Physics I: Oscillations and Waves
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Lecture - 12
The Electromagnetic Spectrum

Good morning. Let me, first recapitulate some of the important things which we have learnt in the past few classes.

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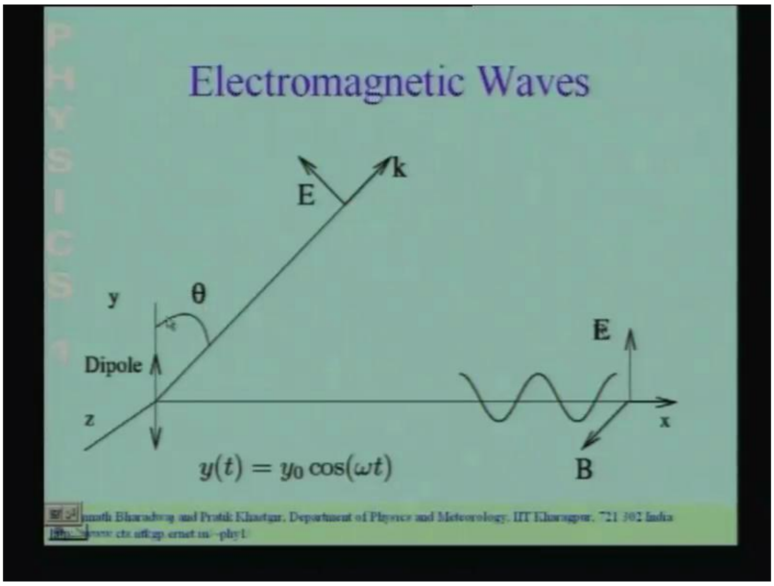

So, we first considered a situation where we have an electric dipole which is essentially, 2 metal wires 2 of their 2 of which aligned like this. And connected to a voltage source and we saw that if you feed a sinusoidal voltage the charged particles inside these 2 metal wires in this oscillate up and down, you have an oscillating electric dipole. And if you look at the radiation pattern at a large distance, you get a sinusoidal plane wave.

So, if you are located along the x axis at a large distance from the dipole remember, the dipole is aligned along the y direction. Then, the electric field at this point is going to be parallel to the direction of the dipole. So, the electric filed is also going to oscillate up and down the dipole oscillates up and down the electric field is also going to oscillate up and down over here with the phase difference with the oscillation the dipole.

The phase difference occurs because, of the propagation time. So, the electric field is going to oscillate up and down. And the oscillating electric field pattern is going to propagate forward along the x direction. So, at any given instant of time you have a sinusoidal electric field and the whole pattern propagates forward along the positive x direction.

Remember, the there is also going to be a magnetic field and the magnetic field is perpendicular to both the direction of propagation of this wave and the electric field. The magnetic field also oscillates at the same phase as the electric field. So, the this is what we refer to as an electromagnetic wave, the electromagnetic wave has an electric field and magnetic field both mutually perpendicular oscillating in phase. And both are perpendicular to the direction in which the wave propagates.

So, if you go to some other direction for example: the 1 over here again you are going to have the electric the wave propagating outward from the dipole. The electric field is going to be along the direction of the dipole projected normal to the line of sites. So, it is going to be in this direction and the magnetic field is perpendicular to both of these. So, this is the pattern which you get, the electromagnetic field pattern which you get when, you have a single dipole oscillating.

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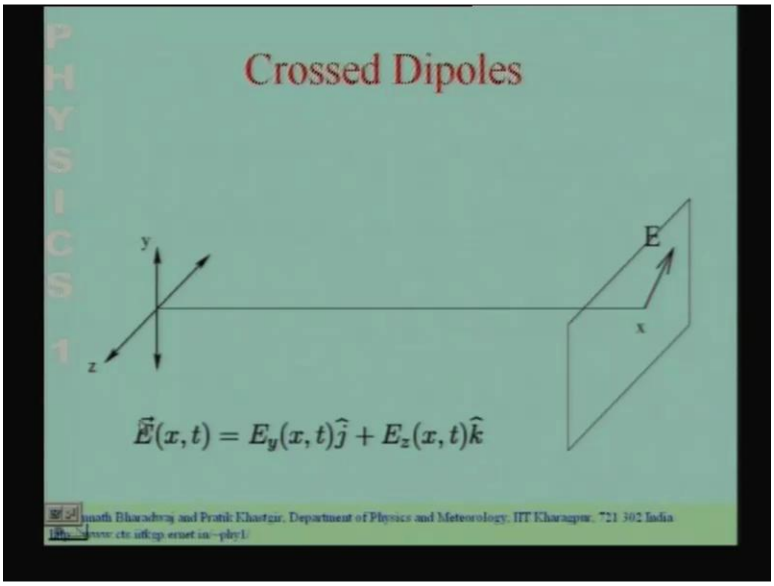

And then, we moved over to a situation in the last class where we have 2 crossed dipoles. So, we have now got 2 dipoles instead of 1 aligned along the y axis and another along the z axis. And we were discussing the electric field pattern at a point along the x direction which is perpendicular to both of these dipoles. So, we were discussing the electric field at a point over here a large distance away along the x direction. Now, the electric field here is going to be in the plane perpendicular to the line of site. So, it is going to be in the plane perpendicular to the x axis and in the situation, where I feed the same voltage.

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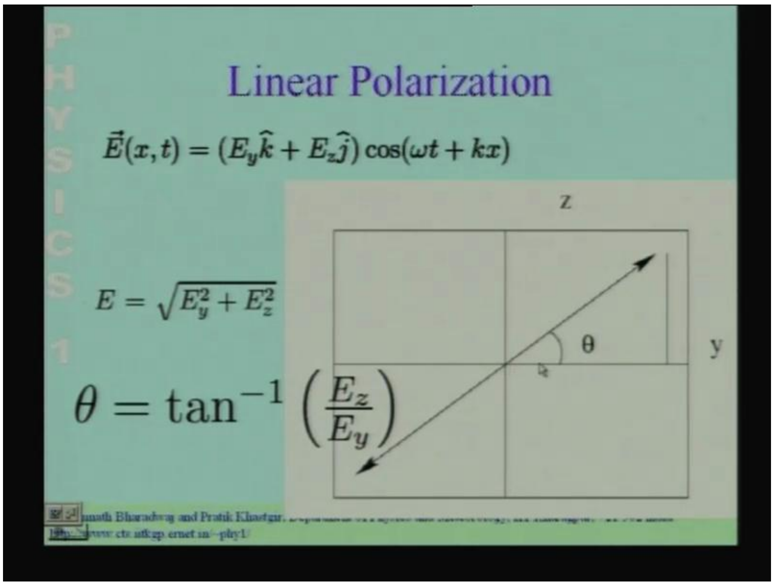

So, if I feed in the voltage which has the same phase, but different amplitudes into these 2 crossed dipoles. Then, both of them are going to oscillate with the same phase. So, the oscillations are both the electric filed along the y direction and the z direction can be represented as the same cos omega t plus kx kz minus kz in this case. And you have these factors Ey into j plus Ez into k outside this should be Ey into z plus Ez into k Ey into j and Ez into k outside.

So, if you change the magnitudes of Ey and Ez the direction in which the electric field oscillates is going to change. The direction quantify through this angle theta with respect to the y axis is the direction that is quantified through theta is given through tan inverse of Ez by Ey. So, if you change the ratio of the voltages the direction in which the electric field oscillates changes.

In all situations when, the electric field when the voltage fed into the these dipoles oscillates in same phase. The electric field is going to oscillate up and down in a line over here this the radiation is said to be linearly polarized and the angle the magnitude of the vector electric field vector and the angle at which it oscillates both of them are given over here.

We then, consider another situation. So, the next situation which we considered the voltage applied to the 2 cross dipoles had a phase difference of phi by 2. So, we considered a situation where the electric field where the voltage applied to the dipole along the z direction had an extra phase of phi by 2. The magnitude of the voltages were the same.

So, let me repeat you have this voltage of the same magnitude applied to both the dipoles, but there is a phase difference of phi by 2 and there is a an extra phase of phi by 2 to in this z direction.

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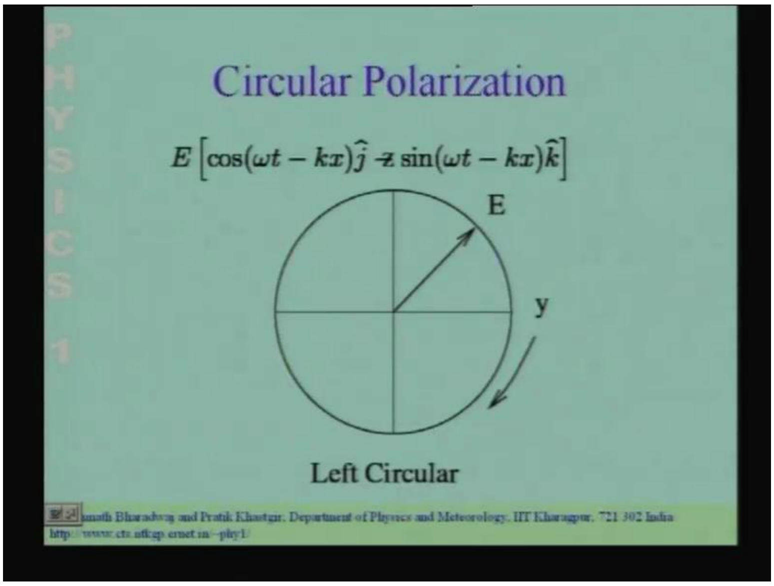

So, again the resultant electric field is a super position of the 2 electric fields produced by the 2 dipoles. But there is extra phase of phi by 2 along the z direction, this extra phase. So, if I put in this extra phase into the cosine omega t minus kz this will become minus sin omega t minus kz. And can see, that the electric field is going to go around in a circle because, the cos and the sin terms are 1 of them peaks the other 1 is going to have a value 0 and then, as this peaks up this is going to go down.

So, if you look at a fixed position fixed value of z you will see that the electric filed goes around in a circle. And in the situation, where you have given an extra phase along the z direction the electric field is going to go around this way along the direction which I show over here. Which is shown over here and I had told you in the last class that this is referred to as being left circularly left circular polarized.

So, this kind of an electromagnetic wave where the electric field at any fixed position goes around in a circle is said to be circularly polarized. And it could go around in 2 different ways depending on the phase which I have given. If I had given an extra phase of phi by 2 along the z direction it goes around this way which we referred to as left circularly polarized.

And if it goes in the opposite direction which would occur if I have to give a phase log of phi by 2 along the z direction the electric field would go around in a circular in exactly the opposite direction. We referred to this as the right circular polarized light. So, light can be the radiation the electromagnetic radiation can be circularly polarized. So, we have seen two situations.

One where the electromagnetic wave is linearly polarized the electric field oscillates up and down in a straight line. And then, we have circularly polarized where it is goes around in a circle. Now, let us consider a more general situation and that the more general situation is as follows. We still have, a phase difference of phi by 2 between these 2 dipoles. The voltage applied to these 2 crossed dipoles still has a phase difference of phi by 2.

But now, the amplitude of these 2 voltages is different. What will be the electric field pattern at a fixed point large distance away along the x axis? Where this fixed point over here a large distance away along the x axis what will the electric field look like. So, this is a small generalization of the circularly polarized electromagnetic wave which we have been discussing. Again, the electric field here is the super position of this electric field at this electric field, but now they both have different amplitudes and there is a phase difference of phi by 2.

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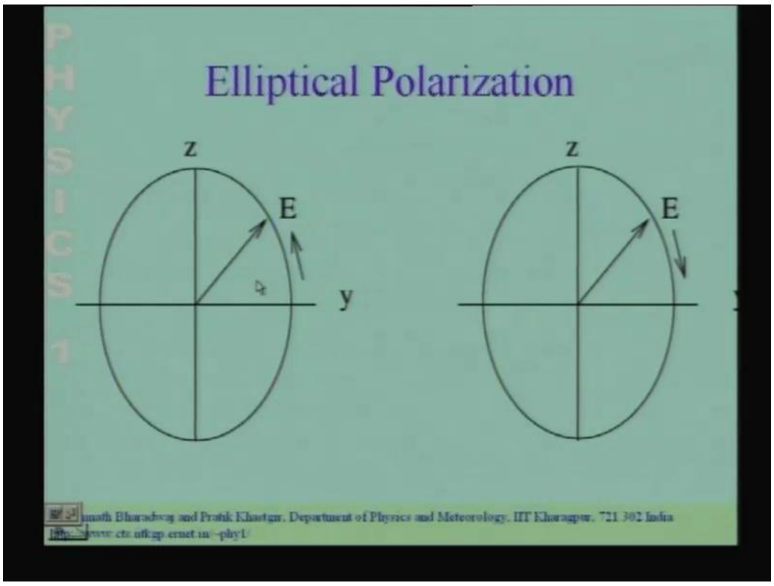

So, it is quite straight forward to realize that the electric field now instead of going around in a circle, it is going to go around in an ellipse. The elliptical motion of the electric field could either be clock wise that is left circular. If it is goes around clockwise and it could be anticlockwise and if you retain the same convention as for the circularly polarized light you can call this 1 where it is goes around anticlockwise at right circular.

So, this is polarized the right circular, this is left circular, left elliptical right elliptical. So, you have a elliptical polarized light. The major axis and minor axis of the ellipse they are aligned with the y z directions in this case. Now, you could think of a even more general situation is that I have voltages being applied to these dipoles. Whose magnitudes are arbitrary, not only are the magnitude of the voltage is arbitrary, but also the phase difference between these 2 voltages is also arbitrary.

So, I have tw2 different voltages and two with arbitrary phase difference could any 30 degree 40 degree any angle whatever. So, I have two difference voltages being applied to these dipoles and the phase difference between these two voltages could be arbitrary.

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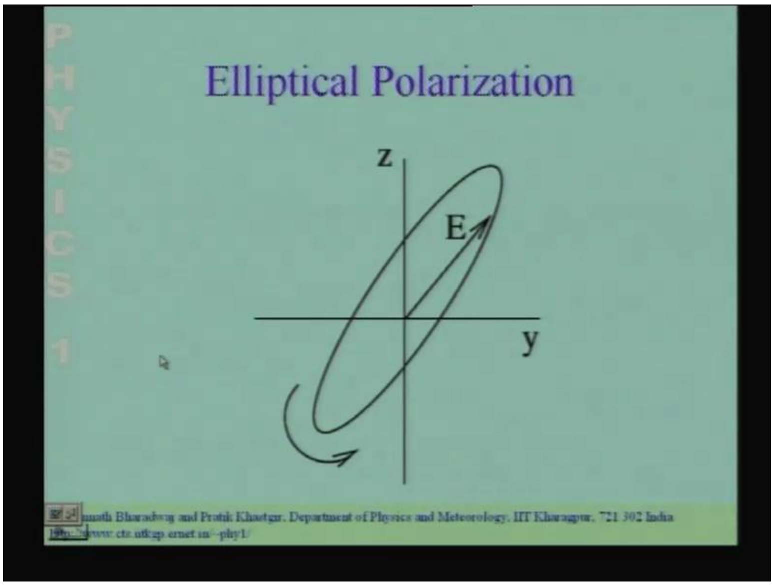

In this situation, the electric filed goes again goes around in an ellipse, but the major axis and the minor axis of the ellipse are no longer aligned with the y and z directions this is the most general situation. So, the most general polarized state of electromagnetic wave is where I have the electric field going around in an ellipse. And the ellipse is not aligned with the y or z axis which I have chosen.

So, let me recapitulate again we have considered a situation where we have 2 crossed dipoles. And we have looked at the electromagnetic wave a large distance away, along a direction perpendicular to both the dipoles. And we saw that, if the voltages fed into these 2 dipoles which are crossed has the same phase. You are going to get linearly, polarized electromagnetic waves. The electric field at any fixed point will be seen to oscillate up and down in a line.

We next considered a situation, where we had a phase difference of phi by 2 in the voltages being fed to the 2 cross dipoles. If you have a phase difference of phi by 2 in the 2 voltages being fed to the 2 dipoles which are perpendicular to each other. Then, at a large distance away along the direction perpendicular to both of these dipoles you will get a circularly polarized electromagnetic wave. If the amplitude of the 2 voltages are the same.

If the amplitude of the 2 voltages being fed to the 2 dipoles are different, you will get elliptically polarized electromagnetic waves. The major axis and minor axis of the ellipse will be aligned, with the y and z direction which are the direction in which the dipoles are also aligned. Now, we then moved on to a more general situation where the magnitude of the voltages is being fed to the 2 dipoles are different also. The phase difference between these 2 voltages could be arbitrary.

In this situation, you will get elliptically polarized electromagnetic waves and the major axis and the minor axis of the ellipse will not be aligned will not be aligned with the directions of the dipole. The major axis and the minor axis will be in some arbitrary direction which 1 can calculate and the major axis and the minor axis will not be aligned with the directions in which the dipoles are aligned which are the y and z axis here.

So, the elliptically polarized electromagnetic wave is the most general situation the most general polarized polarization state of an electromagnetic wave is where we have elliptically where it is elliptically polarized and the major axis and the minor axis of the ellipse are arbitrary. This is the most general polarization state of an electromagnetic wave.

You should also bear in mind that the electric field oscillates perpendicular to the direction in which the wave is propagating and the magnetic field is perpendicular to both the electric field and the direction in which the wave is propagating. So, the magnetic field is perpendicular to the both of these. So, in this case the wave is propagating along the x direction. So, the magnetic field is perpendicular to the x direction it is also in the y z plane.

So, if and if the electromagnetic wave goes around in an ellipse then, the magnetic field also goes around in an ellipse, but the magnetic field is always perpendicular to the direction of the electric field. So, if the electric field goes around in an ellipse with the minor, major and minor axis. The magnetic field will also go around in an ellipse. And the major and minor axis of the magnetic field ellipse will be perpendicular to the major and minor axis of the electric field ellipse.

These two are always perpendicular. So, the and they are in phase. So, the major axis of 1 will be perpendicular to the major axis of the other. And both of them will be in the y z plane. So, this is the general structure of the electromagnetic waves. Now, let me ask you a question. Suppose, we consider a bulb the radiation coming from a bulb. For example: you could, it could be the lamps which are illuminating this room or it could be the light coming out from a torch light. Whatever, whichever situation you consider if I ask you the question what the polarization state of the electromagnetic radiation which is produced by the sources.

Is it elliptically polarized or is it linear polarized or is it circularly polarized. What kind of polarization does the light that comes out from 1 of the sources which we usually, encountered. Let us say, the sun or possibly the bulb in this room or any of these sources, what kind of polarization state does it have.

Now, the point here is that the radiation produced by any of these natural sources of light is usually, unpolarized. So, let me briefly explain to you what we mean by the radiation being unpolarized.

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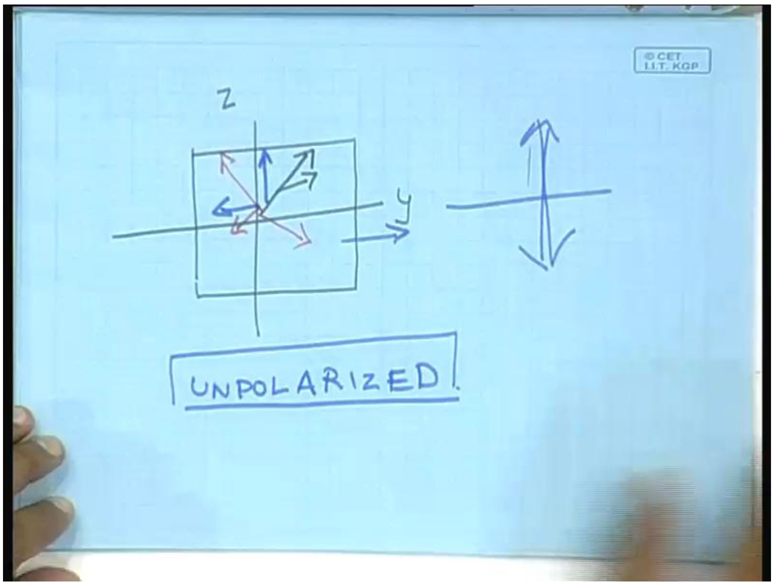

So, if the radiation is propagating along the x direction, the fact that the electric field should be in the y z plane that is the electric field is perpendicular to the direction of the propagation of the wave is true irrespective of what kind of electromagnetic wave. I have whatever, be the source in vacuum if I have an electromagnetic wave in vacuum, the electric field is always is going to be perpendicular to the direction of propagation.

The electric and magnetic fields are always going to be perpendicular to the direction of propagation of the wave. So, even for the electric, electromagnetic wave coming out from a bulb or torch, from the sun the electric field is always perpendicular to the direction of propagation.

But the electric field does not have a well defined polarization. So, it does not the electric field if you follow its evolution as a function of time it does not trace out any well defined trajectory. It randomly changes direction and the magnitude also goes around goes on changing. So, the electric filed from such natural sources, the direction of the electric field and its magnitude both of them actually change randomly. So, it keeps on jumping around in some kind of a random fashion.

So, you cannot associate any of these states of polarization which we have discussed we cannot associate any of them with this kind of a behavior of the electric field. So, the natural light which we have produced by source like a bulb etcetera. The electric field acts to the direction of the electric field and its magnitude also goes around changing randomly and you have what is called unpolarized light.

So, this radiation is not does not have any well defined polarized as you can refer to it as un polarized an electromagnetic wave the electric field keeps on jumping around randomly. And this has to do with the fact that when, you have the radiation from the bulb the radiation from inside the bulb if you look at it at the microscopic level also originates from a large number of oscillating dipoles.

But there are a large number of the fact that there are a large number of dipoles tells us that these and these dipoles did not be aligned with each other. So, you have a large number of dipoles inside all of which are randomly oriented as a consequence the radiation which comes out. If it were a single dipole or if there were many dipoles all aligned together oscillating you would have a well defined polarization for the radiation that comes out.

But you have all these dipoles which are randomly aligned inside the bulb, inside the filament of the bulb the filament which from which the radiation originates. For example: you have a large number of dipoles oscillating, but these dipoles have no well defined direction they are randomly oriented. So, the light which comes out the polarization, the electric field and the light which comes out keeps on jumping around randomly with time.

So, this is what we mean by unpolarized light there are devices are called polarizer’s. Which if you send this light through a polarizer, it will only allow a particular polarization to pass through. So, if there is a there are device called polarizer’s if you send it through that it will allow, only particular polarization to pass through and the resultant electric field will oscillate only up and down in a line.

Then, you can do all kinds of manipulations with it we shall discuss it later on this course. But in this part these course, we just discuss what we mean by light being polarized and what are the possible states of the polarization of light and how these are related with the electromagnetic wave nature of light. And we have discussed it in the more general setting of electromagnetic waves.

Now, so having discussed so, this brings us to kind of a conclusion of our discussion of electromagnetic of the properties of electric magnetic waves. So, we have seen that electromagnetic waves are essentially electric field and oscillating electric field pattern and an oscillating magnetic field pattern both of these oscillate in the direction perpendicular to the direction in which the wave is propagating.

Now, let us now discuss the possible frequency, the frequencies with which you have such electromagnetic waves. So, you have actually got electromagnetic waves of all possible frequencies. And different part so when, you have magnetic waves of a particular frequency we have a different name associated with that.

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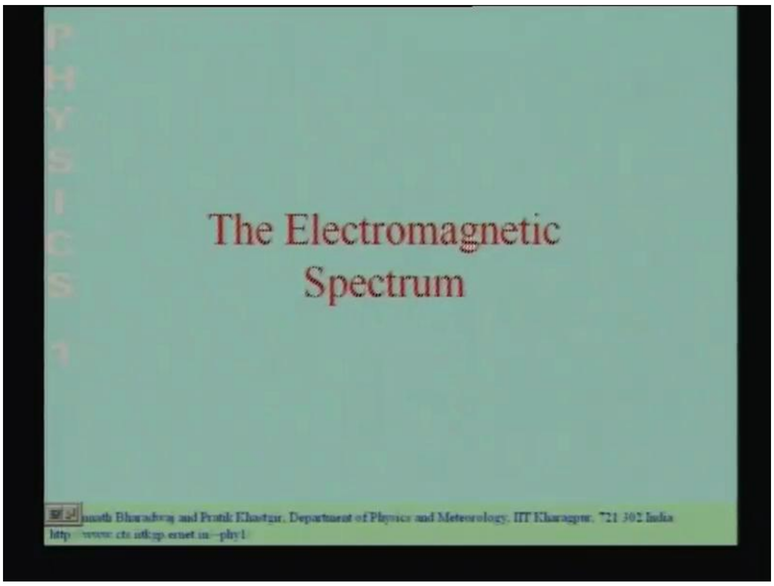

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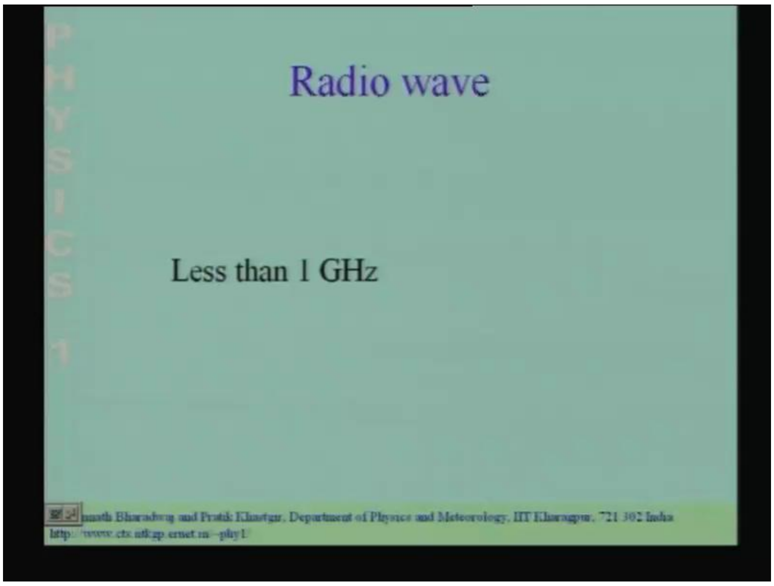

So, this brings us to a discussion of the electromagnetic spectrum. So, let us start with radio before starting our discussion of radio waves we should realize that, in nature and also in manmade situations. We have electromagnetic waves of we could have a electromagnetic waves with large variety of frequencies, large variety of frequencies also means a large variety of wavelengths.

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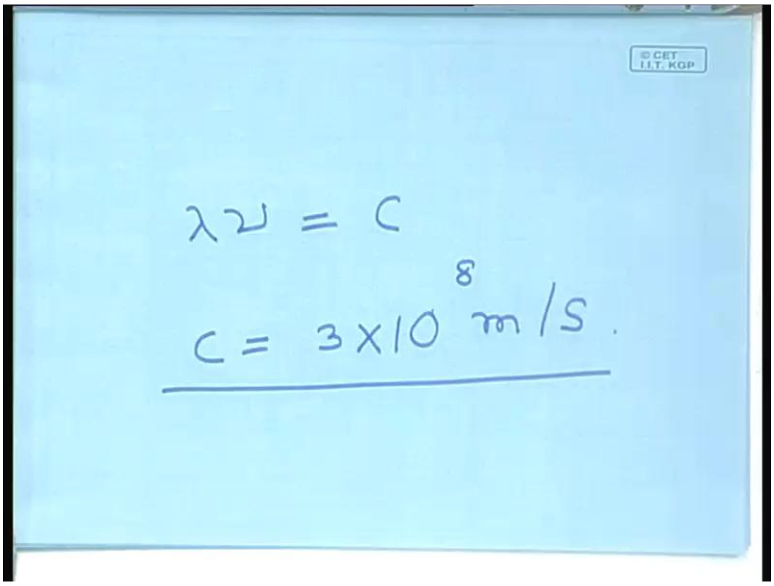

The frequency and wavelength as we have already discussed are related lambda into mu is equal to C where C is the speed of light 3 into 10 to the power 8 meters per second.

And the question is that in our discussion till now, this mu or lambda which are equivalent have not been specified. We in the discussion until now, mu and lambda have not been specified and they the discussion was valid irrespective of the value of the frequency or the wave length. So, the discussion was valid for all for electromagnetic waves of all frequencies or all wave lengths. It was not specific to a particular, to a frequency or to a particular wave length.

Now, in nature or in manmade situations you could have electromagnetic waves of a large variety of frequencies. The frequency can span a large variety a large range. And the phenomena related to different frequency ranges, different frequency bands, different ranges of frequencies in this entire range are different. There is also a different name given to the electromagnetic wave then, it is of a in a particular range of frequencies or range of wavelength.

The phenomena associated with different values of the frequency or the wave length are different. So, the names are different the phenomena associated are also different and this is what we are going to discuss here. So, let us start with the low frequency, the lowest possible frequencies for the electromagnetic waves the low frequency part. So, the electromagnetic waves of the lowest possible frequencies that is frequencies less than 1 gigahertz.

So, if I have electromagnetic radiation waves of frequencies less than 1 gigahertz these are referred to as radio waves. So, radio waves we have encountered them I am sure all of you must have heard the radio sometime or the other and the AM radio transmission about which we shall study in some more little bit more later on as we go long.

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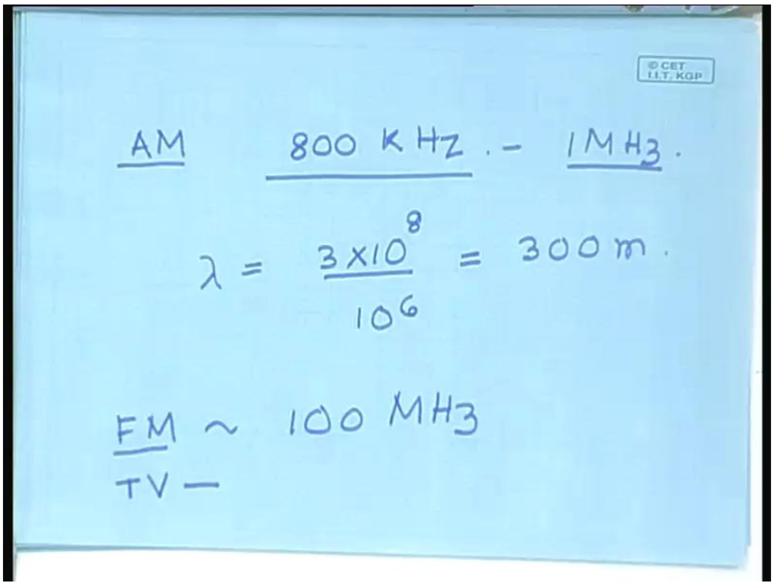

The AM amplitude modulation the radio transmission is usually, in 100s of kilo hertz to 1 megahertz . So, may be 800 900 kilohertz to 1 megahertz. So, if I have a 3 let me let us, also estimate the wave length corresponding to this. So, the amplitude modulation transmission usually, occurs at around 800 900 kilohertz to 1 megahertz. So, let us estimate the corresponding wave length.

So, 1 megahertz means lambda is 3 into 10 to the power 8 divided by 10 to the power 6 which gives us 300 meters. So, the radio waves are typically of the order of 100s of meters may be a kilo meter also kilo meter to 100s of meters. And radio waves have got application as we all know in communications. So, the radio transmission is an important means of communication and these work at frequencies typically less than 1 gigahertz.

FM transmission is at 100s of megahertz roughly, 100s megahertz in order of 100s of megahertz. So, does the TV also works at frequencies of around 100s of megahertz in the radio part of the spectrum.

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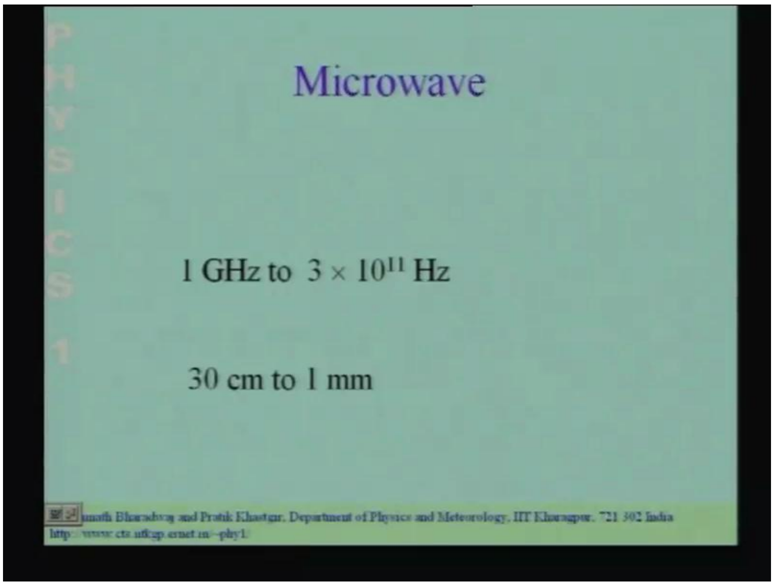

The next part of the spectrum from 1 gigahertz to 3 into 10 to the power 11 hertz. So, this is referred to as microwave. Now, a point which you should remember is that, I am giving you names for different frequency bands. So, I am what I am doing is, I am telling you that this frequency range to this frequency range is called something. So, here I am telling you that 1 gigahertz to 3 into 10 to the power 11 hertz is referred to as microwave.

Now, you should remember that these frequency the values of the frequency limits are not very rigorous they are always quite fussy. And somebody may also refer to for example, as 1 4 gigahertz as radio wave. And it would, you would, it should not be absolutely incorrect because, these boundaries are not all that rigorous are in strict they are quite fussy.

So, somebody could refer to something which is on the boundary as something 1 4 gigahertz also as radio waves. So, these are just some typical numbers you should bear this in mind. So, we refer to 1 gigahertz to 3 into 10 to the power 11 hertz as microwave. The corresponding wave length is 30 centimeters to 1 millimeter.

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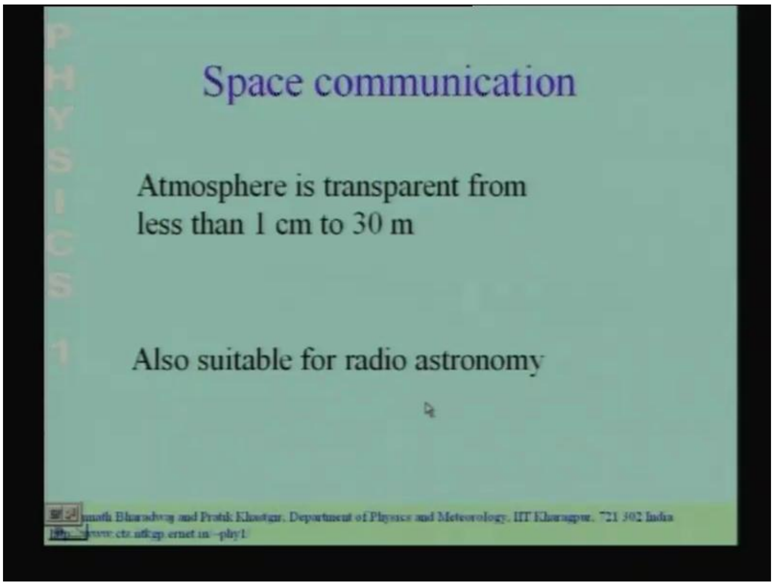

Now, microwave and radio the higher part of the radio frequency and microwave. Have got very important applications in communication So, the earth's atmosphere is transparent from 1 centimeter to 30 meters, 1 centimeter to 30 meters just let us, just go back. So, 1 centimeter is in the microwave and 30 meters. So, this microwave the largest wave length in microwave is 30 centimeters. So, 30 meters would be in the radio.

So, the radio the high frequency radio and the microwave both of these are the atmosphere is transparent to both of these. So, you can use it for space communications. So, if you wish to communicate with the satellite in outer space which is beyond the atmosphere you could use this that wave length range 1 centimeter to 30 meters for such communication.

Radio the radio waves larger than 30 meters are reflected by the ionosphere which is there in the upper atmosphere of the earth they are reflected back. And this reflection prevents it from being used for communication with space for space communication, but it has important applications if you want use this reflected wave for communicating on earth. Let me, explain this point a little bit over here.

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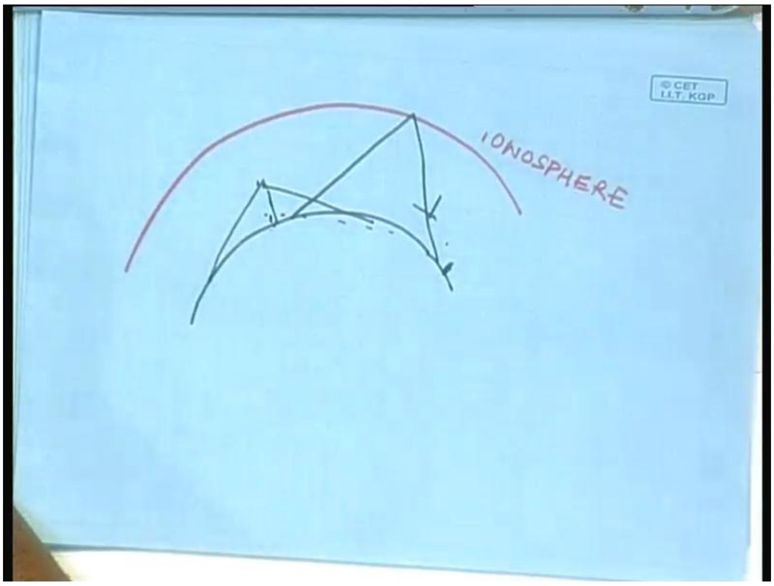

The surface of the earth we know is spherical. So, if you wish to communicate from here to here you cannot send a radio wave straight away. Because, it would then have go through the earth. You could built a antenna which would increase the range, where you could communicate, but still you could not be you would not be, able to communicate to a region over here with an antenna of this size you would have to build a even higher antenna.

Now, this can be overcome if you use radio waves which get reflected from the ionosphere. So, this is the ionosphere which reflects radio waves which are much larger than 13 centimeters. So, 30 meters sorry. So, if you are working in the range where the wave length is more than 30 meters the atmosphere it not transparent. So, the radio wave will get reflected and if the radio wave gets reflected then, you can actually send signal here by reflecting it of the ionosphere.

So, this is also useful in communication. So, before you had satellites this was you could have communicated with the point over here, from here using the reflection from the ionosphere. But now with satellites you could actually send the signal to a satellite and then, the satellite could send it back. So, if you wish to communicate using satellites, you should work in this range the larger wavelengths are reflected back by the ionosphere.

Now, this range where the atmosphere is transparent to microwave and radio waves it also useful for radio astronomy. You cannot see objects beyond the atmosphere at wave lengths much larger than this and it is difficult to see it at wave lengths much smaller than this also. So, this is very suitable for radio astronomy.

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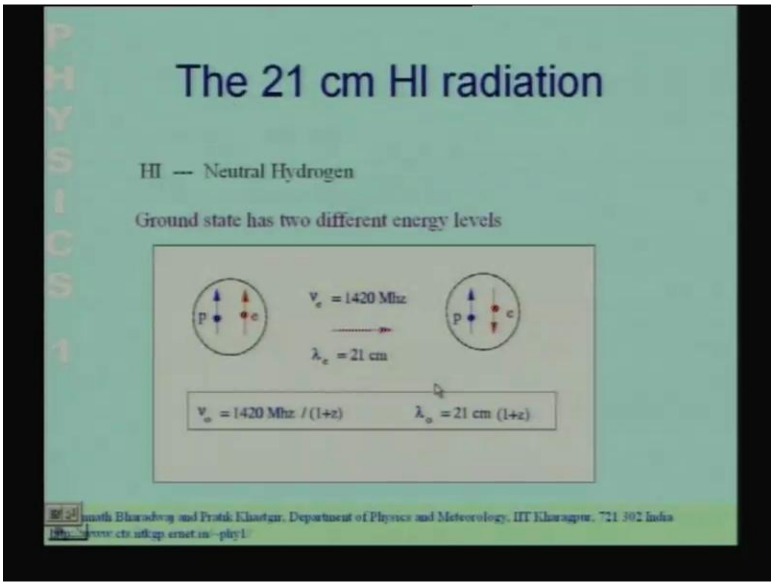

Now, let me just divert a little and tell you a little bit about something which is very interesting in radio astronomy. In particular we know, it is well known now that hydrogen is the most abundant known element in the universe. So, if you ask the question what is it that is most abundant then, it is hydrogen in the universe. And if hydrogen is neutral. So, by neutral hydrogen we have a spectroscopic notation for neutral hydrogen let me, first introduce that.

In the spectroscopic notation neutral hydrogen is denoted by H1. So, if you have neutral hydrogen atom it is referred to as H1. Now, as we know hydrogen, neutral hydrogen has a proton and an electron. So, if you have hydrogen in the ground state, you have a proton and an electron. And the electron is going around in an orbit around the proton. Now, we all know that the proton and the electron both of them have spins.

So, consider a hydrogen atom in the ground state. So, this picture here shows you a hydrogen atom in the ground state. You have the proton and the electron and here the spins of the two particles the spin of the proton and the spin of the electron are both aligned. Now, you could also have a hydrogen atom in the ground state where, the spin of the proton and the electron are aligned in opposite directions.

Now, it turns out that the situation where the 2 spins are in opposite directions has a slightly lower energy then, the situation that the 2 spins are aligned. So, the hydrogen atom could do a transition from this energy state to this energy state. Such a transition is called a hyperfine transition and there will be a small energy difference between these 2 states.

So, if I have a hydrogen atom in the ground state and if it goes state from here to here there will be a small energy difference this energy difference will come out in the form of electromagnetic waves. And the electromagnetic waves that are emitted when, the hydrogen atom goes from here to here comes out at 1420 megahertz a 1 42 gigahertz. Which is somewhere in the border of radio and microwave.

The wave length corresponding to this is 21 centimeters. So, neutral hydrogen in the ground state emits radiation at 21 centimeters to this hyperfine transition. Now, as I told you that hydrogen is the most ubiquitous element it is there all over the universe. So, you can use this to image different parts of the universe.

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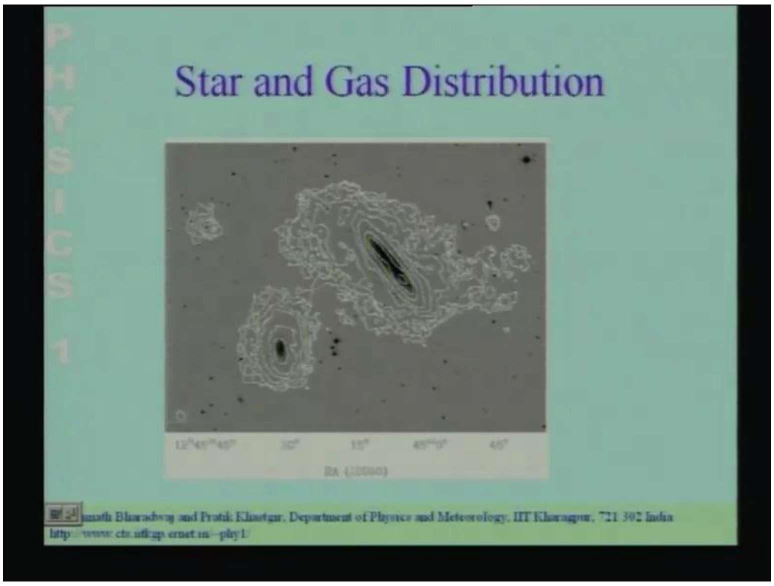

So, here I will show you an image made using the 21 centimeter radiations it is its image of a distant galaxy. A galaxy is a collection of stars it also has gas. So, this shows you 2 galaxies, the black things which you see here is where the stars in the galaxies are. We live in a galaxy like this.

So, there is a this is the galaxy the black thing or the stars in the galaxy. And the white contours white contours show you, how the mutual hydrogen is distributed. The white contours were measured using the 21 centimeter radiation that comes out from the neutral hydrogen.

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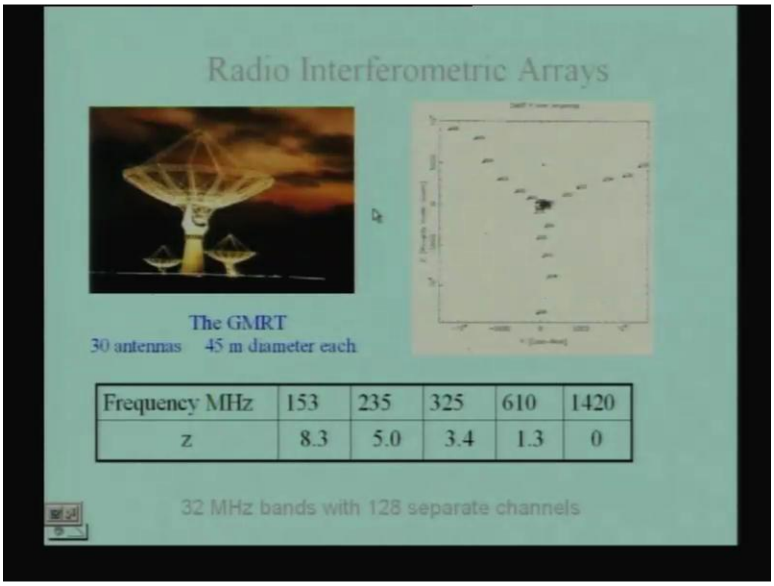

How are such measurements done? So, let me show you something of particular interest to me and to us in general this is because, India now as the world's largest low frequency radio telescope called the joint meter wave radio telescope the GMRT. This is located in a place called Narayangaon near Pune. So, in a place called Narayangaon near Pune we have this radio telescope which is the world's largest low frequency radio telescope at present.

There are 30 antennas, each 45 meters in diameter. This picture shows you 1 of the antennas in the GMRT. The diameter of this antenna is 45 meters. And there are 30 such antennas, the 30 antennas are distributed in a Y shape like this the length of each of these arms in the Y is around 16 kilometers. So, you have this low frequency antennas, the antennas each antenna is a dish it reflects, it focuses the radiation incident on it from far away sources it focuses it to the point over here.

And at this point you have a dipole you have actually 2 crossed dipoles, which can measure the detect the electromagnetic wave which is focused on to it. So, this is roughly how this whole thing works. And this joint meter wave radio telescope works in a range of frequencies shown over here. The 1420 megahertz these values are in megahertz.

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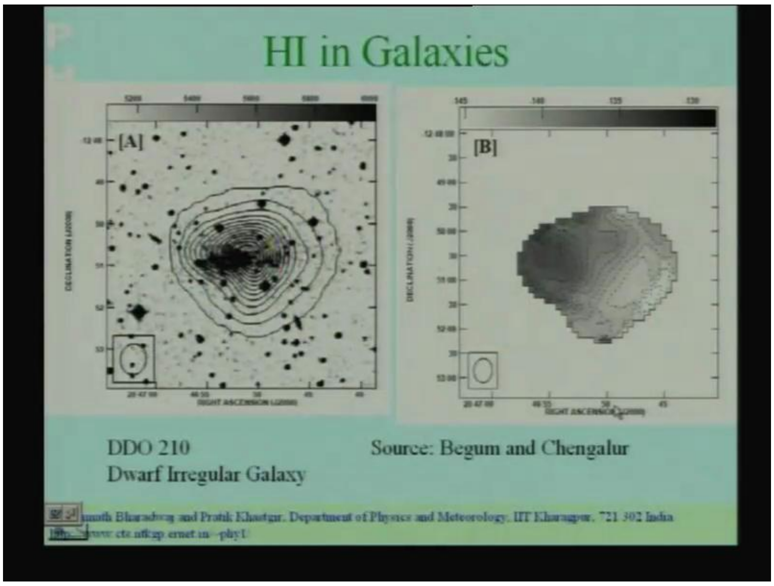

The 1420 megahertz band can be used to make images of the 21 centimeter radiation that comes from neutral hydrogen this shows you another image made using the giant meter wave radio telescope. This is an image of a galaxy called DDO 210 black thing over here is where the stars in the galaxy are. And the contours are determined from radio measurements of the 21 centimeter emission from neutral hydrogen’s.

So, the contours show you how the hydrogen in these galaxies are distributed. This picture is from a paper by Begum and Chengalur who used the giant meter radio wave telescope to observe this particular galaxy. And such studies can be used to infer very interesting things about these galaxies we shall not go into it in over here.

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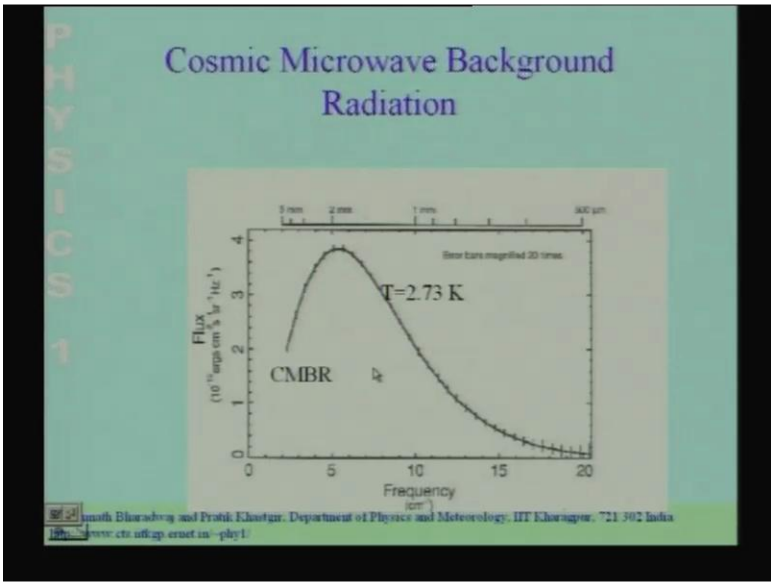

Let me, now move on to another very interesting thing which is there in the microwave band. And this very interesting radiation is referred to as the cosmic microwave background radiation. So, let me first tell you briefly the history of this radiation in the 60s when, microwave radiation radio. And microwave communication was being developed 2 scientists there were essentially, communication engineers at the Bell laboratories were investigating what are the possible sources of noise in radio communication.

And what they did was, they took a radio receiver and they were studying possible sources of noise in that radio receiver. So, you take the radio receiver and point it in different directions and see what is the noise which comes from different directions. And they found that, there was a noise which those noise contribution which seemed to be there present there in all directions in the sky irrespective of where you point your radio receiver there was a noise contribution.

Which seemed to be coming uniformly, from all directions in the sky. And this was something quite mysterious, but interestingly quite unaware of this. And much earlier actually, a Russian scientist called George Gamow had predicted that our universe that the whole of space should be filled with an electromagnetic wave with the radiation. And at the time which, at which this noise in this radio receiver was detected by 2 communication engineers at the Bell labs Penzias and Wilson at the time.

When, they detected this there was a group of scientists at Princeton University who were trying to detect this radiation which was predicted to fill the whole universe. And when, they heard that Penzias and Wilson had discovered this kind of a noise which seems to be coming from all direction in the sky they realize, that Penzias and Wilson had discovered a radiation which fills the whole universe.

So, this radiation is something which fills the whole universe and it was the discovery of this radiation that is that it provides very significant evidence for the big bang theory of the universe. So, it is a consequence of the big bang theory of the universe that the universe should be filled with the radiation like this which permeates the whole universe.

And it is this radiation which was which is being detected by this radio receiver. Which if you point in any arbitrary direction you get same the amount of radiation. This radiation which was the Penzias and Wilson received the Nobel Prize for this discovery. Now, this radiation was also predicted to be a black body radiation. And this prediction was verified roughly, a little more than 10 years ago.

The people who made the person who was the leader of the team which verified the black body nature of this radiation received the Nobel prize in physics this year in 2006, that is last year in 2006. So, let me tell you a little bit now about what was the discovery. What is it that was actually, but measured. So, this curve over here shows you the spectrum of the radiation that was measured this for which the Nobel Prize was given last year. So, now let me digress a little what you mean by a black body radiation.

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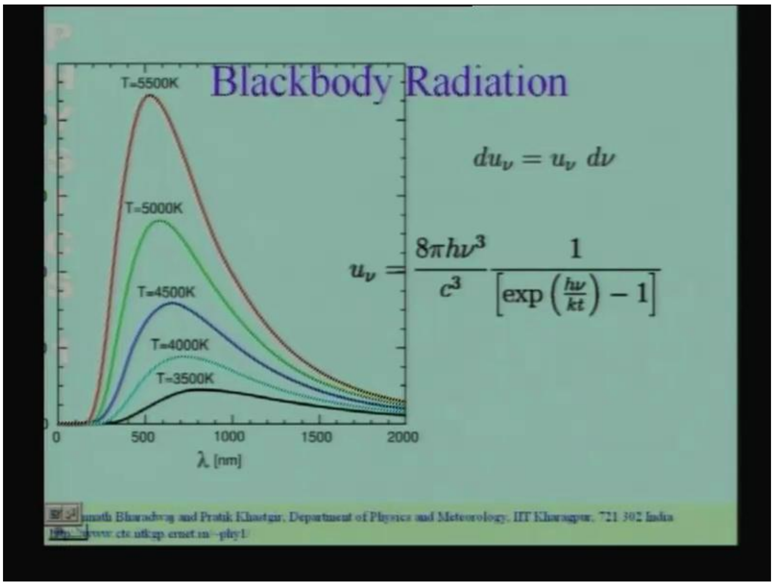

So, I am sure of all of you would have heard of black body radiation earlier. The question is what do we mean by black body radiation? Or rather what do we mean by a black body? The word black body refers to something, which absorbs whatever radiation is incident on it, but it just it does not just keep on absorbing radiation and does nothing else. No, it absorbs whatever is whatever radiation is incident on it and it emits radiation of all wavelengths or of all frequencies with equal efficiency.

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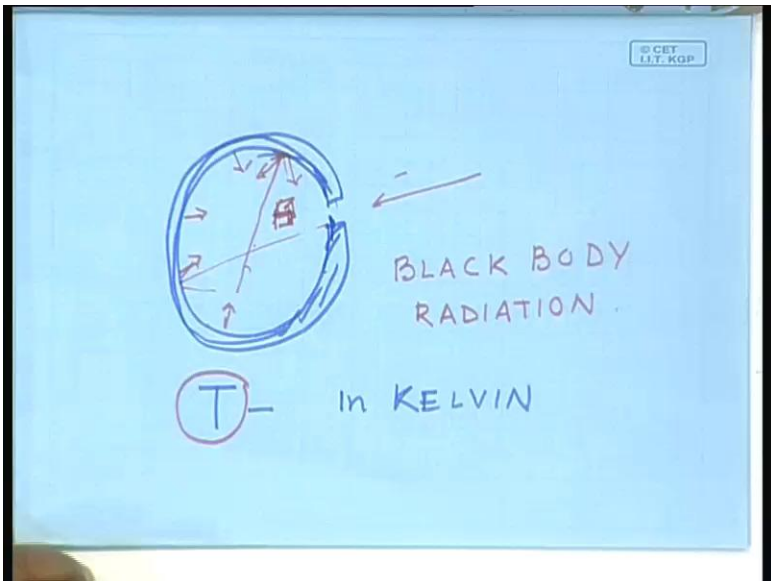

So, this. So, these 2 properties are what define a black body. Let me, take up an example of a black body. So, suppose we have a cavity this is a black body cavity, we have a cavity possibly made up of some metal kind of some kind of metal. And the outer wall the cavity let me join it like this it has a finite thickness also. So, this is my cavity it has some kind of a thickness and this cavity is brought is maintained at a temperature T. So, this T is the temperature of the cavity in Kelvin.

So, I bring this cavity, metal cavity to a temperature T and there is a small hole over here. So, that some radiation can go through and come out. So, we have kept this cavity at the temperature T. Now, what will happen the question is what will happen if some radiation comes inside, what happens to the radiation which is there inside this cavity. Now, the walls of this cavity emit radiation and radiation emitted from here will reach here and get absorbed. And this wall will again, reemit radiation of all wave lengths equally efficiently.

So, any radiation which comes inside which happens to come inside will again get absorbed over here and get reemitted equally efficiently in all wave lengths. So, if you keep this cavity at a temperature T for sufficiently long, the radiation which is there inside the cavity will get emitted absorbed, emitted absorbed many times until finally, the radiation inside this cavity will be in thermal equilibrium with the walls of the cavity with the inner wall of the cavity.

This radiation which is there inside over here some part of it will leak out which, you can measure that is why we have the hole over here. So, this radiation which is there inside this cavity which we assume is in equilibrium with the walls of the cavity through repetitive absorption and reemission. So, it will get absorbed reemitted many times till finally, on the average the radiation inside does not change.

So, the radiation inside this cavity in equilibrium with the cavity at a temperature T is what is called black body radiation. So, this is what is referred to as black body radiation. And since, this radiation is in thermal equilibrium with this cavity at a temperature T. The spectrum of this radiation it is found is characterized is uniquely, characterized by the value of the temperature and nothing else.

So, the spectrum of the black body radiation is completely characterized by the temperature of the black body with which it is in equilibrium. So, the crucial point is that when, radiation is in equilibrium with matter which can emit and reabsorb the radiation equally at all wave lengths. When, this radiation comes to equilibrium with matter it has the black body spectrum.

The spectrum is completely defined just by the temperature of the black body of the matter. So, the radiation also has the same temperature because, it is in equilibrium with the matter and the spectrum of the radiation is completely specified by the value of the temperature. So, how do you quantify the spectrum.

The quantity which, the we use to quantify the spectrum is as follows. I have shown it over here. You take a unit volume element inside and ask the question what is the energy in the a small frequency range in this volume. So, this is what I show over here. The question being asked is how much is the for this small volume which I showed you over there. What is the energy for frequency interval in the frequency interval d nu?

So, if I look at a frequency nu frequency range between the 2 frequencies nu and nu plus d nu. How much energy is there per unit volume? That is what so, d nu is the energy per unit volume in the frequency range d nu. And d nu can be written as u nu this spectral energy density into d nu. And this…So, when I talk of the spectrum of the black body radiation I am essentially referring to u nu.

So, it is being found that u nu has this form given over here. This is called the black body spectrum or the Planck function. So, this the spectrum of the black body radiation has a form which depends only upon the temperature. There are other constants over here which are there are other numbers over here which are constants. So, you have the Planck constant h and the Boltzmann constant K. And the only parameter which depends on the nature of the which decides the spectrum is the temperature.

So, if you wish to calculate the spectrum the value the energy density at any particular frequency you have to put in the value of the nu here And for a particular value of the temperature this has a unique spectrum. So, this shows you the spectrum of the black body here it is plotted as the function of the wavelength. So, you have the energy in the wavelength interval d lambda and it is plotted as a function of the wavelength.

So, the point to note there are a few points very important points to note over here. These black body spectrum the spectrum is decided only by the value of the temperature and nothing else that is the first point. The second point is: that these black body spectrum curves do not intersect if I change the temperature, I will get a different curve which does not intersect with the previous curve that is the second point.

The third point is: that the energy density increases continuous monotonically if I keep on increasing the temperature, the curves get higher and higher. And the peaks of the curve also shift to a smaller wavelength as I increase the temperature. And it has been found, that the product of the peak wavelength and the temperature of the black body, the product is a constant this is called the Wein displacement law.

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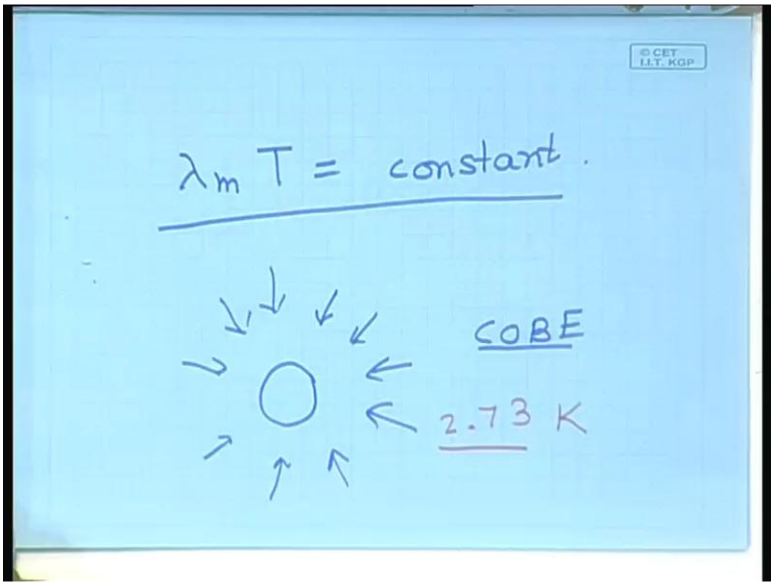

So, it has been found that the product of lambda m into the temperature of the black body this is a constant. Lambda m refers to the wavelength where the black body spectrum peaks. And T refers to the temperature of the black body. So, it has been found that as you increase the temperatures the wavelength where, the black body spectrum peaks keeps on getting smaller and smaller.

So, the black body radiation is the radiation that arises this has is the spectrum of the radiation that arises. When, you have radiation in thermal equilibrium with matter.

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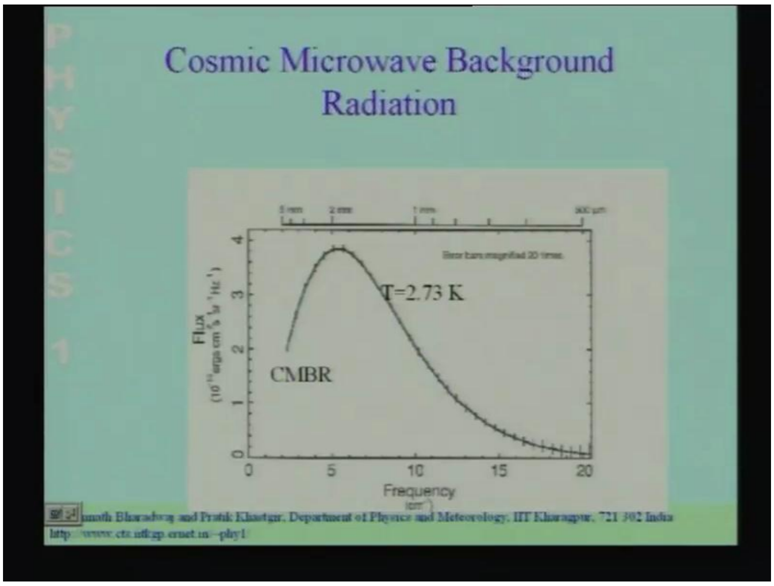

Now, what this curve shows is the spectrum of the radiation that you get coming from space. So, you have if you take a radio receiver and point it in any arbitrary direction you will find that there is some radiation coming which is independent of the direction in which you point your receiver it is coming from all direction in space. So, if I am sitting on the earth over here there is some radiation coming from all directions in space.

This was discovered by Penzias and Wilson and they did the measurements only in a particular frequency. So, the spectrum was not very well known. And if you make a measurement that only 1 frequency if you assume it is a black body if you make measurement at only 1 wavelength of frequency. If you assume it is a black body you can get the temperature straight away because, the curves do not intersect.

So, the observation made by Penzias and Wilson indicated that it had a temperature of around 3 Kelvin the black body nature was not very well known then, but later on people did more on more observations and finally, in the 1990s NASA sent a satellite called COBE. Which measured the spectrum of this radiation which comes from space all comes from all directions in the sky they measured the spectrum and the spectrum was found to be a black body this is what is shown over here.

So, the spectrum of this radiation which comes from all direction in space, all directions in this sky was found to be a black body with the temperature of 2 73 Kelvin. And this black body which was measured by COBE by the COBE satellite is possibly the most precise black body curve that has ever been measured. So, what this finally, tells us is that there is a black body radiation with a temperature of 2 73 Kelvin coming from all directions and we interpret this as the whole universe, the whole of space the whole universe is filled with the black body radiation at a temperature of 2 73 Kelvin. So, it is as if the whole universe is inside a black body cavity and it is filled with a black body radiation of 2 73 at a temperature of 2 73 Kelvin.

This is 1 of the most important discoveries which have been make and this clearly puts the big bang theory of cosmology where the universe is expanding the universe started from a big bang and which this validates the big bang theory of cosmology.

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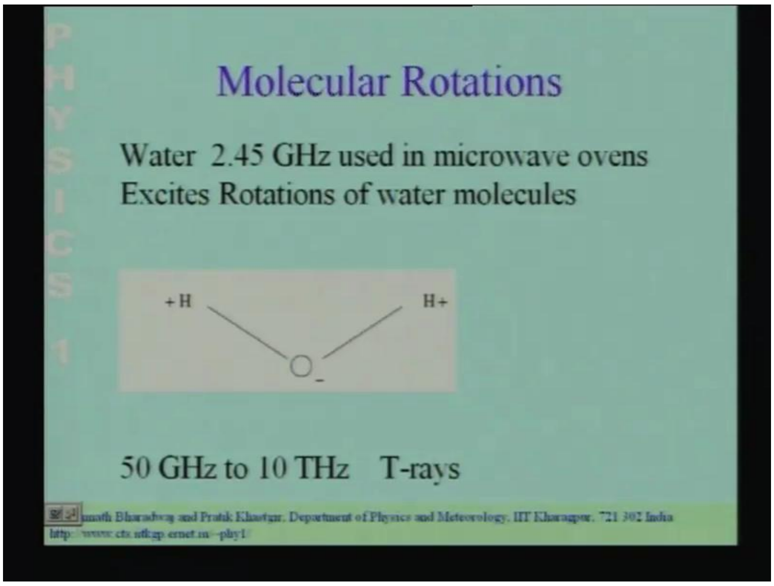

Now, let me move on to another application, another very interesting thing which has to do with microwaves. We have already discussed molecules and the vibrations of molecules. We discussed the vibration of benzene molecules now, molecules in addition to vibrating can also rotate. And molecules have the vibrations and rotation of molecules are actually quantized. So, corresponding to different vibrational and rotational states you have different quantized energy levels.

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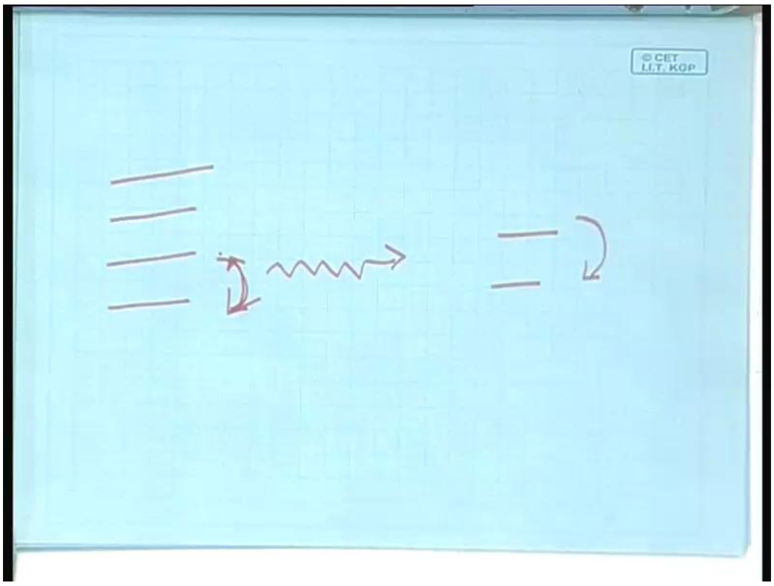

And if you have transitions between these energy levels. So, if I have a molecule in a excited vibrationaly excited energy level. If it is goes back to the ground state there will be some radiation which comes out and these transitions correspond to radiation in the microwave and in the infrared. Now, water molecule we know, the water molecule it has a hydrogen 2 hydrogen atoms and an oxygen atoms it is polarized.

So, if i put in an external electric field the dipole movement of the water molecule will try to align with the external electric field. And if the electric field oscillates, the dipole moment will also start to oscillate and it will set this will basically, set the water molecule into rotation. So, if I have an external electric field which is rotating, which is oscillating the it is sets the water molecule into rotation this is another kind of excitation of a molecule it is a rotational excitation. These rotational excitations are quantized.

So, if I have a water molecule which is rotating and if it comes down to the ground state it will emit radiation and vice versa. So, there is a rotational transition of water molecules which occurs at 2 45 gigahertz. And this is the transition that is used in microwave ovens. So, in microwave ovens you have microwave at 2 45 gigahertz which is incidental whatever you want to heat.

The water molecules inside this thing that you wish to heat will start rotating when, it this radiation falls on it. And this rotational energy gets converted into the random motions of the molecules which is what we call heat. So, this is how the microwave oven works and this is a an important daily, day to day application of this microwave these Another so, I should tell you a interesting thing which follows from this. So, this is why if you put in say dry piece of paper or something like that into a microwave oven the oven. The microwave will not be heated, microwave can only heat things which have water in them. So, I think let us bring today's lecture to a close here. And we shall resume our discussion with the from here in the next class.