Ann. Geophys., 27, 3853–3860, 2009
www.ann-geophys.net/27/3853/2009/

Annales Geophysicae

Electrodynamical response of the Indian low-mid latitude ionosphere to the very large solar flare of 28 October 2003 – a case study

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Received: 26 February 2009 – Revised: 8 September 2009 – Accepted: 17 September 2009 – Published: 9 October 2009

Abstract. The electrodynamic effects on the low-mid latitude ionospheric region have been investigated using GPS (global positioning system) data, ionosonde data and ΔH values, during the very large solar flare (X17.2/4B) of 28 October 2003. The results bring out the flare induced unusual behaviour of the equatorial ionosphere on this day just prior to sunset. The important observations are i) Large and prolonged N_e enhancements observed from ionosonde data just after the flare-related peak enhancement in EUV flux. The observed enhancement in N_e is due to the increase in ionization production due to the enhanced EUV flux and the persistence of the enhancement is probably due to the prompt penetration related upliftment of the F layer (just prior to the flare peak phase) to higher altitudes, where recombination rates are lower. ii) A significant enhancement in total electron content (TEC) (∼10 TEC units) at regions around the Equatorial Ionization Anomaly (EIA) crest region (Ahmedabad) during the flare in association with the flare related EUV flux enhancement. iii) Similar enhancements seen at stations of Jodhpur and Delhi in the mid latitude sector. iv)The flare related flux enhancements in different longitude sectors in the equatorial electrojet region have been shown to produce positive and negative variations in electrojet strength indicating the presence of current systems having positive and negative polarities in different longitude sectors. Thus the flare effect reveals the longitudinal variation of the counter electrojet events in the Equatorial Electrojet (EEJ) region.

Keywords. Ionosphere (Equatorial ionosphere; Ionospheric disturbances) – Magnetospheric physics (Current systems)

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1 Introduction

The sudden enhancement of the solar radiation in the X-ray and extreme ultra-violet (EUV) band during a solar flare can produce great changes in the ionospheric electron density on the dayside of the earth (Thome and Wagner, 1971; Mendillo et al., 1974). Solar flares comprise of X-ray flares. An X-ray flare is an enhancement in the X-ray solar flux intensity at wavelengths less than 20 Å. The X-ray flux enhancements, during solar flare events, are classified based on their strengths in terms of the peak burst intensity (I_B) measured by satellites in the wavelength band of 1–8 Å and it is expressed in units of $\mathrm{W\,m^{-2}}$. X rank flares are the strongest ($I_B > 10^{-4}\,\mathrm{W\,m^{-2}}$) and B rank flares are the weakest ($I_B < 10^{-6}\,\mathrm{W\,m^{-2}}$) according to this classification. Brightness is the relative maximum brightness of a flare in H_α. A flare is classified as faint (F), normal (N) or brilliant (B) depending on the brightness.

The global positioning system is a satellite based positioning system widely used for navigation, relative positioning and time transfer. The ionosphere introduces a time delay in the 1.57542 GHz (L1) and 1.22760 GHz (L2) simultaneous transmissions from GPS satellites orbiting at ∼20 000 km. The relative Ionospheric delay of the two signals is proportional to the total number of electrons along the ray path or the total electron content (TEC). Time delay measurements of L1 and L2 frequencies can, therefore, be converted to TEC along the ray path from the receiver to the satellite. As a dual-frequency satellite navigation system, the GPS has off late been widely used for ionospheric studies. Using worldwide GPS receivers Ho et al. (1996) studied the global distribution of TEC variations during magnetically disturbed periods. Saito et al. (1998) have studied travelling ionospheric disturbances using GPS data. Liu et al. (2004) investigated the ionospheric response to the solar flare of 14 July 2000 and they have shown that TEC is suitable to monitor the overall variations of flare radiations while its time rate of change aids the detection of sudden changes in the flare radiations.

Published by Copernicus Publications on behalf of the European Geosciences Union.

The enhancement of the horizontal component (H) of the geomagnetic field due to an X-ray flare event is called a Solar Flare effect (SFE). The onset, peak and end phases of a flare are characterized respectively by the time when a sudden increase in X-ray peak burst intensity (I_B) occurs, the time when I_B attains a maximum value and the time when the flux has decayed to half the peak value. The maximum enhancement in H value over the pre-flare level indicates the magnitude [SFE (H)] of an SFE event. The solar flare (magnetic crochet) related current was regarded as an augmentation of the S_q current system (Chapman, 1961) in the past. Later studies brought out significant differences between S_q and crochet current systems (Yasuhara and Maeda, 1961; Van Sabben, 1968). Oshio et al. (1967) studied the solar flare effect on the geomagnetic field on a global basis and suggested that the seat of the ionospheric current is a little lower than that of the S_q current system. The response of the ionosphere to solar flares in terms of the increase in electron density (Ne), Pedersen (σ_1) and Hall (σ_2) conductivities and Total Electron Content (TEC) in the dynamo region have been discussed by Sato (1975). Rastogi (1996) have presented Solar flare effects on zonal and meridional currents at the equatorial electrojet station of Annamalai Nagar. Rastogi et al. (1997) have studied the changes in the three components (H, D and Z or X, Y and Z) of the geomagnetic field for a chain of ten geomagnetic observatories in India, during an intense solar flare on 15 June 1991 and the subsequent sudden commencement. They found that SFE (H) values were positive at all stations, SFE (Y) values were negative at all stations and SFE (Z) values were positive at equatorial and negative at non-electrojet stations. They have explained the observed irregular variations of Z components at different stations in terms of possible distortions in the altitude profile of the ionospheric currents at low latitudes. Several studies have reported the effects of solar flares during counter electrojet events (Srivastava, 1974; Sastri, 1975; Rastogi et al., 1975, 1999; Rangarajan and Rastogi, 1981; Manju and Viswanathan, 2005). These studies have shown that SFE (H) amplitude is lower at equator and higher for stations outside the jet due to the counter electrojet related decreasing effect on ΔH. The characteristics of the electrojet response, to solar flares, under conditions of counter electrojet, have been described by Rastogi et al. (1999). They have also confirmed the existence of zonal and meridional components of the ionospheric currents over the equatorial latitudes, which in combination with S_q currents produce complex effects (as seen during flares occurring at the time of partial CEJ events). The effects of the very large solar flare (X17.2, 4B) of 28 October 2003, on the F-region at the low-mid latitudes over the Indian sector and the equatorial electrojet at different longitudes, have been investigated in the present study. The present flare being one of the largest flares ever recorded, its impact on different geophysical phenomena is expected to be substantial.

1.1 Data and method of analysis

The present study has been carried out using TEC values derived from GPS data at the locations of Ahmedabad, Jodhpur and Delhi.

The Absolute Slant GPSTEC (STEC) values are obtained from the carrier phase delays and pseudo ranges of the GPS signals at L1 and L2 frequencies. The STEC are then converted to Absolute Vertical TEC (VTEC) using the mapping function as given below.

$$\mathrm{VTEC}=\mathrm{STEC}\ \cos(\chi),$$

where, χ is the zenith angle at ionospheric pierce point (IPP) which is estimated from the satellite elevation angle. The shell height is taken as 350 km. Here, only those ray paths with elevation angles greater than 50° are used. It has been shown by Ramarao et al. (2006) that an elevation angle cut off of $>50°$ is ideally suited to represent the TEC over the Indian sector. Average VTEC values are obtained by averaging every 15 min values of VTEC from satellites with elevation angle above 50°.

ΔH values (ΔH refers to the deviation of the horizontal component of the earth's magnetic field H from its mean night time level) at Trivandrum, Alibag, Addis Ababa, Qsaybeh, Ascension Island have also been used for the study. Table 1 gives the list of all the stations for which data has been used in this study. The data used are also shown in the table. The locations are also shown (as given in WDC for Geomagnetism, Kyoto site).

The behaviour of the equatorial F-region has been studied using the ionosonde data at Trivandrum. The real height profiles are obtained from the manually scaled ionogram data using POLAN software. The solar EUV radiations in the range of (0.1–50) nm measured using the SEM instrument on board SOHO spacecraft (Judge et al., 2002) are also used in this study.

1.2 Experimental observations

Figure 1 depicts the temporal variation of ΔH at Trivandrum for 28 October 2003(solid spheres) and the sample quiet day of 5 November 2003 (dashed line) along with the corresponding SymH variations (solid line) for 28 October 2003. SYM-H index is used instead of the disturbance storm time (D_{st}) index, since its one-minute resolution is more suitable for studies of phenomena occurring on short time scales. The SYM-H index follows essentially the same variations as the D_{st} index, however it is obtained from a different set of stations and a slightly different coordinate system (Iyemori et al., 2003).

The ΔH values show a sharp rise in the morning from ~09:00 IST on 28 October 2003, unlike the gradual rise on 5 November 2003. The peak value of ΔH on 28 October 2003 is 160 nT attained at ~11:30 IST. On the sample quiet day, the peak is much broader and the value is only 130 nT.

Table 1. Table depicting the location information and the type of data used at each location.

Station	Latitude	Longitude	Dip latitude	Data
Acension Island	7.9° S	14.4° W	2.3° S	Magnetometer
Addisababa	9° N	39° E	5.3° N	Magnetometer
Ahmedabad	23° N	72° E	14.6° N	GPSTEC
Alibag	18.4° N	72° E	10° N	Magnetometer
Delhi	28° N	77° E	19.1° N	GPSTEC
Jodhpur	26.3° N	73° E	17.8° N	GPSTEC
Qsaybeh	34° N	36° E	30.3° N	Magnetometer
Trivandrum	8.5° N	77° E	0.3° S	Ionosonde, Magnetometer

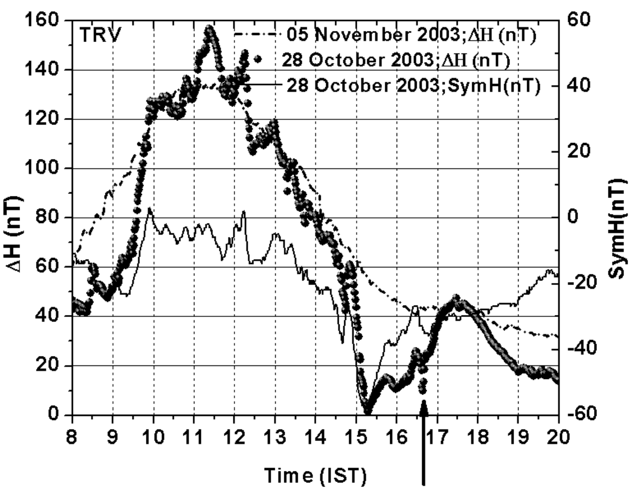

Fig. 1. The temporal variation of ΔH at Trivandrum for 28 October 2003 (solid spheres) and the sample quiet day of 5 November 2003 (dashed line) along with the corresponding SymH variations (solid line) for 28 October 2003.

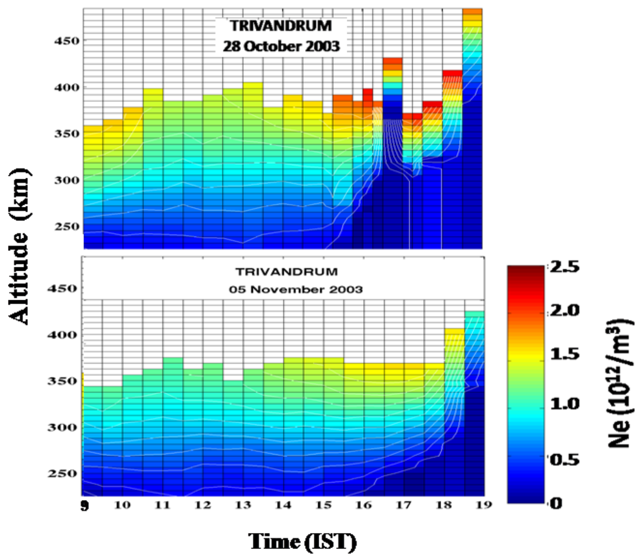

Fig. 2. The time variations of real height and electron density at Trivandrum for 28 October 2003 (top panel) and the sample quiet day (bottom panel).

The falling phases (after attaining the peak), on both the days show similar pattern upto ~15:00 IST. But after 15:00 IST, the ΔH variations on 28 October 2003 show a sharp fall, while the falling phase is gradual on the sample quiet day. The rapid development of the westward ring current is seen in the SymH variations from ~12:00 IST. The modulation of ΔH by the ring current is also clear from the high correlation between the fluctuations in ΔH and SymH during the (12:00–16:30) IST period. The depression seen in ΔH on 28 October 2003 with a deep minimum at 15:15 IST is due to the ring current effect. After 15:15 IST the ring current effect weakens and the ΔH values start increasing. It is during this time that the flare occurs. The upward arrow in this and all subsequent figures indicates the time of flare maximum. In the post 17:00 IST period the ΔH on 28 October 2003 recovers to quiet day levels and then gradually decreases towards late evening hours.

The time variations of real height and electron density at Trivandrum for 28 October 2003 (top panel) and the sample quiet day (bottom panel) are illustrated in Fig. 2. Here the movement of the F layer is discussed in terms of the movement of the regions with higher electron density close to *hm*F2 levels. On the sample quiet day, the N_e values are low in the morning hours and the layer is seen to move up gradually from ~09:45 IST reaching a high value around 11:00 IST indicating the increased effect of $\boldsymbol{E}\times\boldsymbol{B}$ drift. After attaining this high value, the layer gradually moves down till evening when the $\boldsymbol{E}\times\boldsymbol{B}$ effect due to pre-reversal enhancement again causes the upward movement of the layer. In contrast on the event day, the N_e values are higher in the morning itself compared to the sample quiet day. The upward movement of the layer due $\boldsymbol{E}\times\boldsymbol{B}$ drift is much steeper than on the sample quiet day indicating the stronger electric field on the event day. The layer attains maximum height ~12:00 IST

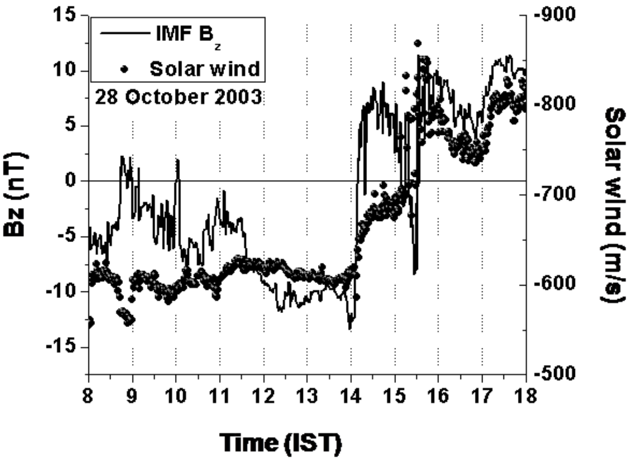

Fig. 3. Temporal variations of IMF B_z and solar wind velocity on 28 October 2003.

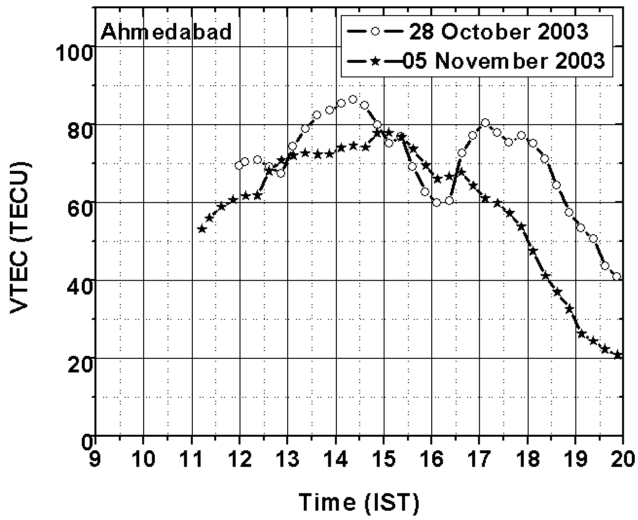

Fig. 4. The temporal variation of VTEC (averaged from satellite passes obtained within 15 min slots) for the station Ahmedabad near the EIA crest on 28 October 2003 (solid line) and 5 November 2003 (dashed line).

and then descends. The flare effect begins around 15:20 IST and the increased ionization due to flare effect is seen in the figure during the ensuing period. The maximum enhancement ($\sim 2.5 \times 10^{12}/m^3$) is seen ∼17:00 IST which is the period close to the maximum of the EUV flux enhancement. For the period (16:35–17:00) IST no trace is available due to D region absorption effects (Belrose and Cetiner, 1962). Hence the maximum effect of the flare enhancement is seen at ∼17:00 IST when the traces reappear. Compared to this, on the sample quiet day, the N_e values are clearly much lower ($\sim 1.5 \times 10^{12}/m^3$) showing the effect of the flare related enhanced ionization produced over Trivandrum on the flare day. At ∼16:30 IST, a sharp spike like rise in the layer height is evident on 28 October 2003. This effect pushes the layer to a maximum altitude of 423 km. This sharp increase in F layer height is probably produced due to the transient IMF B_z southward turning around 15:30 IST as is shown in Fig. 3. At this time there is large increase in solar wind velocity also and the combined effect of these two probably produces prompt electric field penetration (Fejer, 1986) at magnetic equator within 1 h. The probable prompt penetration field effect seems to be very short lived and does not persist long enough to produce significant increase in the fountain effect. But it causes moderate upliftment of the layer, the implications of which are discussed in the next section. In the late evening, the layer rise due to pre reversal enhancement (PRE) is evident on 28 October 2003 also as in the case of the sample quiet day.

The temporal variations of VTEC (averaged from satellite passes obtained within 15 min slots) for the station Ahmedabad near the EIA crest on 28 October 2003 (solid line) and 5 November 2003 (dashed line) are shown in Fig. 4. Data is available only from 11:00 IST onwards on 5 November 2003 and 12:00 IST onwards on 28 October 2003. Around 14:30 IST on 28 October 2003, the TEC attain a maximum value of ∼86 TECU while on the sample quiet day of 5 November 2003, the maximum VTEC of ∼80 TECU is attained around 15:00 IST. The TEC on the sample quiet day is seen to gradually decrease towards evening as expected. But, the TEC on the event day of 28 October 2003, after attaining the peak, shows a tendency to decrease up to 16:30 IST and then shows an enhancement of ∼10 TECU. The enhancement effect persists for around 2 h before finally coming back to the pre flare levels around 18:45 IST.

The VTEC variations observed around the time of the flare as seen by the same satellite from three stations of Ahmedabad (top left panel), Jodhpur (top right panel) and Delhi (bottom panel) are shown in Fig. 5 along with the EUV flux variations. The satellite is moving from south to north. All three stations see a reduction in VTEC (due to south to north movement of satellite) as expected, because the motion is away from the EIA crest region. But at the time when the EUV flux shows a drastic increase ∼16:35 IST, the VTEC at all three stations registers a sharp increase by ∼10 TECU. This is clearly due to the increased production due to enhanced EUV flux. At Ahmedabad, the VTEC falls off as the EUV enhancement abates. But at Jodhpur and Delhi, the enhancement persists for much longer. This is one interesting aspect. It seems that some factor is operating at mid latitude regions which results in persistence of enhanced ionization levels even beyond the time of the flare.

Figure 6a depicts time variation of EUV flux and electrojet strength at the station of Trivandrum on 28 October 2003. The electrojet strength is obtained by estimating the difference in ΔH between an electrojet and an off electrojet station so that disturbance related contamination is removed and the electrojet contribution is delineated. The ΔH at Alibag

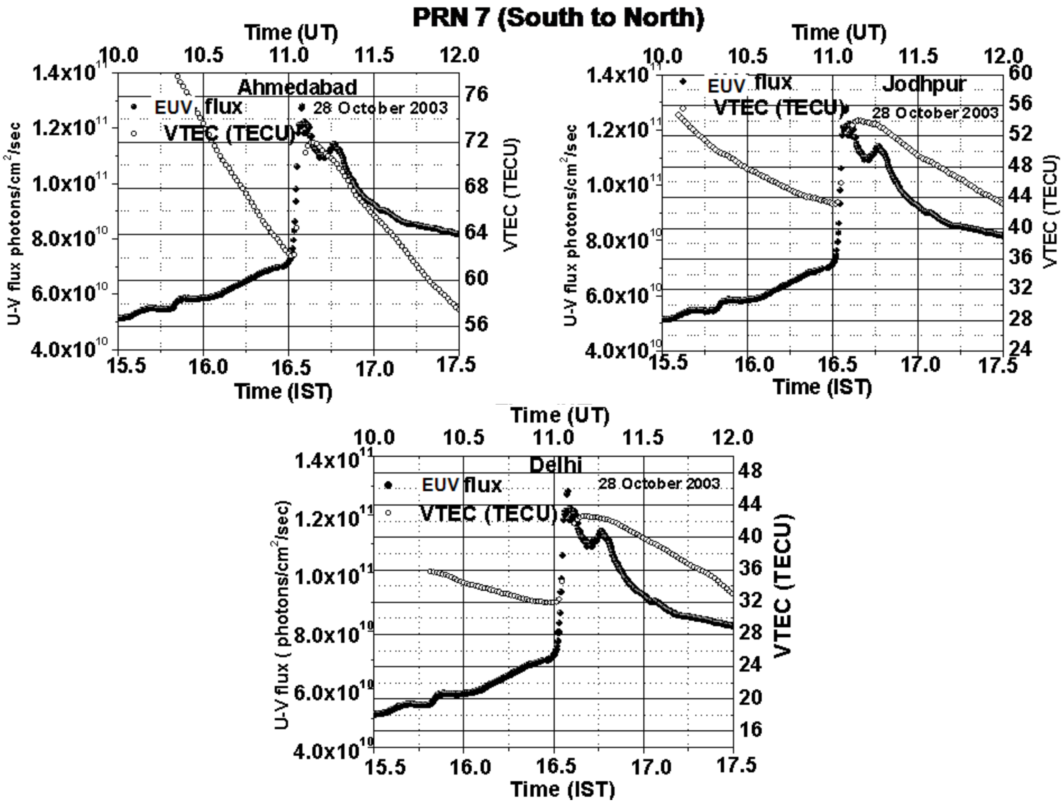

Fig. 5. The time variations of VTEC (around the time of the flare) as seen by the same satellite from three stations of Ahmedabad (top left panel), Jodhpur (top right panel) and Delhi (bottom panel).

an off electrojet station is used here. A double kink variation pattern is shown at Trivandrum corresponding to the double peaked variation seen in EUV flux. The increased EUV flux is expected to cause increased production of ionization. This will in turn cause an increase in the overhead currents due to increased conductivity. The downward kink in electrojet strength (-20 nT with respect to pre flare level) suggests that a reverse or westward current was flowing at the Indian longitudes around this time. The partial counter electrojet current registers a clear increase in association with the flare.

Figure 6b illustrates the time variation of EUV flux and electrojet strength at the station of Addis Ababa in the African sector on 28 October 2003. The ΔH at Qsaybeh an off electrojet station is used here. A double peaked upward variation pattern is shown in electrojet strength ($\sim$60 nT with respect to pre flare level) at Addis Ababa corresponding to the double peaked variation seen in EUV flux. It is clear from the figure that a normal electrojet was prevailing over African longitudes and it was strengthened by the increased conductivity due to the flare.

Figure 6c shows the temporal variation of EUV flux and magnetic filed (H) at the station of Acension Island on 28 October 2003. Here the total field is being shown instead of electrojet strength (as off electrojet station data was not available). Clear downward double kink variation pattern is seen in H (-19 nT with respect to pre-flare level) at Ascension Island corresponding to the double peaked variation seen in EUV flux. Here again the counter electrojet prevailing over this longitude region of $\sim 14°$ E is strengthened by the flare related increase in conductivity.

2 Results and discussion

In the present study the response of the ionospheric E -and F-regions over the Indian sector, during the intense flare of 28 October 2003 have been examined.

From the observations of various parameters like SymH, IMF B_z and ΔH it is clear that 28 October 2003 is a day characterized by only moderate disturbances. Hence the signatures of the flares in the different geophysical parameters can be clearly delineated without being hampered by drastic disturbance effects. The examination of the ionogram real height profiles, over the magnetic equatorial station of Trivandrum, reveals that the N_e values are nearly doubled during the flare time, in comparison with the values around the same time, on the sample quiet day. This increased ionization is produced due to EUV flux enhancement associated

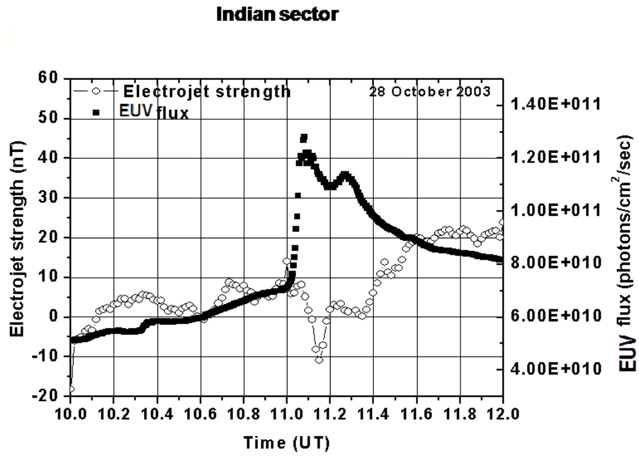

Fig. 6a. The time variations of EUV flux and electrojet strength at the station of Trivandrum (77° E) on 28 October 2003.

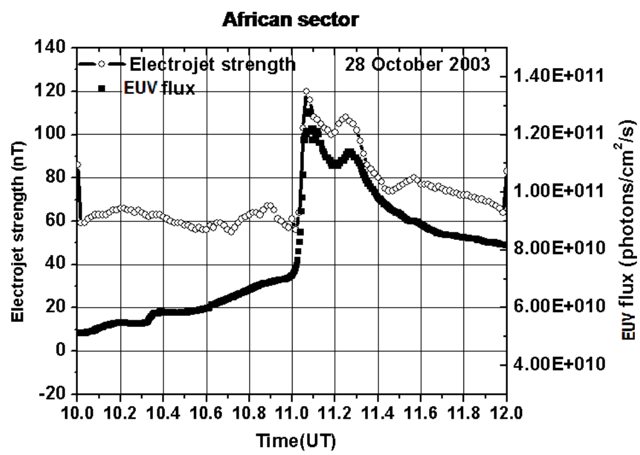

Fig. 6b. Time variation of EUV flux and electrojet strength at the station of Addis Ababa in the African sector (39° E) on 28 October 2003.

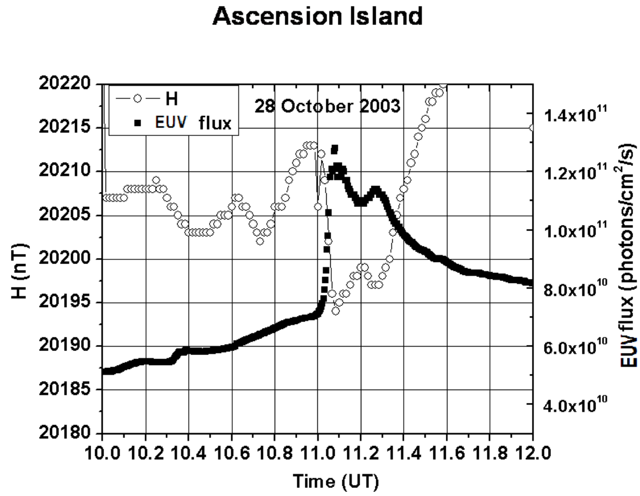

Fig. 6c. The temporal variations of EUV flux and magnetic filed (H) at the station of Ascension Island (14° E) on 28 October 2003.

with the flare (Thome and Wagner, 1971; Mendillo et al., 1974). This flare occurred in the equinoctial period and therefore the N_e enhancements are expected to be more significant in regions close to the equator. The rise of the layer to higher altitudes, where recombination effects are lower, just prior to the flare is another factor that results in the N_e enhancement lasting for longer duration.

The averaged VTEC profiles, on the event day, in comparison with those on the sample quiet day show, the clear cut TEC enhancement in association with the flare. The observed enhancements in TEC during the time of EUV flux increase is of the order of 10 TECU at the stations of Ahmedabad, Jodhpur and Delhi. The TEC enhancement falls off gradually with the decrease of the EUV enhancement at Ahmedabad. But at Jodhpur and Delhi the mid-latitude stations beyond the EIA crest the TEC is found to, decrease at a much slower rate. This probably shows that, an equator ward meridional wind may have been acting at these stations, pushing the ionization, to higher altitudes where the recombination is less. For this same event TEC enhancement at the sub solar point in Africa is reported to be ∼25 TECU (Tsurutani et al., 2005a, 2006).

The geomagnetic variations during normal and counter electrojet events have been discussed by many workers (Srivastava, 1974; Sastri, 1975; Rastogi et al., 1975, 1999; Rangarajan and Rastogi, 1981; Manju and Viswanathan, 2005). These studies have shown that the SFE (H) amplitude is lower at equator and higher for stations outside the jet due to the counter electrojet related decreasing effect on ΔH. The longitudinal variability in occurrence of counter electrojet has also been investigated in the past (Alex and Mukherjee, 2001). Geomagnetic signatures of sudden ionospheric disturbances during extreme solar radiation events are discussed by Dmitriev and Yeh (2008). They have considered solar energetic protons also as a source of ionization of the ionosphere and upper atmosphere, especially at high and mid latitudes. Further, ionospheric effects of solar flares have been studied in the past using Thomson scatter measurements (Thome and Wagner, 1971). The measurements brought out strong electron density enhancement in the E-region of the order of 100% and moderate enhancement in the F-region. The EUV flux being a major source of ionization in the E- and F-regions, the enhancement in the same was proposed to be the cause of the N_e enhancements.

In the present study, we are also looking into the longitudinal variability in flare related geomagnetic signatures at and around the geomagnetic equator. The presence of a partial counter electrojet is evident over the Indian sector and Ascension Island during the flare time and this counter electrojet current is enhanced as mentioned earlier due to the increased ionization produced by the flare related EUV flux enhancement. On the other hand, a strong enhancement of the normal electrojet is evident from the examination of the electrojet variations over African sector. In all three stations, the electrojet currents as seen in the magnetic field are showing a highly correlated response with the SOHO SEM EUV flux variations. The magnitude of the flare related enhancement is 20 nT, 19 nT and 60 nT at Trivandrum, Ascension Island and Addis Ababa respectively. The large amplitude at Addis Ababa is due to the local time being close to noon with normal electrojet prevailing. The significant modulation of the EEJ associated currents systems by the flare related EUV flux enhancements in different longitudes is brought out in the above discussion. In the past the flare related upward kinks in magnetic field during normal electrojet times and downward kinks during counter electrojet times have been discussed for different flare events (Manju and Viswanathan, 2005). But in the present case the upward and downward kink in magnetic field are observed for the same flare event at different longitudes and the flare reveals the pattern of longitudinal variability in the counter electrojet occurrence on the same day.

3 Conclusions

The present study brings out the following aspects related to the ionospheric response to the solar flare event of 28 October 2003:

1. Significant TEC enhancement (∼10 TECU) is observed at and beyond the EIA crest region during the flare. This enhancement is attributed to the increased EUV radiation emitted during the flare and consequent increased production of ionization. The possible role of meridional winds in lifting the layer to higher altitudes, with lower recombination rates, is indicated at the mid latitude stations of Jodhpur and Delhi.

2. The increased vertical drift, just prior to the flare related peak EUV enhancement, lifts the F layer over magnetic equator, to much higher altitudes with lower recombination. As the EUV flux enhancement occurs it produces increased ionization. The F layer being at a higher height than usual also contributes, to the observed prolonged N_e enhancement, by way of reducing the recombination.

3. The modulation of the EEJ current system at different longitudes by the flare related EUV flux variations is clearly brought out in this study.

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