wind streams

High-speed streams, or HSS, are like bursts of wind but occur within the plasma of the solar wind. They can last from a few hours to several days or even weeks and as they carry the magnetic field of the Sun with them, they can drive the magnetosphere activity for relatively long periods. Like ICMEs, high-speed streams are more Geo-effective when their magnetic fields have a southward component. HSS event can be defined in several different ways, the most common ones being a minimum speed threshold or a minimum increase of speed over some period of time.

2.2 The Sun-Earth Relationship

The earth receives almost all its energy from the sun's radiation. The Sun also has the most dominating influence on the changing climate of various locations on Earth at different times of the year. The Earth rotates about on a fixed plane that is 23.5o with respect to its vertical axis around the sun. The rotation of the earth about its axis also causes the day and night phenomena. The length of the day and night depends on the time of the year and the latitude of the location. For places in the northern hemisphere, the shortest solar day occur around December 21 (winter solstice) and the longest solar day occurs around June 21 (Summer solstice). During the time of the equinox, the length of the day should be equal to the length of the night. The average time the earth to move around the sun in approximately 365 days [10].

2.3 Solar Energy from the Sun to the Earth's Surface

The sun emits many forms of electromagnetic radiation in varying quantities. A small part of the sun's energy is directly absorbed, particularly by certain gases such as ozone and water vapor. Some of the sun's energy is reflected back to space by clouds and the earth's Surface. Most of the radiation, however, is absorbed by the earth's surface. When the radiation is absorbed by a substance, the atoms in the substance move faster and the substance becomes warm to touch. The absorbed energy is transformed into heat energy. This heat energy plays an important role in regulating the temperature of the earth's crust, surface water, and lower atmosphere.

2.4 The Earth's Magnetic Field

The Earth's magnetic field is the field that extends from the Earth's interior out into space, where it interacts with the solar wind, a stream of charged particles emanating from the sun. Its magnitude at the Earth's surface ranges from 25 to 65 micro Tesla (0.25 to 0.65 gauss). The Earth's magnetic field serves to deflect most of the solar wind, whose charged particles would otherwise strip away the ozone layer that protects the Earth from harmful ultraviolet radiation.

2.4.1 The Ionosphere

Ionosphere is the region of the upper atmosphere, between 80 and about 600km, where free electrons occur in sufficient density to have an influence on the propagation of radio frequency electromagnetic waves. The ionosphere is created due to the absorption of energetic radiations such as UV, EUV, X-ray from the sun. Its ionization mostly depends on activity of the Sun. The atmospheric atoms and molecules are impacted by the high energy the UEV and X-ray photons from the sun. The amount of energy (photon flux) at EUV and X-ray wavelength varies by nearly a factor of ten over the 11-year solar cycle. The density of the ionosphere changes accordingly. Due to spectral variability of solar radiation and the density of various constituents in the atmosphere, there are layers created within the ionosphere, called the D, E, and F layers [4].

2.4.2 Layers of the Ionosphere

Historically, the ionosphere was thought to be composed of a number of relatively distinct layers that were identified by the letters D, E, and F. The F layer was sub sequently divided into regions F1 and F2. It is now known that all these layers are not particularly distinct, but the original naming scheme persists.

1, D region

The D region is the lowest ionosphere region, at altitudes of about 70 to 90km (40 to 55 miles). The D region differs from the E and F regions in that its free electrons almost totally disappear during the night, because they recombine with oxygen ions to form electrically neutral oxygen molecules. At this time, radio waves pass through to the strongly reflecting E and F layers above. During the day some reflection can be obtained from the D region, but the strength of radio waves is reduced; this is the cause of the marked reduction in the range of radio transmissions in daytime. At its upper boundary the D region merges with the E region.

2, E region

It extends from an altitude of 90km (60miles) to about 160km (100 miles). Unlike that of the D region, the ionization of the E region remains at night, though it is considerably diminished. The ionization density is typically 105 electrons per cubic.

3, F region

The F region extends upward from an altitude of about 160km (100 miles). This region has the greatest concentration of free electrons. Although its degree of ionization persists with little change through the night, there is a change in the ion distribution. During the day, two layers can be distinguished: a small layer known as F1 and above it a more highly ionized dominant layer called F2. At night they merge at about the level of the F2 layer, which is also called the Aphelion layer. This region reflects radio waves with frequencies up to about 35 megahertz; the exact value depends on the peak amount of the electron concentration, typically 106 electrons per cubic centimeter, though with large variations caused by the sunspot cycle [4].

2.4.3 Ionosphere variations

The ionosphere is variable in space and time. Some of the changes are chemical in origin and can be readily understood on the basis of the general considerations outlined above. There is a systematic variation, for example, according to the time of day. In early morning the Sun is relatively low in the sky, so that radiation must penetrate a large column of air before reaching a given level of the atmosphere. As a result, ionization rates are lower, and the location of ionized layers shifts to higher altitudes. As the Sun rises, the D, E, and F1 layers shift in altitude. The layers are lowest and densities of electrons are highest at noon. At night, on the other hand, ionization in the D, E, and F1 regions tends to disappear as electrons and ions recombine to form neutral gases.

The diurnal, or daily, variation of the F2 layer is less dramatic. Ions produced at high altitudes during the day maintain a sizable density of electrons at the F2 peak throughout the day and then diffuse downward at night. This accounts for the fact that radio reception (both in the broadcast and shortwave bands) is generally best at night. Ionization at lower altitudes primarily those corresponding to the D region tend to interfere with radio transmissions during the day. Interference is minimal at night because ionization in the D layer effectively disappears with the setting of the Sun.

The density of ionization varies in response to changes in the intensity and properties of radiation from the Sun. The output of solar energy is relatively constant in the visible and near-ultraviolet portions of the spectrum. It varies appreciably, how- ever, at shorter wavelengths, reflecting changes in the temperature of the outermost regions of the solar atmosphere. The changes are particularly large, in excess of a Factor of 10, at X-ray wavelengths. Variations in the D region are correspondingly large, with smaller though still significant changes in the E and F layers.

2.4.4 Ionosphere disturbances

Ionosphere disturbances can result from solar disturbances or geomagnetic field disturbances. The ionosphere disturbances are associated directly or indirectly with the events on the Sun. The geomagnetic disturbances are also caused by events initiated from the Sun; however, these events rather affect the outermost geomagnetic field line (also called the magnetopause) and compress the geomagnetic field causing the geomagnetic disturbances

2.4.5 Ionosphere storms

The suns produce the varying densities of energized electrons from its surface. When these energized electrons affect the magnetosphere and ionosphere, the variations produced on the surface of the ionosphere. These disturbances, when affecting the ionosphere is called ionosphere storms, and is measured total electron content (TEC). Ionosphere storms have important terrestrial consequences such as disrupting satellite communications, interrupting of electrical system [7]

2.4.6 The Earth's Magnetospheres

In the upper regions of the ionosphere, beginning several hundred kilometers above Earth's surface and extending tens of thousands of kilometers into space is the magnetosphere. The magnetosphere is the region of space surrounding Earth's surface where the dominant magnetic field is the magnetic field of the Earth, rather than magnetic field of the interplanetary space. The magnetosphere is formed by the in- traction of the solar wind with Earth's magnetic field. The pressure of the solar wind on the Earth's magnetic field compresses the field on the wayside of Earth and stretches the field into a long tail on the night side. On the dayside of Earth, the magnetic field is confined to within about 10 times Re from the the center of the Earth and on the night side, the field is stretched to 1000 times Re. A schematic showing the solar wind interaction with the Earth's magnetosphere and different regions of the earth's magnetosphere The boundary between the solar wind and Earth's magnetic field is called the magnetopause. The boundary is constantly in motion as Earth is buffeted by the ever-changing solar wind. This disturbed region is thought to be caused by high velocity solar wind particles. Ahead of this bow shock boundary, toward the sun, is the undisturbed solar wind. The magnetosheath, a region of magnetic turbulence in which both the magnitude and the direction of Earth's magnetic field vary erratically, occurs between 10 and 13 Earth radii toward the sun. Van Allen belts, a torus like region around the Earth, of protons and electrons that became trapped in the Earth's main field. The interaction between solar wind and Earth's magnetic field, and the influence of underlying atmosphere and ionosphere, creates various regions of fields, plasmas, and currents inside the magnetosphere such as ring [1].

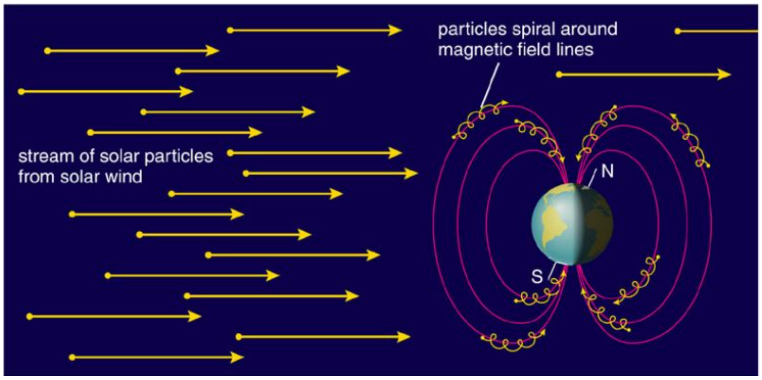

Figure 2.2: showing the solar wind interaction with the Earth's magnetosphere

2.4.7 Magnetosphere Currents

The distortion of the earth's internal dipole field into the typical shape of a magnetosphere produced by the interaction with the solar wind is accompanied by electrical currents in the magnetosphere. These currents are important constituents of the dynamics of plasma around the Earth. Among different types of currents in the magnetosphere, the ring current is discussed. Ring

Current Electrically charged particles trapped in Earth's magnetic field experience an equatorial drift motion resulting in westward flowing ring current in the equatorial plane. The ring current is one of the major current systems in the earth's magnetosphere.

Enhancements in this current are responsible for global decreases in the earth's surface magnetic field, which have been used to define geomagnetic storms. This current produces a magnetic field in opposition to the earth's magnetic field and so an earthly observer would observe a decrease in the magnetic field in this area. It is generally accepted that the ring current is formed partially from ions with direct convective access to low L values and partially from higher energy ions on closed drift paths diffusing in under the influence of fluctuating electric and magnetic fields [2]. During geomagnetic storms, ring current particle fluxes are dramatically increased, with the peak enhancements occurring in the inner ring current . The quiet- time ring current consists predominantly of H+, while the storm-time ring current also contains a significant component of ionosphere O+, whose contribution to ring current energy density may even exceed that of H+ for brief periods near the maximum of particularly intense storms.The storm-time growth of the ring current lasts from 3 to 12 hours and constitutes the main phase of a magnetic storm. Following this main phase, the ring current begins to decay, returning to its pre-storm state in two to three days. Full recovery can require as long as a month in the case of major geomagnetic storms. During the storm recovery phase, particle transport into the ring current slows, allowing various loss processes to reduce ring current particle fluxes to their quiet-time level. The primary loss process during both the main and recovery phases is charge exchange with neutral hydrogen atoms in the geocorona. The storm level of geomagnetic storms can be characterized using different geomagnetic indices [3].

2.4.8 The solar cycle

Solar cycle is a nearly periodic 11-year change in the sun's activity measured in terms of variations in the number of observed sunspots on the solar surface. Over the solar cycle, sunspot populations rise quickly and then fall more slowly. The point of highest sunspot activity during a cycle is known as solar maximum, and the point of lowest activity as solar minimum. Levels of solar radiation and ejection of solar material, the number and size of sunspots, solar flares, and coronal loops all exhibit a synchronized fluctuation, from quiet to active again with a period of 11 years. This cycle has been observed for centuries by changes in the sun's appearance and by terrestrial phenomena such as auroras. Solar activity, driven both by the sunspot cycle and transient a periodic processes govern the environment of the solar system planets by creating space weather and impact space and ground based technologies as well as the Earth's atmosphere and possibly climate fluctuations. Much of the Sun's behavior is characterized by the 11-year sunspot cycle. During the sunspot maximum times, the overall activity of the Sun is highest over the course of the cycle. Vice versa, activity is lowest during minimum times [7].

2.4.9 Solar cycle variation

Measurements of the sunspot number, an indicator of solar activity, show that the Sun goes through a periodic rise and fall in activity with a period of about 11 years. A number of other solar activity indicators also vary in association with the sunspots including; the solar flares and coronal mass ejections. Increased solar activity includes increases in extreme ultraviolet and X-ray emissions from the sun that produce dramatic effects in the Earth's upper atmosphere [3].

2.5 GEOMAGNETIC STORM

GEOMAGNETIC STORM is a disturbance of the Earth's magnetosphere caused by a solar wind shock wave and cloud of the magnetic field that interacts with the Earth's magnetic field. The disturbance that drives the magnetic storm may be a solar coronal mass ejection(CME) or a co-rotating interaction region (CIR),a high-speed stream of solar wind originating from a coronal hole. The frequency of geomagnetic storms increases and decreases with the sunspot cycle. During solar maximum, geomagnetic storms occur more often, with the majority driven by CMEs. During solar minimum, storms are mainly driven by CIRs (though CIR storms are more frequent at solar maximum than at minimum).The increase in the solar wind pressure initially compressed the magnetosphere. The solar wind's magnetic field interacts with the Earth's magnetic field and transfer increase energy to the magnetosphere. Both interactions cause an increase in the plasma movement through the magnetosphere (driven by increased electric fields in the magnetosphere) and increase in the electric current in the magnetosphere and ionosphere. During the main phase of a geomagnetic storm, electric current in the magnetosphere creates a magnetic force that pushes out the boundary between the magnetosphere and the solar wind [8].This include solar energetic particle (SEP) events, Geomagnetic ally induced current (GIC), ionosphere disturbance that cause radio and radar scintillation, disruption of navigation by magnetic compass and aurora displays at much lower latitude than normal. Geomagnetic storm is also defined by change in the disturbance storm time index (Dst). The Dst index estimates the globally averaged change of the horizontal component of the earth's magnetic field at the magnetic equator based on measurements from a few magnetometer station.

2.5.1 Storm Indices

Geomagnetic storms are measured by several different indices. The storms are detected globally especially in the low latitudes due to their origin in the enhancement of the equatorial electro jet currents. Then a measure of the enhancement can be acquired by taking a group of geomagnetic observatories situated close to but not at the equator and derive an index out of Geomagnetic activity indices are rather well correlated with events of the Sun. When the coupling of the solar wind to the magnetosphere becomes strong and pro- longed, geomagnetic activity becomes intense and magnetic storms occur. As a result, the magnetic field of the Earth changes. The ground stations monitor the changes and measure the changes by hourly average 'Disturbance Storm-Time'(Dst) index and its one-minute counterpart Symmetric H-component(Sym-H) index. The Dst index are widely used to monitor geomagnetic storms. They can be separated into indices describing geomagnetic activity at mid-latitudes and those at polar latitudes.

2.5.2 Storm-time disturbance index (Dst)

Dst index (Storm-time disturbance index) is defined as the hourly average of the deviation of H(horizontal) component of magnetic field measured by several ground stations in mid to low latitudes and represents the degree of equatorial magnetic field deviation specifying the magnitude of GMSs. It gives information about the strength of the ring current around Earth caused by solar protons and electrons. The ring current around Earth produces a magnetic field that is directly opposite Earth's magnetic field, i.e. if the difference between solar electrons and protons gets higher, then Earth's magnetic field becomes weaker. Negative Dst values indicate that a magnetic storm is in progress, and the more the negative Dst the more the intensity of the magnetic storm is. These negative deflections in the Dst are caused by the ring current intensification, which flows around the Earth from east to west in the equatorial plane. The Dst index is linearly dependent on the amplitude of the geomagnetic perturbation and is derived from the H hourly values obtained from four magnetic observatories at low and mid-latitudes and distributed evenly in longitude . These observatories are sufficiently far away from aurora and equatorial electro jets and those currents are distributed in longitude as evenly as possible[1].

2.5.3 Phases of Geomagnetic Storm

The phases of geomagnetic storm are divided into three parts which tells about how geomagnetic storm occurs from initial phase to recovery phase, which are as follows:-

1, INITIAL PHASE

In the initial phase of geomagnetic storm, it is illustrated by disturbance storm time or SYM-H, which is a one minute component, increased by 20 to 50nT(in tens of minutes). The initial phase of geomagnetic storms is also known as Storm Sudden Commencement (SSC). However, not all geomagnetic storms have an initial phase and not all sudden increases in Dst or SYM-H are followed by a geomagnetic storm.

2, MAIN PHASE

The main phase of a geomagnetic storm is defined by Dst decreasing to less than-50nT. The selection of -50nT to define a storm is somewhat arbitrary. The period of this phase is typically 2-8 hours. Typically, the lower bound of values during the course of storm is said to be in the range of -50nT and -600nT.

3, RECOVERY PHASE

The recovery phase is when the Dst changes from its minimum value to its quiet time value. This phase ranges from 10 hours to as much as 7 days.

2.5.4 Types of Geomagnetic Storms

about geomagnetic storms as being classified into two major categories, namely, recurrent and non-recurrent storms. The detailed explanation is as follows:

1, Recurrent Storms

The periodicity in storms has a time period of 27 days. These types of storms are typically seen in declining cycle of solar cycle. In the interplanetary medium and specifically at the juncture of low- and high-speed solar winds streams in the vicinity of the Sun, high-pressure magnetic fields are generated. Recurrent storms are formed when the Earth is exposed to these magnetic fields.

2, Non-recurrent Storms

These storms are typically seen when solar phase is at its peak. Interplanetary disturbances due to coronal mass ejections (CMEs) are the source of non-recurrent storms.

2.5.5 History of Occurrence of Geomagnetic Storm

The first observation of the effects of Geomagnetic storm occur early in 19th century, from May 1806 until June 1807, Alexander vone Humboldt recorded the bearing of a magnetic compass in Berlin. The second geomagnetic storm occurred on September 1 to 2, 1859. From August 28 until September 2, 1859, numerous sunspots and solar Flares observed on the sun, with largest Flare on September 1. It can be assumed that a massive CME was launched from the sun and reached to the Earth within 18 hours. That takes normally 3 to 4 days. The horizontal field was reduced by 1600nT as recorded by the Colaba observatory and it is estimated to be approximately$-1760nT$. The disruption of telegraph service and initiation of flares was observed, an aurora of November 17, 1882 and May 1921 and 1960, when widespread radio disruption was reported. The March 1989, Geomagnetic storm caused the collapse of the hydro-Quebec power grid in seconds as equipment protection relays tripped in a cascading sequence. Six million people were left without power for nine hours. The storm causing this event was the result of a coronal mass ejected from the sun (Extreme space weather events national Geophysics data center). The minimum of the Dst-index value was 589nT [7].

On July 14, 2000, an X5- class flare erupted known as the Bastille day event and coronal mass was launched directly at Earth. A typically super Geomagnetic storm occurred on July 15-17, the minimum of Dst-index was -301nT. Despite the storms strength, no power distribution failures were reported. The solar wind also carries with it the sun's magnetic field. This field will have either a North or South orientation. If the solar wind has energetic burst, contracting and expanding the magnetosphere, or if the solar wind takes a southward polarization, geomagnetic storms can be expected. The southward field causes magnetic reconnection of the dayside magnetopause, rapidly injecting magnetic and particle energy into the Earth's magnetosphere. Generally, during a geomagnetic storm, the ionosphere's F2 layer becomes unstable, fragments, and may disappear. In the northern and southern pole regions of the Earth, auroras are observable[2].

2.5.6 Effects of Geomagnetic Storm

There are many effect of geomagnetic storm these include effects in radiation hazards to humans, satellite hard ware damage, disruption of electrical system, mains electrical grid, communications, pipelines and etc. Radiation hazards to humans, this effect of geomagnetic storm exist when an in- tense solar flares release very high energy particles that have tendency to produce radiation which will poison to humans and other mammals, this effect general similar to low energy radiation from nuclear blast. The Earth's atmosphere and magnetosphere allow adequate protection at ground level but Astronauts are subjects to potentially lethal doses of radiation. The penetration of high energy particles into living cells can cause chromosome damage, cancer and other health problems. Extreme exposers are usually fatal. Solar protons with energies greater than 30MeV are particularly hazardless. Solar proton events can also produce elevated radiation abroad air craft flying at high altitudes. Although these risks are small monitoring of solar proton events by satellite instrumentation allows the occasion are exposure to be monitored evaluated and eventually flight paths and altitudes adjusted in order to lower the absorbed dose of the flight [6].Satellite hard ware damage, the Geomagnetic storm and an increase in the solar ultraviolet emission heat Earth's upper atmosphere, causing it to expand. The heated air rises and the density at the orbit of the satellite up to about 1000km (621 mi) increase significantly. This result increased drag, causing satellite to slow and change orbit slightly. Another problem for satellite operators is differential charging, during Geomagnetic storms the number and energy of the electron and ions increases. When a satellite travels through this energized environment the charged particles striking the spacecraft differentially charge portions of the spacecraft. Discharges can across space craft components, harming and possibly disabling them. Bulk changing also called deep charging occurs when energetic particles, primarily electrons penetrate the outer covering of a satellite and deposit their charge in its internal parts. If sufficient charge accumulates in any one component it may attempt to neutralize by discharging to other component. This discharge is potentially hazardous to the satellite and

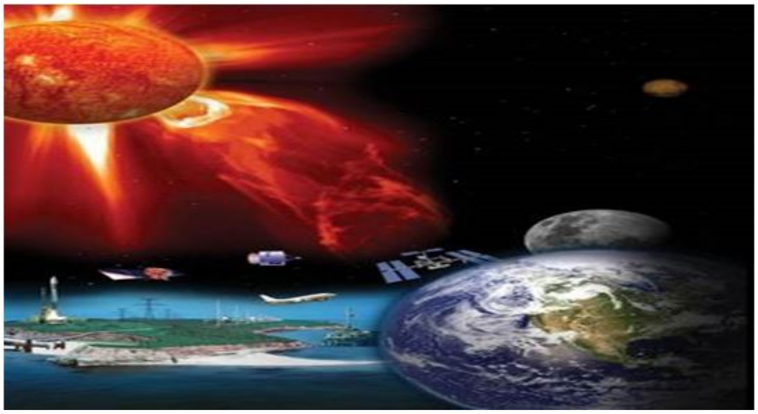

Figure 2.3: : Effects of Geomagnetic storm

satellite's electronic system [3].Disruption of Electrical system, it has been suggested that a geomagnetic storm on the scale of the solar storm of 1859 today would causes billions of dollars of damage to satellite, power grids and radio communications could cause electrical blackout on a massive scale that might not be repaired for weeks. Mains Electrical grid, when magnetic fields move about in the vicinity of a conductor such as a wire, a Gamogenetically induced current is produced in the conductor. This happens on a grand scale during geomagnetic storms (the same mechanism also influenced telephone and telegraph lines before fiber optic) on all long transmission lines. Long transmission lines (many kilometers in length) are thus subject to damage by the effect of Geomagnetic storm. The currents induced in their lines from geomagnetic storms are harmful to electrical transmission equipment, especially transformers, inducing core saturation, constraining their performance and causing coils and corsets heat up [10].

fig 2.3 shows the effects of geomagnetic storm on technology and infrastructure. As the figure shows, the effects of geomagnetic storm are not limited to one country. But the amount of the effect varies from place to place depending on the awareness of and development of the country. And also the figure indicates that all effects come from the same source(solar activity).

Chapter 3

DATA AND METHODOLOGIES

The data used in this thesis to study sunspot and Geomagnetic storm causal relationship as observed from OMNI data is obtained from OMNI data explorer. These data contain the sunspot number and Dst-index. The sunspot number is accessible using the link http://omniweb.gsfc.gov/form/dx1.html. The sunspot numbers (SSN) are used as basic parameter for knowing the behavior of solar activity which appears in the photosphere of the Sun. We compare sunspot numbers with geomagnetic activity index storm (Dst) to understand the causal relationship between sunspots and geomagnetic activity. We also analyze the correlation between the yearly average number of significant geomagnetic storms and the yearly number of sunspots. A list of magnetic storms, based on the Dst indices provided by the World Data Center for Geomagnetism, Kyoto, Japan had been compiled for this study for the period 2008 - 2024. The Dst index is available in its final form for the period from 2008 to 2024.

Chapter 4

RESULT AND DISCUSSION

The results presented here are from the analysis of the interrelationship of SSN and GMSs obtained from the OMNI data explorer during the period 2008-2024. By analyzing the interrelationship of SSN and GMSs and during 2008-2024, we demonstrate the correlation between SSN and GMSs, occurrence of GMSs as per SSNs, SSNs and storms with different intensities, storms on rising, maximum for solar cycle 24 and 25.

4.1 Correlation between Sunspot Number and Geomagnetic Activity

The major geomagnetic storms are associated with both solar flares and coronal mass ejections and ultimately these are all depend on solar activity.
The sun's activity, which drives these storms, varies over an 11 years solar cycle, characterized by changes in sunspot numbs. The number of sun spots increases the

Yearly occurrence during solar maximum and decreases during solar minimum. Solar activity, including the occurrence of CMEs and solar flares, is generally higher during solar maximum, increasing the likelihood of the geomagnetic storms.

THE YEARLY OCCURRENCE

yearly averaged sunspot numbers and occurred CMEs data from 2008-01-01 to 2024-01-01

YEAR	Sunspot no/	kp indx	Cycle
2008	4	13	24
2009	5	10	24
2010	25	13	24
2011	81	13	24
2012	85	17	24
2013	94	13	24
2014	113	17	24
2015	70	20	24
2016	40	20	24
2017	22	20	24
2018	7	13	24
2019	4	13	24
2020	9	13	25
2021	30	13	25
2022	83	20	25
2023	125	20	25
2024	146	17	25

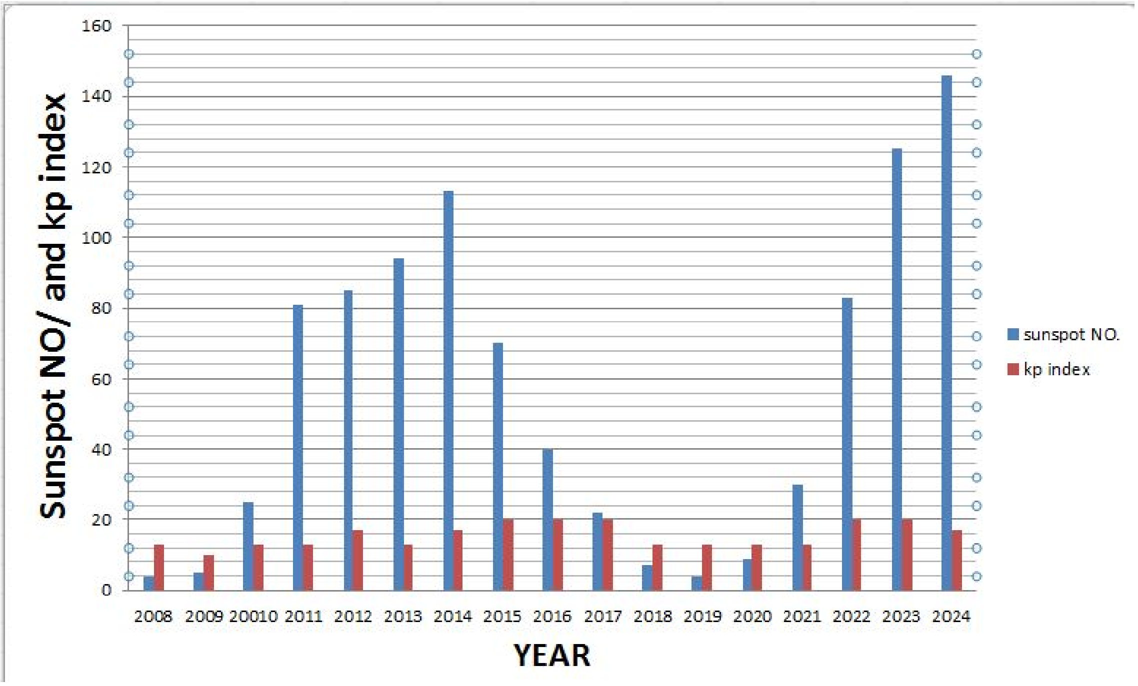

Figure 4.1: The average sunspot number and Geomagnetic storm for year 2008-2024

4.1.1 statical analysis of sunspot numbers and occurrence of geometric storm

Let's analyze the provided Kp index and sunspot number data for the years 2008 to 2024, covering solar cycles 24 and 25. The data represents yearly averages for each parameter, allowing us to observe the variations in solar and geomagnetic activity over time.

Characteristics of Solar cycle 24and geomagnetic storm can be explained as follows. It has the lowest recorded sunspot numbers in over a century. Its peak sunspot number (SSNs) in April 2024 was 113, far below the average of 179 for prior cycles. Despite the weak cycle, several strong storms occurred. The St. Patrick's Day storm (March 2015) as an example, a G4-class storm with (Kp=8) caused auroras visible at mid-latitudes, as far south as Texas. There were also other moderate storms triggered by isolated CMEs and high speed solar wind streams. On the other hand early observations of solar cycle 25, suggest a stronger peaks than solar cycle 24. The predicted SSNs was to reach 115-125. However, updated trends show it could exceed predictions,potentially reaching SSNs Although Sunspot numbers correlate with increased solar activity, some of the strongest geomagnetic storms occur due to isolated events, not directly related to sunspot maxima. For instance the most intense geomagnetic recorded, occurred during a moderate solar cycle. Usually the strength of geomagnetic storm depends on the orientation of the magnetic field in the CME called the interplanetary magnetic field(IMF-Bz). The southward IMF-Bz can strongly couple with earth's magnetic field,leading to severe storms.

4.1.2 Correlation analysis SSNs vs IMF-Bz

Sun spot numbers(SSNs) reflects solar activities, while the IMF-Bz component determines how effectively solar wind interacts with earth's magnetosphere. A southward oriented IMZ-Bz (negative) enhances geomagnetic coupling leading to storms. This analysis explores the relationship between SSNs and IMF-Bz variability. SSNs correlates moderately with IMF-Bz suggesting that while solar activity influences geomagnetic storms, individual events depend heavily on the magnetic structure of CMEs and coronal holes. On the other hand significant Bz southward events align with periods of high SSNs but are not exclusive to solar maxima. strong Bz southward ex -20nT often correlates with major geomagnetic storms with Dst index(Dst¡-100nT).Figure 4.2 shows correlation between SSNs and IMF-Bz shows a mild slop, indicating that while SSNs impacts IMF-Bz trends,others (e.g., CME orientations can play significant roles. Seasonal effects can also lead to enhanced geomagnetic activity observed during equinoxes,regardless of SSNs due to the IMF-Bz coupling efficency.

4.1.3 compering solar cycle 24 and solar cycle 25

The study of this thesis shows the Sunspot and Geomagnetic storm causal relationship in the year 2008-2024 (the span of solar cycle 24 and 25). The maximum phase of solar cycle 24 and 25 has been occurred during the year 2014 and 2024 whereas the year 2008-2013, 2013-2019 and 2015-2018 are the periods of ascending and descending phase of solar activity, which is clearly follow the phase of sunspots cycle. It is also found that maximum number of geomagnetic storm have occurred in year 2015 and 2023 for the solar cycle 24 and 25 respectively. When the year 2009 represents minimum sunspot activity during the descending phase of solar cycle 24 the year 2018

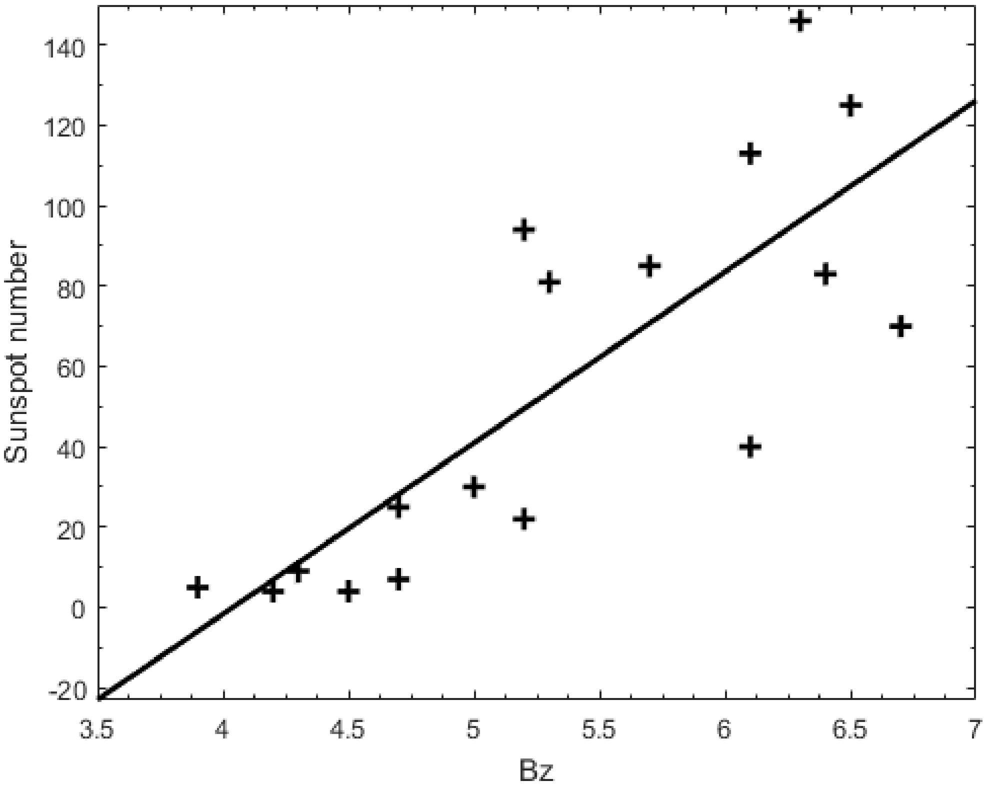

Figure 4.2: Correlation between sunspot number and geomagnetic Activity

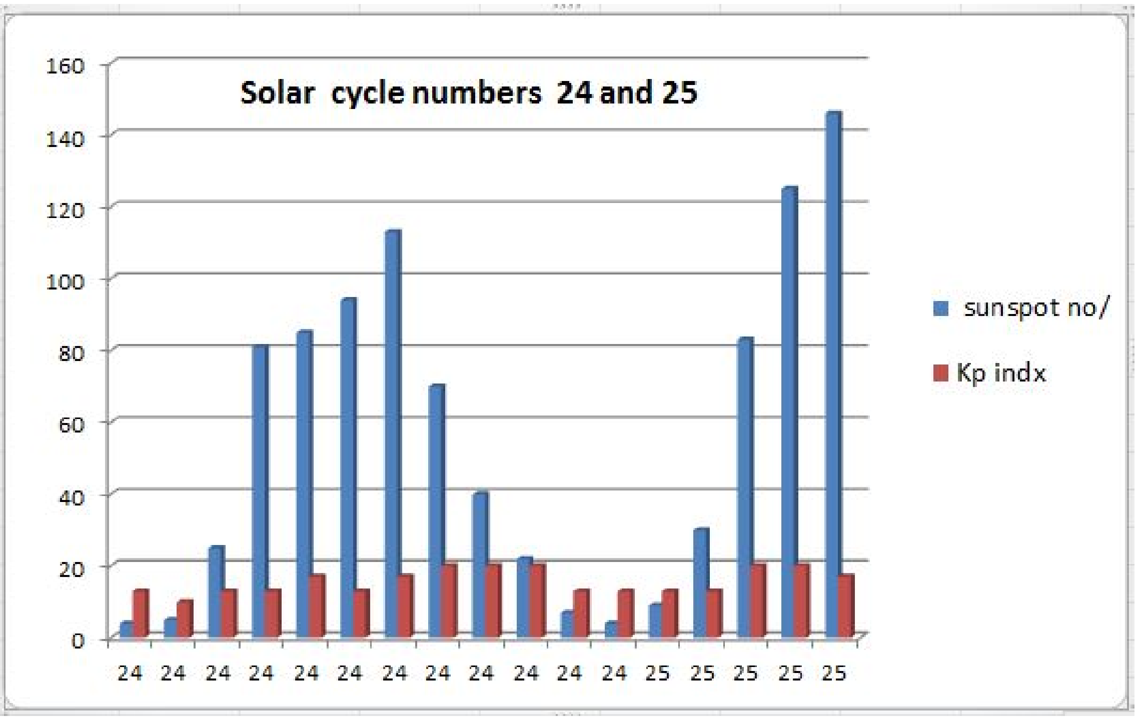

Figure 4.3: solar cycle 24 and Solar cycle 25

represents the minimum sunspot activity during ascending phase of solar cycle 25. In the year 2015-2017 and 2023-2024 the large numbers of geomagnetic storm have occurred.

By comparing the peaks of solar cycle 24(2014) and the expected peak of solar cycle 25(2024), we can analyze if solar cycle 25 stronger than solar cycle 24 interms of solar and geomagnetic activity.

Chapter 5

Conclusion and Future Directions

Understanding the relationship between sunspot numbers and geomagnetic storms is crucial, especially for preparing for the peak of Solar Cycle 25. This analysis could be extended with real-time monitoring and predictive modeling to forecast geomagnetic storms more accurately and mitigate their impact on technology and infrastructure.
In general the following observations can be concluded. Solar cycle 24 and 25 exhibit a moderate correlation between SUN and IMF-Bz, with solar cycle 25 showing slightly stronger relationship. strong geomagnetic storms are influenced by combination of SSN, CME characteristics, and IMF-Bz orientation.

The assending phase of solar cycle 25 shows an increase in storm intensity trend and frequency by 2025, understanding the importance of continuous solar wind and IMF monitoring for forecasting geomagnetic impacts.

The analysis of sunspot numbers and geomagnetic storms during Solar Cycles 24 and 25 not only enhances our understanding of solar-terrestrial interactions but also has practical implications for forecasting space weather and mitigating its impacts. As Solar Cycle 25 progresses, ongoing data collection and analysis will be crucial in refining models, improving predictions, and preparing for the solar maximum around 2024-2025.

Future research might also explore the potential impacts of these solar cycles on climate patterns, as some studies suggest a link between long-term solar activity and terrestrial climate changes. By integrating multiple data sources and extending the analysis over multiple solar cycles, we can build a more comprehensive picture of how solar activity affects our planet.

Bibliography

[1] Natalia Buzulukova, Janet Kozyra, Tim Fuller, and Rowell, *Extreme space weather events*, The United Nations/Germany Workshop on the International Space Weather Initiative **17** (2024), 10–14.

[2] Kaan Kaplan, *The characteristic properties of the solar activities during the solar cycle 24*, Muzeyyen Erkul Science Center **4** (January 2023), 215–225.

[3] Florida Key Largo, *Causes and consequences of the extended solarminimum between solar cycles 23 and 24*, Key Largo, Florida, USA **17** (April 2013), 812.

[4] Gui-Ming Le, Zi-Yu Cai, Hua-Ning Wang, Zhi-Qiang Yin, and Peng Li, *Solar cycle distribution of major geomagnetic storms*, Linear Algebra Appl. **13** (2013), 739–748.

[5] Kim Kwee Ng, *Coronal mass ejections, solar cycles and magnetic poles reversal*, **7** (2019), 10–17.

[6] A. K. Singh, Apeksha Tonk, and A. Bhargawa, *Characterization of last four and half solar cycles on the basis of intense geomagnetic storms*, International Research Journal of Engineering and Technology (IRJET **04** (April).

[7] Dharmendra Singh, Dr. P.K. Chamadia, and Dr. C.M. Tiwari, *A study heliospheric disturbance of solar cycle 24 during period from 10 march to 31 march*

2015, international journal of advance research in science and enginaring **12** (2023), 05, Birkhäuser Verlag.

[8] Sham Singh, A. C. Panda, Kalpana Singh, and A. P. Mishra2, *Effect of geomagnetic storms and their association with solar wind velocity and imf during solar cycle 23 and 24*, International Journal of Pure and Applied Physics **13** (2017), 35–44.

[9] Binod Adhikariand Daha Subodh, Roshan Kumar Mishra, Nirakar Sapkota, Daya Nidhi Chhatkuli, Santosh Ballav Sapkota, Sarala Adhikari, and Narayan P. Chapagain, *Analysis of solar, interplanetary, and geomagnetic parameters during solar cycles 22, 23, and 24*, RUSSIAN JOURNAL OF EARTH SCIENCES **19** (31 January 2019), 57–70.

[10] N.S. Szajko, G. Cristiani, C.H. Mandrini, and A. Dal Lago.

[11] Valentino Patrick van de Heyde, *An investigation of magnetic storm effects on total electron content over south africa for selected periods in solar cycles 23 and 24*, University of the Western Cape (December 2012), 34–65.

[12] Chin-Chun Wu, Kan Liou, Ronald P. Lepping, Lynn Hutting, Simon Plunkett, Russ A. Howard1, and Dennis Socker, *The first super geomagnetic storm of solar cycle 24:*, Earth, Planets and Space **10** (17).