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Study of Energy Injection during Intense and Super Intense Geomagnetic Storm Driven by Coronal Mass Ejection (CME)

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Abstract
We have studied the energy injection process associated with CME driven storms that occurred during 18th February 1998, 4th May 1998, 16th July 2000 and 20th November 2003. The energy injection efficiency was parameterized by the ε parameter as a measure of the energy transfer of solar wind into the magnetosphere; we observed that intensification of ring current (Dst) depends on the energy injection into the magnetosphere and the duration of a particular CME event. In the same vein, we discovered that large geomagnetic storm was more associated with large time difference ($T_{diff.}$) between the peak of storm and peak of energy injection.

Keywords: *Geomagnetic storm, coronal mass ejection, ring current*

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INTRODUCTION
Coronal Mass Ejections (CME_S) are spectacular energetic events in the solar corona that expel plasma and magnetic fields into the solar wind. Manifestation of coronal mass ejections from the sun, are frequently observed in the solar wind near earth and are commonly called interplanetary coronal mass ejection (ICME). ICMEs are also called ejecta, which could be either magnetic clouds (MC) or noncloud ejecta. CME_S are associated with flares, filaments eruptions, shocks, radio bursts, solar energetic particle (SEP) events and have been found to be the primary cause of geomagnetic disturbances. Contemporarily, it is still a topic under deliberation. Actually, geomagnetic storms are caused by coronal mass ejections (CMEs) or other events; even though it has been proved that both of them are correlated. CMEs are the dominant interplanetary phenomena that cause magnetic disturbance of the earth. The CMEs, depending on their shock front velocities, can compress the dayside magnetosphere up to a few earth radii, but their geo-effectiveness is more associated with an intense southward interplanetary magnetic field (IMF) component which permits an efficient transfer of energy from the perturbed solar wind to the earth magnetosphere through magnetic reconnection [1]. Geomagnetic storm events are characterized by disturbance storm time (Dst) index.

A recent study by Benacquista *et al.* examined the dynamics of magnetic storms due to interplanetary coronal mass ejections [2]. They used multi-epoch superposed epoch analysis with choice of epoch times based on the structure of the events. Their result shows that the presence of a shock drives the geoeffectiveness of the sheaths, while both the shock and magnetic structure impact the geoeffectiveness of the ICME. With great appreciation to the large angle spetrometric coronagraph on board the Solar Heliospheric Observatory (LASCO/SOHO), a range of investigations has been performed on the geoeffectiveness of CMEs and the association of geomagnetic storm and CMEs.

DATA SELECTION
In this work, only geomagnetic storms of Dst index with peak≤–100nT (and above) were considered. These storms are referred to as intense geomagnetic storms. This is based on the classification given by Gonzalez *et al*. that a storm is said to be intense if (Dst≤–100nT), moderate if (Dst≤–50nT), small if (Dst≤–30nT) [3]. The storms used in this paper were

identified from the list of intense geomagnetic storms published by Pandey and Dubey and Milos *et al.* [4, 5].

THEORY OF SOLAR WIND ENERGY INJECTION PARAMETER (COUPLING FUNCTION)

The impact of solar activities on the space and land based technologies has become a major challenge and scientists are working to proffer solutions to mitigate the problem. At present, there are no direct observational means of determining the total rate at which energy is extracted from the solar wind by the magnetosphere. In the absence of such a direct measurement, alternative means of estimating the energy available to drive the magnetospheric system have been developed using different ionospheric and magnetospheric indices as proxies for energy consumption and dissipation. The coupling functions are constructed from the parameters of the interplanetary medium as either theoretical or empirical estimates of energy transfer, and the effectiveness of these coupling functions has been evaluated in terms of their correlation with the chosen index [6]. The Epsilon Parameter (ε) is one of the most commonly used coupling functions; it was originally developed in the 1970s. The Epsilon Parameter (ε) depends on the solar wind speed, the IMF intensity B, and clock angle θ of the IMF which is perpendicular to the Sun-Earth line [6–8]. The Epsilon Parameter has turned out to be a very useful tool in energy injection analysis and has survived unmodified for many years of increased understanding of magnetic storms and magnetospheric substorms [9]. One of the attractive features of the epsilon parameter is that it quantifies the energy input into the magnetospherein terms of power. The Epsilon Parameter ε (given by Eq. (1)) expresses the planetary energy flux in terms of poynting flux and it is strongly associated with the energy consumption in the inner magnetosphere [6].

$$\varepsilon = \frac{/E//B/}{4\pi}\sin^4\left(\frac{\theta}{2}\right)l_0^2 \qquad (1)$$

The Epsilon value can be simplified as:

$$\varepsilon = \frac{VB^2}{4\pi}\sin^4\left(\frac{\theta}{2}\right)l_0^2 \qquad (2)$$

Where, V is the solar wind velocity and l_0 is a representative length of the coupling area available for solar wind magnetospheric interactions. We have used the representative optimized length of $7R_E$ [6]. Where, B is the total magnetic field intensity obtained, the clock angle θ is obtained. The storms were analyzed individually and the hourly estimate for the energy injection was calculated. Considering the individual storm's duration with time interval between main phase onsets (MPOs) and Dst peak as identified in Figure 1. The energy dissipation at the magnetosphere is calculated after Balan *et al.* [10].

$$T_{diff} = \text{Peak time of Dst} - \text{Peak time of } \varepsilon \qquad (3)$$

To obtain the peak of the ε parameter coincident with the observation of geomagnetic storm, we fit the time series of the ε parameter with a Gaussian and calculated the T_{diff} between the peak of geomagnetic storm and ε peak. Summary of our results for the four individual storms are presented in Table 1 and Figures 1–4.

RESULT PRESENTATION

Table 1 shows both observed and analytical features of CME driven storms. Column 1 shows the serial number of geomagnetic storm events, column 2 also shows the event date. Column 3 shows the storm driver; column 4 indicates the initial phase of storms while column 5 shows Dst peak. Column 6 is the change in Dst (i.e., Dst peak-initial phase of storm). Colum 7 shows the peak values of energy ejection (ε), column 8 indicates the time of initial phase of storm and column 9 shows time of Dst peak, and column 10 indicates the time of ε peak while column 11 shows the time difference between ε peak and Dst peak. Finally, column 12 shows the energy dissipated in the magnetosphere. In other words, Figure 1 shows clear plots of CME driven storms where ε peak and Dst peak were compared, indicates geomagnetic storm that occurred 9 h before the peak of ε parameter, the geomagnetic storm that occurred at the same time with the ε parameter, the geomagnetic storm that occurred 4 h after the ε parameter.

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Table 1: *Shows Both Observed and Analytical Features of CME Driven Storms.*

s/n	Date of Storm Event	Initial Phase of Dst (nT)	Dst Peak (nT)	Change in Dst (nT)	(ε) Value (GW)	Time of Initial Phase of Storm (h) UT	Time of Dst Peak (h) UT	Time of (ε) peak (h) UT	Time Diff. of Dst and (ε) Value (h) UT
1	18-Feb-98	14	–100	–114	5499	12	1+	10+	–9
2	4-May-98	–60	–205	–145	8210	1+	6+	6+	0
18	16-Jul-00	7	–301	–308	13500	16	1	21	4
54	20-Nov-03	-17	-422	-405	68450	8+	21+	17+	4

+ Indicates Addition of 24 h.

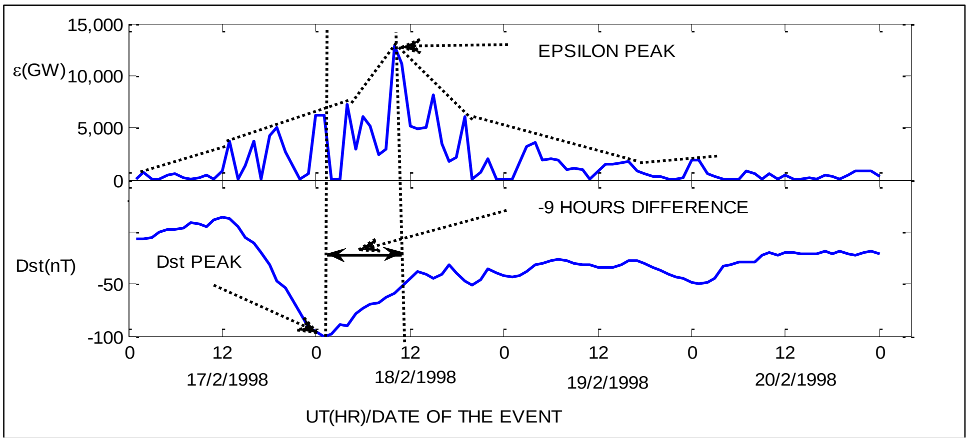

Fig. 1: *A Plot of CME Driven Storm where Peak of Geomagnetic Storm Occurred 9 h before the Peak of ε Parameter.*

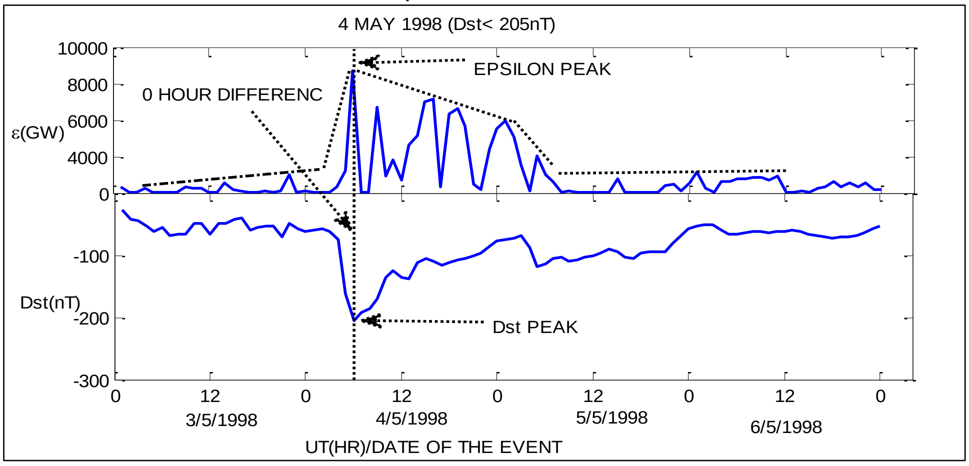

Fig. 2: *A Plot of CME Driven Storm where Peak of Geomagnetic Storm Occurred 0 h with the Peak of ε Parameter.*

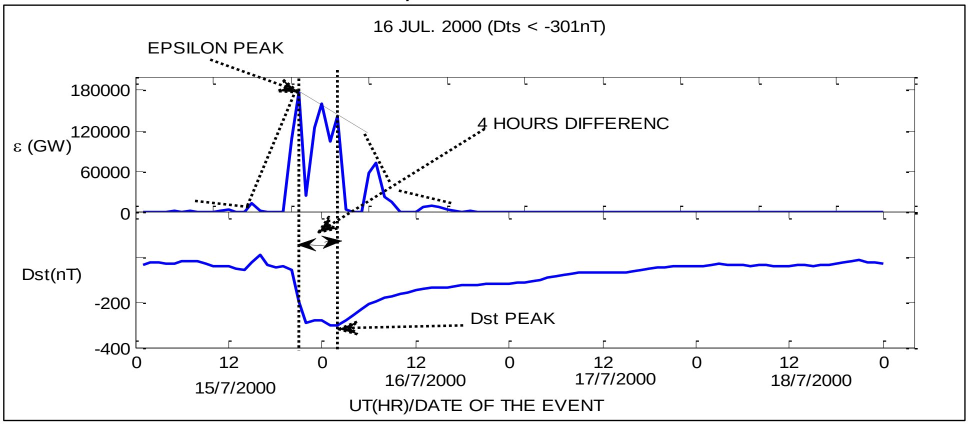

Fig. 3: *A Plot of CME Driven Storm where Peak of Geomagnetic Storm Occurred 4 h after the Peak of ε Parameter.*

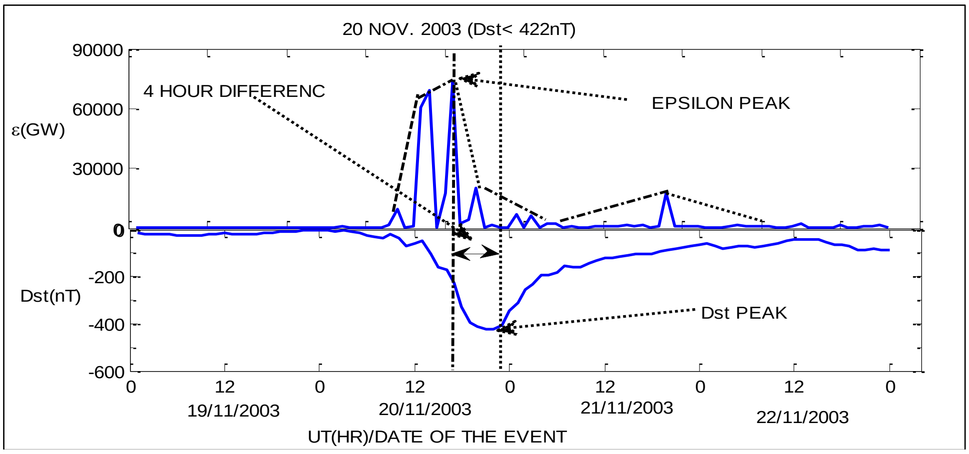

Fig. 4: *A Plot of CME Driven Storm where Peak of Geomagnetic Storm Occurred 4 h after the Peak of ε Parameter.*

DISCUSSION

Energy Injection Processes

The Epsilon Parameter (ε) is a model that quantifies the energy injection into the magnetosphere. The individual properties of the observed geomagnetic storms in relation to the energy injection are the main focus of this work. In other words, we seek to search for the key features of energy injection during geomagnetic storms driven by CMEs.

Results for each of these storms are presented in Table 1, and Figures 1–4. A total of four CME driven storms were individually analyzed to better appreciate the unique features of such storms vis-a-vis the energy injection processes during these storms. The CME driven storms considered here have Dst peaks of ≤–100nT and were shown to exhibit the well known signature of geomagnetic storms. The time difference between the peaks of energy injection and Dst peak does not necessary coincide. Only one event did coincide (i.e. 4th May 1998 storm event). There appears to be a consistency in the relationship between the storms and energy injection, in which large storms have greater energy injection, but this association is not likely linear and would require a bulk study of their association. Nevertheless, these observations tend to confirm earlier works, which revealed that largest geomagnetic storms are caused by extraordinary increase in the solar wind velocity and/or southward interplanetary magnetic field (IMF) produced by coronal mass ejection (CME) and their associated interplanetary shocks [11–13]. Therefore, the intensity of storm can directly serve as an indication of extent of energy input.

Figure 1 shows the ε parameter profile for 18th February 1998 storm along with the signature of the geomagnetic storm. The peak of the geomagnetic storm appears to occur before the peak of the energy injection. This could be a special feature of intense storms (–100nT≤–200nT) and likely linked to the early arrival of shock waves to the vicinity of the earth. This particular storm conforms to the findings of Tappin and Howard and Benacquista *et al.* [2, 14], which revealed that CME driven storms are supersonic, and so will form a shock that gains in strength as the transient evolves through the heloisphere. In the same vein, Benacquista *et al*. revealed that the presence of a shock drives the geoeffectiveness of the sheaths, while the shock and magnetic structure impact the geoeffectivess of the interplanetary coronal mass ejection [2]. In other words, we observed large discrepancies between the time peak of energy injection and storm peaks. The 4th May 1998 storm was more intense (having higher Dst peak and higher ε peak). There was no T_{diff} between the peak of the Dst and ε parameter, suggesting coincident cause-effect scenario. Figure 3 shows the 16th July 2000 storm. The Dst peak was –301nT and this occurred 4 h after the peak of the ε parameter. This storm while showing the classical signature of CME driven storm was characterized by two peaks during the maximum intensity period. The energy injection tends to switch on and off at an interval while the Dst profile tends to respond to the energy injection by a short recovery, giving the storm too small peak during the maximum. In Figure 4, we see a super storm that occurred on 20th November 2003; this storm had a magnitude of –422nT. The peak of ε value was 68450. The T_{diff} was 4 h. There appears, therefore, to be a pattern of variation of the T_{diff} between peak of Dst and peak of ε parameter which tend to depend on the size of the storm. This observation is consistent with the findings of Gonzalez and Tsurutani, who suggested that not only a southward directed IMF but also a long duration are necessary for major magnetic storms to develop [1]. It has been found in a particular study that intense magnetic storms have larger timescale defining the duration of the main and recovery phases (Yokoyama and Kamide, 1997). Contrarily, the study by Taylor *et al.* has suggested that the timescale of magnetic storm is independent of their magnitude [15]. This discrepancy can be accounted for by the procedures used for analyzing the Dst data.

CONCLUSION

We have studied the energy injection process of four CME driven geomagnetic storms to understand its features with regards to the time lag of peak energy injection and peak of intensification of geomagnetic storms. The following are our findings;

1. The time difference between the peak of energy injection and peak of geomagnetic storm signature, tend to be dependent on the strength of the storm.
2. Energy injection tends to be increasing with an increase in storm intensity.

More work is required to understand the bulk association of the injection process and the dissipation process through the intensification of the geomagnetic storms.

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