Journal of Atmospheric and Solar-Terrestrial Physics 72 (2010) 1364–1371

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Storm-time characteristics of intense geomagnetic storms ($Dst \leq -200$ nT) at low-latitudes and associated energetics

R. Rawat *, S. Alex, G.S. Lakhina

Indian Institute of Geomagnetism, Plot No. 5, Sector-18, Navi Mumbai 410218, Maharashtra, India

ARTICLE INFO

Article history:
Received 18 March 2010
Received in revised form
2 August 2010
Accepted 24 September 2010
Available online 15 October 2010

Keywords:
Interplanetary magnetic field
Geomagnetic storms
Ring current
Magnetic cloud

ABSTRACT

Tremendous amount of solar energy is hurled into the space by transient sporadic emissions occurring within the Sun. A fraction of this energy is transferred into the Earth's magnetosphere by the magnetic reconnection process. Interplanetary magnetic field plays a crucial role in the excitation of geomagnetic storms and their subsequent evolution. The present study attempts to determine the influence of post-shock duration of southward B_z on the development and intensification of intense ($Dst \leq -200$ nT) geomagnetic storms. The study presents 18 big storm events that occurred during the solar cycle 23. In all the cases under study, the interplanetary shocks were driven by the interplanetary coronal mass ejections (ICMEs). The ICME structures may contain southward magnetic fields within the sheath, the magnetic cloud or both in succession, which can lead to the development of intense geomagnetic storms. In addition, dependence of storm strength on the total energy influx into the magnetosphere (ϵ) and ring current (E_{RC}) energy is also assessed. Geomagnetic storm characteristics are examined at a low-latitude station, Alibag (geographic lat. 18.63°N, long. 72.87°E; geomagnetic lat. 10.02°N, long. 145.97°), using high resolution digital data. The minimum duration of southward B_z for strengthening the storms is ~ 1.25 h. All intense storms are found to have minimum values of southward directed B_z to be ≤ -18 nT and interplanetary electric field $E_y > 12$ mV/m. Intensity of geomagnetic storms at low-latitudes follows a fairly linear dependence on the ring current energy.

1. Introduction

Geomagnetic storms are the large-scale disturbances in the Earth's magnetic field caused by enhanced solar wind–magnetosphere coupling processes. Solar flares, coronal mass ejections (CMEs) and fast wind streams from coronal holes are known to be the main solar drivers for geomagnetic storms. Largest geomagnetic storms are ascertained to be driven by fast halo coronal mass ejections or their interplanetary remnants known as the interplanetary coronal mass ejections (ICMEs) (Richardson et al., 2006). The two major interplanetary drivers for causing intense geomagnetic storms are magnetic clouds and sheath regions behind the interplanetary shocks. Magnetic clouds are a subset of ICMEs (Burlaga et al., 1981) which typically are characterized by smooth rotation of magnetic field direction over a large angle $\sim 180°$, magnetic field values above average, low proton beta and low steady dynamic pressure. In contrast, the signatures of sheath regions as proposed by Tsurutani et al. (1988) include, enhanced magnetic field strength and highly fluctuating fields, density and dynamic pressure. Also, the sheath fields exhibit increased temperature, density and speed.

Multiple studies by Gonzalez and Tsurutani (1987), Tsurutani et al. (1992), Echer et al. (2008) have shown that regardless of the solar origin, the principal factor for making the solar ejecta geoeffective is a period of prolonged and large southward directed interplanetary magnetic field component (IMF), B_z. Vital role of southward directed B_z is quite explainable, as this particular orientation of B_z allows efficient transfer of energy, mass and momentum from the solar wind into the Earth's magnetosphere through the magnetic reconnection process (Dungey, 1961). The solar wind energy injected into the nightside magnetosphere by the magnetic reconnection process is finally dissipated into different regions (Koskinen and Tanskanen, 2002; Feldstein et al., 2003). A part of the energy injected from the magnetotail towards the inner magnetosphere leads to the reinforcement of the westward flowing equatorial ring current with an addition of a population of particles having energies of $\sim 20-200$ keV (Daglis, 1999). An increase of ring current energy causes a decrease in the horizontal H component of geomagnetic field, this relationship is empirically established by the Dessler–Parker–Sckopke (DPS) relation (Dessler and Parker, 1959; Sckopke, 1966). Magnitude of geomagnetic storms is mainly ascertained by the energy dissipation into the ring current, which is measured by

* Corresponding author. Tel.: +91 22 2748 4060; fax: +91 22 2748 0762.
E-mail address: rashmir@iigs.iigm.res.in (R. Rawat).

1364-6826/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2010.09.029

storm-time disturbance (*Dst*) index. Intense or big geomagnetic storms are defined when the peak value of *Dst* index reaches −200 nT (Gonzalez et al., 1999). Intense storms are of great interest for scientific community due to their strong and dramatic consequences for space weather.

Vichare et al. (2005) studied some characteristics and energy budget of nine intense geomagnetic storms that occurred during the period from 1998 to 2001. Their work reaffirms the dependence of ring current strength on the magnitude of southward IMF. They have also deduced the percentage of solar wind kinetic energy into total magnetosphere and distribution of total magnetospheric energy into ring current and auroral ionosphere (which came to be about 20%) during storm main phase.

In this paper, we study the effect of post-shock duration and magnitude of southward B_z on the strength of 18 intense geomagnetic storms occurred during the solar cycle 23. Correspondence between dawn–dusk electric field (*Ey*) component of solar wind and the storm intensity (*Dst*) is also investigated. The total power supplied to the Earth's magnetosphere and the energy stored in ring current is also estimated to quantify the solar wind–magnetosphere energy transfer.

2. Data base and empirical relations used

For present study, we have used 1-min resolution geomagnetic digital data from Alibag (geog. lat. 18.63°N, long. 72.87°E; geomag. lat. 10.02°N, long. 145.97°), a low-latitude observatory in the Indian region. The current work highlights the storm-time variations observed at single low-latitude station, Alibag during severe magnetic storms of solar cycle 23. As main emphasis is on complete storm duration (> 1 day) the field variation recorded at single station portrayed with superposed *Dst* index gives good idea about geomagnetic activity in response to varying solar wind and interplanetary conditions. Vieira et al. (2003) in their work of multi-scale analysis of geomagnetic symmetric index have clearly stated that long-period variations (> 1 day) of the symmetric index can be estimated from just one station. In contrast, short-period variations need to be calculated from several stations to remove systematic errors introduced by spatially localized current systems. To focus on the disturbance time features during the storms, departure from diurnal variations is extracted from the horizontal component of the geomagnetic field (*H*) for individual storm and hence forth it will be designated by ΔH_{ABG} for Alibag.

Our main objective is to bring out the influence of various types of solar wind and interplanetary drivers on the evolution of intense geomagnetic storms ($Dst \leq -200$ nT) and associated energetics during solar cycle 23. This cycle spans period between May 1996 and 2006 (Echer et al., 2008). Manual inspection of hourly *Dst* index data was done to compile different storm magnitudes. All the 18 storm events identified in current work have occurred between May 1998 and August 2005. Following the categorization, we have adopted the criteria of Echer et al. (2008) for identifying the solar wind and interplanetary drivers. The interplanetary shocks for all the geomagnetic storm cases studied here are driven by interplanetary coronal mass ejections (ICMEs). The events are caused by either strong sheath fields or magnetic clouds driven by shock/sheath or by both as confirmed by works of Zhang et al. (2007) and Echer et al. (2008).

In order to analyze the events, magnetic field data of 5-min resolution in GSM coordinates is acquired from the MAG instrument onboard Advanced Composition Explorer (ACE) satellite located at Lagrangian (L1) point ($\sim 240R_E$). The 5-min sampling interval data were chosen because it smoothes the high frequency fluctuations present in the higher resolution (64 s) data. For correlation between IMF B_z and *Dst* index, 1-h B_z data from ACE (OMNIWeb data base) is used to match with the hourly resolution of *Dst*.

IMF and solar wind data of 5-min resolution is acquired from ACE satellite which are used for computation of energies. We have taken 1-h values of IMF B_z component.

The transfer of solar wind energy into the Earth's magnetosphere is estimated by the coupling function (ϵ) proposed by Perreault and Akasofu (1978):

$$\epsilon = V_{sw}|B|^2 \sin^4(\theta/2) l_0^2 \quad (1)$$

where V_{sw} is the upstream solar wind speed, $|B|$ the magnitude of the interplanetary magnetic field and θ the IMF clock angle defined as $\theta = \tan^{-1}(B_y/B_z)$ for $B>0$, and $\theta = 180^\circ - \tan^{-1}(B_y/B_z)$ for $B \leq 0$. l_0 is scale length empirically assumed to be $7R_E$ (Perreault and Akasofu, 1978).

The measured storm-time disturbance (*Dst*) index responds to the influence of several key current systems substantially. Hence, to remove the effect of magnetopause currents on the *Dst* variations, the *Dst* values are pressure corrected (Burton et al., 1975),

$$Dst^* = Dst - b\sqrt{P_{sw}} + c \quad (2)$$

where the coefficients are set to, $b = 8.74$ nT(nPa)$^{-1/2}$, $c = 11.54$ nT (Turner et al., 2001). The hourly *Dst* values are attained from the World Data Center for Geomagnetism, Kyoto (http://swdcdb.kugi.kyoto-u.ac.jp).

Dessler and Parker (1959) and Sckopke (1966) proposed that geomagnetic field perturbation in the Earth's surface is related to the total energy of the ring current particles by $\Delta B/\Delta B_0 = 2E/3E_m$, where $E_m = 8 \times 10^{24}$ ergs. The ring current energy injection rate, U_{RC}, is obtained from the energy balance equation (Feldstein et al., 2003)

$$U_{RC} = -0.74 \times 10^{10}\left(\frac{dDst}{dt} + \frac{Dst^*}{\tau}\right) \quad (3)$$

The expression consists of two terms, the first term describes the energy storage rate in the ring current and second one characterizes the energy dissipation from the ring current which is caused by different processes. Here, U_{RC} is in Watts, *Dst*, Dst^* are in nT; *dt* and τ are in hours. τ represents the decay time of ring current. The sign of first term defines whether energy is stored (negative) or dissipated (positive). In this study, τ is computed by using expression from Valdivia et al. (1996), $\tau = 12.5/(1 - 0.0012Dst^*)$.

3. Results

Several studies have been done to ascertain the role of interplanetary magnetic fields for modulating the formulation and subsequent evolution of geomagnetic storms (Tsurutani and Gonzalez, 1997; Gonzalez et al., 2002). Gonzalez and Tsurutani (1987) studied 10 intense geomagnetic storms ($Dst < -100$ nT) during the period between 16 August 1978 and 28 December 1979 using ISEE-3 field and plasma data. The interplanetary causes of these storms were described as long-duration (> 3 h), large southward (< −10 nT) IMF B_z structures. Since then these criteria have been referred and confirmed in many studies (Gonzalez et al., 1999, 2007).

In the present study, the main focus pertaining to the development of big geomagnetic storm ($Dst < -200$ nT) is on the duration of southward directed B_z after the passage of interplanetary shock at the magnetopause. The storm main phase duration was selected as the time when *Dst* notably started

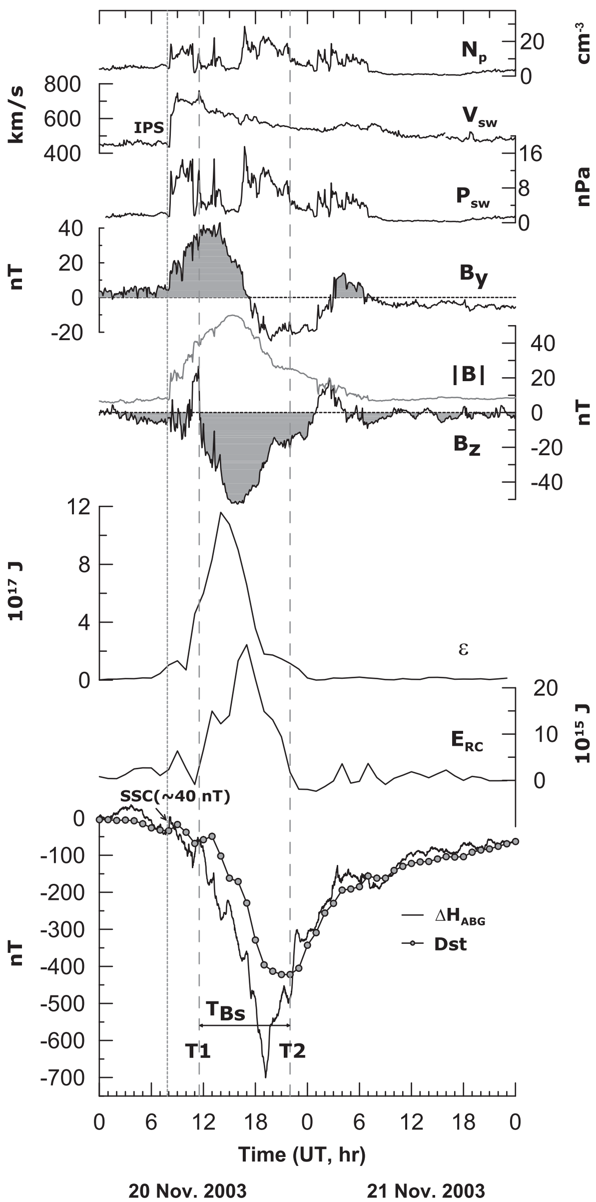

Fig. 1. From top to bottom are shown solar wind density (N_p), speed (V_{sw}), dynamic pressure (P_{sw}), IMF B_y, $|B|$, B_z, ϵ (10^{17} J), ring current energy, E_{RC} (10^{15} J), geomagnetic response as seen at Alibag (ΔH_{ABG}) and *Dst* index for the large storm of 20 November 2003. Vertical dotted line marks IPS. ACE data are time shifted by 45 min to coincide with the storm sudden commencement (SSC) time at ground station, Alibag. Two vertical dashed lines depict time T_1 and T_2. T_{Bs} in figure represents time difference between T_1 and T_2.

decreasing till the occurrence of the minimum *Dst* value of the storm (Gonzalez et al., 1989). In order to emphasize the role of the duration of post-shock B_z conditions in guiding the storm development pattern, we have introduced a parameter T_{Bs}, which is defined as the time period between the onset of sharp southward turning of B_z (T_1) and the time when *Dst* attain its minimum value (T_2). Each of the storm events was manually inspected for determining T_1, T_2 and T_{Bs}. For example, for the event of Fig. 1, the onset of sharp southward turning occurred at 1050 UT (T_1) and *Dst* attained its minimum value at 2200 UT (T_2). The times T_1 and T_2 are marked in Fig. 1 by dashed lines and labels. The time difference between T_2 and T_1 gives T_{Bs}.

For all the 18 storm events, T_{Bs} factor is evaluated using the above criteria for the correlation analysis described in Section 3.2. Determination of T_{Bs} takes into account the following important points:

1. Sharp southward traversal of B_z with significantly large magnitude during post-shock period, associated with major depression in *Dst*.
2. Fluctuating and low magnitude southward orientations of B_z are excluded even if multiple such periods exist post shock.

The super-intense geomagnetic storm of 20 November 2003 is discussed as a case study in Section 3.1, to delineate the period of significance for correlation analysis used for this paper.

3.1. Case study: 20 November 2003

Active region 0501 (N00E18) produced a M3.2/2N flare at 0723 UT on 18 November 2003. An associated full halo CME with estimated speed of 1100 km/s occurred at 0850 UT on same day, as reported by LASCO/SOHO spacecraft. An interplanetary shock (IPS) was observed at 0720 UT (dotted line in Fig. 1) on 20 November 2003 by ACE.

The shock passage was characterized by increase in solar wind density (N_p) from 4.6 cm to 10.8 cm^{-3}, solar wind speed (V_{sw}) from 435 km/s to 504 and IMF $|B|$ from 8 to 16 nT. Dynamic pressure (P_{sw}) increased from 1.4 to 4.8 nPa and further rising to 11.8 nPa. After about 43 min of IPS, a storm sudden commencement (SSC) of amplitude ~ 40 nT, was recorded at 0803 UT as an abrupt increase in the horizontal component (ΔH_{ABG}) of the geomagnetic field at the low-latitude station, Alibag (Fig. 1). Typically the SSC lasts for tens of minutes and then is followed by a magnetic storm or by an increase in geomagnetic activity (Araki, 1977). During the initial period of storm development between 0720 and 0955 UT, B_z exhibits oscillating pattern but still predominantly southward directed (Fig. 1), this resulted in small amount of energy transfer from the solar wind to the magnetosphere. In this duration, the energy influx (ϵ) into the magnetosphere increased from 0.45×10^{17} to 1.3×10^{17} J. A fraction of total energy got transferred to ring current region and enhanced the ring current energy from 1.03×10^{15} to 6.4×10^{15} J for this 2.5 h period. As a result of this, the geomagnetic field experienced a small depression of -133 nT in ΔH_{ABG} ($Dst=-68$ nT). A sharp southward traversal of IMF B_z occurred at 1050 UT on 20 November which sustained for almost 13 h from 1050 to 0010 UT with large values (≤ -10 nT). The peak value (-52.67 nT) of southward B_z was observed at 1510 UT on 20 November 2003. The dawn–dusk component of the IMF, B_y remained steadily duskward for almost 9 h after the shock and attained peak value (43.08 nT) at 1310 UT. Energy transfer process accelerated under the influence of favourable B_z orientation due to significantly enhanced magnetic reconnection at the dayside magnetopause. The energy influx peaked to the value of the order of 11.5×10^{17} J at 1435 UT on 20 November. A large amount of energy was accumulated in the inner magnetosphere, which could have been caused by enhanced convection electric field driving the ring current ions towards inner magnetosphere and their subsequent energization by betatron acceleration (Ebihara et al., 2005). The ring current reinforced rapidly and maximum strength of ring current energy (2.93×10^{16} J) occurred at 1700 UT. Development of sharp single-step main phase (1300–2200 UT) of discernible magnitude (~ -630 nT) as recorded at Alibag, began shortly after magnetopause compression by high solar wind pressure and peak value of ΔH_{ABG} is about -700 nT ($Dst=-422$ nT).

The times T 1, T 2 and post-shock duration of southward B_z (T_{Bs}) for 20 November are marked in Fig. 1 and T_{Bs} is found to be ~ 11 h.

The interplanetary and digital ground magnetic field values and energy budget for the storm cases under study are shown in Table 1. The events are put in order of increasing magnitude of Dst index. In the table last column gives the interplanetary (IP) source of geomagnetic storm, where 'SH' denotes the sheath fields, 'sMC', the magnetic clouds preceded by fast shocks, 'SH+MC', sheath followed by magnetic cloud and 'MC' depicts magnetic clouds. In the discussion, respective storms will be referred with their sequence numbers (1, 2, 3…) mentioned in Table 1.

3.2. Correspondence between IMF and geomagnetic field

In the present study we attempt to look into the influence of magnitude and duration of post-shock southward directed B_z in conjunction on the storm intensity. We have used the hourly values of IMF B_z to examine the correspondence with Dst values available from the OMNIWeb data base. This evaluation is restricted to the main phase duration (ending at the time of peak value of Dst), as that corresponds to the growth of the ring current intensity, since it is during this interval of time that the energy input and therefore the coupling function can be better studied (Gonzalez et al., 1989). Several studies have been done for ascertaining the interplanetary parameters causing intense magnetic storms with $Dst \leq -100$ nT (Burton et al., 1975; Gonzalez and Tsurutani, 1987; Vieira et al., 2004). However, in this work we intend to analyze the more severe storms ($Dst \leq -200$ nT) and their solar wind-interplanetary causative. Also to delineate the threshold values of parameters like T_{Bs}, $B_{z_{min}}$ and E_y for differing storm intensities, the geomagnetic storms were classified into two subsets.

Depending on different magnitudes of storms, represented by Dst index, two categories are made (1) $-300\,\text{nT} < Dst \leq -200$ nT storms and (2) $Dst \leq -300$ nT storms. For both the categories we obtained different values for T_{Bs}. The vertical dashed lines with labels in Fig. 2a clearly demarcate the threshold values of T_{Bs} which assist in intensification of big storms ($Dst \leq -200$ nT).

The correspondence between T_{Bs} and minimum Dst is illustrated in Fig. 2a, where T_{Bs} denotes the interval between the onset time (T_1) of sharp, largely southward B_z just after the shock and the time (T_2) when Dst reaches its peak value. For both the subsets the threshold values of T_{Bs} are depicted by vertical dashed lines and respective labels. Average value of T_{Bs} obtained for 18 storms under study is ~ 5 h with standard deviation: ± 2.98 h. Fig. 2b shows the dependence of storm intensity on minimum value attained by southward B_z after the passage of shock for each storm. The threshold values of $B_{z_{min}}$ which supports the intensification of big storms are represented by labelled vertical dashed lines. A noticeable feature observed from our study of southward B_z magnitude is that a minimum threshold value of $B_z < -17$ nT is essential for the development of all the big geomagnetic storms ($Dst \leq -200$ nT). Average value of $B_{z_{min}}$ is found to be ~ 34 nT with standard deviation: ± 12.31 nT.

It is well established that the dawn–dusk (E_y) component of the solar wind electric field is an important driver of geomagnetic activity (Perreault and Akasofu, 1978; Tsurutani and Gonzalez, 1997). Vasyliunas (1975) suggested that the reconnection rate is proportional to the dawn–dusk component of the solar wind electric field. In view of this, we have also obtained the threshold values of electric field for the development of big storms. Fig. 3 showcases the threshold values of duskward E_y for two subsets of storms based on Dst values. The minimum E_y identified for the $Dst \leq -200$ nT storms is ~ 13 mV/m. For super-intense storms ($Dst \leq -300$ nT), minimum threshold value of duskward E_y is found to be ≥ 25 mV/m. Based on 18 storms the average value of E_y is found to be $\sim 25 \pm 10.5$ mV/m. Our study includes storm events with $Dst \leq -200$ nT. To summarize, we can ascertain the essential interplanetary conditions regulating the development of big storms ($Dst \leq -200$ nT) from Fig. 2a and b. Looking at each

Table 1
Big geomagnetic storm events ($Dst \leq -200$ nT) between the period 1996 and 2006.

S.N.[a]	Events[b]	Dst_{min}[c] (nT)	$B_{z_{min}}$[d] (nT)	T_{Bs}[e] (h)	$\Delta H_{ABG_{min}}$[f] (nT)	ϵ_{max}[g] (10^{17} J)	$E_{RC_{max}}$[h] (10^{15} J)	IP driver[i]
1	17 September 2000	−201	−23.9	3.08	−223.2	1.5	9.34	MC
2	4 May 1998	−205	−28.6	2.83	−281.4	1.45	4.86	SH
3	24 September 1998	−207	−17.9	9.08	−236.6	2.07	16.79	SH
4	24 August 2005	−216	−38.3	2.0	−324.3	6.16	15.95	sMC
5	24 November 2001	−221	−27.8	1.25	–[j]	2.01	14.46	SH+MC
6	12 August 2000	−235	−28.7	5.25	−294.3	3.28	13.93	SH+MC
7	21 October 1999	−237	−30.7	7.25	−259.6	3.07	14.15	CIR
8	15 May 2005	−263	−38	2.83	−329.9	7.10	18.56	sMC
9	11 April 2001	−271	−20.5	2.08	−279.2	4.14	13.63	SH+MC
10	6 April 2000	−288	−27.3	8.25	−350.1	2.88	17.70	SH
11	9 November 2004	−289	−24.7	8.75	−408.9	6.09	25.55	SH+MC
12	6 November 2001	−292	−64	3.67	−346.3	–	–	SH
13	15 July 2000	−301	−49.4	5.67	−417.6	–	–	sMC
14	29 October 2003	−353	−26.5	7.17	−367.3	–	–	SH+MC
15	7 November 2004	−373	−44.9	9.17	−394.4	11.12	25.83	sMC
16	30 October 2003	−383	−27.1	4.58	−440.1	–	–	SH
17	31 March 2001	−387	−44.7	3.92	−392.2	4.62	19.01	SH+MC
18	20 November 2003	−422	−50.9	11.17	−700.5	11.59	29.31	sMC

[a] Serial number of the event.
[b] Commencement date of geomagnetic storm.
[c] Minimum hourly values of Dst.
[d] Minimum hourly values of IMF B_z.
[e] Difference between T_1 and T_2 in hours.
[f] Minimum 1-min values of ΔH_{ABG}.
[g] Maximum hourly value of ϵ.
[h] Maximum hourly value of E_{RC}.
[i] Interplanetary driver for the respective storm events.
[j] 24 November 2001 is excluded in energetics analysis due to the unavailability of Alibag data.

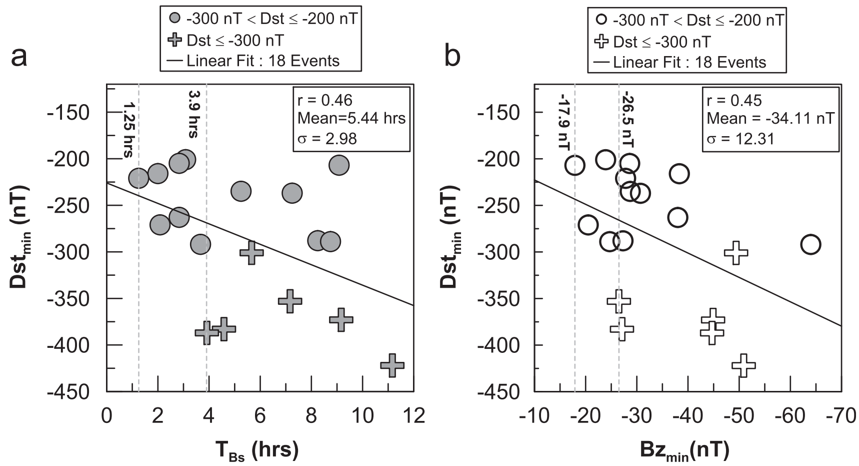

Fig. 2. Dependence of storm intensity measured by *Dst* index on (a) duration of post-shock southward IMF B_z component and (b) minimum B_z during the main phase of storms.

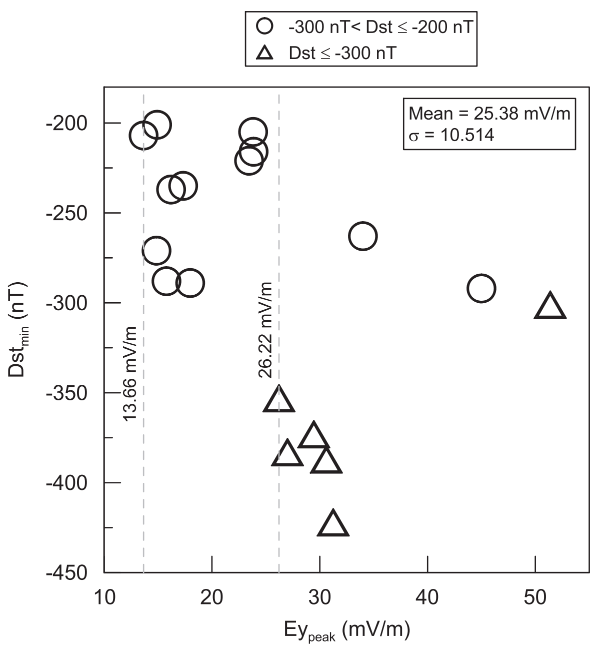

Fig. 3. Dependence of storm intensity measured by *Dst* index on peak value of electric field E_y during the main phase of storms.

category of geomagnetic storms, based on *Dst* values, we obtained that the storms with $Dst \leq -200$ nT have interplanetary condition of minimum southward B_z value as ≤ -17 nT ($E_y > 12$ mV/m) for ~ 1.25 h. For super-intense storms ($Dst \leq -300$ nT), interplanetary condition of B_z southward for ≥ 3.5 h with value of ≤ -25 nT ($E_y > 25$ mV/m). The minimum value of southward IMF B_z for all the storms under study varied from -17.9 to -64 nT and the duration of post-shock southward B_z varied from 1.25 to ~ 11 h.

Importantly, considering all the big storm events together, it can be suggested that the storm intensity is dependent strongly on concurrence of both the factors, namely T_{Bs}, the duration of post-shock southward B_z and magnitude of post-shock southward B_z. Hence, it can be concluded that if the solar and interplanetary driver possess significant magnitude of southward directed B_z for longer durations during the post-shock period then subsequent magnetic storm event will certainly be severe. Noteworthy feature from the study is the higher values of the electric field E_y driving intense geomagnetic storms. Our results are in good conformity with the well established criteria of Gonzalez and Tsurutani (1987) in which long duration (>3 h) southward $B_z \sim 10$ nT or $E_y \sim 5$ mV/m are threshold values to produce intense storms. About 72% of storms in our study followed these criteria except remaining 28% for which duration was <3 h and respective *Dst* ranged from -200 to -271 nT. Echer et al. (2008) studied 90 intense storms ($Dst \leq -100$ nT) during solar cycle 23 and ascertained that about 70% of events under their study followed Gonzalez and Tsurutani (1987) criteria.

In a recent work by Kane and Echer (2007), evolutions of severe geomagnetic storms ($Dst \leq -200$ nT) during solar cycle 23 was examined. They noted time stamps of several features like commencement of storm at ACE satellite location, onset of southward traversal of B_z and starting of *Dst* changes and calculated time lags. Their results showed that faster interplanetary structures did not necessarily produce rapid or stronger *Dst* evolutions, though large southward B_z will give rise to severe storms.

Threshold values of B_z and T_{B_s} between sub-groups show insignificant trend. The velocity (V_{sw}) of only three of the severe storms (available) attained values >1000 km/s, all other events had velocity confined to values below 900 km/s. Correlation of velocity with *Dst* is found to be scatter (not shown). Another important point is that for all the 18 events considered in this study have large value of post-shock southward B_z (<-17 nT). Therefore, velocity (V_{sw}) independently without large IMF B_z factor does not substantially contributes to the storm intensification. Tsurutani et al. (1992) clearly state that extraordinary southward directed B_z is the dominant part of the electric field (E_y) rather than high velocity (V_{sw}).

3.3. Energy budget

Total energy input (ϵ) into the Earth's magnetosphere is redistributed into different magnetospheric regions and subsequently dissipated during various storm phases. The effects of varying rates of total energy supplied to the magnetosphere on the growth and intensification of geomagnetic storms as measured by *Dst* index are examined. In Fig. 4(a)–(d), the energies in the units of Joules are obtained through time integration of the energy rates (power) for the main phase durations.

The labels (e.g. 1, 2, 3...) indicated in Fig. 4a and c refer to the sequence numbers of events given in Table 1, where the events are tabulated in increasing magnitudes of *Dst* index. For the analysis, we have taken into account the maximum values of ϵ and ring current energy rate which are represented by ϵ_{max} and $E_{RC_{max}}$, respectively, during the main phase of individual storm. After the magnetic

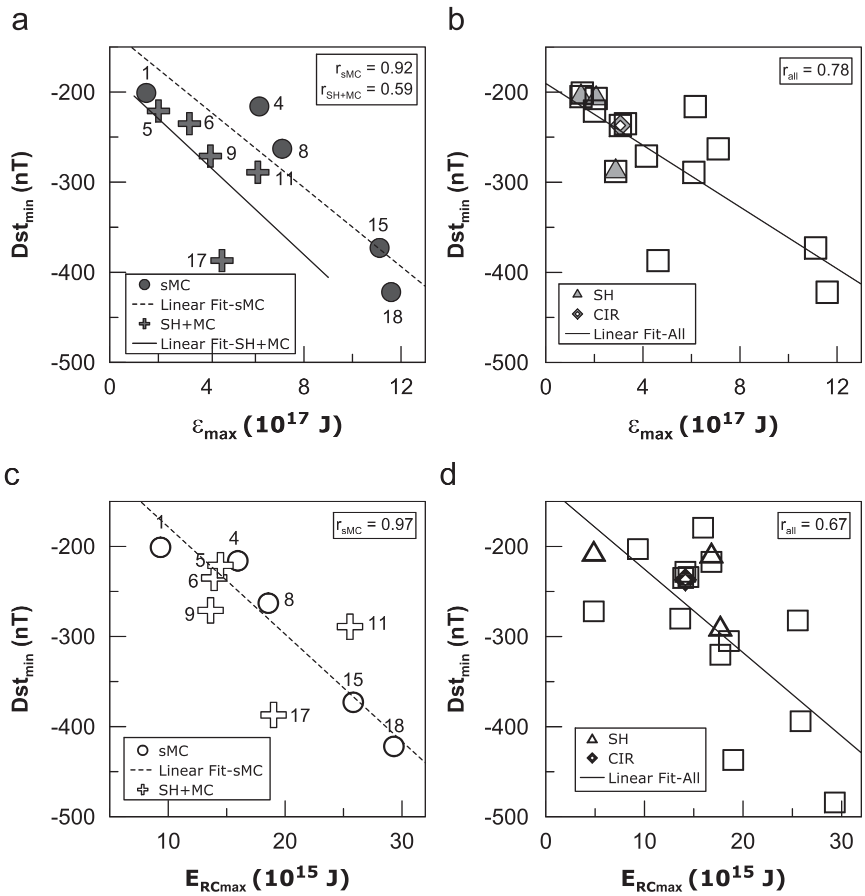

Fig. 4. Correlation between total energy influx into the magnetosphere, ϵ_{max} (J) with the minimum value of Dst_{min} index attained during the main phase of geomagnetic storms for (a) sMC and SH+MC events and (b) all storms. Correspondence between ring current energy, $E_{RC_{max}}$ (J) with Dst_{min} for (c) sMC and SH+MC events and (d) all storms. The labels in the plot indicate the type of solar wind-IP driver for each event. Solid line linear fits in (b) and (d) are for all the storm events while dashed lines in (a) and (c) represent linear trend for magnetic cloud events.

reconnection at the magnetotail, part of the total energy injected into the magnetosphere (ϵ) is accelerated earthward in the equatorial region enhancing the existing ring current. The enhanced ring current is responsible for observed reduction of horizontal component of geomagnetic field at equatorial and low-latitudes after some time from the shock impact.

The solar and interplanetary (IP) drivers causing the intense geomagnetic storms ($Dst \leq -100$ nT) are discussed by Echer et al. (2008). Most common interplanetary structures responsible for the development of intense storms determined in their study are sheath fields, magnetic cloud preceded by a fast shock, sheath field followed by a magnetic cloud and corotating interaction region (CIR) fields. For all the 18 storm cases we have distinguished four types of solar and IP drivers, as stated in Echer et al. (2008). Out of the total 18 storms, five are caused by sheath fields, six by magnetic clouds and six by sheath fields followed by magnetic clouds. The single event of 21 October 1999 was caused by an interplanetary ejecta or interplanetary coronal mass ejection, both followed by a high-speed stream as reported from ACE satellite plasma and magnetic field instruments.

4. Discussion

To quantify the dependence of the total solar wind energy input into the Earth's magnetosphere and ring current energy on the storm evolution and intensification, linear correlation is performed for the geomagnetic storms under study as illustrated in Fig. 4(a)–(d). It can be distinctly observed that the storms driven by pure magnetic clouds (1, 4, 8, 15 and 18) in Fig. 4(a) or by magnetic clouds associated with sheath fields (5, 6, 9, 11 and 17) (Fig. 4b) are more geoeffective than sheath fields alone (Fig. 4b). This can be justified by higher energy influx (ϵ_{max}) into the magnetosphere for magnetic cloud associated events (Fig. 4a) relative to events caused by sheath fields only (Fig. 4b). Total energy influx follows a linear trend (coefficient, $r=0.92$) (Fig. 4a) for the pure magnetic cloud events preceded by shocks (sMC) (1, 4, 8, 15 and 18). Also for storms driven by combination of sheath and magnetic clouds exhibit fairly linear dependence on total energy fed into the magnetosphere (coefficient, $r=0.59$). This can be understood in terms of magnetic cloud features, namely, abnormally high magnetic fields and smooth rotation of large fields (Burlaga et al., 1981). The parameters used for determination of the total energy influx (ϵ) include magnetic field $|B|$, solar wind speed (V_{sw}) and B_y, B_z components of interplanetary magnetic field. Thus, patterns of modulation in these factors will essentially influence the energy transfer rate (ϵ) from the solar wind into the Earth's magnetosphere. The contribution of ring current energy for the total energy dissipation in the magnetosphere during the geomagnetic storm of 20 November 2003, which was driven by pure magnetic cloud is 66.53. Fig. 4b depicts correspondence of storm intensity on ϵ_{max} for all storm events which shows good linearity (coefficient, $r=0.78$).

Our estimation of ring current energy for magnetic cloud structures and sheath fields clearly reveals that the storms caused by pure magnetic clouds and associated with sheath fields (Fig. 4c) have much higher ring current energy as compared to those storms which are caused by sheath fields alone (Fig. 4d). The ring current energy during main phase of the storm events caused by pure magnetic cloud events (1, 4, 8, 15 and 18) exhibit linear dependence (coefficient, r=0.97) on storm strength represented by Dst_{min} (Fig. 4c). For all storm events (Fig. 4d) also the fitting is found to be significant (coefficient, r=0.67).

Our results are in close agreement with the work of Huttunen et al. (2002) in which they clarify that the larger energy influx from the solar wind into the Earth's magnetosphere, assists in strengthening the storms with other favourable background conditions like large, steadily prolonged southward B_z. Magnetic clouds with proper orientation of magnetic fields within it, substantially fulfill the requirement for significant energy transfer from the solar wind into the magnetosphere. This forms magnetic clouds more geoeffective in terms of evolution of intense and big storms. On the other hand, the sheath fields cannot stimulate intense storms owing to rapidly fluctuating magnetic field direction. In another study by Pulkkinen et al. (2007) an interesting feature was concluded. Using superposed epoch analysis based on 28 storms from 1997 to 2002 in which 14 events were magnetic cloud driven and rest 14 were sheath driven storms, they discovered that sheath driven storms exhibiting fluctuating solar wind plasma and IMF drive stronger auroral activity. In contrast, steady convection periods contained in cloud structures show low-level auroral activity. Huttunen et al. (2002) presented another interesting study about variability of magnetospheric storms driven by different types of solar wind drivers during the rising phase of solar cycle 23 using Dst and K_p indices and satellite data. According to their study, the sheath regions drive stronger auroral activity, whereas the geomagnetic storms driven by magnetic clouds exhibit stronger enhancement in ring current. Similar results were reported by Turner et al. (2006, 2009). They studied geoeffectiveness large number of storms from 1995 to 2004 which included CME-driven and CIR-driven storms. Interestingly, they obtained statistically significant differences for energy input, ring current energy and auroral precipitation for the two types of storms. CME-driven storms showed higher values of energies. Coupling efficiency, defined as ratio of output to input energy for CIR-driven storms, is found to be more.

The powerful magnetic storm of 20 November 2003 stands out distinctly in Fig. 4(a) and (b) representing conspicuous influence of high energy influx and ring current energy on the intensification of storm magnitude. Gopalswamy et al. (2005) explained the severity of this storm on the basis of high magnetic field and above average speed (730 km/s) of the interplanetary CME (ICME) showing characteristics of a typical magnetic cloud. A noticeable feature for this event is the enhanced plasma density ($>10\,cm^{-3}$) for almost 5.5 h during the period between 1540 and 2110 UT which also marks the interval for major depression in Dst index. The solar wind density influence on the energy transfer to the magnetosphere is discussed in the work of Kataoka et al. (2005) who have studied this event using in situ observations from GOES and Cluster spacecrafts. Magnetic clouds with higher density are more geoeffective with relatively steady southward IMF as they produce and maintain an enhanced level of magnetospheric convection in the magnetotail. As a result, the protons are pushed from the nightside plasma sheet deeper into the inner magnetosphere, causing reinforcement in the ring current population (Ebihara et al., 2005). Another noteworthy feature in 20 November 2003 storm is pressure enhancement up to values of 17.53 nPa (at 1600 UT) during the main phase (1300–2200 UT). At this instance, B_z is southward directed with sufficient magnitude, which resulted in strong convection. Concurrent to these conditions, there is an increase in the ring current, which peaks up to large magnitude of 29.3×10^{15} J at the same time. A good linear correlation with coefficient, r=0.78 (not shown here) is obtained between the dynamic pressure and ring current energy (E_{RC}) during the main phase interval (1300–2200 UT) of 20 November. This implies that the pressure enhancements in the main phase period assisted in strengthening the ring current and hence intensifying the magnitude of storm. This concurrence was discussed in detail by Wang et al. (2003) and Shi et al. (2005) taking into account the asymmetric ring current. During the main phase of a storm, depression in ground horizontal field (H) is attributed to the symmetric and asymmetric components of the ring current (Akasofu and Chapman, 1964; Cummings, 1966). When southward orientation of IMF B_z persists for longer duration in main phase, then the asymmetric ring current is expected to be strong. During such periods, an enhancement in the dynamic pressure can significantly intensify the asymmetric ring current and lead to dawn to dusk asymmetry in the ground H perturbations, characterized in H by negative perturbations in dusk side and positiveperturbations in dawn side. Strengthening of asymmetric ring current also known as partial ring current during the main phase is caused by the local adiabatic energization of the pre-existing ring current population (Shi et al., 2005). For the 20 November 2003 storm event discussed in the present study, the main phase occurred during 1300–2200 UT when Alibag was at duskside ($\sim 1800-0300$ LT) and subsequent peak value of observed Dst is -422 nT. We can clearly state that the pressure enhancement during the storm main phase (1300–2200 UT, 20 November 2003), which added to the dawn–dusk asymmetry, produced a large depression in the ground ΔH_{ABG} perturbations. Hence, our results are in good agreement with results discussed by Shi et al. (2005).

Occurrence of intense storms ($Dst \leq -250$ nT) is found to be significant during the declining phase of solar cycle 23. This is attributed to the large active regions and multiple flarings and thus multiple ICMEs (Echer et al., 2008). The rate of total energy influx and subsequent dissipation into different magnetospheric regions varies from one storm to another. For the considered set of geomagnetic storm events, the ϵ_{max} varied from 1.4×10^{17} to $\sim 11.6\times10^{17}$ J and the ring current energy varied from 4.86×10^{15} to $\sim 29.3\times10^{15}$ J. Storm intensity varied from -201 to -422 nT.

5. Conclusion

1. Vital role of southward directed magnitude and post-shock duration of IMF B_z for causing big storms ($Dst \leq -200$ nT) is reaffirmed with emphasis on combined effect of these two factors. Interplanetary conditions for big storms are $B_z \leq -20$ nT with $E_y \geq 12$ mV/m prevailing for ~ 1.25 h. Super-intense storms ($Dst \leq -300$ nT) are caused by southward oriented large B_z values of the order of ≤ -35 nT and $E_y \geq 25$ mV/m persisting for ≥ 3.5 h.
2. High solar wind dynamic pressure with steady southward IMF B_z having large magnitude during the main phase of storms enhances the ring current energy and thereby stimulates severe geomagnetic storm activity.
3. The magnetic clouds dominate the several types of interplanetary drivers for causing the intense geomagnetic storms.

Acknowledgements

Authors thank the ACE MAG and SWEPAM instrument teams and the ACE Science Center for providing the ACE data. We also thank WDC, Kyoto, for providing the preliminary Quick look *Dst* indices. Rashmi Rawat extends thanks to the Council of Scientific and Industrial Research, New Delhi, for support under the Research Associate scheme. G.S.L. would like to thank the Indian National Science Academy, New Delhi, for support under the Senior Scientist scheme.

References

Akasofu, S.-I., Chapman, S., 1964. On the asymmetric development of magnetic storm field in low and middle latitudes. Planet. Space Sci. 12, 607–626.

Araki, T., 1977. Global structure of geomagnetic sudden commencements. Planet. Space Sci. 25, 373–384.

Burlaga, L., Sittler, E., Mariani, F., Schwenn, R., 1981. Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations. J. Geophys. Res. 86, 6673–6684.

Burton, R.K., McPherron, R.L., Russell, C.T., 1975. An empirical relationship between interplanetary conditions and *Dst*. J. Geophys. Res. 80, 4204–4214.

Cummings, W.D., 1966. Asymmetric ring currents and the low-latitude disturbance daily variation. J. Geophys. Res. 71, 4495–4503.

Daglis, I.A., 1999. The terrestrial ring current: origin, formation and decay. Rev. Geophys. 37, 407–438.

Dessler, A.J., Parker, E.N., 1959. Hydromagnetic theory of magnetic storms. J. Geophys. Res. 64, 2239–2252.

Dungey, J.W., 1961. Interplanetary magnetic field and auroral zones. Phys. Rev. Lett. 6, 47–48.

Ebihara, Y., Fok, M.-C., Sazykin, S., Thomsen, M.F., Hairston, M.R., Evans, D.S., Rich, F.J., Ejiri, M., 2005. Ring current and the magnetosphere–ionosphere coupling during the superstorm of 20 November 2003. J. Geophys. Res. 110, A09S22. doi:10.1029/2004JA010924.

Echer, E., Gonzalez, W.D., Tsurutani, B.T., 2008. Interplanetary conditions leading to superintense geomagnetic storms ($Dst \leq -250$ nT) during solar cycle 23. Geophys. Res. Lett. 35, L06S03. doi:10.1029/2007GL031755.

Feldstein, Y.I., Dremukhina, I.A., Levitin, A.E., Mall, U., Alexeev, I.I., Kalegaev, V.V., 2003. Energetics of the magnetosphere during the magnetic storm. J. Atmos. Sol.-Terr. Phys. 65, 429–446.

Gonzalez, W.D., Tsurutani, B.T., 1987. Criteria of interplanetary parameters causing intense magnetic storms ($Dst \leq -100$ nT). Planet. Space Sci. 35, 1101–1109.

Gonzalez, W.D., Tsurutani, B.T., Gonzalez, A.L.C., Smith, E.J., Tang, F., Akasofu, S.-I., 1989. Solar wind–magnetosphere coupling during intense magnetic storms. J. Geophys. Res. 94, 8835–8851.

Gonzalez, W.D., Tsurutani, B.T., Gonzalez, A.L.C., 1999. Interplanetary origin of geomagnetic storms. Space Sci. Rev. 88, 529–562.

Gonzalez, W.D., Tsurutani, B.T., Lepping, R.P., Schwenn, R., 2002. Interplanetary phenomena associated with very intense geomagnetic storms. J. Atmos. Sol.-Terr. Phys. 64, 173–181.

Gonzalez, W.D., Echer, E., Gonzalez, A.L.C., Tsurutani, B.T., 2007. Interplanetary origin of intense geomagnetic storms ($Dst \leq -100$ nT) during solar cycle 23. Geophys. Res. Lett. 34, L06101. doi:10.1029/2006GL028879.

Gopalswamy, N., Yashiro, S., Michalek, G., Xie, H., Lepping, R.P., Howard, R.A., 2005. Solar sources of the largest geomagnetic storm of cycle 23. Geophys. Res. Lett. 32, L12S09. doi:10.1029/2004GL021639.

Huttunen, K.E.J., Koskinen, H.E.J., Schwenn, R., 2002. Variability of magnetospheric storms driven by different solar wind perturbations. J. Geophys. Res. 107 (A7), 1121. doi:10.1029/2001JA900171.

Kane, R.P., Echer, E., 2007. Phase shift (time) between storm-time maximum negative excursions of geomagnetic disturbance index *Dst* and interplanetary B_z. J. Atmos. Sol.-Terr. Phys. 69, 1009–1020.

Kataoka, R., Fairfield, D.H., Sibeck, D.G., Rastätter, L., Fok, M.-C., Nagatsuma, T., Ebihara, Y., 2005. Magnetosheath variations during the storm main phase on 20 November 2003: evidence for solar wind density control of energy transfer to the magnetosphere. Geophys. Res. Lett. 32, L21108. doi:10.1029/2005GL024495.

Koskinen, H.E.J., Tanskanen, E.I., 2002. Magnetospheric energy budget and the epsilon parameter. J. Geophys. Res. 107, 1415. doi:10.1029/2002JA009283.

Perreault, P., Akasofu, S.-I., 1978. A study of geomagnetic storms. Geophys. J. 54, 547–573.

Pulkkinen, T.I., Partamies, N., Huttunen, E.J., Reeves, G.D., Koskinen, H.E.J., 2007. Differences in geomagnetic storms driven by magnetic clouds and ICME sheath regions. Geophys. Res. Lett. 34, L02102. doi:10.1029/2006GL027775.

Richardson, J.D., Liu, Y., Wang, C., Burlaga, L.F., 2006. ICMES at very large distances. Adv. Space Res. 38, 528–534.

Sckopke, N., 1966. A general relation between the energy of trapped particles and the disturbance field near the earth. J. Geophys. Res. 71, 3125–3130.

Shi, Y., Zesta, A., Lyons, L.R., Boudouridis, A., 2005. Effect of solar wind pressure enhancement on storm time ring current asymmetry. J. Geophys. Res. 110, A10205. doi:10.1029/2005JA011019.

Tsurutani, B.T., Gonzalez, W.D., Tang, F., Akasofu, S.I., Smith, E., 1988. Origin of interplanetary southward magnetic fields responsible for major magnetic storms near solar maximum (1978–1979). J. Geophys. Res. 93, 8519–8531.

Tsurutani, B.T., Gonzalez, W.D., Tang, F., Lee, Y.T., 1992. Great magnetic storms. Geophys. Res. Lett. 19, 73–76.

Tsurutani, B.T., Gonzalez, W.D., 1997. The interplanetary causes of magnetic storms: a review. Geophysical Monograph, vol. 98, American Geophysical Union, Washington, DC, 1997, p. 77.

Turner, N.E., Baker, D.N., Pulkkinen, T.I., Roeder, J.L., Fennell, J.F., Jordanova, V.K., 2001. Energy content in the storm time ring current. J. Geophys. Res. 106, 19149–19156.

Turner, N.E., Mitchell, E.J., Knipp, D.J., Emery, B.A., 2006. Energetics of magnetic storms driven by corotating interaction regions: a study of geoeffectiveness. AGU Geophysical Monograph Series: Recurrent Magnetic Storms: Corotating Solar Wind Streams, doi:10.1029/167GM11.

Turner, N.E., DCramer, W., Earles, S.K., Emery, B.A., 2009. Geoefficiency and energy partitioning in CIR-driven and CME-driven storms. J. Atmos. Sol.-Terr. Phys. 71, 1023–1031.

Valdivia, J.A., Sharma, A.S., Papadopoulos, K., 1996. Prediction of magnetic storms by nonlinear models. Geophys. Res. Lett. 23, 2899–2902.

Vasyliunas, V.M., 1975. Theoretical models of magnetic field line merging. I. Rev. Geophys. Space Phys. 13, 303–336.

Vichare, G., Alex, S., Lakhina, G.S., 2005. Some characteristics of intense geomagnetic storms and their energy budget. J. Geophys. Res. 110, A03204. doi:10.1029/2004JA010418.

Vieira, L.E.A., Gonzalez, W.D., Echer, E., Guarnieri, F.L., Prestes, A., Gonzalez, A.L.C., Santos, J.C., Dal Lago, A., Schuch, N.J., 2003. Multi-scale analysis of the geomagnetic symmetric index (Sym). Sol. Phys. 217, 383–394.

Vieira, L.E.A., Gonzalez, W.D., Echer, E., Tsurutani, B.T., 2004. Storm-time criteria for several classes of the driving interplanetary structures. Sol. Phys. 223, 245–258.

Wang, C.B., Chao, J.K., C-H, .Lin, 2003. Influence of the solar wind dynamic pressure on the decay and injection of the ring current. J. Geophys. Res. 108, 1341. doi:10.1029/2003JA009851.

Zhang, J., Richardson, I.G., Webb, D.F., Gopalswamy, N., Huttunen, E., Kasper, J.C., Nitta, N.V., Poomvises, W., Thompson, B.J., Wu, C.-C., Yashiro, S., Zhukov, A.N., 2007. Solar and interplanetary sources of major geomagnetic storms ($Dst \leq -100$ nT) during 1996–2005. J. Geophys. Res. 112, A10102. doi:10.1029/2007JA012321.