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Ionosphere near the anomaly crest in Indian zone during magnetic storm on 13-14 March 1989

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The storm time responses of the ionosphere near equatorial anomaly crest in the Indian longitude zone during super magnetic storm on 13-14 March 1989 have been studied using (i) total electron content (TEC) and VHF/UHF scintillation data from location near the equatorial anomaly crest (Calcutta), (ii) h/F, foF2 data from an equatorial station Kodaikanal, and (iii) ion density data from Defense Meteorological Satellite Program (DMSP) satellites. Some distinctive features in the storm time variation of the Indian low latitude ionosphere compared to those of the East Asian and western longitude sectors are revealed through the analysis of DMSP ion density data. The h/F and foF2 data of Kodaikanal exhibit some unusual features, i.e. abnormal height rise and corresponding drop of plasma density at equatorial F-layer in the midnight-post-midnight period of both the main and recovery phases of the storm. From Calcutta large depressions in diurnal variation of TEC for two consecutive days marked the disturbed conditions. An abnormal post-midnight enhancement of TEC is also detected. A remarkable feature of storm time responses of the equatorial low latitude ionosphere is the preferential occurrence of scintillation in the path of trans-ionospheric signals from a particular satellite out of two (ETS-2 and FSC) with a longitude separation of 5^0. VHF/UHF scintillation observations in the post-midnight period from Calcutta exhibit the longitudinally confined nature of the storm induced ionospheric irregularities. A distinctive feature of scintillation occurrence near the anomaly crest of the Indian and East Asian longitude sectors justifies typical local time dependence of disturbance electric field components. Combined studies on scintillation, TEC, ion density, h/ F, foF2 data produce a coherent picture of the storm time equatorial ionosphere over Indian longitude sector.

Keywords: Ionospheric disturbances, Ionospheric irregularities, Storms, Space weather

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1 Introduction

Two important features of equatorial ionosphere are equatorial anomaly and intense form of irregularities in the electron density. During geomagnetic disturbances, these are modified intricately producing rigorous changes in the equatorial low latitude ionosphere. The electric fields, winds and chemical changes are the three major drivers to generate ionospheric disturbances. The equatorial ionosphere, due to its high conductivity, is very sensitive to variations in the electric fields caused by several geophysical effects. The variation in electric field depends on relative contributions of two components, namely prompt penetration of high latitudes electric field and fields from dynamo action of storm time winds. The prompt penetration electric field of magnetospheric origin responds with life time of about 1-2 h while the fields generated due to disturbance dynamo operate in the later periods and may continue for a few days.

The geomagnetic storm related changes in the equatorial ionization anomaly (EIA) can be investigated by analyzing changes in the F-layer parameters like foF2, h/F and total electron content (TEC) at locations inside the EIA. During the last few decades, a large number of observations on the above mentioned parameters have been made by several groups. The effect of magnetic disturbance on the latitude, solar cycle, season and longitude-variations of foF2 were reported long back by Rajaram & Rastogi[1]. The intensity of disturbance in foF2—positive or negative—was reported to be prominent in western longitude zone than in eastern zone. The responses of the Indian equatorial ionosphere to large number of geomagnetic storms were discussed by Lakshmi *et al.*[2] and it was suggested that primary process responsible for the pre- and post- midnight changes in foF2 during magnetic storms could be due to changes in the magnitude as well as direction of usual electric fields. The perturbations in neutral meridional winds also play a prominent role in storm time ionospheric restructuring[3]. A significant increase of storm related electron density at anomaly latitude and a decrease of the same over the equator due to enhanced electric field are also some important effects of magnetic disturbances[3-5]. The reduced daytime pole ward wind or even reversal of the same during the storm time may contribute to the occurrence of positive storm effect at low latitude and composition changes are reported to be the primary causes of positive ionospheric effect during recovery phases[6-7]. A definite latitude difference in responses of TEC during the magnetic storm, with enhancement near the equatorial anomaly crest latitude and both enhancement and depression at mid-latitudes of western longitude sector, was reported by Lanzerotti *et al.*[8]. Using GPS TEC data, a similar type of variation from the northern American sector was reported by Vlasov *et al.*[9]. The time of TEC enhancement was observed to coincide with the sudden drop in Dst and penetration of a very strong electric field to low latitudes. Using TEC data from Indian longitude sector Dabas & Jain[10] suggested weaker equatorial anomaly on storm days may be due to, other than equatorial fountain, equator ward converging meridional wind and composition changes. It has been reported[11] that during magnetic disturbances, TEC variations correlate well with the envelope of magnetic variations having period from 20 to 60 min.

The generation or inhibition of spread-F irregularities in the equatorial low latitude ionosphere is another important effect of magnetic storm. The irregularities may perturb the trans-ionospheric communication link causing scintillation. The technique of scintillation is one of the important methods of tracking irregularities of different scale sizes in the ionosphere. With the increase in magnetic activity, the probability of scintillation increases during post-midnight period in all longitude sectors while the pre-midnight phenomenon is dependent on season as well as longitude. During the post-sunset period, the increase of geomagnetic activity limits height rise of the F-layer and reduces the probability of spread-F[12]. The occurrence or inhibition of scintillations depends on the phase of magnetic storms as well as on local time sectors[13-16]. At low latitude ionosphere both the disturbance dynamo and electric field play major role in the development of equatorial irregularities[17-18].

The super magnetic storm on 13-14 March 1989 occurred with sudden commencement (SC) at 0127 hrs UT on 13 March and followed by another SC at 0747 hrs UT on the same day. Maximum solar wind speed was reported to be greater than 839 km/h and coronal mass ejections (CME) were observed to be associated with type 4 radio burst. The main or growth phase continued up to 0100-0200 hrs UT on 14 March 1989. The maximum negative excursion in Dst value, -589 nT, occurred around 0200 hrs UT on the same day and thereafter recovery phase started [Fig.1(b)].

Several observations on the ionospheric effects of super magnetic storm were made using foF2, h/F, hmF2, TEC, scintillation and DMSP ion density data. A dramatic rise of F-layer height, decrease in foF2 by factor as high as 1 order of magnitude and disappearance of F-layer traces from the usual 900 km height during the interval 1800-2000 hrs LT were reported by Batista *et al.*[19] from the Brazilian sector. Over the South American sector, a dramatic decrease in ion density at 840 km altitude was reported by Greenspan *et al.*[20]. A longitudinal dependence of the storm behavior was studied by Yeh *et al.*[21] using worldwide 52 stations ionosonde data and TEC data for 12 stations. Of the three sectors, Asian-Pacific, American and European-African, positive storm effect, which was much clear in TEC from stations like Beijing (40^0N, 116.3^0E) to Delhi (28.6^0N, 77.2^0E), was recorded only in Asian-Pacific sector for a few hours on the first day of the storm. The severe depression in foF2 as well as in TEC, the disappearance of equatorial anomaly and the development of hemispheric asymmetry in electron density with increase in the North and decrease in the South were observed from global data. Using foF2 data from a long chain of stations in Asian-Pacific sector Ma *et al.*[22] reported severe negative storm effects and asymmetric hemispherical ionospheric responses, with autumnal hemisphere suffering a longer lasting, more latitudinally extended, and deeper depression. From Indian sector, a collapse of equatorial F-region ionization at Kodaikanal in the post-sunset period was reported by Lakshmi *et al.*[23]. The occurrence of strong VHF scintillation and range spread-F in the nighttime of first storm day and nighttime (2000 hrs LT onwards) TEC enhancement during the main phase were major ionospheric responses[24] from East Asian longitude sector. On 14 March an unusually large decrease of TEC and

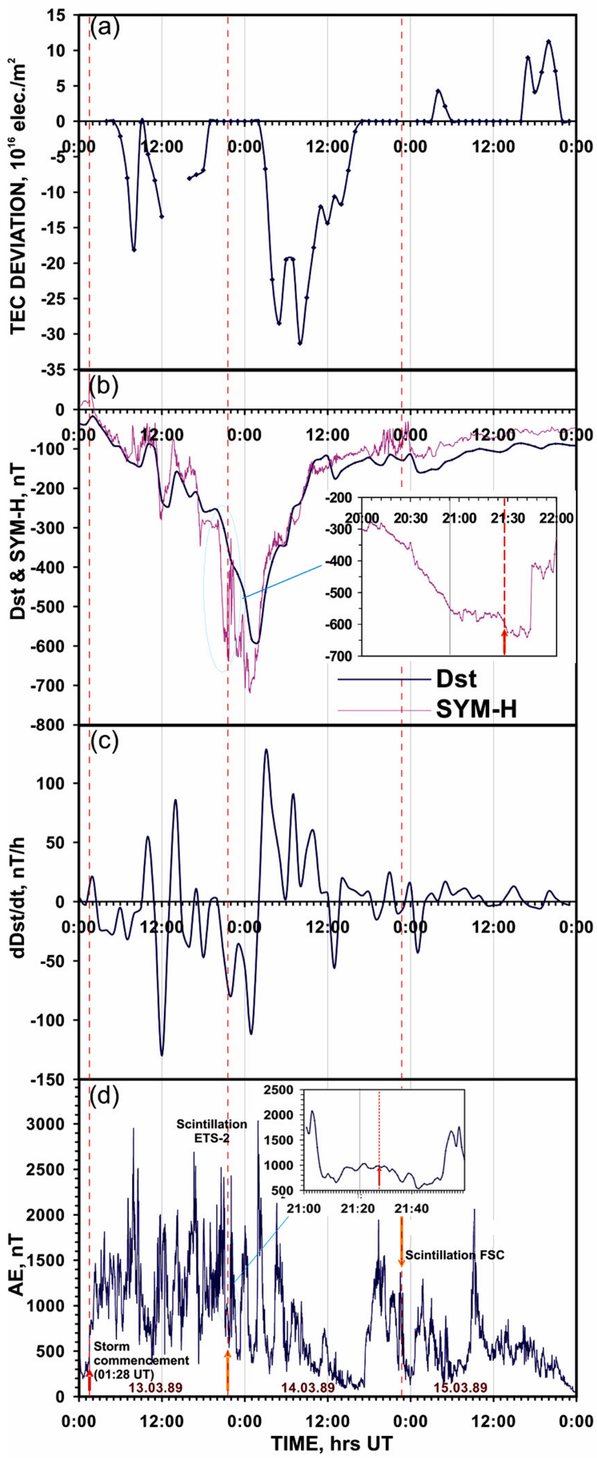

Fig. 1—Plots of (a) diurnal TEC deviation [diurnal TEC-(monthly average ±standard deviation)] in unit of 10^{16} electrons/m^2, (b) temporal variation of Dst and SYM-H indices, (c) hourly variation of dDst/dt, (d) temporal variation of auroral electrojet (AE) index. The figures in the inset represent high resolution temporal variation. Dotted vertical lines in each figure represent time of sudden commencement and scintillation times of trans-ionospheric signals from satellites ETS-2 and FSC, respectively

foF2 and almost completely wiping out of the equatorial anomaly were also reported from the same location. TEC, foF2 and h$^{/}$F at given frequencies show up and down oscillations, which was explained by wave-like perturbation in the ionosphere. During this storm, several geostationary magnetopause crossing caused by extreme conditions of solar wind pressure were also reported[25].

In spite of large volume of literature[19-21,23-25] available on the super magnetic storm, features of storm time ionospheric responses are still coming out through analysis, which deserves further attention to clarify. One such feature, observed from Calcutta both in the main and recovery phase, is the preferential occurrence of scintillation in the path of trans-ionospheric signal from a particular satellite out of two with a longitudinal separation of 5^0. The present paper intends to report the storm time responses of low latitude ionosphere, particularly around anomaly crest of Indian longitude sector, using multiple data set of ion density, h$^{/}$F, foF2, TEC and VHF/UHF scintillation. Efforts have been made to study storm time responses in the light of idea developed later by Fejer & Scherliess[26-27], Scherliess & Fejer[28], Burke *et al*.[29]. The present investigation may throw some light on the distinctive features of storm time variation of the ionosphere over Indian sectors compared to those of the western and East Asian longitude sectors. The results of observations, particularly occurrence/non-occurrence of scintillation at VHF/UHF ranges, may form an important data base in the perspective of space weather scenario.

2 Data

To study the storm time responses of the equatorial low latitude ionosphere in the Indian longitude zone, TEC and scintillation data, recorded at Calcutta (22.58^{0}N, 88.38^{0}E, geographic dip 32^{0}N) situated virtually below the northern crest of equatorial ionization anomaly, have been analyzed in conjunction with (1) h$^{/}$F, foF2 data from an equatorial station Kodaikanal (latitude 10.25^{0}N, longitude 77.5^{0}E, dip 4^{0}N) and (2) ion density data recorded through Defense Meteorological Satellite Program (DMSP) satellites F8 and F9. The DMSP spacecrafts are three-axis stabilized satellites in the circular, sun-synchronous orbits with 98.7^0 inclination at 840 km altitude. DMSP F9 has ascending and descending nodes at 0930 and 2130 hrs LT while DMSP F8 has ascending and descending nodes at 0600 and 1800 hrs

LT. The thermal plasma instrument (a total ion density trap) was used to measure ion density. The trans-ionospheric VHF (136.11 MHz) signal from satellite ETS-2 was used to determine TEC values by the Faraday rotation technique. For scintillation in VHF/UHF ranges transmissions from two satellites ETS-2 (130^0E) and FSC (73^0E) were recorded. The 400 km sub-ionospheric point of ETS-2 satellite path was located at 21^0N, 92.7^0E, and dip 27^0N (geographic) (geomagnetic 11.12^0N, 165.26^0E) and that of FSC was at 21.1^0N, 87.1^0E, dip 27^0N (geographic) (geomagnetic 11.5^0N, 159.94^0E). Using MSIS-E-90 model, neutral particle densities [O], [O_2] and [N_2] are evaluated. Auroral electrojet (AE) index, SYM-H and Dst data, used for the present study, were downloaded from the internet. The SYM-H index is obtained at 1 min interval while Dst data are available at 1 h interval. Both the indices are used in the context of changes in the ring currents. AE index is available with 1 min resolution.

3 Observations and results

A sudden impulse-like feature is detected in the plots [Fig.1(b)] of SYM-H as well as in Dst indices indicating sudden commencement of storm at 0127 hrs UT on 13 March 1989. The auroral electrojet (AE) index also exhibits a sharp rise (>1500 nT) [Fig. (d)]. A subsequent decreasing trend in SYM-H and Dst indices implies the main phase of magnetic storm with minimum around 0100-0200 hrs UT on 14 March. The period is succeeded by recovery phase of magnetic storm which lasts for several hours. An extensive study on storm time responses of the ionosphere near the equatorial anomaly crest has been done considering global coverage data of DMSP ion density, foF2 / h'F data from an equatorial station and, TEC and VHF/UHF scintillation data from a location near equatorial anomaly crest. The results of investigations on the above mentioned parameters are presented.

3.1 Observations with DMSP ion density

A comparative study of the ionosphere over Indian longitude sector in relation to global scenario has been made using DMSP ion density plots during the period of super magnetic storm of 13-14 March 1989. Figure 2 shows ion density *vs* magnetic latitude plots at specified local times (magnetic), the time of magnetic equator crossing of respective satellite. The equatorial ionization anomaly is found to be strongly developed in the longitude (geographic) sector of 86^0W – 35^0E during early morning hours [~9.43 hrs magnetic local time (MLT)] [Figs 2 (a) and (b)] of day-1 with asymmetric peaks. The corresponding local time seems to be too early for development of quiet time equatorial anomaly. A comparatively less developed anomaly in the longitude sector of 142^0 – 168^0E and no signature of the same in the rest of longitude sectors were also recorded. The anomaly persists in the post-sunset period of western longitude sector (54^0 – 154^0W) with a sharp decay of ionization anomaly characterizing the disturbed period [Figs 2 (c) and (d)]. On 13 and 14 March, ion density data from DMSP F8 and DMSP F9 satellites indicate absence of anomaly at the Indian longitude sector (8^0 - 135^0E) [Figs 2 (e)-(g)]. The anomaly is formed by the combined effect of **E×B** drift at the magnetic equator and subsequent diffusion of plasma along the magnetic field lines. The absence of anomaly-like features in the DMSP ion density plots during the period of magnetic disturbances indicates inhibition of fountain-like feature in Indian longitude sector while in the longitude sector of 86^0W – 35^0E, the anomaly seems to be stimulated by the disturbances. The remarkable feature in the variation of ion density[20,30] is the sudden drop of the same in the equatorial belt around magnetic equator of Atlantic and Pacific longitude sector. The time interval for which ionosphere was found to be completely 'wiped out' corresponds to local post-sunset period of 14 March 1989 (~21 MLT) of that longitude sector (20^0 – 77^0W) [Figs 2(h) and (i)]. It may be noted that time of depletions of ion density matches the time (0100 hrs UT) of maximum negative excursion of dDst/dt on 14 March [Fig.1(c)]. The maximum negative dDst/dt corresponds to maximum rate of energy input to the ring current particles and the time of faster decrease (dDst/dt < -50 nT/h) implies prompt penetration of electric field to low latitudes[18]. The drop in ion density may be an indication of prompt penetration effect of magnetospheric disturbance electric field, resulting uplift of ionization to high altitude beyond the detection range of DMSP satellite (840 km). Although the storm time penetration of magnetosphere electric field to low latitudes must be global in nature and is to be observed on both dayside and night side, large conductivity in daytime ionosphere increases the attenuation of disturbance electric field[31]. The time of maximum dDst/dt (1200, 0100 hrs UT) [Fig. 1(c)] corresponds to either afternoon or morning period of Indian longitude

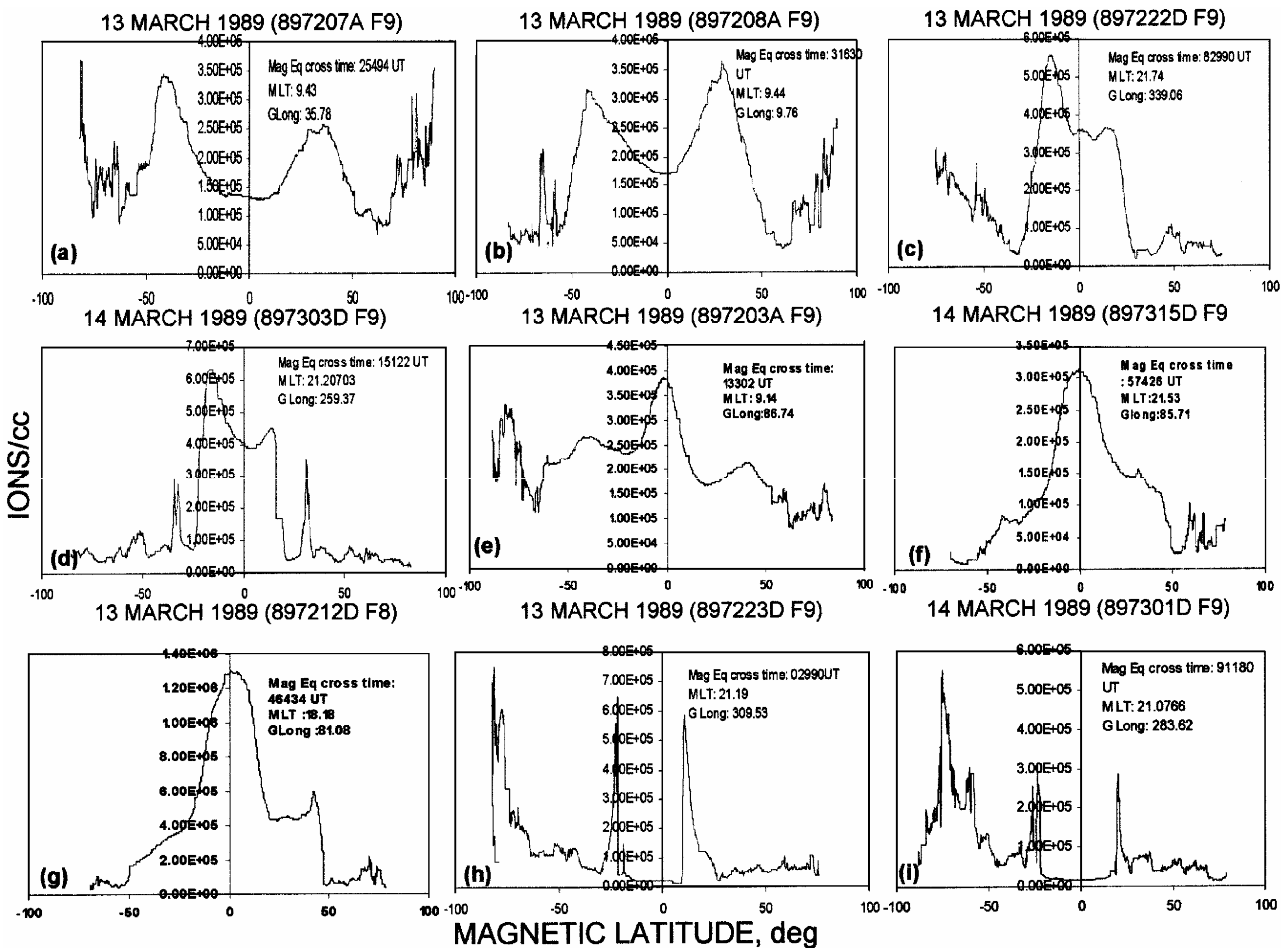

Fig. 2—Latitudinal (magnetic) plots of DMSP ion density. MLT indicates magnetic local time of equator crossing, GLong represents equator crossing longitude (geographic), and numbers within the brackets in figure titles represent DMSP satellite pass numbers and satellite number, respectively

sector to exhibit any penetration effect. But the fields of opposite polarity due to disturbance dynamo[26] may modulate the ionospheric features during this period. The signature of EIA, however, is detected in the post-sunset period of first day of storm from East Asian longitude sector (120-131^{0}E). The local time matches the time of maximum negative excursion (1200 hrs UT) of dDst/dt. Thus local time plays a vital role for penetration effects to occur.

3.2 Observations with TEC from a location near the anomaly crest

State of ionosphere at any location is mainly dictated by TEC which is a measure of ambient level of the ionosphere. Some distinguishing features are observed in the diurnal variation of TEC on 13-14 March 1989 compared to the variations of monthly mean values as well as the preceding and succeeding quiet days' variations [Fig. 3(a)]. During the periods of magnetic disturbances, TEC starts to build up after sunrise as usual. The feature continued up to 0800 - 0900 hrs IST. Thereafter, the normal rate of variation seemed to be prohibited indicating larger depression from the quiet time values. The time period during the quiet days is very critical for fountain effect to dominate the equatorial ionosphere leading to sharp increase in ambient level around the anomaly crest. The deviations in the diurnal TEC from the monthly mean ± standard deviation may be assumed to represent the variation related to magnetic disturbances and the same are plotted in Fig.1 (a). The depressions in TEC are observed to continue for two consecutive days except early morning sector. The much deeper depression is detected on the second day. On the first day the depression continues up to 1830 hrs UT. The depression in TEC on the second

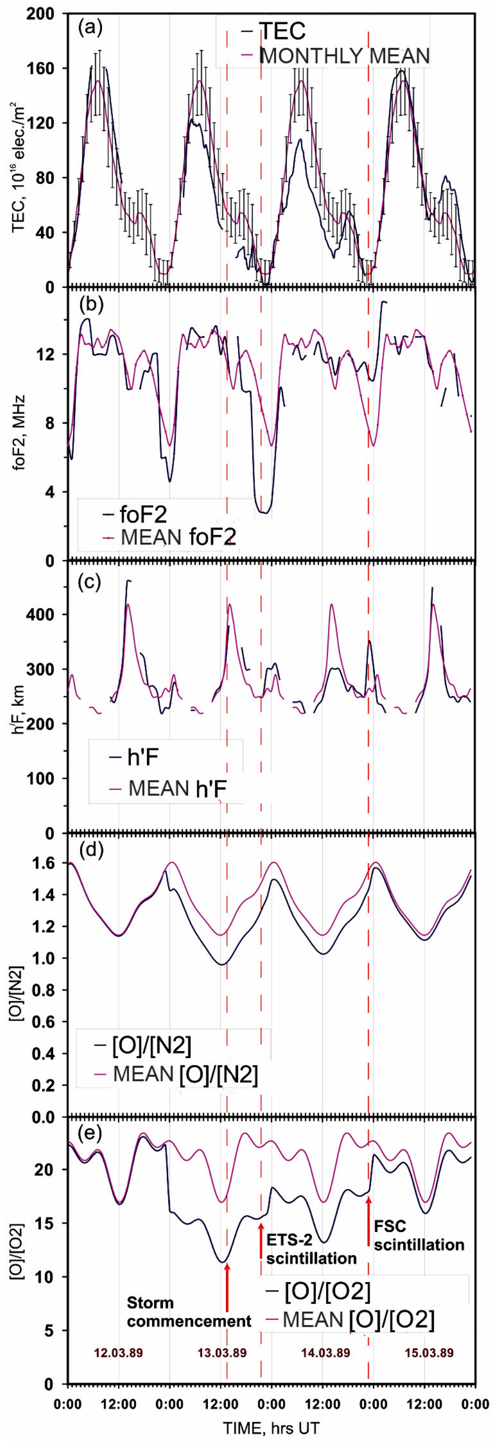

Fig. 3—On 12-15 March 1989, plots of (a) diurnal TEC along with monthly mean and standard deviation, (b) diurnal variation of foF2 at Kodaikanal and the corresponding quiet days' mean value, and (c) diurnal variation of h'F along with quiet days' monthly mean at Kodaikanal. Dotted vertical lines in each figure represent time of sudden commencement and scintillation times of trans-ionospheric signals from satellites ETS-2 and FSC, respectively. Diurnal variation of the ratios (d) $[O]/[N_2]$ and (e) $[O]/[O_2]$ along with the quiet day mean values are also shown

day started around 0730 hrs IST (0200 hrs UT). The time corresponds to end of main phase and initiation of recovery phase. The significant depressions are observed around 0500 and 0800 hrs UT (1030 and 1330 hrs IST). The time period corresponds to larger westward daytime disturbance dynamo related electric field in the recovery phase[26-27]. The diurnal maximum value of TEC, on both the disturbed days, is found to be remarkably less and width of TEC curve is significantly small indicating sharp decay in TEC [Fig. 3(a)]. The diurnal peak value on 13 March shows 18% (27 TECU) depletion from monthly mean values while on 14 March, the depletion is estimated to be about 28% (42 TECU). Diurnal TEC maxima occurred earlier compared to monthly mean peak occurrence time. The diurnal minima occurred, at 0400 hrs IST on 14 March, earlier than occurrence time of monthly mean minimum (0430 hrs IST) and of previous seven days mean TEC minimum occurrence time (0445 hrs IST). The early occurrence of minima and maxima may be due to concomitant effects of geomagnetic disturbance. The overall negative effect observed in TEC from Calcutta may be attributed to: (a) equatorial ionization anomaly has been inhibited; and/or (b) expanded to pole ward of the quiet time crest latitude on both days following the magnetic storm sudden commencement; and/or (c) equator ward shift of the molecularly enriched neutral wind to lower latitude by storm induced equator ward directed circulation consequently decreasing $[O]/[O_2]$ ratio[6,32]. Figures 3 (d) and (e) show the diurnal distribution of the ratios of densities of atomic oxygen to molecular nitrogen ($[O]/[N_2]$) and to molecular oxygen ($[O]/[O_2]$), respectively. The composition data are obtained using MSIS-E-90 model. A decrease in the O content results in decrease in the production rate while an increase in N_2 and/or O_2 content results in an increase in the loss rate. The lower values of $[O]/[O_2]$ and $[O]/[N_2]$ during disturbed days may modulate the disturbed time ambient level. To account for larger TEC depression, observation made with DMSP ion density data of 13-14 March 1989 [Figs 2 (e), (f) and (g)] may successfully be utilized. The data indicate absence of equatorial anomaly in Indian longitude sector which is detected by inhibited fountain effect. This may result in reduced level of ambient ionization near the anomaly crest as well as its faster decay.

An important feature of TEC variations on disturbed days is the appearance of secondary enhancement in the midnight-to-post-midnight period.

The normal post-midnight behavior of TEC on quiet days is the decay of ionization mainly due to F-region dynamo related westward electric field at the magnetic equator restricting the equatorial fountain. TEC enhancement on post-midnight period suggests a reversal of normally prevailing westward electric field at night and resurgence of fountain effect. On 13 March, secondary enhancement occurred in the local post-midnight period at around 0015 hrs IST (1845 hrs UT) with peak around 0100 hrs IST (1930 hrs UT) and enhancement magnitude of $(\Delta TEC)_{13}$ ~16 TECU (1 TECU = 10^{16} electrons/m^2). The secondary enhancement was initiated around 2200 hrs IST (1630 hrs UT) on 14 March and continued up to 0200 hrs IST (2030 hrs UT) with enhancement amplitude of $(\Delta TEC)_{14}$ ~ 34 TECU at 2345 hrs IST (1815 hrs UT). The enhancement of TEC near the anomaly crest latitude is related to, among various other parameters, redistribution of ionization by the equatorial fountain. An indication of the strength of fountain may be obtained through the measured values of $h'F$ or foF2 from an equatorial station.

3.3 Observations with $h'F$, foF2 from an equatorial station

The use of F-layer height parameter $h'F$ is an indirect but widely adopted method for deriving information about F-layer vertical plasma drift (for $h'F$ > 300 km) and hence about zonal electric field responsible for it[19,33-35]. In Fig. 3(c) diurnal values of $h'F$ are shown along with monthly mean values. Two most prominent features in the diurnal variation of $h'F$, which distinguishes the disturbed days from the quiet ones, are: (1) insignificant height rise at the post-sunset period and (2) post-midnight enhancement of the same. On 13-14 March 1989 $h'F$ peak values are found to be reasonably low compared to the values of the preceding and succeeding days as well as of monthly mean values. Throughout the day of 14 March, $h'F$ values are observed to be remarkably low. The recovery phase started around 0200 hrs UT (~0730 hrs IST) on 14 March 1989. The $h'F$ values on the same day show anomalous behavior around sunset. The usual sharp rise was restricted [Fig. 3(c)]. It follows Aarons[36] suggestion relating maximum excursion of Dst at daytime and the height rise of F-layer. The limited post-sunset height rise may indicate the presence of disturbance dynamo electric field[37] of opposite polarity at the dusk sector affecting the usual post-sunset enhancement of eastward electric field. The remarkable feature of $h'F$ variation is its irregular enhancement in the post-midnight period around 0300 hrs IST on 13 and 14 March 1989. The period normally indicates fall/flat responses in $h'F$ for the quiet days. At night normally prevailing zonal westward electric field produces a downward **E×B** drift. The anomalous height rise in F-layer indicates appearance of eastward electric field at that time sector. It was suggested[2,15,36] that the effect of ring current in the midnight-to-post-midnight period, when $h'F$ normally falling, is to create momentarily an eastward electric field. This may produce an increase in F-layer base height and corresponding decrease in foF2 value [Fig. 3(b)] due to redistribution of ionization. On 13 March, a severe depletion of about 42% from the mean in foF2 was observed during the time interval 1900-0200 hrs UT (0030-0730 hrs IST). A similar equatorial depletion in foF2 was also reported in some other longitude sector by Greenspan *et al.*[20] and Ma *et al.*[22]. It was suggested that this depletion does not result from the equator ward extension of the negative phase developed first at higher latitude but contribution of equatorial dynamo field should be taken into account. A rapid increase in $h'F$ during 2200-2300 hrs UT (0330-0430 hrs IST) on 14 March may indicate reversal of normally prevailing westward electric field in the post-midnight sector. The vertical drift velocity is estimated to be ~28 m/s with eastward electric field of 1.05 mV/m near the equator. The combined observations of $h'F$ and foF2 from an equatorial station Kodaikanal and TEC from a location near the crest of the equatorial anomaly may give a concise picture of storm time perturbed state of the ionosphere over Indian longitude sector.

3.4 Observations with VHF/UHF scintillation

The disturbed ionosphere is very sensitive to the generation / inhibition of irregularities / bubbles in the post-midnight period, an indication of which may be obtained through the occurrence of scintillation. For generation of irregularities in the ionosphere, uplift of F-region base height at the magnetic equator, instigated by the reversal of normal westward electric field at the night time to eastward direction, is essential. Previous observations on foF2 and $h'F$ indicate presence of such stimulating environment in the post-midnight period of the disturbed days. Severe scintillation (> 10 dB) is observed in the local post-midnight (2128-2148 hrs UT or 0258-0318 hrs IST) period of 13 March 1989 in the trans-ionospheric path of VHF (136.11 MHz) signal from the satellite ETS-2. On the same day no scintillation was recorded in the path of the UHF (244 MHz) signal from FSC. Again severe scintillation (>10 dB) is observed in the path of UHF signal (244 MHz) from FSC at the local post-midnight period (2250-2310 hrs UT or 0420-0440 hrs IST) of 14 March 1989 while no scintillation was recorded in the path of signal from ETS-2. Though a large volume of literature[14-15,24,36,38-42] based on magnetic storm related scintillation / spread-F is now available, scintillation observations presented in this paper reproduce some unsolved problems yet to be fully addressed.

4 Discussions

During magnetic storm, three important contributing factors to generate disturbance in the equatorial low latitude ionosphere are: (1) the penetration electric field, (2) the disturbance dynamo, and (3) the neutral composition changes. The first one is related to solar wind magnetospheric dynamo leading to fast changes of cross polar cap potential (Φ_{pc})/magnetospheric convection. Magnetospheric dynamo converts solar wind energy into electromagnetic energy in the magnetosphere via reconnection process between solar wind and earth's magnetic fields. The reconnection is favored when the direction of the interplanetary magnetic field (IMF) is southward and is opposed when the direction of IMF is northward. The rapid changes in Φ_{pc} produce sudden variations of region-1 current (the higher latitude current system in the auroral region) and stimulate prompt penetration of electric field to low latitudes. The region-2 current (the lower latitude current system in the auroral zone) can not change at the same rate and the condition is referred to as under-shielding. On the other hand, when Φ_{pc} suddenly decreases, region-2 current remains large and electric field of opposite polarity can propagate to lower latitudes leading to over-shielding condition. The Φ_{pc} changes are key parameters for prompt penetration effect to occur and AE index is taken as proxy index to reflect polar cap potential changes. For a sudden increase in the AE index, high latitude electric fields penetrate almost instantaneously to the low latitude ionosphere[43]. The perturbation effect of prompt penetration electric field, most commonly in zonal electric field, is of short duration (~2 h) with high amplitudes in the midnight-dawn sector[27,33]. The rapid changes in SYM-H or Dst index may give a signature of prompt penetration electric field to low latitude[44].

The ionospheric disturbance dynamo, evolved from the thermospheric disturbance winds generated by Joule heating at auroral latitudes, affects the low latitude ionosphere several hours after the increase in magnetic activity. The disturbance winds produce changes in the ionospheric dynamo that are more persistent than those associated with magnetospheric dynamo (prompt). The climatology of disturbance dynamo (DD) effects at the magnetic equator is reported to generate electric field of opposite polarity. The effects are most prominent in the post-midnight-dawn sector. The typical local time dependence of DD effect was discussed by Fejer & Scherliess[26]. It was reported by Maruyama *et al.*[45] that during daytime, and at early stage of magnetic storm, the penetration electric field is dominant, while at night both the penetration and DD play a significant role in restructuring the storm time equatorial ionosphere and thermosphere. The direct penetration (DP) electric field has a large impact on the DD preferentially at night since it changes F-region electron density, Pederson conductivity and ion drags on the neutral wind. The modification of the DD field by DP field depends on longitude and exhibits both positive and negative feedback effects.

During geomagnetic disturbances enhanced energy deposition from the magnetosphere in the form of particle and Joule heating causes rapid expansion of the neutral atmosphere in the auroral zone. The rapid air expansion can cause upwelling of the molecularly rich air resulting in increase of mean molecular mass of the thermosphere with increased loss rate in the F-region ionosphere. The bulge of enhanced molecular species, or depleted atomic oxygen, is long-lived. Its longevity, of the order of a day, enables the global wind system to transport the composition disturbance over thousands of kilometer, driven by combination of quiet and storm time wind fields[46]. It was reported[47] that regions of decreasing $[O]/[N_2]$ generally coincided with the regions of depleted TEC during and after the development of storm.

A general consensus for the storm time generation of ionospheric irregularities is that the post-midnight equatorial spread-F (ESF) tends to be triggered by storm[15,48] while inhibition effects were reported during post-sunset period[15,49]. Fejer *et al.*[50] suggested that the generation of late-night spread-F irregularities occurs most often at ~0400 hrs LT when the prompt penetration and DD vertical drifts have largest amplitudes. The presence and absence of irregularities at specific longitude sector is reported[15,36] to be connected with the peak storm timing as revealed by

Dst index. The equatorial irregularities in the main phase of disturbance occur, according to Basu *et al.*[16,18], in the particular longitude sector for which early evening period corresponds to the time of rapid Dst variation and strongly negative Dst values. A less stringent criterion was put forwarded by Huang *et al.*[51]. Accordingly, if Dst values change at the rates larger than -5 nT/hr for 2 or more hours equatorial irregularities due to penetration electric field may be triggered.

In the present study, it is observed that with sudden commencement of magnetic storm, AE index exhibits a sharp rise (> 1500 nT). The enhanced value of AE at the high latitude region may set up an equator ward neutral wind system due to Joule heating, which often sets off ionospheric disturbance dynamo. Scintillation at VHF (ETS-2) signal occurs in the main phase of the magnetic storm during the local post-midnight period. Scintillation timing is such that a background eastward electric field may likely to be present due to disturbance dynamo as modeled by Fejer & Scherliess[26-27]. The timing of scintillation occurrence is preceded by a sharp decay of SYM-H index and Dst values show a rapid fall with $dDst/dt < -50$ nT. In the main phase when rapid changes in Dst or SYM-H indices occur, penetration electric field of magnetospheric origin may affect the ionospheric dynamics[18,44]. Further, there is a sharp decay in AE values prior to scintillation occurrence which may correspond to decrease in polar cap potential. Earlier studies[33,50] revealed that penetration electric field at the post-midnight sector of equatorial ionosphere manifests preferentially with the decrease in polar cap potential rather than with increase. The occurrence of scintillation in the post-midnight time sector of main phase may be related to the prompt penetration field in the environment of same polarity disturbance dynamo field. The disturbance generated eastward electric field at the magnetic equator in the post-midnight period may raise the F-layer to high altitudes where conditions favorable for generation of irregularities prevail. The presence of eastward electric field may be manifested through the sharp fall in foF2 value at Kodaikanal situated near the magnetic equator [Fig. 3(b)]. The decrease in foF2 values may be attributed to redistribution of ionization from the magnetic equator to low latitude region. This results in secondary enhancement of TEC at locations near the equatorial anomaly crest. From Calcutta an enhancement of 16 TECU (greater than 100% increase from the minimum value) is observed during this time interval. Persistence of high ambient ionization and injection of irregularities near the anomaly crest latitude may produce strong scintillation. The combined study on foF2 and TEC revealed that ionosphere over the anomaly crest is very susceptible to the occurrence of scintillation.

It may be noted that using signal of the same satellite ETS-2 from East Asian sector (120^0E) Huang & Cheng[24] reported strong scintillation on 13 March 1989 commencing from 2000 hrs LT and continuing for five hours during the main phase. The time matches the time of $(dDst/dt)_{max}$ negative excursion (1200 hrs UT) [Fig.1(c)], which implies prompt penetration effect to occur. Corresponding local time at Calcutta was about 1730 hrs IST. The sunset time at 100 km altitude under the sub-ionospheric point of ETS-2 is ~1844 hrs IST and that for FSC is ~1906 hrs IST. The local time seems to be too early to observe scintillation from Calcutta. According to Basu *et al.*[18] ionospheric disturbance at low latitude occurs early evening period, which corresponds to the universal time interval between rapid Dst variation ($dDst/dt <$ -50 nT/h) and Dst minimum. Scintillation observations from East Asian sector comply with this suggestion. On the contrary, scintillation observed at Calcutta during post-midnight period is also noted to be present near the anomaly crest of East Asian longitude sector (120^0E) and the duration of scintillation is recorded to be longer compared to that of Calcutta. The simultaneous occurrence of scintillation at two locations in the post-midnight period may evidently indicate a local time dependent feature of disturbance effects as suggested by Fejer et *al.*[50]. The local time of post-midnight scintillation onset at Indian sector is a bit earlier compared to that as noted in the paper of Huang & Cheng[24] from East Asian sector. It was suggested[50] that the eastward perturbation of electric field resulting from both the prompt penetration of magnetospheric fields and the effects of ionospheric disturbance dynamo will preferentially occur near 0400 hrs LT. The scintillation occurrence time from East Asian sector properly matches the above suggested timing and the duration/strength of scintillation may accordingly be modulated. Though occurrence of scintillation of VHF signal from ETS-2 more or less followed the criteria put forward by several workers, the peculiarity of scintillation studies from Calcutta was that no scintillation was observed with 244 MHz signal from FSC. The 400 km sub-ionosphere point of this satellite is more or less due west with respect to ETS-2 path with a longitude separation of nearly 5^0. The general perception is, after generation, the disturbance induced irregularities drift westward due to combined effects of disturbance winds and coriolis forces. The scale size of scintillation producing irregularities at 136 MHz is estimated to be ~1 km and that at 244 MHz it is ~800 m. The absence of scintillation in the FSC path may be attributed to fast decay of irregularities or the irregularities are confined to specific longitude sector.

Severe scintillation is, however, observed in the path of UHF signal (244 MHz) from FSC at the local post-midnight period (2248-2310 hrs UT, 0420-0440 hrs IST) of 14 March 1989, while no scintillation was recorded in the path of VHF signal from ETS-2. Scintillation is observed in the recovery phase of magnetic storm dominated by disturbance dynamo effect. The occurrence of scintillation in the post-midnight period may support the long lasting (> 48 h) disturbance dynamo theory[37] and fossil wind theory[52-53]. Since the disturbance winds during this phase lie equator ward of the region-2 current, any electric field they generate is not shielded from lower latitudes and may affect the equatorial electric field[42]. Further, the recovery phase of magnetic storm is characterized by decay of ring current. According to Sastri *et al.*[34], decay of ring current during recovery phase is associated with simultaneous perturbations in zonal electric field of opposite polarity in pre-dawn and post-sunset local time sectors. The polarity of electric field perturbation is eastward (westward) in the pre-dawn (sunset) local time sectors. The reversal of the electric field is evident in the sharp rise of $h^/F$ values (> 350 km) and corresponding vertical drift of plasma near the magnetic equator is estimated to be 28 m/s in the post-midnight period. This is an indication of perturbation of the equatorial ionosphere with respect to geomagnetic quiet conditions [Fig. 3(c)]. Biktash[41] suggested that equatorial irregularities associated with spread-F can be generated if the F-layer is raised above a threshold height (~350 km). An enhancement in TEC (34 TECU) is also detected prior to scintillation occurrence [Fig. 3(a)]. All these features may be conducive for generation of irregularities and observing scintillation. The most striking feature is the preferential occurrence of scintillation in the trans-ionospheric path of the UHF signal from FSC but not in the path of the VHF signal from ETS-2 situated more or less due east of FSC path.

Similar type of disturbance dynamo related non-occurrence of scintillation events of signals from two satellites FLSAT and MARISAT, with a longitudinal separation of only 0.68^0, was reported by Aarons & DasGupta[13]. If the irregularities are generated in a specific longitude sector, i.e. between the longitude of ETS-2 and FSC path, and drifted westward, no simultaneous scintillation may be observed in the two signal paths. Since the period is dominated by disturbed dynamo having a typical local time dependent feature[26], no scintillation is noted in the paper of Huang & Cheng[24] during the interval when scintillation in FSC path was recorded from Calcutta. The corresponding local time of East Asian sector (120^0E) is about 0700 hrs LT.

On 13 March 1989 modification of disturbance dynamo in the main phase by penetration electric field seems to generate irregularities simultaneously in the ETS-2 longitude sector of East Asia and Calcutta but not in the longitude sector of FSC whereas irregularities generated in the disturbance dynamo dominated recovery phase seems to be critically confined within a specific longitude sector. The observations present some unusual features of storm time ionosphere yet to be fully understood. The generation and growth of irregularities depend on several parameters such as ionospheric conductivity, electron density gradient, upward **E×B** drift, ion-neutral collision frequency, neutral wind, tides and waves, etc. It should be noted that the ionospheric conductivity in the post-midnight-dawn sector is generally low. To make any concrete remark about this longitudinally confined nature of magnetic storm related irregularities further case studies, involving the databases of conductivity, wind, tides and waves, are essential.

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