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Response of equatorial ionosphere during the super geomagnetic storm of April 2000

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The effects of super geomagnetic storm of 6 April 2000 on E and F-regions of the ionosphere at Thumba (India) and at Jicamarca (Peru) are studied. The geomagnetic storm started at 1630 hrs UT on 6 April 2000 with sudden increase in solar wind speed and ion density and southward turning of IMF-Bz from 0 to -25 nT. The event was unique with IMF-Bz steady southward for about 6 hours and later turning from -30 nT at 2300 hrs UT to 10 nT at 0200 hrs UT and large fluctuations around 1200 hrs UT on 7 April 2000. The southward turning of IMF-Bz on the night of 06-07 April 2000 inhibited the development of Spread-F irregularities at Thumba. The large excursions of IMF-Bz on 7 April 2000 inhibited the Es-q at Thumba. At Jicamarca, the southward turning of IMF-Bz on 6 April caused a very large enhancement of EEJ current and generated very strong Es-q. The northward turning of IMF-Bz on 7 April 2000 is associated with large rise of F-layer around midnight and ESF was seen at 0100 hrs LT; however, later, the F-layer descended and inhibited ESF irregularities. The results confirm the earlier suggestion of Rastogi & Patel [Effect of interplanetary magnetic field on the ionosphere over the magnetic equator, *Proc Indian Acad Sci,* A 82 (1975) pp 121-141] that northward (southward) turning of IMF-Bz generates an eastward (westward) electric field in night side of ionosphere and westward (eastward) electric field in the dayside of ionosphere. The effect of a solar space weather event on the equatorial ionosphere at different longitudes depends on the local solar time of the event.

Keywords: Equatorial ionosphere, Geomagnetic storm, Solar wind speed, Interplanetary magnetic field

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1 Introduction

The unique geometry of the geomagnetic field at magnetic equator gives rise to several characteristic features of the equatorial ionosphere. The enhanced daily range of the geomagnetic H field close to the magnetic equator was suggested by Chapman[2] due to a narrow band of intense current flowing eastward during the daytime in the ionosphere around 100 km and named it equatorial electrojet (EEJ). The northward geomagnetic field and the daytime eastward electric field in the dynamo region give rise to enhanced effective conductivity and therefore, a band of intense eastward current. Associated with the electrojet current, is the equatorial type of the transparent Sporadic-E known as Es-q (Ref 3). Es-q is due to the scattering of radio waves by small scale plasma density irregularities caused by two stream instability, which operates when electron velocity with respect to ion velocity exceeds the ion-acoustic velocity, or by gradient drift instability that operates when the drift velocity is along the direction of the plasma density gradient.

There are occasions when the daytime geomagnetic H field is below the night time level[4,5] and named counter electrojet (CEJ) by Gouin & Mayaud[6]. Cohen *et al.*[7] first observed the association of the disappearance of Es-q and the decrease of the H field below the night level. Chandra *et al.*[8], from spaced receiver drift measurements near magnetic equator at Thumba, showed a high correlation between the day-to-day changes in the midday value of the drift speed and in the deviation in H at Trivandrum. The correlation improved when the difference in the deviations in H at Trivandrum and Alibag (away from magnetic equator) was used instead. Rastogi. showed disappearance of Es-q at times when the daytime drift at Thumba reversed to eastward. Later studies showed absence or weakening of the equatorial ionization anomaly associated with CEJ events.

The electric fields from dynamo region map to F-region via the highly conducting geomagnetic field lines and give rise to plasma drifts in the F-region. Thus, during the daytime, the vertical uplift of the plasma near magnetic equator gives rise to lower ionization density in F-region as compared to magnetic latitudes around ± 15-20° and known as equatorial ionization anomaly (EIA) or Appleton anomaly[10]. The vertical upward plasma drift also gives rise to noon bite out with peaks in the forenoon and afternoon in the daily variation of ionization density at the magnetic equator.

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Another important feature of the equatorial ionosphere is the presence of diffuse echoes in the ionograms in the post sunset hours known as equatorial Spread-F (ESF)[11]. The presence of ESF is preceded by the large rise of the F-layer just before the evening reversal of the electric field caused by the F-layer dynamo. Later, similar studies were done at Singapore[12], Kodaikanal[13], Ibadan[14], Thumba[15] and Ho Chi Minh City[16]. Post sunset height rise of the F-layer was shown to control the onset of ESF.

Rastogi & Woodman[17] showed that ESF can develop at any time of the night other than the post sunset period if the vertical F-region drifts reverse to upward direction (eastward electric field imposed). Prakash *et al.*[18] observed electron density irregularities associated with ESF over SHAR (dip latitude 11°N) around 280 km in the region of downward electron density gradient when the F-layer was drifting downward indicating that the gradient drift instability was the main mechanism for the generation of irregularities. Thus, the conditions for the development of ESF are: (i) existence of strong plasma density gradient and (ii) continuation of the daytime Sq field for some time after sunset. Comparing the VHF backscatter radar data at Jicamarca and the ionograms at Huancayo, Rastogi[19] suggested that the first seeding of the ESF irregularities in the evening hours occurs due to the gradient drift instability at any height between E and F-layers where large plasma density gradient exists. Later, the irregularities extend upwards throughout the F-region due to the buoyancy effects. The generalized Rayleigh-Taylor instability, that includes the electric field and neutral winds along with gravitational term, is considered to be the primary process for the generation of intermediate scale irregularities. Large-scale plasma depletions, thus, generated rise fast to cover entire F-region including topside. Steep plasma density gradients then provide seat for the generation of small-scale irregularities[20]. Electric field gives rise to gradient drift instability under suitable plasma density gradients besides raising the F-layer to higher altitudes where growth rate due to gravitational term is higher.

Thus, electrodynamics plays an important role in the equatorial ionosphere and day-to-day variability in the electric field gives rise to day-to-day changes in the equatorial ionosphere. While the day-to-day variability during geomagnetic quiet days is fairly well understood, the variability on geomagnetic disturbed periods needs to be understood fully. Apart from the electric fields of dynamo region, there are prompt penetration electric fields from magnetosphere (both under shielding and over shielding types) and the delayed and comparatively longer duration disturbance dynamo fields. Under the international CAWSES program there have been several studies of space weather events.

2 Event of April 2000

A coronal mass ejection (CME) took place close to the western limb of the Sun at 1632 hrs UT associated with the solar flare at 1524 hrs UT on 4 April 2000. A strong southward interplanetary magnetic field (IMF-Bz) in the sheath region caused a magnetic storm with sudden commencement at 1632 hrs UT on 6 April 2000. This was the second largest storm in 2000 with Sym-H index of -300 nT around 0000 hrs UT on 7 April. The unique feature of the storm was an intense and long sustained southward IMF-Bz and a very large solar wind velocity and density causing a large amplitude of SC at low latitudes, about 150 nT at Huancayo (midday LT) and 45 nT at Tirunelveli (midnight LT). The large solar wind velocity and proton density also resulted in a large magnetic pressure. IMF-Bz turned northward after midnight. Huttunen *et al.*[21] have described the response to the April 2000 geomagnetic storm from more than 80 magnetometer stations at latitudes higher than 40°N. Rastogi *et al.*[22] reported the results on a study of geomagnetic data for the April 2000 storm at low latitude stations in India and far-east. There have been a number of studies on the response of ionosphere to this magnetic storm. Afraimovich *et al.*[23] described the traveling ionospheric disturbances (TIDs) using total electron content data from GPS receivers in Russia and central Asia. Lee *et al.*[24] described the observations of TIDs at middle and low latitude stations Wuhan and Chungli. Su *et al.*[25] described the plasma depletion structures associated with equatorial Spread-F in Chinese midnight period from ROCSAT-1 (600 km) observations. Liu *et al.*[26] reported the ionospheric response to the storm of April 2000 using the digisonde data at Chungli, Wuhan and Kokubunji near the anomaly crest region. Jadav *et al.*[27] described the features of interplanetary scintillations recorded at Rajkot. Pimenta *et al.*[28] described the observations of plasma blobs associated with large-scale plasma density depletions in the nighttime low-latitude F-region in the Brazilian sector through the all sky OI 630 nm images. The magnetic storm of April 2000 resulted in both the prompt penetration electric field and the disturbance dynamo effects and also TIDs.

The present paper describes the response of the ionosphere both during daytime and night time at two magnetic equatorial stations Thumba in the Indian longitude sector (8.5°N, 77.0°E, magnetic dip 1.0°N) and Jicamarca in the American longitude sector (12.0°N, 76.8°W, magnetic dip 1.1°N).

3 Results

3.1 IMF, Solar wind and SYM-H variations

The north-south component of the interplanetary magnetic field, IMF-Bz along with the solar wind parameters (flow speed, proton density and flow pressure), computed interplanetary electric field (-V × Bz) and the SYM-H index for 6 and 7 April 2000 (in hrs UT) are shown in Fig. 1. The unique feature of the event is that IMF-Bz turned southward suddenly around 1600 hrs UT and remained southward till 0100 hrs UT on 7 April. Between 1800 hrs UT and midnight, Bz remained around -30 nT. The solar wind

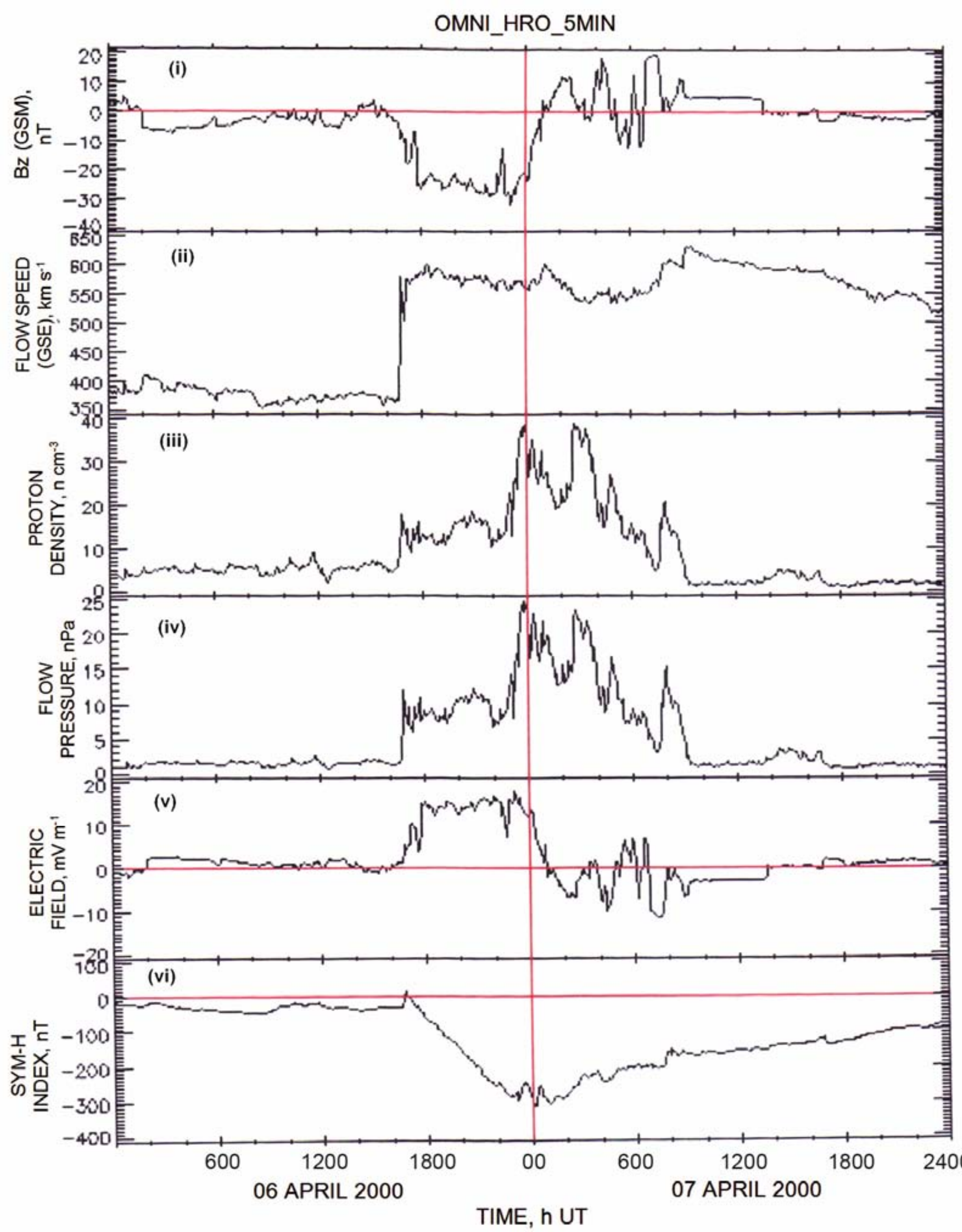

Fig. 1 — Temporal variations of: (i) Interplanetary magnetic field normal to the ecliptic, Bz; (ii) Solar wind flow speed; (iii) Solar wind proton density; (iv) Solar wind flow pressure; (v) Interplanetary electric field (-V × Bz); and (vi) Disturbance ring current index SYM-H during the magnetic storm of 6-7 April 2000 plotted in hrs UT

velocity was between 350 and 400 km s^{-1} till 1700 hrs UT on 6 April 2000 and then increased suddenly to values exceeding 550 km s^{-1} or more throughout the period. The proton density values were only few cm^{-3} but increased to more than 10 cm^{-3} around 1630 hrs UT on 6 April and shot to 35 cm^{-3} at midnight and then again around 0300 hrs UT on 7 April. There were another two peaks around 0500 and 0800 hrs UT. The proton density returned to normal values after 0900 hrs UT on 7 April. As the solar wind velocity remained more or less same from 1600 hrs UT on 6 April to 0900 hrs UT on 7 April, the variations in proton density and flow pressure are similar with large values from around 1630 hrs UT on 6 April to 0900 hrs UT on 7 April with large peaks around midnight, 0300 hrs UT and two secondary peaks around 0500 and 0800 hrs UT. The interplanetary electric field due to the solar wind velocity and IMF-Bz remained high from 1630 hrs UT on 6 April to midnight with values of 10-15 mV m^{-1} and showed large fluctuations from -10 to few mV m^{-1} between 0100 and 0800 hrs UT on 7 April. The SYM-H index showed rapid decrease from 1630 hrs UT on 6 April to about -300 nT around midnight and later recovered gradually to about – 100 nT at midnight of 7 April.

3.2 Ionosphere at Thumba

In the Indian sector, ionograms at Thumba (77°E) are examined. Figure 2(a) shows the variation of IMF-Bz on 6 and 7 April 2000. The x-axis represents local time hour in IST (82.5°E), which is 5.5 h ahead of UT and plotted from 0600 hrs LT on 6 April to 0600 hrs LT on 8 April 2000. Figure 2(b) shows selected daytime ionograms at Thumba on both the days. Daytime of 6 April shows normal values of IMF-Bz. Equatorial type of Sporadic-E (Es-q) is seen in all ionograms for 1100, 1200, 1300, 1400 and 1700 hrs LT and the blowing up of the F2 layer during the daytime. The ionograms at 1800 hrs LT show Es-q echoes and in addition clear E and E2 structures with clear group retardation. The E2 layer is seen around 180 km. The IMF-Bz turns northward around 0700 hrs LT on 7 April and fluctuates between 10-15 nT and -10 nT with northward turnings around 0700, 0900 and 1200 hrs LT in the recovery phase of the geomagnetic storm. The selected daytime ionograms on 7 April show Es-q at 1145 hrs LT but it disappears subsequently and not seen in the later ionograms of 1200, 1300, 1500 and 1615 hrs LT due to the frequent positive excursions of the IMF-Bz. It reappears later as seen in the ionograms of 1630 hrs LT. Thus, for duration of more than 4 h, Es-q is absent implying reversal of the daytime electric field to westward. Rastogi & Chandra[22] had shown from the difference between the deviations in H at an equatorial station and a station away from magnetic equator that in the Indian region EEJ was weak during 0100-0400 hrs UT (0630-0730 hrs LT) and a counter electrojet from 0400 hrs UT to 1100 hrs UT (0930-1630 hrs LT) with maximum strength of -70 nT. Thus, the reversal of electric field gives rise to the disappearance of Es-q for almost 4 h. It must be noted that during the recovery phase of the severe geomagnetic storm, westward electric field of the disturbance dynamo origin is also present that could contribute to the disappearance of Es-q.

The selected ionograms over the two nights are shown in Figs 2(c and d). Looking at the variation of IMF-Bz during the two nights in Fig. 2(a), IMF-Bz values increase after sunset with positive gradient between 1800 and 2030 hrs LT on 6 April and later, it turns southward and remains southward till 0600 hrs LT with values of -20 nT or larger from 2300 to 0600 hrs LT. The ionograms during the night of 6-7 April in Fig. 2(c) show F-layer ascending from 275 km at 1800 hrs LT to more than 400 km at 2015 hrs LT. Range type of Spread-F develops at lower frequencies at 2015 hrs LT and continues as seen in later ionograms at 2030, 2045 and 2100 hrs LT and a sign of very weak range Spread-F at 2130 hrs LT. However, it did not develop into strong range spread covering the entire frequency range of F-layer trace. F-layer descend is seen from 2030 hrs LT and by 2330 hrs LT, it descended to 220 km, which appears to be lower height than the usual. There is no Spread-F as seen in the ionograms 2230 hrs LT onward. Thus, the southward turning of the IMF-Bz has resulted in the descent of the F-layer after 2015 hrs LT and absence of Spread-F later on. The IMF-Bz variation during the night of 7-8 April 2000 shows normal values (between 0 and - 4 nT) and thus, the solar wind did not modify the normal Sq electric field. The ionograms during this night are shown in Fig. 2(d). The F-layer rises in the evening from 250 km at 1715 hrs LT, 280 km at 1815 hrs LT, 375 km at 1915 hrs LT and 405 km at 1945 hrs LT. At 1815 hrs LT, some spread echoes are seen at the level of E2 around 180 km. About 90 minutes later, range Spread-F is seen developing at 1945 hrs LT and it extends to the entire frequency range of the F-region trace at 2030 hrs LT. Though the base of the F-layer is above 450 km

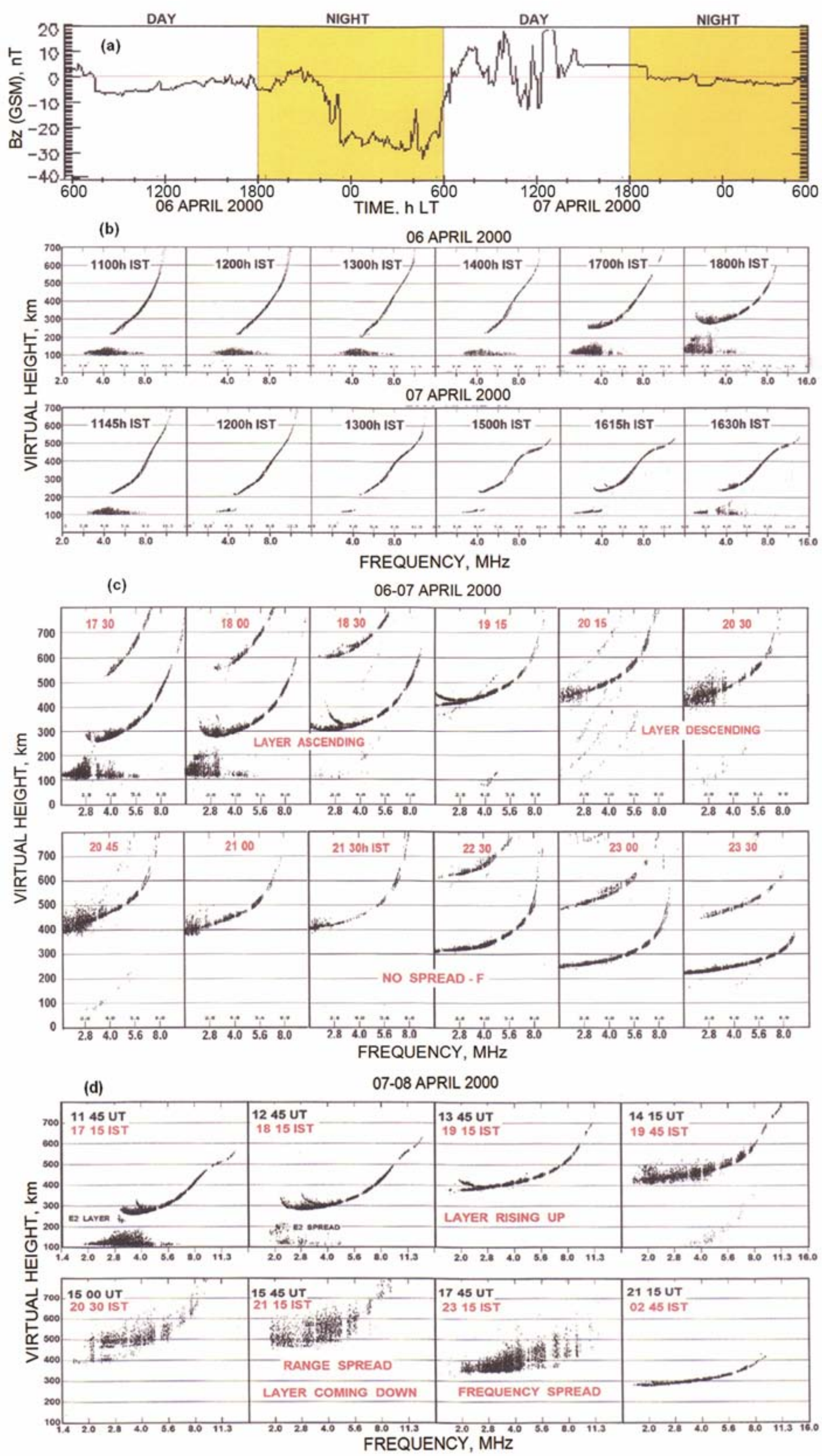

Fig. 2 — (a) Temporal variation of IMF-Bz on 6 and 7 April 2000 plotted in hrs LT at Thumba; (b) Selected daytime ionograms at Thumba on 6 and 7 April 2000 showing the disappearance of Es-q on 7 April 2000; (c) Selected ionograms at Thumba for the night of 6-7 April 2000 showing the normal ascending F-layer resulting in ESF but inhibition later due to changes in IMF-Bz; (d) Ionograms at Thumba for the night of 7-8 April 2000 showing normal development of ESF in the post sunset hours

at 2030 hrs LT, there is echo below the F-layer at 400 km also. In the ionograms at 2115 hrs LT, F-layer trace is not identifiable below 5.6 MHz and discrete layer type echoes are seen at different ranges. The F-layer descends after 2115 hrs LT and at 2315 hrs LT, it has come down to 350 km. By this time, it has transformed into frequency type of spreading with critical frequency unidentifiable and range identifiable. At 0245 hrs LT, there is no spreading of the trace and the F-layer has come down to 280 km. This is a regular sequence on a Spread-F night. Thus, the southward turning of IMF-Bz during the night of 6-7 April 2000 inhibited the Spread-F at Thumba.

Abdu[29] discussed the processes of the development, suppression or disruption of ESF under different phases of a magnetic storm based on published results and some new data. The comprehensive study covered under-shielding or over-shielding electric fields as well as the disturbance dynamo electric fields in different local time sectors of the night. It was concluded that the ESF can occur at any time of the night side ionosphere. Under-shielding electric fields can cause ESF in the post sunset sector and an over-shielding electric field causes ESF in the post-midnight sector. The evening pre-reversal enhancement in the electric field (PRE) and subsequent post sunset ESF can be totally suppressed by over-shielding westward electric fields. Further, the longitudinal variation in PRE or ESF suppression exists in the storm recovery phase by the longitudinal dependence of disturbance dynamo electric field or in the disturbance associated westward thermospheric winds.

3.3 Ionosphere over Jicamarca

In the American sector, the ionograms over Jicamarca are examined. The local time at Jicamarca is 5 h behind UT. Figure 3(a) shows the variation of IMF-Bz from 1800 hrs LT on 5 April 2000 to 1800 hrs LT on 7 April 2000. Figure 3(b) shows selected ionograms recorded at Jicamarca for day time of 6 April 2000 and 7 April 2000 while Fig. 3(c) shows the selected ionograms for the nighttime of 5-6 April 2000 and 6-7 April 2000. Referring to Fig. 3(a), the geomagnetic storm started at local midday of 6 April 2000 imposing a large southward Bz or a positive interplanetary electric field. The ionograms for the daytime in Fig. 3(b) indicate normal Es-q echoes on 7 April but enhanced Es-q echoes with the top frequency fEs exceeding 16 MHz on 6 April 2000. Thus, the enhanced electric field caused stronger Es-q irregularities. Figure 3(c) shows the ionograms over Jicamarca during the nights of 5-6 April 2000 and 6-7 April 2000. During the night of 5-6 April, there were no large incursions of IMF-Bz and the development of ESF was normal. ESF developed after midnight and was seen till sunrise. On the night of 6-7 April 2000, there was a large negative incursion in IMF-Bz at post sunset hours but it turned northward causing a temporary height rise of F-layer and generation of range type of ESF at 0100 hrs LT. Later, large southward and northward excursions of IMF-Bz during the night time inhibited the formation of ESF.

Figure 4 shows the daily variation of the critical frequency of the F2 layer, foF2, the minimum virtual height of the F-layer, h’F and the height of the maximum ionization of F2 layer, hmF2 on 5 and 6 April 2000 from half hourly values. Figure also shows the daily variation of the deviation in the horizontal component of the geomagnetic field, ΔH at Huancayo and at Fuquene along with the difference in the deviation ΔH at the two stations. The difference ΔH (HUA-FUQ) is a measure of the electrojet strength and hence, of the electric field direction. The computed interplanetary electric field ($-V \times Bz$) is also plotted in the figure. The computed interplanetary electric field values rise from about zero at 1100 hrs LT to about 15 mV m^{-1} at 1300 hrs LT and remain high till 1900 hrs LT on 6 April 2000. The interplanetary electric field decreases rapidly from 1900 hrs LT and reverses direction at 2000 hrs LT. The maximum negative value, -7 mV m^{-1} is at 2130 hrs LT. The variations of the ΔH at HUA and FUQ are normal on 5 April 2000 with midday values of slightly less than 100 nT at FUQ and about 200 nT at HUA but on 6 April ΔH values are higher especially at HUA (more than 300 nT). Following the SC, there is large drop in ΔH at both stations during the main phase of the storm associated with the ring current and reaching values close to -300 nT around 1800 hrs LT. The difference ΔH (HUA-FUQ) shows midday value of about 150 nT on 5 April 2000 and about 300 nT on 6 April 2000. Thus, the electrojet was very strong on 6 April 2000. This is because of the large prompt penetration electric field associated with the southward turning of IMF-Bz together with enhanced solar wind pressure. After 1500 hrs LT, ΔH (HUA-FUQ) is negative indicating counter electrojet. Implication of this is seen in the variation of ionospheric parameters on the two days. On 5 April 2000, h’F rises in the post sunset period to about 420 km and remains at that level for about 2 h. On 6 April

2000, h'F rises to about 550 km in the post sunset period but decreases rapidly to low values due to the reversal of electric field at 2000 hrs LT. The variation of the height of maximum ionization, hmF2 is similar with maximum post sunset value of 700 km on 5 April and 800 km on 6 April 2000. The hmF2 value at midday is also very high on 6 April with a value of 600 km. This is associated with high value of the eastward electric field that gave rise to very strong electrojet strength on 6 April 2000. The variation of foF2 on 5 April 2000 shows almost constant values of about 13 MHz from 1200 to 1700 hrs LT and later, decrease to about 8 MHz at 2100 hrs LT. The night time values remain around 8 MHz except for a minor peak of about 10 MHz at midnight that may be associated to small rise of hmF2 around this time. The

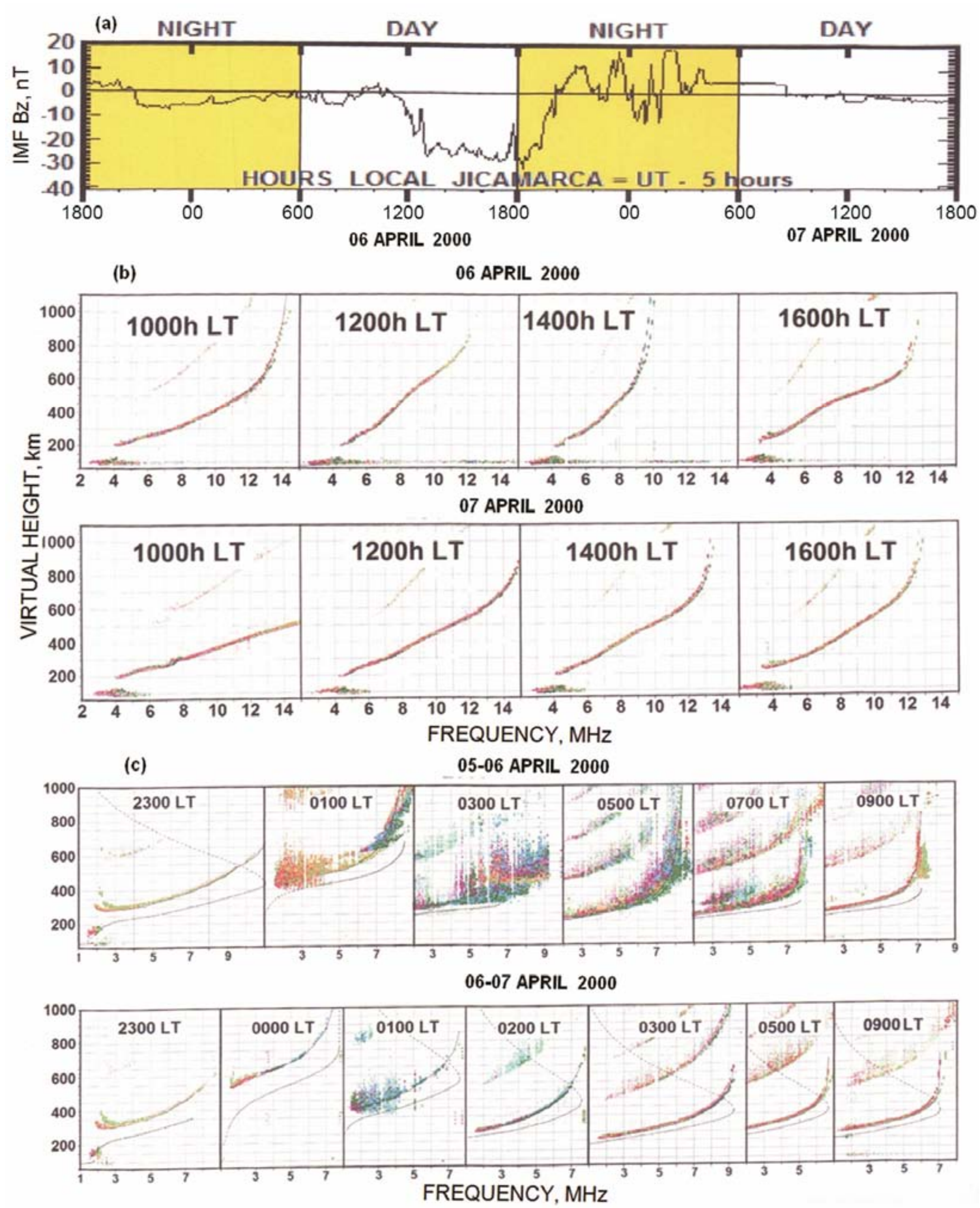

Fig. 3 — (a) Variation of IMF-Bz on 6-7 April 2000 plotted in local time at Jicamarca; (b) Selected daytime ionograms at Jicamarca on 6 and 7 April 2000 showing abnormally strong Es-q echoes on 6 April 2000 due to southward IMF-Bz; (c) Selected ionograms at Jicamarca during the nights of 5-6 April 2000 and 6-7 April 2000 showing the absence of ESF on the night of 6-7 April 2000

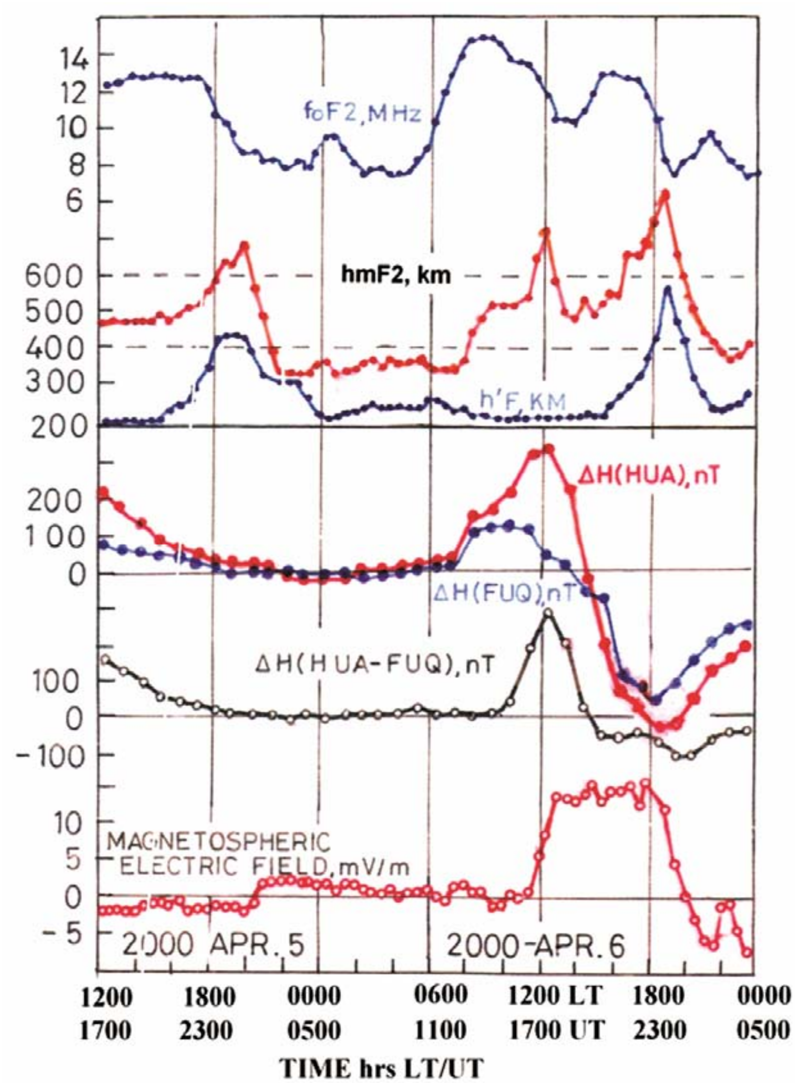

Fig. 4 — Temporal variations at Jicamarca on 5 and 6 April 2000 of: (i) Magnetospheric electric field; (ii) ΔH at Huancayo, ΔH at Fuquene and the ΔH for EEJ (difference of ΔH at Huancayo and at Fuquene); and (iii) ionospheric parameters h'F, foF2 and hmF at Jicamarca [extraordinary large electrojet current at 1700 hrs UT (1200 hrs LT) on 6 April 2000 associated with the large and sudden increase of electric field]

characteristic noon bite out in foF2 variation is absent on 5 April 2000. On 6 April 2000, there is strong noon bite out and the clear peaks at 0900 hrs LT in the morning and 1500 hrs LT in the afternoon with foF2 values of about 15 MHz and 13 MHz, respectively. This is associated with the strong electrojet on 6 April 2000 as compared to on 5 April 2000. High values of hmF2 and low values of foF2 during daytime of 6 April 2000 is consistent with the strong ionization anomaly as seen by the strong midday bite out in the variation of foF2 on 6 April 2000. Equatorial Es-q is also present during the daytime of 6 April 2000. Daytime ionograms on 7 April show higher values of foF2 and lower values of hmF2.

4 Discussion

Farley *et al.*[30] described ESF at Jicamarca using the 50 MHz radar backscatter observations and found that the plasma density irregularities can be generated anywhere in the F-region. They suggested that the plasma density gradient and drift velocity as a possible source of instability besides the gravitational instability and several other well known types of plasma instability. The occurrence of ESF is generally inhibited during geomagnetic disturbances[13-15,31]. Chandra & Rastogi[32] showed that during post-midnight hours of low sunspot years, ESF was more frequent on geomagnetic disturbed days than on the quiet days. Rastogi & Patel[1] had shown that a sudden and large northward turning of IMF-Bz is associated with the sudden reversal of ionospheric plasma drift over Jicamarca. It was suggested that the solar wind moving with a velocity, V, is equivalent to an electric field $E = -V \times Bz$. This field is transferred to the polar region and then to equatorial latitudes without any delay and thereby modifying the dynamo electric field in the ionosphere. It was shown that the direction of the interplanetary electric field was always opposite to the existing Sq electric field. On some occasions, during the daytime hours, the normal Sq field is over compensated and the plasma drifts are reversed and Es-q inhibited. Kelley *et al.*[33] suggested that such an IMF change may quickly reduce the convection electric field on closed magnetic field lines inside the magnetosphere and temporarily un-shield the new electrical structure causing dusk to dawn perturbation field. The propagation of the polar electric field to the equator was studied theoretically by Kikuchi *et al.*[34] and Kikuchi & Araki[35]. Rastogi & Woodman[17] showed that ESF can also develop at any time of the night besides the post sunset period if the vertical F-region drifts reverse to upward direction (eastward electric field imposed). Aarons[36] suggested that the local time when the peak excursion of the ring current occurs affects the equatorial electric field and therefore, the generation or inhibition of the ESF irregularities. If the minimum Dst index occurred during the post-midnight hours, the irregularities are generated and if it occurred in the afternoon hours, the irregularities are inhibited. Martinis *et al.*[37] concluded that for the post sunset periods both the generation and inhibition of ESF can occur depending on which magnetospheric or ionospheric electric field is dominant.

Several strong geomagnetic storms with a number of equatorial crossings by IMF have been studied and the generation or inhibition of the ESF attributed to the prompt penetration electric fields. Abdu *et al.*[38] studied the major geomagnetic storm of 26 August 1998 from multi-station and multi-instrument network at equatorial and low latitudes in Brazil. Southward turning of the IMF-Bz and associated auroral (AE) intensifications in the Brazilian dusk sector produced intense prompt penetration electric field that caused large vertical F-region drift and development of intense post-sunset EIA and strong Spread-F lasting the night as seen by ionosondes and all-sky imagers. The bubbles showed low eastward velocity that turned into steady westward velocity till morning hours. This showed a dominant role of the disturbance dynamo associated westward thermospheric winds to maintain plasma irregularity drift going increasingly westward into post-midnight hours. The results also pointed to the significant contribution to the westward drift of irregularities, normally attributed to disturbance dynamo effect, from the prompt penetration disturbance zonal electric fields. Zonal and vertical velocity perturbations of small scale structures were seen to be anti-correlated (vertical drift associated with westward drift). This pointed to the role of Hall electric field that can be induced by a primary disturbance zonal prompt penetration electric field under enhanced ionospheric conductivity due to the storm associated particle precipitation in the Brazilian sector.

Abdu *et al.*[39] from ionograms at Sao Luis in Brazil, reported downward F-layer drift from about 1830 to 2000 hrs LT on 31 March 2001 with no ESF development under intense southward IMF-Bz condition. Strong over-shielding electric field (westward) resulted in a downward drift of about -60 m s^{-1} at 1900 hrs LT. The normal drift of F-layer on quiet days during March is about 60 m s^{-1} around 1900 hrs LT when ESF is present.

Tulasi Ram *et al.*[40] studied the post sunset ESF during few geomagnetic storms. They showed that the prompt penetration of eastward electric field into low latitudes and subsequent development of ESF occurred at all longitudes where the local time corresponds to post sunset hours. Rastogi *et al.*[41] described the impact of a magnetic cloud at 1635 hrs UT on 25 June 1998 associated with the sudden increase of solar wind velocity and density. IMF-Bz was northward and remained strong (~15 nT) and steady for the next six hours during which the Auroral index and the Dst index were low. IMF-Bz turned southward around 2300 hrs UT and remained around -15 nT from midnight to 0600 hrs UT during which strong auroral index and large drop in Dst index were seen. Strong Spread-F at Jicamarca (night side) and the disappearance of Esq at Thumba (dayside) were associated with disturbance dynamo fields. Huang *et al.*[42] showed that during the main phase of magnetic storm, the shielding effect of the ring current can persist for many hours after the reorientation of the IMF-Bz as long as the strengthening of the magnetic activity goes on under the storm conditions. Rastogi *et al.*[43] described the effect of the magnetic storm of 22 January 2004 at a number of equatorial/low latitude stations at different longitudes. The first phase of the magnetic storm caused strong Spread-F at Jicamarca, Sao Luis and Ascension Island while inhibited Spread-F at Thumba and Waltair in the Indian longitude region.

Rastogi *et al.*[44] reported the effects of the magnetic storm of 9 November 2004 at different equatorial stations around the world. There was a solar event around 1850 hrs UT on 9 November 2004 with an abnormally large solar wind flow pressure and large southward IMF-Bz. At Jicamarca and Sao Luis, in the dayside hemisphere, the F-region was lifted up and part of it blown out of the range of ionosonde. At Indian stations Thumba and Waltair, and at Kototabang, in the night side hemisphere, F-layer was pushed down and later the ionization disappeared. At Kwajalein (0600-0800 hrs LT) equatorial type Sporadic-E disappeared.

Bagiya *et al.*[45] reported the response of the equatorial and low latitude ionosphere-thermosphere to the geomagnetic storm of 15 May 2005 from observations in the longitude sectors of 70-78°E and 270-288°E based on GPS observations at a chain of equatorial to low latitude stations. The strong positive ionospheric storm on 15 May was attributed to the prompt penetration of electric field as evident from equatorial electrojet signatures. TEC enhancements on 16 May were attributed to the enhancement of atomic oxygen at equatorial and low latitudes and the negative ionospheric storm on 17 May observed beyond certain low latitudes was explained in terms of enhancement of molecular species because of the storm time neutral composition changes. Strong ESF plume structures on radar map and L-band scintillation and TEC depletions in GPS measurements were observed in the longitude sectors where the local time of sudden storm commencement falls after the post sunset hours. The ionospheric zonal electric fields were thus altered by the combined effects of eastward disturbance dynamo electric fields and direct prompt penetration of eastward electric fields associated with the northward turning of interplanetary magnetic field.

5 Conclusions

The geomagnetic storm of the April 2000 resulted in both the prompt penetration electric field and later in the disturbance dynamo field and affected both the dayside and night side ionosphere. Following points emerge from the study of both dayside and night side of ionosphere at Thumba and Jicamarca:

(i) The sudden large turning of the interplanetary magnetic field IMF-Bz imposes a prompt penetration electric field at low latitude ionosphere globally.

(ii) An increase (decrease) of IMF-Bz causes an electric field in the equatorial ionosphere opposite (same direction) to the normal Sq electric field.

(iii) The effect on the E-region irregularities during dayside (Es-q) is simultaneous but in the F-region, irregularities during night side is delayed by an hour or so.

(iv) A northward turning of IMF-Bz generates Spread-F at stations in the evening sector.

(v) Southward turning of IMF-Bz at local evening sector inhibits Spread-F.

(vi) A northward turning of IMF-Bz causes the disappearance of Es-q in the dayside ionosphere and generates Spread-F in the night side ionosphere.

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References

1 Rastogi, R G & Patel V L, Effect of interplanetary magnetic field on the ionosphere over the magnetic equator, *Proc Indian Acad Sci*, A 82 (1975) pp 121-141.

2 Chapman S, Equatorial electrojet as detected from the abnormal electric current distribution above Huancayo, Peru and elsewhere, *Arch Meterol Geophys Bioclimatol (Austria).*, A4 (1951) pp 368-390.

3 Matsushita S, Intense ionizations near the magnetic equator; *J Geomagn Geoelectr (Japan)*, 3 (1951) pp 44-46.

4 Bartels J & Johnston H F, Geomagnetic tides in the horizontal intensity at Huancayo, *J Geophys Res (USA)*, 45 (1940a) pp 269-308.

5 Bartels J & Johnston H F, Geomagnetic tides in the horizontal intensity at Huancayo, *J Geophys Res (USA)*, 45 (1940b) pp 485-592.

6 Gouin P & Mayaud P N, A proposal for the possible existence of a counter electrojet at magnetic equatorial latitudes. *Ann Geophys (France)*, 23 (1967) pp 41-47.

7 Cohen R, Bowles K L & Calvert W, On the nature of equatorial slant Sporadic-E, *J Geophys Res (USA)*, 67 (1962) pp 965-972.

8 Chandra H, Misra R K & Rastogi R G, Equatorial ionospheric drift and the electrojet, ***Planet Space Sci (UK)***, 19 (1971), pp1497-1503.

9 Rastogi R G, Sudden disappearance of Es-q and the reversal of equatorial electric Fields, *Ann Geophys (France)*, 28 (1972) pp 717-728.

10 Appleton E V, Two anomalies in the ionosphere, *Nature (UK)*, 157 (1946) pp 691.

11 Booker H G & Wells H W, Scattering of radio waves in the F region at the ionospheric, *Terr Magn Atmos Electr (USA)*, 39 (1938) pp 215-230.

12 Osborne W, Ionospheric behavior in the F2 region at Singapore, *J Atmos Terr Phys (UK)*, 2 (1952) pp 66-78.

13 Bhargawa B N, Observations of spread echoes from the F layer over Kodaikanal – A preliminary study, *Indian J Meteorol Geophys*, 9 (1958) pp 35-40.

14 Lyon A J, Skinner M J & Wright R W H, Equatorial spread F at Ibadan Nigeria, *J Atmos Terr Phys (UK)*, 21 (1961) pp 100-191.

15 Chandra H & Rastogi R G, Spread F at magnetic equatorial station Thumba, *Ann Geophys (France)*, 28 (1972a) pp 37-44.

16 Hoang T L, Abdu M A, MacDougall J and Batista I S, Longitudinal differences in the equatorial Spread-F characteristics between Vietnam and Brazil, *Adv Space Res (UK)*, 45 (2010) pp 351-360.

17 Rastogi R G & Woodman R F, Spread-F in equatorial ionograms associated with the reversal of horizontal F region electric field, *Ann Geophys (France)*, 34 (1978) pp 31-36.

18 Prakash S, Pal S & Chandra H, In-situ studies of equatorial Spread-F over SHAR-Steep gradients in the bottom side F-region and transitional wavelength results, *J Atmos Terr Phys (UK)*, 53 (1991) pp 977-986.

19 Rastogi R G, Seasonal variation of equatorial Spread-F in the American and Indian zones, *J Geophys Res (USA)*, 85 (1980) pp 772-775.

20 Haerendel G, *Report - Theory of equatorial Spread-F* (Max Planck Institut fur Physic und Astrophysic, Garching, Germany), 1974.

21 Huttunen, K E, Keskinen H E, Pulkkinen T I, Pulkinen A, Palmorth A, Reeves E G D & Singer H S, April 2000 magnetic storm: solar wind drivers and magnetosphere response, *J Geophys Res (USA)*, 107 (A12) (2002), 1440, doi:10.1029/2001/JA009154.

22 Rastogi R G & Chandra H, Response of equatorial electrojet during the super geo-magnetic storm of April 2000, *Indian J Radio Space Phys*, 41 (2012) pp 524-535.

23 Afraimovich, E L, Ashkaliev Ya F, Auskev V M, Beletsky A B, Vodyanikov V V, Leonovich L A, Lesynta O S, Lipko Yu V, Mikhalev A V & Yakovets A F, Simultaneous radar and optical observations of the mid-latitude atmospheric response to a major geomagnetic storm of 6-8 April 2000, *J Atmos Sol-Terr Phys (UK)*, 64 (2002) pp 1943-1955.

24 Lee C C, Liu J Y, Reinisch B W, Lee Y P & Liu L, The propagation of traveling ionospheric disturbances observed during the April 6-7 2000 ionospheric storm, *Geophys Res Lett (USA)*, 29 (2002) 1068, doi:10.1029/2001GL013516.

25 Su S Y, Yeh H C, Chao C K & Heelis R A, Observations of large density dropout across the magnetic field at 600 km during the 6-7 April 2000 storm, *J Geophys Res (USA)*, 107 A11(2002) 1404, doi: 10.1029/2001JA007552.

26 Liu L, Wan W, Lee C C, Ning B & Liu J Y, The low latitude ionospheric effects of the April 2000 magnetic storm near the longitude 120^{o} E, *Earth, Planet Space (Japan)*, 56 (2004) pp 607-612.

27 Jadav R M, Iyer K N, Joshi H P & Vats H O, Coronal mass ejection of 4 April 2000 and associated space weather effects, *Planet Space Sci (UK)*, 53 (2005) pp 671-679.

28 Pimenta A A, Sahai Y, Bittencourt J A & Rich F J, Ionospheric plasma blobs observed by OI 630 nm all-sky imaging in the Brazilian tropical sector during the major geomagnetic storm of April 6-7 2000, *Geophys Res Lett (USA)*, 34 (2009), L02820, doi: 10.1029/2006GL028529.

29 Abdu M A, Equatorial spread F/plasma bubble irregularities under storm time disturbance electric fields, *J Atmos Sol-Terr Phys (UK)*, 75-76 (2012) pp 44-56.

30 Farley D T, Balsley B B, Woodman R F & McClure M J, Equatorial Spread-F: Implications of VHF backscatter observations, *J Geophys Res (USA*), 75 (1970) pp 7199-7216.

31 Alex S & Rastogi R G, Geomagnetic disturbance effect on equatorial Spread-F, *Ann Geophys (France)*, 5 (1987) pp 83-88.

32 Chandra H & Rastogi R G, Equatorial Spread-F over a solar cycle, *Ann Geophys (France)*, 28 (1972b) pp709-716.

33 Kelley M C, Fejer B G & Gonzales C A, An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field, *Geophys Res Lett (USA)*, 6 (1979) pp 301-304.

34 Kikuchi T, Araki T, Maeda H & Maekawa K, Transmission of polar electric field to the equator, *Nature (UK)*, 273(1978) pp 650-651.

35 Kikuchi T & Araki T, Horizontal transmission of the polar electric field to the equator, *J Atmos Terr Phys (UK)*, 41 (1979) pp 927-936.

36 Aarons J, The role of ring current in the generation and inhibition of equatorial F-layer irregularities during geomagnetic storms, *Radio Sci (USA)*, 26 (1991) pp 1131-1149.

37 Martinis C R, Mendillo M J & Aarons J, Towards a synthesis of equatorial Spread-F onset and suppression during geomagnetic storms, *J Geophys Res (USA)*, 110 (2005, A07306, doi: 10.1029.2003JA010362.

38 Abdu M A, Batista I S, Takahashi H, MacDougall J, Sobral J H, Medeiros A F & Trivedi N B, Magnetospheric disturbance induced equatorial plasma bubble development and dynamics, *J Geophys Res (USA)*, 108 (2003) 1449, doi: 10.1029/2002JA009721.

39 Abdu M A, Kherani E A, Batista I S & Sobral J H A, Equatorial evening pre- reversal vertical drift and spread-F suppression by disturbance penetration electric fields, *Geophys Res Lett (USA)*, 36 (2009) L19103, doi: 10.1029/2009GL039919.

40 Tulasi Ram S, Rama Rao P V S, Prasad D S V V D, Niranjan K, Gopi Krishna S, Sridharan R & Ravindran S, Local time dependent response of post sunset ESF during geomagnetic storms, *J Geophys Res (USA*), 113 (2008) A07310, doi: 10.1029/2007JA012922

41 Rastogi R G, Chandra H, Das A C, Sridharan R, Reinisch B W & Khurshid Ahmed, Space weather event of 25-26 June

1998: Effects on equatorial ionosphere in midday and midnight sectors, *Earth, Planet Space (Japan)*, 64 (2012) pp 353-360.

42 Huang C S & Foster J C, Long duration penetration of the interplanetary electric field to the low latitude ionosphere during the main phase of the storms, *J Geophys Res (USA)*, 110 (2005) A11309, doi: 10.1029/2005JA011202.

43 Rastogi R G, Chandra H, Janardhan P, Thai Lan Hoang, Condori Louis, Pant T K, Prasad DSVVD & Reinisch B, Ionospheric Spread-F during the magnetic storm of 22 January 2004 at stations in Asian zone, *J Earth Sys Sci (India)*, 123 (2014) pp 1273-1285.

44 Rastogi R G, Chandra H, Condori L, Abdu M A, Reinisch B, Tsunoda R T, Maruyama T, Khurshid Ahmed, Pant T K & Prasad D S V V D, Abnormally large magnetospheric electric field on 9th November 2004 and its effects on the ionosphere around the world, *J Earth Sys Sci (India)*, 121 (2012) pp 1145-1161.

45 Bagiya M S, Iyer K N, Joshi H P, Thampi S V, Tsugawa T, Ravindran S, Sridharan R & Pathan B M, Low-latitude ionospheric-thermospheric response to storm time electro dynamical coupling between high and low latitudes, *J Geophys Res (USA)*, 116 (2011), A01303, doi: 10.1029/2010JA015845.