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Magnetic Storms of October–November, 2003: Ground Geomagnetic Signatures from Maitri, Antarctica

Ajay Dhar, Anand K. Singh, P. Elango, Arun N. Hanchinal and B. M. Pathan

Indian Institute of Geomagnetism
Plot 5, Sector 18, New Panvel (W), Navi Mumbai – 410 218

ABSTRACT

A series of solar eruptions occurred during October-November 2003 resulting in severe magnetic activity observed on Earth during this period. A severe magnetic storm was recorded on 29 October 2003, which lasted 22 hours following an X17 flare event on the Sun. The energy released by the Sun took nearly 19 hours to enter the Earth's magnetosphere resulting in this magnetic storm. Another X10 solar flare occurred in the course of the first magnetic storm. Nearly 20 hours after the second X10 solar flare event, another magnetic storm commenced, noticeably weaker and of shorter duration (13 hours). On November 20, 2008, the largest geomagnetic storm of the solar cycle 23 occurred with Dst index of -422 nT. The geomagnetic storm was generated following a coronal mass ejection (CME) from active region of the Sun.

The extremely large solar eruption on 28 October 2003 caused an intense geomagnetic storm observed on Earth. A second solar eruption on 29 October intensified the storm about a day later. These two events in terms of solar eruption and their resulting effect on the near-Earth environment are investigated. During the course of second storm some of the strongest substorms in the history of magnetic recordings occurred at Maitri, Indian Antarctic Station. The ground geomagnetic signatures at Maitri during this period are analyzed and compared with the IMF parameters.

INTRODUCTION

The Earth's magnetic field acts like a barrier and shields us against the continuous flow of charged particles called solar wind, coming from the Sun. Due to the Earth's magnetic field, most of this solar material gets deflected and does not reach the Earth's environment. Without this magnetic field barrier, the solar wind could blow away the atmosphere of the Earth, and the cosmic rays might have destroyed our optic nerve system and mutated our cells leading to the extinction of life on the Earth (Lakhina et al., 2005).

The solar wind also carries the Sun's magnetic field lines throughout the Solar system, called Interplanetary Magnetic Field. This interplanetary magnetic field is either aligned with the Earth's magnetic field or points in the opposite direction. Nighttime phenomena occurring in high latitudes (Akasofu, 1964) and is a combination of large-scale phenomena lasting tens of minutes, with sudden auroral brightening, its poleward expansion and simultaneous sudden decrease of horizontal component of the ground geomagnetic field more than 500 nT caused by a strong and expanding westward electrojet. The onset of such expansion (substorm onset) takes place in the nightside sector with highest probability in the premidnight region.

During the high-energy solar activity of late October and mid November, 2003–called as the "Halloween storm" of 2003 — the outer Van Allen belt was pushed and shifted to a nearly unprecedented degree. The center of the outer Van Allen belt is usually about 20,000 to 25,000 km away from Earth's surface, as measured above the equatorial region of the Earth. However, during this Halloween storm, the belt of high-energy electrons that normally cradles Earth from afar was greatly enhanced and pushed unusually close to our atmosphere during the violent solar activity that occurred in late October, 2003. The Van Allen radiation was greatly increased and pushed inward toward Earth's surface to an unusually close degree. From Nov. 1 to Nov.10, the outer belt had its center only about 9,500 km from Earth's equatorial surface, a place where ordinarily there are almost no energetic electrons at all. The charged particles within the belts can have The Earth's magnetic field is oriented from South to North at the magnetopause subsolar point. Therefore, when the IMF is strongly southward, the Earth's magnetic field is anti-parallel to the IMF. In this configuration, Earth's field lines can spontaneously break and join themselves to the Sun's IMF. The solar wind then drags the reconnected field lines from the dayside to the nightside, allowing the plasma to pour into the tail of the magnetosphere. This process, known as magnetic reconnection, is considered to be the most efficient mechanism for solar material to penetrate the Earth's magnetic shield. It requires the IMF and the Earth's magnetic field to point in opposite directions. Therefore, southward IMF together with the occurrence of magnetic reconnection implies an increase of plasma density in the magnetosphere.

When the IMF is northward oriented, it points in the same direction as the Earth's magnetic field. In this case, no or little dayside reconnection occurs. The density in the tail of the magnetosphere (or plasma sheet) should therefore logically decrease. However, the plasma sheet often becomes denser and colder for periods of northward IMF and resulting in quiet geomagnetic conditions.

The Earth directed CME's generally cause large geomagnetic storms (Dst < -100 nT) on Earth. High-speed streams and coronal holes generate moderate to weak storms (Sheeley et al., 1976). Wilson (1987) and Gosling et al., (1990) have established a close association between CME's and magnetic storms, but it is difficult to quantitatively relate earth-directed CME's and geomagnetic storms. A CME released from the Sun's gravity travels faster than the solar wind giving rise to a shock front which may cause strong interplanetary disturbances resulting in non-recurrent geomagnetic storms in the Earth's magnetosphere and ionosphere (Gosling et al., 1991; Gosling, 1993; Tsurtani et al., 1988; Richardson et al., 2001). The effectiveness of CME's will depend on orientation of IMF and Earth directed mass ejection from the Sun striking the Earth's magnetosphere.

A major magnetic storm normally starts with a storm sudden commencement (SSC) followed by large negative changes in the Dst index. At high latitudes, large substorm activity is observed which takes place shortly after the SSCs, with delay time of tens of minutes from the initial rise of SSC before the onset of the substorm expansion phase. The geomagnetic activity related to the substorm expansion phase normally propagates from the nightside to the dayside (Chapman and Bartels, 1940). Some SSCs are followed by substorm onsets only after several minutes (Akasofu and Chapman, 1972). A substorm is a nighttime phenomena occurring in high latitudes (Akasofu, 1964) and is a combination of large-scale phenomena lasting tens of minutes, with sudden auroral brightening, its poleward expansion and simultaneous sudden decrease of horizontal component of the ground geomagnetic field more than 500 nT caused by a strong and expanding westward electrojet. The onset of such expansion (substorm onset) takes place in the nightside sector with highest probability in the premidnight region.

During the high-energy solar activity of late October and early November – called the "Halloween storm of 2003", the outer Van Allen belt was pushed and shifted to a nearly unprecedented degree. The centre of the outer Van Allen belt is usually about 19,000 km to 22000 km away from the Earth's surface, as measured above the equatorial region of the Earth. However, during this Halloween storm, the belt of high energy electrons that normally cradles Earth from afar was greatly enhanced and pushed unusually close to our atmosphere during the violent solar activity that occurred in late October, 2003. he Van Allen radiation was greatly increased and pushed inward towards Earth's surface to an unusually close degree. From Nov. 1 to Nov. 10, the outer belt had its center only about 10000 km from Earth's equatorial surface, a place where ordinarily there are almost no energetic electrons at all. The charged particles within the belts can have profound and deleterious effects on commercial and operational satellites in near-Earth orbit (Baker D., 2003).

The greatest solar flare ever recorded, X28 on November 4, 2003. This type III solar radio burst accompanying X28 flare did not cause any noticeable magnetic storm activity on the Earth as the orientation of the interplanetary magnetic field (IMF) which solar wind drags away from the Sun did not match the magnetic field of the Earth, and no energy from the solar wind could enter the magnetosphere. For the occurrence of a major storm on Earth, some sufficient and necessary conditions are required. A sufficiently strong and prolonged period of southward orientated Interplanetary Magnetic Field (IMF) B_z of large magnitude (less than -5 nT) for a period of 3h or more, resulting in strong dawn-to-dusk electric fields at Earth are important and necessary conditions. One of the many interplanetary sources of such regions of negative Bz fields are so-called magnetic clouds (Klein and Burlaga, 1982; Burlaga et al., 1987) which are formed by the magnetic field, that is embedded in solar plasma ejected during so-called Coronal Mass Ejections (CMEs). Magnetic clouds are characterized following a turbulent sheath region by enhanced magnetic field strengths and a smooth rotation of the magnetic field vector over a 1-day period. The Bz component within the observed portion of such a flux rope can therefore be either north-south (NS) or south-north (SN) orientated. Zhang and Burlaga [1988] found that the storm onset is correlated with the magnetic field direction of the cloud, normally beginning when the cloud Bz turns south. They also found that the strongest storms, characterized by the Dst index, occurred for SN storms. However, they did not attribute this to the polarity of the cloud but concluded that it might be due to higher bulk flow speed which they observed in SN clouds. Generally, the Earth directed solar wind speed and the southward component of the IMF are of most importance in terms of storm geoeffectivness (Snyder et al., 1963; Fairfield and Cahill, 1966) in comparison the duration of the region of southward IMF has been suggested to be less important (Wang et al., 2003). The geoeffectivness of the different regions of magnetic clouds, sheaths, leading and trailing fields have been investigated by Zhang et al. (2004). It was found that the sheath and leading regions are equally effective at causing magnetic storms. Although, magnetic clouds that are fast enough to drive shocks have been found to be more geoeffective because of the combined effect of their high ejecta fields and due to draping/shock effects (Gonzalez et al., 1999).

During October and November 2003, high solar activity was felt on Earth. Spectacular aurorae, power outages, disruption to radio communications and damage to spacecraft were all credited to this 'Halloween storm'. This X ray event which took place during this period was unexpected as it occurred during solar minimum, when activity is usually quiet on the Sun. The region between the two Van Allen belts was one of high particle radiation intensity. The very energetic electrons in the magnetosphere caused 'space weather' effects on Earth, though very few outright spacecraft failures or other permanent damage was caused during this storm. The record solar storms that erupted in late October and early November, 2003, particularly the largest X-ray flare ever recorded, threatened power systems on the planet's surface and communications and weather satellites in orbit above Earth.

Seven major solar outbursts jolted Earth's upper atmosphere towards the end of the year 2003, setting records for extreme space weather. The space-weather records set during this period included:

- The largest X-ray solar flare ever recorded
- The fastest-moving solar storm ever. It splashed over us at nearly 6 million mph.
- The hottest storm ever. It was tens of millions of degrees as it doused Earth.

The solar blasts caused power outages in Sweden, disturbed airplane routes around the world, damaged 28 satellites, ending the service life of two **Earth Satellites.** Satellites as part of daily life are used for communications, weather forecasting, navigation, observing land, sea and air, other scientific research, and military reconnaissance. Large doses of electrically charged solar particles can shock those satellites and even kill them.

The waves of solar energy blasted away from the Sun by the flares didn't stop at Earth. They went beyond to burn out the radiation monitor aboard the Global Surveyor spacecraft orbiting Mars. That instrument had been tracking the radiation future explorers might encounter on trips to the Red Planet (Ref). And beyond Mars near the planet Saturn, the Cassini spacecraft measured the intense energy from the Sun. Months later, the energy from the storm reached beyond Pluto's orbit to the edge of the Solar System, washing over the Voyager spacecraft.

Scientists found the Halloween Storms intriguing because they came some three years after the peak of the most recent sunspot cycle. Sunspot activity varies on the face of the Sun in eleven-year cycles. As the number of sunspots increases, so does the solar storm activity, which can sometimes leave the Earth's magnetic field shaking as though a giant hurricane were approaching. A flare is a brilliant outbreak in the Sun's upper atmosphere at or near a sunspot. It is an explosive release of large amounts of electromagnetic radiation and huge quantities of charged particles. (Baker D., Earth Radiation Belts Spectacular Following Halloween Solar Storm).

OBSERVATIONS

The data used for this study are the digital magnetic data from the high latitude Indian Antarctic Station, Maitri (Geog. 70.77^o S, 11.75^o E, Geomag. 67.29^o S, 57.97^o E) along with the available parameters of the solar wind and the interplanetary magnetic field from the Satellites. Solar Wind data from the Advanced Composition Explorer (ACE) at L1 point and Geotail at X~3 RE are used to highlight the salient features of the event.

SOLAR WIND CONDITIONS AND THE GLOBAL MAGNETOSPHERIC RESPONSE

Figure 1 shows the solar wind parameters as measured by the ACE spacecraft at L1. Arrival of the high speed flow starts at about 0545 UT at ACE. Over a period of about 2 hr the solar wind speed increases from a typical speed of 525 km/s to nearly 2000 km/s. During this period, the density drops from about 13 cm^{-3} to about 4 cm^{-3}, though the overall dynamic pressure of the solar wind increases. IMF B_y on average is the dominant component. For the first 35 min between 0555 and 0630 UT it is strongly

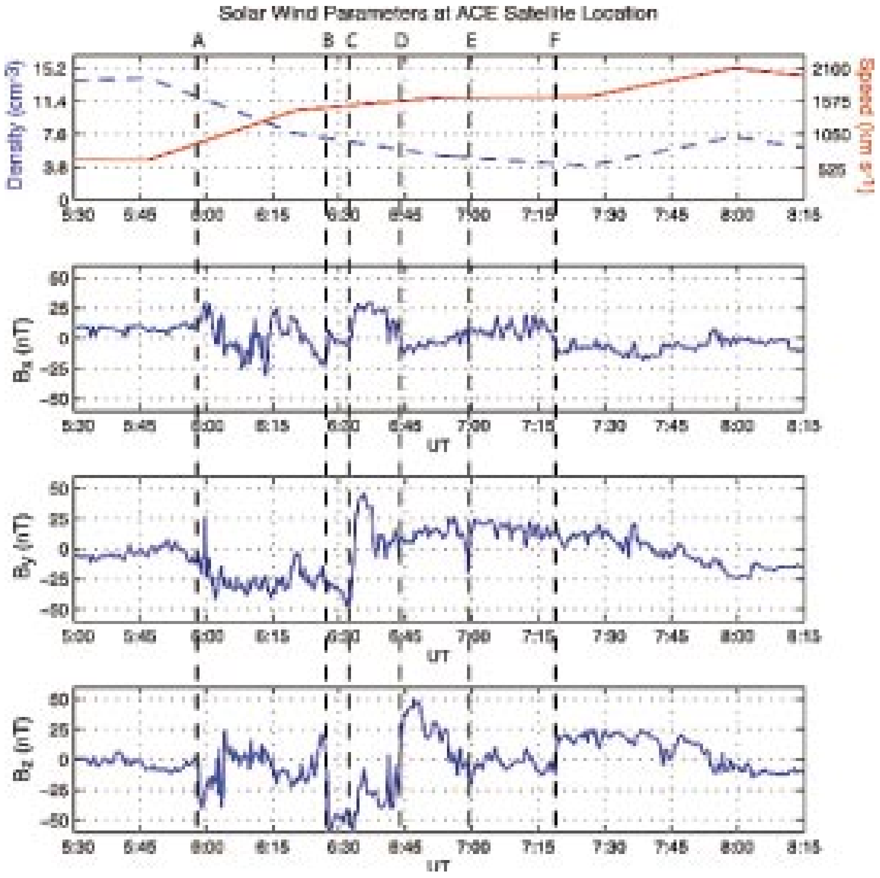


Fig. 1 : The solar wind conditions on 29 October 2003 as measured by ACE (Skoug et al., 2004). The top panel is the solar wind density (dashed line) and speed (solid line). The bottom panels are the components of the IMF. There is approximately a 20–10 min propagation time for the features seen in these plots to arrive at the Earth, when assuming a propagation speed of 1000 to 2000 km/s. The vertical dashed lines (A–F) show critical IMF features that drive key features in the cross-polar cap potential

negative. At 0630 there is a rapid rotation where on average IMF B_y stays positive for the next 75 min where it again flips sign. The B_z component is much more variable, with sign or abrupt magnitude changes every 5–10 min. These swings in IMF B_z are useful in providing insight into trigger mechanisms.

On 28 October, Kp had moderate values between 3-5. Following the shock on 29 October at 06 UT, it suddenly jumped to values of 8 and 9. It continued to have high values on 30 October with values ranging from 9-5.

Kp continued to retain high values of 8-5 for the major part of 31 October. The Kp started decreasing at 15 UT on 31 October. The Kp index is an index of geomagnetic activity for mid latitudes.

The large magnetic storm starting at around 0610 UT on 29 October 2003 (see Dst in **Figure 2**) shows a slightly different behaviour from the

OCTOBER 28-NOVMEBER 01, 2003
Kp Index

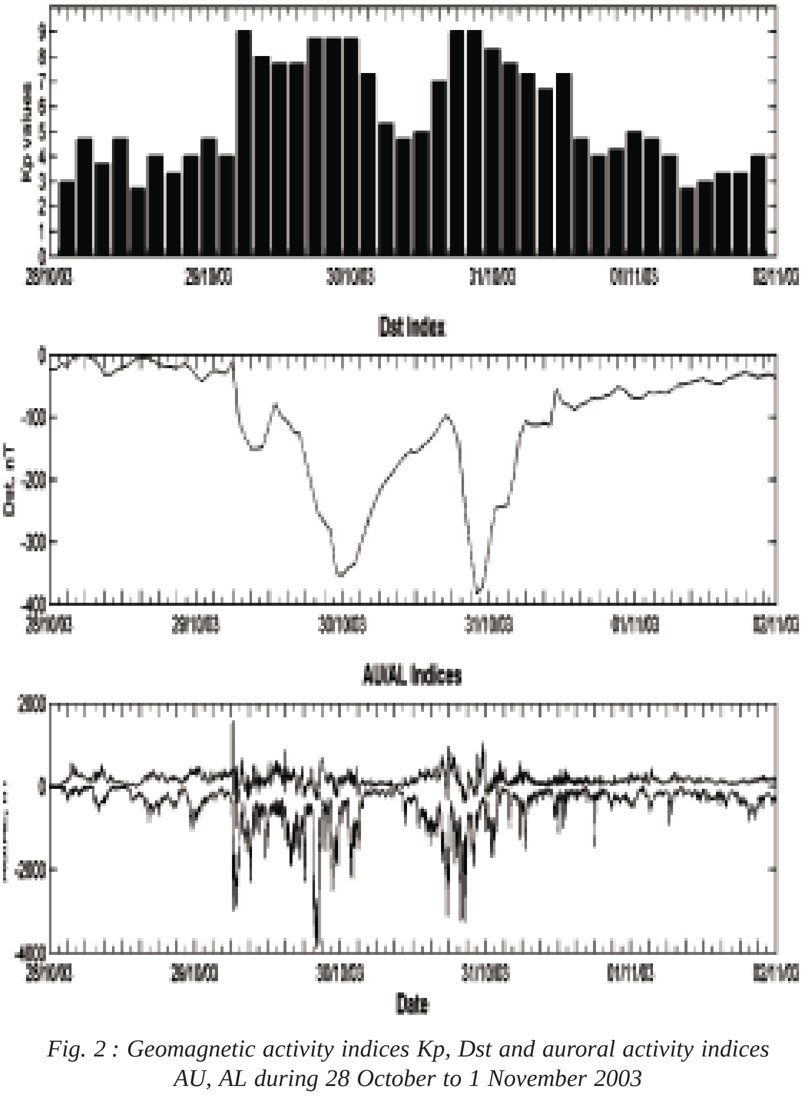


Fig. 2 : Geomagnetic activity indices Kp, Dst and auroral activity indices AU, AL during 28 October to 1 November 2003

standard storms (Lopez et al., 2004). For example, Dst shows three unusual peaks of -151 nT, -353 nT and -383 nT, indicating that the initial activity could have died away if the second period of large southward interplanetary magnetic field (IMF) not started at around 18 UT.

The continuous activity seen in the AL index between the Dst peaks might provide an important clue in understanding the storm-substorm relation (Kamide et al., 1998; Ohtani et al., 2001, and references therein) because the peaks of Dst correspond precisely to peaks of AL with extremely large values (nearly “4000 nT) and strongly southward IMF (more than “20 nT). Yamauchi et al. (2006) examined 10.5 years data of final AE (with error-checked calibrated data from all 12 stations) from January 1978 to June 1988 and found only 32 days of AL < “2000 nT, with none of the events registered as quickly as the present case after the start of SSC.

OBSERVATIONS AND RESULTS

On 26 October 2003, the Sunspot group 486 became active with a series of X-class flare eruptions. Twenty-sixth October was a very unusual day for geomagnetic activity. In spite of the sharp growth of the solar wind velocity from 380 km/s (08 UT) to 500 km/s (12 UT) by OMNIWeb data (OMNIWeb-site), the magnetic field from 05 to 16 UT was quiet. The AE-index did not exceed 80 nT, and Proton Flux values were small, about 10 (proton/cm^2). Therefore, there was no geomagnetic disturbances from 05 to 16 UT on 26 October (not shown here). Data of OMNIWeb also showed that there was a long duration X1 flare during this period. This event occurred at 06.54 UT and was associated with Types II and IV radio sweeps resulting in substorm activity on 27 October. Disturbance on 26–27 October was longer lasting than the substorm considered above. According to OMNIWeb data, the magnetic storm on 26–27 October was due to an X1/3b flare that occurred at 18:19 UTC on 26 October with an associated Type II and a partial halo CME off to the west.

By 28 October, this region developed into a giant sunspot, emitting a powerful solar flare of X17/4B magnitude. Region 486 was reported by NOAA as one of the largest and active regions of solar cycle 23. The ACE satellite recorded the first shock at 0600 UT on 29 October and a second shock at 1600 UT on 30 October. The CME’s of 29 and 30 October 2003 were the third fastest to reach the Earth in a transit time of 19h (Skoug et al., 2004). The large shock front hit the Earth’s magnetosphere to cause a storm sudden commencement at 0612 UT, followed by the magnetic storm.

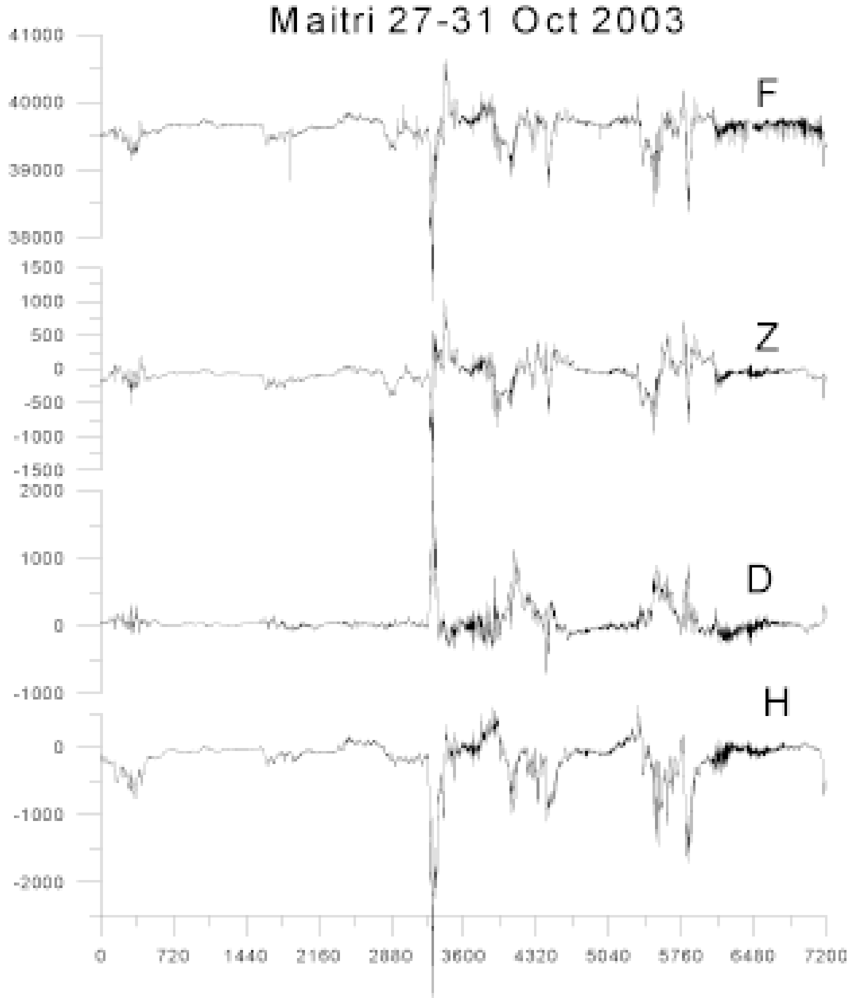
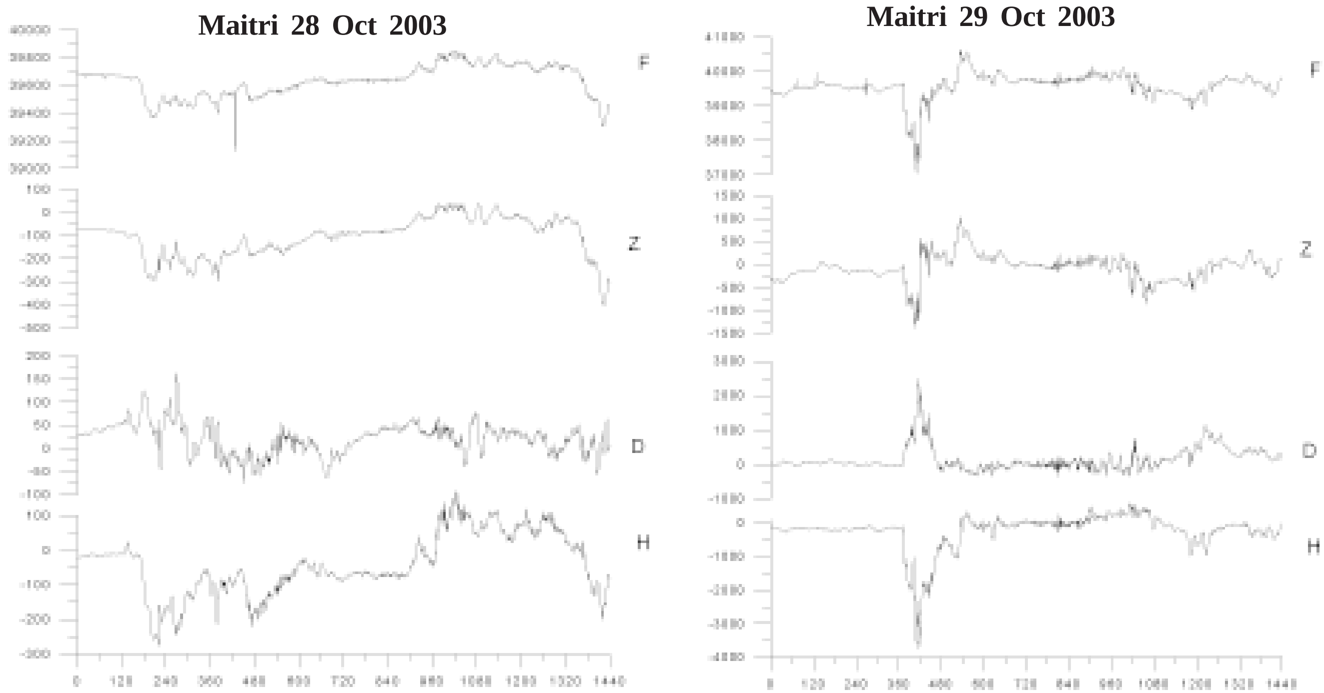


Fig. 3 : Magnetic variations in the three components H, D and Z and total field 'F' as recorded at Maitri during 27-31 October 2003

The solar flare which erupted on 28 October 2003, the ejecta took nearly 19 hours to reach the Earth's magnetosphere. It did generate magnetic disturbance on this day. **Figure 3** shows the variations recorded in H, D and Z component of the magnetic field at Maitri, Antarctica for the period 27-31 October 2003. The variations in the total field 'F' are also shown in the top panel. We focus on the initial development of the storm because of its unusual behavior. Three onsets of strong westward electrojet current (**Figure 2 b**) took place within this short interval, and the activity levels of


Maitri 28 Oct 2003

Maitri 29 Oct 2003

Figure 4 (a) and (b). The magnetic variations in three orthogonal components H, D and Z and total field 'F' recorded at Maitri on 28 and 29 October 2003 these westward electrojets are quite high, reaching 2000 nT deviations of the geomagnetic horizontal (H) component for the first two activities within 5 min after the start of SSC, and nearly 4000 nT (Figure 4 b) for the last activity within 10 min after the start of SSC. Such a quick and extremely large development of multiple current systems immediately after the start of SC has never been reported. Immediately after the SSC at 0612 UT on 29 October 2003, an intense magnetic storm developed resulting in a drop of nearly 4000 nT, as seen in H component **(Figure 4 b)**. The main phase of the storm started immediately after the B_z component became negative and persisted. The first peak in Dst was recorded at -180 nT and started recovering for a short duration before dropping again to -363 nT at midnight. The recovery of B_z was slow on 30 October, before dropping further to new lower value of -401 nT around 2200 UT on 30 October 2003. This intense storm has a long initial phase as ring currents developed ~19 hours after the occurrence of storm sudden commencement (SSC). The Riometer data from Maitri showed strong ionospheric radio absorption coincident with field aligned current enhancement (not shown here). The dominance of field aligned currents is manifested in the large fluctuations as observed in the variations of H and D components. The large fluctuations in Z component manifest the movement of auroral current system equatorward of Maitri.

We now concentrate on the magnetic variations recorded during the period 17-23 November 2003. The highly disturbed phenomena of October 2003 were followed by complex series of flares and associated CME, which occurred on 18 November. This produced a an intense geomagnetic storm on 20 November **Figure 5** shows the Geomagnetic activity indices Kp, Dst, AU, AL for the period 19-23 November 2003. On 18 November, a flare accompanied by CME with speed of nearly 100 km/s. The shock from the CME increased the solar wind speed from 350 to over 750 km/s. With the fall in Dst on 20 Nov (-422 nT), the auroral activity increased and touched values of roughly -4000 nT. This however did not generate a large variation in magnetic field as the polarity of the Interplanetary magnetic field remained predominantly northward and the CME was not directed towards the Earth.

Strong and long period ULF activity was observed during the recovery phase of the October storm. The amplitude of oscillations in the Pc5 frequency range was as high as 150 nT at mid-latitude stations (Potapov et al., 2006). Pc5 ULF pulsations represent the longest hydromagnetic waves

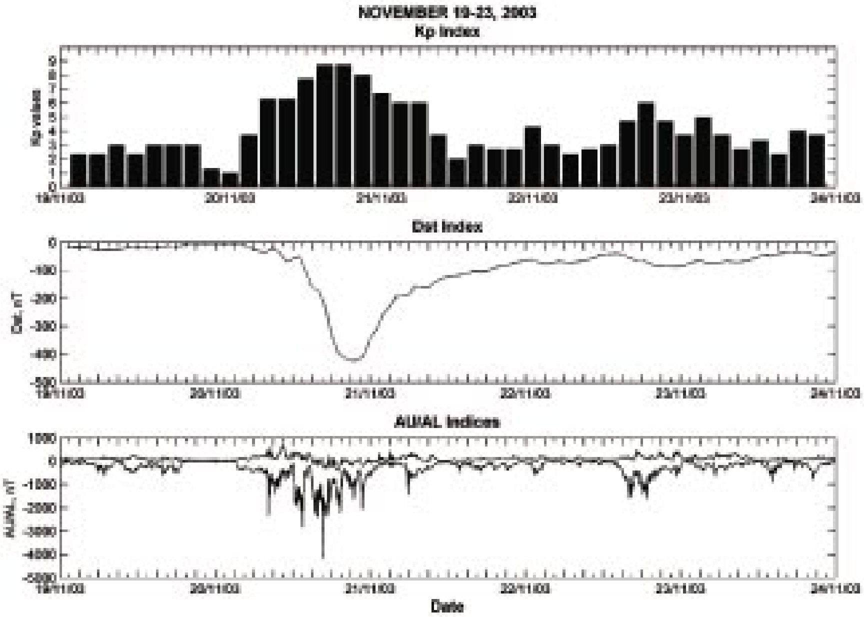


Fig. 5 : Geomagnetic activity indices Kp, Dst and auroral activity indices AU, AL during 19-23 November 2003 (Kyoto University)

existing in the Earth's magnetosphere and play an important role in the processes of the solar wind interaction with the geomagnetic field. The pulsations can be used as a probing tool to explore the magnetosphere structure. Mathie et al., (1999) carried out a comprehensive study of the Pc5 pulsations. On the basis of detailed analysis of 137 pulsation events observed by IMAGE magnetometers during three spring months and classify them as "classical" pulsations. The pulsations recorded during the October 2003 event differ drastically from these "classical" events for amplitude and duration of the event. The amplitude decay from auroral to mid latitudes was also gentler than the classical Pc5. The Classical Pc5 pulsations are typically auroral and subauroral phenomena, while as the event of October, 2003 was a global phenomenon recorded at all observatories over the world.

Figure 6 shows the filtered magnetic field at geosynchronous altitude measured by GOES10 and GOES12 satellites in Pc5 band range (2-7 mHz). A black bar represent the local midnight at corresponding locations. It is evident that Pc5 pulsations are observed during day as well as night times. The lower panel shows the filtered H, D and Z components at Maitri in Pc5 range. The occurrence of simultaneous pulses at geosynchronous altitudes and at ground is observed.

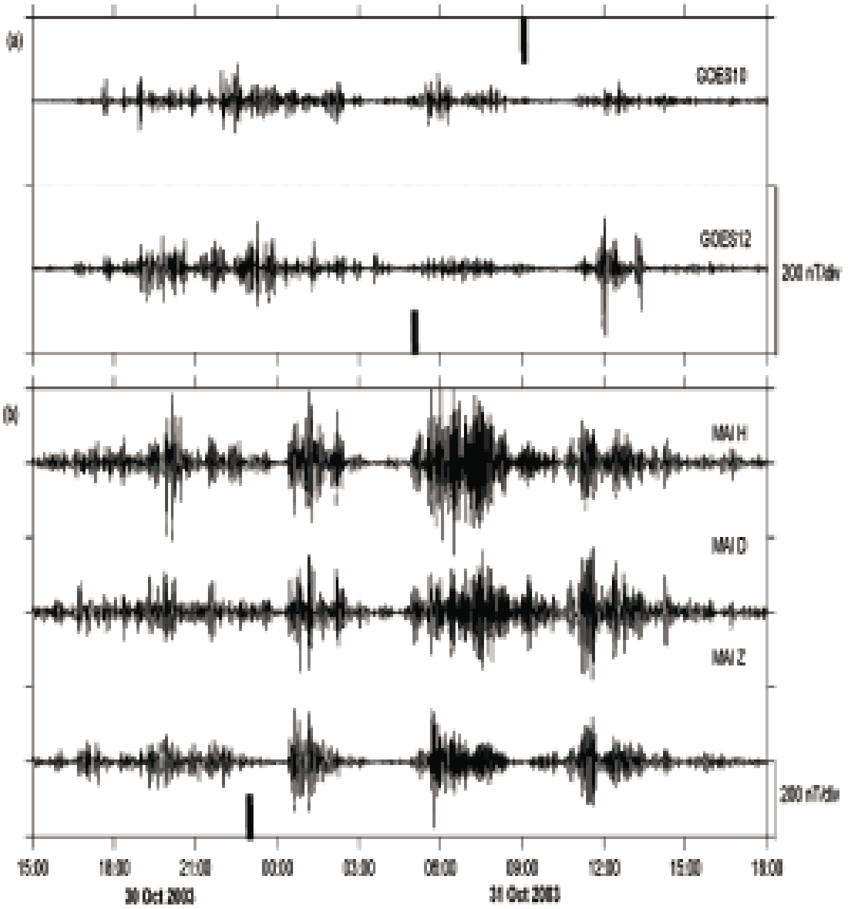


Fig. 6 : Plot of three orthogonal components of H, D and Z from Maitri on October 30-31, 2003. The two top panels show magnetograms from GOES-10 and GOES-12 satellites

The Pc5 pulsations (2-7 mHz) are commonly observed on the dayside of the magnetosphere due to Kelvin-Helmholtz instability along the flanks of the magnetopause (Southwood 1968). The interplanetary shocks impacting on the magnetopause may trigger global cavity oscillation (Kivelson et al., 1984) and can be an additional source of low frequency pulsations. The signature of cavity oscillation is globally found in magnetic observations. During the Halloween storm of the October 2003, global Pc5 oscillations started with the beginning of the second day and lasted until the dusk of third day. Maximum Pc5 intensity was observed on the morning of October 31, 2003.

DISCUSSION AND CONCLUSION

The CME associated with 28 October 2003 solar activity was so intense and produced an intense storm as recorded at Maitri on 29 October. The activity saturated the recording of solar wind parameters on most of the spacecrafts at L_1 point. The ground magnetic field variations at Maitri followed the fluctuating interplanetary magnetic field. The results provide a glimpse of the violent events of October-November 2003. This solar eruption occurred during the declining phase of the current solar cycle and will help us in understanding the extremes of the Sun's behavior over different time scales. It will also help us to calculate the free energy budgets available at the Sun. Tsurtani et al. (1992) studied great geomagnetic storms for the period 1978-1979 and observed two main interplanetary causes for these storms. The first one is the shock compressed magnetic field, which is a shock wave propagating in the solar wind driven by a CME related structure compressing the existing solar wind magnetic field and pointing anti-parallel to the Earth's magnetic field. The second cause responsible for the storm were referred as geoeffective structures were interplanetary ejecta; the ejected material from the CME's. Comparing the most significant difference is that the storms of October-November 2003 events were caused by an interaction between an ejecta and a high speed stream following it.

The two magnetic storms of October – November, 2003 reported here are characterized by unusually high geomagnetic activity at low and mid latitudes (as represented by Dst and Kp indices) and also at auroral and polar latitudes, with AL attaining values of -4000 nT. This reflects that ionospheric current systems in high latitudes were significantly modified. During the event of November 2003, the solar wind velocity was significantly lower than the event of October 2003. Therefore, variations in the southward Bz mainly contributed to the electric field magnitude.

Solar flares in November 2003 were much weaker than the flares of October 2003. never the less, the strongest disturbance was observed in Interplanetary medium during November event. The IMF strength within the disturbance was very high (above 55 nT) and the IMF southern component Bz was lower than -40 nT for 3 hours generating very high electric field of solar wind. This magnetic storm was the second strongest (after the great magnetic storm of 13 March 1989, with Dst of -589 nT).

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