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Research Article

SOLAR ACTIVITY VARIATION AND ITS EFFECTS ON IONOSPHERIC ION DENSITIES

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ABSTRACT

As the Sun progresses through its solar cycle and its activity increases, a greater number of sunspots occur, and solar fluxes become more intense. The change in solar activity is related to the change in electron and ion density of the ionosphere. Studying this relation is very important in terms of space plasma studies and space weather predictions, which play a significant role in radio and satellite communication as well as GPS navigation. In this paper, we are presenting the sunspot and solar flux data for solar cycle 24 (year 2008-2020). We are using C/NOFS satellite data to understand the variation of ion densities of the upper atmosphere with solar cycle 24. Our analysis shows decrease of H+ density by a factor of 10 and increase of O+ density by a factor of 10 during solar maxima. This data set can be used as a framework for future advancement in empirical modelling of regional and global ion density of the ionosphere.

KEYWORDS

Solar cycle, Ion density, Ionosphere, Solar flux, Sunspot.

INTRODUCTION

Understanding of the space weather is important as it has a major impact on satellites and astronauts. Parametric models can describe and predict space weather and Earth's upper atmosphere (Mannucci AJ, 2016). Knowing the distribution and evolution of ionospheric mass density is crucial for tracking the drag impacting low-Earth-orbiting satellites (Zhang, 2015). The high energy electromagnetic radiation produced by the Sun can cause major harm to astronauts exposed to it. Ionizing radiation breaks down DNA and

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creates high levels of clustered DNA damage (Lomax, 2013). Telecommunication and GPS coordinates are made possible through hundreds of satellites monitoring the Earth and producing an improved model that can better describe the Sun's interactions with our atmosphere. As the Sun progresses through its eleven-year solar cycle the production of amount of charge particles and radiation changes. This causes the change in ion densities of the Earth's ionosphere. Hydrogen, Helium, and Oxygen (H+, He+, O+) are the three main species of ions found in the ionosphere. The highly active Sun during solar maxima emits highly energetic plasma, but its effect on Earth's ionosphere depends on factors like propagation from Sun to Earth and interaction with Earth's magnetosphere (Triskova, 2000), (Baker, 2016); (Hathaway, 2015), (Yermolaev, 2013). OGO, AE, DEMETER, DMSP, and CNOFS are a few satellites that provide in-situ measurements of ionospheric ion densities. Measurements by satellite ISS-b at 1100 km altitude shoed that H+ ions have a negative correlation with solar flux (F10.7) and O+ ions have positive correlation with solar flux and H+ ions have negative correlation with solar flux (Iwamoto, 2000), (Gonzalez, 2004). (Truhlik, 2005) have found an increase of He+ ions with solar activity at an altitude above 1000 km. They have used databases from OGO-6, AE-C, AE-E, and IK-24 satellites over the period of 1960 up to 1990. Using SROSS C2 and FOMOSAT-1 satellite data, (Borgohain A. and Bhuyan, 2010) have studied diurnal, season, and latitudinal variation of O+, H+, He+, and O2+ ion density distribution. (Shen, 2017) have studied H+ ion densities and drift using DEMETER and DMSP satellite data at an altitude of 670 km. They have found seasonal enhancement of hydrogen ion during December in the northern hemisphere. Using CNOFS/CINDI data during solar minimum time, (Heelis, 2008) have found that the O+/H+ transition height is around 450 km altitude during at night time and rises to 850 km during day time.

Method

In this research, the H+, He+, and O+ ion densities were studied to see the changes that occur during the solar maxima and minima of cycle 24. Solar cycle 24 started December 2008 and ended in December 2019. The sunspot data gathered was recorded by the Royal Observatory of Belgium (http://www.sidc.be/silso/datafiles) and the solar irradiance data was collected by Natural Resources Canada (http://www.spaceweather.gc.ca/solarflux/sx-5-mavg-en.php). The Royal Observatory of Belgium recorded the data using a coronagraph telescope called the swap, which stands for the Sun Watching using Active Pixel System Detector and Image Processing. A coronagraph telescope is a type of telescope that mimics the effects of a solar eclipse and blocks out the light coming from the sun's photosphere. This allows scientists to gather data on the corona. The swap telescope is mounted on a satellite called the PROBA2, which stands for Project for On Board Autonomy. We have used the ion density data from the instrument CINDI of C/NOFS satellite. The data is available on NASA'swebsite (https://hpde.io/NASA/NumericalData/CNOFS/CINDI/IVM/PT0.5S.html). C/NOFS stands for Communication/Navigation outage Forecast System and is a United States minisatellite with the objective to observe and forecast the ionospheric irregularities in the Earth's equatorial region which can impact satellite communication systems, like GPS. The Coupled Ion-Neutral Dynamics Investigation (CINDI) is a NASA sponsored Mission of Opportunity conducted by the University of Texas at Dallas (UTD). CINDI and C/NOFS were designed specifically to study the disturbances in Earth's ionosphere that can cause

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satellite damage and interference of communication between ground and satellites. C/NOFS was air-launched on April 16, 2008, at Ronald Reagan Ballistic Missile Defense Site located near the equator to obtain an equatorial orbit easier. This satellite had an apogee near 850 km and perigee near 400 km with an orbital inclination angle of 130. The satellite decayed in the atmosphere in December 2015. To study the specific major elements that have the biggest impact on space weather they used an onboard instrument called CINDI. It has both ion and neutral sensors called the Ion Velocity Meter (IVM) and the Neutral Wind Meter (NWM) which allows it to make measurements of the variations of the neutral and ion densities. Measurement of the total number of ions entering the IVM can provide information on ion density is at that point in space. Measuring the variations of the ion velocities over a short period of time can provide both the temperature of the ions and their relative composition by elements. Studying the motion of the ions and its density variation with time, season, and solar cycle can help us understand and predict the formation and movement of ionospheric density structures and irregularities. Ionospheric irregularities can cause scintillations which can interfere with the radio signals traveling between the Earth and satellites further out, they can begin to forecast when these outages will occur and how severe they will be. These findings will further advance the study and prediction of space weather, similar to our ability to predict weather events on Earth.

Results

Both solar flux (F10.7 cm) and sunspot are good indicators of solar activity and correlate very well. The graphs in figure 1 show that the variation of number of sunspots and the solar flux are directly related with solar activity during the period December 2008 to December 2020. As the Sun's activity increases both the number of sunspots and the solar irradiance increase. This relationship is important to understand how the solar cycle affects the ionosphere. With higher activity the sun produces more high energy electromagnetic radiation which impacts Earth's atmosphere. From 2008 to 2010 our sun was going through a solar minimum, which means the sun was in a less active state. During this time the earth was impacted by less high energy electromagnetic radiation and high speed charged particles than when the sun is at a more active state. The solar flux varies 60 sfu (solar flux unit) up to 68 sfu during solar minima time. There were about 12 days with zero sunspot on Sun's surface during solar minima. From 2013 to around 2014 our Sun was in a solar maximum activity period. During this time the solar flux varies between 90 to 150 sfu and sunspot number varies between 60 to 140. The high energy electromagnetic radiation that impacts Earth interacts with our atmosphere. This interaction of high energy radiation with the gases in the atmosphere ionizes the atoms and molecules.

Hydrogen ions are one of main constituents of the ionosphere and comprise of more than 90% of total ions. It is highly affected by the change in solar activity shown in figure 2. The blue data points were taken from May 11 to June 11 in the year 2009 (during extreme solar minimum period). The red stars represent the data taken from May 11 to June 11 in the year 2013 (during extreme solar maximum) period. The graph shows that during the solar maximum hydrogen ion density decreased by about a factor of ~10 compared to hydrogen ion density during solar minimum period.

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During solar minima hydrogen ion density varies between ~103 cc to ~104 cc and during solar maxima hydrogen ion density varies between ~102 cc to ~103 cc. The altitude covers the plot from 400 km to 800 km, latitude covers from -12.5 degree to 12.5 degree. This shows that when the Earth's atmosphere is exposed to less amounts of radiation the rate at which hydrogen atoms ionize increases. It is the ionization of oxygen atoms that affects the ion density of hydrogen. As the oxygen atoms get ionized, they produce electrons to move around freely. This increases the electron and ion densities. With the higher electron, ion densities the free electrons bond with the hydrogen ions. This can be shown in in the equilibrium equation $O + H^+ \rightleftharpoons O^+ + H$. The ionosphere is in equilibrium with atoms becoming ionized and ions interacting with electrons to form neutral atoms. These two reactions are at a balance, and if the electron ion density is increased then there will be more electrons interacting with the hydrogen ions to produce more neutral hydrogen atoms. (Shen, 2017).

Figure 3 shows the oxygen ion density in the ionosphere covered by C/NOFS satellite. Blue circles are the data from May 11 to June 11 in 2009 (extreme solar minimum), and the red stars are the data from May 11 to June 11 in 2013 (extreme solar maximum). The data presented in figure 2-b covers altitude from 400 km to 800 km, latitude from -12.5 degree to 12.5 degree. Overall, during the minimum period, oxygen ion density changes from ~ 5x103 cc to ~ 6x105 cc and during solar maximum period it changes from 105 cc to 106 cc. On average oxygen ion density decreases almost by a factor of 10 during the solar minimum compared to solar maxima period. Since oxygen is a denser element, it sinks lower into the atmosphere, so the oxygen is not as exposed to solar radiation. When the Sun is more active and more solar radiation impacts the Earth, there is more penetration of high energy radiation to the oxygen atoms in the atmosphere. The more exposure to radiation causes more oxygen atoms to ionize. This does increase the electrons in the environment but unlike hydrogen ions the oxygen ions do not get affected a substantial amount. The data shows that electrons tend to bond to hydrogen ions more than oxygen ions. This would explain why the oxygen ions increase during the solar maximum. (Shen, 2017).

Helium ions constitute a very small portion of the ionospheric constituents (1-2%). As shown in figure 4, helium ions do not show much dependence on solar activity as compared to hydrogen and oxygen ions. The time range the data was taken for the solar minimum, blue circles, was from May 11 to June 11 in the year 2009 and for the solar maximum, red stars, was from May11 to June 11 in the year 2013. The data presented in figure 2-c covers altitude from 400 km to 800 km, latitude from -12.5 degree to 12.5 degree. Overall, during the minimum period, oxygen ion density changes from ~102 cc to ~104 cc and during solar maximum period it changes from ~103 cc to ~104 cc.

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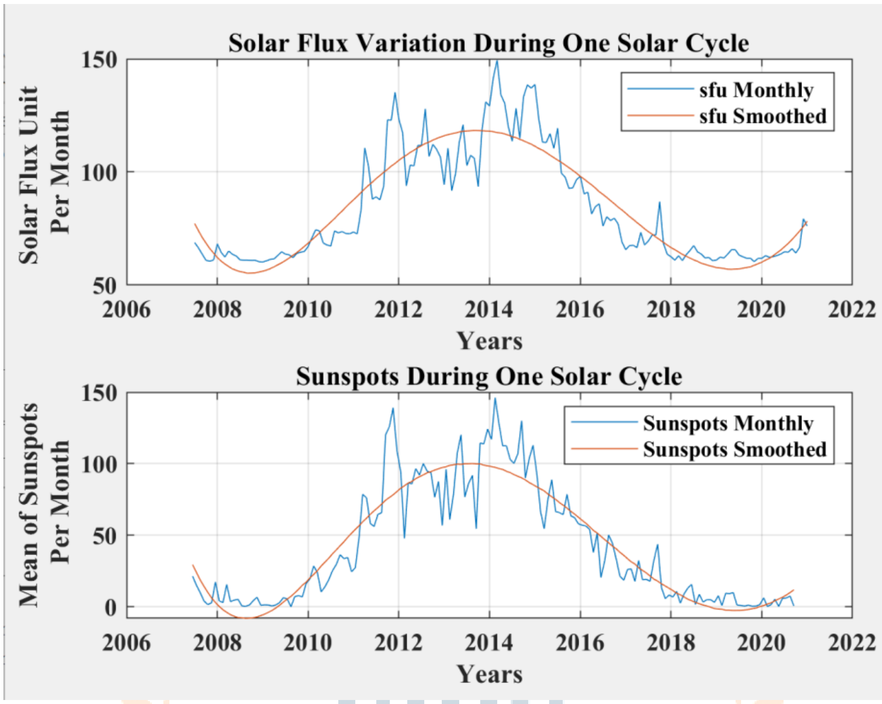

Figure 1. solar flux and sunspots variation during solar cycle 24.

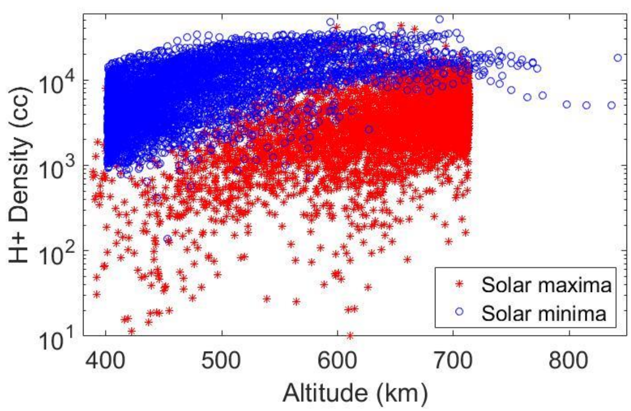

Figure 2. Hydrogen ion density variation

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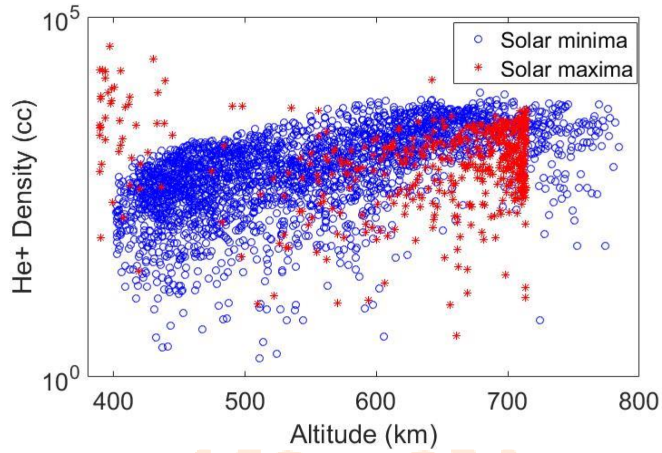

Figure 3. Oxygen ion density variation

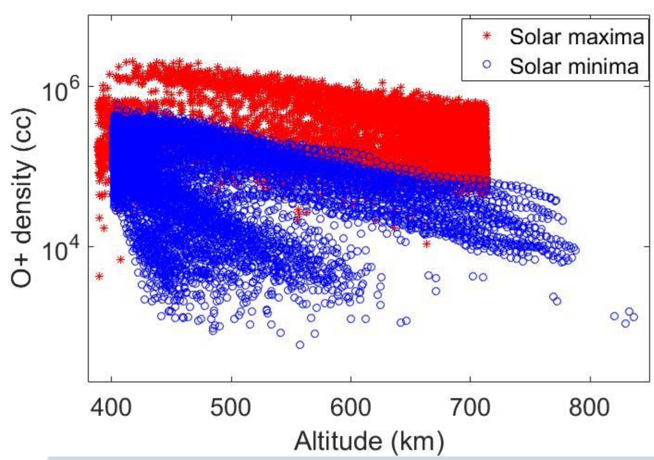

Figure 4. Helium ion density variation

CONCLUSION

In this research we have analyzed the solar activity variation and compared it to the changing ion densities of the topside ionosphere. The Sun plays a major role in the ionization of particles in the atmosphere as the amount of radiation changes with solar activity. During the solar minimum in 2008 the data showed an increase in hydrogen ions and decrease in oxygen ion density. During the solar maximum in 2013 the hydrogen ion density decreased, and oxygen ion density increased. The hydrogen ion shows a negative correlation with solar activity, oxygen ions show positive correlation with solar activity, and helium being the minor constituents of the ionosphere, does not show much variation with solar activity. As the Sun grows more active over the solar cycle more high energy electromagnetic rays and high energy particles come into our atmosphere. This causes more oxygen and hydrogen atoms to be ionized and release more electrons into the atmosphere. Charge exchange between Oxygen ions and hydrogen atom can cause the increase in hydrogen ions during solar minimum as given by O+ + H ⇌ O + H+. During solar minima, the decrease in solar ionization flux and lowering of the neutral oxygen atomic scale height cause the decrease of oxygen ion density. Also, there is an increase in hydrogen density accompanied by decrease in oxygen during solar minima and hydrogen atom has scale height much higher than the oxygen atoms. Oxygen ions created by solar photo ionization exchange electrons with neutral hydrogen atoms and causes the increase in hydrogen ion density during solar minima (West, 1997), (Shen, 2017).

RECOMMENDATIONS

Understanding of the ion density in ionosphere is important as it can provide better understanding of the cold plasma distribution of the plasmasphere. As a part of future work, we can analyze more data on ion density distribution based on solar activity, seasonal variation, and latitudinal variation. This database can provide a framework for empirical model of ion density distribution of the ionosphere along with data from other satellites like OGO, AE, DEMETER and DMSP. The transition height and effective ion mass are the two very important parameters of ion density. Further analysis of our data can provide more information on these two parameters.

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