Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://journal.nsps.org.ng/index.php/jnsps

J. Nig. Soc. Phys. Sci. 4 (2022) 620

Journal of the Nigerian Society of Physical Sciences

A Study of the Relationship Between Southward BZ > −10 nT and Storm Time Disturbance Index During Solar Cycle 23

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Abstract

Magnetic reconnection can be used for studying the geoeffective processes in the coupled Sun–Solar wind – Magnetosphere dynamics leading to geomagnetic disturbance. In this study, 1-hour resolution solar wind plasma parameters from OMNIweb were used to investigate the relationship between moderate southward interplanetary magnetic field, IMF-B_z (i.e., $B_z > -10$ nT) and geomagnetic storm time disturbance, D_{st}, during the ascending, maximum and descending phases of solar cycle 23. Occurrences of different classes of geomagnetic storms during moderate southward B_z are reported. The occurrence of weak and moderate geomagnetic storms is more predominant during maximum solar activity than intense and super intense storms. It was found that 10.11 % (181) of all the classes of the storm were intense, and 0.17 % (3) were super intense storms. Furthermore, it was found that 4 (2.2 %) out of the 181 intense storms were caused by southward $B_z > -10$ nT which were associated with the complex structure due to the high-speed solar wind stream and corotating interacting region. In such a complex structure and $B_z > -10$ nT, we observed that an intense geomagnetic storm rarely occurs and if it does, would be predominant around solar maximum. It was found that long-duration ($\Delta t > 6$ hrs) of southward B_z (i.e., $-10\, nT < B_z \leq -3.6\, nT$) can also lead to an intense geomagnetic storm during the solar maximum and descending phase (moderate solar activity) of a solar cycle. The complex structure of intense geomagnetic storms associated with the $B_z > -10$ nT is rare and possesses a special configuration of magnetic field and solar wind parameters structures which are CIR manifestations.

DOI:10.46481/jnsps.2022.620

Keywords: Magnetic reconnection, D_{st}, intense geomagnetic storm, moderate southward IMF- B_z, solar maximum, solar minimum, solar cycle.

Article History :
Received: 28 January 2022
Received in revised form: 15 September 2022
Accepted for publication: 16 September 2022
Published: 11 November 2022

Communicated by: S. J. Adebiyi

1. Introduction

The Earth's near-space environment is not surrounded by vacuum, but by a highly dynamic and coupled system of plasmas and magnetic fields, whose complex interplay with sunspot number, coronal mass ejections (CMEs) and solar flares eruption could cause a time-varying condition that constitutes the subject of space weather [1-3]. The solar wind, consisting mainly of protons and electrons, originates from the sun and streams radially into space, pervading the solar system. The Sun's Magnetic field flows with these particles. The magnetic field of the Earth poses an obstacle to this oncoming flow of plasma from the Sun and thereby carves out the magnetosphere. The solar wind interacts with the Earth's magnetic

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field and reconfigures its dipolar shape by compressing it on the sunward side while stretching it to a tail-like shape on the night side. During an anti-parallel orientation of the interplanetary magnetic field (IMF) to the geomagnetic field lines, solar wind energy, momentum and mass could be transferred into the Earth's magnetosphere, thereby influencing its dynamics and geomagnetic storms. Landmark studies [3-9] have shown that B_z, which is the north-south direction component of the IMF, is a good index that plays a vital role in the reconnection between the solar and terrestrial magnetic fields, leading to additional energy in the magnetospheric flux tube and the geoeffectiveness of geomagnetic storms. A southward B_z, fluctuating in the corotating interacting regions (CIRs), is a prerequisite for magnetic reconnection leading to the development of geomagnetic storms [4] whereas, a northward B_z rarely leads to storms except during extremely high solar wind speed [5, 10]. On the other hand, the storm time disturbance index, D_{st}, has been extensively used to measure the degree of moderate magnetic perturbation experienced by the dipolar field of the terrestrial planet [11]. The D_{st} index represents the magnetic depletion resulting from the westward drift of the ring current formed by ions and electron energy which would be detectable by an appropriate ground-based instrument [10].

The interplanetary origin of intense geomagnetic storms has been widely studied [3,12-21]. Many have explained the interrelation between the southward interplanetary magnetic field and the depletion in the D st index leading to intense magnetic storms. They recognised that the orientation of the interplanetary magnetic field played a great part in the strength of the main phase of geomagnetic storms. Gonzalez et al. [22, 23] were among the leading research work on the relationship between the interplanetary magnetic field and the resulting ring current system. Meanwhile, Gonzalez and Tsurutani [24] and Gonzalez et al. [15] had drawn an inference that B_z and the geomagnetic storm's development are interrelated, where they observed that the magnitude of the southward B_z leading to an intense storm is ≤ -10 nT and over a period exceeding 3 hours. This intense nature of B_z appears to originate from the different interplanetary and solar wind structures and the interaction between them. Also, it was established that the Poynting flux from the interplanetary medium is a driver of the main phase of storm development in the magnetosphere and determines the strength and magnitude of the storm [3, 15, 21].

Several studies [25-28] while studying the ring current, tried to quantify the energy deposited in the magnetosphere by the stream of charged particle/solar wind, coupled with the solar magnetic field it drags. They also looked at the magnetospheric dissipation rate of this energy. The stored magnetosheath energy (i.e., pressure gradient force and magnetic tension force) realigns the magnetic field, the energy along the field lines causes the westward ring current of the plasma under the influence of gradient and curvature drift [29]. The main phase of geomagnetic storms results from ring current development, in which energisation depends on storm time disturbance index, D_{st} , solar wind speed, ram pressure and B_z component of the IMF [3, 26, 30]. The drivers of events with large geomagnetic storms are described to be of complex interplay [14]. The complexity includes several steps at the main phase of the storm, the phase of the solar cycle, the occurrence of shock at the sheath, the speed of the interplanetary coronal mass ejection (ICME), etc. Borovsky and Denton [16] explained that while coronal mass ejection-driven storms are inimical to the electrodynamics system on Earth, storms driven by the corotating interacting region (CIR) affect assets in the space region. Many of the CIRs have transient properties that are similar to that of ICMEs and contain small ICME-like transient, that is, the solar wind properties feature many ICME signatures, such as smooth/coherent field rotation and enhanced fields, but that is significantly reduced in duration (a few hours on average) than typical large-scale ICMEs [31, 32, 33]. Entrainment of such transients, when they have southward fields, may enhance the geoeffectiveness of a CIR. The interaction between such transients may enhance the geoeffectiveness of a CIR, especially, when they have moderate southward fields [32]. Adekoya and Chukwuma [3] reported that these types of storms may be originated from small explosions that are more intense than the CMEs-caused storms. And were caused by the interactions between a shock driven by the symmetric transient disturbances and the corotating stream [34]. Gonzalez et al. [15] added B_s structures (southward magnetic field) to the list of causative elements of events with large geomagnetic storms. They pointed out that the long duration of the enhanced B_s would offer support for a magnetic cloud to produce a large magnetic storm. Kumar et al. [35] observed that the magnitude and duration of the southward B_z are fundamental in the occurrence and development of the geomagnetic storm. In all, none of these investigations has been able to categorically report or linked the geoeffectiveness of an intense magnetic storm to a lower magnitude of southward B_z.

Similarly, studies exist on the interplay of solar wind parameters and geomagnetic activity during the solar cycle 24. For example, Rathore [36] in a case study of a geomagnetic storm during the solar cycle 24 shows that IMF parameters including the B_z component are linked to geomagnetic storm given the increase in the value of B_z at the storm commencement. This is relatable to a previous observation of a high B_z value by Rawat et al. [37] during several intense geomagnetic storms in solar cycles 23 and 24. However, the B_z cannot be isolated as the main driver following Rathore [36], since the value of other solar wind parameters such as solar wind speed and plasma temperature were equally large during the same period of the storm commencement. Pokharia et al. [38] suggest that combining solar wind speed and B_z is a better approach to depicting the production of geomagnetic storms than considering both parameters separately. The foregoing shows B_z is a relevant interplanetary condition for geomagnetic storm commencement, which is in tandem with the requirements suggested in Gonzalez and Tsurutani [24] for intense geomagnetic activity.

This work looks at the statistical analysis of the occurrence of geomagnetic storms associated with the IMF-B_z as well as the geoeffectiveness of $B_z > -10$ nT. In comparison to previous works, a complete solar cycle will be investigated in this study, which will allow every phase of the solar cycle to be investigated. Previous studies [22, 24, 39] had argued that an intense storm can only occur when the B_z component of the IMF stays at least three hours in the southward direction with a threshold of $B_z \leq -10$ nT. Attention is restricted in the present study to events during a southward turning of B_z such that $B_z > -10$ nT. The term "moderate southward B_z " in this work refers to the range of B_z component of the IMF such that $-10\ nT < B_z \leq -5$ nT. Solar cycle 23 has been chosen not for any special reason, but it is worth mentioning that it is the longest solar cycle in history. Figure 1 shows the time series of the sunspot number enclosing the period of solar cycle 23, where the peak (solar maximum) shows a double hump between the year 2000 - 2003 and a solar minimum in 2008 ending the cycle. The black line in Figure 1 is the daily total while the red line is the yearly smoothed sunspot numbers. The minimum and maximum sunspot numbers during the cycle are respectively about 5 and 180.

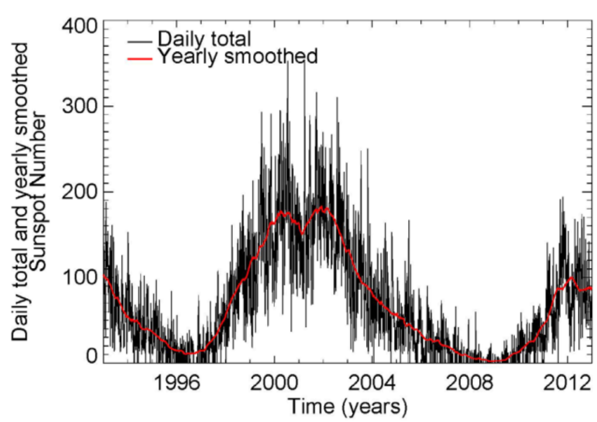

Figure 1: The time series sunspot number enclosing the period of solar cycle 23.

2. Data source and method

The period under investigation is the solar cycle 23, with a time interval from August 1996 to December 2008. For this period, the solar wind plasma and geomagnetic parameters data employed in this study consist of hourly values of the B_z component of the Interplanetary Magnetic Field (B_z, nT), the storm time disturbance index (D_{st} index, nT), plasma flow speed (V_{sw}, km/s), Proton density (ρ, n/cm^3) and corresponding plasma temperature (T, K). These interplanetary and hourly geomagnetic data are obtained from the Space Physics Data Facility (SPDF) OMNIWEB website (http://omniweb.gsfc.nasa.gov/). This research is focused on a statistical analysis of the different classes of geomagnetic storms indicated by the storm time disturbance index as a result of moderate southward B_z at the nose of the Earth's magnetopause. The geomagnetic storms classifications are: weak ($-30\ nT \leq D_{st} > -50$ nT), moderate ($-50\ nT \geq D_{st} > -100$), intense ($-250\ nT < D_{st} \leq -100$ nT), and super intense ($D_{st} < -250$ nT), while ($D_{st} \geq -30$ nT) is regarded as period of quiet activity [39, 40, 41]. In this study, the period at which the OMNI data set of solar wind plasma parameters at the bow shock region of the Earth records $-10nT < Bz \leq -5$ nT is taken to be a moderate southward B_z event. There were 1790 geomagnetic events during the solar cycle 23, and the frequency of the hourly values is shown in Table 1.

3. Result and Discussion

3.1. Hourly analysis of events

Table 2 indicates the hourly distribution (in UT) of geomagnetic storms as indicated by the D_{st} index in Table 1. The data in Table 2 shows the frequency of the hourly values of the 1790 events during the solar cycle 23 and its occurrence, which is the frequency of a particular class at a particular hour divided by the total frequency for that hour (see equation (1)). It is clearly shown that weak geomagnetic storms dominate every hour throughout the period under investigation, while the super intense class is a rare phenomenon.

Figure 2 shows the bar chart of the temporal distribution of events with weak, moderate, intense and super intense geomagnetic storms caused by moderate southward B_z during the period under investigation. The hourly occurrence of the different classes of storms is calculated as the percentage ratio of the number of events in each class to the total events caused by moderate B_z at the particular hour (see Table 2).

$$D_{st}\text{Occurrence} = \frac{\text{Total of each storm category}}{\text{Total storm event}} \times 100\%. \quad (1)$$

The blue, green, yellow, and red colours represent the percentage occurrence of the weak, moderate, intense and super intense geomagnetic storms, respectively. As more field lines are opened due to dayside re-connection, the open field lines stretch in an anti-sun ward direction and the solar wind energy is transported into the magnetosphere, where it is stored in the magnetotail [42]. The eventual release of the energy as a result of reconnection in the neutral sheet gives rise to varying degrees of storm categories. It could be seen from Figure 2 that apart from the super intense geomagnetic storms that rarely occur, all other classes of geomagnetic storms are general phenomena at all times. Furthermore, Figure 2 indicates that though moderate geomagnetic storms have no distinct peak, it attains a maximum occurrence of about 49 % during the moderate southward B_z conditions. However, when the class of geomagnetic storms is above moderate, the occurrence peak

Table 1: Frequency of different range of classes of D_{st} corresponding to moderate southward B_z 165 during the solar cycle 23.

D_{st}	Weak	Moderate	Intense	Super Intense
Frequency	878	728	181	3

Table 2: Frequency of hourly peak values and percentage occurrence for different classes of geomagnetic storms during solar cycle 23.

UT	Frequency of D_{st}				D_{st} Occurrence (%)			
	Weak	Moderate	Intense	Super Intense	Weak	Moderate	Intense	Super Intense
0	42	28	7	0	54.55	36.36	9.09	0.00
1	39	28	7	0	52.7	37.84	9.46	0.00
2	29	34	7	0	41.43	48.57	10	0.00
3	30	31	7	0	44.12	45.59	10.29	0.00
4	32	30	7	0	46.38	43.48	10.14	0.00
5	34	28	8	0	48.57	40	11.43	0.00
6	33	30	13	0	43.42	39.47	17.11	0.00
7	34	33	5	0	47.22	45.83	6.94	0.00
8	48	34	5	0	55.17	39.08	5.75	0.00
9	31	24	5	0	51.67	40	8.33	0.00
10	37	37	5	0	46.84	46.84	6.33	0.00
11	29	29	6	0	45.31	45.31	9.38	0.00
12	45	37	8	0	50	41.11	8.89	0.00
13	45	28	8	0	55.56	34.57	9.88	0.00
14	45	34	8	0	51.72	39.08	9.2	0.00
15	33	26	3	0	53.23	41.94	4.84	0.00
16	38	30	4	0	52.78	41.67	5.56	0.00
17	33	31	4	0	48.53	45.59	5.88	0.00
18	36	38	7	0	44.44	46.91	8.64	0.00
19	39	27	14	0	48.75	33.75	17.5	0.00
20	33	31	14	0	42.31	39.74	17.95	0.00
21	28	24	13	2	41.79	35.82	19.4	2.99
22	47	30	9	0	54.65	34.88	10.47	0.00
23	38	26	7	1	52.78	36.11	9.72	1.39
Total	878	728	181	3				

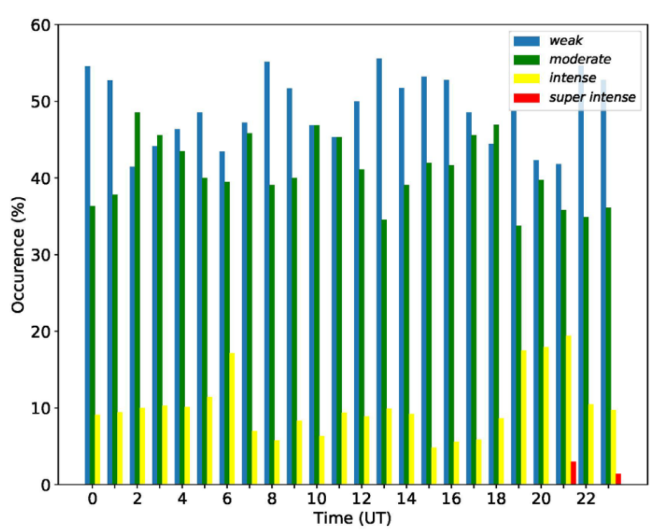

Figure 2: The hourly occurrence values for different classes of geomagnetic storms associated with southward moderate B_z during solar cycle 23.

reduces below 20 %. A clear observation of Figure 2 shows a higher occurrence of intense storms during the night sector with respect to the universal time. Around 19 − 23 UT and 00 − 06 UT, the occurrence of an intense storm is higher in comparison to during the period 08 − 18 UT. Less than 0.2 % of the events are super intense storms, and about two-thirds are driven by midnight mechanisms.

3.2. *Yearly analysis of events*

Table 3 indicates how the total number of 1790 events indicated by the D st index in Table 1, is distributed across the years in solar cycle 23. As stated earlier, frequency is the number of events for the different classes of geomagnetic storms (measured by the D_{st} index) according to the southward B_z due to the magnetic reconnection. The occurrence on the other hand is the frequency of a particular class in a particular year divided by the total frequency for that year. It can be seen that the maximum frequency of all the classes of geomagnetic storms is during solar maximum (see Figure 1). In all, the percentage occurrence of intense and super intense storms peaked during solar maximum, while the occurrence of weak geomagnetic storms was dominant during solar minimum. This is partly because the sunspot number being at maximum, increases solar activity level and provides an opportunity for geoeffectiveness. The occurrence of moderate geomagnetic storms was higher at the declining phase of the solar cycle, which occurs at solar moderate periods, meanwhile, the lowest occurrence rate was at solar minimum. This result was congruent with the report of Echer et al. [10] who reported the highest rate of moderate storm occurrence in the declining phase of the solar cycle 23. The moderate storms were dominantly driven by CIRs and high-speed streams (HSSs), but with variable contributions from ICMEs, their shocks (sheaths), and combined occurrence within the solar cycle [10, 21, 43]. Whereas, the weak class of geomagnetic storm's highest occurrence was found at the solar minimum, lowest during the solar maximum periods, the ascending and descending phases of the solar cycle shows non-linear variations.

3.3. Analysis of the southward $B_z > -10$ nT and solar wind conditions leading to an intense geomagnetic storm

The intense geomagnetic storms ($D_{st} \leq -100$ nT) are caused by the intense southwardly directed IMF-B_z of magnitude > 10 nT, with a duration greater than 3 hours [22, 24, 39]. However, not all intense storms are associated with the intense nature of B_z [3, 10]. That is, there are intense storms that are likely caused by moderate southward B_z, ($-10\ nT < B_z \leq -5$ nT) whose complex solar wind and interplanetary interplay may be different from other storms [44, 45]. Kumar et al. [35] observed that the magnitude and duration of the southward B_z are fundamental in the occurrence and development of geomagnetic storms. Therefore, onward in this section, the interplay of the intense storms associated with the moderate southward B z ($-10\ nT < B_z \leq -5$ nT) turning for long-duration of three consecutive hours and solar wind conditions during the solar cycle 23 is presented. This event is a rare occurrence and only occurred during the solar maximum and descending phase (moderate solar activity) of the solar cycle 23. Its properties and geoeffectiveness as related to the moderate southward B_z are explained below.

Figure 3 shows the interplanetary and solar wind plasma characteristics during the geomagnetic storm event of 25 – 27 September 2001, representing the moderate southward B_z event during the solar maximum phase of the solar cycle 23. The region within the two red vertical lines presents the structure of the solar wind characteristics associated with the moderate southward B_z . The duration of the moderate southward B_z turning is represented with Δt, that is, the changes in time at the first and second vertical lines. Looking at Figure 3, the peak value of southward B_z was -3.6 nT which is contrary to the earlier suggested magnitude of the moderate southward B_z [19, 22]. From the view of the solar wind plasma structure associated with this southward B_z , the intense signature of $D_{st} = -102$ nT corresponds with the respective high-scale variations of the plasma density, ρ is 39.2 N/cm^3, plasma temperature, T is 706094 K, plasma flow speed, V_{sw} is 675 km/s above the typical value of 450 km/s and plasma Beta, β, is 4.88. Choi et al. [7] referred to such an event with a duration ≥ 3 hrs as long-weak B_z and has characteristics of HSSs/CIRs driven intense storms. The event properties emanated from coronal holes and are associated with stream interaction regions [5] and are identified as complex ejecta [3, 45].

In a similar configuration, the solar wind properties during

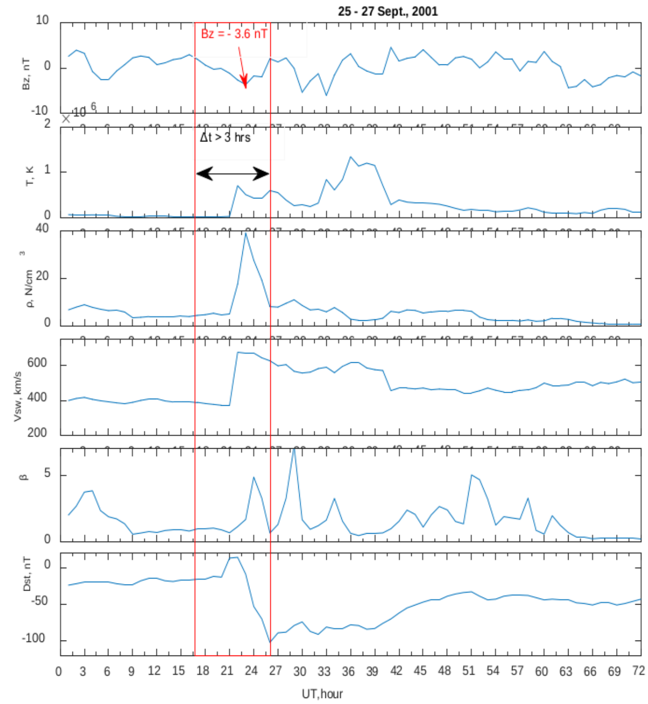

Figure 3: Interplanetary and Solar wind plasma parameters of a moderate southward B_z turning caused intense storm during the solar maximum phase of the solar cycle 23. The shaded region marked the corresponding interplanetary and geomagnetic profiles associated with the moderate southward B_z. The September 25 – 27, 2001 geomagnetic storm event.

the intense geomagnetic storm of 3 – 5 April 2004 represent the moderate southward B_z event during the descending phase of the solar cycle 23 is presented in Figure 4. Looking at this figure, the intense storm ($D_{st} \geq$ -100 nT) originated from the long-duration ($\Delta\ t > 7$ hours) moderate southward B_z turning of magnitude -7.9 nT. The corresponding solar wind parameters suggest that there is a high-scale variation of flow speed with a peak magnitude of 504 km/s below the typical value of 450 km/s. The plasma flow speed increases from 423 km/s around 1300 UT on April 3 to a peak magnitude of 504 km/s around 0000 UT on April 4 corresponding to the periods of the moderate southward orientation of the B_z. Contrary to the high plasma temperature of the events during the solar maximum phase of the solar cycle, the plasma temperature during the descending phase was reduced (the peak plasma temperature at the confined period of the moderate southward B_z was 121,155 K) below the typical of 400,000 K [41]. Corresponding to the moderate southward directed B_z are high proton density, ρ with a peak value of 24.5 N/cm^3 and high plasma Beta, β, with a peak value of 3.46. The characteristic signature of this intense storm is depression in the magnitude of the D_{st} resulting from the westward ring current associated with the moderate southward directed B_z system encircling the Earth. Following the sudden storm commencement of the storm, the D_{st} decreases to a minimum value of -117 nT at exactly 0000 UT on April 4.

During the window of the southward directed B_z, the characteristic of this complex ejecta-driven storm during the solar

Table 3: Frequency of yearly peak values and percentage occurrence for different classes of D_{st} during solar cycle 23.

Year	Frequency of D_{st}				D_{st} Occurrence (%)			
	Weak	Moderate	Intense	Super Intense	Weak	Moderate	Intense	Super Intense
1996	13	3	1	0	76.47	17.65	5.88	0.00
1997	52	66	5	0	42.28	53.66	4.07	0.00
1998	120	61	22	0	59.11	30.05	10.84	0.00
1999	100	77	11	0	53.19	40.96	5.85	0.00
2000	173	105	26	1	56.72	34.43	8.52	0.33
2001	118	119	57	2	39.86	40.2	19.26	0.68
2002	50	97	38	0	27.03	52.43	20.54	0.00
2003	136	103	2	0	56.43	42.74	0.83	0.00
2004	20	25	10	0	36.36	45.45	18.18	0.00
2004	40	30	2	0	55.56	41.67	2.78	0.00
2005	26	30	7	0	41.27	47.62	11.11	0.00
2006	19	11	0	0	63.33	36.67	0.0	0.00
2007	11	1	0	0	91.67	8.33	0.0	0.00
2008	878	728	180	3				

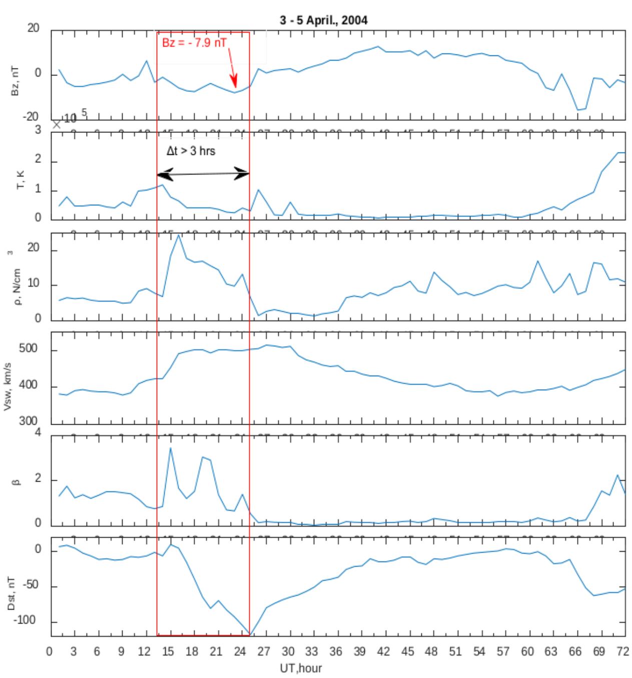

Figure 4: Same as Figure 3, but during the descending phase of the solar cycle 23. The April 3 − 5, 2004 geomagnetic storm event.

maximum and descending phase are presented in Table 4. In Table 4, the peak value of the solar wind parameters and magnetic index associated with the moderate southward directed B_z were highlighted. Four (4) intense geomagnetic storm events were identified to be related to the $B_z > -10$ nT, three (3) were during the solar maximum and one during the descending phase (around moderate solar activity periods) of the solar cycle 23. This rare occurrence event was not found during the ascending phase of the solar cycle 23, which indicates the possibility of not having such an event during the ascending phase of a solar cycle. The occurrence rate of this moderate southward B_z -driven storm is very rare. The only condition for an increase in the occurrence of the moderate southward B_z is when the geomagnetic storm classification is moderate (i.e. $-100\ nT < D_{st} \leq -50$ nT) and during solar minimum [5, 32]. From Table 4, one can see that the peak response of southward B_z during the storm of 25 - 27 Sept. 2001 was -3.6 nT, which is above the typical value for moderate southward B_z of ($-10nT < B_z \leq -5$ nT). Aside from this low-weak B_z, the parameters show high- scale variables compared to other storms. Choi et al. [7] have suggested that this weakly event of southward B_z should be considered significant from the viewpoint of their geoeffectiveness. Therefore, the occurrence rate may be too low to be considered, but the solar wind characteristics and geoeffectiveness of the storm compared to the other storms with a higher magnitude of southward B_z should be classified as moderate southward B_z-driven intense storm. The sudden increase and high flow speed and proton density of the plasma indicate that the geoeffectiveness of stream interacting region/high-speed streams can be explained by solar wind properties. Therefore, either low-weak southward B_z or moderate southward B_z-related intense storms should be considered as geoeffective significant events that can affect space-based and ground-based technology as much as those of the intense southward B_z signature.

4. Summary and Conclusions

We have carried out a statistical analysis of the occurrence of geomagnetic storms associated with the southward interplanetary magnetic field in the range of B_z ¿ -10 nT, using the complete solar cycle 23 data. The complex structure of intense geomagnetic storms associated with the B_z > -10 nT is rare

Table 4: The characteristics of the solar wind parameters associated with the southward directed B_z (> -10 nT) with long-duration of intense geomagnetic storm during solar cycle 23. The peak response of the parameter during the southward B_z turning was highlighted.

S/N	YEAR	DOY	B_z (nT)	Δt (hr)	T (K)	V_{sw} (km/s)	ρ (N/cm^3)	β	D_{st} (nT)
1	2001	269	-3.6	> 8	706094	675	39.2	4.88	-104
2	2002	233	-9.2	> 12	35238	495	7	0.88	-106
3	2002	325	9.4	> 6	478599	728	54.8	1.26	-128
4	2004	95	-7.9	> 7	121155	504	24.5	3.46	-117

and possesses a special configuration of magnetic field and solar wind parameters structures which are HSSs/CIR manifestations. It was found that 10.11 % (181) of all the classes of the storm were intense, 0.17 % (3) were super intense storms, 40.67 % (728) were moderate geomagnetic storms while 49.05 % (878) were weak storms. Furthermore, it was found that only 4 (2.2 %) out of the 181 intense storms were caused by the southward $B_z > -10$ nT which were associated with the complex structure due to the High-Speed solar wind stream and corotating interacting region. The results are further summarised as follows:

- The complex structure and $B_z > -10$ nT event of the intense geomagnetic storm is a rare occurrence and only occurred during the solar maximum and descending phase (moderate solar activity) of the solar cycle 23.
- Sometimes the southward turning of $B_z > -5$ nT with a complex configuration of solar wind characteristics may lead to an intense geomagnetic storm which may occur during solar maximum. Therefore, the geoeffectiveness of an intense storm associated with the southward $B_z > -10$ nT is controlled by the solar wind characteristics (i.e., high plasma flow speed, high proton density and complex structure of plasma beta).
- The yearly analysis shows a predominance in the weak and moderate geomagnetic storms resulting from -10 nT ¡ $B_z \leq -5$ nT.
- The complex structure associated with the moderate geomagnetic storms is more predominance during solar minimum.
- The peak occurrence for all classes of geomagnetic storms, associated with moderate southward B_z, is observed during solar maximum.
- In contrast to previous studies that a 3-hour intense southward B_z is a pre-requisite for an intense geomagnetic storm, a 3-hour southward $B_z > -10$ nT with a complex structure can lead to an intense geomagnetic storm at the phases of the solar cycle.
- About 75 % of the southward $B_z > -10$ nT leads to intense geomagnetic storms occurring at the maximum phase of the solar cycle.

Acknowledgements

The authors appreciate the staff of Space Physics Data Facility (SPDF) OMNIWEB (website: http://omniweb.gsfc.nasa.gov/) for free accessibility of data. We thank the Olabisi Onabanjo University, Ago-Iwoye, Nigeria, for creating the enabling environment for this research. The University of Leicester, United Kingdom, is deeply appreciated for making UoL Spectre available for the analysis.

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