Response of the equatorial ionosphere in the Indian (midnight) sector to the severe magnetic storm of July 15, 2000

J. Hanumath Sastri
Indian Institute of Astrophysics, Bangalore, India

K. Niranjan
Physics Department, Andhra University, Waltair, India

K. S. V. Subbarao
Space Physics Laboratory, Vikram Sarabhai Space Center, Trivandrum, India

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[1] During the severe magnetic storm of July 15, 2000, an impulsive and remarkably large downward movement of F region occurred simultaneously at locations throughout the equatorial region (dip 0.3–20°N) in the Indian sector, in close association with episodes of rapid ring current intensification. The abnormal midnight descent of equatorial F region (maximum amplitude close to the magnetic equator, 215 km/hr) indicative of a short-lived westward electric field disturbance (peak amplitude ≈4.6 mV/m) is interpreted as the signature of prompt penetration electric fields associated primarily with impulsive ring current injections. The westward electric field disturbance in the Indian (midnight) sector occurred near simultaneous with the eastward electric field disturbances in the dusk sector, reported by *Basu et al.* [2001a]. Moreover, the prompt electric field penetration to the magnetic equator both in the dusk and midnight sectors occurred in an environment already under the influence of ionospheric disturbance dynamo (IDD) electric fields, illustrating the profound manner in which the equatorial F region plasma dynamics can get modified globally during the main phase of severe magnetic storms. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2411 Ionosphere: Electric fields (2712); 2435 Ionosphere: Ionospheric disturbances; 2788 Magnetospheric Physics: Storms and substorms

1. Introduction

[2] The solar wind-magnetosphere dynamo [*Senior and Blanc*, 1984; *Spiro*, 1988] and the ionosphereic disturbance dynamo [*Blanc and Richmond*, 1980] are considered to be responsible for the storm-time behavior of the equatorial electric fields (plasma drifts). The first of the mechanisms operates at times of rapid changes in magnetospheric convection (cross polar cap potential) leading to short-lived (≈2 hr duration) disturbances most commonly in the zonal electric field (F region vertical plasma drift) with high amplitudes in the midnight-dawn sector [*Sastri et al.*, 1992; *Fejer and Scherliess*, 1997 and see references therein]. On the other hand, the ionospheric disturbance dynamo becomes effective due to modifications in the global thermospheric circulation brought about by Joule heating at high latitudes and generates long-lived (several hours duration) electric field disturbances with a polarity opposite to the quite time pattern at all local times and with high amplitudes also in the midnight-dawn sector [*Sastri*, 1988; *Scherliess and Fejer*, 1997]. The study of storm-time patterns of equatorial ionospheric electric fields and their effects on the spatial distribution of plasma density and the onset of plasma instabilities that cause VHF/UHF/L-band scintillations is a subject of much current research interest [e.g., *Fejer et al.*, 1999; *Basu et al.*, 2001a, 2001b].

[3] A halo coronal mass ejection (CME) left the sun around 1054 UT on July 14, 2000 and the CME-driven shock wave impacted the Earth's magnetosphere at 1437 UT on July 15, 2000, followed by a severe magnetic storm, the largest such event in nearly a decade. As may be seen from the variation of the 1-min resolution SYM-H index (which closely follows the D_{st} index) plotted in Figure 1, the growth of the ring current on July 15, 2000 took place in two impulsive steps, the first one starting at 1920 UT and the second commencing at 2004 UT, with SYM-H eventually reaching the minimum value of −347 nT at 2155 UT. The storm was preceded by disturbed geomagnetic conditions on July 14, 2000 (A_p = 51; K_p = 7^+) and the first half of the UT day on July 15, 2000 was also disturbed with the AE index reaching 1000 nT at 10 UT. *Basu et al.* [2001a] showed that the impulsive ring current injection between 2000 and 2100 UT was accompanied by the onset of 250 MHz and L-band scintillations at Ascension Island (7.9°S, 14.4°W; dip lat. 16°S) and anomalous TEC dropouts at Fortaleza (4°S; 38°W; dip lat. 4.5°N) and severe ion density bite outs extending over 30° latitude in the South Atlantic Magnetic Anomaly region.

[4] In this paper, we shall present evidence to show that an impulsive westward electric field disturbance of large amplitude (peak value ≈4.6 mV/m) also prevailed at the midnight dip equator (Indian sector) in association with the rapid ring current injections between 1900 and 2100 UT on July 15, 2000. Our analysis indicates that the westward electric field perturbation in the midnight sector which is a signature of prompt penetration electric fields occurred against a background of eastward electric fields of ionospheric disturbance dynamo origin.

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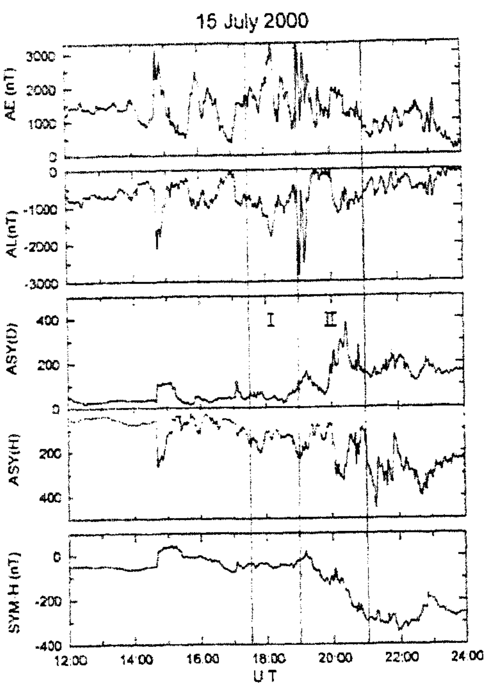

Figure 1. Time histories of the auroral electrojet indices, AE AL, asymmetric ring current indices, ASY(H/D) and the symmetric ring current index, SYM-H for the period 1200–2400 UT on July 15, 2000. The vertical lines bound the intervals labelled **I** and **II** during which short-lived upward and downward F region plasma drift disturbances, respectively, were evidenced in the Indian dip equatorial region on the nightside.

2. Observations

[5] The study is based on IPS42 ionosonde data of Trivandrum (8.5°N, 76.9°E; dip 0.3°N), Kodaikanal (10.2°N; 75.5°E; dip 4°N) and Waltair (17.7°N, 83.3°E; dip 20°N). The time rate of change of h'F (minimum virtual height of F region) at dip equatorial latitudes is a resourceful means of studying disturbances in the F region vertical plasma drift for the nighttime period, especially if simultaneous measurements from stations spanning 20° in latitude from the magnetic equator are used [*Sastri et al.*, 1992; *Reddy and Nishida*, 1992 and many others]. The ionosonde method relies on the mechanisms that cause vertical plasma transport in the equatorial region. At and close to the magnetic equator, vertical plasma drift is essentially due to zonal electric fields. Meridional winds are also usually ineffective in producing vertical plasma drifts close to the dip equator but gain in importance with increase of dip angle (I) with maximum effect at I = 45°.

[6] Figure 2 shows the variation of h'F at Trivandrum, Kodaikanal and Waltair for the interval 1230–2400 UT (1800–0530 IST) on July 15, 2000 covering both the initial and main phases of the magnetic storm (see Figure 1). The average quiet day h'F pattern at the individual stations derived from data of the seven designated quiet days (Q1–Q7) of the month with Ap ≤ 6, is also shown in the figure for reference. The quiet day h'F pattern at Trivandrum and Kodaikanal close to the magnetic equator displays the well known postsunset increase and the bottomside F region remains elevated above 300 km till well past midnight, with a perceptible downward drift starting as late as 0315 IST. At Waltair (dip 20°N), on the other hand, h'F increases till around 2200 IST under the influence of equatorward winds set up by solar forcing, but experiences the well known 'midnight collapse' from about 2330 IST till 0145 IST due to the poleward reversal of neutral winds induced by the semi-permanent equatorial midnight temperature maximum, MTM [*Sastri et al.*, 1994; *Goembel and Herrero*, 1995; *Colerico et al.*, 1996].

[7] It is clear from Figure 2 that the nighttime variation of h'F on July 15, 2000 deviated quite significantly from the quiet time trend at the three equatorial stations. There was a significant and coherent increase in h'F at all the stations over the interval 1730–1900 UT (marked **I** in Figure 2). This implies that unlike during quiet times, the F region vertical plasma drift in the region from close to magnetic

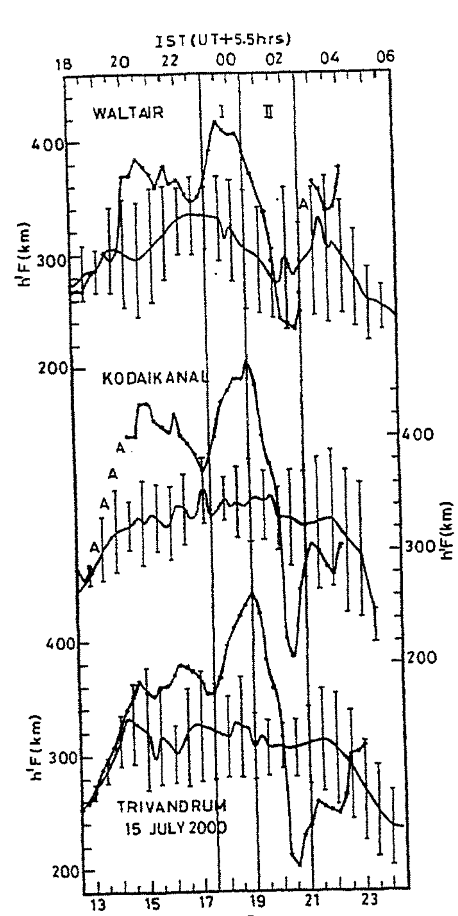

Figure 2. Time variation of h'F, the minimum virtual height of F region over Trivandrum (dip 0.3°N), Kodaikanal (dip 4°N) and Waltair (dip 20°N) in the Indian sector for the period 1200–2400 UT on July 15, 2000, covering both the initial and main phases of the severe magnetic storm. Also shown is the average quiet day variation of h'F at the individual stations along with the standard deviations of the average values. Note the anomalous and rapid decrease in h'F from 1900 UT simultaneously at the three stations (segment marked **II**) and the increase of h'F that preceded it (segment marked **I**).

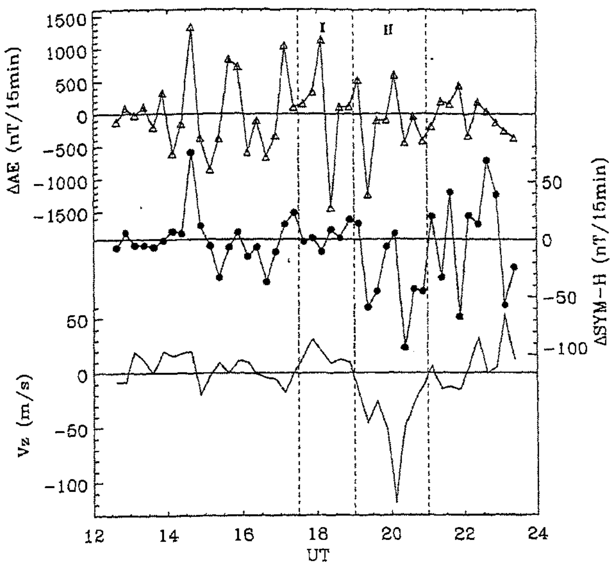

Figure 3. F region vertical plasma drift over Trivandrum (derived from h'F data and corrected for chemical loss effects) for the period 1200–2400 UT on July 15, 2000. Also shown is the time rate of change of the SYM-H and AE indices. Note the conspicuous downward drift disturbance (westward electric field) that occurred in association with impulsive ring current injections in the interval marked **II**.

equator to a dip angle of 20 came under the control of an eastward electric field disturbance in this period, with h'F > 400 km, well above the quiet time values and their day-to-day variability. But the most dramatic magnetic storm effect was the impulsive and abnormal decrease in h'F at all the three stations starting from 1915 UT, with the bottomside F region eventually reaching the collision dominated altitudes around 220 km by 2015 UT. The amplitude of this anomalous midnight descent of F region is a maximum close to the equator, the values of the time rate of change of h'F at Trivandrum, Kodaikanal and Waltair over the interval 1915–2015 UT being 215 km/hr, 220 km/hr and 128 km/hr, respectively. The simultaneity of the height perturbation at the three stations and the dip angle variation of its amplitude unambiguously demonstrate the prevalence of a transient westward electric field disturbance of large amplitude during the development of the main phase. The values of downward drift derived from the time derivative of h'F are reliable only when h'F is >300 km and the same will be underestimated for lower altitudes because the height increase due to chemical loss counteracts the height decrease due to the westward electric field. The strong westward electric field disturbance, therefore, might have extended beyond 2015 UT in reality because h'F at Trivandrum did decrease by 10 km between 2015 UT and 2030 UT (apparent downward drift 11.1 m/s) even when the bottomside F region reached altitudes around 210 km (see Figure 2).

[8] To arrive at the magnitude and duration of the vertical plasma drift disturbance near the dip equator, the values of vertical drift derived from the time derivative of h'F at Trivandrum are corrected for chemical loss effects following standard procedure [e.g., *Sastri*, 1992]. The corrected values of vertical plasma drift, Vz presented in Figure 3 show that the downward drift disturbance (westward electric field) prevailed between 1900 and 2100 UT (time interval marked **II** in Figures 2 and 3) with a maximum amplitude of 117 m/s (≈4.6 mV/m) around 2000 UT, which is precisely the time when eastward electric field disturbances were evidenced in the equatorial regions of the dusk sector (Atlantic and East Brazil) by *Basu et al.* [2001a]. It is to be recalled here that the anomalous downward drift disturbance at Trivandrum was preceded by an upward drift perturbation (eastward field) for 1.5 hr (time interval marked **I** in Figures 2–3) with a peak amplitude of 31.1 m/s.

3. Discussion

[9] An unique short-lived ionospheric disturbance developed in the Indian equatorial region corresponding to the midnight sector during the main phase of magnetic storm on July 15, 2000. The storm-related disturbance is characterized by a 2-hr long interval of abrupt and large downward drift of F region preceded by a shorter period (1.5 hr) of upward plasma drift. The rapid changes in F region height that reflect these vertical drift perturbations were simultaneous at stations spanning the dip range 0.3–20°N. Let us now examine the equatorial ionospheric effects in the context of the changes in the ring current (SYM-H) and the auroral electrojet (AE) on July 15, 2000. Note that SYM-H and AE indices are generally considered as proxies of the cross polar cap potential. Figure 3 shows the time rate of change of SYM-H and AE indices (at 15 minute intervals) along with the F region vertical drift variation at Trivandrum.

[10] As mentioned earlier, geomagnetic activity was disturbed prior to the start of the geomagnetic storm on July 15, 2000 (see Figure 1) and the global energy injection rate estimated from the AE index touched 3 × 10^5 MW by 1000 UT on that day [*Basu et al.*, 2001a]. From then on AE activity continued to be high and bursty with concomitant bay activity at low latitudes as seen in ASY(H/D) till the ring current intensification occurred impulsively between 2000 and 2200 UT. These geophysical conditions can be expected to activate the ionospheric disturbance dynamo (DD). *Basu et al.* [2001a], in fact, showed that during this storm DD was launched first and the prompt penetration of high latitude electric fields took place later in the presence of this dynamo effect in the dusk sector. On the other hand, the polarity of the penetration electric fields associated with a sudden increase of polar cap potential is opposite, i.e., eastward in the postsunset period and westward in the postmidnight period.

[11] We consider the F region upward drift disturbance (eastward electric field) in the interval 2300–0030 IST (1730–1900 UT, labeled **I** in Figures 1–3) over Trivandrum to be of disturbance dynamo (DD) origin. This interpretation seems logical and valid on two counts. Firstly, the onset of the eastward field at 2300 IST is consistent with the nighttime pattern of the DD electric field which is known from both theory and observations to reverse to eastward around 2200 LT [*Blanc and Richmond*, 1980; *Scherliess and Fejer*, 1997]. Secondly, it is unlikely to be a signature of prompt penetration electric fields associated with rapid changes in the cross polar cap potential. Models predict an eastward electric field near the midnight dip equator with a rapid decrease in the polar cap potential [*Senior and Blanc*, 1984; *Spiro et al.*, 1988]. But there are no significant changes in SYM-H of either sign during the time interval **I** (see Figures 1 and 3).

There is, however, an impulsive reduction in AE between 1815–1830 UT that could have caused the observed eastward electric field but this is immediately preceded (within 15 min) by an impulsive enhancement. Moreover, it is known that the eastward field associated with a sharp reduction in the polar cap potential decreases with a decay time constant of about 70 min [*Fejer and Scherliess*, 1995]. So, if electric field penetration is primarily responsible for the eastward fields evidenced, then, the decrease in AE ought to have occurred before the increase in time segment **I** which is quite opposite to the observed sequence (Figureo 3). The same argument applies to the decrease in AE around 1730 UT.

[12] In contrast to the situation obtained in time segment **I**, the intense downward drift disturbance in segment **II** (1900–2100 UT) finds a ready interpretation in terms of prompt electric field penetration to low latitudes. As may be seen from Figure 3, there were sharp and large decreases in the time rate of change of SYM-H (59–94 nT/ 15 min) during this period signifying impulsive intensifications of the ring current and hence increases in cross polar cap potential. The westward polarity of the electric field disturbance (downward drift) is consistent with the theoretical studies which predict a westward electric field perturbation in the midnight-dawn sector for a step-like increase in polar cap potential [*Senior and Blanc*, 1984; *Spiro et al.*, 1988]. The electric field disturbance can not be due to penetration effects associated with rapid changes in AE, because what was seen in time segment **II** is a series of decreases in AE of varying amplitude (see Figure 3) instead of the expected increase(s) in AE (indicative of increase(s) in polar cap potential) that could lead to westward electric fields at the postmidnight dip equator. Our observations thus lend further support to the view of *Basu et al.* [2001b] that in an environment already under the influence of disturbance dynamo (DD) as in the severe storm of July 15, 2000, the equatorial penetration electric field perturbations on the nightside are ordered by changes in SYM-H index.

[13] We would like to highlight in conclusion that the impulsive westward electric field perturbation which is the major equatorial effect of the severe storm of July 15, 2000 in the midnight (Indian) sector is remarkable for two reasons. The first one is its very development just after local midnight against a background of eastward field most likely of DD origin as argued earlier and the second one is its unusually large amplitude. Earlier experimental studies consistently showed that penetration electric fields at the postmidnight dip equator manifest preferentially with decreases in polar cap potential rather than with increases. This asymmetric response is currently understood in terms of the simultaneous presence of penetration and disturbance dynamo effects during severe storm conditions, with the latter swamping the former thereby affecting its visibility [*Fejer and Scherliess*, 1995, 1997; *Abdu et al*, 1997]. In other words, the eastward penetration field due to a decrease in polar cap potential becomes prominent due to the addition of DD field of the same polarity, while the westward field associated with an increase in polar cap potential gets suppressed depending on its amplitude relative to the DD field of opposite polarity. The westward electric field disturbance that is found to appear at the midnight dip equator during the severe storm of July 15, 2000 is indeed anomalously large in amplitude to overcome the prevailing eastward field and still manifest with a peak amplitude as large as ≈4.6 mV/m. The observations reported by *Basu et al.* [2001a] for this storm also imply the simultaneous presence of a similar physical situation in the postsunset sector, where intense eastward penetration electric fields overcame the ambient westward fields due to DD and lead to uncommon VHF and L-band scintillations and ion density and TEC dropouts. Penetration electric fields of eastward polarity with large amplitude (4 mV/m) were sometimes seen at the predawn (around 0430 LT) dip equator [*Reddy and Nishida*, 1992 and references therein; *Fejer and Scherliess*, 1997] but to the best of our knowledge, this is the first time that westward fields of this magnitude were found just after midnight.

[14] **Acknowledgments.** Some of the data used in this study were sourced from the archives maintained by the World Data Center for Geomagnetism, Kyoto University, Kyoto, Japan. The ionosonde at Waltair is operated with financial support from the Department of Science & Technology, New Delhi and University Grants Commission, New Delhi.

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J. H. Sastri, Indian Institute of Astrophysics, Bangalore, India.

K. Niranjan, Physics Department, Andhra University, Waltair, India.

K. S. V. Subbarao, Space Physics Laboratory, Vikram Sarabhai Space Center, Trivandrum, India.