Introduction to Atmospheric and Space Sciences
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Lecture - 41
Ionospheric layers and Photochemistry

Hello dear students. In today's class we will try to understand important aspects about earth's ionosphere. So, in our discussions of the Introduction to earth's Atmosphere; we have seen the temperature structure of the earth's atmosphere where we have categorized the atmospheric layers into four different regions based on the temperature. So, during that discussion itself we have made a mention that the earth's atmosphere can also be characterized based on the electrical properties, such as electron density, conductivity and stuff like that.

So, in today's class we will try to see how different is the earth's ionosphere, what are the physical and chemical processes that will be dominant in the earth's ionosphere, what is the physical reason for the existence of electrons and ions in the ionosphere. And why should it be called as ionosphere and so many important things concerning the ionosphere. Now, most importantly let us say if you want to understand the basic definition of ionosphere let us say.

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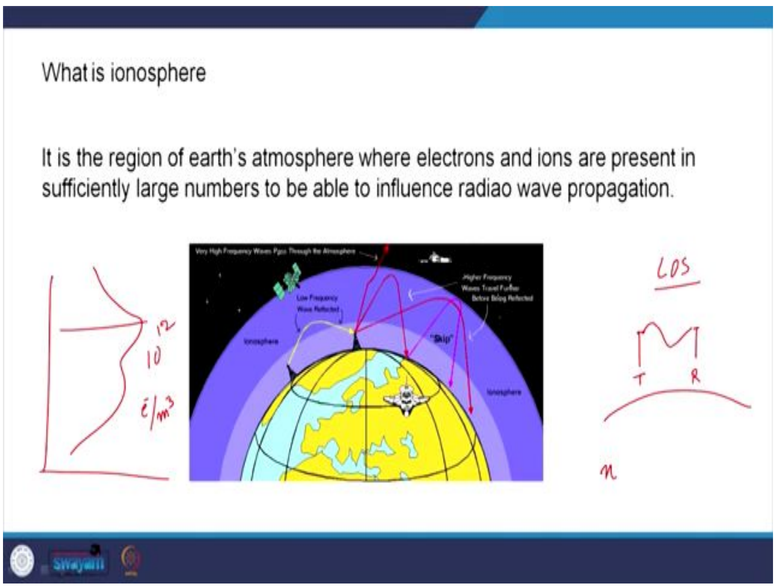

what is ionosphere? Ionosphere can be defined or can be precisely let us say given the definition saying that; it is the region of earth's atmosphere where the electrons and ions are present in sufficiently large numbers to be able to influence the radio wave communication.

So, this whole purpose of earth's ionosphere is that it acts as a refracting layer allowing propagation of radio wave signals or communication using radio wave signals beyond line of sight. So, what generally happens is, since the earth is curved. So, in this picture what has been shown is that the earth's ionosphere has the ability to reflect radio waves.

So, the ability to reflect a radio wave generally depends on the refractive index of the medium. If there is an incoming incident radiation, the refractive index of the medium will decide whether the wave should be allowed to propagate or the wave should be reflected.

So, based on the amount of charge density that exists in the ionosphere, the refractive index can be defined and similarly another parameter which is called as plasma frequency can be defined and there will be a matching criteria or condition between the frequency of the ionosphere. There is a plasma frequency and the frequency of the incident wave if it matches a particular condition; we will realize that this particular radio wave will be reflected.

So, what has been shown in this figure is that. So, generally line of sight propagation is a most earliest way to transmit signal from one point to another point. So, what has been seen is that the wavelength. So, for achieving line of sight propagation if you have let us say two term two antennas; one is transmitter and another receiver.

If you have sufficiently a wave with sufficiently longer wavelength, then probably it may be possible that you can transmit and you can receive this particular signal. But if you want to achieve this communication over a very longer distances then preferably this may this method may not work.

So, then it has been realized after beginning that , there was communication which was possible beyond line of sight. So, this was using the ionosphere. So, people realized there is a conducting layer in the sky which acts as a mirror and reflects the incoming radio waves and allows propagation of signal or communication beyond the line of sight.

So, it may happen that generally, higher frequency waves travel further before they get reflected. So, in this lecture, we will realize that ionospheric density is not something which is constant in height. ionosphere has a density. So, when I say density I mean the number of electrons or ions per unit volume. So, density of the ionosphere in terms of charge concentrations is the number of electrons or ions per unit volume.

So, the ionospheric density increases as you go up from the ground and it will decrease as you go away again towards the higher altitudes. So, the density reaches a maximum at a particular height which is called as F layer. This particular height the density is 10 to the power of 12 electrons per unit volume. So that means higher frequency waves travel further, I mean; they travel towards higher altitudes before they get reflected. So lower frequency waves will get reflected at much lower altitudes and higher frequency waves will get refracted at very high altitudes

So, this is the basic idea. And very high frequency waves will pass through the ionosphere. So, ionosphere will not be able to influence these very high frequency waves. So, the role of ionosphere is to reflect radio wave propagation that is happening from the earth and it will only be able to reflect radio waves up to a certain frequency. Beyond certain frequency in the higher cut off region, the ionosphere will not be able to reflect radio waves, rather the ionosphere acts as a transparent layer for the radio waves to escape into the space.

So, it has been seen that various communication devices or various communication methods have been devised to exploit this reflecting property of the ionosphere. So, the ionosphere is the charged layer of the earth’s atmosphere where enough number of electrons and ions are present to be able to influence the radio wave propagation right. So, that is the basic definition.

So, in this class what we will try to do is we will try to understand the various layers of ionosphere, what is the fundamental existence, when was the fundamental existence of ionosphere was realized and what were the major scientific breakthroughs in this particular area of research and things like this.

So, we will try to understand how does the ionospheric layers appear, when do they appear what is the chemical scheme behind the production in these particular regions. And this discussion is mainly going to be focused on the understanding of ionospheric layers and photochemistry.

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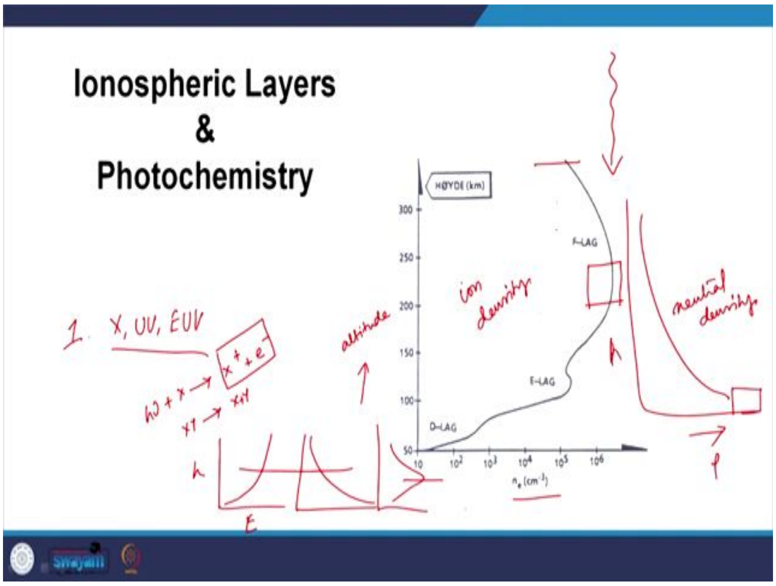

So, this figure shows the number of electrons per unit volume let us say per centimeter cube and on the y axis you have the altitude. So, as you see from this figure. So, the number of electrons will increase as you go up and it will reach a maximum value at nearly 200 to 250 kilometers and then again it will decrease.

So, now the first thing that we want to ask ourselves is that why is the ions, why are the ions and electrons forming? So, the main reason is that we have seen in our earlier discussions that the solar electromagnetic spectrum consists of X rays and ultraviolet extreme ultraviolet radiation. So, these radiations are very much energetic and they have the ability to ionize, let say they have the ability so, if you take a photon; they have the ability to ionize atoms and they also have the ability to dissociate atoms like that. So, this results in the formation of electrons and ions.

So, basically it is the incoming radiation which is coming from the top, from the sun and we know that this figure goes hand in hand with the density. So, you see that the density decreases exponentially with the so, density with height. So, this is the height this is the density. So, we know that the density decreases exponentially as you go up. So, what you can see is that. So, this figure has to be complemented with this figure.

So, this is the neutral density; neutral density as a function of height and this is the ion density. So, this figure shows the ion density as a function of height. So, one striking feature is that the ion density achieves a maximum at nearly 200 to 250 kilometers and the neutral densities are maximum at the surface.

So, the main reason for this is that the incoming radiation has its maximum amount of energy or maximum availability of photons is at the top. So, when it is not exposed to the atmosphere; the incident energies is the most energetic as it travels , it encounters more and more number of neutral atoms. So, it will keep ionizing and building up electrons and ion densities.

Now, as it travels further down, what you will realize is that the number of available species, the number of atoms and molecules that are available for a dissociation or ionization increases drastically. And at the same time the number of available photons to cause ionization decreases drastically.

So, there is a balance which is reached because. So now, we have the; so, if you consider the amount of energy. Energy will be maximum let us say if you consider altitude and energy will be maximum. So, energy will decrease like this according to the simple Beer Lambert's law. So, energy and this will if this is an exponential decrease and the number of species will decrease like this.

So, if you combine these two things, what you will realize? There is a balance which will be reached in middle and this middle point is generally the layer or the point where there is maximum amount of ionization happening right. So, now, we will try to see more details into this idea .

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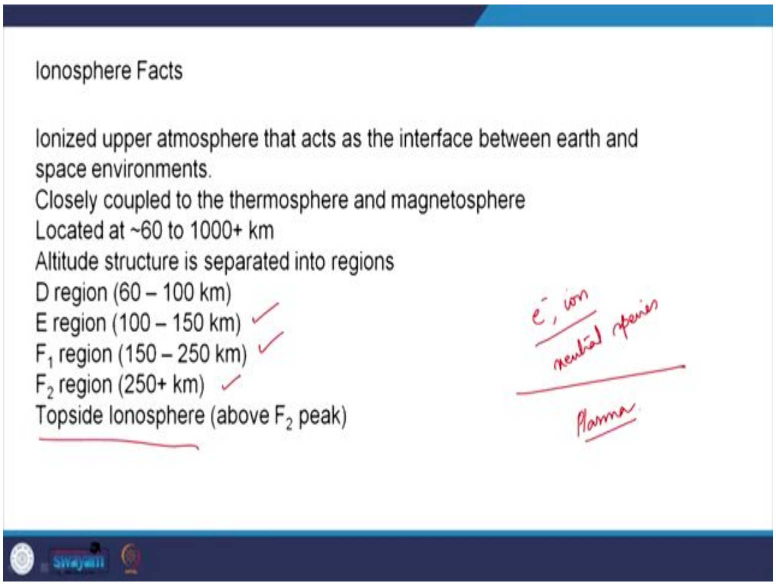

Now, so quick facts if you talk about the ionospheric phenomena . So, ionosphere is ionized upper atmosphere that acts as an interface between the earth and space environment , ionosphere also is the layer which comes in between. So, if you have energetic particles or solar winds which are trying to enter into the earth's atmosphere. Ionosphere is the layer which acts as an interface between the solar plasma and the earth's atmosphere. And the ionosphere is closely coupled to the thermosphere and magnetosphere.

So, ionosphere is very much this is the interactions that happen in the ionosphere are very much coupled with both the sides I mean with the lower atmosphere as in with the thermosphere on the bottom side and on the top side it is coupled very closely with the magnetosphere.

So, ionosphere is typically located between 60 to 100 kilometers. below 60 kilometres is generally the neutral atmosphere and above 60 kilometers it is the ionosphere. And the altitude structure just like we have troposphere, stratosphere, mesosphere and thermosphere depending on the fluctuation of temperature or variation of temperature with respect to height. Depending on the similarly, depending on the available number of electrons in at each height of the ionosphere it can be categorized into four different regions which is which are called as D region, E region, F1 region, F2 region.

So, D region is the ionospheric layer which exists from 55 or 60 kilometers to 100 kilometers and E region exist from 100 to 150 kilometers and F1 region exists from 150 to 200, 250 kilometers and F2 region is the one which exists above 250 kilometres. So, above F2, the layer is generally called as the top side ionosphere .

So, the point is ionosphere can be categorized or can be classified into 4 different regions D, E, F1 and F2. So, we will discuss how these layers are different in all these layers what the common species there exist is just electron and ion. So, it is not that in different layers, different types of species exist in all these layers it is only the electrons and ions. Of course, there will be neutrals neutral species.

So, the entire ionosphere can be considered as plasma. So, what kind of plasma is it? Is it a weak plasma? Is it a strong plasma? What is the temperature of this plasma? All these details will be discussed as we go further. So, the point is there are electrons and ions which are present in all these layers, but there is a clear rule why they should be different layers why do not we treat the entire ionosphere as a single entity or not categorize into various different layers.

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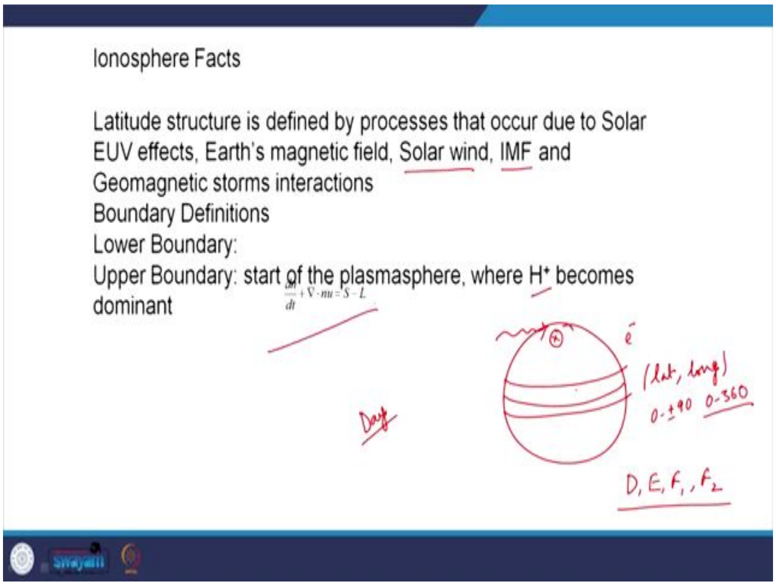

Now, so ionosphere latitude structure; ionosphere at any given point on the earth. has to be defined with respect to latitude, longitude and these are the main parameters which will define or which will identify any point on the atmosphere on the earth. So, the ionospheric structure varies with latitude. Latitude structure is defined by processes that occur due to solar EUV effects, earth's magnetic fields, solar wind, interplanetary magnetic field and geomagnetic storms and interactions.

Let us say for example, if you want to understand more about this let us say if you consider the earth this is the equator. So, what I am trying to say is any point on this earth has a latitude and longitude. So, latitude will vary from 0 to plus minus 90 and longitude will vary from 0 to 360 .

Now, the ionospheric densities the overall structure of the ionosphere; that means, having distinctly layers of D, E, F1 and F2. So, these four different layers of course, they are distinct in the sense that they have variously clearly defined parameters how we are going to call it as D layer, E layer, F1 layer and F2 layer.

So, they will have, but the variation will be in terms of the number densities will hugely depend on let say on the position let say for example, the equatorial region receives maximum amount of solar energy. So, it is natural to expect that electron densities or the degree of ionization or the amount of ionization that happens in the equatorial region will be very large, it is natural to expect. Then there are other physical processes which will make electron density available in a different concentration.

Then let us say for example, the other type of variation would be generally day time the electron densities will be larger and during the night time the electron densities will be smaller. Then at the poles let us say if you take a point here, the electron densities will also depend not just on the solar radiation spectrum, rather it will also depend on the amount of energetic particles that are trying to precipitate into these regions. That means; the latitudinal structure of the ionosphere not just depends on the solar electromagnetic spectrum it also depends on several other parameters such as solar wind the direction of interplanetary magnetic field and geomagnetic storms, so many things, .

So the upper boundary of the ionosphere is the beginning of the plasmasphere and where generally, hydrogen being the lightest species will escape into these altitudes and becomes available in the plasma sphere. So, this is the basic nature of the continuity equation we will discuss more on this later .

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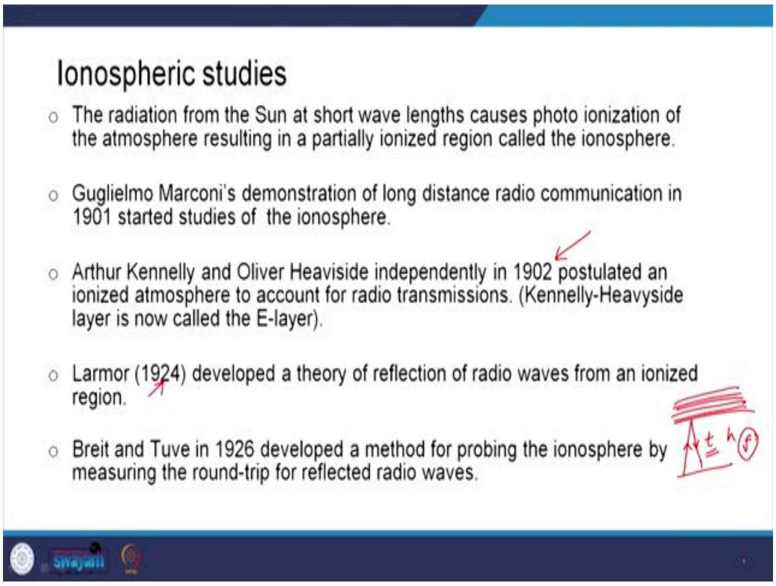

So, ionospheric studies if you just look into the background I mean how does this ionosphere came into existence or when did people realized that there is an ionosphere which is existing in the sky. So, generally what happens? The radiation from the sun at shortwave and that is the X rays, ultraviolet and EUV, Extreme Ultraviolet Radiation causes photo ionization of atmosphere resulting in partially ionized region called as the ionosphere. So, this is not completely ionized. So, there are majority of the species will be neutrals, there will be electrons and there will ions.

The Marconi's demonstration of long distance radio wave communication in 1901 started the studies of the ionosphere. So, this was the first time when a long distance communication was achieved between England and Canada where without any repeaters or without any signal transmitters propagation of radio waves was achieved. So, this started the beginning of the ionosphere.

Kennelly and Heaviside independently in 1902 postulated an ionized postulated the idea postulated that an ionized atmosphere in the upper altitudes to be able to account for the radio wave transmission. So, if the transmission has been achieved so then they must have wondered why or how this radio wave travel. because the radio waves have very low wavelength and very high frequency right. So, this was the existence of the reflecting layer was formerly kind of postulated in 1902.

Larmor in 1924 developed a theory of reflection of radio waves from an ionized region. So, if the electromagnetic wave is reflected; what should be the criteria between the electromagnetic wave and the plasma. This theoretical framework was provided by Larmor in 1924. So, this came much later if 1902 was the point of discovery when the ionosphere was found to be existing and the theoretical background came much later.

So, Breit and Tuve in 1926 developed a method for probing the ionosphere by measuring the round trip reflected radio waves. So, at different points of time they could measure what is the time of travel for the electromagnetic wave depending on the time they could calculate the height of this particular refracting layer. And this height of the reflective layer like I said before will depend on the frequency of the wave.

So, different frequencies were found to be travelling at different intervals of time indicating that the criteria for the reflectance was matching at different heights rather at the same height. Since, all this information was also very important to understand the vertical structure of the ionosphere.

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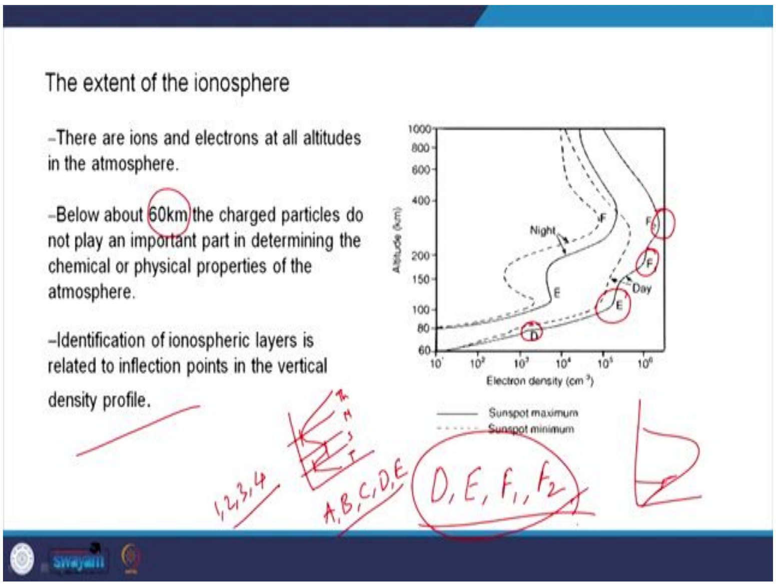

So, the extent of ionosphere, how far does it stretch. So, there are electrons and ions at altitudes in the atmosphere. It is not that only it stops somewhere, but below about 60 kilometers, the charged particle do not play any important role in determining the chemical and physical properties of the atmosphere.

So, we do not generally deal or we do not generally talk about the electron and ion density that exists below 60 kilometers because they are very very low in number and so, they will not be able to contribute or participate in any or the physical or chemical processes that may happen.

So, identification of ionospheric layer is related to the inflection points in the vertical density profile. So, this is the density; just like we have seen in the earth's atmosphere the thermal structure. So, these were called as the turning points where the temperature structure or where the temperature structure it changed its path and was behaving in a different way . So, these are the turning points that we generally call or we can call these are the points where the slope changes the sign.

So, depending on this , we call this as a layer, this as a layer, this as a layer, like this . So, this is the troposphere, this is the stratosphere, this is the mesosphere and this is the thermosphere. So, just like that so, the profile does look like a single let us say Gaussian or something like that like this, but in this there are small inflection points which will. So, let us say for example, this point that you see, this point that you see, this point that you see, this point.

So, these four points are the ones which will be the boundaries of this particular layer. So, if you see the D layer is ending here, the E layer has the maximum density at this point and F layer is the one here; that you see F1 is the one and F2 is the one.

So, the identification of ionosphere layers is related to the inflection points in the vertical density profile. So, this is the basic idea that why should you call the these layers as the single profile as a layered profile. Why should you name D, E, F1 and F2?

Now, the most important thing is let us say maybe you want to look up some books or resources, why should these layers be called as D, E layer , F1 layer and F2 layer? Why do not they can be called as simply A, B C, D or whatever or let us say layer 1, 2, 3, 4. So, there must be some reason why the ionospheric layers are named like this D, E, F1 and F2, why not anything else right. So, probably you may you may want to look up some books or resources just to find the answer for this curiosity question.

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Primary Ionospheric Regions

Region	Altitude	Peak	Density
D	60-90 km	90 km	$10^8 – 10^{10}$ m^{-3}
E	90-140 km	110 km	Several x 10^{11} m^{-3}
F1	140-200 km	200 km	Several 10^{11}-10^{12} m^{-3}
F2	200-500 km	300 km	Several x 10^{12} m^{-3}
Topside	above F2		

Now, how, what are the numbers pertaining to this different layer? So, like I said there are four layers; D layer is the bottom most layer, E layer is the layer in between F1 and F2 are generally the same layer F layer, but this is for a reason this is called as F1 and F2. So, if for example,there is one more thing that I have to mention here.

So, during this density profile is what you generally see during the daytime. So, daytime; the solid line that you see is the electron density profile during the daytime and the dashed line is the one that you see during the night time. And so, these two figures on the right on the higher side of electron density are the ones during the sunspot maximum.

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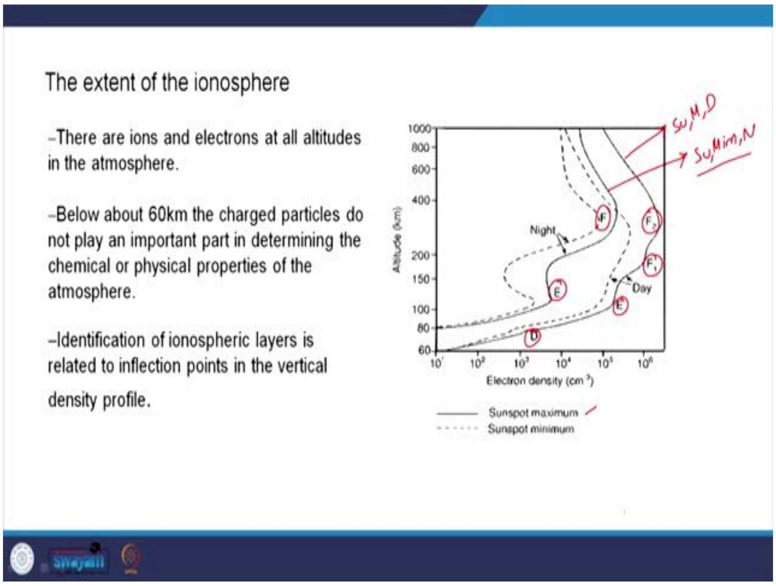

So, this during the sunspot maximum and the dashed curves are the sunspot minima actually . So, this is sunspot, sunspot maxima and day and similarly for this is the night one, night one is this one; sunspot minima and during the night time sunspot minima.

So, what you see from let us say you if you want to classify day night variations daytime the electron densities will be larger, of course. But interestingly during the night time the F2 and F1 will just be called as F layer . And this is the so, in the daytime you have the existence of all these layers; D, E, F1 and F2 and similarly, one more so, this is the day night variation.

And if you talk about the solar cycle variation; we have already seen what is the solar cycle and what how does it change so many things. So, generally solar cycle maxima is the time when you expect more amount of energy from the sun and as a result during the solar maxima; the amount of degree of ionization is also large as you see here . So, this is the main aspect of ionosphere.

Now, coming back. you have four different layers D, E, F1 and F2. The altitudes already 60 to 90 kilometers is the D layer, 90 to 140 is the E layer, F1 is 140 to 200 and 200 to 500 or 600 kilometers is the F2 region. So, this is the peak. So, within the layer, what is the point where maximum amount of electron density can be formed is called as a peak. So, the D layer will have a typical density of 10 to the power of 8 to 10 to power 10 per meter cube. So, this is electron.

So, in the ionosphere we always assume that the number of electrons are equal in number to the number of ions. So, the charge concentration is 10 to the power of 8 to 10 to the power of 10 per meter cube electrons slash ions. So, E layer will have is roughly of the order of 10 to the power of 11 per meter cube and F1 layer which will be like 200 kilometers will have a charge concentration of nearly 10 to the power of 11 to 10 to power of 12 per meter cube and F2 layer the most dense ionospheric layer is will have a charge concentration of nearly 10 to the power of 12 per meter cube.

So, the electron density profile does not look the same at all altitudes. So, there is a clear variation at every altitude .

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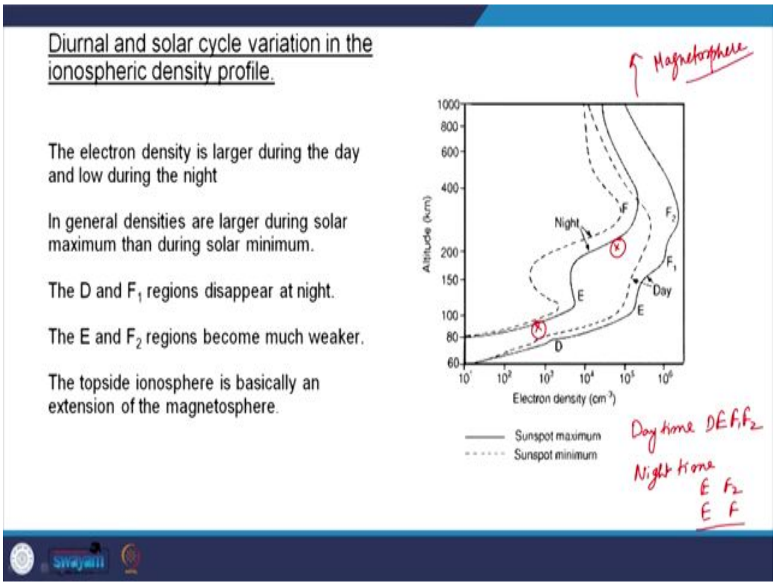

So, if you look at the diurnal and solar cycle variations. Diurnal variations are with the day' during the day with the time how does anything change. So, what you will be able to observe is that the electron density is larger during the day and lower during the night. And in general, the densities are large during solar maximum and they are lesser during the solar minimum and D layer and F1 layer will disappear during the night time.

So, D layer that is why you do not see a D layer here. So, D layer will not be here and F1 layer will not be seen. So, in the day time it will be D, E, F1 and F2. And in the night time it will be E and F 2 or we generally call it as E layer and F layer. So, the top side of the ionosphere mergers into the magnetosphere. So, the top side of ionosphere is extends or mergers into magnetosphere .

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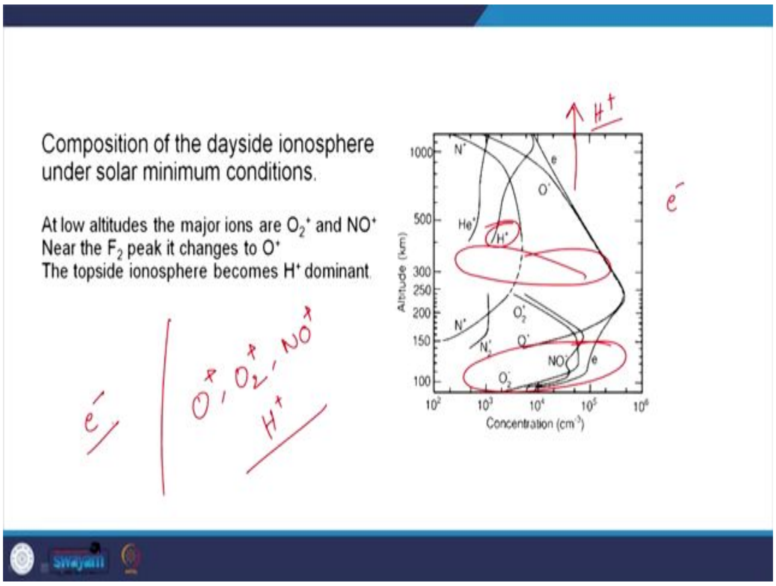

Now, so, if you see so; obviously, if there incident energy is causing ionization. It should be able to create electrons and ions. But generally what you see at different heights of the ionosphere, the major charge concentrations are or all heights its electron of course, but at different heights, it will be different ion species which will exist because this is due to the availability of these particular species for ionization to happen.

So, at lower altitudes; the major ions are O 2 plus and NO plus, O 2 plus and NO plus at lower altitudes, this is the one and near the F2 peak it changes to O plus. So, F2 peak is generally in this region. So, F2 peak is this entire F2 peak is this region, 250 or 300 kilometres and the top side of the ionosphere is generally hydrogen dominated. So, this is the top side let us say, if you go here. So, it is also called as the (Refer Time: 29:06) sphere or something .

So, what I wanted to say is that; as you go vertically up from the ground the electron density is the negative charge species is always electrons , but the positive charge species could be O plus, O 2 plus , could be O plus , O 2 plus and O plus and H plus. So, this is and this is equivalent all this, all of this combined will be equal in number for with an electron density right.

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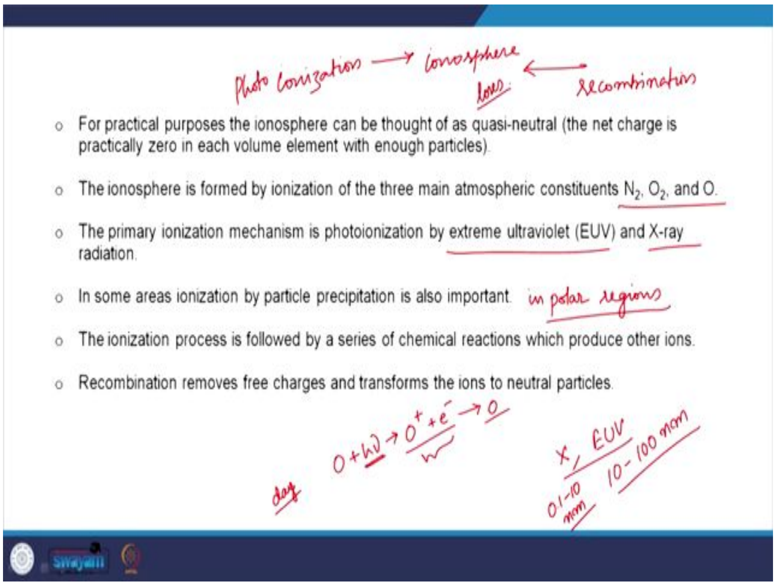

So, for practical purposes, the ionosphere can be thought of as quasi neutral which means that the net charge density is practically 0 in each volume element with enough number of particles. So, if you take the ionosphere as a whole, electron density is equal to the ion density; that means, overall charge neutrality ,overall charge polarity is neutral .

So, the ionosphere is formed by ionization of three main atmospheric constituents nitrogen, oxygen and atomic oxygen. So, this is I mean; we already know that these are the primary chemical species that we see in atmosphere. So, this is have to be ionized to be able to release electrons. The primary ionization mechanism is the photo ionization of by extreme ultraviolet radiation and X radiation.

So, you always remember this, these are the main X rays and extreme ultraviolet rays. So, these are the main wavelengths which will produce maximum amount of energy. So, extreme ultraviolet is 10 to 100 nanometers and X rays probably can be 0 to 0 0.1 to 10 nanometers.

In some areas, the ionization by particle precipitation is also important; that means, in the polar region. So, this is happens in the polar region. So, polar regions are the ones which will allow extremely energetic particles to be precipitated into the earth's atmosphere. So, when these particles come; obviously, they have a lot of energy and they will ionize electrons and they will ionize atoms to release electrons.

So, in addition to extreme ultraviolet and X radiation, ionization may also happen with extremely energetic particles. The ionization process is followed by a series of chemical reactions which produce other ions. So, it is not just a single step process rather very lengthy or very long cycles of processes exist for various species to be able to account the observed or seen electron density with respect to height.

So, once the electrons and ions have formed. let us say for example, atomic oxygen releases an electron. So, this is happens during the day time when there is available photon. So, what happens is that? So, once these they are released, they need not stay as electrons, they need not stay as free electron and ion. So, generally, what happens? Immediately they will recombine. So, they will recombine and just give you back the oxygen that is it.

So, during the day time electron ionization happens and during this time electrons and ions are released and immediately depending on the lifetime of the particular reaction and the concentration of the participating chemical species, they will limit recombine giving you back the neutral species. So, this process is called as the recombination. Ionization leads to the formation of recombination. So, ionization or photo ionization to be more precise. So, let us say photo ionization leads to the formation or existence of ionosphere and recombination, recombination causes the ionospheric electron density to be lost .

So, these two processes are the ones which will control the strength of ionosphere at any given point of time. How much amount of photo ionization is happening and how much amount of recombination is happening. So, if they do not balance you will see that there is still available electron density. So, it is very I mean it is a clear example that it is very easy to understand. So, if you say that electron density is created by the solar energy it is of course.

Then once day passes and if that particular part of the earth enters into the night side there is no reason for electron to be created again, electron to be ionization to be happening again. So, that time all the electrons and ions should recombine eventually leaving neutral atmosphere that is, but that does not happen. So, various other things come into picture, we will see how the electron density is retained during the night time as well, not just during the day time, but also during the night time.

So, if you look at this the basic temperature structure of the atmosphere, we have seen this earlier.

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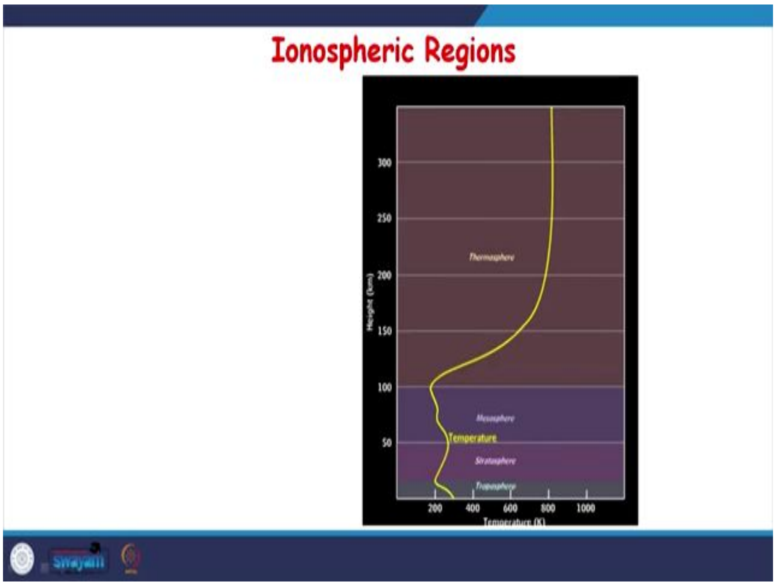

So, what you see, you see is the various layers of atmosphere. So, this is how the temperature structure looks like. So, this figure has to be brought closer to understand how the ionospheric regions will be identified or tagged with respect to the neutral species.

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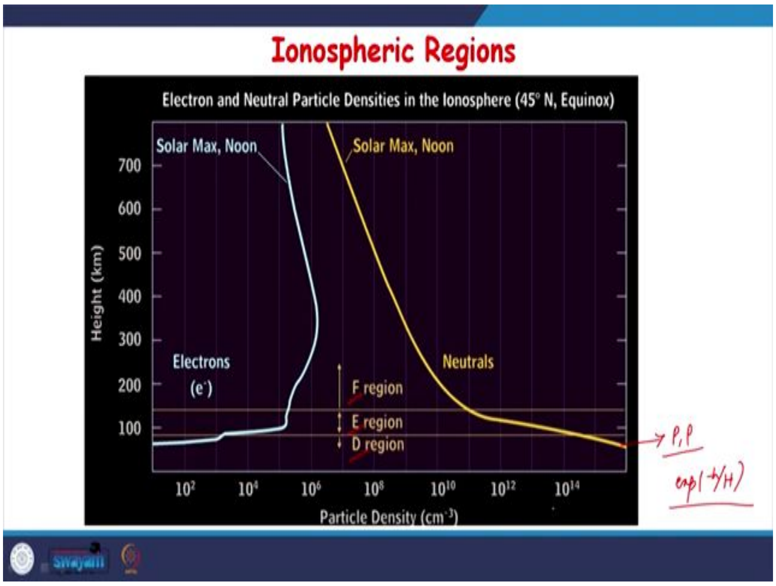

So, this figure shows the electron density, this is the ionosphere or so, this. So, on the right side this yellow curve that you see is the neutral density that is varying with respect to height. So, this is an exponential decay. So, this varies similar to pressure or density. So, this is just an exponential of minus h by H.

So, pressure or density or number of particles per unit volume or number of atoms neutral atoms per unit volume will vary exponentially, will decrease exponentially as you go up this is what you see. So, generally and on the left hand side you have the electron density which is not exponential in nature which is a totally different kind of behaviour if you compare it with the neutral species.

So, what is shown ? You see different distinct layers D layer you see, you see E layer and you see F layer right. So, this is the basic comparison between the electron densities and the neutral species. So, the electron density of course, is clearly different from the neutral densities variation.

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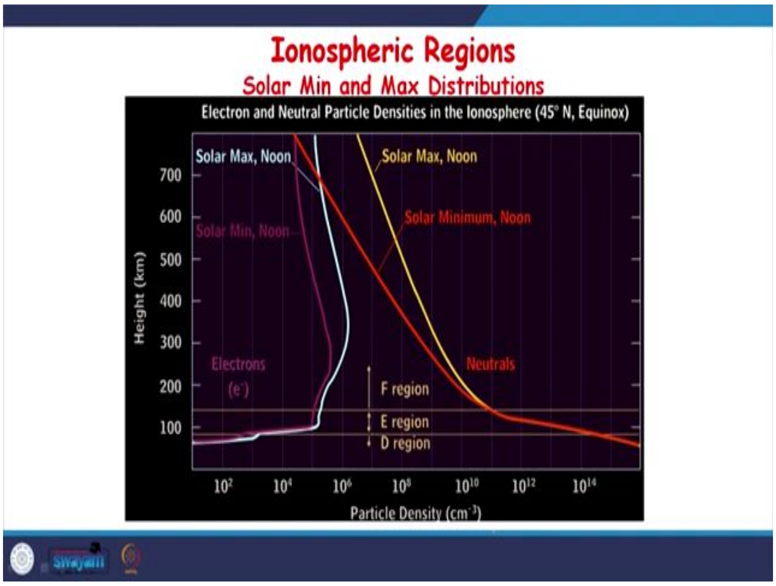

And during the solar maximum and minimum, what will happen , solar minimum will have the neutral species will decay much faster. And at the same time solar maximum will have more amount of ionization available at any given height. Since this is the basic way in which solar cycle variations are induced into the neutral atmosphere as well as in the in the charged or ionosphere .

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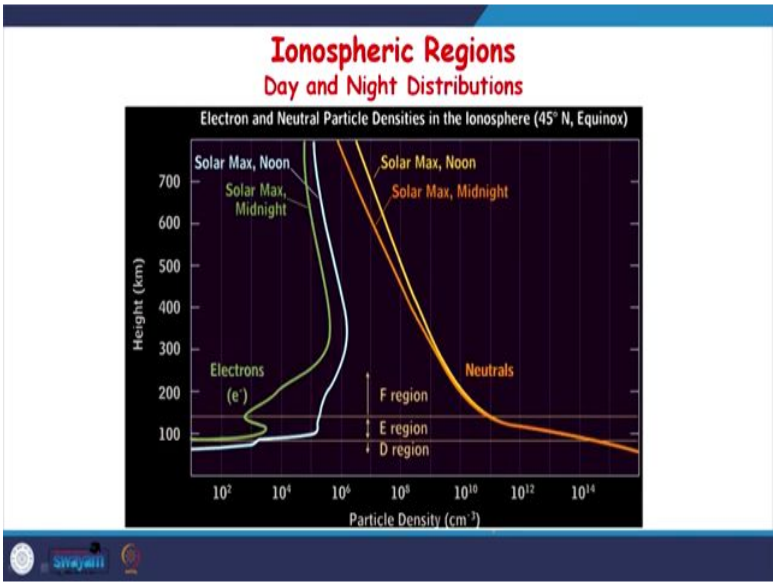

And if you consider the day night variations during the daytime, the electron densities are highest and you have the existence of all the D layer, E layer, F 1 layer and F 2 layer and during the night time the D layer does not appear its only the its only the E layer and F layer right.

So, this is something about the basic structure of the earth's atmosphere. So, of the basic structure of the ionosphere, how does the ionosphere form? What are the salient features of ionosphere? I mean; why should this be called as ionosphere and what purpose does it serve and when was the discovery about ionosphere made and how was the discovery made and how do you identify various different regions of earth's ionosphere things like that. We will continue this discussion with more details about various chemical schemes that are in place in ionosphere. To account for the observed or for the for the available density of charged species in the ionosphere, ok ,yeah.