GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 19, PAGES 2649-2652, OCTOBER 1, 1995

Response of equatorial-low latitude ionosphere to sudden expansion of magnetosphere

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

Y. N. Huang
Directorate General of Telecommunications, M.O.T.C., Taipei, Taiwan.

T. Shibata and T. Okuzawa
Department of Electronic Engineering, Denki-tsushin University (UEC), Tokyo, Japan.

Abstract. The response of the equatorial-low latitude nightside ionosphere to the geomagnetic negative sudden impulse(si$^-$) on March 15, 1993 is studied using recordings of Doppler velocity of ionospheric echoes at vertical incidence at Kodaikanal(10.2°N) and Doppler shift of standard HF signals on oblique paths at Lunping(25.0°N) and Kure(34.25°N). The si$^-$ at 1541 UT is characterised by a simple decrease of H-field at low latitude stations widely distributed in longitude, and by a double-pulse structure at mid and high latitude stations on the dayside. The usual downward drift of F region plasma during the premidnight hours over Kodaikanal near the dip equator abruptly increased for $\approx$ 2.5 min coincident with the first pulse of the si$^-$ and immediately reversed direction to upward. Recordings at Lunping and Kure also showed short-lived Doppler frequency deviations simulataneous with those at Kodaikanal and of the same polarity and sequence. These observations constitute the first and direct experimental evidence for vertical plasma motions due to si$^-$ associated electric fields in the nighttime equatorial-low latitude ionosphere. The case study supports the view that si$^-$ can be explained by the physical model of sc/si$^+$ with a reversal in the direction of the global current systems responsible for the groundlevel magnetic field variations.

Introduction

Sudden increases in the dynamic pressure of solar wind lead to geomagnetic sudden commencements(sc) and positive sudden impulses(si). The impulsive increase in the H-field(main impulse, mi) that characterises the sc at low latitudes is widely understood as due to an abrupt increase in the magnetopause current due to shock-induced compression of the magnetosphere and associated dynamical processes [see Araki, 1977; 1994 and references therein]. Ionospheric electric fields and currents do also contribute to the sc at high latitudes as well as at dip equatorial latitudes where the sc waveform exhibits considerable structure [e.g. Araki, 1977; 1994]. According to the model of Araki [1977,1994], the disturbance field of sc consists of fields of magnetospheric sources(DL) as well as of polar origin(DP). While DL predominates at low latitudes during the main impulse(mi) of sc, DP accounts for the preliminary impulse(pi) that precedes the mi and also contributes to the main impulse(DP_{mi}). The model is based on extensive theoretical studies as well as ionospheric/geomagnetic observations on ground and by satellites [e.g. Araki, 1977; Araki et al, 1982; Araki et al, 1985; Kikuchi, 1986; Sastri et al, 1993a; Tsunomura and Araki, 1984].

Although earlier studies have helped grasp the response of the magnetosphere-ionosphere system to sudden compression of the magnetosphere, due attention has not been paid so far to sudden magnetospheric expansion, i.e. to negative sudden inpulse(si$^-$). The basic question is whether the electric fields and the current systems associated with si$^-$ are exactly opposite to those associated with sc/si$^+$. Based on the similarities between positive and negative sudden impulses on a global basis, Nishida and Jacobs [1962] asserted that any theory of sc should also be able to explain si$^-$. To our knowledge, the only work done on this issue subsequently was the study of Araki and Nagano[1988] using magnetic field measurements on ground and by satellites. Based on the equivalent current systems during the course of si$^-$ (derived from groundlevel magnetic recordings), they explained the complex waveform distribution of si$^-$ as due to the superposition of the effects of ionospheric currents associated with polar electric fields on the simple magnetic decrease produced by the expansion of the magnetosphere as a whole. Their study did not touch on the physical situation at the nightside dip equator. In this paper we present the results of a case study, for the first time, of ionospheric plasma motions at equatorial- low latitudes associated with si$^-$.

Experimental Technique

The current study is based on ionospheric observations at Kodaikanal (10.2°N, 77.5°E; dip 4°N), Lunping (25.0°N, 121.17°E) and Kure(34.25°N, 132.53°E). The experiment at Kodaikanal is a HF pulsed phase path

Paper number 95GL02669
0094-8534/95/95GL-02669$03.00

sounder that provides continuous data on the time rate of change of phase path or Doppler velocity, V_d of ionospheric reflections at vertical incidence with a time resolution of 6 sec [Sastri et al, 1985]. The experiments at Lunping and Kure are the conventional passive HF Doppler sounders that record the changes in the Doppler frequency shift of standard HF transmissions on oblique paths. At Lunping, standard frequency transmissions on 5.2 MHz and 7.8 MHz from three stations, Keelung, Hsintien and Shihmen are received. At Kure JJY transmissions on 5, 8 and 10 MHz from Nazaki are recorded with a sampling time resolution of 10 sec.

Observations and Discussion

The si^- studied here occurred on March 15, 1993 at $\approx$ 1541 UT. It is observed in groundlevel geomagnetic records of a number of stations widely distributed in latitude and longitude. Figure 1 shows the signature of the si^- at the low latitude stations, Alibag and Kakioka and the high latitude stations Glenlea, Cambridge Bay and Resolute Bay. It is clear from Figure 1 that the si^- possesses a double-pulse structure at the high latitude stations in the forenoon sector namely, Glenlea, Cambridge Bay and Resolute Bay (magnetic local time was between 0800 and 0900 at 1500 UT) unlike at low latitudes where it manifests as a simple decrease in the H- field.

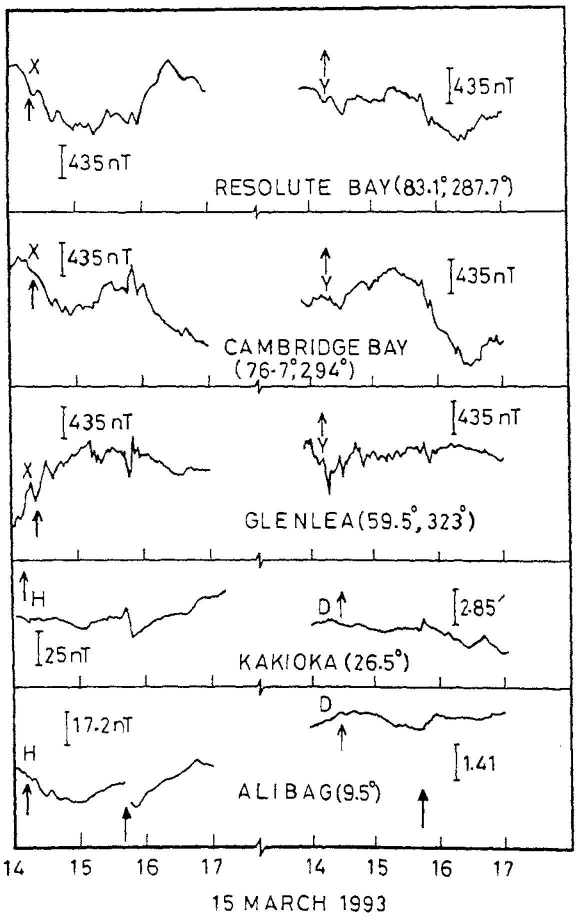

Figure 1. Geomagnetic negative sudden impulse (si^-) on March 15, 1993 as observed at low latitude and high latitude stations. Arrow on the time axis indicates the si^-. The geomagnetic dipole centered coordinates are given in the parentheses for the high latitude stations and the geomagnetic latitude for the low latitude stations.

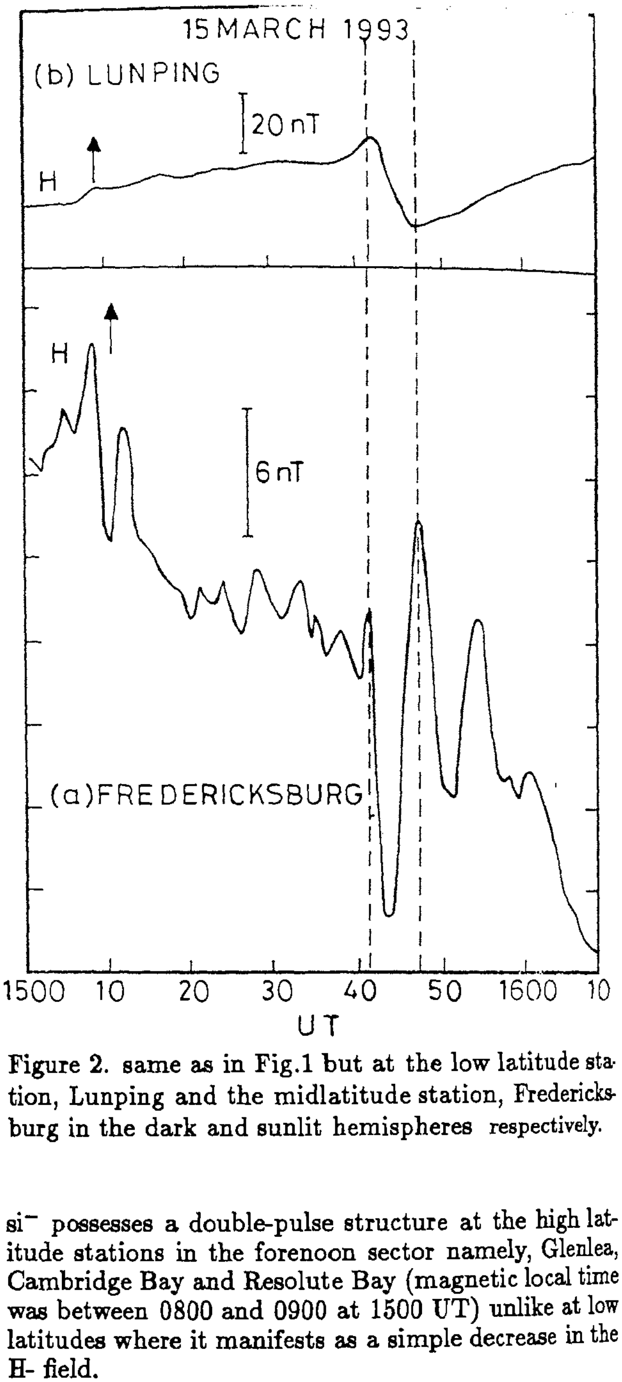

Figure 2. same as in Fig.1 but at the low latitude station, Lunping and the midlatitude station, Fredericksburg in the dark and sunlit hemispheres respectively.

Figure 2 shows the waveform of the si^- in H-field (based on 1 minute interval data) at Fredericksburg (Geomag.lat 49.41°N) in the sunlit hemisphere and at the low latitude station, Lunping (enlarged version of the original magnetogram) in the dark hemisphere. A simple decrease in H-field is also seen at the low latitude station, Vassouras (22.4°S, 43.65°W) in the sunlit hemisphere(courtesy, M. A. Abdu). The double-pulse structure of the si^- at Fredericksburg can clearly be seen from Figure 2. The waveform is such that the H-field at Fredericksburg reaches the minimum value earlier than at Lunping and then increases to a maximum higher than the initial value. The total duration of the si^- at Lunping is $\sim$ 6 min. The characteristics of the waveform distribution of the si^- of March 15, 1993 studied here are in broad agreement with those of the five successive si^- on July 6, 1977 analysed by

Araki and Nagano [1988]. We could not, however, confirm the double-pulse structure (short positive pulse followed by the main field decrease) of the si$^-$ at the dayside dip equator due to lack of access to such data. At Trivandrum (dip 0.6°N) near the nightside dip equator, the si$^-$ manifested as a simple decrease in H-field (not shown here) with an amplitude of 20.6 nT which is more or less the same as at low latitude stations (the amplitude of the si$^-$ was 16.4 nT and 21.2 nT at Alibag and Kakioka respectively).

Figure 3 displays the transient response of the low latitude nightside ionosphere to the si$^-$. Measurements at Kodaikanal near the nightside dip equator showed the F region vertical plasma drift, $V_z(=1/2V_d)$ to be downward just prior to the si$^-$ (curve with filled circles in Figure 3), as can be expected for the premidnight period. It is to be noted, however, that V_z derived from Doppler velocity, V_d represents the combined effect of vertical plasma motion due to ExB drift and a minor positive contribution from chemical loss. The effect due to chemical loss is negligible during evening/nighttime conditions provided the height of reflection is > 300 km [Bittencourt and Abdu, 1981]. Since the height of F region reflections over Kodaikanal was well below 300 km around the time of the si$^-$, the observed downward drift represents an underestimate because of the contribution of an apparent upward drift due to layer decay. Corrections for layer decay are therefore made to estimate the true values of V_z following standard procedure (see for example, Sastri et al, 1992). The upward vertical drift, V_β due to chemical loss = β L where β is the loss coefficient and L is the electron density scale length. L is determined from the ionograms of a co-located ionosonde and β is calculated from the expression of Thitheridge and Buonsanto[1983] using MSIS-86 model [Hedin, 1987] values of the neutral composition for the relevant geophysical conditions. The corrected values of V_z (continuous line in Figure 3a) show the average value of downward plasma drift to be 19.6 ± 2.6 m/sec over the interval 1503-1541 UT (2033-2111 IST) prior to the si$^-$. The average V_z and its standard deviation are shown in Figure 3 as horizontal lines and shaded for reference.

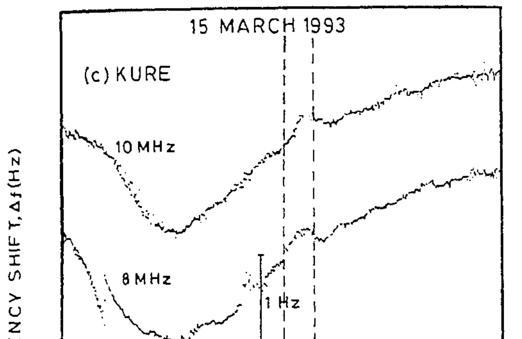

Figure 3. Time variation of F region vertical plasma drift, V_z (Doppler velocity, V_d) at the dip equatorial station, Kodaikanal and Doppler frequency shift of standard HF transmissions recorded at the low latitude stations, Lunping and Kure on oblique paths in the nighttime ionosphere(see text for further details). The vertical dashed lines mark the duration of the si$^-$ in low latitude magnetograms.

It is quite evident from Figure 3a that with the onset of si$^-$ at 1541 UT, the ambient downward drift over kodaikanal underwent a sudden enhancement over a period of ≈ 2.5 min, followed immediately by a reversal of direction to upward. The usual nighttime downward drift seems to have resumed around 1551 UT. The time of onset of the sudden enhancement in downward drift coincides with the preliminary impulse of the si$^-$ at mid and high latitudes as shown by the first vertical dashed line in Figure 3 (see also Figure 2). The short-lived perturbation in V_z over Kodaikanal thus indicates the presence of a transient westward electric field near the nightside dip equator at the time of the preliminary impulse of the si$^-$ and an eastward field thereafter. The amplitude of the westward (eastward) electric field is ≈ 1.0 mV/m (≈ 1.08 mV/m) corresponding to the segments marked XY(YZ) on the V_z curve in Figure 3a.

Doppler frequency recordings at Lunping and Kure (Figure 3b,c) corroborate and confirm the occurrence of a transient disturbance in vertical motion of the low latitude ionospheric plasma in the dark hemisphere. The Doppler frequency shift on all the paths at Lunping as well as Kure underwent first a rapid increase(indicative of downward plasma motion or westward electric field) and then a decrease (indicative of upward plasma motion or eastward electric field) in close temporal association with the vertical drift perturbation over Kodaiknal as can be seen from Figure 3. The fact that the sense and sequence of the frequency deviations(and therefore the plasma motions they imply) at Lunping and Kure are consistent with those evidenced at Kodaikanal bear testimony to their genuineness. Moreover, the larger amplitude of the disturbance in Doppler shift observed on the Shihmen-Lunping path on 7.8 MHz(0.71 Hz) than on 5.2 MHz(0.5 Hz) supports the interpretation of the frequency deviations in terms of vertical motions of the reflection point under the influence of electric fields. So also is the feature of a larger amplitude (and therefore better definition) in general of the frequency deviations at Lunping than at Kure. This is because other factors being equal, the vertical plasma drift due to an electric field of a given amplitude decreases with increase in dip angle being proportional to cos I where I is the dip angle. It is pertinent to add here that vertical plasma motion due to ExB drift is one of the three mechanisms generally invoked to explain HF Doppler observartions [e.g. Poole et al, 1988].

The present case study provides unambigious experimental evidence for the presence of a transient electric field disturbance of composite polarity in the low latitude nightside ionosphere at the time of si^-. The electric field disturbance is westward field at the time of the first pulse(negative at middle latitudes on the dayside) of the si^-, and eastward field thereafter corresponding to the second pulse (positive at midlatitudes) and the main decrease of H-field at low latitudes. According to Araki and Nagano [1988], the net consequence of the physical initiated by a sudden magnetospheric expansions is the imposition of a dawn-to-dusk electric field on the polar ionosphere by a pair of field-aligned currents (FAC). The dawn-to-dusk electric field, in turn, drives a twin vortex type ionospheric current system such that, as viewed from the north pole, the rotational sense of the current is clockwise on the morning side and is anticlockwise on the afternoon side. As per this scenario, the small positive pulse that precedes the main field decrease of si^- near the dayside dip equator can be understood as in terms of an extension to the equator of the afternoon current vortex as it can cause an eastward current. If this physical situation is valid, then, the extension of the morning current vortex to lower latitudes should produce a westward electric field at the dip equator and low latitudes on the nightside. The westward sense of the transient electric field disturbance evidenced at Kodaikanal, Lunping and Kure is, therefore, consistent with the current understanding of the physics of si^-.

The study of Araki and Nagano [1988] showed that the ionospheric current system associated with the second pulse of si^-it has the same pattern but opposite sense to that of the first pulse. The current system has been interpreted as the effect of reduced magnteospheric convection due to reduced dynamic pressure of solar wind. One can therefore expect an eastward electric field near the nightside dip equator and low latitudes at the time of the second pulse/ main field decrease of the si^-. This is precisely what is observed at Kodaikanal, Lunping and Kure with the si^- on March 15. 1993(see Figure 3). It is to be noted here that the amplitude of the main decrease in H-field of the si^- is more or less the same near the dip equator(Trivandrum) and at low latitude stations(Alibag and Kakioka) in the dark hemisphere. This is in sharp contrast to the dayside situation where the amplitude of the main component of si^- is greatly enhanced (by a factor of 3.27) at the dip equator when compared to low latitudes [Araki and Nagano, 1988]. We hypothesise that unlike on the dayside, where the contribution of the westward current associated with the second pulse leads to an enhanced amplitude of the si^- at the dip equator; on the nightside, because of the contribution of the eastward current, the amplitude of the main field decrease of si^- remains essentially the same near the dip equator and low latitudes.

Acknowledgements. One of the authors(JHS) is grateful to Dr Donald C. Herzog, Geological Survey, US Department of the Interior, Denver, Colorado, USA and Dr G. Jansen van Been, Canadian Observatories Network, Ottawa, Canada, for providing magnetic data of their respective stations for the study.

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

Araki, T., and H. Nagano, Geomagnetic response to sudden expansions of the magnetosphere, *J. Geophys. Res., 93,* 3983, 1988.

Araki, T., A physical model of the geomagnetic sudden commencement, in *Solar wind sources of Magnetospheric Ultra-low-frequency Waves Pulsations, Geophys. Monogr. Ser., Vol 81,* Edited by M. J. Engebretson, K. Takahashi and M. Scholer, p183, American Geophysical Union, Washington DC, 1994.

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.

Hedin, A. E, MSIS-86 The thermospheric model, *J. Geophys. Res., 92,* 4640-4662, 1987.

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.

Nishida, A., and J. A. Jacobs, Equatorial enhancement of worldwide changes, *J. Geophys. Res., 67,* 4937, 1962.

Poole, A. W. V., P. R. Sutcliffe and A. D. M. Walker, The relationship between ULF pulsations and ionospheric Doppler oscillations: Derivation of a model, *J. Geophys. Res., 93,* 14656, 1988.

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

Sastri, J. H., J. V. S. V. Rao and K. B. Ramesh, Penetration of polar electric fields to the nightside dip equator at times of geomagnetic sudden commencements, *J. Geophys. Res., 98,* 17,517, 1993a.

Titheridge, J. E. and M. J. Buonsanto, Annual variations in the electron content and height of the F layer in the northern and sothern hemispheres, *J. Atmos. Terr. Phys., 45,* 683, 1983.

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

J. Hanumath Sastri, Indian Institute of Astrophysics, Bangalore 560 034, India(e-mail: jhs@iiap.ernet.in).

Yinn - Nien Huang, Directorate General of Telecommunications, M.O.T.C, 31 Ai-Kuo E.Rd, Taipei, Taiwan, R.O.C.

T. Okuzawa and T. Shibata, Department of Electronic Engineering, Denki-tsushin University (UEC), 1-5-1, Chofugaoka, Chofu-shi, Tokyo 182, Japan.

(Received May 3, 1995; accepted July 8, 1995.)