Multiple flare occurrences and the geomagnetic storm characteristics during solar cycle 23

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Abstract. High solar activity occurred during solar cycle 23, having its solar maximum peak in the years 2000 and 2001. The dual peak occurrence of the solar activity as seen in 2003, during the descending phase of the solar cycle suggests the geo-effective nature of the solar activity following the solar maximum. The most remarkable series of activities were seen during these times. Major flares are invariably followed by an abrupt increase in the solar radiation emissions from the sun. Active regions in the sun gave rise to a sequence of X- & M- class flares, a number of coronal mass ejections and several major solar energetic particle events of varying amplitudes and characteristics. Following these energetic emissions, the geomagnetic field variations recorded on the ground experienced several storm phenomena in 2005 unlike the 2003 geomagnetic storm events. Storm manifestation process as seen in the equatorial and low-latitude digital magnetic records from Indian longitude are explained in association with the prolonged fluctuations in the interplanetary magnetic field during the descending phase of the solar cycle in contrast to intense storm feature of the events in 2003.

Index Terms. Flares, geomagnetic storms, ring current, interplanetary magnetic field and solar wind parameters.

1. Introduction

Highly dynamic processes associated with the large active regions in the atmosphere of the sun are solar flares and coronal mass ejections (CMEs). The electromagnetic emission related to the flare events are known to produce near instantaneous effects on the horizontal component of the magnetic field over the equatorial and low-latitude locations. Geomagnetic storms are known to be the planetary manifestations of the highly energized release from the solar plasma and coronal magnetic fields (Gosling et al., 1991). However, the differing configuration and dynamics of magnetic fields produce varied magnitudes of geoeffective signatures (Kahler, 1992). Findings by Munro et al. (1979), Hundhausen (1987) and Harrison et al. (1990) reinforced the idea that the conditions that lead to major flares also lead to CMEs in active regions.

The major component of the coupling mechanism, during the interaction of the solar wind at the earth's magnetosphere is known to be the magnetic reconnection between the southwardly directed component of the interplanetary magnetic field and the anti-parallel field at the magnetopause (Dungey, 1961). Gonzalez and Tsurutani (1987), Gonzalez et al. (1989) and Kamide et al. (1998) demonstrated that the dominant interplanetary phenomena causing intense magnetic storms are the interplanetary manifestations of fast CMEs with substantially large magnitudes of southward magnetic field component (Bz). The efficiency of reconnection is shown to be significantly large during the period where interplanetary structures have long duration southward magnetic fields (Gonzalez et al., 1994). Immediate response of the earth's magnetosphere to the dramatically large increase in the solar wind dynamic pressure is the compression on the dayside magnetopause which continues to extend to the tailside (Wilken et al., 1982). The impact of the shock is seen as an enhancement (SSC) in the 'H' component of the magnetic field over the equatorial and low-latitudes. Joselyn and Tsurutani (1990) have expressed the SSC as Sudden Impulse (SI).

2. Database

Major solar flares and CME events occurred from sunspot group 486 (S17E04) during October to November 2003. This region gave rise to a powerful solar flare of X17/4B magnitude on 28 October 2003 at 1110 UT. Sunspot group 488 gave rise to two X-class flares on 03 November 2003, X2 at 0130 UT and an X3/2b at 0955 UT. One of the largest and most significant flare of magnitude X28 occurred from AR486 at 1931 UT on 04 November 2003. The study uses

Table 1. Geographic and Geomagnetic Co-ordinates

Station	Code	Geographic		Geomagnetic		Dip
		Latitude	Longitude	Latitude	Longitude	Lat.
Tirunelveli	TIR	08° 42′N	77° 48′E	0.32°S	149.76°	0.2°N
Pondicherry	PON	11 55	79 55	2.7 °N	152.13	4.8
Visakhapatnam	VSK	17 41	83 19	8.17	155.89	11.5
Alibag	ABG	18 37	72 52	9.64	145.39	13.2
Jaipur	JAI	26 55	75 48	17.99	149.64	23.2
Hanle	HAN	32 47	78 58	23.53	153.2	30.5

digital magnetic records from the Indian longitude chain of observatories, listed in Table 1, run by IIG for the major geomagnetic storms associated with intense solar events during November 2003. Interplanetary magnetic field parameters (GSM co-ordinate data of B_y, B_z and B_{mag}) are taken from the ACE/MAG and WIND satellites. The solar activity conditions were obtained from the *Report and Forecast of Solar Geophysical Data*.

3. Results and discussion

The active sunspots AR 484, 486 and 488 were responsible for the generation of a string of major flares and CME events during the late October and early November 2003. The X17/4B flare from the active group 486 at 1110 UT on October 28 and an earth-directed fast CME gave rise to the Halloween storm of October 2003. Following this, Active Region 488 continued to produce major multiple flares. Two prominent X-class flares occurred on November 03, an X2/Sf at 0130 UT and X3/2b at 0955 UT as observed by GOES 12 X-ray sensor. As a result of these X-class flares, the ground magnetic field variations experienced sudden enhancements in the 'H' and 'D' components. While the geomagnetic signatures of the 'H' component showed marginal increase, the flare occurrence during these active conditions has exhibited a prominent influence in the declination component, alternately the field aligned current pattern over the equatorial and low-latitudes for both the days selected in this study.

Fig. 1 delineates the pattern and the effect of multiple flare occurrences during the descending phase of the solar cycle 23, which was observed on October 28 and November 03, 2003. The one minute digital magnetic data used in the study are from a chain of geomagnetic observatories in the Indian longitude zone (Table 1) ranging from the equatorial station, TIR, to a station in the focal latitude of the Sq current system, HAN. Due to loss of data from Alibag, the variations are discontinuous for the event of November 03. The flare event on October 28 occurred at a time when the geomagnetic activity was not very steady as shown by the Kp index in the bottom panel. This flare event occurred at 1610 LT (1110 UT), when the field was almost at its turning point from its Westerly maximum towards the late afternoon hours.

For the multiple flare occurrences on November 03, the X2 flare at 0630 LT (0130 UT) during the morning hours is seen from the equatorial latitude itself, though with lesser magnitude compared to the afternoon X3 flare event. The X3 flare occurred during the afternoon at local time 15 hours (0955 UT) in the declination component, when the field was already at its Westerly maximum. Substantially large increase of magnitude in the meridional current due to the effect of the flare has led to produce a further enhancement in the westward field at all the locations, with prominent magnitude as one moves away from the equator towards higher latitudes.

Major geomagnetic storms that occurred during October–November 2003 are associated with the sequence of flare events and geoeffective CMEs. The low-latitude geomagnetic signatures for the two storm events during November 20-21 and November 04, 2003 are dealt in the present study to highlight the differing response to the solar wind plasma and interplanetary conditions. As is evident from Fig. 2 and Fig. 3, the interplanetary magnetic field parameters governing the storm event on November 20 were more intense than the November 04 event. A distinctly different feature for the two storm events is the development of an intense main phase (~ -700 nT) for the storm on November 20 and delayed main phase (~ -150 nT) following a prolonged initial phase for ~3 hours on November 04. The hourly Dst index parameter is also shown to present the contribution from the symmetric part of the ring current. The WIND/MFI data for November 20 were discontinuous, so ACE/MAG data are used. Likewise, the ACE/MAG data were available with gaps for the event on November 04 hence WIND/MFI data are used.

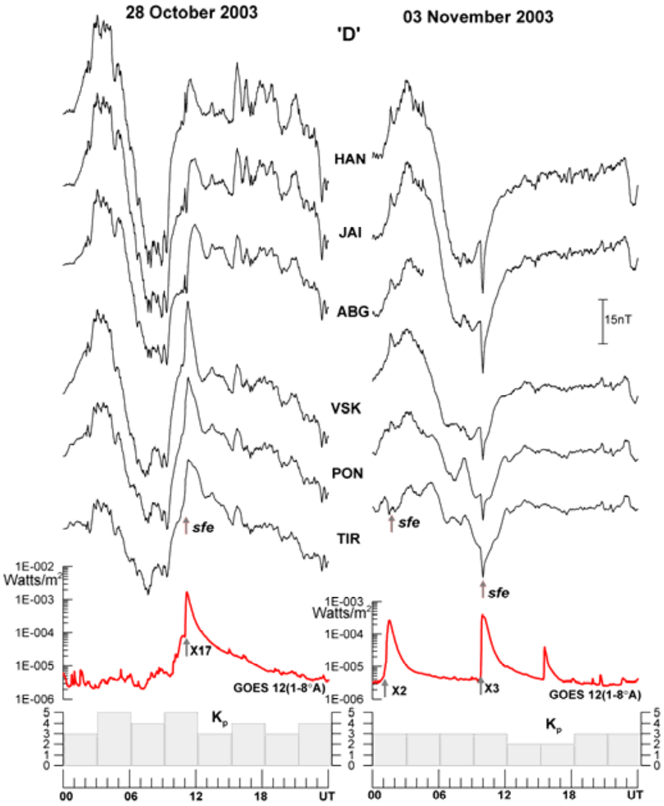

Fig. 1. One minute digital magnetic field data of the declination component during the multiple flare events on October 28 and November 03, 2003 in the Indian longitude zone. X-ray flux from GOES 12 satellite shows the flare occurrences. Three-hourly Kp index parameter shows the geomagnetic activity.

An M-class flare (M3.2/2N) at 0723 UT and CME from sunspot region 501 on November 18, 2003 produced an intense storm on November 20 with the Dst index reaching a peak value ~ -500 nT. Fig. 2 displays the diurnal variation pattern (one minute values) of the 'ΔH' component at the low-latitude stations PON and ABG for the intense storm event during November 20-21, 2003. The CME on November 18 gave rise to a shock front which arrived at the L1 point as reported by SOHO/ACE at 0740 UT on

November 20. The shock gave rise to a Storm Sudden Commencement (SSC), marked by an arrow, at 0803 UT as seen in the digital ground magnetic records of the 'ΔH' component at the low-latitude stations, PON and ABG (Fig. 2). Development of an intense main phase of magnitude (~ -700 nT) at PON corresponds to the peak point of Dst (~ -500 nT) is seen. The interplanetary magnetic field parameters, $B_{y,}$ B_{mag} and B_z [ACE (X ~ 240 Re)], illustrate the configuration of the interplanetary structure for this severe storm. At the time of shock arrival (0740 UT), an abrupt increase in B_{mag} (~ 30 nT) is also evident as the occurrence of a positive excursion of the interplanetary magnetic field B_y of sufficiently large magnitude. The polarity of B_z remained mostly northward for almost 3 hours after the shock. Once the southward turning of B_z commenced at 1120 UT, attaining a significantly large magnitude of ~ -50 nT around 1550 UT, the pronounced main phase conditions prevailed with the sharp and intense southward 'H' field at the two low-latitude stations PON and ABG.

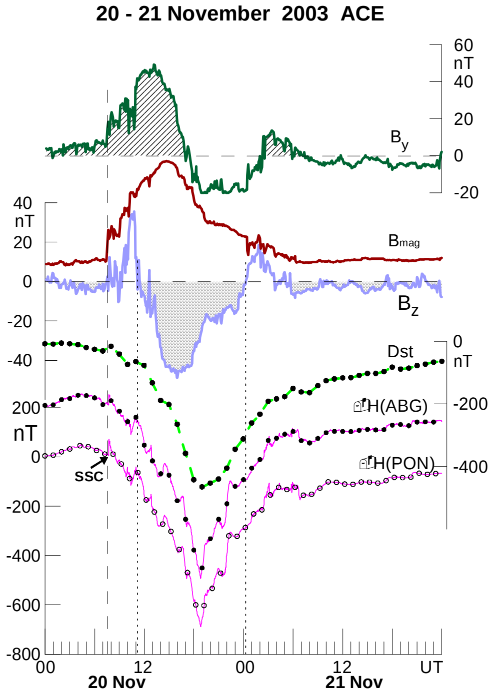

Fig. 2. The vertical dashed line indicates the shock arrival at 0740 UT on 20 November 2003. The data are time shifted by 23 minutes to coincide with the arrival of the shock event. One minute digital magnetic field data of 'ΔH' at Pondicherry and Alibag on 20-21 November 2003 are shown. The arrow marks the SSC onset (0803 UT) on 20 November.

Fig. 3 shows the diurnal variation pattern of 'ΔH' component at the low-latitude stations PON and VSK (as the data at Alibag had gaps) on November 04, 2003. A CME shock from the X8 flare at 1725 UT on November 02, has given rise to a sudden impulse (SSC) at 0627 UT on November 04 as seen in 'ΔH' at the low-latitude stations, PON and VSK. The reduction in the 'H' field is seen with the main phase commencing at ~0900 UT following a period of ~3 hours of initial phase. For the November 04 event, recovery of the storm after the main phase maximum at 1017 UT is not rapid enough to reach the pre-storm level in spite of the prominent reversal in B_z.

The interplanetary magnetic field parameters $B_{y,}$ B_{mag} and B_z for the storm event on November 04 are taken from WIND (X=-178Re), as the ACE/MAG data were available with gaps. At the shock (0646 UT) on November 04, the abrupt increase in B_{mag} (~20 nT) is almost four times the upstream level. This large magnetic field has persisted for a period of ~3 hours during which the low-latitude ground magnetic records experienced prolonged initial phase conditions. The sharp increase in the southward B_z at ~0855 UT has clearly effected the main phase condition, though of short duration, maximizing at 1017 UT. With the rotation of B_z component towards the northward direction, the ground magnetic field begins to recover. A noticeable feature seen for this storm event, as evidenced from the ground magnetic field variations ΔH (PON) and ΔH (VSK), is the near correspondence in the highly oscillating nature of the interplanetary magnetic field components, which supports the energy injection into the magnetosphere by a fluctuating convection pattern in the magnetosphere (Chen et al., 1993).

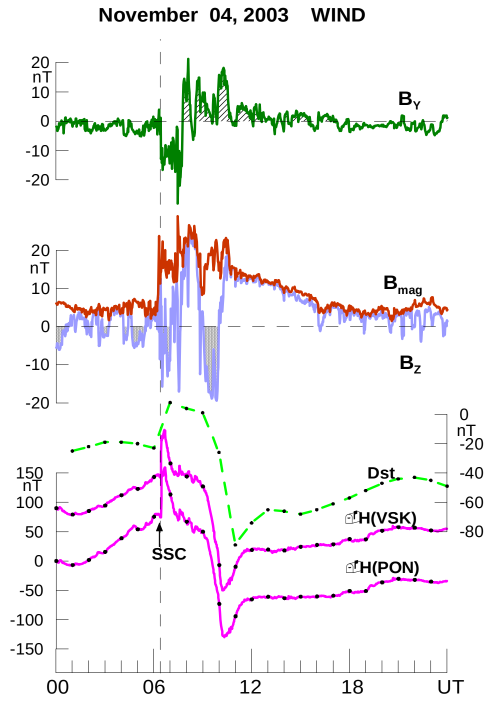

Fig. 3. The vertical dashed line indicates the onset of SSC at 0627 UT. The WIND data are time shifted by 19 minutes to coincide the shock arrival (0646 UT) with the SSC onset. One minute digital magnetic field data of 'ΔH' at Pondicherry and Visakhapatnam on 04 November 2003 are shown.

Fig. 4 is presented to quantify the extent of plasma parameter (WIND) contribution in defining the modulating initial phase manifestation for the storm event on November 04 compared to the intense storm on November 20. Despite similar conditions of solar wind density and velocity parameters prevailing for both the events at the respective times of shock, the magnitude of proton temperature was twice as much for the storm on November 04 compared to that on November 20. This is discussed in Fig. 4, by presenting the dynamic pressure, P_{dyn} and thermal pressure, P_{th} for the two events.

The dynamic pressure (P_{dyn}) and thermal Pressure (P_{th}) for the magnetic storm events on November 04 and November 20, 2003 are shown in Fig. 4 (a). The SSC amplitudes measured at the low latitude station, PON, for the geomagnetic storm event on November 20 is 66 nT (1303 LT) and 86 nT (1127 LT) on November 04. Enhanced thermal Pressure at the SSC/SI (Joselyn and Tsurutani, 1990) is pronounced for the November 04 event. The marked increase in the magnitude of SSC/SI (86 nT) at PON, exhibits close correlation with the significant increase in thermal pressure, at the shock, from 0.2 to 0.9nPa. Scatter plot in Fig. 4 (b) shows the extent of correlation between 5 minute averages of ΔH (PON) and P_{th} during the period (0627-0900 UT) for November 04 and (0803-1100 UT) on November 20. For the storm day, November 04, the period 0627-0900 UT corresponds to the duration of initial phase, with a prominent compression for almost an hour (0627-0727 UT) following the shock. The interval mentioned in brackets for November 20 corresponds to the duration of compression until the beginning of the intense main phase. Good correlation is seen for the event on November 04 than for the November 20 event. NASA reported the occurrence of >10 MeV and >100 MeV proton events following the X8 flare at 1725 UT on November 02, 2003. The >10 MeV proton event continued to progress until November 04. For the November 04 event, just after the shock, the spike-like structure in 'ΔH' component at PON lasted for 1 hour (0627-0727 UT, lower panel in Fig. 4 (c)). The energy flux pattern at >1 MeV to >10 MeV levels as recorded at GOES 10, 134°W, are given in upper panel, for the period when the spike-like structure was seen in the low-latitude 'ΔH' component at PON.

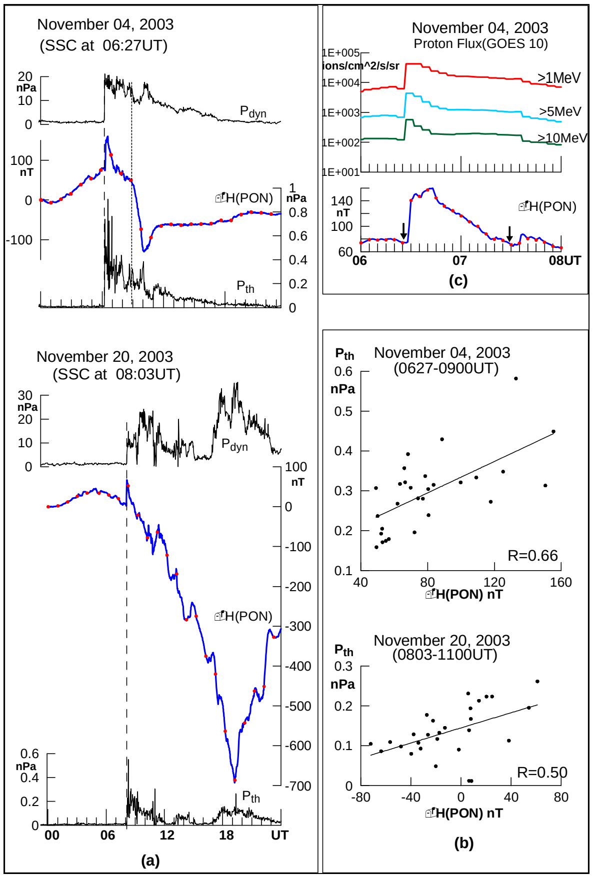

Fig. 4. (a) Shows the one minute digital data of 'ΔH' at Pondicherry for the magnetic storm events on November 04 and November 20, 2003. The vertical dashed lines mark the SSC/SI for the storm events. The dynamic Pressure (P_{dyn}) and thermal pressure (P_{th}) (WIND) are shown. **(b)** Scatter plot of ΔH (PON) against P_{th} are shown for the intervals mentioned. **(c)** The after shock spike in ΔH (PON) and the corresponding Proton flux enhancement (GOES 10) is plotted. Arrows mark the period (0627-0727 UT) of spike in ΔH (PON).

4. Conclusions

Intense storm development of Dst ~ -500 nT on November 20, 2003 could be attributed to a strikingly large magnitude of positive B_y persisting for a period of ~ 7 hours from the commencement of the storm followed by a strong southward B_z (Fig. 2). A dominant negative B_y following the shock and fluctuating B_{mag} along with a North-South oscillating B_z could certainly have restricted the development of the storm main phase on November 04, 2003 (Fig. 3). Tsurutani et al. (1988) showed that not all solar ejecta caused intense storms, however storms with low intensity levels have more diverse interplanetary conditions responsible for oscillating B_z variation.

SSC or SI is known to be linked to the sudden perturbation caused by the increase in magnetopause currents due to the rapid compression of the magnetosphere and the significantly varying dynamic pressure at the time of shock. Moore et al. (1999) and Russell et al. (2000) have reported the sudden compression of the magnetosphere resulting from the rapidly increased dynamic pressure following the intense shock passage. They also discussed the immediate response of the magnetosphere to the shock passage and flows over the polar cap.

Dominantly large values of thermal pressure (changing from 0.2 to 0.9 nPa) during the compressional event (November 04) infers significant energization during initial phase to maintain the impulse period for about an hour (Fig. 4 (c)). Impulsive ion enhancement at higher energies (GOES 10, 134°W), dominating after the shock encounter, presents a substantial correlation with the post shock spike (Gosling et al., 1980; Kennel et al., 1985; Tsurutani et al., 2001) in the 'H' component at the low-latitude station.

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