URSI AP-RASC 2019, New Delhi, India; 09 - 15 March 2019

Response of the southern polar ionosphere to St. Patrick's day storms of 2013 and 2015.

Shreedevi P. R.(1), Raj Kumar Choudhary(1), Smitha V. Thampi(1) and Sneha Yadav(1)
(1) Space Physics Laboratory, Vikram Sarabhai Space Center, ISRO, Trivandrum, 695022

Abstract

The occurrence of geomagnetic storms on the St. Patrick's Day (17 March) during two different years (2013 and 2015) with similar solar flux levels provided an unique opportunity to compare and contrast the responses of the terrestrial Magnetosphere-Ionosphere (MI) system to different levels of geomagnetic activity. In this paper, the response of the southern polar ionosphere to these events has been studied using GPS derived Total Electron Content (TEC) and Defence Meteorological Satellite Program (DMSP) satellite measurements. During the main phase of both the storms, significant enhancements in the TEC and phase scintillation were observed at the polar cusp station, Bharati near magnetic midnight. The magnitude of the midnight increase in the TEC on 17 March 2015 was significantly higher compared to that on 17 March 2013 despite both being at the same level of solar activity. The larger enhancement in the TEC near the magnetic midnight during the storm of 2015 is caused by the enhancement of the Tongue of Ionization (TOI) by steady convection resulting from long-lived magnetopause erosion. The same was weaker during the St. Patrick's day storm of 2013 due to the fast fluctuating nature of IMF B_z. We show that the differences in the duration of magnetopause erosion and the related changes in the MI system led to the varied response of the southern polar ionosphere during the St. Patrick's day storms of 2013 and 2015.

1 Introduction

The origin of geomagnetic storms and their impact on geospace has been studied by many in the past. Nevertheless, a complete understanding of the physical processes involved in the Solar Wind-Magnetosphere-Ionosphere (SWMI) coupling has been difficult to acheive because the event-to-event differences and the dependence of the degree of response of the ionosphere on factors like solar cycle, time of year and the time of day are involved. In this context, the St. Patrick's day storms of 2013 and 2015 provide an unique opportunity to understand how two distinct events of different intensities and nearly identical commencement times, occurring when the background conditions on the Sun and the Earth are almost similar, affects the polar ionosphere. The St. Patrick's day storm of 2015, the largest storm of the 24th solar cycle with Dst index reaching a minimum value of -238 nT, has been a subject of several investigations [1]. It is reported that the differences in the magnetic field geometry, changes in the O/N_2 ratio and IMF B_y component gave rise to hemispheric asymmetries in the ionospheric response on this day [2].In the same solar cycle, another intense storm (minimum Dst $\sim$ -130 nT) occurred on the St. Patrick's day of 2013. Large enhancements in the magnetic field associated with substorm injections were observed using Van Allen probes on this day [3]. The response of the ionosphere over the northern hemisphere during both these storms has been studied extensively while the southern hemispheric polar region, on the other hand, has remained relatively unexplored. In this paper, we study the relative impact of the St. Patrick's day storms of 2013 and 2015 on the plasma density distribution over the southern polar region.

2 Data and Methodology

The response of the southern polar ionosphere to the St.Patrick's day storm events has been studied using the GPS TEC measurements from the southern polar stations, Bharati, Davis and Casey. The Slant TEC (STEC) obtained at an interval of 1-min have been converted into vertical TEC (VTEC) using the standard mapping function. Only those satellites having an elevation angle greater than 30° and lock time greater than 240 seconds are used in this study. The phase scintillation index (σ_ϕ) at Bharati averaged over 60-second intervals are used to study the scintillation activity. The VTEC data from the Antarctic stations Davis (68.5°S, 77.9°E; 76.2°S Mlat) and Casey (66.2°S, 110.5°E; 76.0°S Mlat) were obtained from the IGS website (ftp://cddis.gsfc.nasa.gov) and processed using GPS-TEC application (http://seemala.blogspot.com/). Daily Differential Code Biases (DCB) for satellites and receivers are obtained from the CODE IGS Analysis Centre (ftp://ftp.unibe.ch/aiub/CODE/).

The solar wind, interplanetary and geomagnetic parameters used to study the evolution of geomagnetic storm are obtained from the CDAWeb (http://cdaweb.gsfc.nasa.gov). *In situ* measurements of plasma density and cross-track velocity components by DMSP satellites at an altitude of 850 km have been used to study the signatures of particle precipitation, Sub-auroral Polarization Streams (SAPS) and the Tongue of Ionization (TOI). The DMSP ion drift meter and the DMSP SSUSI measurements used in this study are obtained from the NOAA data center (http://www.ngdc.noaa.gov/stp/satellite/dmsp/) and the JHU/APL website (http://ssusi.jhuapl.edu/) respectively. We have also used observations by the Special Sensor Ultraviolet Spectral Imager (SSUSI) instrument onboard DMSP F16 to study the auroral activity.

3 Geomagnetic conditions

The geomagnetic storm on 17 March 2013 started with the Sudden Storm Commencement (SSC) at 0600 UT. Although the SSC during the St.Patrick's day storm of 2015 took place an hour before the SSC on 17 March 2013, the onset of the main phase of both the storms was at 0600 UT. The nature of variation of SymH index was also quite similar in both the cases till it reached the first minimum at 1000 UT. During the entire duration of the main phase, the AE index remained high indicating intense heating taking place at the polar latitudes.

4 Response of the polar ionosphere

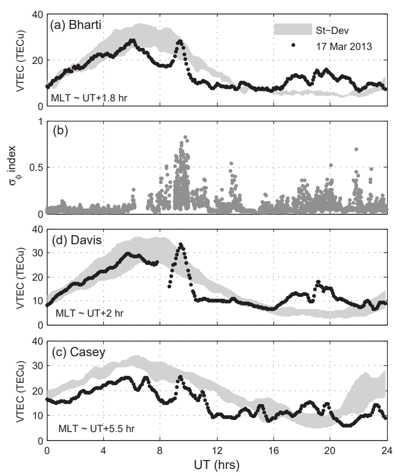

Figure 1. Panels (a) and (b) represent the diurnal variation of TEC and σ_ϕ index, over Bharati on 17 March 2013. Panels (c) and (d) represent the diurnal variation of TEC over Davis and Casey stations on 17 March 2013. The black curve in panels (a), (c) and (d) represent the variation in TEC on the day of the storm and the gray shade represents the quiet day standard deviation.

To examine how the ionosphere over the southern polar region responded to the St.Patrick's day storms of 2013 and 2015, we present the diurnal variation of TEC at the Antarctic stations, Bharati, Davis and Casey in panels (a), (c) and (d) of Figure 1 respectively. The immediate effect of the commencement of the geomagnetic storm on this day can be seen as a sudden decrease in the TEC starting at 0600 UT at all the three stations. A striking feature is the enhancement in TEC at two distinct time zones. The first sharp enhancement in TEC is observed at around 1000 UT. A second enhancement in the TEC of $\sim$10 TECu appeared during $\sim$16:00-22:00 UT at Bharati, Davis and Casey as well. These abrupt surges in TEC during the two time periods coincided with enhanced levels of phase scintillation activity at Bharati as shown in panel (b) of Figure 1. An interesting thing to note is the timing of the increase in the TEC. While the first increase in the TEC is seen at around 10:00 UT (15:30 LT), a post solar noon period; the second enhancement at 20:00 UT (03:30 LT) corresponds to the post solar midnight.

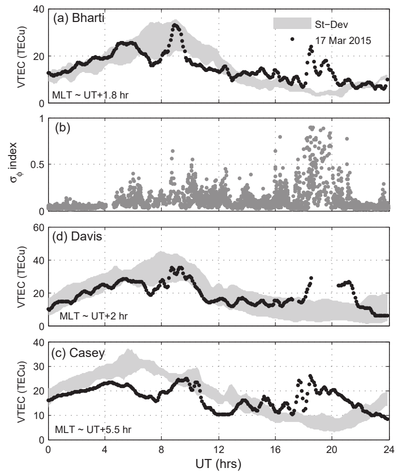

Figure 2. Same as Figure 2, but for 17 March 2015.

Similarly, panels (a), (b) and (c) of Figure 2 presents the diurnal variations in the TEC on 17 March 2015 at Bharati, Davis , and Casey. Alike the case on 17 March 2013, a sudden decrease in the TEC is observed at all the three stations on 17 March 2015 following the commencement of geomagnetic storm at $\sim$0600 UT. An important feature to note is the large enhancements in the TEC ($\sim$20 TECu) observed around 1900 UT at Bharati, Davis, as well as at Casey. Such a huge increase in the plasma concentration is intriguing as it happens during the time when the station is located in the night sector, quite bereft on solar radiation. This increase in TEC at Bharati is also seen to coexist with higher values of σ_ϕ index ($\sim$0.9) indicating high scintillation activity. A comparatively smaller enhancement in the TEC that remains well below the upper bound of 1-σ can be seen at $\sim$0900 UT at all the three stations on this day. We may note that the TEC over all the three stations on 17 March 2015 appears to vary in a similar fashion to that observed on 17 March 2013. Although, the surges in TEC appeared at similar time intervals suggesting that the M-I system behaves in a similar manner for equivalent geophysical conditions, the magnitude of enhancements in the TEC on both the days were different. This feature is discernible over Bharati, Davis (despite the data gap), and Casey stations, during both the events. It is also clear from the comparison that the midnight enhancement in TEC and phase scintillations on 17 March 2015 is substantially larger as compared to that observed on 17 March 2013. The differences in magnitude could be a result of the variabilities in the electrodynamics of the polar ionosphere arising from the differences in the solar wind and magnetospheric conditions that existed during these events. We discuss this aspect in detail in the subsequent section.

4.1 Plausible reasons for the response of the TEC

To investigate the reasons for the enhancements in the TEC at Bharati, Davis and Casey during the St.Patrick's day storms of 2013 and 2015, we examined the ion density, cross-track velocity and the auroral images of the southern polar ionosphere obtained from the DMSP F16 satellite [not shown here]. On 17 March 2013, the cross track velocity and ion density as measured by the DMSP satellite showed large sunward plasma velocity (upto $\sim$3000 m/s) to be colocated with regions of SED. This is a signature of the SAPS electric field [4], under the action of which large ion fluxes of magnitude $\sim$5x10^{13} m^{-2} s^{-1} were seen to be flowing in the sunward direction. Strong antisunward velocities ($\sim$1000 m/s) accompanied with antisunward stream of plasma of flux density as high as $\sim$-5x10^{13} m^{-2} s^{-1} were found in the polar cap region around 19:40 UT on 17 March 2013. Likewise, on 17 March 2015 also, large sunward flow velocities of upto $\sim$2000 m/s were observed at around 43° S Mlat. Enhanced ion flux of magnitude $\sim$1x10^{14} m^{-2} s^{-1} were measured in the sunward direction at these latitudes. At around 1840 - 1910 UT on 17 March 2015, enhanced ion flux with antisunward velocities of upto 1000 m/s and magnitude $\sim$-1.5x10^{14} m^{-2} s^{-1} were seen to be flowing in the antisunward direction across the polar cap

On both the St.Patrick's day of 2013 and 2015, the ionospheric/plasmaspheric plasma is seen to drift in the sunward direction towards the noontime cusp under the action of the SAPS electric field. The SED plumes, thus transported towards the polar cusp, is known to form a tongue of high density plasma extending across the polar cap and into the nightside region [4]. The three stations under consideration were seen to be in the path of the TOI, since they are in the vicinity of the noontime cusp around 1000 UT [as seen in the Superdarn convection maps, not shown here]. All the three stations were located in the vicinity of such a high density stream of plasma that is flowing in the antisunward direction. Hence, the nighttime enhancement in TEC observed at all the three stations on both the storm days could be associated with this stormtime TOI. It has been shown that the TOI may break into polar cap patches while convecting through the polar cap [5] and form the source of ionospheric irregularities. Our results also demonstrates the presence of intense phase scintillation activity over Bharati which is seen to be associated with the abrupt enhancements in TEC. Increased particle precipitation in the cusp region and strong ionospheric convection during the St.Patrick's day storms could also give rise to irregularities in the polar ionosphere [5].

The expansion/contraction of the auroral oval and brightening of the aurora were also inferred using SSUSI images (not shown here) obtained from DMSP satellites during both these storms. On 17 March 2013, before the commencement of the storm, the brightness of the aurora was very weak, commensurate with geomagnetically quiet periods. The auroral oval which was centered around 70° MLAT at 0805 UT, expanded and reached to lower latitudes (60° MLAT) by 0947 UT. The 2015 storm event, however, had more dramatic ionospheric effects. The polar cap expanded upto 50° MLAT on 17 March 2015. Strong auroral emissions and complex flows were observed during a better part of the storm duration which indicates significant energisation of the southern polar ionosphere on 17 March 2015. In contrast, the auroral emissions on 17 March 2013 were much weaker, perhaps due to the fluctuating nature of the IMF B_z. Over the southern hemisphere on 17 March 2015, the appearance of the most extended aurora (equatorward boundary at $\sim$50°MLAT) in association with intense particle precipitation and strong electrojet currents corresponds to dayside magnetopause erosion [1]. The polar cap remained expanded and the auroral oval extended upto 55° MLAT on 17 March 2015. This is a signature of magnetic reconnection of field lines taking place at regions closer to the Earth. The changes in the solar wind conditions and the orientation of IMF B_z controls the magnetopause standoff distance which is a signature of magnetopause erosion [1].

The magnetopause standoff distances during 16-18 March 2013 and 16-18 March 2015, calculated to the first order by using the pressure balance equation described by [6], is presented in panels (a) and (b) of Figure 8 along with the IMF B_z. At about 0600 UT on 17 March 2013, the magnetopause is seen to have moved earthward ($\sim$8 R_E) in response to the southward turning of IMF B_z. As the IMF B_z turns southward, magnetic reconnection drives the erosion of magnetic flux and the magnetopause moves earthward in order to maintain the balance between the solar wind and the magnetospheric pressure [6]. At the point of minimum B_z, i.e., around 1000 UT on 17 March 2013, the magnetopause moved further closer to $\sim$7 R_E. During the 17 March 2015 storm also, the magnetopause was pushed to $\sim$7 R_E in response to the southward turning of IMF B_z and remained around $\sim$7-8 R_E for $\sim$6 hours after the onset of the main phase of the storm. A second southward turning pushed the boundary further earthward to $\sim$6 R_E at about 1200 UT.

It is clear that during the geomagnetic storm of 17 March 2015, the magnetopause erosion sustained for a much longer time ($\sim$13 hours) as compared to that on 17 March 2013, wherein the magnetopause was seen to revert back to its original position within $\sim$3 hours after the onset of the main phase. In contrast, as the IMF kept on changing its polarity on 17 March 2013, the dayside reconnection would have decreased leading to the reverting of the magnetopause distance within $\sim$ 3 hours from the onset of the main phase. The FACs and particle precipitation weakens under such conditions. It is suggested that these differences in the duration and extent of magnetopause

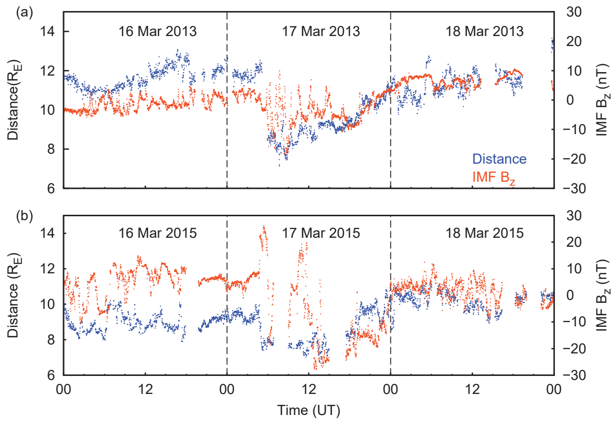

Figure 3. Panels (a) and (b) represent the temporal variation of the magnetopause along with the IMF B_z during 16-18 March 2013 and 16-18 March 2015. The blue and red dots represent the magnetopause standoff distance and the IMF B_z respectively. The black vertical lines indicate change of day.

erosion, cause the observed changes in the dynamics of the polar cap and auroral oval during the St.Patrick's day storms of 2013 and 2015 discussed in the previous section. In this context, the large enhancement in TEC observed during the St.Patrick's day storm of 2015 is proposed to be a result of the continuous enhancement of the polar TOI due to steady convection and particle precipitation. The same for the St.Patrick's day storm of 2013 was weak and short-lived due to the fast fluctuating nature of the IMF B_z.

5 Summary and Conclusions

The response of the southern polar ionosphere to the St.Patrick's day storms of 2013 and 2015 is studied using measurements from ground based GPS TEC receiver and DMSP satellites. We find that TEC response at polar cusp latitudes is largely a function of the disturbance onset time. Enhanced ionospheric convection and associated formation of polar cap patches give rise to intense phase scintillations in the polar cusp and the polar cap ionosphere. Particle precipitation and ionospheric flows were excited due to prolonged magnetopause erosion and the occurrence of multiple substorms. The continuous enhancement of the polar TOI under the action of steady convection gave rise to a large enhancement in TEC in the polar cap region on 17 March 2015. This was not the case during the St. Patrick's day storm of 2013 mainly because magnetopause erosion is sustained for a much shorter period due to fluctuating IMF B_z. This study highlights the fact that the behaviour of the polar ionosphere is strongly influenced by the magnetospheric dynamics, and the duration of magnetopause erosion is an important parameter which controls the electrodynamics of the magnetosphere and spatio-temporal evolution of the various stormtime processes in the polar ionosphere.

6 Acknowledgements

This work is supported by the Indian Space Research Organization (ISRO), Department of Space, Government of India. The GPS data from Bharati used in the paper has been collected as a part of the Polar Research Program of the Space Physics Laboratory(SPL), VSSC, ISRO and can be made available on request to R.K. Choudhary (rajkumar_choudhary@vssc.gov.in).

References

[1] G. Le, H. Luhr, B. J. Anderson, R. J. Strangeway, C. T. Russell, H. Singer, J. A. Slavin, Y. Zhang, T. Huang, K. Bromund, P. J. Chi, G. Lu, D. Fischer, E. L. Kepko, H. K. Leinweber, W. Magnes, R. Nakamura, F. Plaschke, J. Park, J. Rauberg, C. Stolle, and R. B. Torbert, "Magnetopause erosion during the 17 March 2015 magnetic storm: Combined field-aligned currents, auroral oval, and magnetopause observations," *Geophys. Res. Lett.*, vol. 43, pp. 2396–2404, 2016.

[2] E. Astafyeva, I. Zakharenkova, and M. Forster, "Ionospheric response to the 2015 St.Patrick's Day storm: A global multi-instrument overview," *J. Geophys. Res.*,, vol. 120, 2015.

[3] J. C. Foster, P. J. Erickson, D. N. Baker, S. G. Claudepierre, C. A. Kletzing, W. Kurth, G. D. Reeves, S. A. Thaller, H. E. Spence, Y. Y. Shprits, and J. R. Wygant, "Prompt energisation of relativistic and highly relativistic electrons during a substorm interval: Van Allen Probes Observations," *Geophys. Res. Lett.*, vol. 41, 2013.

[4] J. C. Foster, A. J. Coster, P. J. Erickson, F. J. Rich, and B. R. Sandel, "Stormtime observations of the flux of plasmaspheric ions to the dayside cusp/magnetopause," *Geophys. Res. Lett.*, vol. 31, no. L08809, 2014.

[5] J. J. Sojka, M. D. Bowline, R. W. Schunk, D. T. Decker, C. E. Valladares, R. Sheehan, D. A. Anderson, and R. A. Heelis, "Modeling polar cap F-region patches using time varying convection," *Geophys. Res. Lett.*, vol. 20, p. 1783, 1993.

[6] E. C. Roelof and D. G. Sibeck, "Magnetopause shape as a bivariate function of interplanetary magnetic field bz and solar wind dynamic pressure," *J. Geophys. Res.*, vol. 98, pp. 421–450, 1993.