Indian Journal of Radio & Space Physics
Vol 50, November 2021, pp. 190-197

Low latitude, topside ionosphere composition and its variation with changeable solar activity

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Received: 13 November 2020; Accepted: 23 August 2021

The ions composition and their densities have been studied for different solar activity periods - along with their diurnal, seasonal and annual variations - for half of the 23rd solar cycle, covering solar minima (1995) to solar maxima (2000) over Indian sector (65–95°E and 5–35°N) at an average altitude of ~500 km. The study has been done by processing the data obtained from *in situ* measurement made by separate Retarding Potential Analyser (RPA) for electrons and ions, aboard Indian satellite SROSS C2. The plasma density has been found to be rich in O^+ ion for all instances of time and showed a direct increase with solar activity. H^+ has been observed to be in plenty during night time, especially from moderate to high solar activity period. The difference between H^+ and O^+ densities widens with increasing value of F10.7. He^+ always constitutes a small part of plasma but its density exceeds H^+ - during moderate to high solar activity period. O_2^+ has been found to be a minor constituent, even 3-4 folds lesser than He^+ density. A positive correlation with solar activity has been found for O_2^+.

Key Words: Topside Ionosphere, Solar activity, Solar Flux, SROSS C2, Ionospheric Constituents, F10.7

1 Introduction

Many scientific investigations have been carried out to explore topside ionospheric parameters like composition, electron and ion temperature and their density, critical frequency etc., along with their variation with geographical and magnetic latitude, longitude and altitude, solar activity, local time, season etc. In recent years studies have been done with *in situ* experiments, using retarding potential analyser (RPA) and Langmuir probe on board of various satellite missions, ground-based technology of incoherent scatter radar and various computer-based models[1,2,3,4]. However, *in situ* measurement database for F-region ionospheric studies over equatorial and low latitudes, particularly over the Indian subcontinent is not sufficiently available. Indian satellite SROSS C2 provides[5] the most advanced database of the topside ionosphere, especially F2 region over the Indian subcontinent for a period of almost half solar cycle starting from solar minimum to maximum. Solar radiations which show temporal and spatial variations affect chemical and physical processes, and make remarkable changes in the upper atmosphere. Carlson[6] estimated the ion composition for summer and winter seasons for solar minimum from 225-1400 km altitude range over Arecibo and asserted He^+ to be a minor constituent (about 20% or less) at all times. They found the dominance of light ions (more profoundly H^+) at an altitude of 450-500 km at night, but at much higher altitude (about twice) in the daytime of winter season. However, in summer season the transition region is thicker and higher. They also pointed out the seasonal difference in terms of the rate of change of composition at sunrise and sunset. Vickrey[7] in their study of postsunset physical processes-responsible for ionospheric-protonospheric coupling at Arecibo found that velocities of H^+ and O^+ ions differ largely in the topside ionosphere. The temporal behaviour of two vertical fluxes is different at higher and lower altitudes. They ruled out the possibility of a simple relationship between topside O^+ flux and total ion transport (ion transport is a well-established phenomenon) between ionosphere and protonosphere and thus led to future scope of study of the nighttime ionosphere. Kohlein[8] discussed the diurnal and seasonal variation of H^+, He^+,

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N^+, O^+ and electron density at an altitude of 1400 km, using longitudinally averaged observation of ISIS-2. Goel[9] discussed qualitatively the factors which are possibly liable for the anomalous increase of ion transition height during nighttime of solar maximum period in the equatorial ionosphere. The dominance of He^+ ions at an altitude of 900 km during the night-time of solar maximum (1981) was observed at mid-latitude by DE2[10]. Furthermore, Heelis[10] also analysed the neutral species distribution and appropriate ionization rates for the resultant light ions dominance. Hoegy[11] gave the altitude profile of ionospheric ion composition during 1970-1980 from satellite mission, Orbital Geophysical Observatory-6 and Atmosphere Explorer-C and compared their results with early altitude profiles by IRI-90 and other theoretical and empirical models. Klenzing[12] investigated the topside equatorial ionospheric density and composition during and after an extreme solar minimum of 2008, and concluded that the night-time topside ionosphere between the altitude range of 400 to 850 km is different in shape as predicted by IRI. The post-sunset ion density was found to decrease more rapidly than expected.

In this paper, ion composition of the topside ionosphere at an average altitude of ~500 km in terms of various ion concentrations (smoothed and averaged), along with their diurnal seasonal and annual variations under the influence of variable solar activity for almost half of the solar cycle, have been studied. The database is taken from the *in situ* measurements made by Indian satellite SROSS C2, in the region of the Indian subcontinent which is considered as the latest satellite data in the said geographical arena. The study of these ionospheric features, concerning solar events like coronal mass ejection and solar flare etc is beyond the scope of this paper. In the current study, solar activity, referred as solar cycle, defines activity in terms of sunspot numbers and this solar activity is scaled down with F10.7 index which is considered as a direct indicator of it. The half of 23rd solar cycle (1995-2000) has been considered in three solar ranges according to their F10.7 values viz: low solar activity period, 1995 (F10.7=77.1) to 1996 (F10.7=72.2), medium solar activity period, 1997 (F10.7=81.6) to 1998 (F10.7=117.4) and high solar activity period, 1999 (F10.7=154.5) to 2000 (F10.7=177.9).

2 Materials and Methods

Indian satellite SROSS C2 was launched on 4 May 1994 in an elliptical orbit of 938x437 km which was brought down to 630x430 km after two months of operation, for making the orbit less elliptical. This satellite mission ended on 12 July 2001, covering seven years of its active life - a period from minima to maxima of 23rd solar cycle. An aeronomy payload consisting of separate sensors - Retarding Potential Analysers (RPA) for electron and ion, and a potential probe (PP) - was onboard the satellite for making *in situ* measurements of the equatorial and low latitude ionosphere[13,14]. The satellite was also equipped with a reaction control system (RCS), which could correct the orbit on a routine basis and also alter the orbital height if required. The electron and ion RPA sensors consist of four grids and a collector electrode, which are mechanically identical but are provided with different grid voltages. By applying appropriate bias voltages on different grids, only those electrons or ions with energies greater than the applied voltage on the retarding grid are allowed to reach the collector plate, to cause collector current which is measured by sensitive electrometer amplifiers. The characteristic ***I-V*** curves of the collector current (*I*) versus retarding grid bias voltage (*V*) thus obtained is used to derive information about plasma characteristics like electron and ion densities, their temperatures, irregularities in ion and electron temperature, densities and ion composition (H^+, He^+, O^+, O_2^+/NO^+, Fe^+) and other parameters. The RPA payload was designed to measure electron/ion densities within the limits of 100-5x10^6 particles per cm^3 with an uncertainty of ±5%. Some aspects of this aeronomy experiments have been discussed by Garg & Das[15] and Garg[5] et al. Payload data collection was done at the main ground station, Bangalore (12.5° N, 77.3° E); the other two ground stations were Lucknow (26.8° N, 80.8° E) and Mauritius (20° S, 56° E). For the present study Data for O^+, O_2^+, H^+ and He^+ ions were derived from ion RPA within error limit of ±5% during the experiment, over Indian sector (65–95°E and 5–35°N) at an average altitude of ~500 km. A seasonal study has been carried out by classifying dataset for three different seasons viz: winter (November, December, January, February), summer (May, June, July, August), and equinoxes (March, April, September, October). Data for F10.7 was assimilated from the website of National Geophysical Data Center (NGDC), Boulder, Colorado. In the current study averaged values of F10.7 are used.

3 Results and Discussion

The topside ionosphere, especially F2 region over Indian subcontinent area (65–95°E and 5–35°N) at an average altitude of~ 500 km is explored for ion composition and its variation with solar activity for 23rd solar cycle with the database obtained from *in situ* measurements made by Indian satellite SROSS C2. At this altitude, the most abundant ions found were O^+, O_2^+, H^+ and He^+, and the satellite also gives the data for these ions.

3.1 Low Solar Activity Period, 1995 (F10.7=77.1) to 1996 (F10.7=72.2)

The average of total ion density during a period of low solar activity (1995-1996) is found about 1.5E+11 m^{-3}. The ionosphere for the same period is found least dense during early morning pre-sunrise hours (2:00-6:00 hrs LT) and show a diurnal maximum during noon time (11:00-14:00 hrs LT), however, the phenomenon is delayed by 1-2 hrs for the winter season (Fig. 1). The topside ionosphere at altitude approximately 500 km is found to be mostly populated with O^+ ions, and O^+ ions are the major contributors of the ionospheric ion density based on SROSSS-C2 *in situ* measurements. The O^+ ion density shows a diurnal minimum (10^9 m^{-3}) in early morning pre-sunrise, and dawn hours (3:00-5:00 hrs LT) with minor variations for different seasons then it reaches its peak value (10^{11} m^{-3}) at local noon time in equinox and summer seasons (11:00-14:00 hrs LT However, for the winter season the maximum ion density was

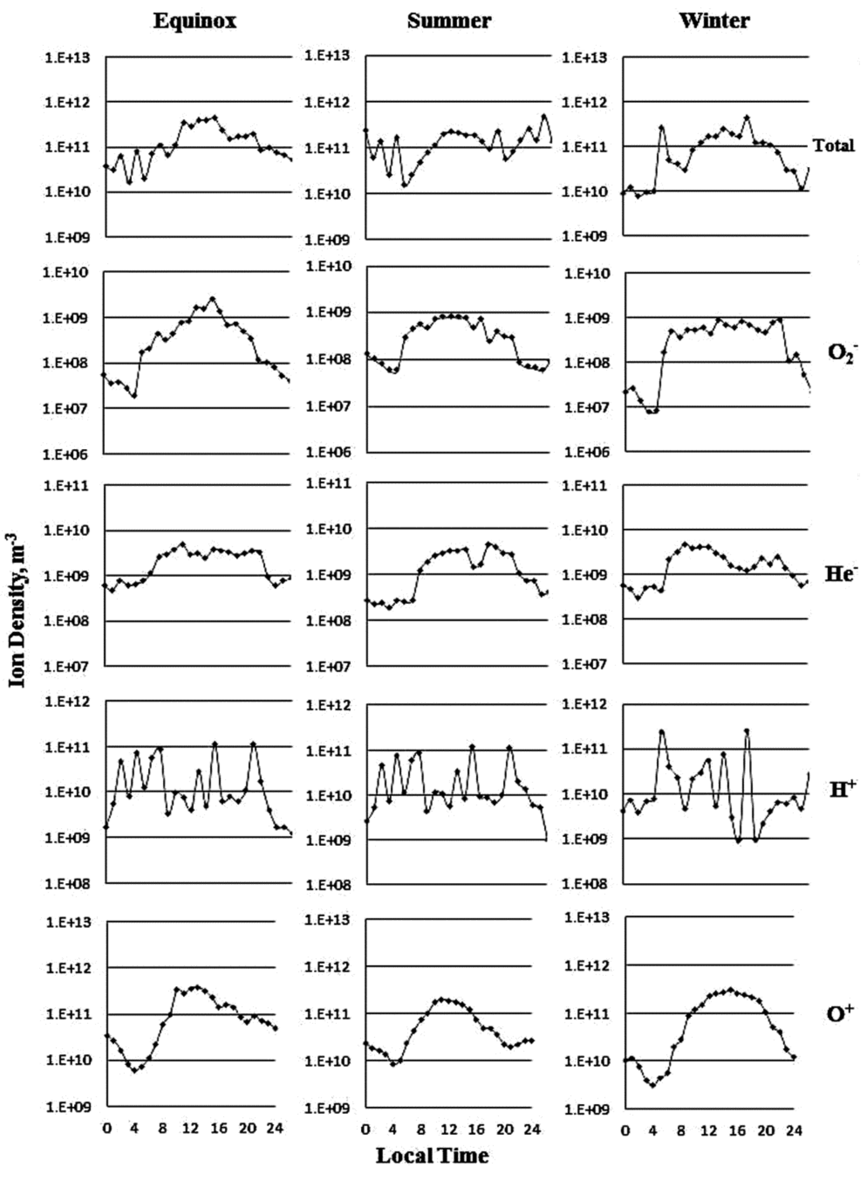

Fig. 1 — The ion density distribution with respect to local time over Indian region at an altitude of ~ 500 km during the low solar activity period as measured by SROSS-C2 for three seasons.

observed at at later time (13:00-15:00 LT). than equinox and summer.

It is clear from Fig. 1 that sharper peaks of O^+ ion density are obtained during the summer season than winter season or equinox. The average O^+ density exemplifies a variation between 10^9-10^{11} m^{-3} during the low solar activity period for different seasons.

H^+ ion, another important constituent of the ionosphere and its dynamics, its density plot against local time shows many small peaks and troughs, so time slot cannot be confined for perfect diurnal minimum and maximum. Additionally, a variation with the seasons is observed, although ion density is high around local sunrise (5:00-7:00 hrs LT). The day's maxima and minima values differ by one order of magnitude from the day's average values, although the exact values vary with season. During the considered low solar activity period, night-time values are comparable or slightly higher than daytime values. During the daytime (10:00-14:00 hrs LT), the H^+ ion density is found to be two orders of magnitude lower than O^+ ion density during the same period, however, the difference is marginal for the night-time values of H^+ and O^+ densities. For a solar minimum period of 1995-96 over Indian region, Bhuyan[16] observed that O^+ - H^+ transition height drops to as low as ~500 km at night and this holds good reason for our observation of the small difference in nighttime values of O^+ & H^+ densities during the low solar activity. Similarly, Coley[17] also reported extremely low transition height of O^+ - H^+, during solar minimum in the year 2008. The similar kind of observation, i.e., O^+ - H^+ transition altitude during solar minimum was made by Gonzalez[18]. They found the transition altitude at about 750-825 km during the daytime and 550-600 km during the night-time. He^+ ion, earlier, was considered to be a minor species of topside plasma and even sometimes was neglected in ionospheric studies, however, the recent research established the very existence of He^+ ion in the ionosphere. Day's lowest He^+ ion density is found at late night hours (00:00-4:00 hrs LT) during low solar activity period. Gonzalez[19], in their study of altitude distribution of He^+ ion from topside incoherent, scatter radar measurements (ISR) at Arecibo during equinox solar minimum conditions, find the intensification of He^+ ion layer near the O^+-H^+ transition height, especially during the night, although this intense layer is still not comparable with H^+ or O^+ ion concentrations and it constitutes only 10-20% of topside plasma. Since the O^+-H^+ transition height shows diurnal variation; similarly He^+ ions follow the same variation w.r.t. altitude. Winter season shows the higher concentration in forenoon hours, unlike the summer season. However, equinox shows many small diffused peaks as compared to the sharp peak of the other two seasons. During the low solar activity period, H^+ density is always found to be higher than that of He^+. The observational results presented in the paper support and confirm previous observations[19].

We observed O_2^+ is a minor constituent in the Indian longitude sector at an average altitude of ~500 km with a variation of 10^7-10^9 m^{-3}. Furthermore, it is detected 2-3 times lower in number than that of O^+ and even 3-4 fold less dense than He^+. The diurnal minima is observed at late night (00:00-3:00 LT) irrespective of the season and solar flux, whereas, the diurnal maxima is detected between 11:00-15:00 LT which is perhaps slightly delayed during the winter season.

3.2 Medium Solar Activity Period, 1997 (F10.7=81.6) to 1998 (F10.7=117.4)

The average values of the total ion density over 2 years (1997-98) during the medium solar activity is approximately twice to that observed during the low solar activity with the similar patterns of diurnal and seasonal behaviours (see Fig. 2). We have also observed that O^+ ion density enhanced almost to double in number from low to medium solar activity with a similar pattern of diurnal and seasonal behaviours. A positive correlation with solar flux can be seen as evident from Fig. 4. Higher values of H^+ ion density at late night hours than daytime values are found for this solar activity period and this difference is more pronounced than that of low activity period for all seasons. However, the difference is highest for equinox season and December solstice shows the lowest difference between two values of night and daytime. The average value of H^+ density depletes by one order of magnitude from low to medium solar activity period which suggests its negative relation with F10.7. Daytime values of He^+ ion are higher than night values irrespective of solar flux but this difference deepens from low to medium solar activity period (Fig. 5). Seasonal variation during this period is almost similar to a low activity period in the same geographical region. Diurnal and seasonal behaviour of O_2^+ during this period is similar to that of a low activity period. Enhancement in O_2^+ density values from low to medium solar activity period suggest its

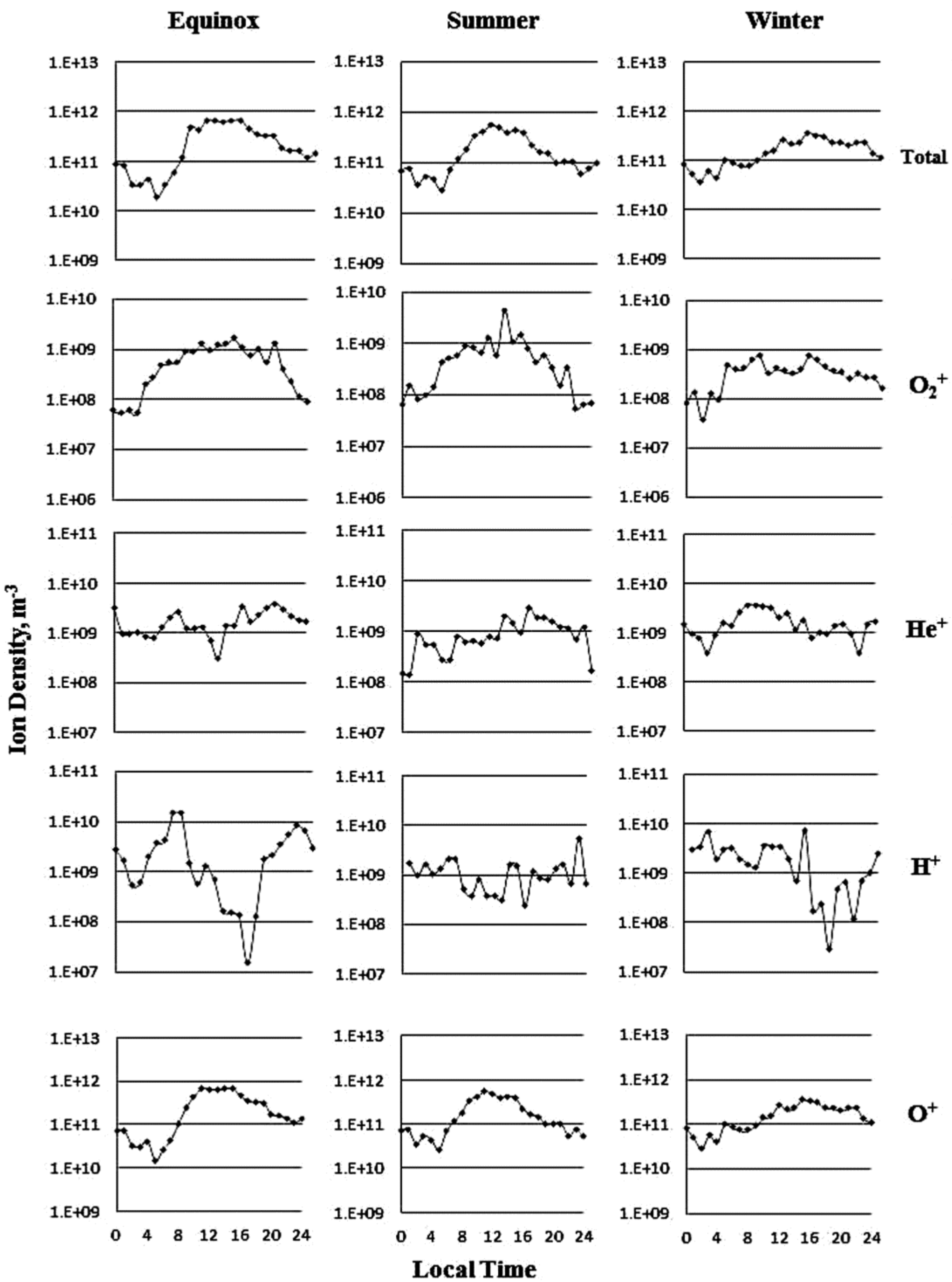

Fig. 2 — The ion density distribution with respect to local time over Indian region at an altitude of ~ 500 km during the medium solar activity period as measured by SROSS-C2 for three seasons.

positive variation with solar flux, however, still, it remains a least abundant constituent of plasma, among detectable ions.

3.3 High Solar Activity Period, 1999 (F10.7=154.5) to 2000 (F10.7=177.9)

An enhancement in the total ion density by more than one order of magnitude is observed from low to high solar activity periods with similar patterns of diurnal and seasonal variations and is clearly illustrated in Fig. 3. Values show a strong positive correlation with F10.7 as evident from the correlation coefficient, R^2=0.8778 and it is mostly influenced by O^+ ion. On an average basis, O^+ ion density varies between 10^{10}-10^{12} m^{-3} during high solar activity period for different seasons. Diurnal and seasonal variations are similar for all solar flux values. A perfect correlation with F10.7 is confirmed by R^2 value (R^2=0.9354).

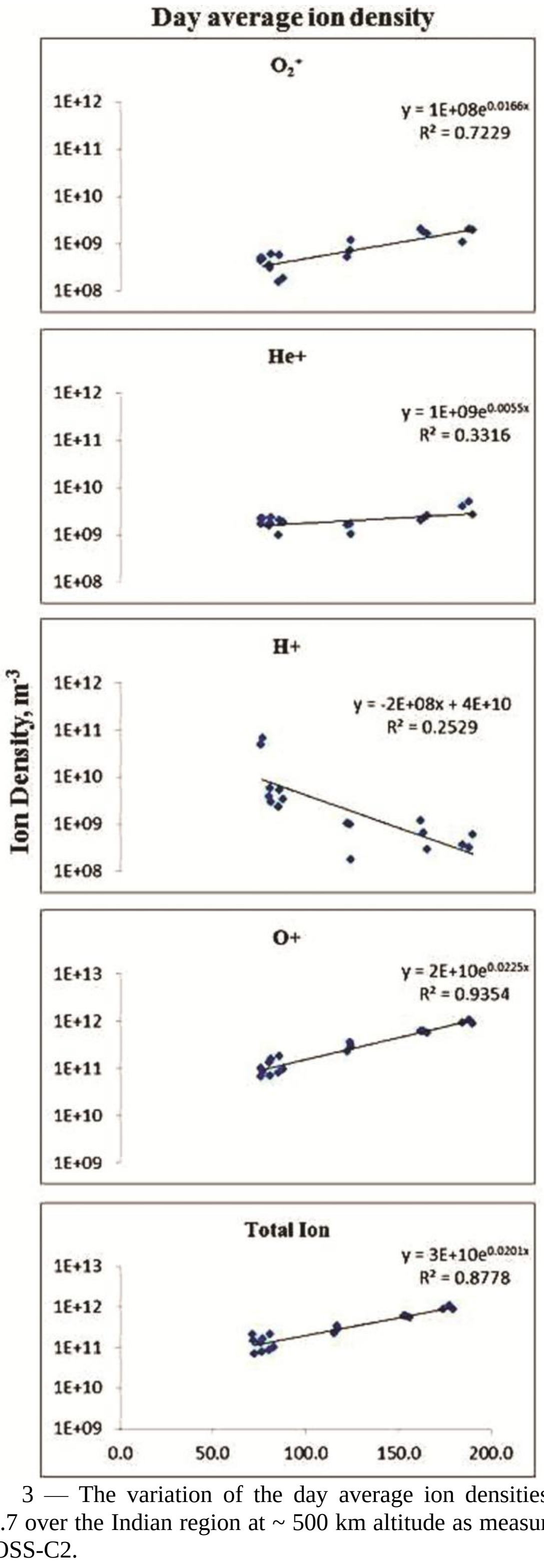

Fig. 3 — The variation of the day average ion densities with F10.7 over the Indian region at ~ 500 km altitude as measured by SROSS-C2.

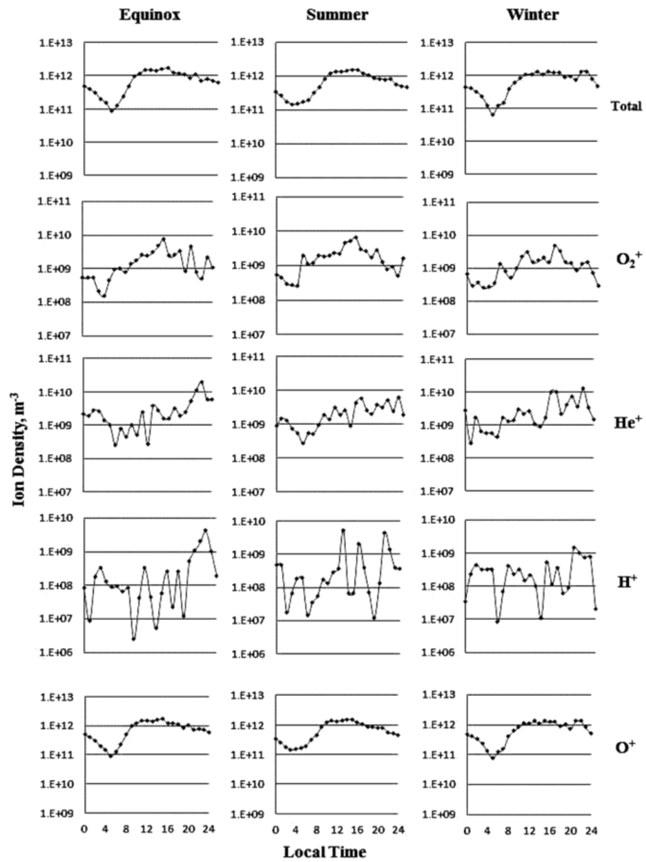

Fig. 4 — The ion density distribution with respect to local time over Indian region at an altitude of ~ 500 km during the high solar activity period as measured by SROSS-C2 for three seasons.

H^+ ion density further depletes by one order of magnitude on moving from medium to high solar activity periods**.** During the high solar activity period, the peak in the H^+ ion densities is seen at night-time which also vary with season. Daytime (10:00-14:00 hrs LT) H^+ ion density is found to be four order of magnitude lesser than corresponding O^+ ion density for this period, although this difference is slightly low for corresponding night-time values of H^+ and O^+ densities. It can be concluded as; H^+ ion density at late night hours is relatively higher than daytime values for medium to high solar activity period during all seasons.

The day's lowest He^+ ion density during high solar activity occurs around local sunrise (5:00-7:00 hrs LT). Daytime values are found higher than nighttime values. The night-time ion density is relatively more influenced by F10.7 than the daytime values[20], however, the daytime ion density is hardly affected by F10.7. He^+ ion density does not show a significant variation with solar flux but shows a weak positive correlation with it (R^2=0.3316) (Fig. 4). During the low solar activity period, day average H^+ density is found to be higher than that of He^+, but from moderate to high solar activity period day average He^+ ion density surpasses H^+ concentration in the

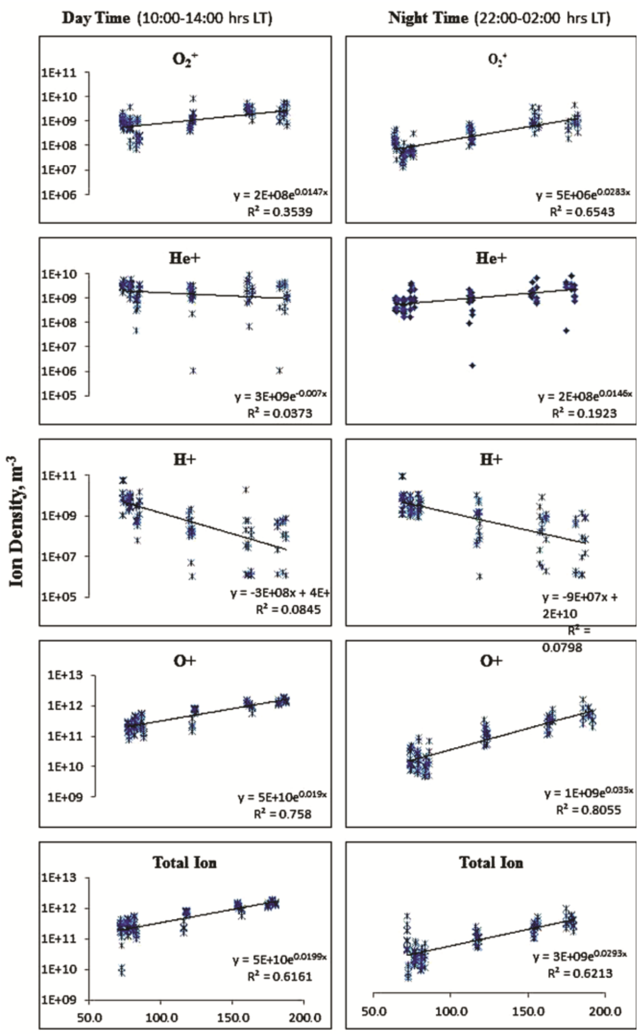

Fig. 5 — Variation of daytime (10:00-14:00 hrs LT) and night-time (22:00-02:00 hrs LT) averaged ion density with F10.7 over Indian region at ~500 km altitude, as measured by SROSS-C2.

same geographical region. Su[21], found the dominance of light ions H^+ and He^+ at 600 km topside ionosphere during moderate to high solar activity at night hours with more events with high H^+ density than He^+. The diurnal and seasonal behaviour of O_2^+ are independent of solar activity. An increase in O_2^+ density by one order of magnitude is witnessed on moving from low to high solar flux periods; and hence a positive correlation with F10.7 is seen (R^2 = 0.7229) in Fig. 4.

4 Conclusion

The topside ionosphere composition at an average altitude of ~500 km and its variation for variable solar activity period over Indian subcontinent region has been studied with dataset obtained from *in situ* measurements made by separate electron and ion RPA aboard Indian satellite SROSS C2. It has been found that total ion density is directly affected by solar activity and hovers by 2 order of magnitude on moving from low to high solar activity periods. O^+ is the main contributor to total ion density. A perfect correlation of O^+ ion density with F10.7 (Fig. 4) is confirmed with R^2 = 0.9354. H^+, He^+ and O_2^+ are other important constituent ions of plasma at this altitude. A negative correlation of H^+ density with F10.7 is from the dataset. He^+ ion density shows a weak positive correlation with solar flux (R^2=0.3316). Nighttime He^+ ion density is relatively more affected with F10.7 than daytime values. A positive correlation of O_2^+ with F10.7 (R^2=0.7229) is made obvious from the study. Nighttime ion density is found to be marginally affected more than daytime with F10.7

Acknowledgement

Authors pay their gratitude to teams of Indian Space Research Organization, India and National Physical Laboratory, Delhi, India for design and execution of the SROSS C2 satellite mission and payloads. One of the authors, Bindu Mangla is thankful to J C Bose University of Science and Technology, YMCA and Manav Rachna International Institute of Research and Studies, Faridabad for providing the necessary help and conducive atmosphere. N. K. Dwivedi acknowledges the Austrian Agency for International Cooperation in Education and Research Project No. IN 05/2018 and Department of Science and Technology, India Project No. INT/AUSTRIA/BMWF/P-14/2018.

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