Radio and Optical Signatures of Interplanetary Electric fields over the Dip Equatorial Upper Atmosphere

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***Abstract*—Radio and Optical techniques from both ground and space based platforms have been used to study the effect of prompt penetration electric field over the equatorial upper atmosphere. It has been observed, for the 'first time', that the effects of penetration electric fields are not restricted to ionosphere/thermosphere only, but also seen at the mesopause altitudes owing to the ubiquitous coupling therein. An unusual decrease in the thermospheric OI 630.0 nm dayglow and an intense heating (~30 K) at OH emission altitudes over a magnetic dip equatorial station, Trivandrum, India was observed on April 09, 2006 concomitant with penetration of a noon time westward interplanetary electric field. The SABER observations onboard TIMED satellite also revealed a conspicuous heating at mesopause during this period. The ionosonde and magnetometer observations vindicated presence of strong penetration electric fields. It is found that strong heating at the mesopause resulted in the intrusion of additional neutrals like N_2 into the emission altitudes which quenched the $O(^1D)$ atoms therein. The reduced Cowling conductivity at the E region inferred using magnetometer observations further corroborates this mechanism.**

***Index Terms*— Coupling, Dayglow, Prompt Penetration, Space weather.**

I. Introduction

THE prompt penetration electric fields (PPEF) and their effects in the ionospheric region over the equatorial and low latitudes have generated great scientific interest in recent years [1]. The effects of penetration events over the dynamo region were first reported using magnetometer observations [2]. Several studies since then have shown the impact of PPEFs over the F region using coherent/incoherent scatter radars [3] and ionosonde observations [4]. Simultaneous effects of PPEFs over E and F region of equatorial ionosphere have also been studied [5]. Although there are mounting evidences showing the signatures of PPEFs in the dynamo and F region over the equator/low latitude ionosphere, there had been no observation indicating, directly or indirectly, the effect of PPEFs in the mesopause region. In this context, an attempt is made using the radio and optical techniques from ground and based platforms to understand the effect of PPEFs over the dip equator. The study presents observations made on 9th April 2006, which are indicative of the manifestation of PPEFs, not only in the equatorial ionosphere-thermosphere system but also in the mesopause region. The paper also adduces the evidence for strong neutral heating in the mesopause and unusual quenching in the daytime OI 630.0 airglow emissions associated with the penetration events.

II. Experiments

The intensity of OI 630.0 nm dayglow emissions from the thermosphere and Hydroxyl OH (8-3) emissions at wavelengths 731.6 and 740.2 nm from the mesopause altitudes were measured using the unique Multi wavelength Dayglow Photometer (MWDPM), over the dip equatorial station Trivandrum (8.5° N, 77°E, dip 0.5°N), India. The comprehensive details of this system and data analysis procedure had been published elsewhere [6]. The mesopause temperature (MT) derived using the OH emissions over Trivandrum obtained from MWDPM and the temperature profiles estimated using CO_2 emissions at 15 μm measured through SABER onboard TIMED satellite were also analyzed for substantiating the results.

Simultaneous high cadence (~5 min.) measurements of the critical frequency (foF2) and peak height (hmF2) of the ionospheric F2 region were obtained using a collocated KEL-Digital ionosonde. The strength of the surface magnetic field measured every minute over Trivandrum (ΔH_{TVM}) an Equatorial Electrojet (EEJ) station and Alibag (ΔH_{ABG}) (18.6° N, 72.9° E, dip 12.8° N), an off-EEJ station have been used to obtain the variability associated with the EEJ. The symbols $\Delta H_{TVM/ABG}$ stand for the difference in the instantaneous values of horizontal component of magnetic field from its nighttime mean value for Trivandrum and Alibag respectively.

In order to assess the prevailing geomagnetic conditions on April 09, 2006 (Ap=46), the high resolution (~5 min.) data of interplanetary magnetic field (IMF Bz) and dawn-dusk component of interplanetary electric field (IEF) are used. These data were obtained using the OMNI data resource (http://omniweb.gsfc.nasa.gov/). The data have already been time shifted to account for the propagation delay of solar wind transiting from the location of the satellite at L1 point (~1.41 $\times 10^6$ km from Earth) to the earth's bow shock nosecone.

III. Geomagnetic Conditions

The penetration events discussed in this paper occurred on 9th April 2006 on the day side dip equator over the Indian longitudes. For the clear identification of the penetration

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events, the IMF Bz and dawn-dusk component of IEF are plotted along with the equatorial ionospheric parameters in Fig. 1.

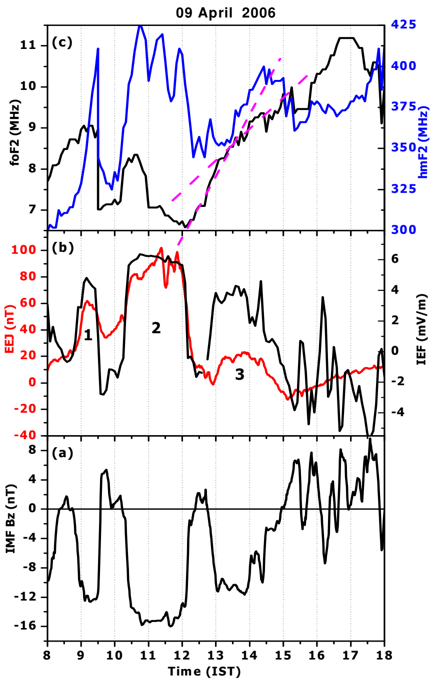

Fig. 1. Temporal variation of the equatorial ionospheric parameters (a) foF2 (MHz) and hmF2 (km) (b) EEJ (nT) along with the Interplanetary Electric field (mV/m) and (c)IMF Bz (nT) during the penetration event of April 09, 2006.

As is evident from the Fig. 1 a, the IMF Bz was oscillating south and northward during the day. Each southward/northward excursion of IMF corresponds to an enhancement of IEF Ey in the dusk ward/dawnward direction. The concomitant variation of the eastward and westward fluctuations in the interplanetary and equatorial zonal electric field during the period 08:30-15:30 IST vindicates the presence of prompt penetration.

IV. Results and Discussion

A. Response of ionosphere/thermosphere to the penetration event of 9th April 2006.

For convenience of description, the three prominent positive pulses in IEF and EEJ are marked as 1, 2 and 3. During the rising edge of the 1st pulse (~08:45 IST), an increase in hmF2 (Fig. 1c) was observed till ~09:30 IST, which is indicative of an eastward PPEF. The penetrated field increased the foF2 and hmF2 during this period through the upward E×B drift as is evident from the Fig. 1c. The ascend of the F2 layer to higher altitudes (~425 km) at ~09:30 IST produced an F3 layer. This resulted in the reduction of foF2 and hmF2 till 10:15 IST. The F3 layer was observed during the different time frames 09:25-10:30 and 10:50-11:15, when hmF2 reached to higher altitudes (~425 km) due to upward drift induced by the penetration electric field (not shown here). These observations are consistent with many of the earlier studies dealing with the formation of F3 layers associated with the PPEF from different longitudinal sectors [4], [5].

At ~10:15 IST, (in the rising edge of the 2nd pulse), the hmF2 increased up to 425 km and remained high till ~12:00 IST, indicating a possible eastward penetration. The PPEF initially increased the foF2 due to the upward E×B drift till 10:30 IST. Thereafter foF2 showed a decrease, which continued till 12:00 IST. This is due to the enhanced plasma diffusion along the field lines to off-equatorial latitudes owing to the fountain effect generated by the prevailing PPEF.

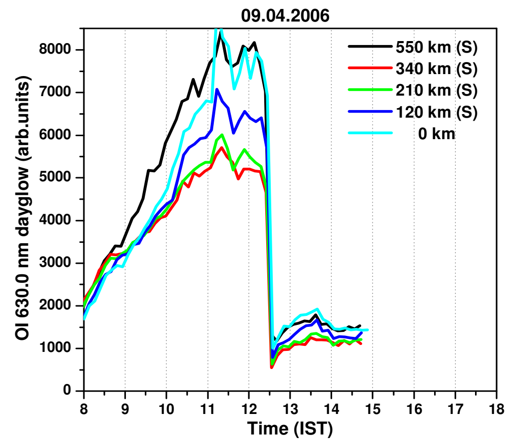

Fig. 2. Time evolution of equatorial OI 630.0 nm dayglow on 09th April 2006. Different colors represent the different horizontal distances in km from zenith sky (0 km) over Trivandrum in southern (S) direction.

In the falling edge of the 2nd pulse (~12:00 IST), the hmF2 showed a decrease which ensued till 12:30 IST, indicating that the penetration occurred in westward phase. This noon time westward penetration resulted in the negative fountain over equator, and an increase in foF2 through the reduced upward E×B drift. However interestingly, concurrent with the westward penetration electric field at ~12:00 IST, an unusual depletion of the OI 630.0 nm dayglow was observed as is shown in Fig. 2. In fact, this depletion was noticed at all elevations which continued the rest of the day too. It is quiet unexpected, as over the equator the temporal evolution of the OI 630.0 nm dayglow follows solar zenith angle superposed with electrodynamical variabilities at the emission altitudes (~150-300 km) [7]. The plausible mechanism for the present observations is discussed in the section IV.B.

During the 3rd pulse (13:00-15:00 IST), the eastward PPEF was experienced over equator as evidenced by the concomitant enhancement in hmF2 and EEJ during this period. Although, the enhanced plasma diffusion to off-equatorial latitudes during this penetration did not decrease the foF2, it reduced the rate of increase of foF2. This is obvious from the difference in the rate of change (slope) of foF2 before and after 13:00 IST, as is indicated using dotted magenta lines in Fig. 1c. Further decrease in the hmF2 during 15:00-15:30 IST indicates the presence of a westward penetration as the IMF Bz shows a northward turning during this period. Following this, the equatorial ionosphere behaved more or less similar to that on a normal day.

B. Plausible mechanism for the unusual response of OI 630.0 nm dayglow

As is known, the OI 630.0 nm dayglow is produced due to the (i) photoelectron impact of O (ii) photodissociation of O_2 and (iii) dissociative recombination of O_2^+ions [8]. It is understood that the first two processes follow solar zenith angle, and the temporal variability seen in this dayglow is mainly due to the third process which is closely correlated with the electron density at emission peak (~220 km) [9] over low latitudes. The first two processes are not expected to vary abruptly. Further our observations during the westward penetration at ~12:00 IST showed a clear-cut decrease in hmF2 and increase in foF2. This actually should have increased the dayglow intensity through the increase in dissociative recombination. Therefore, in the present case, the possibility of reduction in dayglow due to the electrodynamical effects can be excluded. Another possibility of the reduction in airglow intensity can be due to the change in the centroid of the emission. However the statistical analysis of WINDII measured $O(^1D)$ profiles revealed that the emission peak cannot go beyond 220 ±20 km [10]. Further one cannot comment on the emission altitude of the OI dayglow emission in the absence of $O(^1D)$ profiles over Trivandrum during this time. The third and important possibility of the depletion in OI 630.0 nm dayglow could be due to the quenching of $O(^1D)$ atoms, by the intrusion of additional molecular species like N_2 into the emission altitudes. However, the possibility of such a scenario will necessitate a strong heating at the thermospheric altitudes and lower below (for instance mesopause). In fact, many of the earlier studies have revealed prompt [11] and delayed [12] heating at thermospheric altitudes during the geomagnetic storms over equatorial/low latitudes.

In this context, in order to investigate the third possibility in more detail, we analyzed the simultaneously measured mesopause temperature (MT). Fig. 3 (top panel) depicts the temporal evolution of the optically estimated MT on April 09, 2006 obtained using the MWDPM. For comparison, the mean MT during the geomagnetic quiet days of April 2006 (Ap<7, Ap being the index representing the planetary level of geomagnetic disturbance) along with their standard deviations are also shown (thick yellow solid lines). As is obvious from the Fig., the mesopause exhibited significant heating (~30 K) after 12:15 IST, when the westward penetration occurred. The temperature was indeed as high as ~230 K, whereas on normal days it ranged between 180 and 210 K. The enhancement in MT as seen in the present case is conspicuous, as the dynamical forcing due to waves (gravity/planetary), tides and chemistry can induce a temperature difference only of the order 5-10 K. Nevertheless large changes in temperature (~30 K) were also observed using ground based/satellite measurements, but for special events like solar eclipse [13].

In order to further verify aforementioned mesopause heating, the SABER observations onboard NASA's TIMED satellite have also been looked into. These passes were at ~06:45 UT, which was 15 min after the penetration event. Fig. 3 (bottom panel) depicts these temperature profiles on April 09, 2006. The co-ordinates corresponding to the satellite observations are labelled on the left bottom corner of the Fig.. The same on the normal day (April 02, 2006) are averaged and plotted (thick yellow line) along with their standard deviations. The enhancement in temperature from SABER measurements is indeed as high as ~30 K for all the profiles on the event day throughout the altitudes ~87-97 km. This strongly corroborates the heating at mesopause as observed by the ground based MWDPM irrespective of the techniques used for the temperature estimation.

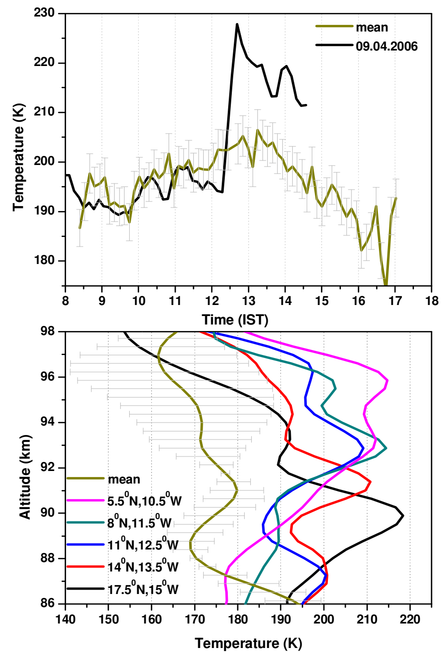

Fig. 3. The temporal variation of optically estimated mesopause temperature (MT) on the event day and the monthly mean temperatures during April 2006 along with their standard deviations (top panel). The SABER measured temperature profiles during the event over low latitudes along with the average of the same on the control day with their standard deviations (bottom panel).

However, the presence of additional neutrals over equator due to the heating at mesopause will decrease the conductivity of the E region through the increase in neutral-ion collisions. In this context, the magnetic field measurements at an EEJ station, Trivandrum (ΔH_{TVM}) and a station just outside the EEJ belt, Alibag (ΔH_{ABG}) can better yield this information. The rationale is that during penetration time, the variation which can arise in the current (J=σEx) induced magnetic field measurements is solely due to the changes in conductivity (σ). It is because the zonal electric field (Ex) is global in nature and should be the same over Trivandrum and Alibag due to the overshielding/ undershielding effects in the present case. Therefore, to understand the changes in conductivity during the westward penetration at ~12:00 IST on 9th April 2006, we have analyzed the time evolution of ΔH_{TVM} and ΔH_{ABG} separately and is plotted in Fig.4 (bottom panel) along with the same on a geomagnetically quiet day in Fig. 4 (top panel). As is evident from the Fig., on the normal day, a discrete difference in the ΔH values between Trivandrum and Alibag can be noticed throughout the day, which maximizes (~60 nT) at ~12:00 IST. This is due to the enhanced cowling conductivity over equator during noon time. Nonetheless, this is not the case on 9th April 2006, where the difference in the ΔH_{TVM} and ΔH_{ABG} exists only till 12:00 IST, thereafter it decreases. This indicates that the Cowling conductivity on this day at EEJ altitudes over Trivandrum drastically reduced at ~12:00 IST and thereafter. This clearly corroborates the idea that the intense heating at mesopause resulted in drastic decrease in conductivity at dynamo region, due to the intrusion of additional molecular species like N_2 from below. This inturn provides the basis for the unusual quenching of OI dayglow during the westward penetration time.

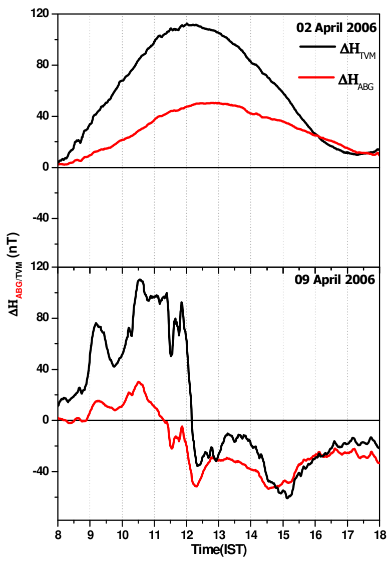

Fig. 4. The time variations of ΔH_{TVM} and ΔH_{ABG} separately on the event day plotted (bottom panel) along with those on a geomagnetically quiet day (top panel).

Although, conspicuous enhancement in MT associated with PPEF is explained in the light of present understanding of penetration effects over equatorial ionosphere-thermosphere system, considerable efforts are needed for the better understanding of storm time changes in the equatorial MLTI region. Nevertheless, the results which provided strong evidence for the effect of PPEF at equatorial upper atmosphere 'for the first time', are unique and we believe that it can have significant implications in the understanding of the effects of PPEFs over low/equatorial region. In a complementary point of view, the results also reveal the potential of multi wavelength dayglow spectro-photometry as a unique tool for investigating the space weather effects.

V. Concluding Remarks

The study adduces the effect of penetration events that occurred on April 09, 2006 over the equatorial MLTI region in the Indian longitudes using ground and space based measurements. The ionosonde/magnetometer observations revealed that the equatorial ionosphere responded to PPEFs almost instantaneously. The thermospheric OI 630.0 nm dayglow showed strong depletion associated with the noon time westward penetration. The study, 'for the first time', revealed a simultaneous heating (~ 30 K) in the mesopause. This heating created (a) a reduction in Cowling conductivity in the dynamo region over the equator as inferred using magnetometer observations and (b) unusual quenching of $O(^1D)$ atoms at the dayglow emission altitudes in thermosphere as measured using MWDPM. The results highlight the scope of the studies that deal with the concomitant variations originating from solar wind, interplanetary medium, and equatorial ionosphere/thermosphere extending down to mesosphere. These studies are deemed very important to get a comprehensive understanding of solar terrestrial coupling, particularly during geomagnetically disturbed periods.

Acknowledgment

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