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Geomagnetic Storms in Relation to Magnetic Clouds, Hard X-Ray Solar Flares, and Disturbances in Interplanetary Magnetic Fields During 1996-2008

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Abstract

Geomagnetic storms ≤-50nT observed during the period of 1996-2008 with X-ray solar flares, magnetic clouds, interplanetary magnetic fields (IMF) and southward component of interplanetary magnetic fields (IMF Bz) have been studied. 224 geomagnetic storms of defined criteria, out of which 198 (88.39%) are found to be associated with hard X-ray solar flare, have been determined. The association rates of X-class, M-class, C-class, B-class, and A-class X-ray solar flares are 11.61%, 28.28%, 38.88%, 14.64%, and 6.56%, respectively. 133 out of 224 (59.38%) geomagnetic storms are associated with magnetic clouds (MC) of varying quality. The association rates for Excellent, Good, and Poor-quality magnetic clouds are 24.06%,58.64%, and 17.29%, respectively. Further, all the geomagnetic storms are found to be associated with disturbances in interplanetary magnetic fields, and a strong positive correlation with a correlation coefficient 0.79 has been found between the magnitude of geomagnetic storms and the maximum value of IMF disturbances. A large positive correlation with correlation coefficient 0.77 has been found between the magnitude of geomagnetic storms and the maximum value of IMF Bz disturbances during 1996-2008.

Keywords: - Geomagnetic storms, X-ray solar flare, Magnetic clouds, Interplanetary magnetic fields and Southward component of interplanetary magnetic fields.

1. Introduction

Geomagnetic storms are very huge disturbances in the magnetospheric plasma populations and electrical flows that occur during periods of enhanced solar wind-magnetosphere energy coupling (Akasofu, 1981, Echer et al., 2008, Echer et al., 2013, Gonzalez and Echer, 2005; Gonzalez et al., 1994, Gonzalez et al., 2011, Lakhina and Tsurutani, 2016, Rawat et al., 2018, Hajra et al., 2021,). These disturbances are categorized by a main phase during which the horizontal constituent of the Earth's magnetic field restrained at low-latitude observatories is meaningfully depressed over an intermission of one to a few hours trailed by its recovery phase which may spread from numerous hours to several days (Gonzalez et al., 1994). Geomagnetic storms are classified rendering to strength of Dst into four classes, namely weak (-30 minimum of Dst > −50 nT), moderate (−50 nT > minimum of Dst > −100 nT), intense (−100 nT > minimum Dst > −250 nT) or super-storm (minimum of Dst < −250). There are two kinds of geomagnetic storms on the basis of their *Dst* profile and interplanetary drivers. They can be either sudden storms, when produced by interplanetary coronal mass ejections (ICMEs) and/or their driving shocks, or gradual storms triggered by corotating interaction regions (CIRs) (Gonzalez et al., 1994, Gonzalez et al., 2011, Tsurutani et al., 1997, Echer et al., 2008, Echer et al., 2013). In some revisions, statistical analysis of geomagnetic storm and solar wind plasma parameters such as solar wind plasma velocity, density pressure and interplanetary magnetic fields has been performed (Balan et al., 2014, Balan et al., 2017a, Balan et al., 2017b, Balan et al., 2021, Selvakumaran et al., 2016) and a very close connection between geomagnetic storms and instabilities solar wind plasma parameters has been obtained. CMEs in the IP space (ICMEs) is known to give rise to the most intense geomagnetic storms (Tsurutaniet al 1997). Wu et al 2016 defined a sudden decrease in their Dst profile compared to the gradual GSs caused by corotating interaction regions (CIRs) (Borovsky et al. 2006). Such fast ICMEs are usually related to shocks promulgating ahead of the magnetic ejecta acting as the driver of the wave. Both shock waves and magnetic ejecta yield a cascade of procedures in near-Earth space interfering with modern technology (Pulkkinen et al. 2007). Earth-directed fast ejecta has the potential to be the most geo-effective. In addition, CMEs farm a strong negative, i.e., southward directed magnetic field component, cause the toughest geomagnetic storms. Rawat et al. (2018) have studied the reasonable analysis between the two consecutive solar cycles 23 and 24. They found out that both the cycles displayed dual highest feature as pragmatic in the flattened sun spot numbers SSN smoothed version. The southward directed Bz and dawn-dusk electric field (Ey) were reliably weaker for sc-249 December 2008-December 2016) as compared to SC-23(may 1996-July 2004); the geomagnetic field response characterized by Dst index simultaneously displayed similar disparity patterns during both the stages; moderate storm incidence was reduced only by 32% in SC-24 as equated to SC-23, Al-Feadh et al (2019) have calculated the solar magnetic storm for the period (2010-2017) allied with disturbance geomagnetic storm intensity less than (-50nT). They have determined 50 great solar magnetic storms, 32 were moderate, 16 were strong, and two were severe. The major severe storm occurred on 17th march in 2015 with (Dst= -223nT). The most of CME that initiated the geomagnetic storms have visual width of 360 degree, and with sky plane speed around 350-2500 km/s. There is a better correlation for sunspot number than CME sky plane with Dst index. Watari et al. (2017) have briefly presented certain results obtained up to now by the Russian scientific groups regarding powerful solar ejections as the main reasons of geomagnetic disturbances in the near-Earth space. They have inferred that the strongest perturbations on the Sun and in the near-Earth space are accountable for large geomagnetic disturbances. In this examination, geomagnetic storms $\leq 50nT$ were observed during the period of 1996-2008 with hard X-ray solar flares, magnetic clouds and interplanetary agnetic field also with south ward component of interplanetary magnetic fields to explore the characteristic features of geomagnetic storms.

2. Data Reduction and Analysis

In this research, geomagnetic storms Dst $\leq$-50nT with hard X-ray solar flares, magnetic clouds, interplanetary magnetic fields (IMF) and southward component of interplanetary magnetic fields (IMF Bz) has been examined for the period of 1996-2008). For this work, the SOHO large angle spectrometric, coronagraph (SOHO / LASCO), and extreme ultraviolet imaging telescope (SOHO/EIT) data are the sources of data of hard X-ray solar flares. For magnetic cloud/ejecta data, the ACE list of transients and disturbances is used. To determine the disturbances in geomagnetic fields and solar wind plasma parameter, interplanetary magnetic fields and southward component of interplanetary magnetic fields, hourly data of Dst index and interplanetary magnetic fields, southward component of interplanetary magnetic fields have been utilized. These data have been obtained from omni web data(http;//omniweb.gsfc.nasa.gov/form/dxi.html)).

3. Data Analysis and Results

3.1. Analysis of Geomagnetic Storms with X-Ray Solar Flares During 1996-2008

Solar flares (SF) and coronal mass ejections (CMEs) are the most explosive phenomena in the solar system. During these explosions, the emitted radiation and particles can lead to disturbances in the Earth-space environment. Both flares and CMEs are supposed to be the consequence of an explosive release of energy from the active regions in the solar outer atmosphere. A solar flare is defined as the transient brightening on the solar surface detected in the H∝ emission line (λ= 656.3 nm). This explosion of energy discharges electromagnetic releases from and X-rays to radio waves. In the emission line Hα, flares normally appear as two ribbon-like bright areas, known as a two-ribbon flare. X-ray flares are classified according to the order of magnitude of the geostationary operational environmental satellite (GOES) X-ray (0.1- 0.8 nm) peak burst intensity, I (Wm^{-2}), measured on the Earth. The following is an X-ray flares classification with corresponding energy range in 1-Class B with I < 10^{-6}, 2-Class C with $10-6 \leq I \leq 10^{-5}$, 3-Class M with $10-5 \leq I \leq 10^{-4}$, 4-Class X with $I \geq 10^{-4}$. In this section geomagnetic storms with hard X-ray solar flares have been studied. Data analysis of geomagnetic storms and X-ray solar flares during 1996-2008 solar revealed that 224 geomagnetic storms were observed, and most of the 198 out of 224 (88.39%) of the geomagnetic storms were associated with various categories of X-ray solar flares. The association rates of X-class, M-class, C-class, B-class, and A-class X-ray solar flares are 11.61%, 28.28%, 38.88%, 14.64, and 6.56%, respectively. This indicates that most geomagnetic storms closely observed are associated with M- and C-class solar flares.

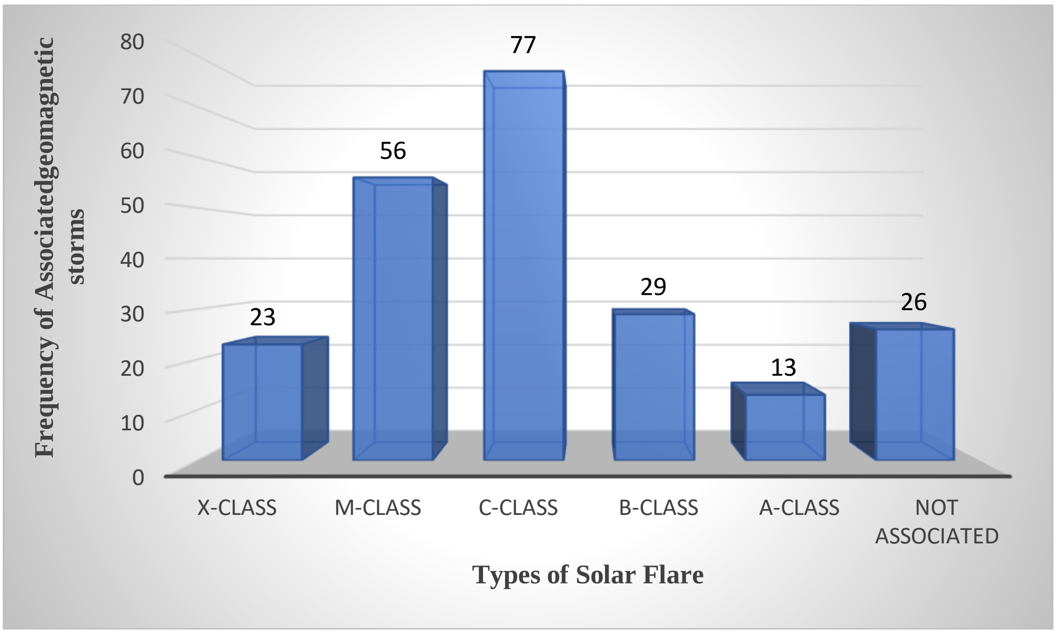

Figure-1 Bar diagram of types of solar flares and frequency of associated geomagnetic storms during the period of 1996-2008.

3.2. Statistical Relation Between Geomagnetic Storms and Magnetic Clouds During 1996-2008

A magnetic cloud is a momentary ejection in the solar wind that is defined by relatively strong magnetic fields, a large and smooth rotation of the magnetic field direction over approximately 0.25AU at 1AU, and a low proton temperature. An MC is also characterized by in situ observations of an enhanced magnetic field strength with respect to ambient values, a smooth and high rotation of the magnetic field vector, and low proton temperature. The observed coherent rotation in MCs is interpreted as the passage of a large-scale twisted magnetic flux tube through the spacecraft. In this part of the study, geomagnetic storms with magnetic clouds have been associated. Data analysis of geomagnetic storms and magnetic clouds during the period of 1996-2008 indicates that 133 of the 224 (59.38%) of geomagnetic storms are associated with magnetic clouds of varying quality. The association rates for Excellent, good, and poor magnetic clouds are 32 out of 224 (24.06%), 78 out of 224 (58.64%), and 23 out of 224 (17.29%), respectively. From these results, it can be concluded that the majority of the geomagnetic storms are associated with good quality magnetic clouds.

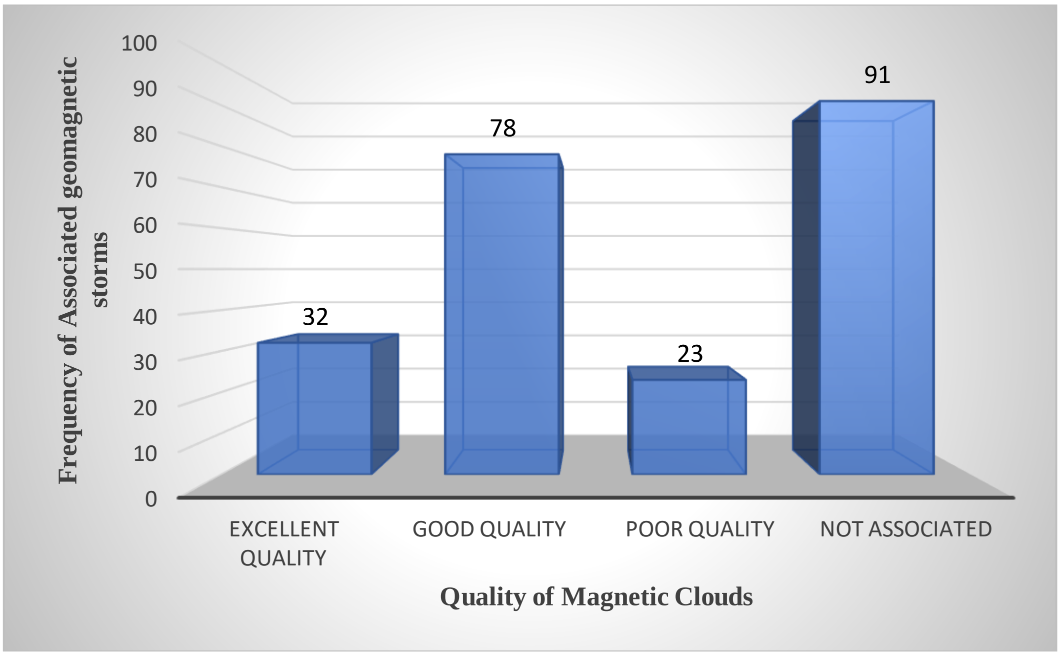

Figure-2 Quality of magnetic clouds and frequency of associated geomagnetic storms during the period of 1996-2008.

3.3. Correlation Between Magnitude of Geomagnetic Storms and Maximum Value of Disturbances in Interplanetary Magnetic Fields During 1996-2008

The interplanetary magnetic field (IMF), now more commonly referred to as the heliospheric magnetic field (HMF), is the component of the solar magnetic field that is dragged out from the solar corona by the solar wind flow to fill the solar system. In this section, geomagnetic storms Dst $\leq -50nT$ with disturbances in interplanetary magnetic fields during the period of 1996-2008 have been analyzed. From the data analysis, it is observed that all the geomagnetic storms are associated with disturbances in interplanetary magnetic fields (IMF) .To know the statistical behavior of magnitude of geomagnetic storms and maximum value of associated disturbances in interplanetary magnetic fields and also to see that how the magnitudes of geomagnetic storms are correlated with maximum value of interplanetary magnetic fields disturbances events, a scatter diagram between the magnitude of geomagnetic storms and maximum value of disturbances in interplanetary magnetic fields events has been plotted as shown in fig. 3. It is clear from the figure that most of the geomagnetic storms which have large magnitude are associated with such disturbances in interplanetary magnetic fields events which have large maximum value. Yet the magnitude and maximum value of these two events do not have any fixed proportion. Some geomagnetic storms which have large magnitude have been found yet they are associated with such disturbances in interplanetary magnetic fields events which have small maximum value. Also, some geomagnetic storms have small magnitude, yet they are associated with interplanetary magnetic fields disturbances events having large maximum value. These results indicate, that although these events do not have any quantitative relation, the geomagnetic storms of higher magnitude are generally associated with such interplanetary magnetic fields disturbances events which have relatively higher maximum value. A strong positive correlation with correlation coefficient 0.79 has been found between the magnitude of geomagnetic storms and the maximum value of IMF disturbances during the solar cycle 23.

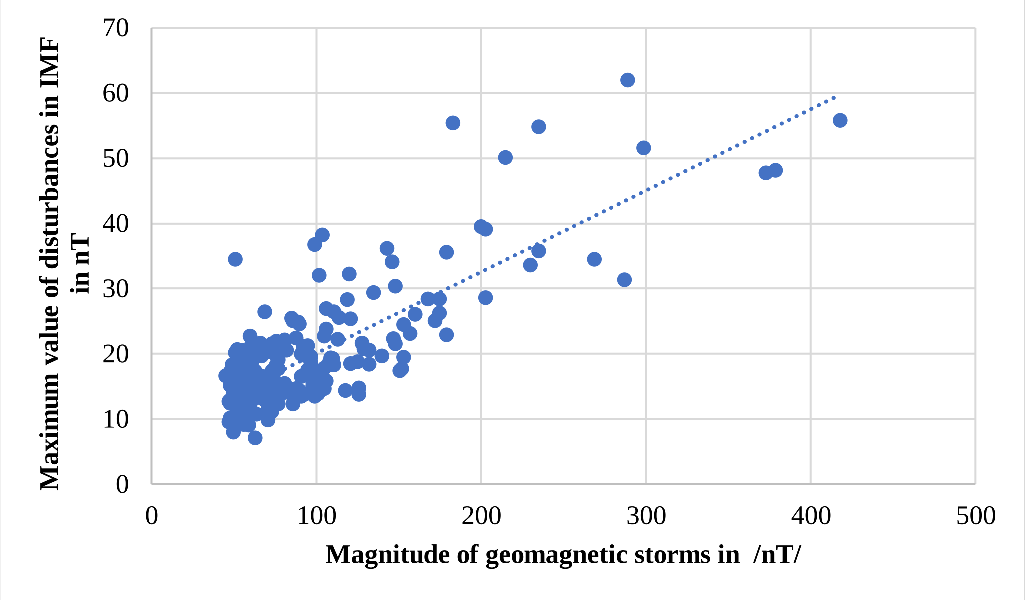

Figure-3 The scatter plot between the magnitude of geomagnetic storms and the maximum value of interplanetary magnetic fields (IMF) disturbances events during the period of 1996-2008.

3.4. Correlation Between Magnitude of Geomagnetic Storms and Maximum Value of Disturbances in Southward Components of Interplanetary Magnetic Fields During 1996-2008

From the data analysis, it is observed that all the geomagnetic storms are associated with disturbances in southward component of interplanetary magnetic fields. To see how the magnitudes of geomagnetic storms are correlated with maximum value of disturbances in southward components of interplanetary magnetic fields events during the period of 1996-2008, a scatter diagram between the magnitude of geomagnetic storms and maximum value of disturbances in southward components of interplanetary magnetic fields (IMF Bz) events has been plotted as shown in fig. 4. It is clear from the figure that most of the geomagnetic storms which have large magnitudes are associated with such disturbances in southward components of interplanetary magnetic fields events which have large maximum value, yet the magnitude and maximum value of these two events do not have any fixed proportion. Also, some geomagnetic storms which have large magnitude, but are associated with such disturbances in southward components of interplanetary magnetic fields events which have small maximum value and some geomagnetic storms which have small magnitude but are associated with such southward components of interplanetary magnetic fields events having large maximum value have been found. These results indicate that although these events do not have any quantitative relation, the geomagnetic storms of higher magnitude are generally associated with such disturbances in southward components of interplanetary magnetic fields events which have relatively higher maximum value. A strong positive co-relation with correlation coefficient 0.77 has been found between the magnitude of geomagnetic storms and maximum value of IMF Bz disturbances during the period of 1996-2008.

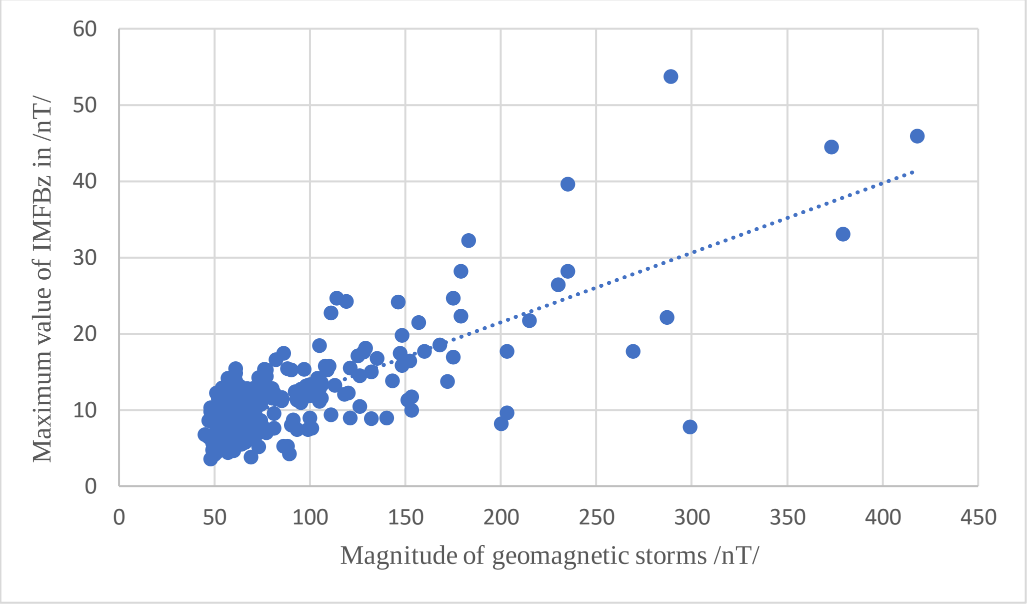

Figure-4 The scatter plot between the magnitude of geomagnetic storms and the magnitude maximum value of disturbances in southward components of interplanetary magnetic fields (IMF Bz) events during the period of 1996-2008.

4. Main Results

1- Geomagnetic storms $\leq -50nT$ observed during the period of 1996-2008 with X-ray solar flares, magnetic clouds and interplanetary magnetic fields and southward component of interplanetary magnetic fields have been studied. 224 geomagnetic storms of defined criteria, out of which 198 (88.39%) are found to be associated with hard X-ray solar flare have been determined.
2-133 out of 224 (59.38%) geomagnetic storms are associated with magnetic clouds of varying quality. The association rates for Excellent, Good, and Poor-quality magnetic clouds are 24.06%,58.64%, and 17.29%, respectively.
3- A strong positive correlation with a correlation coefficient 0.79 has been found between the magnitude of geomagnetic storms and the maximum value of IMF disturbances.
4- A large positive correlation with correlation coefficient 0.77 has been found the between magnitude of geomagnetic storms and the maximum value of IMF Bz disturbances during 1996-2008.

5.0. Conclusion

From this study, it is concluded that hard X-ray solar flares which are signature of occurrences of coronal mass ejections are energetic solar phenomena wherein large numbers of solar material are ejected from the Sun, thus resulting in perturbations in measurements of solar wind plasma parameters, including interplanetary magnetic fields and southward component of interplanetary magnetic fields. Hard X-ray solar flare which are signature of occurrences fast CMEs associated with solar flares play an important role in the formation of geomagnetic storms. This study further shows that most of the geomagnetic storms are associated with magnetic cloud of different categories and disturbances in interplanetary magnetic fields including disturbances in southward component of interplanetary magnetic fields. As such it can so it may conclude that the main interplanetary structures that cause strong southward Bz are the high-velocity shock-induced magnetic cloud (MC), the mantle field (Sh), and the combined mantle-MC field (Sh+MC) that causes the co-rotating interaction region (CIR). Finally, these interplanetary structures are the major cause of the magnetic storm.

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Conflict of Interest

The Authors declares that there is no conflict of interest in this manuscript.

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