On magnetic storms and substorms

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Abstract. Magnetospheric substorms and storms are indicators of geomagnetic activity. Whereas the geomagnetic index AE (auroral electrojet) is used to study substorms, it is common to characterize the magnetic storms by the Dst (disturbance storm time) index of geomagnetic activity. This talk discusses briefly the storm-substorms relationship, and highlights some of the characteristics of intense magnetic storms, including the events of 29-31 October and 20-21 November 2003. The adverse effects of these intense geomagnetic storms on telecommunication, navigation, and on spacecraft functioning will be discussed.

Index Terms. Geomagnetic activity, geomagnetic storms, space weather, substorms.

1. Introduction

Magnetospheric storms and substorms are indicators of geomagnetic activity. Where as the magnetic storms are driven directly by solar drivers like Coronal mass ejections, solar flares, fast streams etc., the substorms, in simplest terms, are the disturbances occurring within the magnetosphere that are ultimately caused by the solar wind. The magnetic storms are characterized by the Dst (disturbance storm time) index of geomagnetic activity. The substorms, on the other hand, are characterized by geomagnetic AE (auroral electrojet) index.

Magnetic reconnection plays an important role in energy transfer from solar wind to the magnetosphere. Magnetic reconnection is very effective when the interplanetary magnetic field is directed southwards leading to strong plasma injection from the tail towards the inner magnetosphere causing intense auroras at high-latitude nightside regions. The solar wind energy input in the magnetosphere is ~ 10^{11} W during substorms and it is ~ 10^{13} W during moderate magnetic storm. The basic process of energy transfer remains the same, i.e., magnetic reconnection, but it occurs on different time and spatial scales.

Magnetospheric substorms usually last for a period ~ one to a few hours. During substorms there is an explosive release of stored magnetotail energy in the form of energetic particles (~ 5-50 keV) and strong plasma flows (~ 100-1000 km/s or so) and dissipated in the near-Earth nightside auroral region. This results in the excitation of discrete auroras which become widespread and intense, also much more agitated. The Earth's magnetic field gets disturbed due to intensified field-aligned currents and auroral electrojets. Fig. 1 shows the aurora observed over Indian Antarctic station Maitri.

Geomagnetic storms are characterized by a *Main Phase* during which the horizontal component of the Earth's low-latitude magnetic fields are significantly depressed over a time span of one to a few hours followed by its *recovery* which may extend over several days (Rostoker, 1997).

Fig. 1. Pictures of aurora taken at Indian station Maitri at Antarctica on 19 June, 2003 by Dr. Arun Hanchinal, IIG, Navi Mumbai.

Geomagnetic storms occur when solar wind-magnetosphere coupling becomes intensified during the arrival of fast moving solar ejecta like interplanetary coronal

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mass ejections (ICMEs) and fast streams from the coronal holes, etc. accompanied by long intervals of southward interplanetary magnetic field (IMF) as in a "magnetic cloud" (Klein and Burlaga, 1982). As mentioned earlier the major mechanism of energy transfer from the solar wind to the Earth's magnetosphere is magnetic reconnection (Dungey, 1961). The efficiency of the reconnection process is considerably enhanced during southward IMF intervals (Gonzalez et al., 1989; Tsurutani and Gonzalez, 1997), leading to strong plasma injection from the magnetotail towards the inner magnetosphere causing intense auroras at high-latitude nightside regions. Further, as the magnetotail plasma gets injected into the nightside magnetosphere, the energetic protons drift to the west and electrons to the east, forming a ring of current around the Earth. This current, called the "ring current", causes a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial magnetic stations. The decrease in the equatorial magnetic field strength, measured by the Dst index, is directly related to the total kinetic energy of the ring current particles; thus the Dst index is a good measure of the energetics of the magnetic storm. The Dst index itself is influenced by the interplanetary parameters.

Here we shall discuss first the relationship between magnetic storms and substorms, and then some characteristics of intense magnetic storms including October-November 2003 intense magnetic storm events.

2. Magnetic storm–substorm relationship

In the earlier view, magnetic storms are caused by frequent occurrence of intense Substorms (Akasofu and Chapman 1961). This view was substantiated further by the observations of energetic particles transported impulsively from the plasma sheet into the outer region of the ring current region during substorms (McIlwain, 1974).

The modern view is that the magnetic storms are driven by the enhanced magnetospheric convection from sustained southward interplanetary magnetic fields (Kamide 1992). The particles residing in the plasma sheet can be transported closer to the Earth by a large magnetospheric electric field arising from the interaction of strong southward IMF with the geomagnetic field. Enhancement in the dawn to dusk magnetospheric electric field allows a deeper penetration of energetic plasma sheet particles Earthward by overpowering the azimuthal deflection of the particles due to gradient and curvature drifts. Above two views of the magnetic storms are illustrated schematically in Fig. 2 (Lui, 2003).

We shall first briefly describe the studies supporting the idea of frequent substorms as driver for magnetic storm. Analyzing the magnetic perturbations from the world wide observatory network by natural orthogonal components technique, two prominent current patterns are found; a two-cell current pattern associated with the magnetospheric convection which is correlated well with solar wind parameter but poorly with Dst, and an impulsive one-cell system, well- known to be associated with the substorm. It is highly correlated with the Dst and poorly with the solar wind. Such a separation of magnetic observatory network data into convection and substorm components strongly supports the idea of substorms driving the magnetic storm (Sun et al., 1998; Sun and Akasofu, 2000).

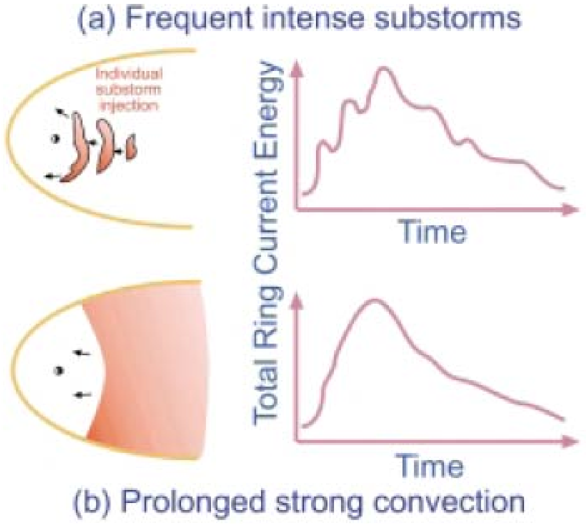

Fig. 2. Shows schematically two driving mechanisms of magnetic storms (Lui, 2003)

Numerical simulations of ring current with impulsive electric fields mimicking the substorm effects indicate that a stronger ring current than one that can be produced from only a convection electric field is generated (Fok et al., 1999).

There are several studies that support the convection as driver for magnetic storm. The Dst index can be predicted well using interplanetary conditions alone (Burton et al., 1975; Kamide et al., 1998). This idea is further strengthened by the fact that intense magnetic storms are found during long duration (>3-5 hrs) of southward IMF, a condition favoring strong dawn-to-dusk magnetospheric electric field (Gonzalez and Tsurutani, 1987).

A superposed epoch analysis shows a decrease in the rate of development of Dst index with substorm occurrence, contrary to the view that substorm contribute to the build-up of the ring current as measured by Dst index (Iyemori and Rao, 1996). Numerical simulations of enhanced magnetospheric convection indeed show build-up of ring current without including the impulsive injection from substorm (Chen et al., 1994).

Tsurutani et al. (2003a) did not find substorms (i.e., substorm expansion phases) in a limited subset of magnetic storms, those that were caused by interplanetary magnetic cloud magnetic fields. Further, Tsurutani et al. (2004) looked at the converse of storm-substorm relationship also, and found intervals where there were very intense substorms without magnetic storms. These events are now called as high intensity long duration continuous AE activity (HILDCAAs).

We would like to make a few more comments on the magnetic storm-substorm relationship. It is noticed that interplanetary electric fields Ey (dawn-dusk component corresponding to southwards IMF) play important roles in both magnetic storms and substorms activity. It is believed that fluctuating E_y gives rise to substorms and quasi-steady E_y can drive magnetic storms (Kamide, 2001). Further, it is believed that substorm onset is triggered by some plasma instabilities, e.g., ion tearing (Schindler, 1974; Lakhina and Schindler, 1988), shear flow (Kakad et al., 2003), cross-field current instability (Lui et al., 1992), ballooning modes (Ohtani and Tamao, 1993; Liu, 1997), lower hybrid (Huba et al., 1977), helicon modes (Lakhina and Tsurutani, 1997) etc. Magnetic storms, on the other hand, are driven by the interplanetary conditions and not by any internal plasma instability of the magnetosphere. Plasma instabilities, however, could be important during the main as well as the recovery phase. Role of electromagnetic ion cyclotron modes (Horne and Thorne, 1994; Fok et al., 1996) and Quasi-electrostatic modes in ring current decay has been studied in the literature (Lakhina and Singh, 2003; Singh et al., 2004; 2005). The magnetic storm-substorm relationship is an active topic of debate. More details on this can be found in Sharma et al. (2003).

3. Some characteristics of intense geomagnetic storms

We studied 9 intense magnetic storms (Dst < - 175 nT) that occurred during the period from 1998 to 2001. Ground magnetometer digital data of Alibag (9 deg North) Magnetic Observatory and Maitri (66 deg South), Antarctica have been used. Plasma and magnetic field data from NASA's Advanced Composition Explorer (ACE) spacecraft have been used to find the effects of interplanetary parameters that cause intense storm. Geomagnetic indices, like, disturbance storm time (Dst) index, and Auroral Electrojet (AE) index have been used to compute the energy budget of intense storms.

In Fig. 3 we have shown variation of Dst against the main phase duration (panel a), duration of southward IMF versus main phase interval (panel b) and Dst against magnitude of maximum southward IMF (panel 3), for all 9 intense storms studied by us (Vichare et al., 2005). In Fig. 3(a), a label on a point corresponds to the event number as listed in Table 1. The scatter plot of Fig. 3(a) shows a large scatter indicating no clear dependence of the main phase with intensity of the storm. However, it is noticed that all magnetic cloud events (labeled by 2, 5, 6, and 9) lie on the right hand side and indicate inverse proportionality of Dst deviation with the main phase duration, which is not in agreement with the earlier statistical study by Yokoyama and Kamide (1997) for the period between 1983 and 1991. The underlined conclusion apparently disagree with statistical study of Yokoyama and Kamide (1997). One reason for the disagreement may be that we have studied only a few cases of intense storms. The other reason may be that our study is individual storm based, the analysis of Yokoyama and Kamide (1997) considers the average values of Dst index for different categories of magnetic storms. From Fig. 3(b), it is evident that the main phase duration shows a clear dependence on the duration of southward IMF. The intensity of the storm increases with the magnitude of the southward IMF (see Fig. 3(c)).

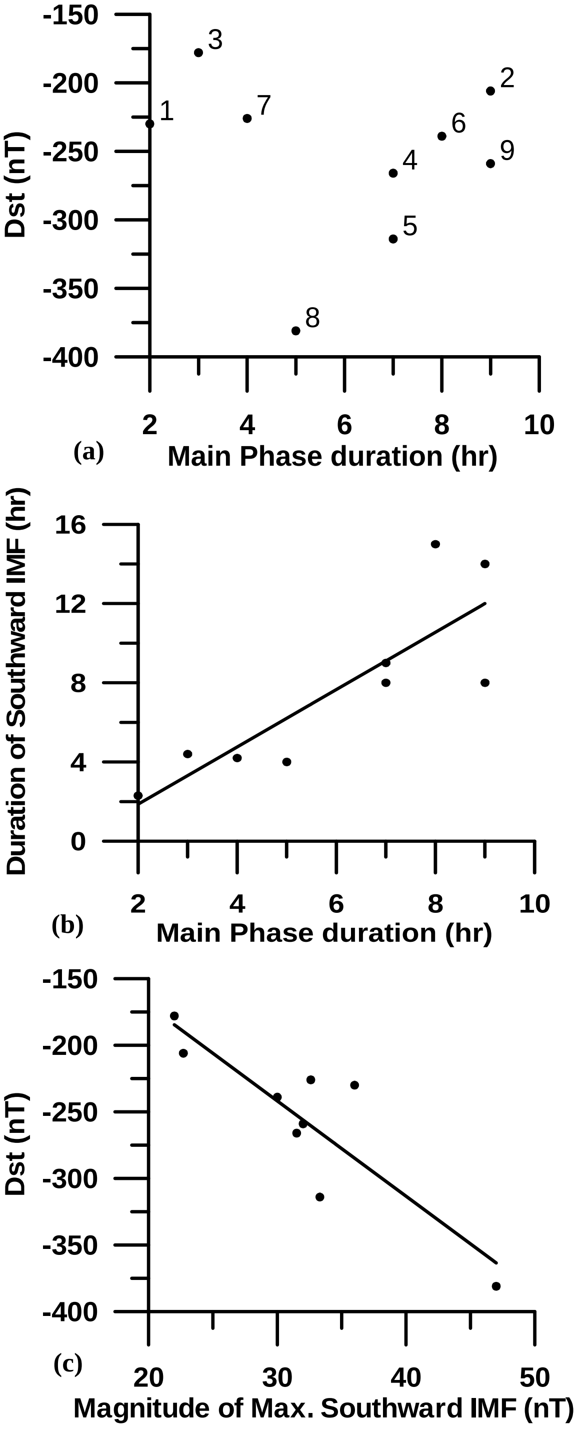

Fig. 3. shows a scatter plots of maximum deviation of Dst verses main phase duration (a), duration of southward IMF verses main phase duration (b), and maximum deviation of Dst verses maximum southward IMF (c) (Vichare et al., 2005). In panel a, each point is labeled by the serial number of the event shown in table 1.

Table 1. Characteristics of 9 Intense Geomagnetic Storm Events Studied.

Sr. No.	Date	Dst* (pressure corrected) Min (nT)	Time delay for shock to get recorded at ground station (min)	Main phase duration (hr)	Bz Magnitude of Max Southward IMF (nT)	Duration of southward IMF (hr)	Comment
1	4 May 98	-230	30	2	36	2.3	No Initial phase
2	25 Sep 98	-206	35	9	22.7	14	Magnetic Cloud
3	22 Sep 99	-178	30	3	22	4.4	Long Initial phase (~7 hr)
4	22 Oct 99	-266	60	7	31.5	8	SSC is seen ~22 hr before storm development. Slow magnetic cloud
5	6 Apr 00	-314	38	7	33.3	9	Magnetic Cloud
6	12 Aug 00	-239	No SSC	8	30	15	Magnetic Cloud
7	17 Sep 00	-226	No SSC	4	32.6	4.2	Disturbed before onset of the storm
8	31 Mar 01	-381	35	5	47	4	Two-step storm
9	11 Apr 01	-259	40	9	32	8	Magnetic Cloud

In order to quantify the energy budget of intense magnetic storms, we computed the solar wind energies, magnetospheric coupling energies, auroral and Joule heating energies and the ring current energies for each storm. It is found that during main phase of the storm, almost 5% of the total solar wind kinetic energy is available for the redistribution in the magnetosphere, whereas during total storm period (main phase + recovery phase) it reduces to 3.5%.

4. Some features of 29-31 October and 20-21 November 2003 magnetic storms

A series of powerful solar flares and CMEs erupted from the Sun during October-November 2003 and caused intense magnetic storms on 29-31 October and 20-21 November 2003. Solar cycle 23 also witnessed several intense solar enegetic particle events (SEP) associated with flare and CME erruptions from the active Sun. We studied these events by using the digital ground magnetic field measurements from the equatorial station Tirunelveli (TIR)(Geogr. 8° 42′ N, 77° 48′ E; Geomag. 0.36° S, 149.78°) and the low latitude station Alibag (ABG) (Geogr. 18° 37′ N, 72° 52′ E; Geomag. 9.7° N, 145.6°) in conjunction with the available parameters of solar wind and interplanetary magnetic field from the satellites. Solar wind data is from the Advanced Composition Explorer (ACE) / Solar Heliospheric Observatory (SOHO) at L_1 point. The solar activity conditions were obtained from the *Report and Forecast of Solar Geophysical Data*. In Table 2, we have given the solar events and ground observations corresponding to October-November 2003 magnetic storms.

Fig. 4 shows the interplanetary magnetic field (IMF) parameters, |B| and its components B_y and B_z measured by ACE (top 3 panels), and the variations of the SYM ‘H’ component of the ring current along with the 'H' component of the geomagnetic field recorded at Alibag and Tirunelveli (bottom 3 panels) for the October 29-31, 2003 event (Alex et al., 2006). Vertical dashed lines indicate arrival of the first shock at ACE at 06:00 UT on October 29 and the second shock at 16:00 UT on October 30, 2003. These shocks are associated with the solar ejecta of the solar flare events of 28 and 29 October 2003 listed in Table 2. The data of SYM ‘H’ and ‘H’ component of ABG and TIR are time shifted by 12 min. to correspond to the interplanetary shock arrival time from the location of ACE to the magnetopause. The impact of the first shock produced storm sudden commencement (SSC) of 113 nT at the equatorial station Tirunelveli and 62 nT at the low latitude station Alibag (bottom 2 panels) on 29 October. The second shock produced SSC of magnitude 45 nT and 47 nT at Tirunelveli and Alibag, respectively, on 30 October 2003. After the passage of the first shock, both B_z and B_y field components of IMF were highly fluctuating for a period of one hour until 0700 UT. The IMF polarity remained northward during the CME passage for sustained periods during a major part of the main phase. Both ABG and

TIR H components show fluctuating negative magnetic fields. However, the oscillating field magnitude tends to become less negative when the interplanetary magnetic field B_z becomes positive but keeps on modulating during the period 0900 UT-1300 UT. When the interplanetary magnetic field component B_z turned southward again, the main phase depression restarted with the decrease of ground magnetic field at the two stations (1300 UT-2400 UT).

Table 2. Solar, Interplanetary and Ground Events Associated with October-November 2003 Geomagnetic Storms.

Solar event	29 October	30 October	20 November
Solar flare	X17/4b	X10/2b	M3.2/2N
Occurrence	28 October /1110UT	29 October /2049 UT	18 November /0723 UT
CME Speed	~2000 km/s	~1950 km/s	~1100 km/s
Transit time	19 hours	19 hours	48 hours
Solar source	S17E04	S17W09	N00E18
Proton events	>10MeV, >100MeV	>10MeV, >100MeV	>2MeV
Shock at 1AU	0600 UT	1600 UT	0740 UT
V_{sw} at 1AU	~1850 km/s	~1710km/s	~750 km/s
IMF B_Z min (nT)/UT	-27 / 18:09	-32.5/ 19:04	- 48 / 15:20
Duration of southward IMF B_Z (hr)	10	6	12
Dst*	-358 nT	-406 nT	-491 nT
SSC onset	0612 UT	1620 UT	0803 UT

The storm development in this event clearly follows a double storm signature (Kamide et al., 1998). However, starting from 1800 UT onwards sharp and steady southward B_z persists for almost 6 hours leading to an intense geomagnetic storm occurrence with a peak intensity of ~350 nT in Dst at 2400 UT. A slow recovery of the storm followed when a steady rotation of the B_z field occurred. The main phase of 30 October magnetic storm started rather sharply at 1800 UT when the B_z turned southwards and increased to about –32 nT and produced a Dst ~ -400 nT. Abrupt turning of the B_z to northward direction around 2100 UT resulted in the beginning of the recovery.

To get a better understanding of the correlation between the pulsating variations of the ground magnetic field and the corresponding fluctuating interplanetary magnetic field behind the large pressure gradient of the prime shock at 0600 UT on 29 October 2003, we have shown in Fig. 5 a scatter plot of disturbance ‘H’ component of the magnetic field at Alibag and the corresponding interplanetary magnetic field Bz component for the time period of 0615-1400 UT. Lag time of 25 minutes in the Alibag data is considered for this plot. The scatter plot shows the close correspondence for the extreme values of Bz and the dips in the disturbance ‘H’ component. The circled points in the figure indicate the points of coincidence between intense negative Bz peaks (viz.-31.1 nT at 0625 UT, -48.2nT at 0630 UT and -21.1 nT at 0835UT) and the Alibag ‘H’ minimum values (viz. -182.9 nT, -214.1 nT and -212.3 nT).

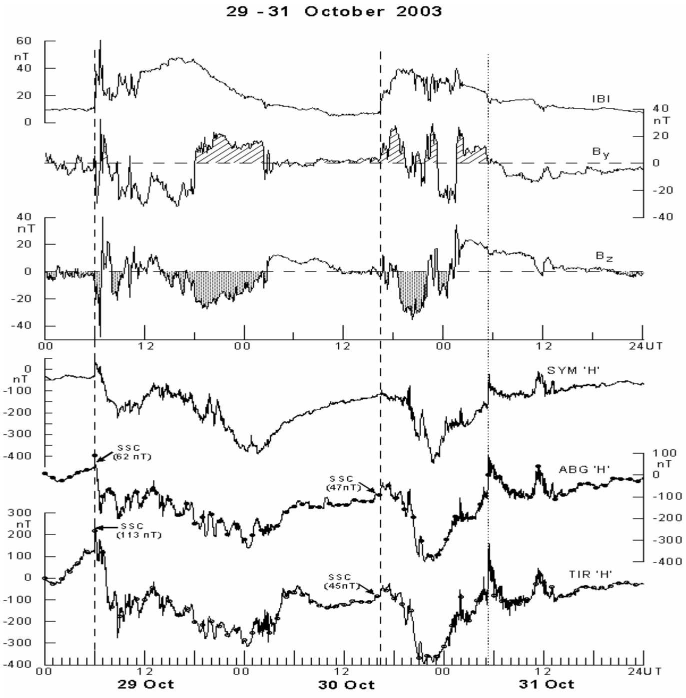

Fig. 4. Interplanetary magnetic field parameters (ACE) of the magnetic storm events during October 29-31, 2003. Vertical dashed lines indicate arrival of the first shock at ACE at 06:00 UT on October 29 and the second shock at 16:00 UT on October 30, 2003 respectively. The arrows show SSC’s at Alibag (ABG) and Tirunelveli (TIR) at 06:12UT on October 29 and 16:20 UT on October 30, 2003. The ground magnetic field data are time shifted by 12 min. to correspond to the interplanetary shock arrival on October 29, 2003. The shaded portion marked by slanted lines show intervals of northward B_y and the dotted portion represents southward B_z. (Alex et al., 2006).

The linear prediction filter method has been employed to study the response of the magnetosphere to the fluctuations in the solar wind energy input (Clauer, 1986; Bargatze et al., 1985; McPherron et al., 1988). The AL index (auroral low, a high latitude index) was used as a measure of substorm activity and the product V_{sw} B_s (where V_{sw} is the solar wind speed and B_s is the magnitude of southward IMF) as the measure of the solar wind energy input. Two dominant peaks were found, the first at a time lag of approximately 20 min and the second at approximately 1 hour for weak to moderately strong geomagnetic activity. The 20 min lag was interpreted as response of the magnetosphere-ionosphere system to solar wind driving, and the 1-hour time lag as the loading –unloading cycle of the substorm (Baker, 1992). In view of this, the plot shown in Fig. 6 strongly suggest that the 25 minutes lag is response time of the magnetosphere-equatorial ionosphere to the interplanetary driving.

Fig. 6 depicts the variation in interplanetary magnetic field parameters |B|, B_y and B_z from ACE/MAG and the variation in the horizontal component of the magnetic field at Tirunelveli and Alibag for the intense storm event during 20 –21 November 2003 (Alex et al., 2006). The shock associated with the M class solar flare on 18 November impacted the magnetopause on 20 November and gave rise to the SSC enhancement of 40nT at Alibag and 100nT at Tirunelveli around 08:03 UT. The IMF B_z turned southward and attained large values of nearly -50 nT for several hours. This lead to an intense main phase with Dst ~ -500 nT. The recovery started with the sharp rotation of B_z to northward at 1800 UT as evident in Fig. 6.

To summarize the main results of October-November 2003 storm events, it is observed that very intense CME associated with 28 October 2003 solar activity failed to produce an equally intense magnetic storm but produced pulsating variations of the ground magnetic field on 29 October 2003, which followed the corresponding fluctuating IMF behind the large pressure gradient of the shock, with a time lag of 25 min; this could be identified as the response time of the magnetosphere to the interplanetary driving. The intensity of the storm is controlled mainly by the magnitude of the peak of the southward component of the IMF B_Z and its duration rather than the speed of the CME ejecta. That is why large southward IMF lasting for a longer time gave rise to more intense magnetic storm on 20 November 2003 despite the low CME speed.

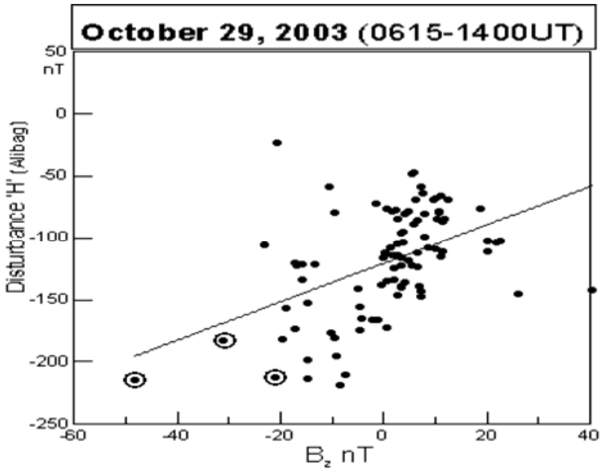

Fig. 5. Scatter plot using disturbance 'H' component (5 minute) of the magnetic field at Alibag and the corresponding interplanetary magnetic field parameter Bz for the time period of 0615-1400UT during the magnetic storm of 29 October 2003. A lag time of 25 minutes for the Alibag data is used (Alex et al., 2006).

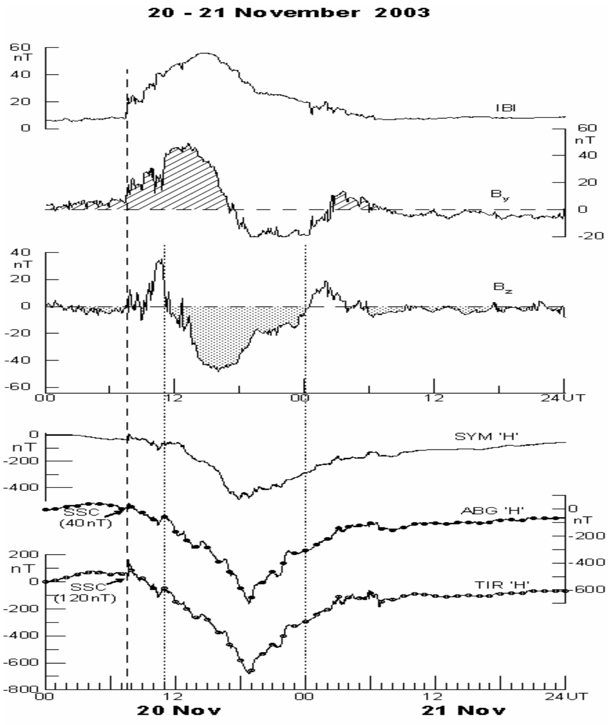

Fig. 6. Interplanetary magnetic field parameters (ACE) during the magnetic storm events on November 20-21, 2003. Vertical dashed line indicates the shock at 07:40UT. The arrows show the occurrence of SSC at 08:03UT at Alibag and Tirunelveli. The one minute data of SYM 'H' and the magnetic field data of the 'H' component of Alibag and Tirunelveli are time shifted by 23 min (Alex et al., 2006).

5. Magnetic storms and society

In modern times, our society is relying more and more on technology that is affected in some way by conditions in the space environment. Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Magnetic storms form a major component of space weather. The most dramatic events on the Sun, in so far as space weather effects are concerned, are solar flares and coronal mass ejections during solar maximum. During the descending phase of the solar cycle, the high speed streams emanating from coronal holes can cause recurrent geomagnetic storms at 27-day interval. Intense and super-intense geomagnetic storms create hostile space weather conditions that can generate many hazards to the spacecraft as well as technological systems at ground. Some adverse effects of intense magnetic storms are life-threatening power outages, failure and malfunctioning of satellite instruments due to deep dielectric charging by relativistic or "killer" electrons. Several NASA mission reported loss of Instrument data, and 2 spacecraft reported instrument damage during 2003 Halloween (i.e., 30-31

October 2003) storms. The Swedish power grid reported failure of transformer at some stations for several hours.

The energy dissipated in the atmosphere during intense magnetic storms produces quick expansion of the thermosphere which give rise to extra drag on the low earth orbiting satellite leading to its reduction of life time or even death. Further, intense magnetic storms can give rise to satellite communication failure, data loss, and Navigational errors. There can also be severe errors in GPS measurements and geophysical surveys. Adverse space weather conditions during intense magnetic storm can pose threat to astronauts and jetliner passenger due to both high radiation dosage and loss of contact with the ground station. Several trans-polar flights were cancelled during October-November 2003 intense magnetic storms. There can be malfunctioning or even permanent damage to spacecraft, e.g., one Japanese spacecraft was probably damaged beyond salvage during October-November 2003 magnetic storms. The geomagnetically induced currents (GICs) during intense magnetic storms can damage power transmission lines and corrode the long pipelines and cables. The most intense magnetic storm in the recorded history of the Earth occurred on 1-2 September 1859 (Tsurutani et al., 2003b) and was driven by a huge solar flare on August 31, 1859 (Carrington 1859, Hodgson 1859). The main phase depression of the H component of the magnetic field (or simply SYM- H) recorded at Colaba Observatory was about –1600 nT (Tsurutani et al., 2003b). If such a super storm were to occur today it would have catastrophic effect on the technological system in space and on ground that are being used by the modern society!

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