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Low latitude ionospheric variations during geomagnetic storms measured using ROCSAT-1 satellite observations

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In the present paper the response of ionospheric parameters- ion densities and ion temperature (H^+, O^+ and Ti) to a weak (30 July 1999) and a moderate (13 November 1999) geomagnetic storm (GS) at low latitude Indian region using observed and modelled values has been analyzed. The study has been carried out by using ROCSAT-1 satellite data over the region encompassed between 5-35º geog N and 65-95º geog E at an average altitude ~ 600 km. A comparative study has also been done with the IRI-2016 modelled values. The ionospheric plasma parameters have shown anomalous behaviour during disturbed days in comparison to the quiet days. For the weak GS, both the average O^+ and H^+ density have been increased by a factor of around 1.8 during disturbed and quiet days respectively as calculated by ROCSAT-1. For the moderate GS, the average O^+ and H^+ density has been increased by a factor of around 2.7 and 6.3 respectively during disturbed and quiet days respectively, as calculated by ROCSAT-1. And the least or negligible variation has been observed in Ti for both measured and modelled values during weak and moderate GS.

Keywords: Geomagnetic storm, Ionospheric parameters, F2 region ionosphere, low latitude, satellite measurements, IRI-model

1 Introduction

The study of ‘geomagnetic storm (GS) effects’ falls under one of the most significant research areas, while learning about the solar-terrestrial environment. The above study is important due to the following reasons. Firstly, the ionosphere acts in a very complex manner during the geomagnetic storm[1]. Secondly, Geomagnetic storms affect the solar-terrestrial environment, the ground-based communication systems, ionospheric radio propagation, and military and commercial operations[2-3]. Thirdly, it also helps in improving the prevailing ionospheric models. Thus, the study of ‘geomagnetic storm’s effects’ on ionospheric parameters has become a necessity.

The Earth's outer space atmosphere known as the magnetosphere is an extremely energetic configuration that responds dramatically to solar activities. When an enormous amount of solar energy exchange takes place at the magnetosphere, the geomagnetic field gets disturbed which persists for a long interval of time and consequently, a GS is said to occur. They generate perturbations in neutral composition, enhanced electric fields, currents, and can produce heating in theionosphere-thermosphere system[4-9]. The primary sources causing GS are Coronal Mass Ejection (CMEs), high-speed solar wind streams or solar flares[10]. Apart from that, the important condition noticed for GS development is that the orientation of the Interplanetary Magnetic Field (IMF) must be southward with a sufficiently prolonged negative value (~ -10nT or lower). With this condition the geomagnetic field gets disturbed which is noted with an abrupt drop in the geomagnetic field strength and this stage of reduced magnetic field strength which may last for a few hours to a period of several days is considered as the main phase of a GS. It then recovers back to its original value, known as recovery phase[11-12].

The geomagnetic field lines are directed parallel to the equator with a shift between the geographic and geomagnetic equator[13]. Hence, some distinctive features such as equatorial electrojet (EEJ), equatorial ionization anomaly (EIA), plasma fountain, plasma bubbles and the equatorial temperature and wind anomaly (ETWA) etc.[14-16] are displayed by the equatorial and low latitude ionosphere unlike to the mid and high latitude ionosphere.

Two major causes of disturbance in low latitude ionosphere during storm time are namely (1) prompt penetration of electric-field (PPEF) deriving through

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magnetosphere[17-18]. (2) Disturbance dynamo (DD) electric-field generated from the disturbed neutral winds[19-22].

The PPEF is an immediate response to GSs because as soon as the geomagnetic storm is initiated on account of the southward turning IMF, the expansion of convection currents in the high latitude ionosphere takes place rapidly. This expansion is so fast that it cannot resist more there and hence penetrates promptly towards the low latitude to equatorial ionosphere, which subsequently results there into a dawn-dusk electric field[23].

The DDEF varies slower than PPEF. During GSs, the meridional winds are reinforced to generate equator ward winds, which alter the distribution of ionospheric plasma and creates plasma density irregularities in the low latitude F2 region[21,22,2425].

During the GSs, energy transfers to high latitudes regions, in terms of particle precipitation and joule heating which results in wind circulation, expansion of air, increment in the atomic to molecular ratio and rise in the temperature of low latitude F2 regions[26].

Several researchers have studied the geomagnetic storm effects on ionospheric parameters and have validated the variations in plasma density, plasma temperature, and total electron content (TEC), etc. over low latitude F2 regions. For instance, in TEC significantvariations were observed over EIA ionosphere of the Indian subcontinent[27-28]. GPS-TEC data analysis was performed to study the response of the Indian sectorionosphere to the GSs[28] and depressions and enhancements were observed in Vertical Total Electron Content (VTEC) during the occurrence of GSs. It was inferred that the perturbed VTEC was caused due to PPEF, DDEF, and thermospheric composition changes. The TEC variation was also explained by utilising GPS-signals measurements at Rajkot, where enhanced/little diminished TEC was observed on the storm day/following day[27]. The analysis of low latitude ionospheric response of EIA sector over India by using GPS data also resulted out similar observations[29]. The GS that commenced on 15 May 2005 was analysed by using the GPS data, collected from various stations situated near the northern EIA crest regions and it showed simultaneous existence of eastward Interplanetary Electric Field (IEF) along with maximum southward IMF Bz which as a consequence resulted in a peak in TEC[30]. This large enhancement in TEC and $[\frac{O}{N_2}]$ ratio was attributed to the travelling atmospheric disturbances (TADs). The different cases of GSs (weak, Moderate, and intense) were also analysed over the low latitude ionosphere in association with the IMF, measured by Jicamarca and Millstone Hill observatories that demonstrated a long duration enhancement in the ionospheric electric field specifically when the GS was in its main phase[31].

In this paper, we present the behaviour of ionospheric parameters (H^+, O^+ and Ti) during weak and moderate geomagnetic storms over the low latitude, F2 (~600 km altitude) region by using ROCSAT-1 satellite data. The novelty of the present study covers two aspects. Firstly, one can find abundant literature that analyses the effects of high magnitude geomagnetic storms (severe or great storms) on ionospheric parameters over high/mid-latitudes using GPS data but the effects of weak to moderate magnitude GSs, over the low latitudinal region are still sparse. Thus more work needs to be done in this direction. Secondly, most of the earlier work focuses on the study of variabilities in electron and ion density due to GSs. A very few reporting on electron and ion temperature over the low latitudes can be found. The ROCSAT-1 satellite measures ion density and ion temperature. Thus, provides us with a prospect to reveal the anomalous behaviour of ions temperature as well, during geomagnetic storms. Moreover, the study has also been compared with the IRI-2016 model.

2 Data

2.1 Data selection

To analyse the behaviour of the ionospheric ion density and temperature during GSs, data from one of the instruments on boarded the Republic of China Satellite, ROCSAT-1 has been used. ROCSAT- 1 launched on January 27, 1999, at an altitude of 600 km and with an inclination angle of 35^o was orbiting in a circular orbit[32-34]. The ionospheric plasma and electrodynamics instrument (IPEI) onboard the satellite had four sensors for the measurement of the ion concentration, temperature and drift velocity vector. The ROCSAT-1 data is well calibrated. The error limits for ion temperature is ± 10 % in the temperature range from 500 to 10,000 K and similar (±10%) for total ion density Ni in the range[34] from 50 to 5×10^6 cm^{-3}.

The IRI-2016 is a newly released empirical model by The Community Coordinated Modeling Centre (CCMC) and sponsored by the Committee on Space Research (COSPAR) and the International Union of

Radio Science (URSI) which provides the scientific community with an access to the ionospheric parameters (electron temperature, ion composition, ion temperature, equatorial vertical ion drift and vertical ionospheric electron content etc.) with their monthly average values and an altitude range of 50-2000 km[35-36].

The earthquake activity data during the year 1999 was taken from USGS website[37].

The Dst index data[38] and the Kp_{max} data[39].

2.2 Data Analysis

To study the behaviour of the ionospheric parameters: H^+, O^+ and Ti, the ROCSAT-1 satellite and IRI 2016 model data was sorted out for the region encompassed between 5-35° geog. N and 65-95° geog. E. In the IRI-2016 model the average values for H^+, O^+ and Ti were calculated over a latitudinal range of 5° to 35° N geog latitude and 77° E geog longitude as an input.

In the present work, the two GS events selected[40] were one on 30 July 1999 ($K_{p_{max}} = 8-$, $D_{st} = \sim -53$ nT), and second on 13 November 1999 ($K_{p_{max}} = 6+$, $D_{st} = \sim -106$ nT). Although according to the storm selection scheme[41], these storms falls under the category of moderate and strong GS but as the Dst values -53 and -106 nT are very close to -50 and -100 nT and also these storms did not end up with significant results or variations hence we considered them as weak and moderate storms.

The present study has been explained in two sections. In section one, the behaviour of ion density and temperature has been discussed for the period of existence of the main and recovery phase of the GS.

Whereas, in section two the behaviour of ion density and temperature has been observed during a time window of 15-24 UTC. This time window has been restricted to ±3 hour of the Kp_{max} range (1800-2100 UT) to get a more precise analysis and is kept the same for both the disturbed and quiet days. The quiet days for the corresponding months were selected from the website[39]. This analysis is then compared with IRI-2016 modelled values which demonstrate marked differences.

The ionospheric parameters vary due to seismic activities too, over low latitude F2 region. Thus, only those geomagnetic storms were selected which were free from earthquakes in the coverage area of ROCSAT-1. This was done by first selecting all the geomagnetic storms with $K_{p_{max}} \geq 5$. After that, all the days associated with earthquakes with magnitude of 4-10 and within 0-30 km depth were excluded from the present analysis. Recently, it has been observed that seismo-ionospheric coupling is an emerging field of research. One can find enough literature that suggests the anomalous behaviour of ionospheric parameters due to seismic activities. For instance, variations in ion temperature and density due to moderate seismic activity at around 500 km altitude by utilising SROSS-C2 satellite data have been accounted[42-43].Changes in total electron content over Qinghai station were observed by using GPS data[44] whereas by using topside sounders extensive plasma variabilities were reported in the EPZ (Earthquake Preparation Zone)[45]. Plasma density variations were computationally analyzed by utilizing data from Intercosmos-24 satellite. Alarger database collected from Intercosmos-24 satellite was studied and a correlation between the abnormalities of ionospheric density and seismic activity was reported[46-47]. Also, considerable precursory variabilities in the ionospheric ion density at around 500 km altitude over the earthquake epicentres have been noticed, during the night time[46]. Hence, in this paper, there is the necessity of excluding the events that are affected by seismic activities.

3 Results and Discussions

Figure 1, the passes of ROCSAT-1 satellite during quiet and disturbed days during the two GSs events (30 July 1999 and 13 Nov 1999), considered in the present study have been shown. It cleared that the spatial coverage of the ROCSAT-1 satellite during the disturbed and quiet days was same.

Section 1

A geomagnetic storm that commenced on 30 July 1999 at around 1800 UT was associated with M class flare and interplanetary coronal mass ejection (ICME). The maximum X-ray intensity of solar flare as recorded by GOES satellite was 8.6E-03 W/m^2 during the peak flare time. The maximum velocity of ICME[48] was noticed as 660km/sec. On 30 July, the maximum solar wind proton density and solar wind velocity were around 41.5 N/cm^{3}and 670 km/sec at about 20 UTC and 23 UTC respectively as observed[49]

Figure 2 represents the speed of solar wind (a), solar wind density (b), IMF Bz (c) and Dst index (d) during 30, 31 July and 1 August 1999. From Figure, it is observed that there were southward as well as some

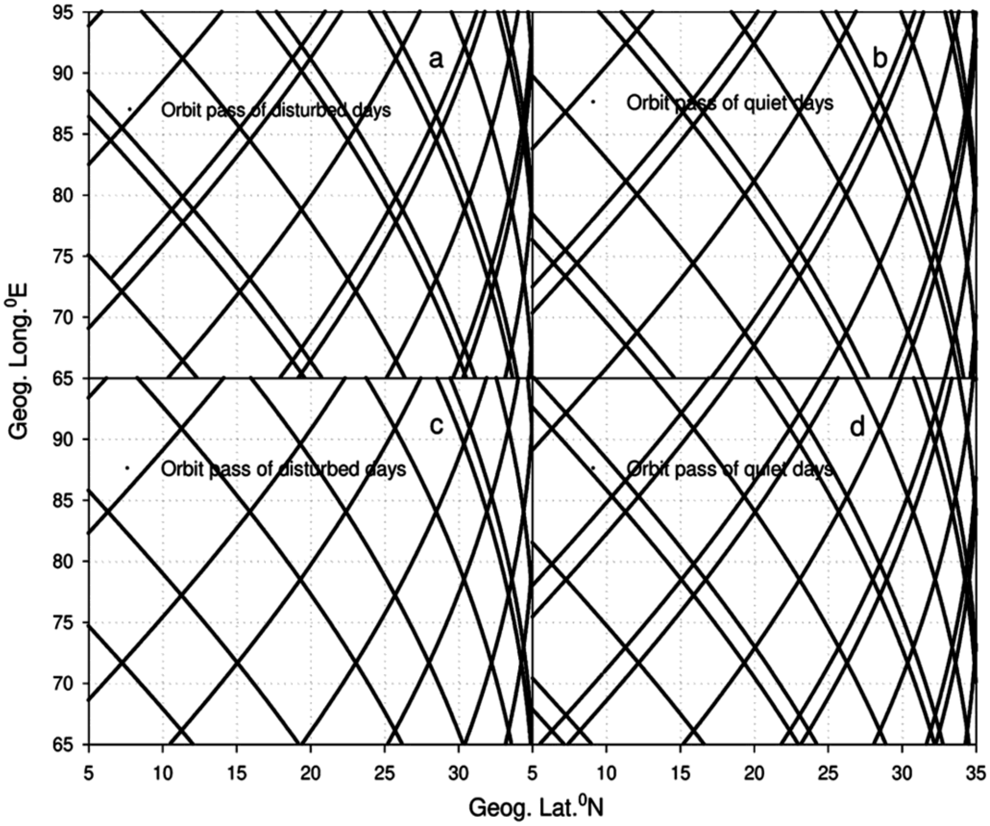

Fig. 1 — Orbit Pass of ROCSAT-1 satellite on disturbed days (a-13 Nov 1999 event, c-30 July 1999 event) and quiet days (b-13 Nov 1999 event, d-30 July 1999 event).

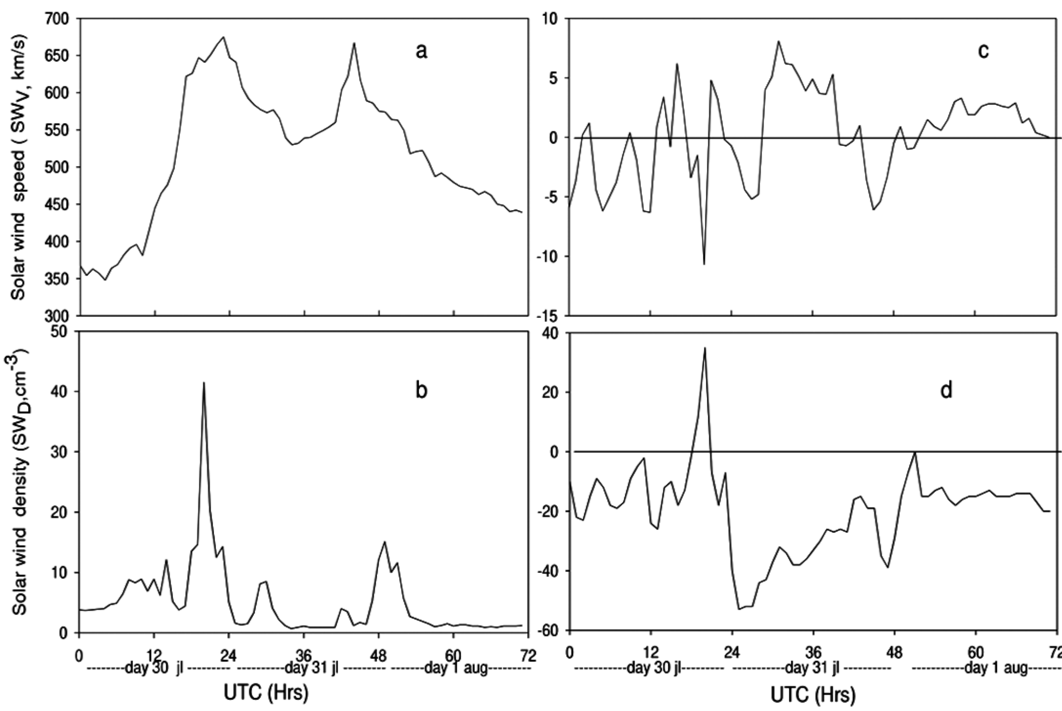

Fig. 2 — Representation of solar wind speed, (SW_V,(km/s)) (a), solar wind proton density, (SW_D, (cm^{-3})) (b), IMF Bz, nT (c) and Dst index, nT (d) during 30, 31 July and 1 August 1999.

northward excursions of the IMF bearing a maximum value of -10.7 nT at 20 UTC, which might have resulted in ring current. However, the magnitude of the ring current was not significantly high to decrease Dst noticeably. The Dst value started decreasing significantly from around 21 UTC on 30 July, consequently on setting its main phase from thereon, which stayed till 25 UTC (i.e. 1 am on 31 July) where Dst fell to its maximum value of about -53 nT and thereafter recovery phase took place uptill 50 UTC (i.e. 2 am on 1 August, where the Dst value returned to about $1/4^{th}$ (~ -15 nT) of its maximum value).

Figure 3 represents the variations in O^+ density (a), H^+ density (b) and ion temperature (c) for the duration whenthe main and the recovery phase took place. Since this was a weak magnitude GS, and even took place in the night time so the ion density and temperature were not expected to show many variations. The ROCSAT-1 data analysis also reflectedthe same behaviour that O^+density and Ti didnot exhibit any significant variation during the main and recovery phase but Ti decreased notably on termination of the recovery phase (1st August). However, H^+ density showed marked variations for the period of the recovery phase where it increased significantly than in the main phase.

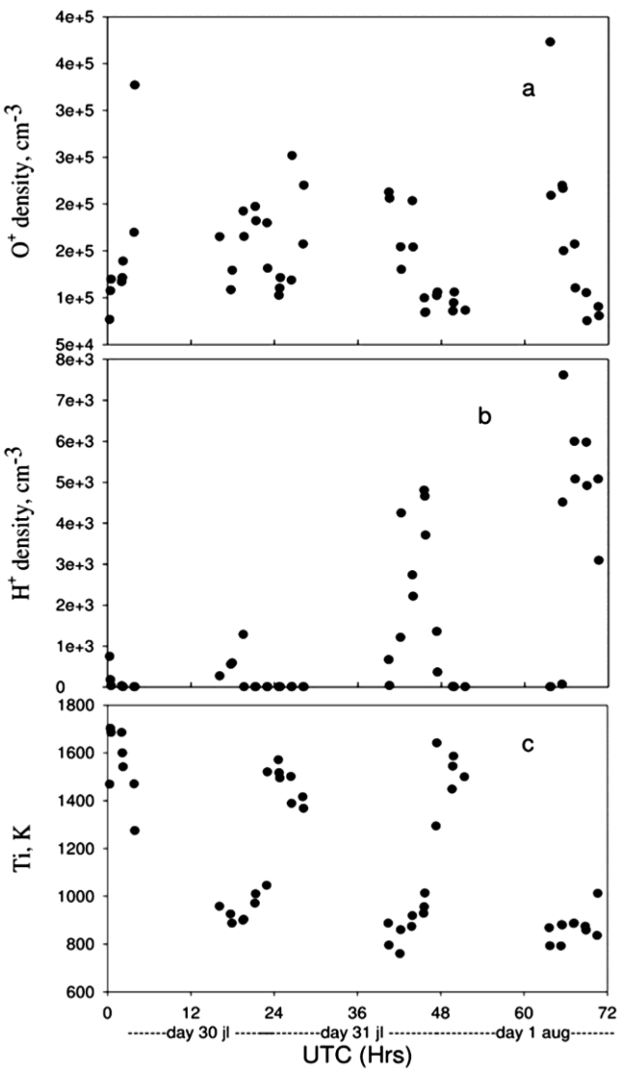

Fig. 3 — Variation of O^+ density, cm^{-3} (a), H^+ density, cm^{-3} (b) and Ti, K (c) during main phase (21-25 UTC) and recovery phase (25-50 UTC) for GS on 30 July 1999.

Another GS that commenced on 13 November 1999 was associated with M class flare and ICME. The maximum X-ray intensity of solar flare as recorded by GOES satellite was 8.4E-02 W/m^2 during the peak flare time. The maximum velocity of ICME[48] was noticed as 480 km/sec. Whereas the maximum solar wind velocity and solar wind proton density was around 480 km/s and 5 N/cm^3 at around 16 UTC and 21 UTC respectively as observed[49]

Figure 4 represents the speed of solar wind (a), solar wind density (b), IMF Bz (c) and Dst index (d) during 13, 14 and 15 November 1999. This moderate GS evolved gradually with small southward Bz bearing a maximum value of -11.5 nT for 18-19 UTC. On 13 November, the Dst at around 16 UTC started dropping continuously and reached up to a maximum value of ~ -106 nT. Hence, after staying in the main phase (16-22 UTC) on 13 Nov, it then entered in its recovery phase. It recovered back completely at 65 UTC (i.e. 17 UTC on 15 Nov) where the Dst value returned to about $1/4^{th}$ (~ -26 nT) of its maximum value.

Figure 5 represents the variation of O^+ density (a), H^+ density (b) and ion temperature (c) during the main and recovery phase of strong GS. O^+ density was found to increase during the main phase (13 Nov.) than in the recovery phase. However, the H^+ density increased intherecovery phase than the main phase. And Ti didnot show any significant variation during the main and recovery phase except a notable decrement near the end of the recovery phase (on 15 Nov).

Section 2

In this section, the variations in ion density and temperature have been observed in a certain time window of 15-24 UTC. This time window was kept same for both quiet and disturbed days and was

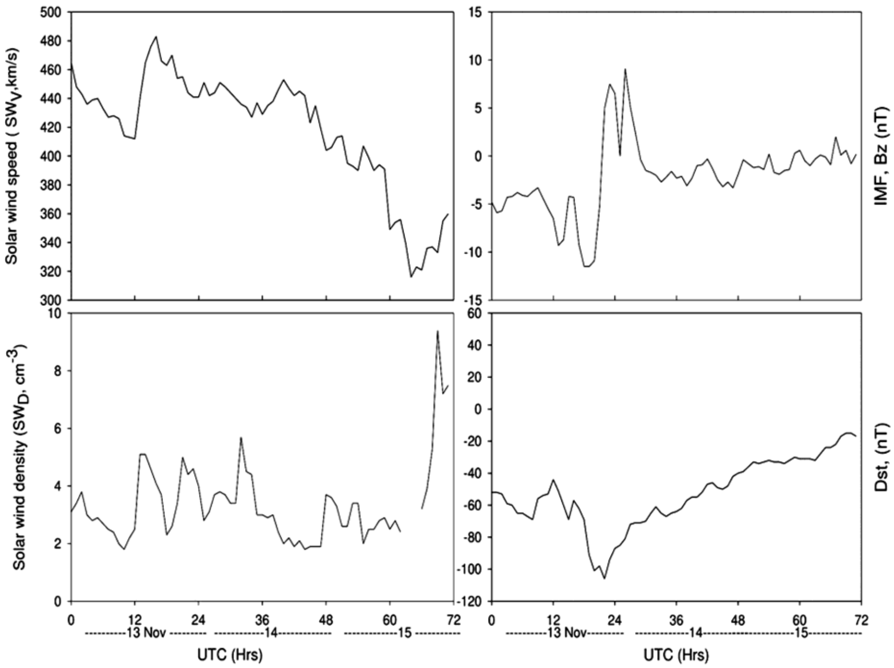

Fig. 4 — Representation of solar wind speed, (SW_V,(km/s)) (a), solar wind proton density, (SW_D, (cm^{-3})) (b), IMF Bz, nT (c) and Dst index, nT (d) during 13, 14 and 15 November 1999.

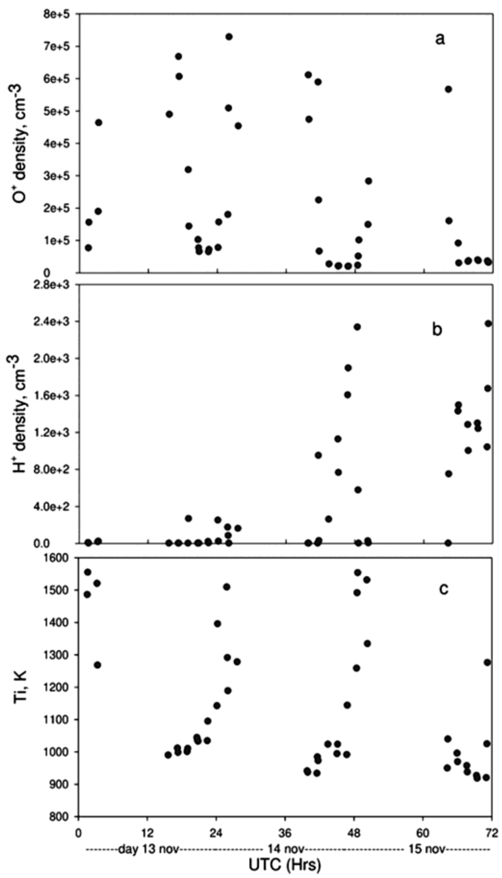

Fig. 5 — Variation of O^+ density, cm^{-3} (a), H^+ density, cm^{-3} (b) and Ti, K (c) during main phase (16-22 UTC) and recovery phase (22-65 UTC) for GS on 13 November.

restricted to ±3 hour of the Kp_{max} range. For both of the storms, the Kp index was maximum in the 3-hour interval of 18-21 UTC. Hence, this time window was set to study the variations in ion density and temperature during disturbed days and quiet days which were then further compared with the IRI-2016 modelled values.

Figure 6, the variation of ion density and temperature (event - 30 July 1999), measured and modelled in an interval of 15-24 UTC have been shown with their average values during disturbed days(shown in red colour) and quiet days (shown in black colour). The disturbed days were 30, 31 July and 1 August whereas the quiet days selected were 16, 17 and 18 July.

The average ionospheric O^+ density during disturbed days was 1.49E+05 $cm^{-3}$and 7.98E+04 cm^{-3} during the quiet days. Thus the O^+ density during disturbed days was found to be ~1.8 times higher than the normal day's ion density. Whereas by the IRI model, this incremental ratio $(O_D^+/O_Q^+)$was ~1.06.

The average H^+ density observed during disturbed days was 1.27E+03 cm^{-3} and during the quiet days 2.36E+03 cm^{-3}, which illustrated that H^+density during quiet days was ~1.8times higher than the disturbed days. Whereas by the IRI model, this incremental ratio (H_Q^+/H_D^+) was ~2.51.

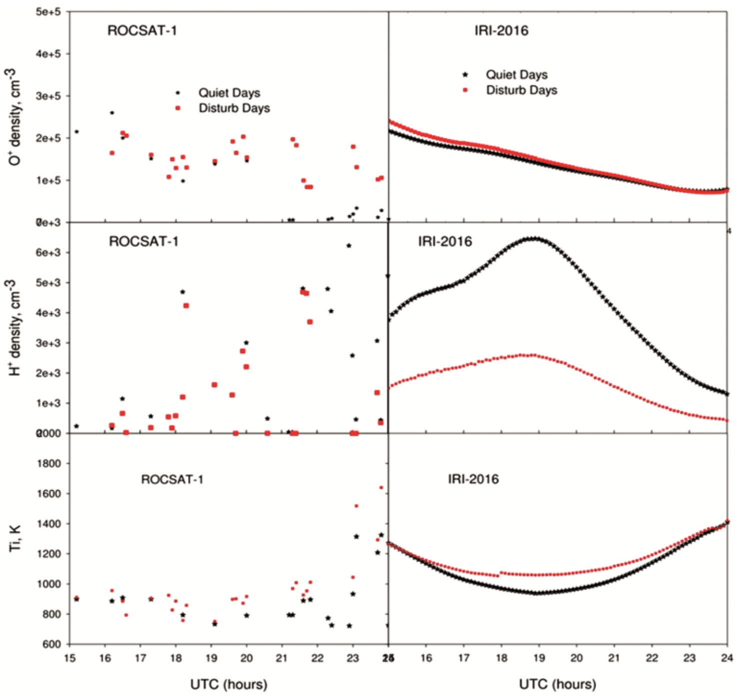

Fig.6 — Representation of ROCSAT-1 measurements (Left panels)) and IRI-2016 estimations (Right Panels) for average O^+ density (cm^{-3}), H^+ density(cm^{-3}) and Ti(K), during quiet days (black) and disturbed days (red) for GS on 30 July 1999.

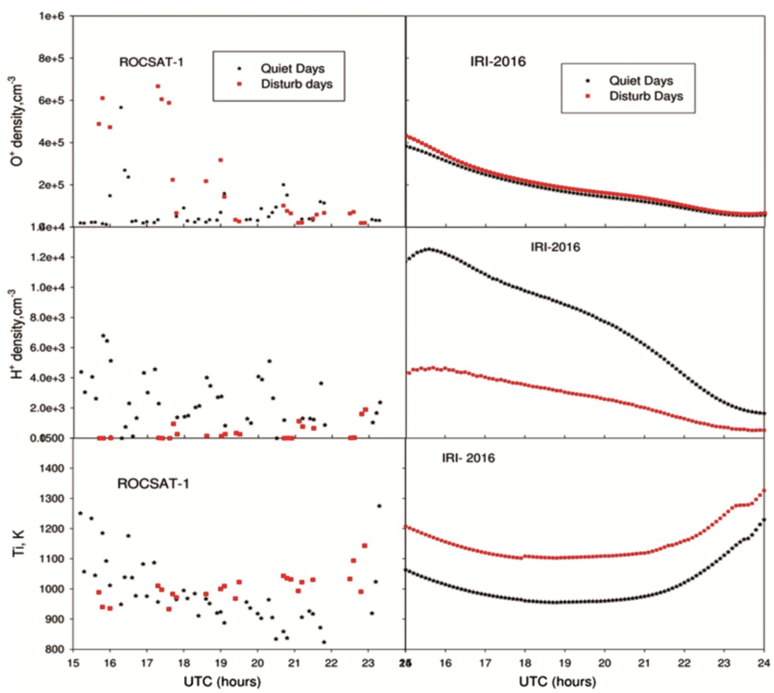

Fig. 7 — Representation of ROCSAT-1 measurements (Left panels)) and IRI-2016 estimations (Right Panels) for average O^+ density (cm^{-3}), H^+ density(cm^{-3}) and Ti(K), during quiet days (black) and disturbed days (red) for GS on 13 November 1999

Similarly, the average ion temperature during disturbed days was 975 K and 895 K during quiet days which showed an average increment by a factor of ~1.08during disturbed days as compared to the quiet days whereas, with the modelled values, the ratio (T_{iD}/T_{iQ}) was found ~1.05.

Figure 7 (event – 13 Nov, 1999), illustrates the ion density and temperature variations, measured and

Table 1 — Variations observed in O^+, H^+ and Ti by ROCSAT-1 and IRI-2016, during a moderate (30 July 1999) and strong (13 November 1999) geomagnetic storm.

30 July 1999

Parameter	ROCSAT-1			IRI-2016		
	Disturb Days (D)	Quiet Days (Q)	Ratio Factor	Disturb Days (D)	Quiet Days (Q)	Ratio Factor
Avg. O^+ density (cm^{-3})	1.49e+05	7.98e+04	D/Q=1.8	1.41e+05	1.34e+05	1.0
Avg. H^+ density (cm^{-3})	1.27e+03	2.36e+03	Q/D=1.8	2.47e+03	6.20e+03	2.5
Avg. Ti (K)	975.2	895.4	D/Q=1.08	1154.44	1092.90	1.05

13 November 1999

Parameter	ROCSAT-1			IRI-2016		
	Disturb Days (D)	Quiet Days (Q)	Ratio Factor	Disturb Days (D)	Quiet Days (Q)	Ratio Factor
Avg. O^+ density (cm^{-3})	2.07e+05	7.51e+04	D/Q=2.7	1.91e+05	1.74e+05	1.1
Avg. H^+ density (cm^{-3})	3.67e+02	2.34e+03	Q/D=6.3	2.71e+03	7.69e+03	2.8
Avg. Ti (K)	1007.0	986.3	D/Q= 1.02	1153.19	1013.63	1.13

modelled with their average values in an interval of 15-24 UTC during disturbed days (shown in red colour) and quiet days (shown in black colour). The disturbed days were 13, 14, 15 November, whereas the quiet days selected were 26, 27 and 28 November 1999.

The average ionospheric O^+ density calculated during disturbed days was2.07 E+05 cm^{-3} and 7.51E+04 cm^{-3} during the quiet days. Thus the O^+ density during disturbed days was found to be ~2.7 times higher than the normal day's ion density. Whereas by the IRI model, this incremental ratio (O_D^+/O_Q^+) was ~1.1.

The average H^+density observed during disturbed days was 3.67 E+02$cm^{-3}$and during the quiet days 2.34 E+03cm^{-3}, which illustrated that H^+ density during quiet days was ~6.3 times higher than the disturbed days. Whereas by the IRI model, this incremental ratio (H_Q^+/H_D^+) was ~2.8.

Similarly, the average ion temperature during disturbed days was 1007 K and 986 K during quiet days which showed an average increment by a factor of~1.02 during disturbed days as compared to the quiet days whereas, with the modelled values, the ratio (T_{iD}/T_{iQ}) was found ~1.13.

This anomalous variation observed in ion density could be due to the movement of both meridional and storm-induced winds towards the equator. These winds uplift the ionosphere from the equator towards the poles. However, over the low latitudes, these ions diffuse down hence, showing an increment in ion density[50].The enhanced ion density might also be linkedwith the PPEF which triggers the extension of equatorial ionisation anomaly and hence, varies the pattern of ion distribution. It has also been confirmed that specifically during the occurrence of the main phase of GSs the ionospheric electric field increases which results in the variations in ionospheric parameters[51].

4 Conclusions

In the present study, the variations in ionospheric parameters-ion densities and ion temperature (H^+, O^+ and Ti) over the low latitude Indian region, using ROCSAT-1 satellite observations and IRI-2016 estimations, in response to a weak and moderate magnitude GS occurred on 30 July 1999 ($K_{p_{max}} = 8-$, $D_{st} = \sim -53$ nT) and 13 November 1999 ($K_{p_{max}} = 6+$, $D_{st} = \sim -106$ nT) has been analysed. The conclusion of the studyhas been explained in the following points.

1 For weak GS, both the average O^+ and H^+ density has been found to increase by a factor of around1.8 during disturbed and quiet days respectively as calculated by ROCSAT-1.According to the IRI-2016 model, only H^+ density has increased by a factor of around 2.5 during quiet days as modelled by IRI-2016 model whereas any significant variations have not been shown by Ti as measured by both ROCSAT-1 and IRI-2016 model values.

2 For moderate GS, the average O^+ and H^+ density has been found to increase by a factor of around 2.7 and 6.3 respectively during disturbed and quiet days respectively as calculated by ROCSAT-1 whereas according to IRI-2016 model the O^+ and H^+ density has increased by a factor of around 1.1 and 2.8 respectively during disturbed and quiet days respectively. Again, no significant variation has been observed, except by

a factor of around 1.1 with the modelled values only.

3 The study of both the GSsby ROCSAT -1 reveals that O^+ density showed variation according to the strength of GS. For weak storm, it showed little variation and a significant variation for moderate GS. For the H^+ density it has been noticed that for both weak and moderate GS, it varied notably with measured and modelled values. And the Ti has been observed showing the least or negligible variation both by measured and modelled values during both weak and moderate GSs.

5 Acknowledgement

The hourly Dst index, proton density and speed of the solar wind, and IMF Bz data were collected online[38]. The ROCSAT-1 satellite was obtained from NASA CDAWeb. The geomagnetic storm data for the year 1999 was available[40]. The earthquake data during the study period were taken from the USGS website[37] The authors are thankful to all these websites for providing this valuable data.

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