Solar Flare imprints of Equatorial electrodynamics: An investigation using radio and optical techniques

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***Abstract*—This paper deals with the response of equatorial ionosphere-thermosphere system to the X3.8 solar flare of January 17, 2005 using the coordinated measurements of GPS derived Total Electron Content (TEC), OI 630.0 nm dayglow and magnetic field measurements over a dip equatorial station Trivandrum (8.5° N, 77°E, dip 0.5°N), in India. It has been observed that the Equatorial Electrojet (EEJ) as inferred using the ground based magnetometers and GPS derived TEC measurements show prompt enhancements during the peak flare, as expected. Interestingly, the temporal evolution of TEC at different latitudes revealed that, the X3.8 class flare produced significant weakening of the plasma fountain and hence in the Equatorial Ionization Anomaly (EIA). Further, the response of OI 630.0 nm dayglow during the flare is found to be strongly affected by the prevailing electrodynamics. The plausible physical mechanism for these effects are discussed in context of the current understanding of the neutral and electrodynamical coupling processes over the equatorial upper atmosphere.**

Keywords*—*GPS TEC, Equatorial Ionosphere, OI 630.0 nm dayglow, solar flare, Equatorial Ionization Anomaly (EIA)

I. INTRODUCTION

Recently, the solar flare effects and its repercussions on the electrodynamics of the equatorial ionosphere have got significant attraction across the globe [1]. Reference [2] has shown that Equatorial Ionization Anomaly (EIA) got significantly weakened during the flare due to the dominant role of electrodynamics than the photochemistry. Corroborating their results, recent simulation studies [3] showed that the ***E*×*B*** drift over equator weakens during the flare. This is consistent with the earlier observations of decrease in eastward electric field in the dynamo region [4]. However, in past both increase [3] and decrease [1] in the field-line integrated Hall-to Pedersen Conductivity ratio over equator had been reported.

Nevertheless, the effects of solar flare on the neutral thermosphere is not properly understood so far mainly due to the lack of observations. Although recent CHAllenging Mini satellite Payload (CHAMP) observations provided several new insights in this regard [2], they are normalized to a higher altitude of 400 km and have poor temporal resolution (~93 min) due to the inherent time for the satellite to revisit the same latitude and local time. Therefore the need for high cadence data from lower thermosphere is well appreciated.

TABLE I. GEOGRAPHIC CO-ORDINATES OF DIFFERENT STATIONS USED

Station	**Geographic Latitude**	**Geographic Longitude**
Delhi	28.75°N	77.25 °E
Bhopal	23.00°N	77.2°E
Hyderabad	17.5 °N	78.5°E
Bengaluru	13 °N	77.5°E
Trivandrum	8.5 °N	77°E

In this context, the ground based neutral thermospheric OI 630.0 nm dayglow emissions are ideal for investigating such ephemeral events like flare, as they emanate from the altitudes, where maximum EUV absorption takes place. These dayglow measurements over Trivandrum, in recent years have brought out many significant results pertaining to the equatorial upper atmosphere [1]. In the present work, an attempt is made to investigate the effects of X3.8 solar flare, which occurred on January 17,2005, over equatorial ionosphere thermosphere system, using combined high cadence measurements of thermospheric OI 630.0 nm dayglow, GPS measured ionospheric Total Electron Content (TEC) and the strength of Equatorial Electrojet (EEJ) Experiments

The high cadence (one minute) data of thermospheric OI 630.0 nm dayglow have been obtained using a unique Multiwavelength Dayglow Photometer (MWDPM), over a magnetic dip equatorial station Trivandrum (8.5° N, 77°E, dip 0.5°N), in India.. For studying the F region response to the flares, the TEC measured using GPS receivers at different stations covering the trough to crest location of the EIA in the Indian longitudinal sector are used. The station names and their coordinates used for this study are listed in Table 1. The flare effects in the dynamo region are studied using the one minute values of the strength of EEJ (i.e., $\Delta H_{TVM} - \Delta H_{ABG}$) obtained using the magnetometer observations over an equatorial station Trivandrum (TVM) and an off-EEJ station Alibag (ABG), where ΔH stands for the difference in the instantaneous values of horizontal component of magnetic field from its nighttime mean value. For the Flare characterization, high cadence measurements of the X ray (1-8 Å) flux obtained using GOES-10 (Geostationary Operational Environmental Satellite) and EUV flux (26-34 nm) obtained from the SEM (Solar EUV Monitor) onboard SOHO (Solar Heliophysical Observatory) are used.

II. RESULTS AND DISCUSSION

A. *Solar Flare Event of January 17, 2005*

As is clear from the Fig.1, both X-ray and EUV radiations showed a steep enhancement at ~15:15 IST reaching a maximum at 15:20 IST. It is long duration flare (~4 hour), which continued till ~17:30 IST. It is interesting to note that though the X-ray showed a single peak, a double peak has been observed in the EUV flux. The percentage enhancement in the EUV flux (difference in the EUV between the pre-flare and peak flare) is found to be 39%.

B. *Response of equatorial Ionosphere*

1) *Effects in the Dynamo region*

The time evolution of EEJ is plotted along with the flare radiations in Fig.1. In conjunction with the peak X-ray/EUV flux, a clear-cut and conspicuous enhancement of ~26 nT is seen in the EEJ, as expected.

2) *Effects in the F region*

Fig. 2 shows the temporal evolution of absolute VTEC and rate of change of TEC (rTEC) along with the X-ray/EUV flux variations during the period 12:30-18:30 IST for the station Bengaluru, obtained using a single PRN. A clear cut enhancement in both TEC and rTEC concomitant with the flare radiations can be noticed.

In order to address the effect of flare induced changes in the time evolution of EIA, the latitudinal distribution of TEC at every 30 minutes during the period 12:00-17:00 IST is shown in Fig. 3 (top panels). For comparison, the same for the control day (13th February 2005) is also shown in the bottom panels. A clear-cut development of anomaly has been observed on the control day. However, the evolution of the EIA, as seen in the TEC, on January 17, 2005 is found to be quite different.

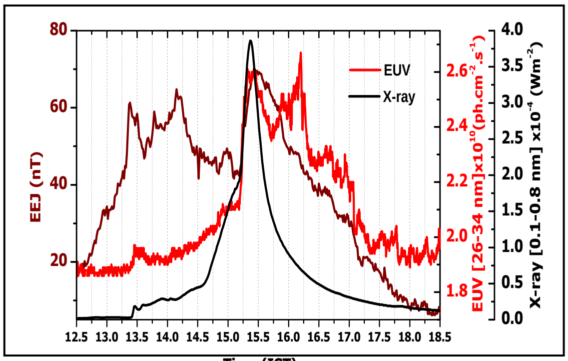

Fig.1. The daytime variation of the X-ray and EUV flux along with EEJ.

On this day, the anomaly development is found to be inhibited prior to the peak flare, suggesting that the relevant electrodynamical processes on this day had been rather weak or less intense. Nevertheless, the latitudinal distribution of VTEC at ~13:30 IST showed a gradual increase over the latitudes 12-20°, indicative of the development of the EIA. The subsequent profiles during the period 14:00-15:00 IST exhibited gradual growth of EIA, with the crest shifting systematically from latitudes 15° to 17°.

Although, the flare associated enhancement in the VTEC throughout the latitudes can be clearly seen on the profiles from 13:30 IST onwards, the additional increase in VTEC within 12-20° as compared with other latitudes clearly indicates the role of EIA associated electrodynamics. From 15:30 IST onwards, the anomaly again showed a significant weakening, which continued till 17:30 IST. Therefore during the flare period (flare peak time is 15:20 IST), inhibition of the EIA has been observed. These results are consistent with the recent observations using the CHAMP, where a significant weakening of the EIA associated plasma fountain has been reported during the X17 flare event on 28th October 2003 [2].

In order to understand the causative mechanism for the observed temporal variability in the EIA, the time variations of EEJ on both the flare and control days are shown in Fig. 4. As is clear from the Fig., a negative excursion has been observed in the EEJ on the flare day, till ~11:00 IST.

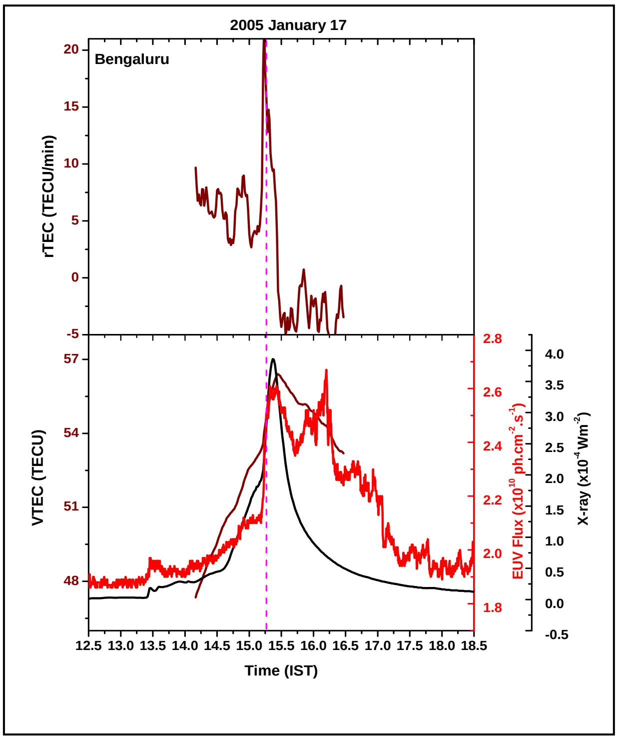

Fig.2. The Time evolution of VTEC variations obtained for a particular PRN at Bengaluru on January 17, 2005 along with the X-ray and EUV flux (bottom panel) .Top panel shows the rate of change of TEC. The dotted line (magenta) indicates the peak in the rTEC.

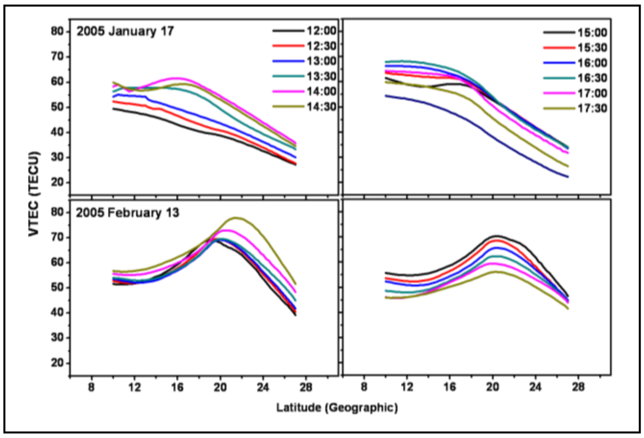

Fig.3. Latitudinal variation of VTEC during the period 12:00-17:30 IST on January 17, 2005 (top panels) in comparison with the same for control day.

A substantial decrease in the EEJ till ~13:00 IST can be noticed on the flare day in comparison with that on the control day. In an earlier study, it has been shown that on the flare day, the development of anomaly was inhibited till 13:00 IST owing the effect of the disturbance dynamo [6]. Therefore the weakening of the anomaly during the pre-flare period (12:00-13:00 IST), can be attributed mainly to the westward electric field associated with disturbance dynamo. However, the development of anomaly crest during the period 13:30-15:00 IST necessitates the presence of an eastward electric field. The positive excursion of EEJ from 13:00 IST and increase in the EEJ due to the increase in solar wind pressure at ~13:30 IST (not shown here), indicates the presence of an eastward electric field. This eastward electric field enhances the plasma fountain and hence the anomaly after certain period, as there involves a characteristic delay (30-90 minutes) between EEJ and EIA.

However, after the pressure induced enhancement at ~13:20 IST, the EEJ followed a similar pattern as that of the control day with an additional enhancement due to the flare induced radiations. This suggests that from 15:30 onwards, the EIA should either grow in a similar pattern as that of the control day or should develop further due to the additional positive amplitudes seen in the EEJ. Interestingly, contradictory to the expected behavior, it is found that the EIA got completely suppressed from 15:30 onwards which continued the rest of the day. This strongly corroborates the flare associated weakening of the EIA as reported in the recent study [2]. This weakening of EIA is believed to be associated with the reduction in the eastward electric field due to the flare. As is well known, the flare is expected to cause the rapid change in the conductivity, especially in the vertical direction. This in turn affect the ratio of Hall to Pedersen conductivity, which is a crucial factor in regulating the dynamo electric field. As the present case is an X3.8 class flare, it can increase the conductivity (particularly below 100 km), due to the increase in ionization at D region by the X-rays. This inturn can decrease the zonal electric field depending on the vertical polarization electric field and ratio of the Hall to Pedersen conductivity. Similarly the height varying winds in the vicinity of the dynamo region due to the formation of a highly conducting layer because of the flare can also modulate the zonal electric field [2]. Therefore the flare induced change in the EIA can be attributed to the combined effect of the photochemistry and the electrodynamics related to the plasma fountain.

C. *Response of equatorial thermosphere*

To further investigate the thermospheric response of the X3.8 flare on January 17, 2005, the time variation of the OI 630.0 nm dayglow on this day during the period 12:00-18:00 IST is plotted in Fig. 5 (bottom panel). For comparison, the same on a control day (January 25, 2005) is also plotted in the same panel. As is clear from the Fig., three distinct signatures (highlighted using circles) on January 17, 2005 can be observed during this period as compared with the normal day's behavior. As there were significant variabilities in both EEJ and flare radiations during this time, these signatures are attributable to the combination of the flare induced changes and electrodynamics as described below.

As mentioned earlier, the eastward electric field increased at ~13:20 IST due to the increase in the solar wind dynamic pressure. The associated development of EIA as shown in Fig. 4 further confirms this aspect. This results in the pumping of more ionization over the equator due to the upward $\boldsymbol{E}\times\boldsymbol{B}$ drift. This increases the number of effective dissociative recombination at the emission altitudes due to the pumping of enhanced ionization in the emission region. This inturn increases the airglow intensity over Trivandrum as seen in the present case. Therefore the increase in airglow intensity, a few minutes after the increase in the EEJ at ~13:20 IST can be attributed to the prevailing eastward electric field. This increase in dayglow continued till ~14:30 IST, and showed an abrupt decrease at ~14:45 IST, which persisted till ~15:00 IST. The reduction in the dayglow intensity during the period

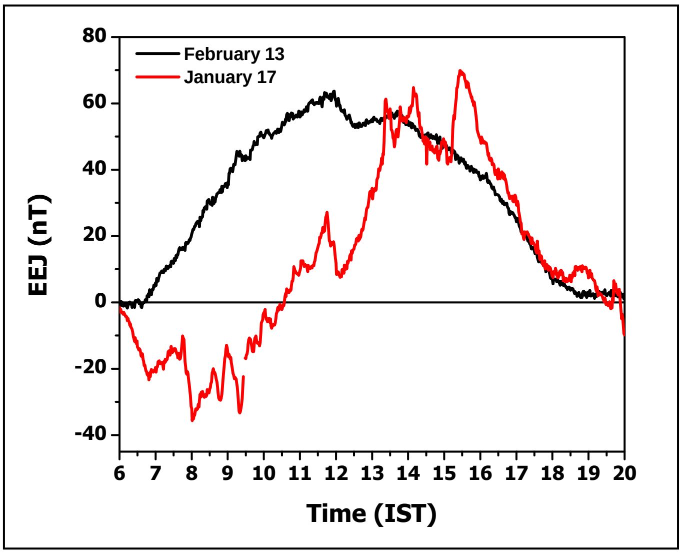

Fig.4. The time variation of EEJ on January 17, 2005 as compared with the control day.

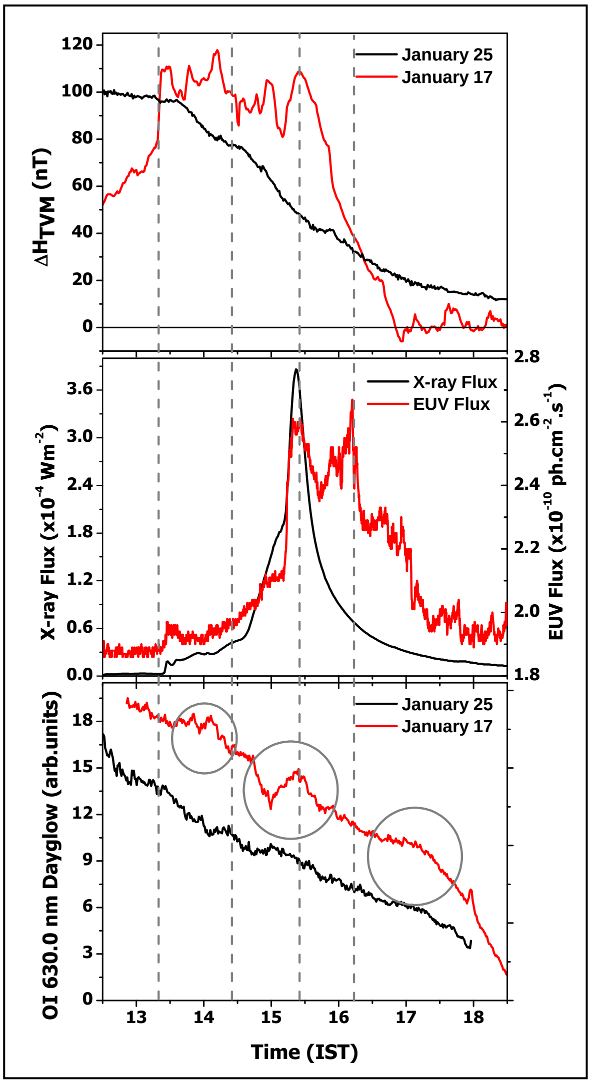

Fig.5. The top panel shows the time variation of OI 630.0 nm dayglow on January 17, 2005 along with that of a control day. The middle panel shows the time variation of flare radiations. The top panel indicates the time variation of ΔH at Trivandrum for the flare and control day.

14:30-15:00 IST can be attributed to the decrease in the effective recombination at the emission altitudes due to the transport of more ionization density from equator to off-equatorial latitudes because of the prevailing eastward electric field. Following this, the dayglow intensity increased concomitant with the X-ray/EUV radiations during the flare event. This increase in dayglow, which showed a peak at ~15:30 IST is attributed to the increased $O(^1D)$ production during the flare time due to all the three production mechanisms, viz, photo electron impact of O, photo dissociation of O_2 and dissociative recombination of O_2^+, as discussed in [1].

However, the dayglow did not show any appreciable signature associated with the secondary peak in the EUV flux. This is due to the fact that, during this period the EEJ started to recover and flare associated westward electric field, as discussed early, started dominating. This weakened the plasma fountain over equator, and filled more ionization over equator. This further increased the ionization at the emission altitudes, resulting in an increase in the dayglow intensity. Thus the electrodynamics associated plasma dominated over equator, diminishing the flare induced peak in the dayglow intensity. The further enhancement in the dayglow intensity during the period 16:30-17:30 IST can be attributed to the subsequent weakening of plasma fountain as is evident from the Fig. 3. However, the delayed enhancement in the dayglow due to the time delay in the charge exchange of O_2+O^+ reaction, as well as the delayed response of neutral density during the flare cannot be precluded in this context.

III. Concluding Remarks

The study adduces the effects of X3.8 flare of January 17, 2005 over the equatorial upper atmosphere using combined radio and optical measurements. Prompt responses have been noticed in the magnetic field inferred EEJ and GPS measured TEC measurements. The latitudinal distribution of TEC revealed a substantial reduction in the EIA. This is consistent with the earlier observations [2], and suggests that the flare induced radiation has altered the ratio of Hall to Pedersen conductivity and subsequently resulted in the weakening of the eastward electric field. Although, the thermospheric dayglow revealed concomitant enhancement during the peak flare period, did not show any enhancement associated with later increase in the flare (EUV) radiation. This suggests the dominant role of electrodynamical imprints of these dayglow features when compared with the photochemistry.

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