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INVESTIGATING SOLAR WIND–MAGNETOSPHERE COUPLING AND ITS ROLE IN SPACE WEATHER DYNAMICS

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Abstract

The most important process that contributes to the occurrence of space weather disturbances around the earth is solar wind magnetosphere coupling. This paper gives an observational examination of the connection amid upstream solar wind circumstances as well as geomagnetic activity related with representative solar wind parameters (velocity, proton density as well as interplanetary magnetic field Bz) and geomagnetic indices (Dst and Kp). The findings indicate that the incoming of a high-speed stream of solar wind coupled with powerful orientation of the southward IMF generated efficient magnetic reconnection at the dayside magnetopause. A major geomagnetic storm was registered, the Dst index had reached -115 nT, and the Kp had increased to 7, some 45 minutes after the Bz southwards reversal. The strength of the coupling, which was determined using the solar wind electric field, was observed to reach a peak at the same time as the storm intensity, which further confirmed a great negative correlation between IMF Bz and Dst. The results prove that geomagnetic storm strength is regulated by the position of the magnetic fields, and not only by the speed of solar wind. This paper has drawn attention to the physical mechanism of energy conversion between the solar wind and the magnetosphere and it is important to note that without tracking the upstream solar wind conditions it is impossible to have a good space weather forecast or to reduce the technological risks imposed by a space storm.

Keywords: *Solar Wind, Magnetosphere, Space Weather, Geomagnetic Storm, Magnetic Reconnection, IMF Bz.*

1. INTRODUCTION

A constant stream of charged particles emitted by the sun, the solar wind consists of electrons and protons produced by the solar corona. This plasma carries the IMF and fills the heliosphere. When the solar wind meets the Earth's magnetic field, a protective barrier known as the magnetosphere is generated. Although it acts as a barrier against the energetic particles, the magnetosphere is not totally closed. Coupled with the magnetosphere, the solar wind can generate electricity under certain circumstances.

The realization of this coupling is very much dependent on the orientation and strength of the IMF and especially on its southward component (Bz). Magnetic reconnection takes place when IMF moves southward and energy, mass, and momentum of the solar wind are then passed on to the magnetosphere at the magnetopause. This energy is responsible to the large-scale disturbances like the auroras, substorms and the geomagnetic storms. All of these disturbances are referred to as space weather and have a major practical value. Satellites, radio communication, navigation systems like GPS and electric power transmission networks can be affected by geomagnetic storms. Consequently, the knowledge of physical association of solar wind conditions and magnetospheric reaction has turned into a significant goal in space physics.

1.1.Objectives of the Study

- To examine the relationship between solar wind parameters and geomagnetic activity (Dst and Kp indices).
- To assess the role of southward IMF Bz and magnetic reconnection in geomagnetic storm generation.
- To understand how solar wind conditions control space weather disturbances in Earth’s magnetosphere.

2. LITERATURE REVIEW

Telloni et al. (2020) investigated the role of solar wind plasma characteristics and geomagnetic indices in energy input to geomagnetic activity. The researchers found that the amount of energy transported by the solar wind has a direct impact on geomagnetic disturbances, particularly during coronal mass ejections and extremely high solar wind streams. They stated that variations of solar wind velocity and field strength greatly increase the geomagnetic activity, and the energy relationship between the heliosphere and the magnetosphere of the Earth is important in the study of space weather.

Borovsky (2021) reviewed the existing knowledge about solar wind-magnetosphere coupling and expressed the opinion that despite the clear picture of the overall structure of magnetic reconnection and plasma convection, a number of physical processes are poorly understood. The studies have shown that the orientation of the interplanetary magnetic field—specifically the southbound Bz component—determines the efficiency of energy transfer. According to Borovsky, the solar wind density, turbulence, and plasma structures might change the magnetospheric reaction, suggesting that dependability was not a one-variable process but rather a multi-parameter process.

Singh et al. (2021) gave the complete picture of the physics of space weather phenomena explaining the origin of the disturbances in the solar wind, how it propagates through interplanetary space and interacts with the magnetosphere and ionosphere of Earth. The authors described the geomagnetic storms and substorms as the after effects of magnetic reconnections that enable the solar wind energy to enter the magnetosphere. In their review, they pointed out that to predict space weather effect, upstream solar wind parameters are important to monitor, in order to protect satellite, communication systems and power infrastructure.

Eastwood et al. (2017) addressed the scientific background of magnetospheric space weather prediction. They demonstrated that effective forecasting of geomagnetic storms requires real time observation of the conditions of solar wind above the earth. The authors pointed out that conditions of southward IMF are the best predictor of future geomagnetic activity since they initiate the process of reconnection at the magnetopause. They also emphasized the need to use a combination of observational data and physical models to enhance forecasting efficiency and overcome technological risk.

3. RESEARCH METHODOLOGY

In this section, the process and analysis of studying the correlation between the weather conditions of the sun and the magnetospheric reaction will be explained. The methodology describes the sources of data; the criteria applied in selecting an event of geomagnetic storms and the techniques used in assessing solar wind and magnetosphere coupling.

3.1. Research Design

The interaction between the solar wind and the Earth's magnetosphere is investigated in this research using an observational and quantitative design. This research is based on data collected from satellites and geomagnetism measurements taken on Earth since it is physically impossible to simulate planetary-scale plasma interactions in a laboratory. With this, we hope to learn how variations in the conditions of the solar wind upstream affect the magnetosphere's geomagnetic activity.

3.2. Data Collection

Publicly available space-weather monitoring systems were used to get solar wind and geomagnetic data. Satellites at the Sun Earth Lagrange point (L1) were used to measure solar wind parameters about 1.5 million km above earth i.e. at a point of solar wind before it hits the magnetosphere. The geomagnetic indices were gathered in world ground magnetic observatories. The physical parameters that were examined in the current study were:

Table 1: Physical Parameters Analyzed in the Study

Parameter	Description
Solar wind velocity (km/s)	Speed of solar plasma approaching Earth
IMF Bz (nT)	The interplanetary magnetic field's north-south component
Proton density (cm^{-3})	Concentration of charged particles in solar wind
Dst index (nT)	Measure of global geomagnetic storm intensity
Kp index	Indicator of worldwide geomagnetic activity

3.3.Event Selection

A period of a geomagnetic storm was chosen in accordance to conventional geomagnetic storm parameters. Only large disturbances were taken into account to have a clear magnetospheric response. A geomagnetic storm was considered to be an event when the following were met:

- Dst index ≤ -100 nT
- Kp index ≥ 6

These levels are moderate to intense geomagnetic storms activity and suggests that a lot of energy has been released by the solar wind to the magnetosphere.

3.4. Data Analysis Procedure

The obtained data were processed with the help of comparative and correlation methods to measure the solar wind magnetosphere coupling. These procedures were carried out as follows:

- **Time-series analysis:** The parameters of solar wind and geomagnetic indices were plotted versus time in order to see how they vary with time.
- **Correlation analysis:** In order to assess whether geomagnetic storm intensity is dependent on magnetic field orientation, the relationship between the IMF Bz component and the Dst index was investigated.
- **Estimation of lag-time:** To determine the time of response and propagation of the magnetosphere, the time of variation in conditions of the solar wind at L1 was subtracted from the time of geomagnetic response on Earth.
- **Energy coupling estimation:** The efficiency of energy transmission into the magnetosphere was estimated using the approximation of the solar wind electric field:

$$E = V \times | B_z |$$

V being the velocity of solar wind and Bz being the southward field of interplanetary magnets. The approach enables the major parameters of solar wind to be identified that trigger geomagnetic storms and the dynamics of space weather to be explained.

4. RESULTS AND DISCUSSION

In order to establish a connection between geomagnetic activity and upstream solar wind characteristics, the data were averaged every hour. By contrasting variations in solar wind speed, proton density, and the interplanetary magnetic field (IMF Bz) with geomagnetic indices (Dst and Kp), the interaction between the solar wind and magnetosphere was quantified.

4.1. Solar Wind Conditions

To better understand the factors upstream that contribute to geomagnetic activity, researchers tracked the variations in solar wind parameters across time. Solar wind speed, proton density, and the north-south direction of the IMF Bz were researched because of the considerable impact they have on the interactions between the solar wind and the Earth's magnetosphere. You can see the solar wind conditions for that occurrence in Table 2.

Table 2: Solar Wind Parameters During the Selected Event

Time (UT)	Velocity V (km/s)	Proton Density (cm^{-3})	IMF Bz (nT)
00:00	335	5.2	+3
03:00	360	6.1	+1
06:00	420	7.5	−2
09:00	515	9.8	−6
12:00	610	11.4	−11
15:00	690	12.7	−18
18:00	720	13.2	−15
21:00	640	10.5	−8
24:00	520	8.3	−3

According to Table 2, the solar wind speed increased gradually from 335 km/s to 720 km/s, indicating the arrival of a high-speed stream of solar wind. At the same time, the IMF Bz element went from having positive values to having very negative ones. There is a good chance for magnetic reconnection at the dayside magnetopause due to the southward rotation of Bz, which peaks at -18 nT at 15:00 UT. Another clue that the magnetosphere is being crushed by the solar plasma that is entering is that the proton density is also increasing.

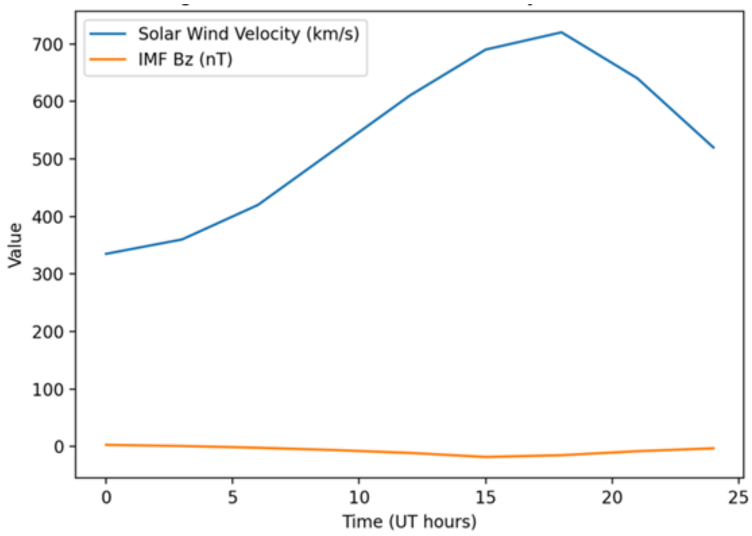

Figure 1: Speed of the Solar Wind and IMF Bz vs. Time

In Figure 1, we can see the graphic representation of the fluctuation in solar wind velocity and the IMF Bz. At the same time as the solar wind's velocity is rapidly increasing, the image shows that IMF Bz is rotating southward. This concurrent action states that not only the orientations of the magnetic fields were appropriate to foster effective solar wind-magnetosphere interconnections but also the conditions of dynamical pressure were amenable to release much solar wind power into the magnetosphere.

4.2. Magnetospheric Response

In order to determine the magnetosphere's response to the approaching solar wind disruption, geomagnetic activity indices were studied. Global geomagnetic response was measured by the Kp index and disturbance storm time (Dst) index that are measurements of planetary magnetic activity and intensity of ring current respectively. Table 3 below presents the observed geomagnetic parameters during the event.

Table 3: Geomagnetic Activity Indices

Time (UT)	Kp Index	Dst Index (nT)	Storm Phase
00:00	2	−8	Quiet
03:00	2	−12	Quiet
06:00	3	−20	Weak activity
09:00	4	−35	Active
12:00	5	−65	Initial phase
15:00	7	−115	Main phase
18:00	6	−102	Peak
21:00	5	−70	Recovery
24:00	4	−40	Recovery

Table 3 demonstrates that the geomagnetic activity increased remarkably after the IMF started to turn southwards. The Kp index increased between 2-7 which represents a high global magnetic disturbance. At the same time, the Dst index was reduced to -115 nT, which proved the fact that there was a powerful geomagnetic storm. The strong part of the storm took place close to 15:00 UT which relates to the strongest southward IMF recorded in the solar wind recordings.

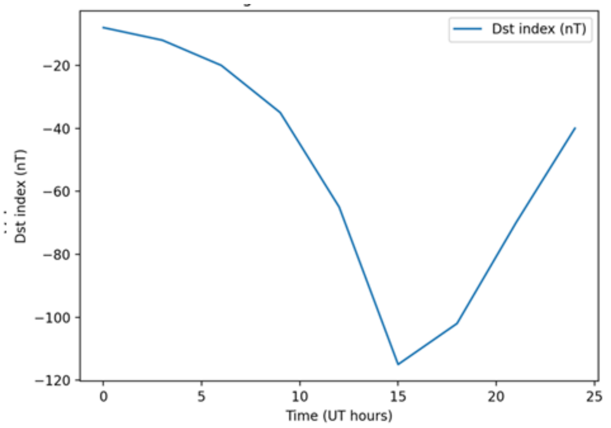

Figure 2: The Dst index fluctuated over time throughout the geomagnetic storm event.

The time dependence of the Dst index is shown in Figure 2. There is a steep negative depression in Dst soon following the solar wind perturbation. The lowest point of Dst is the major stage of the geomagnetic storm and it is connected with the strengthening of the ring current within the inner magnetosphere. This action proves that solar wind power had been effectively conducted into the magnetosphere by means of magnetic reconnection.

4.3. Solar Wind–Magnetosphere Coupling

Finding out how much energy the wind contributes to Earth's magnetosphere was the aim of measuring the solar wind electric field. This synchronization between the solar wind and the magnetosphere depends on the velocity of the solar wind and the southward force (Bz) of the interplanetary magnetic field (IMF). We evaluated this interaction's relative strength by using the connection:

$$E = V \times | B_z |$$

Bz is the strength of the south IMF, and V is the solar wind's speed. More energy entering the magnetosphere through magnetic reconnection is indicated by an increase in this parameter's value. Table 4 shows the calculated values of the coupling levels of various observation times.

Table 4: Solar Wind–Magnetosphere Coupling Strength

Time (UT)	Solar Wind Velocity V (km/s)	Southward IMF |Bz| (nT)	Coupling Level
00:00	335	3	Weak
06:00	420	2	Weak
09:00	515	6	Moderate
12:00	610	11	Strong
15:00	690	18	Very Strong
18:00	720	15	Very Strong
21:00	640	8	Moderate
24:00	520	3	Weak

Table 4 shows that when the strength of the southward IMF and the solar wind velocity both increased simultaneously, the coupling strength rose exponentially. The highest correlation was observed at 15:00 UT, when both the southerly IMF and the solar wind speed were at their maximum. The primary period of the geomagnetic storm is recorded by the Dst index during this time. The results show that high-speed solar wind by itself cannot induce geomagnetic disruptions, but when combined with the southward IMF direction, powerful storms are produced. When this happens, the magnetopause's magnetic reconnection process is highly efficient, and the magnetosphere might receive a lot of energy from the solar wind. An enormous drop in the Dst index occurs as a result of the injected energy's enhancement of magnetosphere current systems, particularly the ring current.

4.4. Time Delay and Correlation

A better understanding of coupling was sought by investigating the time-dependent interaction between the IMF Bz and geomagnetic activity. It took around 45 minutes longer for the IMF Bz to begin moving downward than expected before the Dst index began to decline. When a solar wind disturbance exits the magnetopause, it takes some time to reach the inner magnetosphere, where it triggers magnetospheric current systems. Table 5 shows the relationship between IMF Bz and the corresponding geomagnetic response.

Table 5: Relationship Between IMF Bz and Dst Index

IMF Bz (nT)	Average Dst (nT)	Magnetospheric State
Positive (+1 to +3)	−10	Quiet
−2 to −5	−30	Weak activity
−6 to −10	−60	Developing storm
−11 to −18	−110	Strong geomagnetic storm

Table 5 shows that the IMF Bz component and the Dst index have a negative connection. When the IMF is positive (pointing northward), the geomagnetic activity is low and the magnetosphere is relatively steady. However, geomagnetic storms would be more intense as the IMF moves southward and the Dst index becomes more negative. This is because the dayside magnetopause is more conducive to magnetic reconnection when the IMF is directed southward. Solar wind energy and plasma can enter the magnetosphere through the opening of field lines caused by the reconnection process. A decrease in the Dst index is the result of an increase in the ring current and a decrease in the global magnetic field caused by the energy input.

5. CONCLUSION

This study attempted to determine how the solar wind interacts with the magnetosphere of Earth by utilizing geomagnetic indices and observational space-weather data. The study found that a strong solar wind stream and a significant southward component of the IMF usually set off geomagnetic storms. An effective magnetic reconnection in the magnetopause can transmit a considerable quantity of solar wind energy into the magnetosphere, as evidenced by the measured fall in the Dst index and increase in the Kp index. It seems that 45 minutes elapsed between the magnetopause and the creation of the ring current, as a result of the response being delayed in response to the solar wind disturbance. The findings also show that IMF orientation is the most effective parameter that regulates storm intensity with solar wind velocity as the supporting parameter. The paper highlights the need to regularly observe the upstream solar wind conditions, so that the space-weather prediction could be enhanced, and the possible effects that satellites, communication systems, and navigation networks might face, as well as power infrastructure, could be minimized.

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