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Study of Geomagnetic Storms Associated with Solar Wind and Interplanetary Parameters During Solar Cycles 23 and 24

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Abstract

The aim of this paper is to investigate the relationship between solar wind parameters, such as solar wind speed (V), interplanetary magnetic field IMF (B, Bz) and geomagnetic activity index (Dst, Ap). We identified 103 intense geomagnetic storms (GMS) associated with decrease in Dst (disturbance storm time) ≤ -100nT during 1997- 2006 and 2011-2018, the period spanning over solar cycle 23 and 24. A comparative study has been done using the superposed epoch analysis, often used to demonstrate an effect or a periodicity (Chree analysis). The strength of the geomagnetic storm (Dst) shows significant dependency on the interplanetary magnetic field (IMF) B. The average correlations during solar cycles 23 and 24 are -0.60 and -0.62 respectively, which is quite reasonable. Considering previous studies, Dst is strongly dependent on the southward magnetic field component (Bz), whereas in our present study the average correlation coefficient has been found to be weak and the time lag between Bz minimum and Dst minimum has found up to 5 hours. These results indicate that significant growth in Bz occurs before the main phase of the GMS and not during the main phase. Dst shows high correlation with solar wind speed V during solar cycle 23 (-0.71) than 24 (-0.58) whereas the A_p index exhibits low average correlation with V for solar cycle 23 (+0.51) and SC 24 (+0.31). The correlation coefficient between Dst and Ap index for solar cycle 23 (−0.62) is lower than that for solar cycle 24 (-0.72). Dst shows higher anti-correlation with BV then with B alone but shows low correlation with BzV.

Keywords: Geomagnetic storms; Solar wind; Interplanetary magnetic field; Dst index; Ap index.

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1. Introduction

Space weather refers to disturbances that occur in space around the earth, especially in the magnetosphere, ionosphere, and thermosphere. It is primarily a result of the Sun's variability in its mass and photon emission across different time scales. Geomagnetic storms (GMSs) are disturbances in the earth's magnetosphere that occur in the presence of the interplanetary magnetic field (IMF) and a solar wind [1-3]. GMSs are among the most

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important space weather phenomena and Dungey was the first person to explain the mechanism of GMS [4]. The massive explosions of materials from the Sun's corona are responsible for significant energy transfers into our magnetosphere, which are primarily influenced by the solar wind, solar flares, coronal mass ejections (CMEs) and their interplanetary counterparts, co-rotating interaction regions (CIRs) and solar energetic particles (SEPs) [5-7]. Part of this energy enters our magnetosphere, causing changes in geomagnetic activity that lead to geomagnetic storms, substorms, and stunning auroras in the polar regions of the planet with typical durations of days and hours. Coronal mass ejections (CMEs) and corotating interaction regions (CIRs) are the two large-scale interplanetary structures that can cause GMSs under certain conditions [8].

CMEs are large-scale bubbles of plasma and magnetic fields that form on the Sun in closed field regions, while CIRs are formed in the Sun's outer surface where high- speed streams (HSS) of solar plasma are emitted from coronal holes [9]. After being launched from the Sun, CMEs travel through the IP medium and reach Earth within a span of the 1 to 5 days, and Earth-directed fast ejecta has the potential to trigger geomagnetic disruptions and may also cause geomagnetic storms. Furthermore, the intense and severe GMS are associated with the passage of Magnetic clouds (MCs), which are the interplanetary manifestations of the CMEs [10-12].

The IMF B plays a significant role in the generation of GMS, particularly when the southward IMF Bz and geomagnetic field lines are oriented opposite or antiparallel to one another. This facilitates magnetic reconnection, resulting in a transfer of energy, mass, and momentum from the solar wind to the Earth's magnetosphere. The strongest coupling occurs when the IMF Bz component is oriented southward. An enhanced ring current is the prime indicator of a magnetic storm. The Dst (disturbance storm time) index [13] is a commonly used measure of ring current development and is widely utilized to monitor the global magnetic storm level [14,15]. It is derived from hourly averages of the horizontal component of the Earth's magnetic field obtained from four to five mid-latitude and equatorial magnetograms from various locations worldwide [13]. A geomagnetic disturbance begins with a sudden rise in the horizontal component of the geomagnetic field H and negative values of Dst index indicate that a magnetic storm is in progress, and the more the negative value of Dst indicates the more the intensity of the magnetic storm. A GMS has a main phase in which the horizontal component of the Earth's low-latitude magnetic fields is significantly depressed for one to a few hours, followed by a recovery period that may last several days [16,17]. The Ap index indicates the global level of geomagnetic activity for a given (UT) day [18]. It is based on data collected from multiple stations worldwide, capturing changes in the geomagnetic field resulting from currents in the earth's ionosphere and, to a smaller degree, its magnetosphere. Since the beginning of the space age, the causes of geomagnetic activities and their association with different solar and interplanetary features have been discussed by many authors [13,19-23].

The study of GMS is important in understanding the dynamics of solar-terrestrial environment and is also useful to explore adverse effect in life threatening power outages, radio communications failure, radar observations, long- distance pipelines and spacecraft navigational problems. In this paper, statistical analysis has been conducted to examine geomagnetic activity as defined by a variety of planetary plasma/field parameters, including solar wind velocity V, IMF B, and their southward component Bz, Dst, and Ap index.

2. Data Sources and Methodology of the Analysis

The study analysed 103 intense Geomagnetic storms with a magnitude of Dst ≤ -100nT during the periods of SC 23 (1997-2006) and 24 (2011-2018) by applying the superposed epoch analysis (Chree method) [24]. Chree method has been widely used to study of the effects of various solar / interplanetary phenomena, for example corotating interaction regions, magnetic clouds, high speed streams and, interplanetary shocks and GMS [25-27]. The GMS with a Dst ≤ -100 nT was used as the zero-epoch hour, the subsequent 30 values above and below it was considered to be ±1, ±2, ±3..., ±30 h, respectively. Observations were taken at an hourly average, and graphs were plotted between any two or three parameters for the respective years. The data used in the study was obtained from the Omni web data center (omniweb.gsfc.nasa.gov/form/dx1.html) with 1-h time resolution for the Dst and Ap index, IMF B and Bz components, and solar wind speed (V). The average correlation coefficient was also calculated by employing cross-correlation analysis between the geomagnetic indices and the various interplanetary field/plasma parameters for the respective years, in order to identify the underlying factors of geomagnetic activity.

3. Results and Discussion

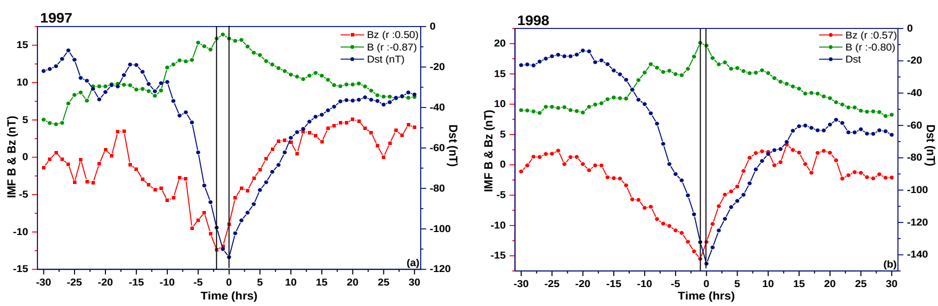
The study confirms previous findings that the variations in geomagnetic indices and interplanetary field/plasma parameters can be influenced by solar active regions and associated phenomena. To account for this variation, the present study focused on major geomagnetic storms as individual events associated with solar and interplanetary disturbances. The minimum value (maximum depression) of the Dst has been used as a storm indicator, and the study gathered data on 103 GMS with a Dst ≤ -100 nT during solar cycles 23 (1997-2006) and 24 (2011-2018). These data were selected and correlated with various parameters of solar wind at the time of Dst minimum. The correlation coefficients (r) for individual solar wind parameters with Dst (IMF B vs Dst, Bz vs Dst, V vs Dst, V vs Ap, BV and BzV vs Dst) were calculated, and the values were plotted in Figs. 1-7. This study helps to understand the causes of geomagnetic activities during the occurrence of GMS and the role of various interplanetary field/plasma parameters in modulating geomagnetic activities.

3.1. *IMF B, Bz and GMS*

Interplanetary magnetic field (IMF) is a part of the Sun's magnetic field that is carried into interplanetary space by the solar wind, and its orientation can be either northward or southward. Meanwhile, there is also abrupt change in B_z component from northward to southward. The southward component of the IMF (Bz < 0) is responsible for intense GMS [28,29], with the most intense storms with peak Dst ≤ -100 nT, primarily caused by strong negative IMF southward component Bz, with duration greater than 3 h [14].

From the plots in Figs. 1(a-j) and 2(a-h), it is clear that the maximum decrease in Dst happens on average 3 h after the IMF B and Bz peak. This suggests that the magnetic field strength commences to increase prior to the onset of GMSs, and there exists a time lag between the maximum decrease in Dst, Bz, and B peak values, which spans from 1 to 5 h. This finding is supported by observations of [30] (observed finite time lag of 3 h), [31,32] (time lag of 1 day). A possible explanation for the discrepancy in the time lags could be the difference in time resolution between different observations. However, the existence of a time lag may provide important information about the energy transfer mechanisms involved in the development of GMSs. It has been found that the average correlation coefficient of Dst with IMF B and Bz is -0.60 and 0.42 for SC 23, and -0.62 and 0.47 for SC 24, respectively. This suggests that the stronger the value of IMF B, the stronger the GMS, and that IMF B is a geoeffective parameter.

Previous studies have suggested that the strength of the GMS is strongly dependent on the southward component Bz. However, in the present analysis, the correlation between them appears to be low [32]. Based on the present study, it can be concluded that the significant growth in the southward magnetic field component B_z occurs before the main phase of the GMS and not during the main phase. The absence of a significant correlation between the solar wind magnetic field parameter Bz and Dst during the primary phase of the GMS does not imply that Bz is not a geoeffective as a parameter. These results are different from previous findings, which emphasized the importance of the southward component of the IMF in the development of GMSs [32,34]. So, we can conclude that, the study provides insights into the relationship between solar wind magnetic field parameters and GMSs and highlights the importance of considering the duration of negative Bz and IMF B in addition to its magnitude in the development of intense GMSs [35].



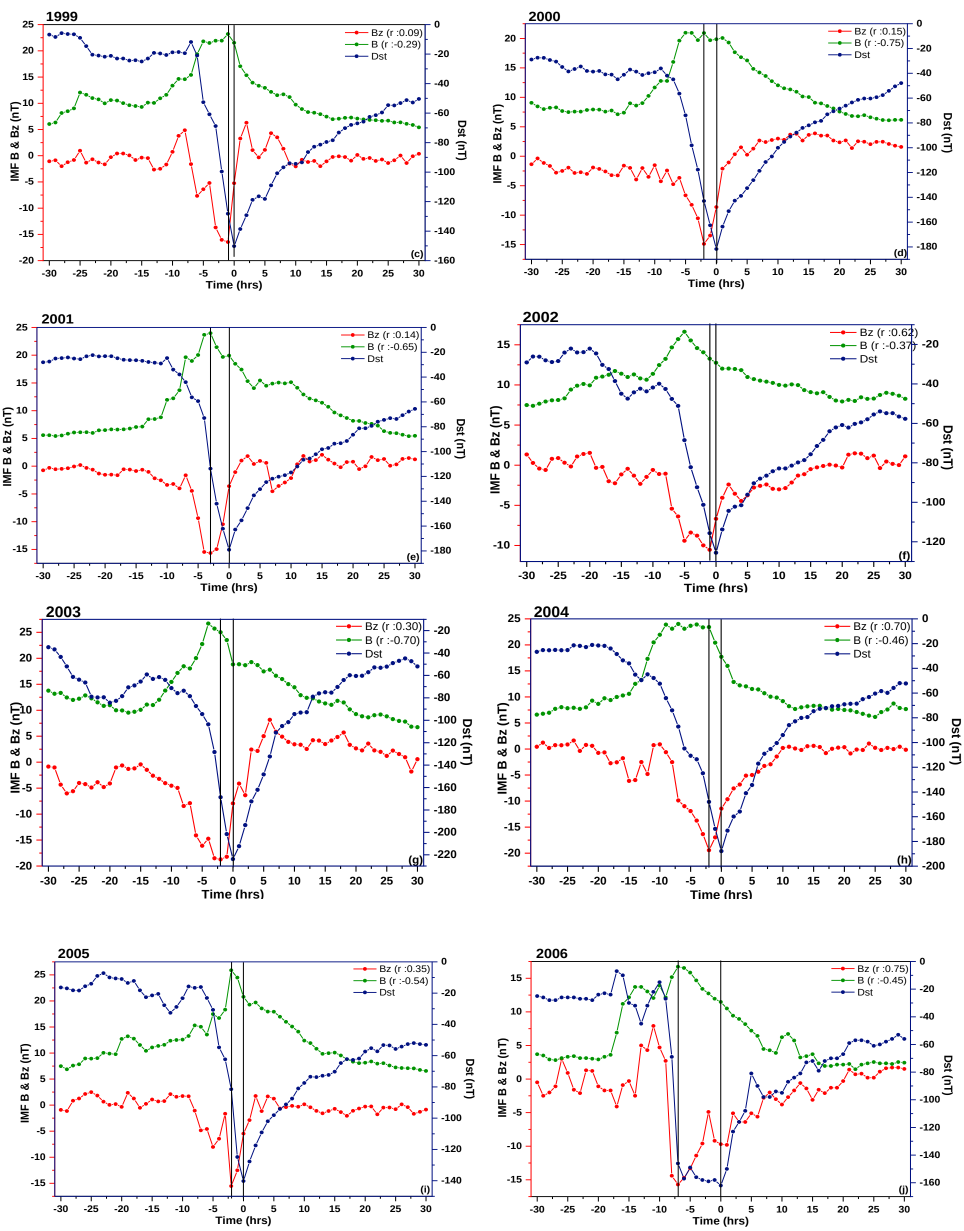


Fig. 1. The superposed epoch results range from -30 to +30 h with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst with respect to IMF B and Bz mean values for the period spanning 1997 to 2006. The vertical lines depict the time lag between Bz and Dst.

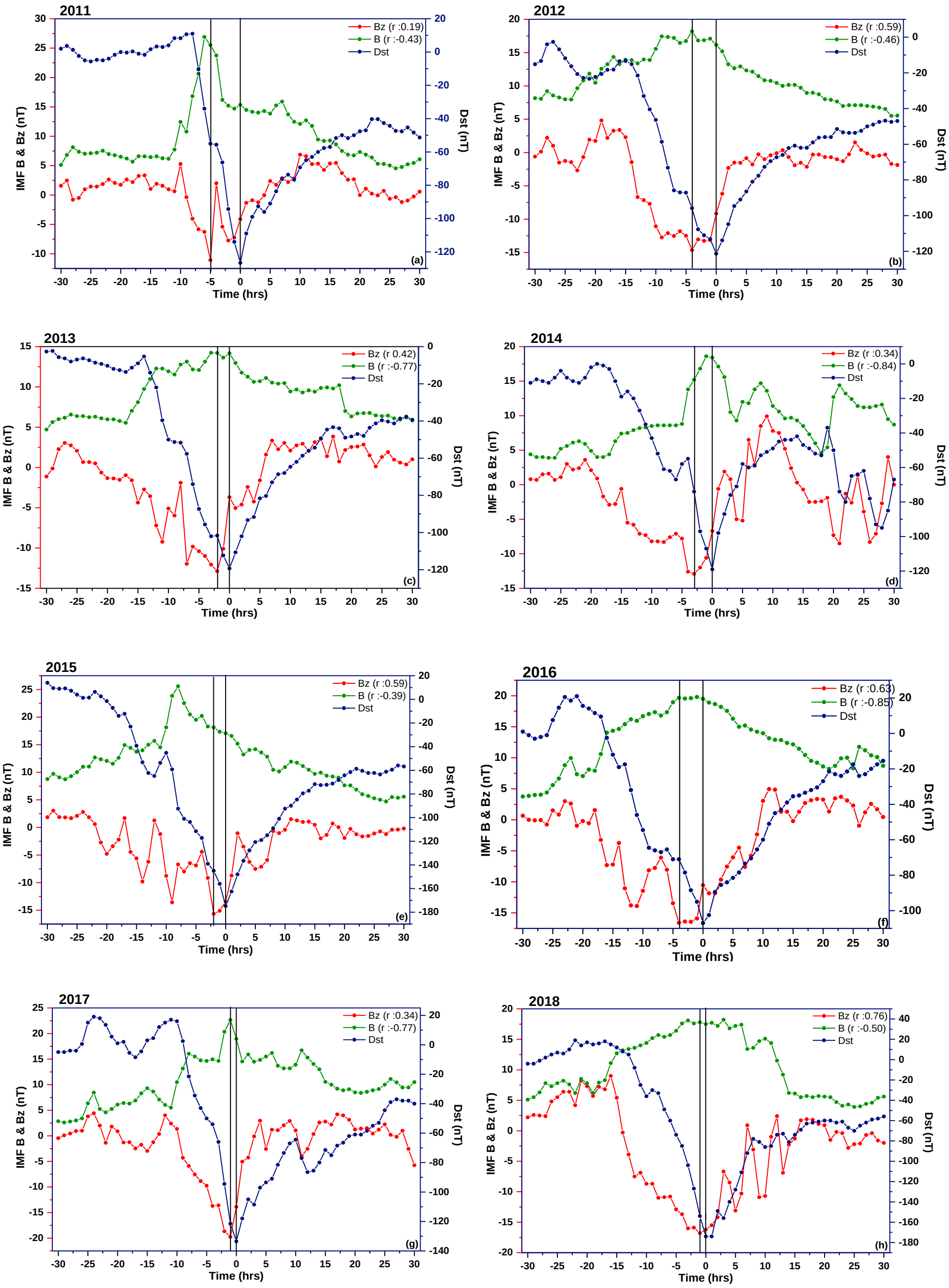
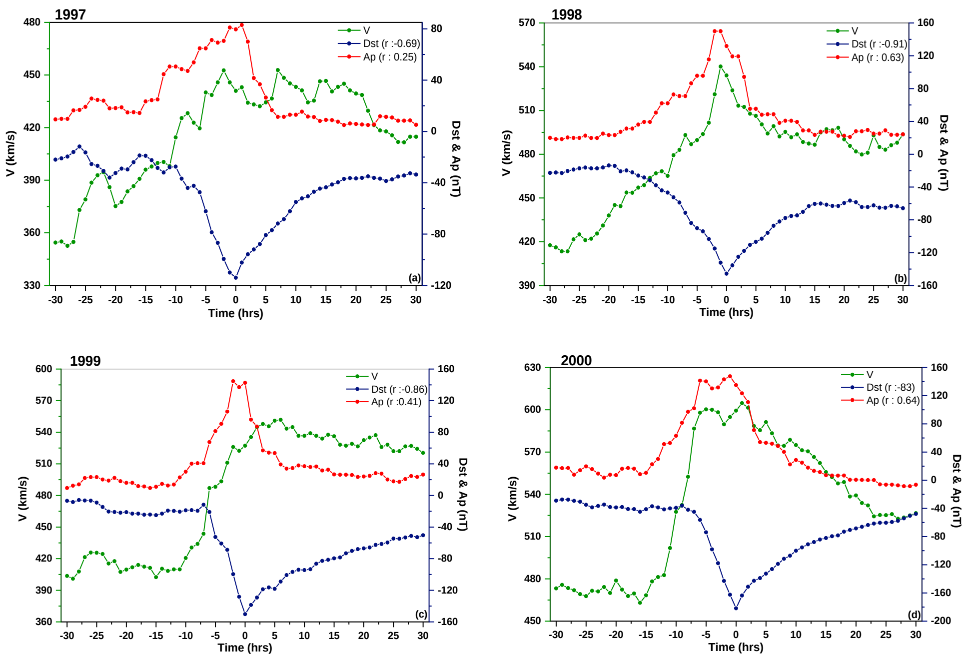


Fig. 2. The superposed epoch results range from -30 to +30 hours with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst with respect to IMF B and Bz mean values for the period spanning 2011 to 2018. The vertical lines depict the time lag between Bz and Dst.

3.2. *Solar wind speed (V) and GSM*

It is widely known that the solar wind velocity is a potential variable for geomagnetic activity, which is the consequence of a complicated interaction process between the solar wind and the magnetosphere. The compression and depression in the magnetosphere are supposed to be dependent on the bow shock, so the linear relationship between solar wind velocities and Dst is expected. Figs. 2(a-j) and 3(a-h) show the variation of Dst and Ap with the corresponding value of V at the instant of Dst minimum as zero epoch. The correlation coefficient of V with Dst for SC 23 and 24 was 0.71 and 0.58, respectively. As solar wind velocity increases, the Dst index tends to decrease, whereas the correlation between V and Ap index is low, with values of 0.50 and 0.31 for SC 23 and 24, respectively. Our study further observed that during SC 23, most of the time Dst showed high correlation with V except for the years 2001, 2003, and 2006, whereas during SC 24, the trend was different. Only the years 2011, 2014, 2015, and 2017 showed a high correlation, and the rest of the years did not correspond to the depression peaks of Dst. The solar wind speed ranged from 300 to 900 km/s, and the study concluded that 80 % of the intense GMSs during SC 23, whereas only 50 % of the intense GMSs during SC 24, were associated with significant solar wind speeds. Finally, our findings are in agreement with previous studies [2,36].



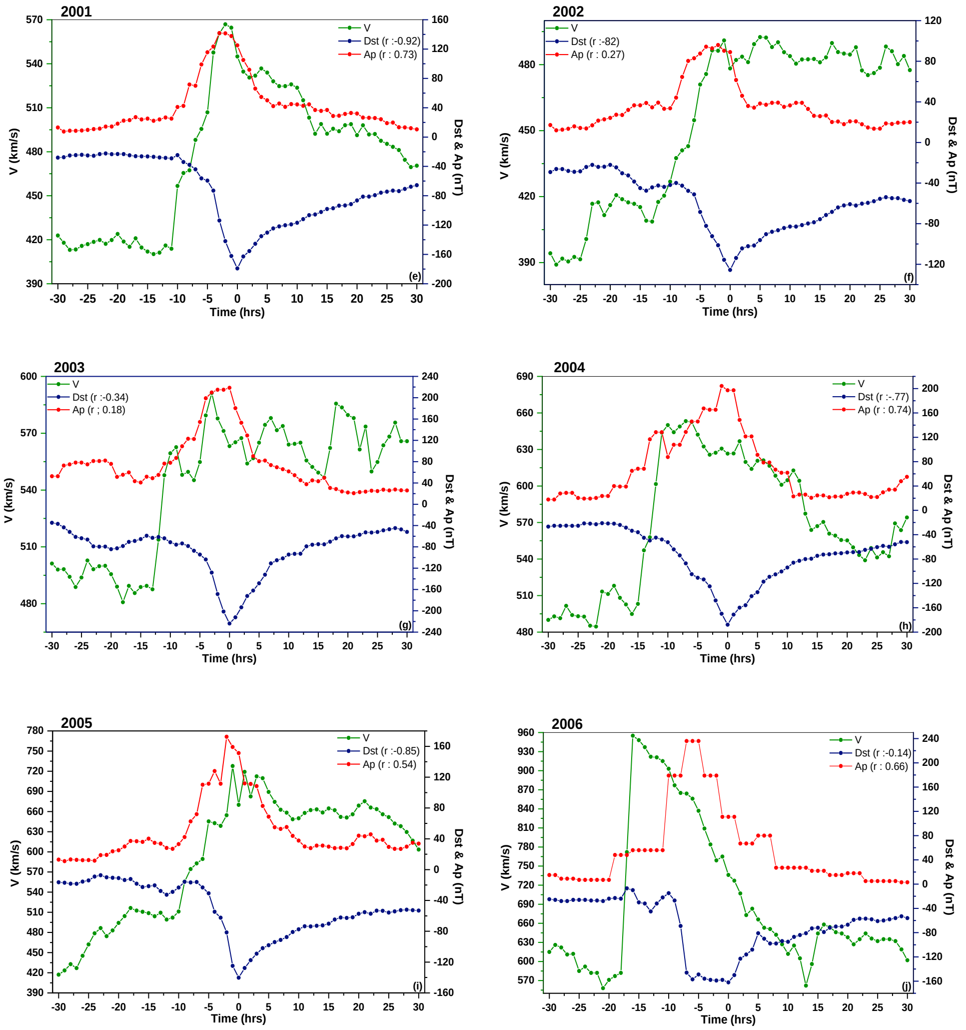


Fig. 3. The superposed epoch results range from -30 to +30 h with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst & Ap with respect to V mean values for the period spanning 1997 to 2006.

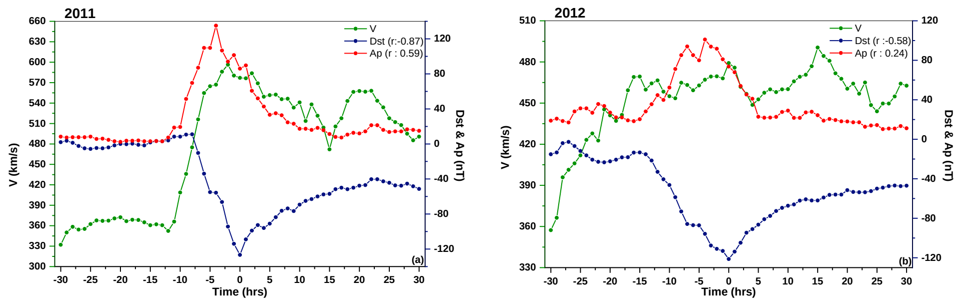


Fig. 4. The superposed epoch results range from -30 to +30 h with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst & Ap with respect to V mean values for the period spanning 2011 to 2018.

3.3. *BV, BzV and GMS*

The investigation of the variation of Dst with the solar wind speed and the IMF B, Bz, revealed that the correlation of Dst with V and the IMF B is high, whereas it exhibits a low correlation with the southward component of the IMF Bz. The study also examined the variation of Dst with the product of IMF B, Bz, and V, as shown in Figs. 4(a-j) and 5(a-h). We found that Dst and BV have an anti-correlation coefficient for SC 23 and SC 24, with average values of -0.64 and -0.66, respectively. The findings are in agreement with previous studies conducted by Wang *et al.* [37] and Rathore *et al.* [38], which demonstrated acceptable anti-correlation coefficients of BV with Dst, rendering it the more geoeffective parameter for generating GMS in comparison to B alone.

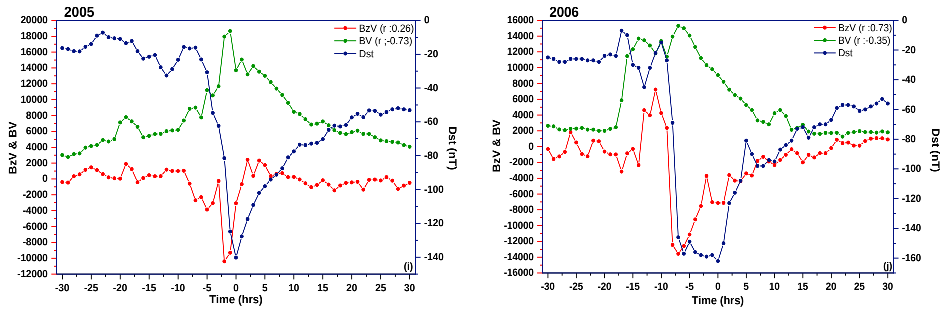
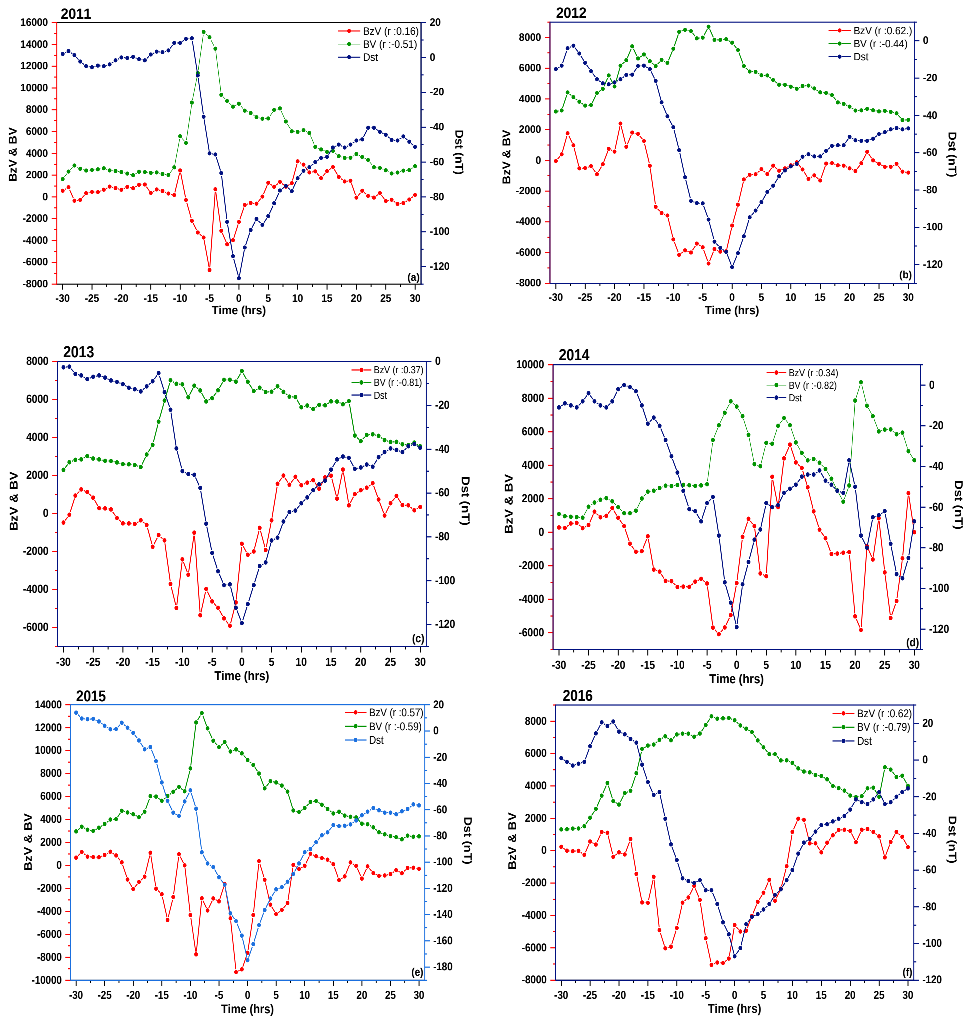


Fig. 5. The superposed epoch results range from -30 to +30 h with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst with respect to BV and BzV mean values for the period spanning 1997 to 2006.



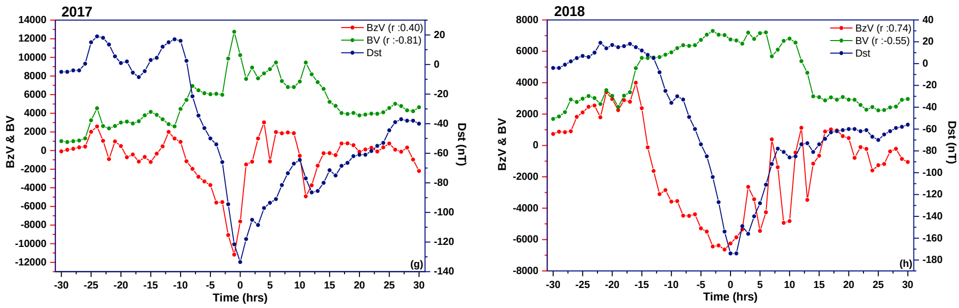


Fig. 6. The superposed epoch results range from -30 to +30 h with respect to the occurrence hour of GMS (zero epoch). The graph depicts the variation of the mean value of Dst with respect to BV and BzV mean values for the period spanning 2011 to 2018.

The study also found that, as Dst tends to decrease with BzV, the strongest decrement in BzV occurs before the occurrence hour of the GMS. The correlation coefficient of Dst with BzV is comparatively low, with values of +0.40 for SC 23 and +0.47 for SC 24. They are consistent with findings of Rathore *et al*. [32], but show a contradiction with earlier findings, which showed high correlation and made BzV more geoeffective than Bz and V alone [28,35,39,40]. Therefore, it can be inferred that BV is a more effective parameter for generating GMS in comparison to B alone. Furthermore, despite the low correlation between Dst and BzV, it cannot be ruled out as a good geoeffective parameter.

4. Conclusion

Based on the analysis of geomagnetic storms (Dst ≤ 100 nT) and interplanetary parameters from 1997 to 2006 and 2011 to 2018 for solar cycle 23 and 24, several important results have been summarized.

The occurrence rate of geomagnetic storms was higher during SC 23 compared to SC 24.

The strength of the GMS, (Dst index) is strongly anti-correlated with the IMF B, with an average value of -0.60 for both the solar cycle.

The relationship between Dst and the southward magnetic field component Bz is not as strong as previously thought, with an average correlation coefficient of 0.42 for solar cycle 23 and 0.47 for solar cycle 24. The time lag between Bz minimum and Dst minimum was found to be up to 5 h, indicating that the significant growth in Bz occurs before the main phase of the GMS and not during the main phase.

Dst shows a higher correlation with solar wind speed V during solar cycle 23 (-0.71) than during solar cycle 24 (-0.58). The Ap index, another indicator of geomagnetic activity, exhibits a lower average correlation coefficient with V for both solar cycle 23 (0.51) and solar cycle 24 (0.31). The study also found that 80 % and 50 % of the intense geomagnetic storms during solar cycles 23 and 24, respectively, are associated with large values of solar wind speeds.

The correlation coefficient between Dst and Ap index for solar cycle 23 was found to be -0.62, which is less than solar cycle 24 (-0.72), indicating that the Ap index is also a geoeffective parameter.

Dst shows a reasonable anti-correlation with BV (the product of IMF B and solar wind speed V) than with B alone. However, the correlation between Dst and BzV (the product of Bz and solar wind speed V) is found to be low.

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