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Variability of ion density due to solar flares as measured by SROSS–C2 satellite

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In the present paper the effect of solar flares on ion density has been studied. The ion densities have been measured for the period 1995-1998 using RPA payload of SROSS-C2 satellite. Solar flare data has been obtained from National Geophysical Data Center (NGDC) Boulder, Colorado (USA). The study indicates considerable decrease (1.2 to 2.8 times) in total ion density during flare time as compared to normal time. Out of four ion species, i.e. O^+, O_2^+, H^+ and He^+, the O^+ ion density is most affected by the effects of the flare as measured by SROSS–C2. There is considerable decrease in O^+ ion density while O_2^+, H^+ and He^+ density show negligible change during flare time as compared to normal time. Furthermore, relation between change in ion density (ΔN) as a response to change in ion temperature (ΔT) during flare time and normal days has been estimated. A comparison of ion density obtained from SROSS-C2 with IRI–2012 during the flare time indicates an overestimation by IRI-2012.

Keywords: F2-region, Solar flares, Ion density, Ion temperature

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1 Introduction

F-region ionospheric affects, as a response to solar activity effects, is probably one of the most complex study of ionospheric physics, involving the study of almost all ionospheric parameters. Solar flare is one of the most interesting solar activities. Solar flares are magnetically driven sudden explosions from localised active region of the sun's surface (corona), usually near a complex group of sunspots, covering almost entire range of electromagnetic spectrum[1]. Solar flares, when associated with coronal mass ejections (CME), can interact via Earth's magnetic field to produce a geomagnetic storm. When CMEs carrying energetic plasma hit Earth's magnetosphere, suitable solar wind energy and momentum transfer to magnetosphere is created. This causes change in ring current, responsible for variations in geomagnetic field, thus, causing geomagnetic storms. The detailed morphology is presented by Kumar *et al.*[2]. The Dst index is an indicator of magnetic disturbance intensity and total energy of particles responsible for ring current[2]. The geomagnetic storms are divided into intense (Dst_{min} > -100 nT), moderate (-100 ≤ Dst_{min} ≤ -50 nT) and weak (-50 ≤ Dst_{min} ≤ -30 nT) storms. The intense storms are further subdivided into strong (-200 ≤ Dst_{min} ≤ -100 nT), very strong (-350 ≤ Dst_{min} ≤ -200 nT) and great (Dst_{min} ≤ -350 nT) storms[3]. As the intensity of geomagnetic storm increases, it creates major disaster to earth's ionosphere. Almost all the ionospheric layers and parameters are affected by magnetic storm. Many researchers have studied the geomagnetic storm effects on the ionosphere[2-8]. The Earth's ionosphere reacts to variations in geomagnetic situations. This reaction is different for different ionospheric regions (lower layers and F2 layer) due to different physical mechanisms governing changes in electron concentrations. The lower ionosphere experiences an increase in Ne (electron concentration) as an effect of geomagnetic storms. Contrary to it, F2-layer's reaction to geomagnetic disturbances consists of both signs of electron concentrations (Ne): increase as well as decrease and are often termed as positive and negative effects of geomagnetic storms[3].

The present work focuses only on the effects of solar flares on O^+ ion density concentrations. The effect of solar flares on the ionospheric F-region has also been studied[9] by VHF radio beacons experiment on geo-stationary satellite and enhancement of total electron content (TEC) is noticed. Global observations of outstanding flares of 7 August 1972 using 17 stations in North America, Europe and Africa revealed that TEC was increased by 15-30% during the solar flares[9]. The low latitudes showed larger increase in TEC as compared to high latitudes. Some solar flare events have also been studied to see the effect on E and F-regions of the ionosphere and it was found that electron density was enhanced at these heights[10,11]. Theoretical study was carried out to see the effect of solar flares on electron density and found that electron density is enhanced in E and F-regions of the ionosphere[12]. After advent of GPS, scientists have reported global views of ionospheric solar flares effects by means of GPS technique[13-15]. Instead of global view, Zhang *et al.*[13] in 2002 examined several flare events and found that for similar classes, flares occurring near the solar meridian result in stronger ionospheric responses. Many researchers[16-20] have studied the effect of solar flares using GPS and other satellite data. Researchers have studied the effects of solar flares of 23 September 1998 and 29 July 1999 on ionosphere with the help of GPS network[16]. They found that the fluctuation of total electron content (TEC) and its time derivative by removing the linear trend of TEC with a time window, are coherent for all stations on the dayside earth and no such effect of solar flares was detected on the night side of the earth[16]. A brief review on solar flare effects on ionosphere is reported by Tsurutani *et al.*[21]. They studied the number of photon and energetic particle effects on TEC and reported the increase in TEC as a response to solar flare associated with energetic particles[21]. Effect of solar flare on ionospheric TEC at Varanasi has been studied by Kumar & Singh[22]. They reported increase in TEC as a response to weak solar flares. Also, the dependence of increase in TEC on class of flares has been observed by Kumar & Singh[22].

Most of the studies on the solar flares effects on ionosphere have been devoted to large flares and study of TEC or effect of energetic particles associated with flares using GPS data. There has been very few studies reporting on effects of solar flare on ion density in low latitude region. Several researchers[23] have reported enhancement in electron and ion temperatures due to solar flares as measured by SROSS-C2 satellite. In the present work, effects of solar flares on ion density over low latitude region during 1995–1998 using SROSS-C2 satellite have been studied. Satellite data is preferred for the study as it has an attribute of high resolution. Further, co-relation between change in ion temperature and density as a response to solar flares has been established.

2 Data collection and Analysis

The data of ion densities and temperatures have been measured during the period 1995-1998 using RPA payload of SROSS-C2 satellite to study the effect of solar flares. Solar flare data has been procured from National Geophysical Data Center (NGDC) Boulder, Colorado (USA). To examine the background thermospheric neutral composition changes during the study period, the neutral composition $[O]/[N_2]$ have been obtained for ~500 km altitude corresponding to solar flare location and time period by NRLMSIS–00 atmospheric model (http://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php)

2.1 SROSS-C2 data

The ionospheric parameters (ion densities and temperatures) are obtained using a Retarded Potential Analyser (RPA) payload aboard the SROSS-C2 (Stretched Rohini Series Satellite), which was launched by Indian Space Research Organization (ISRO) on 4 May 1994 around 420×620 km altitude. The RPA payload consisted of two sensors (i.e. electron and ion sensors) and associated electronics[24]. In addition, a spherical Langmuir probe is included, which acts as a probe to estimate the spacecraft potential as the satellite spins. The electron and ion sensors have a planar geometry and consist of multi–grid Faraday cups with a collector electrode. These mechanically identical sensors are mounted on the top deck; they move in the cartwheel mode perpendicular to the spin axis of the spacecraft. Both sensors have different grid voltages as suitable for the collection of electrons and ions in the earth's ionosphere. The temperature data (Te and Ti) is obtained by analysing one complete electron and ion I–V plots through linear and nonlinear curve fitting techniques, respectively. The ion density (O^+, O_2^+, H^+, He^+) is obtained by the curve fitting to a composite I-V curve using a nonlinear curve method of iteration to the observed characteristics. Although RPA sensor measurements were made throughout the spin cycle of the satellite, data taken only within ±30° and ±60° of the velocity vector for ion and electron sensors are considered for the analysis (after including the empirical corrections for spin modulation for density calculations) as mentioned by Garg *et al.*[25]. The measurements outside the mentioned angle between sensor normal and velocity vector could not be used for ion density calculations as correction for spin modulation could not be applied outside the said limit[24]. Hence, the ion density data is not continuous and is scattered with some data points taken within the specified limits and a loss for the rest of the spin cycle, i.e. for about 80 km in space there are no data points and again some data points with 170 m interval and so on[25].

2.2 Data analysis

For the present work, five solar flare events have been selected, during the period 1995–1998 over India (5.35°N, 65.95°E) that match with ion density and temperature data recorded by the satellite. These solar flares events were observed as: one at Bhopal (23.16°N, 77.6°E), two at Panaji (15.30°N, 73.55°E) and two at Pune (18.31°N, 73.55°E). Data for ion densities (O^+ and total ion densities) and temperatures have been analysed for these locations in the altitude range 425-625 km. Data selection is most vital and difficult task for studying the effect of solar flares on ion density variations and its relation with temperature, as satellite passes rarely coincide with flare event at the meteorological data centres. Only solar flare events that are free from diurnal, seasonal, latitudinal, longitudinal and altitudinal effects have been selected. This is done by selecting the appropriate data window at a fixed location with ±5° variation in longitude and latitude. A window of 5° in latitude and longitude for the satellite observations at the meteorological data center has enabled the latitudinal and longitudinal effect to be ineffective. Further, it has been ensured that those solar flare events, which were masked with seismic and thunderstorm event days, or associated with geomagnetic storm ($Kp<4$, $Dst<-30$ nT), have been excluded. Also, nighttime solar flare events have not been considered. Thus, only five solar events free form the perturbations could be selected for the study. To compute the normal day's ion densities and temperatures for the flare duration, the ion densities and temperatures data for normal days are selected for the same time interval for a month, which includes about 15 days before the solar flares and about 15 days after the event. To calculate the normal day ion densities and temperatures, only event time duration data have been used to avoid any perturbation due to diurnal effect. Thus, the possibility of diurnal and seasonal effects has been ruled out. The maximum possible data points available for the study duration have been used. The solar flare events selected for the study are also free from thunderstorm activity, which have been verified using data on thunderstorm obtained from Indian Meteorological Department (IMD), Pune. There is ionospheric temperature enhancement during sprites associated with active thunderstorm. This is due to generation of ultra low frequency (ULF) during lightning sprite activity, which propagate further upwards at ~500 km altitude and heat the local plasma in the ionosphere[27,28], further affecting the ion density. Thus, it is necessary to select solar flare events that are free from thunderstorm activity.

Furthermore, relation between change in ion density (ΔN) as a response to change in ion temperature (ΔT) during flare time and normal days has been estimated. All the data recorded by the SROSS-C2 satellite are within the error limit of ±50 K for ion temperature and 5% for ion density measurement[24] and is applicable to all data presented in this paper.

The data of ion temperature of the selected events have been taken from Sharma *et al.*[23]. All the five events fall in the category of subflare having almost same area, brilliancy faint on three level scale and intensity of 5 sfu (solar flux unit). The details of the flares have been given in Table 1. A great flare can cover an area up to 10^9 km^2 and a subflare up to 10^8 km^2 as reported earlier[26].

3 Results and Discussion

3.1 Variation of O^+ and total ion density due to solar flares

In the span of 1995-1998, five solar events have been chosen during day time for studying the variability of O^+ and total ion density during solar flares as compared to normal days on Earth's dayside ionosphere. Present study has been carried out on low latitude ionospheric F2-region (~500 km). For this purpose, five events correspond to the locations at Bhopal, Panaji, and Pune in India.

Table 1 gives the values of geographic location, time, class, X–ray flux intensity, average O^+ and total ion density during flare and normal days and IRI-2012 values of O^+ and total ion density during flare time. Figure 1 shows X-ray flux intensity during flare period for different events. From the measured values of total and O^+ ion density obtained from SROSS-C2 satellite data and IRI-2012, it can be verified that major contributor of total ion density remains O^+ ion in this altitude range. O^+ ion

Table 1 — Geographic location, time, class, X- ray flux intensity of the flare event and average O^+ and total ion density compared with IRI-2012 values of O^+ ion density during flare time

S No	Place (latitude, longitude)	Date	Time of the flare, hrs LT	Average O^+ ion density, m^{-3}		Average total ion density, m^{-3}		IRI (O^+)-2012	Class of solar flare	X-ray flux
				Normal days	Solar flare time	Normal days	Solar flare time			
1	Bhopal (23.16°N, 77.36°E)	09.11.1998	06:00-06:17	1.50E+11 ± 5.463E+10	6.43E+10 ± 1.801E+09	2.01E+11 ± 5.47E+10	7.08E+10 ± 1.13E+09	7.6E+10	B41	4.2E-07
2	Panaji (15.30°N, 73.55°E)	19.05.1995	17:03 - 17:07	1.11E+11 ± 2.7E+10	6.55E+10 ± 1.4E+09	1.23E+11 ± 2.8E+10	7.06E+10 ± 1.6E+09	3.44E+11	B91	9.2E-07
3	Panaji (15.30°N, 73.55°)	10.07.1996	11:07-11:27	2.2E+11 ± 1.403E+10	7.6E+10 ± 2.85E+09	2.4E+11 ± 1.36E+10	8.5E+10 ± 4E+09	2.35E+11	C27	2.7E-06
4	Pune (18.31°N, 73.55°E)	05.06.1995	09:30-10:03	1.36E+11 ± 1.715E+10	1.07E+11 ± 7.72E+09	1.39E+11 ± 1.8E+10	1.13E+11 ± 7.0E+09	2.32E+11	C53	5.0E-06
5	Pune (18.31°N, 73.55°E)	28.12.1998	09:04-10:23	1.81E+11 ± 3.48E+10	1.41E+11 ± 9.9E+09	1.84E+11 ± 3.47E+10	1.43E+11 ± 8.42E+09	1.6E+11	C25	2.3E-06

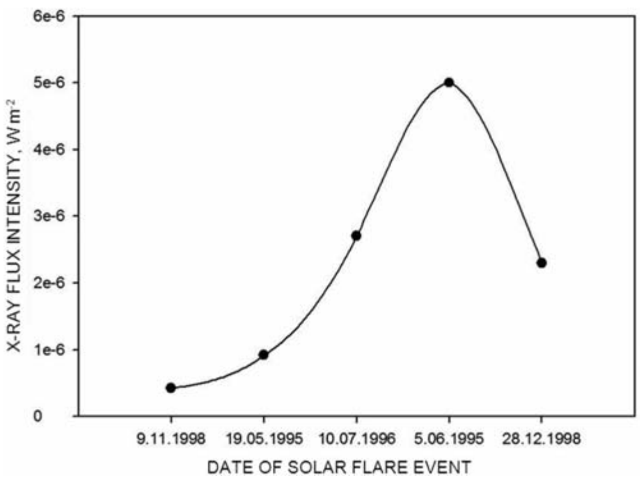

Fig. 1 — X-ray flux intensity during solar flare events

percentage remains more than 90% of total ion density. Moreover, data analysis of ion density values as measured by SROSS-C2 satellite shows that out of four ion species, viz. O^+, O_2^+, H^+ and He^+, O^+ ion density is most affected by the effects of the flare. There is considerable decrease in O^+ ion density while O_2^+, H^+ and He^+ density show negligible change during flare time as compared to normal time. Thus, for better presentation of the paper, figure representations of only O^+ ion density variability as a response to solar flares have been included. Figure 2 shows variation of O^+ ion density during normal days and solar flare event time as measured by SROSS-C2 satellite and estimated value by IRI-2012 during flare period.

Flare event, which showed up on 9 Nov 1998 during 06:00 – 06:17 hrs LT has been studied at Bhopal meteorological station (23.16°N, 77.36°E) in India. Figure 3(a) shows variation of O^+ ion density during solar flares as compared to normal days recorded by SROSS-C2 satellite at Bhopal. It is found

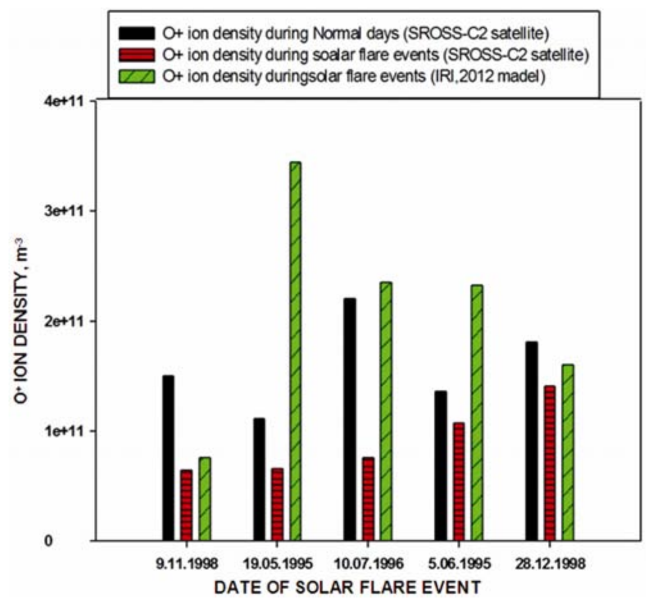

Fig. 2 — Variation of O^+ ion density during normal and solar flare events as measured by SROSS-C2 satellite and IRI-2012 model

that average O^+ ion density during normal days is 1.50E+11, while during flare, it is 6.43E+10 and density estimated by IRI-2012 is 7.62E+10. It may be noted that there is considerable decrease in O^+ ion density during flare time. During normal days, O^+ ion density is 2.3 times more than solar flare time.

Two more solar flares events (19 May 1995 from 17:03 to 17:07 hrs LT and 10 July 1996 from 11:07 to 11:27 hrs LT) are administered on meteorological station Panaji (15.30°N, 73.55°E). Figures 3(b and c) depict the O^+ ion density variation as a response to solar flare event compared to normal days on 19 May 1995 and 10 July 1996, respectively. The observed O^+ ion density is recorded as 1.11E+11 during normal days and 6.55E+10 during solar flare (19 May 1995). The value estimated by IRI–2012

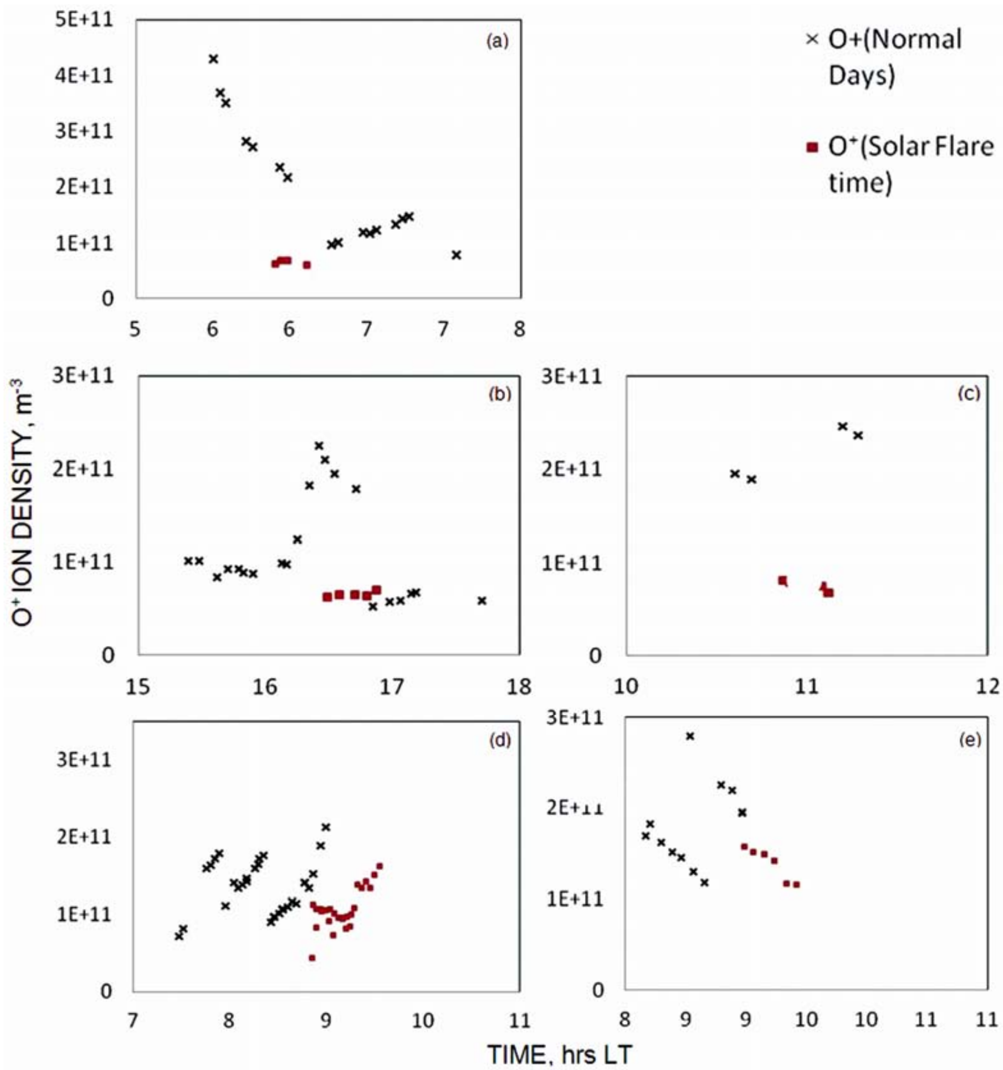

Fig. 3 — Variation of O^+ ion density during solar flares and normal days as recorded by SROSS-C2 satellite at: (a) Bhopal (09.11.1988); (b) Panaji (19.05.1995); (c) Panaji (10.07.1996); (d) Pune (05.06.1995); and (e) Pune (28.12.1998)

model is 3.44E+11. Comparing values of O^+ ion density during normal and solar flare, it is found that density value is 1.69 more during normal days over solar flare time. On similar note, when observations is made during second solar flare event at Panaji (10 July 1996), it showed 2.89 times O^+ ion density more during normal days over solar flare day. The values recorded during normal days and solar flare day of O^+ ion density is 2.2E+11 and 7.6E+10, respectively. The IRI-2012 model estimates a value of 2.35E+11.

Furthermore, two more events (5 June 1995 from 09:30 to 10:03 hrs LT and 28 December 1998 from 09:04 to 10:23 hrs LT) are studied at Pune Meteorological Station (18.31°N, 73.55°E). Figures 3(d and e) show variability of O^+ ion density during 5 June 1995 and 28 December 1998, respectively. The values recorded during normal days are found to be 1.36E+11 and during solar flare event on 5 June 1995 is 1.07E+11. The estimated value by IRI-2012 is 2.32E+11. This event also summarised similar results. O^+ ion density during normal days is 1.27 times more over solar flare event. On 28 December 1998, O^+ ion density value during solar flare time is 1.41E+11 and during normal days is 1.81E+11. The value given by IRI–2012 is 1.60E+11. This event accounted 1.28 times O^+ ion density during normal days over solar flare time.

All the above observations made by SROSS–C2 satellite supports decreased O^+ ion density during solar flare events compared to normal days and the values vary from 2.8 to 1.2 times during normal days over solar flare event. According to SROSS–C2 data records, the IRI–2012 model overestimates O^+ ion density values. It is well known that in the earth's ionosphere, the chemical processes are controlled by solar flux and thermospheric composition, while dynamic processes are controlled by thermospheric neutral winds and ionospheric electric fields. At low altitudes, the loss of ionization is mainly by dissociative recombination, the O^+ is proportional to $[O]/[N_2]$. Hence, an increase in the molecular gas number density in the F-region support O^+ loss by reacting with molecular gases and subsequent dissociative recombination of the molecular ions. Hence, the neutral composition in the thermosphere has a strong effect on plasma density in the upper thermosphere as the electron production rate depends on the concentration of atomic oxygen, O; whereas the loss rate is controlled by the molecular species N_2. Thus, increases in the ratio O/N_2 will increase the equilibrium electron density varying the plasma temperatures and ion densities. The higher $[O]/[N_2]$ signify higher production of O^+ ions and lower loss due to recombination with molecular N_2 (Ref. 29). Figure 4 represents estimated $[O]/[N_2]$ average value of normal days and $[O]/[N_2]$ values during solar flare period at corresponding solar flare location by NRLMSIS–00 neutral atmospheric model. Figure 4 shows decrease in $[O]/[N_2]$ ratio during flare time compared to normal days. Decrease in O^+ ion density during all the solar flare events as observed by SROSS-C2 satellite is explained by neutral composition analysis. Authors do realize that NRLMSIS–00 is a neutral atmospheric model and could be associated with some uncertainties. However, interaction via neutral composition could be a possible candidature of decreased O^+ ion density during flare period as compared to normal days.

3.2 Relation of ΔN (change in density) as a response to ΔT (change in temperature)

Table 2 represents the values of average ion temperature during normal, average O^+ and total ion densities during normal days and flare days, change in ion density (ΔN) and change in ion temperature (ΔT) during flare time and normal time. As per analysis of data measured by SROSS-C2 satellite, average O^+ and total ion density decrease and average ion temperature increases during these five selected solar flare events as compared to normal days. Thus, by convention in graphical analysis of Fig. 5, decrease in ion density is taken as positive physical quantity and increase in ion density is taken as negative physical quantity. At the same time, increase in ion temperature is taken as positive physical quantity and decrease in ion temperature is considered as negative physical quantity. Figure 5 shows relationship between ΔN as a response to ΔT of O^+ and total ion. Horizontal (x) axis represents ΔT and vertical axis (y) represents ΔN. Therefore, ΔN is dependent function and ΔT is

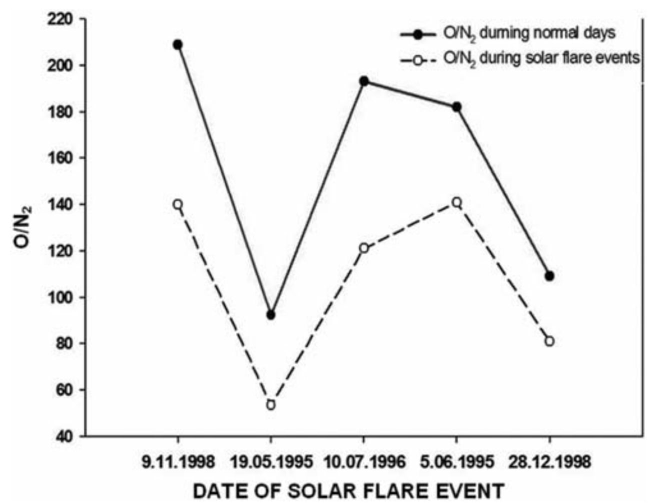

Fig. 4 — Variation of O/N_2 ratio during solar flares and normal days as estimated by NRLMSIS-00 model

Table 2 — Change in ion density (ΔN) and change in ion temperature (ΔT) during flare time and normal days for all selected five events as measured

S No	Date of event	Average ion temperature (T), K		ΔT, K	Average ion density (N), m^{-3}				ΔN (O^+ ion), m^{-3}	ΔN (Total ion), m^{-3}
					O^+		Total ion			
		Normal days	Solar flare time		Normal days	Solar flare time	Normal days	Solar flare time		
1	9.11.1998	1000	1190	190	1.50E+11	6.43E+10	2.01E+11	7.08E+10	8.57	13.02
2	19.05.1995	1050	1260	210	1.11E+11	6.55E+10	1.23E+11	7.06E+10	4.55	5.24
3	10.07.1996	1180	1630	450	2.2E+11	7.6E+10	2.4E+11	8.5E+10	14.4	15.45
4	5.06.1995	950	1310	400	1.36E+11	1.07E+11	1.39E+11	1.13E+11	0.29	0.26
5	28.12.1998	1240	1630	390	1.81E+11	1.41E+11	1.84E+11	1.43E+11	0.40	0.41

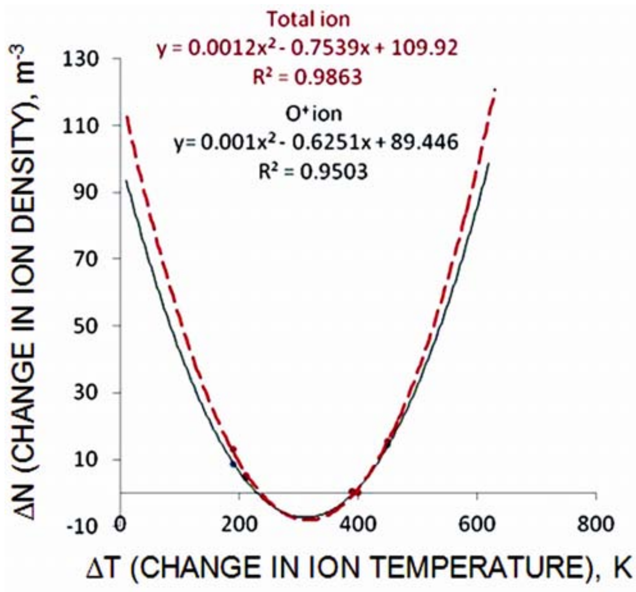

Fig. 5 — Variation of ΔN (change in ion density) with respect to ΔT (change in ion temperature) as response to solar flares

independent function. The solid line represents variation of ΔN as a function of ΔT of O^+ and dashed line represents variation of total ion. Both the curves of O^+ and total ion (solid and dashed) are in the form of parabola. Both the curves cut x and y axis allowing positive as well as negative values of ΔN and ΔT. As the curves are parabolic in nature, the quantities, ΔN and ΔT, are governed by quadratic equations.

Discussing ΔT *vs* ΔN of O^+ ion first, it is observed that both the quantities are governed by the equation $y = 0.001x^2 - 0.6251x + 89.446$, where y axis represents ΔN and x axis ΔT. Both the quantities are highly co-related to each other in accordance with the above equation, with co-relation factor, $R^2 = 0.9503$. The equation $y = 0.001x^2 - 0.6251x + 89.446$ is of the form $y = ax^2 + (-)bx + c$, where a and b are constants, c is the y intercept when x = 0. When y = 0, equation takes up the form $ax^2 + (-)bx + c = 0$. Solving the equation, $y = 0.001x^2 - 0.6251x + 89.446$, one gets x = 222 and 403 when y =0; and y = 89.446 when x = 0. Thus, it can be inferred that density can even increase within the limits of 222 < ΔT > 403 Kelvin. That is, if enhancement in temperature of ion between flare time and normal time is more than ~220 K and less than 450 K, density of O^+ can increase. At the same time ΔN = 89.446, when ΔT = 0. Extrapolating the graph, it can be said that if the decrease in O^+ ion density is more than 89.446 m^{-3}, ion temperature can decrease as an effect of flare.

On the similar lines, ΔT *vs* ΔN of total ion can be discussed. The relationship between ΔT (x parameter) and ΔN (y parameter) of total ion is governed by the equation $y = 0.0012x^2 – 0.7539x + 109.92$ has regression $R^2 = 0.9863$, which again indicates a strong univariate relationship between them. Analysis of parabolic curve of total ion density curve suggests that total ion density can increase as an effect of flares, if the increase in temperature is more than ~250 K and less than ~360 K during flare time as compared to normal days. At the same time, if the decrease in density is more than 110 K, ΔT takes up positive value that is ion temperature can decrease during flare time.

Data and graphical analysis using Indian satellite SROSS-C2 suggests negative and positive effects of solar flares. In the present analysis, positive and negative effects have been analysed during solar flares of almost same area and intensity ~5sfu, where ion temperature and density can increase or decrease as an effect of solar flares over low latitude F2-region.

4 Conclusion

The effect of solar flares on ionospheric ion density at low latitude F2-region have been studied for five selected solar flare events during 1995-1998 using Indian satellite SROSS-C2. It has been found that total ion density decreases during the solar flare events by 1.3 to 2.8 times over the normal day's average value of ion density. The density value has been compared with estimated IRI-2012 model values. The model indicates an overestimation of ion density data during flare event. Most affected species of ion during solar flares as measured by SROSS- C2 satellite (O^+, O_2^+, H^+ and He^+) remains O^+. Further, relation between change in ion density (ΔN) as a response to change in ion temperature (ΔT) during flare time and normal days, reveals that positive and negative effect of solar flare on temperature and density of ion is possible. That is, ion temperature and density can increase or decrease as an effect of solar flares over low latitude F2-region.

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