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Penetration of Polar Electric Fields to the Nightside Dip Equator at Times of Geomagnetic Sudden Commencements

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Measurements of Doppler Velocity, V_D of F - region reflections at normal incidence over Kodaikanal (dip 3°N, 77°28′E) are used to study the nature of perturbations in F - region vertical plasma drift, V_z associated with the geomagnetic sudden commencements (sc) on July 8, 1991, and January 1, 1992. Both the events which occurred in a narrow time window, 1630-1700 UT (2200-2230 IST) were of sc* type at middle- and high- latitude stations in the afternoon sector. At Kodaikanal, which is on the nightside, the sc of January 1, 1992, is characterized by a double-step main impulse (MI) in H - component (the structure of the sc on July 8 could not be ascertained from normal run magnetograms because of the large amplitude and very small rise time of the sc). It is found that the usual downward motion of F - region plasma during the premidnight hours at Kodaikanal suddenly ceased (and even reversed to upward in one event) for ~1 min coincident with the preliminary impulse (PI) and was immediately enhanced in association with the MI of the sc*. This pattern which is consistently seen in the two events implies that an eastward electric field prevails near the nightside dip equator at the time of the first impulse of double-step MI there and the PI of sc* at high latitudes. Our Doppler velocity observations constitute the first and direct experimental evidence of vertical plasma motions due to the sc - associated electric fields in the nighttime dip equatorial ionosphere. They substantiate the view based on theory (*Kikuchi and Araki*, 1979) and ground-based magnetic observations (*Araki et al*, 1985) that the dusk-to-dawn electric field imposed on the polar ionosphere with the onset of PI of sc* is instantaneously transmitted to the dip equator on the nightside as on the dayside.

INTRODUCTION

The geomagnetic sudden commencement (sc) is conventionally understood in terms of a compressional hydromagnetic (HM) wave set up by the interaction of a shock wave in the solar wind with the magnetosphere [e.g., *Francis et al.*, 1959; *Dessler et al.*, 1960]. The impulsive increase in H - component that characterizes the main impulse (MI) of the sc is generally attributed to the abrupt increase in magnetopause current due to shock-induced compression and accompanying dynamical processes in the magnetosphere [see *Araki*, 1977, and references therein]. The complex latitudinal and local time dependence of the sc wave forms, nevertheless, indicates that the structure of the sc is determined not only by magnetospheric current sources but also by those nearer to the Earth. Several authors, in fact, have indicated the contribution of ionospheric electric currents to the sudden commencement part of geomagnetic storms at high latitudes as well as at dip equatorial latitudes [e.g., *Nishida et al.*, 1966; *Rastogi*, 1976; *Araki*, 1977; *Reddy et al.*, 1981]. Of specific relevance to the present work is the global ionospheric current system that is widely considered as responsible for the preliminary impulse (PI) that precedes the MI of the sudden commencement. The PI manifests as a distinct negative impulse (with a duration of ~1 min) in H - component simultaneously near the dip equator on the dayside and at high-latitudes in the afternoon sector and also as a positive impulse in the high latitude forenoon sector [see *Araki*, 1977, and references therein]. It is therefore termed as the preliminary reverse impulse (PRI) and the corresponding sc as sc*. *Araki* [1977] interpreted the equatorial PRI as due to the extension to the dayside equator of the DP2 type ionospheric current system driven by a dusk-to-dawn electric field transmitted to the polar ionosphere along the magnetic lines of force by anisotropic HM waves from the compressional wavefront propagating tailward in the dayside magnetosphere as described by *Tamao* [1964]. Theoretical studies showed that the Earth-ionosphere waveguide facilitates the instantaneous transmission of a suddenly imposed polar electric field to the equator as a zeroth-order transverse magnetic (TM) electromagnetic wave [*Kikuchi et al.*, 1978; *Kikuchi and Araki*, 1979]. Multidimensional numerical calculations of the global distribution of ionospheric currents caused by field-aligned currents flowing into and away from the polar ionosphere (source currents) predict that the intensity of the current reduces with decrease of latitude but gets enhanced at the dayside equator in spite of the shielding effect of the enhanced Cowling conductivity there [*Takeda*, 1982; *Tsunomura and Araki*, 1984]. This prediction is in agreement with the observed latitudinal variation of the amplitude of PRI [*Araki*, 1977 and references therein]. There are also compelling lines of experimental evidence for the polar origin of PI and the extension of the PI current system (and electric field that drives it) to the dayside equator. One is the detection of the ionospheric current associated with PI from simultaneous magnetic observations above and well below the ionosphere [*Araki et al.*, 1982, 1984]. The other is the observation of westward electric field during PRI of the equatorial sc* from data of the transequatorial VHF forward scatter experiments [*Rastogi*, 1976].

The polar electric field responsible for the PI of sc* seems to penetrate to lower latitudes not only on the dayside but also on the nightside. The HF Doppler observations of *Kikuchi et al.* [1985], and *Kikuchi* [1986] demonstrate the unambiguous presence of negative preliminary frequency deviations (PFD) at low latitudes on the nightside (2100-0600 LT) simultaneous with high latitude sc*. The sense of PFD which corresponds

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to an eastward electric field is consistent with the transmission of the dusk-to-dawn polar electric field associated with the PI of sc* to low latitudes. Although the detection of the PI in groundbased magnetic recordings at nightside dip equatorial latitudes is rather difficult (partly due to the sense of PI being the same as of MI), the careful analysis of *Araki et al.* [1985], did demonstrate that the PI current system can extend to the nightside equator and produce a small but observable magnetic effect despite the much reduced ionospheric conductivity at night. The magnetic effect is seen as a stepwise sc (or sc with double-step MI) simultaneous with the sc* on the dayside equator. If this physical situation implied by earlier experimental work indeed prevails, then, there should be short-lived perturbations in F- region vertical plasma motion near the dip equator on the nightside in association with sc* at high-latitudes/dip equator on the dayside. This is because (1) the F- region plasma in the vicinity of dip equator drifts upward (downward) during daytime (nighttime) under the influence of zonal electric fields of E- region dynamo origin (with a contribution from F- region dynamo around sunset) and the latter responds very sensitively to disturbances originating in the electrodynamic coupling of high latitude - low latitude ionospheres [see *Fejer*, 1991, and references therein; *Sastri et al.*, 1992], (2) the electric field associated with the PI of sc* is to be eastward on the nightside dip equator (as indicated by the double-step MI in geomagnetic records) and ought to be detectable being impulsive in nature and opposite in sense to the ambient westward field of dynamo origin as mentioned earlier and (3) though the strength of the polar electric field responsible for the PI of sc* is expected to be nearly the same at the dip equator as at low latitudes the F - region vertical plasma drift speed due to an electric field of a given amplitude will be larger near dip equator than at low latitudes being proportional to cos I where I is the dip angle [*Rishbeth and Garriott*, 1969]. To the knowledge of the authors these points have not been verified. In this paper we present experimental evidence, for the first time, for the occurrence of sc - associated perturbations in F- region vertical plasma motion in the nocturnal dip equatorial region. The nature of the evidenced short-lived disturbances in plasma vertical motion confirms that the polar electric field responsible for the PI of sc* indeed penetrates right down to the dip equator in the nightside hemisphere.

EXPERIMENTAL TECHNIQUE

The present study is based on data of the HF-pulsed phase path sounder at Kodaikanal (10°14′N, 77°28′E, dip 3°N) which provides continuous information on the changes in phase path (P) of ionospheric reflections at normal incidence [*Sastri et al.*, 1985]. The sounder consists essentially of a broadband pulse transmitter, a phase-coherent receiver with quadrature detection, a frequency synthesizer unit, timing and logic circuitry and analog recording facilities. The system is rendered phase-coherent by generating all the signals required for the transmitter and the receiver from a single 16.0-MHz temperature - controlled crystal oscillator by performing the standard operations of frequency division, mixing and filtering and adopting digital logic. The master crystal oscillator ensures the phase coherence of the signals as it has a frequency stability of better than 1 part in 10^7. The transmitter radiates vertically pulsed rf energy (pulse width 100 μs, pulse repetition rate 50 Hz, peak power ~3KW) on any chosen carrier frequency (f) in the band 2-20 MHz. The pulsed rf after reflection from the ionosphere is received by the receiver. The phase of the ionospheric echo is compared at the intermediate frequency (IF) with two reference signals in phase quadrature (derived in the frequency synthesiser unit) in two separate phase detectors in the receiver. The output of the two phase detectors are separately amplified and band-limited using low-pass filters. A gate pulse (10 μs width, pulse repetition rate 50 Hz) whose delay w.r.t. the transmitter pulse can be varied is generated in the frequency synthesizer unit, and is fed to the receiver to activate the sample and hold (S/H) circuits in the quadrature channels. The sampled outputs of the quadrature channels (A sin ϕ, A cos ϕ) of the receiver are used in a logic scheme (which essentially identifies the $2n\pi$ phase condition) to provide data of the sense and magnitude of the changes in phase path to the limit equivalent to a total phase path change of a wavelength, λ of the probing radio waves. The time delay of the S/H gate pulse is adjusted to select the reflecting region (height resolution 1.5 km) of interest and is made to coincide with the echo maximum. The data are recorded continuously on a strip chart recorder run at a speed of 10 cm/min which gives a time resolution of 6 s.

OBSERVATIONS

Since February 1991 we have been recording the phase path of F- region reflections at 4.0 MHz at Kodaikanal over the interval 1600-0600 IST to attempt detection of perturbations in vertical plasma motion associated with geomagnetic sudden commencements, besides several other studies concerning ionospheric dynamics in the equatorial electrojet region. The phase path measurements at 4.0 MHz correspond to the bottomside F region during the evening and nighttime conditions. They are quite suitable for the intended study because (1) vertical plasma motions near the reflection level are very effective in producing changes in the phase path of ionospheric reflections at normal incidence [e.g., *Georges*, 1967] and, as mentioned earlier, such bulk plasma motion perpendicular to the magnetic field commonly prevails in the vicinity of the dip equator driven by zonal electric fields and (2) at night the time rate of change of phase path or the Doppler velocity V_D of F region echoes represents the vertical plasma motion due to the electromagnetic ExB drift with a minor positive contribution due to chemical loss. It is pertinent to add here that the HF Doppler technique is a sensitive experimental arrangement available for the detection of sc - associated electric fields [e.g., *Huang*, 1973; *Kikuchi et al.*, 1985; *Kikuchi and Araki*, 1985; *Kikuchi*, 1986].

Scrutiny of our data for the period February 1991 through April 1992 showed the availability of phase path measurements encompassing the storm sudden commencements on July 8, 1991, and January 1, 1992. It is fortuitous that both the events occurred in a narrow local time window, 2200-2230 IST (1630-1700 UT) which provided us with an opportunity to check the repeatability of the sc - associated perturbations in F region vertical drift which is an index of the genuineness of their detection. In the following we present the salient features of the two sudden commencements and the associated disturbances in F region plasma motion over Kodaikanal near the dip equator and discuss the same in the light of the current understanding of the physics of sudden commencements.

Event of July 8, 1991

Consultation of Solar-Geophysical Data [National Oceanic and Atmospheric Adminstration, World Data Center A (NOAA/ WDC-A), Boulder, Colorado] showed the occurrence of an sc in the global network of geomagnetic observatories at 1635-1637 UT on July 8, 1991. The sc is impressive from the view point of its spatial extent as well as amplitude. It was reported by 27 stations (25 stations categorized it as *A* type, i.e., very remarkable and two stations as *B* type, i.e., fairly ordinary but unmistakable). At 16 of these stations it was recorded as sc* out of which 7 were in the afternoon (European) sector. The amplitude of the sc in *H* - component at dip equatorial locations on the nightside (Indian sector) was quite large being in the range 108-168 nT. Examination of normal run (stormtime) magnetogram of Fredericksburg (Geomagnetic latitude 49°25′N) in the forenoon sector confirmed the occurrence of sc* with a PI at 1634 UT (2204 IST) as can be seen from the enlarged version of the relevant portion of the magnetogram reproduced in Figure 1a. The (expected) presence of a stepwise sc at Kodaikanal near the nightside dip equator could not be ascertained with any confidence from the normal-run magnetograms due to the very small risetime of the sc.

In Figure 2 is displayed the transient response of the ionosphere over Kodaikanal to the sc event as evidenced in the measurements of phase path of lower *F* - region reflections at normal incidence. The phase path data of Figure 2 clearly show the prevalence of a monotonic decrease in phase path prior to the onset of sc. The line of best fit to the P versus time curve for the interval 2157:24 - 2204 IST indicates a gross negative Doppler velocity, V_D of 42 ms^{-1} or a downward plasma drift Vz ($V_D/2$) of 21ms^{-1}. It is known from the theoretical work of *Bittencourt and Abdu* [1981] that during

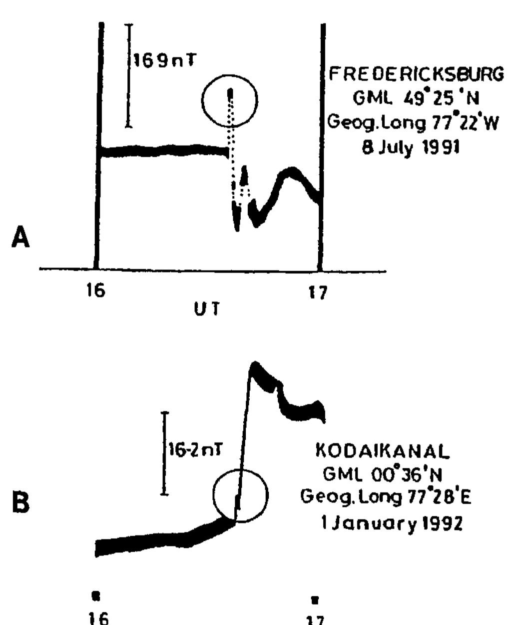

Fig. 1. Geomagnetic sudden commencements (sc) on July 8, 1991, and January 1, 1992, as observed at Fredericksburg and Kodaikanal, respectively. The preliminary impulse (PI) of sc* on July 8 at Fredericksburg in the forenoon sector and the stepwise sc on January 1 at Kodaikanal near the dip equator in the night hemisphere are indicated by solid circles.

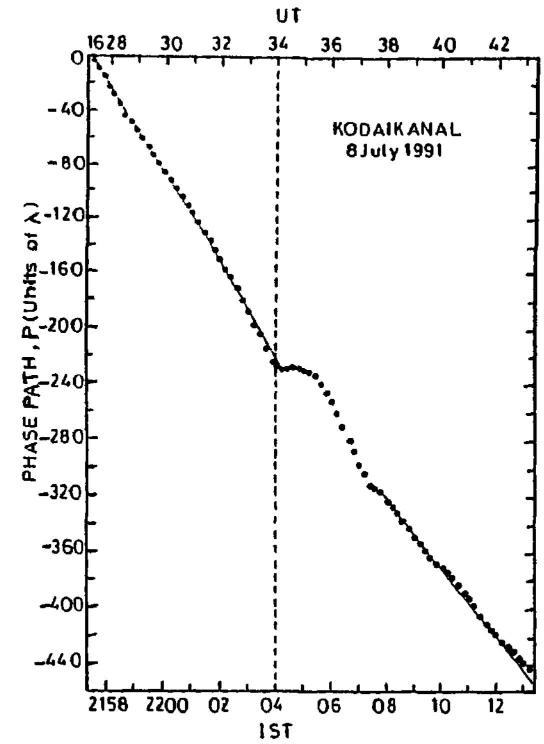

Fig. 2. Time variation of *F* - region phase path (P) at Kodaikanal on July 8, 1991, during the interval 2157:24 - 2211:12 IST. The vertical dashed line represents the time of PI of sc* recorded at Fredericksburg in the forenoon sector. The lines of best fit to the P versus time curve before and after the sc-associated disturbance are also shown.

the nighttime the upward plasma drift due to layer decay is insignificant if the height of the reflection region is above a threshold altitude of 300 km and that the vertical drift near the dip equator derived from F region height data is quite reliable under such conditions. The height of bottomside F region at Kodaikanal was well above 300 km around the time of the sc on July 8, 1991, as can be seen from the values of $h'F$ scaled from the ionograms of a colocated ionosonde and graphed in Figure 3. The $h'F$ data also testify to the gross downward movement of *F* - region around the time of the sc. The V_D (Vz) values of -42 ms^{-1} (-21 ms^{-1}) therefore represent essentially the electromagnetic *ExB* drift due to the ambient westward electric field. That the *F* - region plasma usually moves downward under the influence of a westward electric field in the premidnight hours near the dip equator is established from the extensive measurements of *Vz* with the incoherent scatter radar at Jicamarca [see *Fejer*, 1991, and references therein].

It is quite evident from Figure 2 that there was an unambiguous short-lived disturbance in *F* region phase path at Kodaikanal in association with the sc* at 1634 UT (2204 IST) at Fredericksburg in the forenoon sector. The disturbance is characterized by an abrupt cessation of the steady downward drift for 1 min starting at 2204 IST followed by enhanced downward drift for 2 min. Within the errors of measurement of time from normal-run magnetograms, the cessation of downward drift corresponds to the duration of PI of the sc* at Fredericksburg and the subsequent enhanced downward drift to the duration of MI. The normal pattern of a steady decrease of phase path (P) resumed after the passage of the disturbance, i.e., from ~2207 IST. The slope of the line of

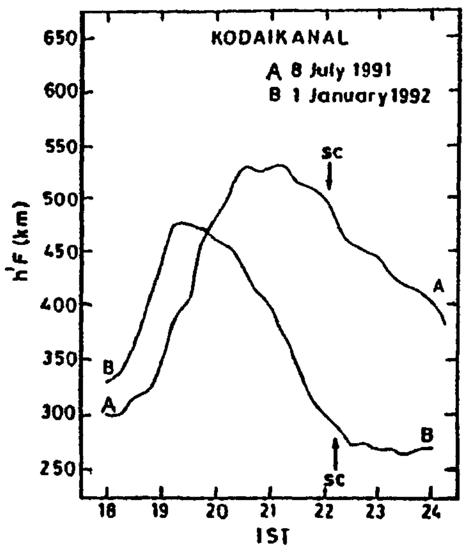

Fig. 3. Variation of $h'F$ at Kodaikanal on July 8, 1991, and January 1, 1992, illustrating the gross downward motion of bottomside F region prior to and after the sudden commencements.

best fit to the P versus time curve for the interval 2207:48 - 2211:12 IST indicates a negative V_D of 29.2 ms $^{-1}$ or a downward Vz of 14.6 ms^{-1}. To bring out more clearly the nature of the sc-associated perturbation in F region plasma motion, the temporal profile of V_D (Vz) is shown in Figure 4 as obtained from differentiation of the P versus time curve in Figure 2. The dashed vertical line in the figure represents the time of onset of the PI of sc* at Fredericksburg. The shaded regions in Figure 4 indicate the ambient state of V_D (Vz) prior to and after the sc-associated disturbance with the horizontal lines representing the average values of V_D (Vz) and the standard deviations. It is interesting to see the ubiquitous presence of quasi-periodic fluctuations of small amplitude superposed on the steady component of V_D (Vz) in the data of Figure 4. Such fluctuations are a common feature of the phase path variation of F region echoes at locations in the dip equatorial region during daytime as well as nighttime [e.g., *Krishnamurthy et al.*, 1976; *Sastri et al.*, 1988; *Nair et al.*, 1992]. While the daytime fluctuations in V_D are established to be due to phase path changes caused by the refractive index variations associated with the convective motions of electrojet irregularities of E region altitudes [*Sastri et al.*, 1991a, b], the origin of the nighttime fluctuations remains to be understood. Further discussion of this noteworthy feature of the spectral content of nighttime V_D (Vz) near the dip equator is beyond the scope of the present paper. The average values of V_D (Vz) prior to and after the sc-related disturbance were -42.2 and -29.2 ms^{-1} (-21.1 and -14.6 ms^{-1}), respectively which are very close to the steady component of V_D (Vz) derived from the slopes of the corresponding portions of the P versus time curve (Figure 2) mentioned earlier. It is quite clear from Figure 4 that with the onset of the PI of the sc*, the ambient downward drift ceased and even reversed to upward over a period of one minute, followed by enhanced downward drift over the next 2 min. This transient perturbation in V_D (Vz) indicates the existence of an eastward electric field during the PI of the sc* and a westward field during the MI. The amplitude of the eastward field is ≈0.95 mV/m (corresponding to the segment marked XY on the V_D/Vz curve in Figure 4) and that of the subsequent westward field ≈ 1.35 mV/m (corresponding to the segment marked YZ on the V_D/Vz curve in Figure 4).

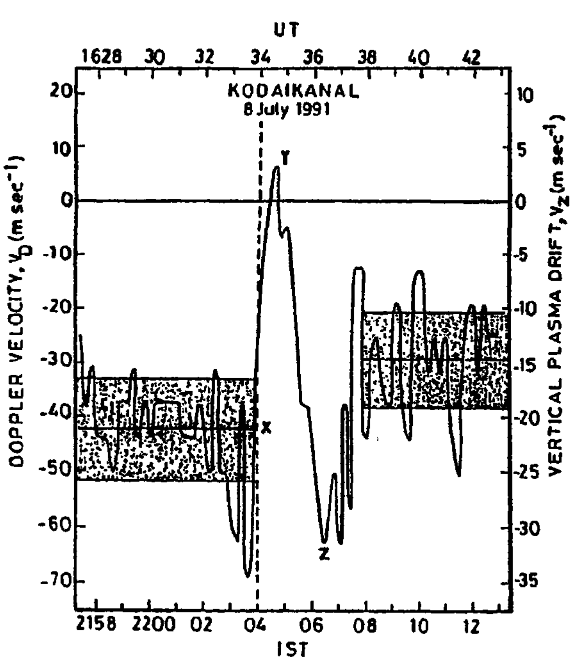

Fig. 4. Time variation of F - region Doppler velocity, V_D (and vertical plasma drift, $Vz = V_D/2$) at Kodaikanal on July 8, 1991. The unambigious cessation and small upward reversal of the ambient downward plasma drift at the time of PI of sc* at Fredericksburg (vertical dotted line) may be noted. The portion of the V_D/Vz curve marked XYZ is used to estimate the amplitude of the sc*-associated electric fields.

Event of January 1, 1992

The sudden commencement at 1642-1645 UT on January 1, 1992, was reported to have been observed by 26 observatories out of which 16 categorized it as A type and 10 as B type (Solar-Geophysical Data, NOAA/WDC-A, Boulder, Colorado). It was recorded as sc* at seven stations some of which were in the afternoon sector at high/middle latitudes. At Kodaikanal it manifested as a stepwise sc or sc with a double-step MI, as can be seen from the enlarged version of the relevant portion of the normal-run magnetogram reproduced in Figure 1*b*. This is, of course, to be expected from the earlier work of *Araki et al.* [1985]. The preliminary impulse of the stepwise MI is estimated to be from 1642 to 1643 UT and the second one from 1643 to 1647 UT. The risetime of this sc is thus longer than that on July 8, 1991 which feature permitted the assessment of its structure at Kodaikanal from normal-run magnetograms.

The changes in the F region phase path and the Doppler velocity V_D (vertical plasma drift, Vz) at Kodaikanal to the sc event are displayed in Figures 5 and 6 respectively in the same format as of Figures 3 and 4. Prior to the onset of the stepwise sc at Kodaikanal at 2212 IST (1642 UT) there was a steady decrease of the phase path, P with time as in the previous event and also as can be expected at this time of the night. The slope of the line of best fit to the P versus time curve for the interval 2203-2212 IST indicated a negative Doppler velocity, V_D of 27.2 ms^{-1} or a downward Vz of 13.6 ms^{-1}. Simultaneous with the onset of the first impulse (step) of the double-step MI, the steady downward drift suddenly ceased for the duration of that impulse and was succeded by

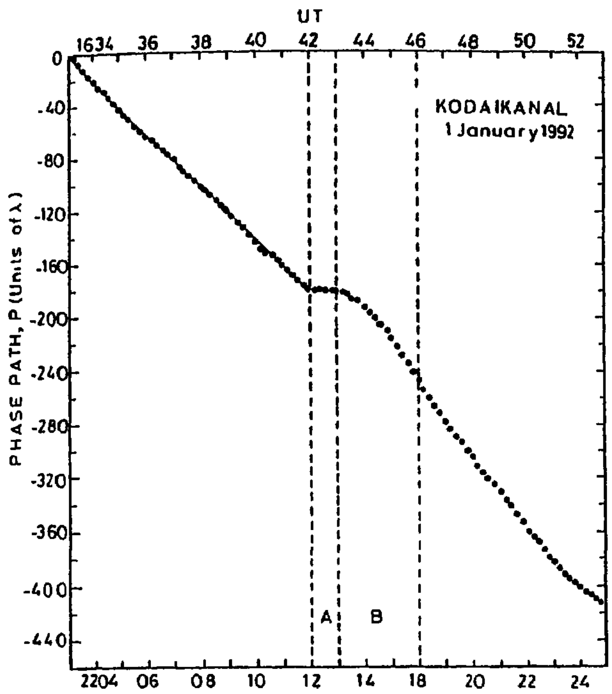

Fig. 5. Same as in Figure 2 but for the interval 2203 - 2222:48 IST on January 1, 1992. The intervals A and B correspond to the duation of the first and second impulse of the stepwise sc recorded at Kodaikanal.

enhanced downward drift during the longer second step of the MI. The temporal profile of V_D (Vz) shown in Figure 6 testifies to this nature of the transient perturbation associated with the sc and also the existence of a background negative V_D (downward Vz) with an average value of 25.4 ms^{-1} (12.7 ms^{-1} over the interval 2203-2212 IST prior to the sc. The abrupt cessation of downward drift in coincidence with the first impulse of the stepwise sc implies the presence of a transient eastward electric field of at least 0.51 mV/m and the enhanced negative V_D (downward Vz) that followed implies a westward field of 0.75 mV/m (maximum). The estimation of the eastward electric field is quite reliable as the height of bottomside F region at Kodaikanal at the time of onset of the sc is > 300 km as can be seen from Figure 3. The maximum am-

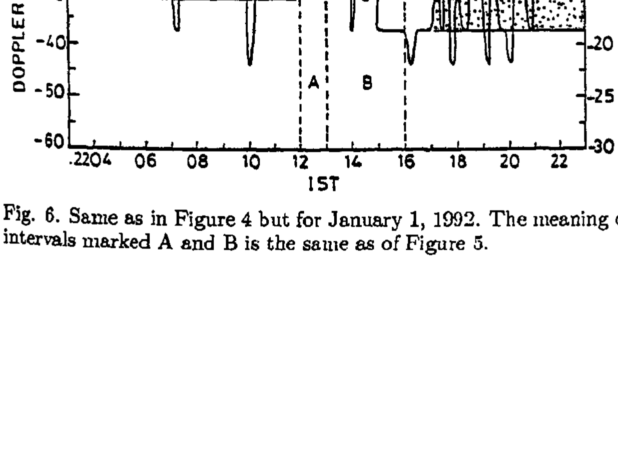

Fig. 6. Same as in Figure 4 but for January 1, 1992. The meaning of intervals marked A and B is the same as of Figure 5.

plitude of the westward electric field could have been slightly underestimated as the height of bottom F- region went just below 300 km during the period of its manifestation. The normal monotonic decrease of P resumed after the passage of the sc-associated disturbance from ~2217 IST. The V_D (Vz) temporal variation over the interval 2217:12 - 2222:48 IST, infact, indicated the prevalence of an average downward Vz (westward electric field) of 14.4 ms^{-1} (0.58 mV/m).

DISCUSSION

The results of the case studies presented above constitute unambiguous evidence for the appearance of a transient eastward electric field near the dip equator in the nightside hemisphere in association with the first pulse of the stepwise sc there and with the PI of sc* at high latitude on the dayside. They also showed clearly the existence of a short-lived westward electric field during the MI of sc* at high latitudes on the dayside and the second pulse of the stepwise sc at the nightside dip equator. According to *Araki* [1977], the disturbance field of an sc (D_{sc}) is composed of three components as follows:

$$D_{sc} = DP_{pi} + DL_{mi} + DP_{mi}$$

where DP_{pi} and DP_{mi} are fields of polar origin that manifest during the PI and MI of the sc respectively and DL_{mi} is the field due to magnetospheric sources that predominates at low latitudes. The DP_{pi} field is associated with the global ionospheric current system driven by the dusk-to-dawn electric field mapped along lines of force onto the polar ionosphere from the magnetosphere [*Tamao*, 1964]. It is considered as responsible for the simultaneous occurrence of PRI of sc* at high latitudes in the afternoon sector and at the dip equator on the dayside, as well as the stepwise sc at the dip equator on the nightside [*Araki*, 1977; *Araki et al.*, 1985]. The theoretical work of *Takeda* [1982] and *Tsunomura and Araki* [1984] indicates that the ionospheric zonal electric field or current responsible for PI of sc* is eastward (westward) at the dip equator on the nightside (dayside). The eastward polarity of the short-lived (duration 1 min) electric field disturbance evidenced at Kodaikanal in the nightside hemisphere coincident with the first impulse of the stepwise sc there (and PI of sc* at high latitude) is therefore consistent with the theoretical predictions. The agreement between theory and our observations, however, becomes rather tenuous when details are taken into consideration. The two-dimensional model calculations of *Tsunomura and Araki* [1984] show that the amplitude as well as the sense of the equatorial zonal electric field produced by high latitude field-aligned currents (FAC) is a strong function of local time. It is westward from 0800 to 2300 LT and eastward from 2300 LT to 0800 LT with peak values ~1800 and 0600 LT (see Figure 5 of their paper). For the sudden commencements under discussion here which occurred between 2200 and 2230 IST, the perturbation electric field associated with the PI of sc* is therefore to be weak and westward, while our Doppler velocity observations clearly show the field to be eastward and quite strong (0.5 - 0.8 mV/m). Discrepancies between theory and observations of this nature were also present in the earlier investigations regarding the characteristics of the geomagnetic effects of PI at the nightside dip equator and PI-associated electric field effects at low latitudes . The HF Doppler observations of *Kikuchi et al.* [1985] showed the polarity of the preliminary freqency deviations (PFD) associated with PI of sc* to be consistent with the model predections, i.e., positive (signature of westward electric field) during daytime and negative (signature of eastward electric field) during nighttime at low latitudes. The sense of the PFD on the nightside is, however, found to be negative not from 2300 LT as predicted by *Tsunomura and Araki* [1984] but from 2100 LT. Similarly, the magnetometer observations of *Araki et al.* [1985] clearly showed the occurrence rate of the sc with stepwise MI at the nightside dip equator to be a maximum at 0300 LT (indicative of larger amplitude of the causative electric currents which aid easy detection of the steplike structure of the sc in magnetometer data), whereas the calculations of *Tsunomura and Araki* [1984] showed the peak of the equatorial ionospheric current to be ~0700 LT. These points of agreement/disagreement between observations and theoretical simulations merit some consideration as they reflect the current state of our understanding of the complex electrodynamic coupling of the magnetosphere-polar ionosphere-equatorial ionosphere domains. It is worthwhile to recall here that the local time variation of the strength and polarity of the purturbation electric fields at the dip equator depend quite sensitively on the assumed models of ionospheric conductivity and source field-aligned currents (FAC). The very recent model results of *Denisenko and Zamay* [1992], though of direct relevance to the changes in the equatorial zonal electric fields due to those in high-latitude field-aligned currents (or polar cap potential) during the different phases of substorms, do support the view. Their calculations show that during the recovery phase of a substorm (which corresponds to the physical situation obtained during PI of sc*), an eastward electric field appears at the geomagnetic equator on the nightside right from 2200 MLT with peak values ~0300 MLT (see Figure 8 of their paper). The global convection models of *Senior and Blanc* [1984] and *Spiro et al.* [1988] also show the nighttime eastward electric fields near the dip equator associated with a sudden decrease in polar cap potential (corresponding to recovery phase of a substorm) to have largest amplitudes in the 0200-0500 LT sector. The local time dependence of the occurrence rate of stepwise MI near the nightside dip equator derived by *Araki et al.* [1985] is thus consistent with the recent theoretical simulations. Experimental evaluation of the local time variation of the amplitude of perturbation electric fields at dip equatorial latitudes associated with PI of sc* is therefore essential for a rigorous assessment of the results of theoretical simulations and also to help understand the physical factors that control the penetration of polar electric fields to lower latitudes. These issues we hope to examine in future from the continuing F- region Doppler velocity measurements at Kodaikanal.

The westward electric field near the nightside geomagnetic equator evidenced in the present case studies at the time of second impulse of the stepwise sc there (and MI of sc* at high latitudes on the dayside) may have contributions from both DL_{mi} and DP_{mi} fields. The MI of sc is basically caused by an enhancement in magnetopause current which propagates as a compressional hydromagnetic wave through the magnetosphere to the nightside low latitude ionosphere [e.g., *Francis et al.*, 1959; *Dessler et al.*, 1960]. The westward electric field that accompanies the compressional hydromagnetic wave manifests at low latitudes with a delay of ≈50 s with respect to the transmission by way of the polar ionosphere of the dusk-to-dawn electric field that produces PI of sc* at high latitudes [see *Kikuchi*, 1986, and references therein]. It can therefore be expected to play a prominent role in the initial part of the MI and induce a downward motion of F - region plasma at the nightside dip equator. Such a plasma motion can also be caused by the DP part of MI which sets in because of enhanced magnetospheric convection after the conclusion of the magnetospheric compression by the interplanetory shock. The study of the local time dependence of the sense of main frequency deviation (MFD) by *Kikuchi et al.* [1985], in fact, showed that the dawn-to-dusk electric field associated with MI penetrates into the low-latitude ionosphere. It is therefore not unreasonable to expect the westward electric field of DP_{mi} to manifest at the dip equator in the nightside hemisphere in the later part of MI. We hold the view that the enhanced downward plasma drift (westward electric field) that immediately followed the cessation of the ambient downward drift (eastward electric field) in our observations is due to DL_{mi}, and the persistent westward field seen later, particularly in the event of January 1, 1992 from 2215 to 2217 IST is due to DP_{mi} (see Figures 4 and 6). It is to be stressed here that it is very difficult to ascertain the relative contributions of DL_{mi} and DP_{mi} to the observed westward field in the absence of rapid-run magnetograms, and information on the local time dependence of the polarity of electric fields during MI of sc as is the case here (the electric field due to DP_{mi} will be of opposite polarity between day and night while that of DL_{mi} will be the same). To conclude, the F - region Doppler velocity measurements at Kodaikanal studied here confirm that the magnetospheric dusk-to-dawn electric field imposed on the polar ionosphere at the time of PI of sc* penetrates instantaneously to the geomagnetic equator in the nightside hemisphere. Prominent westward electric fields attributable to both DL_{mi} and DP_{mi} are also evidenced in our data, but further measurements for a large number of sc events occurring at different local times are required to assess the specific contributions of DL_{mi} and DP_{mi} fields to the observed electric fields.

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REFERENCES

Araki, T., Global structure of geomagnetic sudden commencements, *Planet. Space Sci.*, 25, 373, 1977.

Araki, T., T. Iyemori., S. Tsunomura., T. Kamei, and H. Maeda, Detection of an ionospheric current for the preliminary impulse of the geomagnetic sudden commencement *Geophys. Res. Lett.*, 9, 341, 1982.

Araki, T., T. Iyemori, and T.Kamei, Sudden commencements observed by MAGSAT above the ionosphere, *J. Geomagn. Geoelectr.*, 36, 507, 1984.

Araki, T., J. H. Allen, and Y. Araki, Extension of a polar ionospheric current to the nightside equator, *Planet. Space Sci.*, 33, 11, 1985.

Bittencourt, J. A., and M. A. Abdu, A theoretical comparison between apparent and real vertical ionization drift velocites in the equatorial F- region, *J. Geophys. Res.*, 86, 2451, 1981.

Denisenko, V. V., and S. S. Zamay, Electric field in the equatorial ionosphere, *Planet. Space Sci.*, 40, 941, 1992.

Dessler, A. J., W. E. Francis, and E. N. Parker, Geomagnetic storm sudden commencement rise times, *J. Geophys. Res.*, 65, 2715, 1960.

Fejer, B. G, Low-latitude electrodynamic plasma drifts: A review, *J. Atmos. Terr. Phys.*, 53, 677, 1991.

Francis, W. E., M. I. Green, and A. J. Dessler, Hydromagnetic propagation of sudden commencements of magnetic storms, *J. Geophys. Res.*, 64, 1643, 1959.

Georges, T. M, Ionospheric effects of atmospheric waves, *Tech. Rep. IER 57-ITSA* 54, U. S. Dep. of Comm., Environ. Sci. Serr. Admin., Boulder, Colo., 1967.

Huang, Y. N., K. Najita, and P. Yuen, The ionospheric effects of geomagnetic sudden commencements as measured with an HF Doppler sounder at Hawaii, *J. Atmos. Terr. Phys.*, 35, 173, 1973.

Kikuchi, T, Evidence of transmission of polar electric fields to the low latitude at times of geomagnetic sudden commencements, *J. Geophys. Res.*, 91, 3101, 1986.

Kikuchi, T, and T. Araki, Horizontal transmission of the polar electric field to the equator, *J. Atmos. Terr. Phys.*, 41, 427, 1979.

Kikuchi, T., and T. Araki, Preliminary positive impulse of geomagnetic sudden commencement observed at dayside middle and low latitudes, *J. Geophys. Res.*, 90, 12,195, 1985.

Kikuchi, T., T. Araki, H. Maeda, and K. Maekawa, Transmission of polar electric fields to the equator, *Nature.*, 273, 560, 1978.

Kikuchi, T., T. Ishimine, and H.Sugiuchi, Local time distribution of HF Doppler frequency deviations associated with geomagnetic storm sudden commencements, *J. Geophys. Res.*, 90, 4389, 1985.

Krishnamurthy, B. V., C. R. Reddy, K. S. V. Subbarao, R. R. Rao, and P. Sharma, Some new observations on equatorial spread- F using phase path technique, *J. Geophys. Res.*, 81, 705, 1976.

Nair, R. B., N. Balan., G. J. Bailey, and P. B. Rao, Spectra of the a.c. electric fields in the post-sunset F- region at the magnetic equator, *Planet. Space Sci.*, 40, 655, 1992.

Nishida, A., N. Iwasaki, and T. Nagata, The origin of fluctuation in the equatorial electrojet: a new type of geomagnetic variation, *Ann. Geophys.*, 22, 478, 1966.

Rastogi, R. G, Equatorial E region electric field changes associated with a geomagnetic storm sudden commencement, *J. Geophys. Res.*, 81, 687, 1976.

Reddy, C. A., V. V. Somayajulu, and K. S. Viswanathan, Backscatter radar measurements of strom-time electric field changes in the equatorial electrojet, *J. Atmos. Terr. Phys.*, 43, 817, 1981.

Rishbeth, H., and O. K. Garriott, *Introduction to Ionospheric Physics*, Academic, San Diego, Calif., 1969.

Sastri, J. H., K. B. Ramesh, and K. S. Ramamoorthy, A system for recording phase path variations of ionospheric reflections, *Kodaikanal Obs. Bull.*, 5, 15, 1985.

Sastri, J. H., K. B. Ramesh., D. R. K. Rao, and J. V. S. V. Rao, Manifestations of short-period electric field fluctuations in the equatorial lower thermosphere, *Phys. Scr.*, 37, 501, 1988.

Sastri, J. H., K. B. Ramesh and J. V. S. V. Rao, Doppler frequency fluctuations of lower thermospheric reflections in the equatorial electrojet region, *J. Atmos. Terr. Phys.*,53, 567, 1991*a*.

Sastri J. H., K. B. Ramesh, V. V. Somayajulu, and J. V. S. V. Rao, Origin of short-period (30-300 s) Doppler frequency fluctuations of lower F region reflections in the equatorial electrojet region, *Radio Sci.*, 26, 1403, 1991*b*.

Sastri, J. H., K. B. Ramesh, and D. Karunakaran, On the nature of substorm-related transient electric field disturbances in the equatorial ionosphere, *Planet. Space Sci.*, 40, 95, 1992.

Senior, C., and M. Blanc, On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities, *J. Geophys. Res.*, 89, 261, 1984.

Spiro, R. W., R. A. Wolf, and B. G. Fejer, Penetration of high latitude electric field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, 6, 39, 1988.

Takeda, M, Three-dimensional structure of ionospheric currents produced by field-aligned currents, *J. Atmos. Terr. Phys.*, 44, 695, 1982.

Tamao, T, Hydromagnetic interpretation of geomagnetic ssc*, *Rep. Ionos. Space Res., Jpn.*, 18, 16, 1964.

Tsunomura, S., and T. Araki, Numerical analysis of equatorial enhancement of geomagnetic sudden commencement, *Planet. Space Sci.*, 32, 599, 1984.

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