Introduction to Atmospheric and Space Sciences
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Lecture - 44
Chapman's Theory of Layer Production

Hello dear students. In today's class we will continue our discussions on ionosphere. So, far we have seen what is ionosphere, how many different layers exist in ionosphere, what is the reason for naming all these regions as different layers, but not a continuum of ionosphere. So, these layers are preliminary D, E, F1 and F2. We have also seen that some of these layers will disappear during the night time due to the lack of direct sunlight or due to the lack of resulting ionization. So, what we will learn today is an extension to the same discussion.

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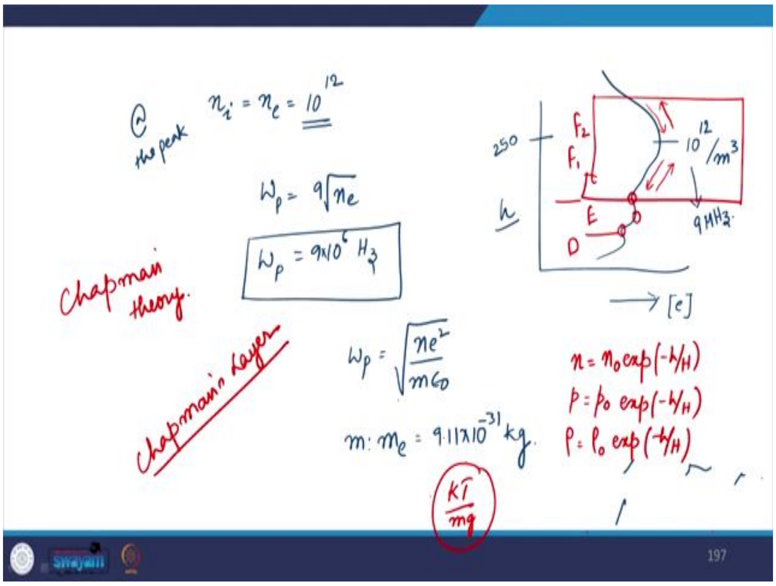

Plasma frequency

$$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}}$$

So, we have seen from the earlier class that if you look at the density of ionosphere it will look something like this. So, on the x axis you have the number density let us say the electron density; on the x axis and on the y axis you have the height.

So, here the basic idea was we have seen that the peak which occurs nearly at 250 kilometres or 230, 250 kilometers. We will see that the electron density peaks to nearly 10 to the power of 12 per meter cube, it is 10 to the power of 12 electrons per meter cube. So, per unit volume there are 10 to the power of 12 electrons. So, we also take it always that the number of electrons is always equal to the number of ions.

So, that the neutrality is maintained at in the ionosphere So, the peak ionospheric density always, remember this number is 10 to the power of 12 per meter cube. So, if we calculate the plasma frequency omega P is 9 times square root of n e which is 9 times 10 to the power of 6 Hertz.

So, plasma frequency is a very large frequency for this peak we know that, this happens because the plasma frequency depends heavily on the mass of electron. So, this is m epsilon naught. So, where n is the number density m is generally the electron plasma frequency, we are calculating the mass of electrons which is 9.11 into 10 to the power of minus 31 kg. So, what are we trying to do here, we are trying to realize what exactly is the ionosphere.

Now, from this simple discussion one thing is evident it is evident that electron density is not the same throughout the ionosphere. Electron density peaks at a particular value of nearly 250 kilometres is 10 to the power of 12 per meter cube. So, if you evaluate this plasma frequency at this it will be 9 mega Hertz fine. In today's discussion, what we are going to do? What we will try to understand is that what is the reason that the ionosphere density peaks at a particular point before that it is less and after that it is again less? Let us say we concentrate on this height, let us say we concentrate on this height.

So, this is the height that we are trying to understand let us say on this region. What do you see that the electron density is increasing and then, the electron density decreases. If you look up electron density is increasing as you go like this and electron density again decreases. So, why does such a thing happen? So, this shape is generally known as the Chapman layer.

So, this Chapman's we call it as a Chapman's layer. We have also mentioned at some point that this is the entire structure of the ionosphere. We have also mentioned that this structure of ionosphere is going to be split into, four layers actually D, E, F1 and F2.

What was the basis for defining this layers is that, whenever you see a turning point this is the turning point. Where the slope changes its direction, this is the turning point this is the turning point. So, these are the inflection points, where you have identified the layer. So, everything below this you have called one layer everything below this you have called the another layer and everything like that.

So, the point is why do such layer I mean why do such layered ionospheric densities are seen in the atmosphere, that is going to be the topic of discussion for today. So, this entire mathematical framework that we are going to derive is based on the Chapman's theory. So, this is going to be the Chapman's theory. So, we will try to understand the layered production.

So, for example, simple intuitively we can understand, why does the electron density reaches a maximum thereafter the electron density decreases,. So, why does such thing happen? Now from your basic understanding of the atmosphere we have in the very beginning itself we have made a remark saying that. The number density of electron a number density of let us say neutral species you will vary exponentially as you travel up.

So, this is how it looks like what is n? n is the number of atoms slash molecules per unit volume. Which is also in accordance with the pressure exponential minus h by H or the density exponential minus h by H,. what it tells you is that, if you consider a parameter which is called as scale height which is k T by m g this is a length dimensional parameter. What you will realize is that as you go up, the help the density of neutral species will decrease exponentially; will decrease like this will decrease exponentially.

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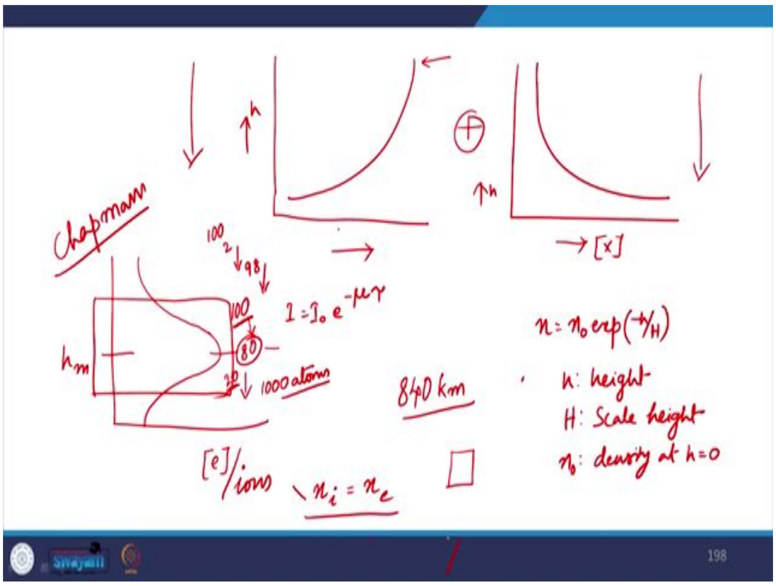

So, as you go up with the height and you have , let us say the number density or the pressure or the density. Number of atoms or molecules that you can find per unit volume will decrease exponentially.

Then this is something that we have known from the basic atmosphere or atmospheric thermodynamics for that matter. Now if you plot let us say with height. So, this n is equals to n naught exponential minus h by H where h is the height at which you want to calculate the number density, capital H is the scale height n naught is the number density at h is equal to 0 .

Now if you simply look at how the radiation changes with respect to height. You have learned from the Beer-Lambert rule that, I is equals to I naught e to the power of minus mu tau right.

So, this is the idea of basic optical depth you will realize that the density or the available photons at the top of the atmosphere will be very very large. And as it travels towards the ground, the available number of photons will decrease; why do they decrease? Because, the photons will be consumed by the atoms and molecules which are existing in the upper atmosphere for the processes of dissociation or ionization. That means, eventually the energy that is available at a particular height at the maximum height let us say is maximum. And I mean there are at the top of the atmosphere.

Let us say you consider the top of the atmosphere to be let us say 840 kilometres. For example, you take the top of the atmosphere to be 840 kilometers where there is absolutely nothing which is a near or perfect vacuum that is existing there. That means, there are no atoms and molecules even if there are atoms and molecules the typical mean free paths of these atoms and molecules will be several 100s of kilometres. That means, any 1 molecule will not come in contact with another atom or molecule for several 100s of kilometres.

So,; that means, there is if you consider a cubical volume, if there is you know you think of the number of atoms that could exist in a cubical volume of let us say 1 meter cube you will realize its 0 right. So, what I am trying to say is at this heights when you consider what is the density of photons. Or what is the amount of in energy that is available to the Earth's atmosphere, which probably kind of enters into the Earth's atmosphere is very high.

As the radiation travels towards the surface, we have already seen that not all this radiation is relevant for the atmospheric species I mean not all the spectral bands of this radiation are relevant for the atmospheric species. Its mainly the extreme ultraviolet and X rays which will cause ionization and dissociation thereby get consumed by the atmosphere.

So, having said that we can simply say that as the radiation travels towards the surface more and more, it encounters more and more amounts of gas species thereby more ionization more dissociation will happen. So, in this process the photon density the available energy that is coming from the top gets consumed. So, as it travels know so, if the basic idea is to be able to combine these two.

One tells you from the top the number densities are increasing at an exponential rate towards the surface if you see from the top. And another tells you if you say that it decreases exponentially, the number of available photons energetic photons will decrease exponentially as it travels towards the surface.

So, now you can say that see here the number of photons are maximum, you can say that we can get maximum ionization here, but it does not happen like that. Because even though number of photons are large there are not many atoms which could use this photons.

So, as a result when you combine these two plots let us say what you will see is that, at some point the rate of ionization will increase drastically as the photons travel into the denser atmosphere, but there has to be a balance in the sense. So, as what you see from here is that then this is now let us say the number of electrons slash ions; because we are always going ahead with the assumption that the number of ions are always equal to the number of electrons.

So, that point is as the radiation travels towards the surface, it encounters more and more amounts of atoms and molecules; but, at the same time the available number of photons are becoming less because of the absorption. So, these two things balance each other at a particular point; let us say let us call this point as hm what is hm? hm is the height of peak production. So, this is where the energy that is available. And the atoms that are available are balanced with each other they are in balance; I mean they are whatever the amount of radiation that is coming out is appropriately or completely used by the atom.

So, at this point we can simply say that there are photons available there are let us say there are 100 photons which are available, but there are only 80 atoms right. 80 atoms which are completely which I mean here the photon count is more than the number of atoms. So, 80 photons will get absorbed here whatever the remaining 20 photons will travel downwards here, what was the situation let us say the same 100 photons available at the top, but there are only 2 atoms that are available. So, what will happen? So, there are 98 photons which are travelling downwards.

So, here is the balance point where whatever the amount of whatever the number of atoms that are available they are completely ionized to let us say to an ideal case. That means, here the photons are still outnumbering the number of atoms, its not that you will never be able to create an atmosphere which will completely absorb whatever the photon count that is coming from the top.

So, what happens now, after this inflection point, when the photon count is of course, most efficiently used when the photons or when the energy travels further down , it will start in encountering denser and denser atmosphere. That means, now the photons are going to be little in comparison to the number of atoms what happens, the production rate will decrease. So, now, at this point there are 20 photons so, but what happens after it travels let us say there are 1000 atoms.

So, it 20 photons will never be comparable to let us say 1000 atoms whatever have what happens? As a result the electron density or the production rate is the rate at which electrons or ions are generated. So, it will decrease. So, the point is now you due to a balance between the energy that is incident into the atmosphere. And the away and the density of the atmosphere will strike at a point and as a result you have something like this.

So, this curve or this layer like phenomena is properly explained in terms of in mathematics by Sydney Chapman. So, what we will do is, we will try to understand the mathematical framework, we will try to derive the rate at which the layer or the peak production happens.

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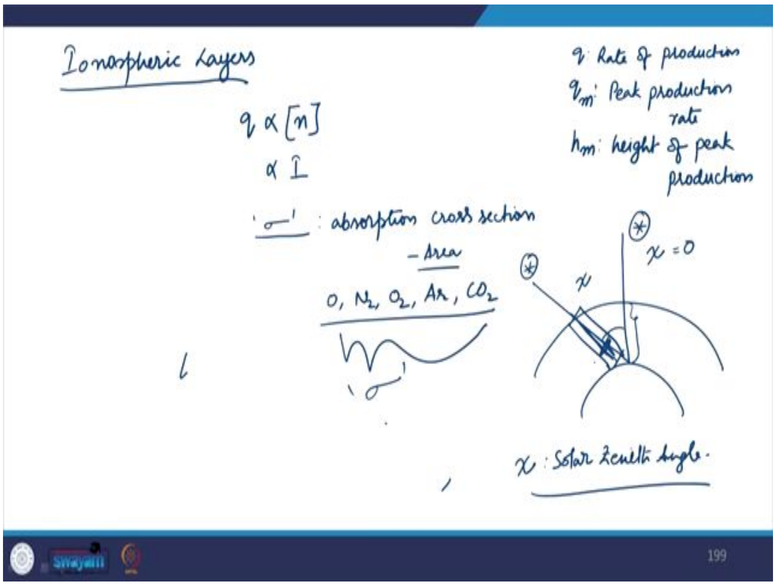

So, here our terminology will be mainly based on. Let us say two things we will call q as the rate of production and qm as the peak production rate and hm is the height of peak production. So, ionospheric layers so, this is going to be the topic of discussion for today. Now let us say how does the photons, how does the radiation gets absorbed when radiation from the sun is absorbed in the atmosphere it heats it. So, atmosphere is getting heated.

So, which it heats it dissociates the molecule and liberates free electrons. The rate at which dissociation or ionization is produced or which you can also call as the rate of production at any level is proportional to the product of gas concentration and the intensity of radiation. So, we can say that the rate at which a production happens is proportional to the gas concentration. Let us say we call the gas concentration with n gas concentration and the available intensity q, is proportional to n and q is also proportional to I, I is the intensity.

So, at the top of the atmosphere the rate is very small because the concentration of the available species is very small. As the radiation penetrates downwards the concentration increases and with it the rate of production also increases. Below a certain height; however, the strength of the radiation decrease downwards is greater than the rate of increase of the concentration. Thus the height , where the rate of production reaches a maximum is generally called as a peak of production.

So, the approximate level of the peak production can be deduced from simple arguments. Let us say we can use simple arguments let us say suppose that the atmosphere consists of molecules all having the same absorption cross section that means.

So, let us consider atmosphere made up of many different types of gas species of which let us say we consider that all of them have the same absorption cross section; sigma is absorption cross section what are the units? The units are area. So, what I am trying to do is let us say we have oxygen, we have nitrogen, we have argon, we have carbon dioxide we have so many other species.

So, in order to do this, the first assumption that we are going to make is that see these molecules or the atoms are of different sizes. So, the rate at which a photon can be absorbed by this species will be different; obviously, why is it basically different? Because these are different sizes and the interaction happens as a function of the distance or the size of the atom or molecule.

So, we what we are doing is, we are going to say that sigma is the cross section which is going to be assumed to be the same for all the atoms. And the radiation falls it from the outside possibly in an oblique direction. Now let us say we consider the earth like this and we consider the atmosphere like this and the radiation is falling like this.

So, let us say this is the sun. So, if the sun is in the noon position, the angle at this point let us say we take it to be chi is equals to 0. At any other position away from the noon the angle that is subtended by the sun is chi what is chi? Chi is the solar, zenith, angle.

So, what I am trying to do? I am trying to put the atmosphere like this in a column of let us say this. And we are saying that sun is at a point and it is making the radiation fall obliquely towards the earth. So, why am I doing this? If the radiation falls normally the height or the length over which radiation penetrates or travels through the atmosphere, will be smaller when the radiation will be smaller in comparison to when the radiation falls in an oblique direction simple.

So, then in a column of unit cross section, let us say you consider this column of unit cross section the area is 1; then drawn in the direction of the length sufficient to contain n molecules. So, what we are going to do is we consider this.

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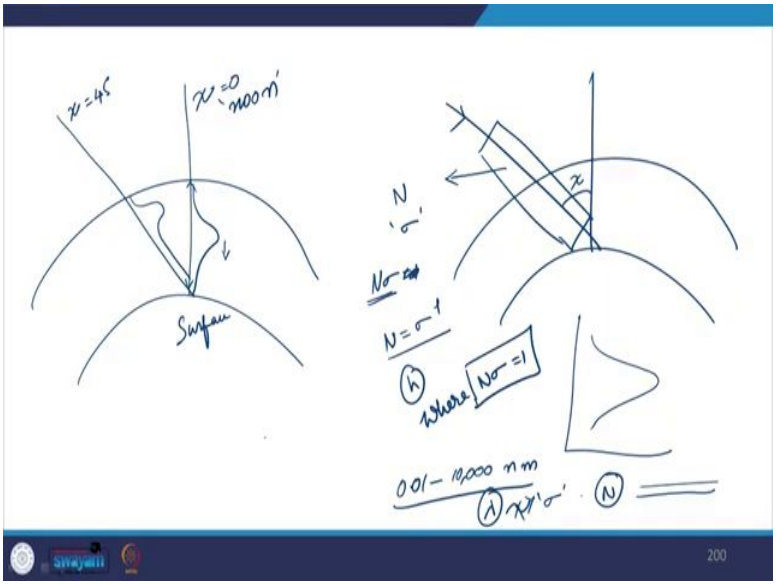

We consider let us say the radiation is falling like this, we consider a column of air like this which is in this oblique direction at an angle chi. Let us imagine, there are N atoms or molecules let us say molecules inside, each of which has the same cross section sigma.

So, the total projected absorption cross section what happens the total projected absorption cross section for this incoming radiation what does this radiation see? Within a unit surface area unit cross section, the total area that is radiation is offered to ionize or to what do whatever it is N sigma. Now is the total absorption cross section that is being offered is N sigma.

Now how far does this radiation travel inside is the real question. The radiation thus descends to a level, where the total number of molecules in oblique column or unit area is exactly equal to 1; where N is equals to sigma inverse. So, this is number per unit area or the radiation travels to that particular height where N sigma is equals to 1, this is the condition for the radiation. So, when the rate of production is plotted against the height, the resulting curve represents what we call as the production layer, we have already seen how the production layer will look like.

So, this is how it looks like. So, its shape depends jointly on the nature of let us say nature of gas, the angle at which the radiation is; I mean the angle or the time during which you plot it, time is indirect function of the angle. So, let us say in the noon let us say the sun is exactly on your head. So, the angle is 0. So, the radiation is penetrating well how is it how does it matter let us say this is chi is equals to 0. And let us say so, if you take the atmosphere to be like, this if you have the sun rays directly. So, this is chi is equal to 0 or we call it as noon and let us say this chi is equals to 45; whatever it is the time.

Now, what I am trying to say is as the radiation travels, there will be a balance point where the production is maximum. Now what you will realize is that, as the radiation is travelling normally, it is taking less distance to reach the surface. If it travels oblique in oblique direction, it will be travelling more distance. Now as a result ,because this is travelling more distance, the height or the penetration of the maximum energy will be to lower altitudes. As the radiation has to travel larger distances; obviously, the penetration will be in the higher altitudes that is the difference.

So, it is thus convenient to establish the form of production layer, when ionizing radiation falls normally or obliquely on a horizontal stratified gas. Distributed vertically with a constant scale height and having absorption cross section independent of wavelength. So, we are not considering the entire spectrum of let us say wavelengths let us say 1, 2; let us say what about 10000 nanometres; for example, 0.01. So, the entire spectrum of sun we are not going to consider this.

This wavelengths variation is not going to affect in any way the sigma; that is what we have taken. And we have taken all the species to be of the same cross section area. And we also say that the atmosphere is horizontally stratified; that means, there are no variations as long as you are in one particular height.

So, this is the basic framework before we start deriving the mathematics of the Chapman's theory of layered production. So, let us say we will go there.

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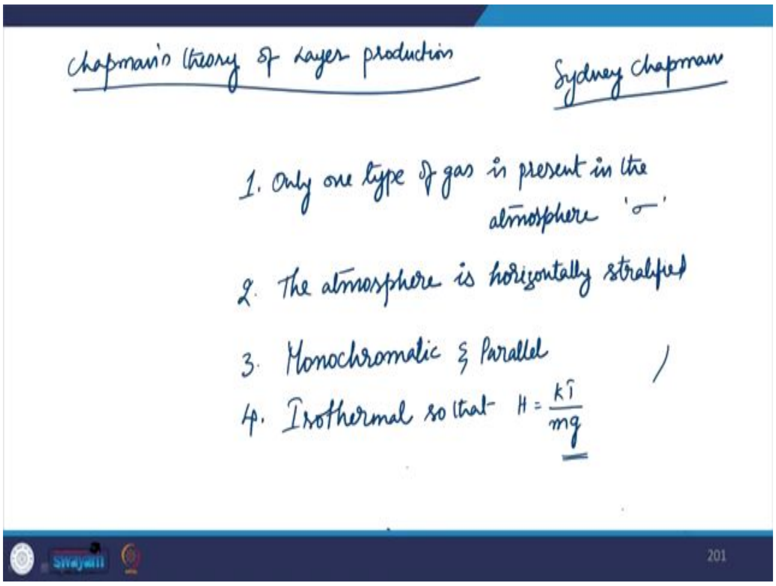

So, the topic is Chapman's theory of layer production. Who did this? Sydney Chapman. So, this is considered a very important or very key concept in understanding ionosphere; because various other parameters are to be included in this discussion.

So, the research that happens in ionosphere in terms of the frequencies or in terms of the number densities any fluctuations that you see, always require a prior knowledge of Chapman's theory. Because otherwise we will not be able to understand or will not be able to appreciate in result as it as such. So, Sydney Chapman proposed this particular theory to understand how an ionospherical layer will form what is the basic reason behind it?

So, this ionospheric layer is typically consisting of electrons and ions. So, this theory was based on the fact that the solar radiation ionizes gaseous atoms and molecules, which are present in the atmosphere that is what we have been telling all the while. So, ionization of atmospheric constituent depends on the intensity and the wavelength and the number density of atmospheric species. So, ionization happens means. So, ionization has to depend on the available number of atoms or molecules, the wavelength which is entering into the atmosphere or what kind of atoms are there, all these things.

So, before we start the discussion there are a few assumptions based on which the Chapman's theory of layer production was kind of derived. So, we say that only one type of gas is present in the atmosphere. That means, we will take all the gases have a single cross section. The second assumption the atmosphere is horizontally stratified. What does it mean? There are no fluctuations as long as you are confined to a one particular height; things change only when you move up.

The third assumption is the incident radiation is monochromatic and parallel. The incident radiation from the sun is assumed to be monochromatic; that means, single wavelength which is not like that. But for an assumption we will say that the incident radiation is monochromatic and parallel. The fourth assumption is that we assume that the atmosphere is isothermal, the temperature is constant everywhere. So, that we take a single scale height throughout. So, scale height is k H is equal to k T by m g.

So, we are not taking any variations in g; that means, throughout this height of let us say 250 kilometres or 400 kilometres. We do not say that g changes appreciably we do not say that and k of course, is a constant, m is of course, a constant because you have taken only one type of gas. You take the mean weight of the gas or whatever it is, but temperature which is supposed to change as a function of height is also assumed to be a constant.

Because we can take a simple or single scale height for throughout the atmosphere, otherwise you have to substitute the temperature every single time we may change you over a considerable altitude region. In order to avoid that you take the same temperature throughout. Now the idea of, let us say solid zenith angle.

So, we are just building up separate things for the Chapman’s theory of layer production; we will add all of them together to derive the mathematics let us say.

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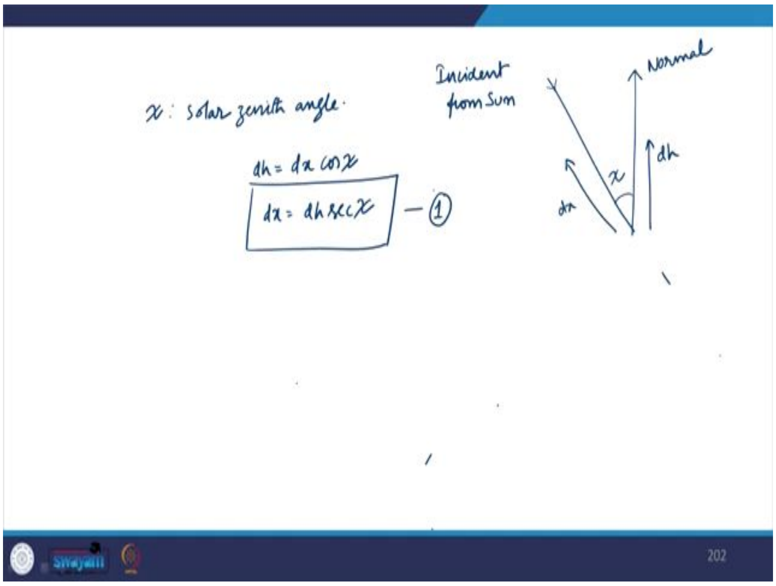

So, let us say this is the normal direction and say that the radiation is incident in this direction so, this is the angle chi. So, this is the normal and this direction is incident direction from sun. So, this is the height dh and let us say this is this height we refer as the oblique height as refer as dx. So, here chi is the solar zenith angle. So, we use simple trigonometry let us say we say that dh is equal to dx cos(chi) or dx is dh secant chi let us call this relation as 1. So, when the solar radiation passes through the atmosphere, a fraction of intensity is absorbed and scattered by the atmosphere.

So, let us say we stop here we will take this mathematical treatment ahead in the next session. So, basically what we have learned is, we have learnt how the number densities and the intensity of radiation from the top. Combine and give you a layer of ions or electrons how these two things balance each other at a particular height. Now then we made some assumptions about how the atmosphere should be treated; if you want to understand the Chapman's theory of layer productions. So, this is where we stop and will continue this discussion in the next session.