Bull. Astr. Soc. India (2007) **35**, 499–509

Geomagnetic storm characteristics under varied interplanetary conditions

R. Rawat*, S. Alex and G. S. Lakhina†

Indian Institute of Geomagnetism, Plot No. 5, Sector-18, New Panvel (W), Navi Mumbai 410 206, India

Abstract. Solar cycle-23 witnessed many successive intense X-ray solar flares and coronal mass ejections (CME) during the peak activity period, as well as in the descending phase of the cycle. Some of these emissions had large solar energetic particle events associated with them. When such solar ejecta impact the Earth's magnetosphere, they cause large scale disturbances in the geomagnetic field known as geomagnetic storms. Large variability in the occurrence characteristics of geomagnetic storms is controlled ultimately by the solar activity. Thus the changes in the interplanetary conditions are distinctly seen in the low latitude geomagnetic records as each storm event differs from the other. Several intense storm events of solar cycle-23 are analyzed for assessing the role of interplanetary magnetic field components B_y (east-west) and B_z (north-south) in controlling the generation and development of various types of storms.

Keywords : Sun: coronal mass ejections (CMEs) – Sun: magnetic fields – (Sun:) solar-terrestrial relations

1. Introduction

Active sun is characterized by powerful solar transient eruptions, like solar flares, coronal mass ejections (CMEs) and fast solar wind streams that are accompanied by enormous energy and mass. Impact of these disruptive solar emissions on the earth's magnetosphere leads to sudden disturbances in the geomagnetic field, which are widely evidenced at all

*email: rashmir@iigs.iigm.res.in

†gslakhina@gmail.com

latitudes and are known as geomagnetic storm phenomena (Sugiura & Chapman 1960; Gonzalez & Tsurutani 1987). A significant fraction of the solar wind energy is transferred into the Earth's magnetosphere by the process of magnetic reconnection at the magnetopause (Dungey 1961; Gonzalez et al. 1999). The favourable condition for magnetic reconnection at this site is the presence of southward oriented B_z component, which aids the transfer of solar wind energy into the magnetosphere (Tsurutani & Gonzalez 1997; Feldstein et al. 2003). Subsequently, the transferred solar wind energy is redistributed into different regions of the magnetosphere, generating various current systems through the interaction between highly energetic charged particles and geomagnetic field lines.

Evolution of geomagnetic storms takes place in several phases. The passage of supersonic solar ejecta through the solar wind produces shock waves in the interplanetary medium, ahead of the ejecta. The impact of shock waves on the magnetopause compresses the magnetosphere producing a sudden hike in the horizontal component (H) of the geomagnetic field, known as storm sudden commencement (SSC). After the energy injection into the magnetosphere, that occurs on the arrival of solar ejecta at the magnetopause, the energetic protons and ions in the energy range between ∼20 to ∼300 keV are trapped in the geomagnetic field lines and gyrate around the ambient field as a result of the Lorenz's force. These ions also experience a westward drift owing to the presence of gradients and curvatures in the geomagnetic field. The energetic electrons, on the other hand experience an eastward drift due to gradients and curvatures of the geomagnetic field. The drift between ions and electrons generates a toroidal current in the region from ~ 2 R_E to 7 R_E and is known as the ring current (Singer 1957; Daglis et al. 1999). This in turn induces a magnetic field opposite to the ambient geomagnetic field, reducing the intensity of earth's magnetic field and identified as a sharp depression in the geomagnetic field (ΔH), as recorded in magnetic records. The period between the onset of actual depression in ΔH and minimum value attained by ΔH is called the main phase of geomagnetic storm. Subsequently, the ring current particle population diminishes through the major process of charge exchange and the energy dissipates in a period ranging from few hours to days, leading to the recovery of the geomagnetic field to its pre-storm quiet conditions and this phase is called as, recovery phase of magnetic storm.

Response of the magnetosphere is different for different interplanetary conditions, resulting in a variety of geomagnetic storms. Great deal of work has been done to investigate the interplanetary causes of geomagnetic storms (Burton et al. 1975; Gonzalez & Tsurutani 1987; Gosling et al. 1991). The crucial role of meridional component (B_z) of IMF is discussed in particular for the intensification of storms (Gonzalez et al. 2002). Effect of dawn-dusk component (B_y) of IMF for magnetic reconnection and convection has been discussed by Crooker (1979) and Gosling et al. (1985). For the IMF $B_y < 0$, magnetic reconnection occurs at the north-dusk and south-dawn flanks of the magnetopause. In other words, in the presence of positive (> 0) B_y, the tailward convection is deflected duskward (dawnward) in the dayside and then dawnward (duskward) in the nightside.

The present study deals with several intense storms within the period of 2000-2005, that covers solar maximum and descending phase of solar cycle. Investigation is carried out to examine the contribution of IMF B_y and B_z components in particular.

2. Data selection and set

The geomagnetic activity can be expressed by several magnetic indices. For low latitudes, the most accepted index is the disturbance storm time (D_{st}) derived by Sugiura (1964). On the basis of D_{st} index, we have identified several intense storms ($D_{st\_min} \leq -200$ nT), using the hourly values of D_{st} obtained from Kyoto World Data Center. The study uses interplanetary and solar wind data, with time resolution of 5 minutes that is extracted from SWEPAM and MAG instruments onboard ACE satellite at L1 Lagrangian point ($\sim$ 240 R_E) upstream solar wind. ACE data set provides solar wind velocity (V_{sw}), proton density (N_p) (from SWEPAM), IMF components B_y, B_z and total $|B|$ (from MAG). Also solar wind data is taken from (PM) onboard SOHO satellite ($\sim$ 240 R_E). Low latitude variations in response to the changing IMF conditions are observed through low latitude geomagnetic digital data with 1-min time resolution from Alibag observatory (geographic lat. 18° 37′ N, long. 72° 52′ E; geomagnetic lat. 9.7° N, long. 145.6°).

Solar wind-magnetosphere coupling was quantified by the pointing flux parameter proposed by Perreault & Akasofu (1978) and can be written as

$$\varepsilon = V_{sw} B^2 \sin^4(\theta/2) l_0^2, \tag{1}$$

where, V_{sw} is the solar wind velocity, $|B|$ is magnitude of total interplanetary magnetic field, θ is arctan (B_y/B_z) for $B_z > 0$ and 180°-arctan (B_y/B_z) for $B_z \leq 0$, l_0 is the dayside magnetopause scale length and is equal to 7R_E.

Akasofu (1981) quantitatively estimated the total energy consumption rate for magnetospheric energy. Intensity of geomagnetic storms is primarily represented by the intensification in the ring current energy, which is caused by energy injection in magnetotail. The ring current injection rate can be estimated by combining the energy balance equation with Dessler-Parker-Schopke (DSP) relationship, (Akasofu 1981)

$$U_{RC} = -0.74 \times 10^{10} \left(\frac{dD^*_{st}}{dt} + \frac{D^*_{st}}{\tau} \right), \tag{2}$$

where, D^*_{st} is the pressure corrected D_{st} (Burton et al. 1975). The pressure correction was incorporated in the calculation of U_{RC}, in order to avoid the interference of magnetopause currents due to dynamic pressure.

Two main energy sinks in the ionosphere for the solar wind energy are Joule dissipation (U_J) and auroral particle precipitation (U_A). Joule dissipation is controlled by Pedersen conductivity in the ionosphere, and the auroral particle precipitation leads to increase in Hall currents. The joule heating rate (U_J) and auroral particle precipitation (U_A) were approximated by the following relationship to the auroral electrojet (AE) index (Akasofu 1981)

$$U_J = 2 \times 10^8 AE, \tag{3}$$

$$U_A = 1 \times 10^8 AE. \tag{4}$$

3. Results and discussions

Solar cycle-23 evidenced many intense storm events during maximum and descending phase. For assessing the role of interplanetary conditions in guiding the dynamics associated with geomagnetic field variations, several great storm events are studied. The events are selected with $D_{st\_min} \leq -200$ nT and total 13 events are identified between 2000 and 2005. The most intense storm event of solar cycle-23 occurred on 20 November 2003 and is discussed further in detail with respect to solar and interplanetary conditions.

3.1 A case study of intense magnetic storm of 20 November 2003

This is the most intense magnetic storm ($D_{st\_min} \sim -472$ nT) of the current solar cycle. The event originated from X-ray solar flare (M3.2) that occurred on 18 November 2003 at 0723 UT (recorded by GOES-8). Following this a halo CME was observed by LASCO/SOHO with a speed of 1660 kms^{-1} on 18 November 2003 at 0819 UT. On 20 November 2003, the fast halo CME drove an interplanetary shock, observed by ACE (L1 point, $\sim$240 R_E) at 0720 UT, featured by sudden increase in all solar wind parameters and IMF $|B|$. Fig. 1 illustrates solar wind velocity (V_{sw}), proton density (N_p) and IMF $|B|$ increased to values $\sim$ 620 kms^{-1}, $\sim$ 18 cm^{-3} and $\sim$ 22 nT respectively. After the shock IMF $|B|$ increased to larger values peaking later to values as high as $\sim$ 56 nT and IMF B_z was predominantly southward just after the shock till 0955 UT on 20 November 2003, when it turned sharply northward followed shortly by southward traversal at 1050 UT. Southward orientation prevailed for $\sim$ 13 hr with a peak of ~ -50 nT. Large dusk-ward directed B_y and southward directed B_z were observed to occur with some time lag. Peak B_y (dusk-ward) increased to $\sim$ 40 nT. After $\sim$ 45 minutes from interplanetary shock (IPS) at ACE, the increase in solar wind dynamic pressure ($\sim$ 12 nPa) produced magnetopause compression marked by storm sudden commencement (SSC) at 0805 UT with amplitude $\sim$ 25 nT. The epsilon function increased to $\sim 9.8 \times 10^{11}$ Watts during the shock passage (0720 UT) when B_z was southward (-10 nT). Later on with B_z turning largely southward, energy input is enhanced considerably to values as high as $\sim 3.6 \times 10^{13}$ Watts. Main phase depression observed in $\Delta \mathrm{H}_{ABG}$ started shortly after the SSC in consistence with southward B_z on 20 November 2003 and the main phase (1156-1911 UT) prevailed for $\sim$7 hrs followed by rapid recovery. Main phase for this intense storm event reached a maximum magnitude of $\sim$ 626 nT at Alibag when D_{st} attained a peak of -472 nT. Large fraction of solar wind energy input to the magnetosphere under the favourable IMF B_z conditions contributed to the large ring current development for this intense storm event ($D_{st} \sim -472$ nT).

3.2 IMF $\mathbf{B}_z$ and storm intensity

Table 1 gives a list of 11 out of total 13 intense magnetic storms with $D_{st\_min} \leq -200$ nT that occurred during the period from 2000 to 2005. All the 11 selected events are associated with single interplanetary shock driven by single solar emissions; whereas, rest of the two events of 11 April 2001 and 7 November 2004 are associated with two or more shocks and therefore are excluded here. Table 1 summarizes the energetic budget of the 11 events. Maximum values for energy rate during the storm duration are indicated below. Minimum values of ΔH_{ABG} and D_{st} give the largest deviation of these quantities from zero level. For some events the data loss occurred due to satellite degradation caused by heavy proton showers. For such events, few energy functions could not be computed and they are represented by dash (–) in the table.

The crucial role of meridional component (B_z) for the storm intensification has been proposed many a time. Gonzalez & Tsurutani (1987) and Gosling et al. (1991) analyzed intense geomagnetic storms ($D_{st} < -100$ nT) for a period of 500 days and suggested critical values of IMF B_z (~ -10 nT) for long duration ($>$ 3 hr) as important interplanetary cause for intense geomagnetic storms. This crucial role of southward interplanetary magnetic field has been re-confirmed by Tsurutani & Gonzalez (1997), O'Brien et al. (2000) and Wang et al. (2003). Their work suggests the existence of threshold for IMF B_z for the initiation and strengthening of the ring current. Significant increase in the ring current may not result even though IMF B_z, below threshold values, persists for a longer time.

In our study, we investigate the dependence of storm intensity on post shock southward duration (T_{Bs}), which is defined as, the time interval between the onset of sharp southward traversal of B_z after the shock impact and subsequent northward orientation during the storm. Fig. 2 depicts the correspondence between T_{Bs} and D_{st_min}. A good dependence (R = 0.79) of storm intensity on the duration of southward B_z during the main phase of storms is distinctly seen. Noticeable observation from the study of these 11 events is the existence of large peak of B_z after the shock, with $B_{z\_min} < -25$ nT and subsequent development of the main phase intensity.

Thus, under the conditions of prolonged southward directed B_z with significant magnitude, the rate of magnetic reconnection increases, which leads to increase in energy transfer and consequently the reinforcement of ring current energy. Our result is in good agreement with the criteria proposed for storm intensification (Wang et al. 2003). For the storm events of 12 August 2000 and 17 September 2000, the main phase developed after long period ($>$ 12 hrs) following the shock due to unsteady B_z. As seen from the scatter plot (Fig. 2), 6 April 2000 and 31 March 2001 storms do not fit in the trend; it

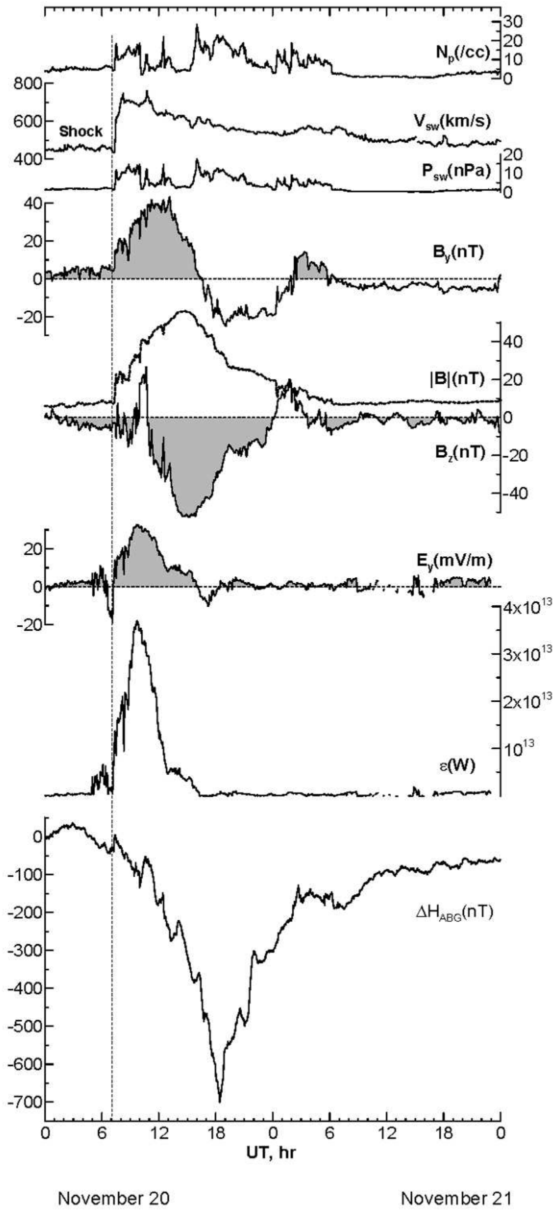

Figure 1. Reproduced above are the solar wind and interplanetary conditions for the 20-21 November 2003 storm. From the top are, Np, V_{sw}, P_{sw}, IMF B_y, B_z, $|B|$, E_y, ε and variations in the horizontal component of geomagnetic field (ΔH_{ABG}).

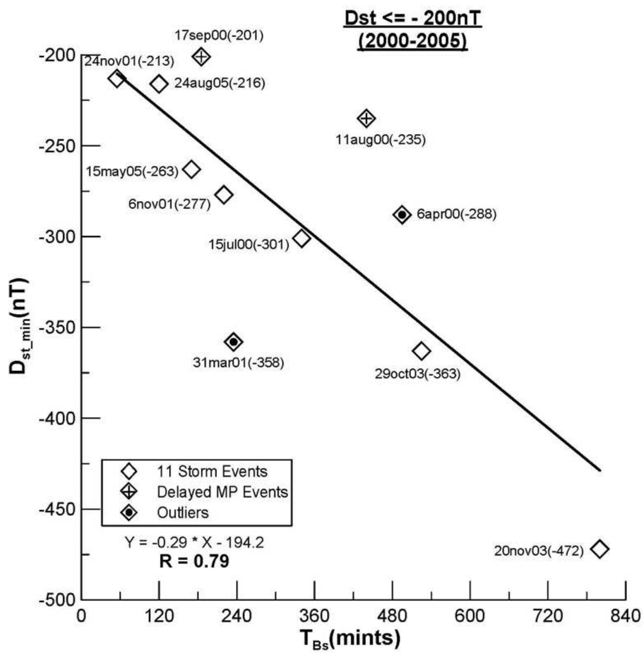

Figure 2. Above figure represents the dependence of storm intensity on T_{Bs}, defined as the duration of post-shock southward B_z during the storm period of events.

Table 1. Storm events examined during 2000-2005 and their characteristics. Events are listed in increasing order of D_{st_min} (i.e., D_{st} magnitude).

Storm events	$Bz_{\_min}$ (nT)	ΔH_{ABG_min}	D_{st_min}	$(\varepsilon_{\_max})$ (GW)	U_{RC_max} (GW)	U_{J_max} (GW)	U_{A_max} (GW)	U_{tot_max} (GW)
17 Sep 2000	−29.4	−223	−201	14,301	169	518	259	946
24 Nov 2001	−36.3	−344[1]	−213	10,440	–	601	301	–
24 Aug 2005	−55.4	−324	−216	39,493	153	662	331	1,147
11 Aug 2000	−16.7	−294	−235	12,063	465	539	269	1,274
15 May 2005	−44.4	−330	−263	47,386	–	369	184	–
6 Nov 2001	−77.2	−346	−277	35,981	–	578	289	–
6 Apr 2000	−31.9	−350	−288	12,526	609	422	211	1,242
15 Jul 2000	−57.3	−418	−301	–	–	2,588	1,294	–
31 Mar 2001	−46.3	−392	−358	30,806	974	451	225	1,101
29 Oct 2003	−28.7	−367	−363	45,320	794	2,054	693	3,541
20 Nov 2003	−52.7	−700	−472	28,259	1,140	1,622	553	3,315

[1] ΔH_{min} taken from Vishakhapatnam (VSK) as data was bad for Alibag observatory for 24 November 2001 storm.

could be attributed to the variation pattern of IMF B_y component. Significant dawnward B_y during the southward incursion of B_z supports the intensification of ring current for

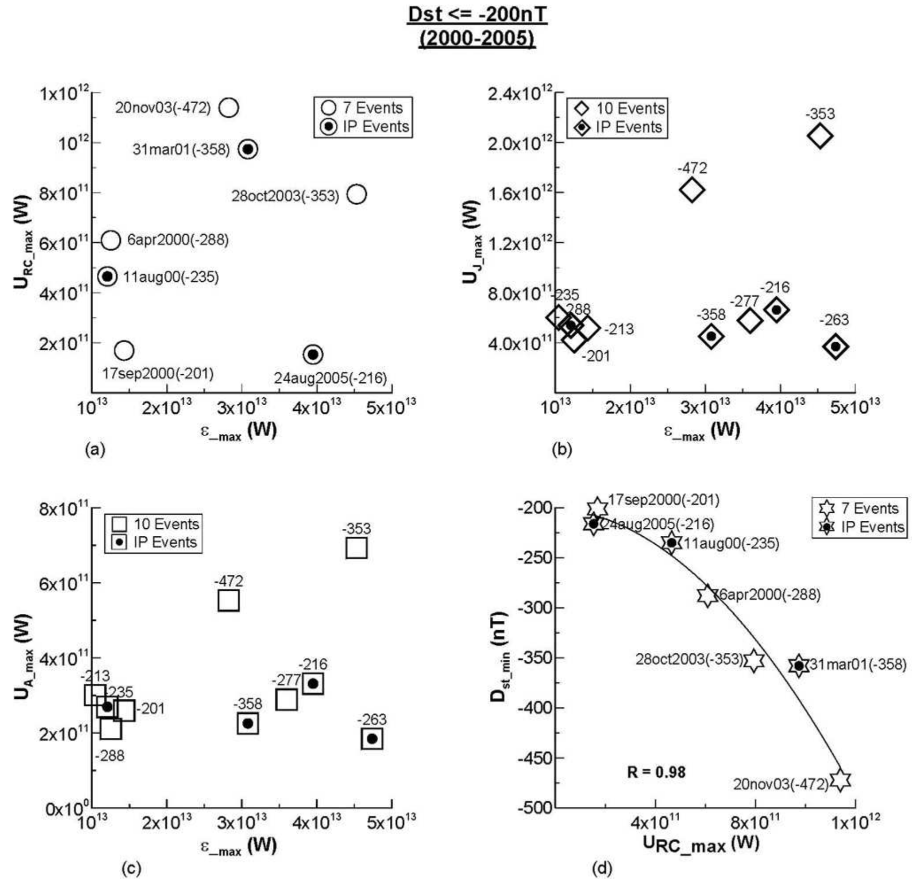

Figure 3. For the duration of years 2000-2003, shown above are (a) correspondence of maximum energy transferred into the magnetosphere (ε), with ring current injection rate (U_{RC}) and (b) correspondence of maximum ϵ with maximum joule dissipation power (U_J). Fig. 3 (c) shows the percentages of U_{RC}, U_J, U_A in response to ε.

all 7 events, whereas 6 April 2000 has insignificant magnitude of dawnward B_y and 31 March 2001 has fluctuating B_z in the period of dawnward B_y.

3.3 Energy estimate

The total energy transferred into the magnetosphere is distributed into various regions and the energy consumption rate (U_{RC}, U_J, U_A) at these regions differs for each storm. Figs 3a–c display qualitative distribution of total energy transferred into the magnetosphere (represented by $\varepsilon_{\_max}$) amongst three major sinks for 7 intense storms ($D_{st\_min} \leq -200$ nT) from years 2000-2005.

It can be clearly seen from three scatter plots (Fig. 3a – Fig. 3c) that the correspondence of U_{RC}, U_J, U_A with ε for the intense magnetic storms does not exhibit any significant pattern. For storms with large energy input (ε), as for the 28 October 2003 and 24 August 2005 cases, the ring current injection rate is lesser than other events for which ε is relatively lesser like the events of 31 March 2001 and 20 November 2003 (Fig. 3a). Joule dissipation (U_J) and auroral particle precipitation (U_A) rates are illustrated in Fig. 3b and Fig. 3c. Large values of U_J and U_A are distinctly observed for the cases for which U_{RC} was lesser. Therefore, giving a clear idea that for some storms, ring current fraction is more intensified as compared to Joule dissipation and auroral particle precipitation and vice-versa, depending on changing interplanetary and solar wind conditions.

The distribution proportionality of solar wind energy input into various regions of magnetosphere differs to a large extent from one storm to another. Initial phase storms are also investigated and no significant pattern is detected in such cases also. Reproduced in Fig. 3(d) is the correspondence of ring current energy injection rate and intensity (D_{st_min}) of magnetic storms for 7 intense events. Storm intensification shows a clear dependence on U_{RC} with R = 0.98, and is well defined by a second order fit.

It is clearly observed that amongst all the events, U_{RC} is largest for 20 November 2003 storm event, and can be ascertained as a cause for huge intensification of the storm $D_{st\_min} = -472$ nT (Fig. 3d).

3.4 Storm intensity dependence on IMF B_y

Earlier studies have shown that for positive IMF B_y, the reconnected flux tubes get azimuthally accelerated, such that those connected to the southern (northern) hemisphere, move duskward (dawnward) (Gosling et al. 1990; Cowley et al. 1991; Khurana et al. 1996). From our study of the selected storms, it has been found that the zonal component, B_y of IMF plays a substantial role for the development of intense main phase in the presence of significant southward B_z component.

Fig. 4 reproduces this observation, wherein T_{lag} is plotted with D_{st_min}. T_{lag} is defined as the difference between onset timings of substantial duskward B_y and subsequent sharp southward B_z after the shock impact. Logarithmic fit well defines the correspondence (R = 0.95). The three events of 6 November 2001, 24 November 2001 and 28 October 2003 do not fit in the trend. All these events showed double dips in main phase. Also depicted in Fig. 4 are initial phase storms marked by circles enclosing filled circles which exhibit good dependence of storm intensity on T_{lag}.

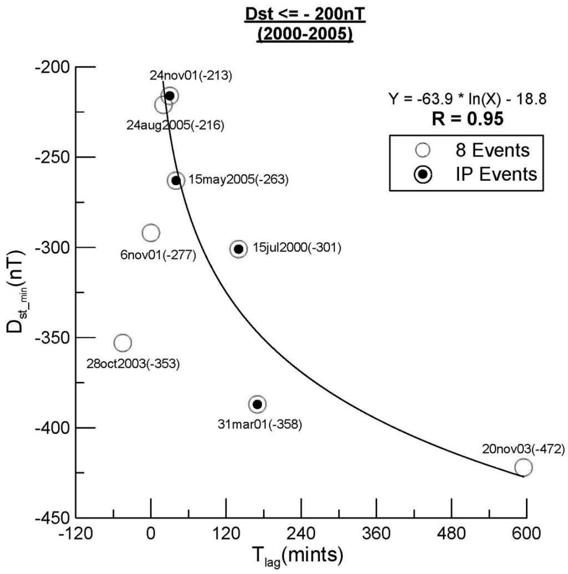

Figure 4. The correspondence between T_{lag} and minimum D_{st} attained for 8 intense storm events. T_{lag} is defined as the difference between onset times of significant duskward B_y and southward turning of B_z.

4. Conclusions

1. The crucial role of IMF B_z is examined for the intense storms and earlier results for the dependence of storm intensity on the duration and magnitude are verified.

2. Estimation of total solar wind energy distributed in various sinks in the magnetosphere clearly gives an idea that irrespective of total quantity of energy fed into the magnetosphere, the percentage of U_{RC}, U_J, U_A may vary from one storm to other in response to changing solar wind and IMF conditions. Significant role is played by ring current energy for the storm intensification. However, for large storms substantial fraction of energy is supplied to ionosphere also, as inferred from Joule dissipation and auroral particle precipitation estimates.

3. For the intense magnetic storms presented in our study, the estimation of energy budget shows that about 8% on average of total energy injected into the magnetosphere (ε) is distributed in various regions of the magnetosphere as, U_{tot}, which consists contribution of ring current, Joule dissipation and auroral particle precipitation. The remaining fraction of energy must be stored and dissipated in the magnetotail and field aligned currents.

4. A key result obtained from our study is substantial dependence of storm intensity on the two IMF components, namely zonal (B_y) and meridional (B_z). Duskward orientation of B_y followed by southward incursion of B_z seems to aid the storm

strength. Thus, time lag between the onset timings of dusk-ward B_y and southward B_z can be ascertained as one of the precursory factor for assessing the main phase magnitude and thus the storm intensity.

Acknowledgements

The authors are thankful to CELIAS/MTOF experiment on the Solar Heliospheric Observatory (SOHO) spacecraft for providing the solar wind and the interplanetary data. SOHO is a joint European Space Agency (ESA) and United States National Aeronautics and Space Administration (NASA) mission. We thank ACE SWEPAM instrument team and the ACE Science Center for providing the interplanetary data. We acknowledge WDC, Kyoto for providing the *AE* and *Dst* indices. We also thank NASA website from where coronal mass ejection information was extracted. This CME catalog is generated and maintained by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. G. S. Lakhina thanks the Council of Scientific and Industrial Research, Government of India, for providing support under emeritus scientist scheme.

References

Akasofu, S. I., 1981, SSRv, 28, 121
Burton, R. K., McPherron, R. L., & Russell, C. T., 1975, JGR, 80, 4204
Cowley, S. W. H., Morelli, J. P., & Lockwood, M., 1991, JGR, 96, 5557
Crooker, N. U., 1979, JGR, 84, 951
Daglis, I. A., Thorne, R. M., Baumjohann, W., & Orisini, S., 1999, RvGeo, 37, 407
Dungey, J. W., 1961, PhRvL, 6, 47
Feldstein, Y. I., Dremukhina, L. A., Levitin, Mall, U., A. E., Alexeev, I. I., & Kalegaev, V. V., 2003, JASTP, 65, 429
Gonzalez, W. D., & Tsurutani, B. T., 1987. P&SS, 35, 1101
Gonzalez, W. D., Tsurutani, B. T., & Clúa de Gonzalez, A. L., 1999, SSRv, 88, 529
Gonzalez, W. D., Tsurutani, B. T., Lepping, R. P., & Schwenn, R., 2002, JASTP, 64, 173
Gosling, J. T., Baker, D. N., Bame, S. J., Feldman, W. C., Zwickl, R. D., & Smith, E. J., 1985, JGR, 90, 6354
Gosling, J. T., Thomsen, M. F., Bame, S. J., Elphic, R. C., & Russell, C. T., 1990, JGR, 95, 8073
Gosling, J. T., McComas, D. J., Phillips, J. L., & Bame, S. J., 1991, JGR, 96, 7831
Khurana, K. K., Walker, R. J., & Ogino, T., 1996, JGR, 101, 4907
O'Brien, T. P., & McPherron, R. L., 2000, JGR, 105, 7701
Perreault, P., & Akasofu, S. I., 1978, GeoJRAS, 54, 547
Singer, S, F., 1957, Eos Transactions. AGU, 38, 175
Sugiura, M., & Chapman, S., 1960, Abandl. Akad. Wiss., Gottingen Math. Phys. K1 (4)
Sugiura, M., 1964, Annual International Geophysical Year 35, 945
Tsurutani, B. T., & Gonzalez, W. D., 1997 in Magnetic Storms, eds B. T. Tsurutani et al., Geophysical Monograph Series, 98, AGU, Washington, 77
Wang, C. L., Shen, C. L., Wang, S., & Ye, P.Z., 2003, GeoRL, 30, 2039