Astrophysics & Cosmology
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Lecture – 24
Galaxies and the Expanding Universe

Welcome, in the last lecture, I told you how astronomers a little more than hundred years ago around hundred years ago analyse the distribution of stars and the distribution of globular clusters and finally came to the conclusion that we live in a collection of stars called the galaxy.

After this, we discussed a little bit about different kinds of galaxies and then we moved on to discuss the rotation curve of galaxies and I how these rotation curves tell us that there is a component of matter that we do not see directly but we know it is there because you require this matter to have a flat rotation curve which is observed and this matter is referred to as dark matter whose nature is still unknown, one of the big problems in astrophysics and physics.

Today we shall back track a little, I had mentioned that the distribution of globular clusters had played a very important role in understanding the nature of our galaxy, the structure of our galaxy. The question as to how the distances to these globular clusters were determined had been avoided in the last class. I did not touch upon this in the last class. You can see them in the sky but unless you know the distances you will not know how they are distributed in space.

So today let us start off by discussing to some extent how distances are determined. So the entire subject of determining distances is extremely important in astrophysics and particularly in cosmology because you need to know the distances to objects without distances you cannot make any progress. What is seen is that these things are there in the sky, you need to know the distances to make further progress.

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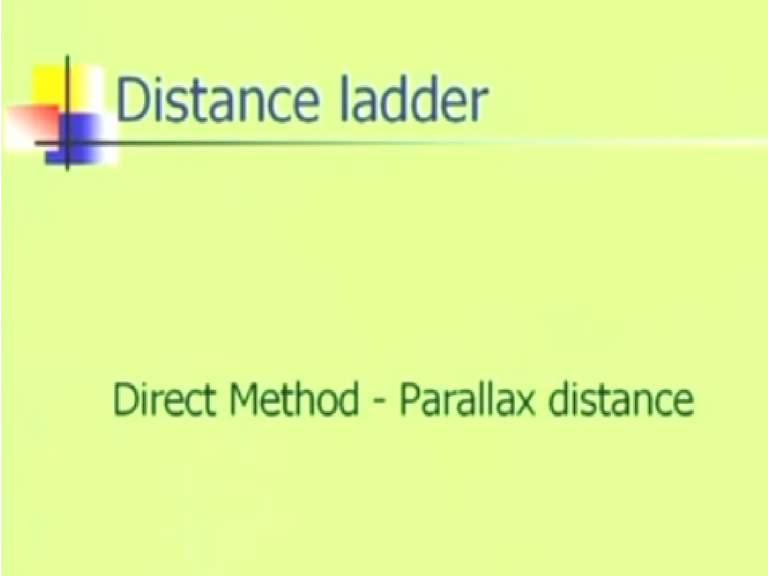

So the entire study of distances is based on a concept called the distance ladder. So it is like the determination of distances is the entire process is like a ladder. So when you have a ladder there are steps in the ladder you climb, you are standing on one step and you are holding another step somewhere else to climb up, you move a foot up. So one foot remains there and one foot goes up and then you move both the feet up.

So you have moved up a little bit. So the entire business of finding distances is essentially like this. It starts off from the solar system. So we know that the earth goes around the sun and this causes a parallax in the nearby stars and from this parallax you can determine the distances to the nearby stars. I also told you that this entire thing is restricted because from earth, the atmosphere of the earth restricts the angular resolution and thereby you are also restricted in determining distances because you need to determine the parallax.

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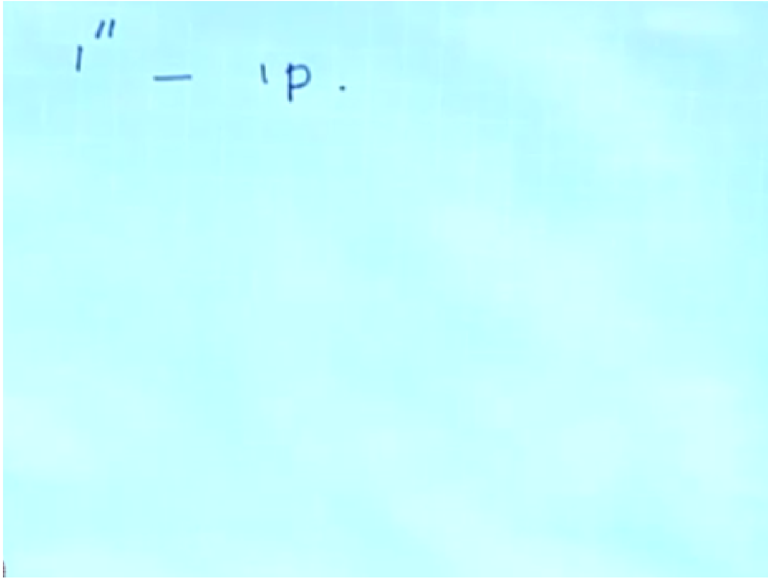

1 arcsecond, a parallax of 1 arcsecond corresponds to 1 parsec and you are restricted to a fraction of an arc second on the earth.

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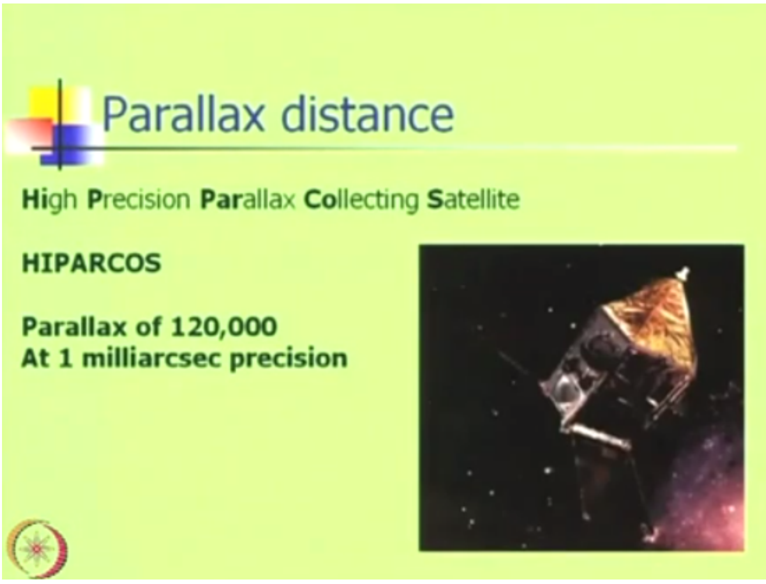

Recently not okay not very recently in the 90's early 90's. In the 90's there was this satellite called Hipparcos, the entire thing is given over here high-precision parallax collecting satellite. So this satellite was launched with the aim of determining the parallax to 1 milliarcsecond precision.

So this satellite could determine parallax to 1 milliarcsecond precision and it could determine the distances by this method of 120,000 stars in our own galaxy okay. So historically and even at present, the first step in the distance ladder is depends on determining distances through parallax and historically also this is how it has progressed.

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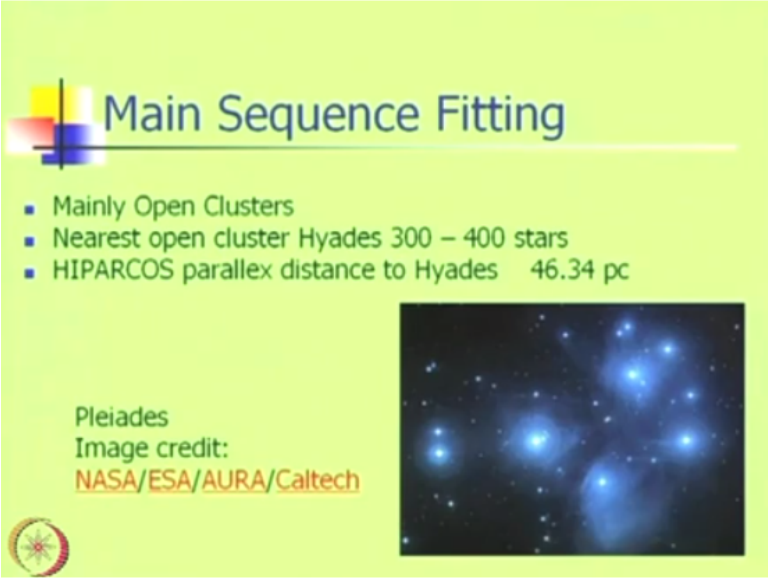

Then you determine the distances to different stars and the stars I have told you, you find that there are collections of stars which you can make out in the sky. In the last class, I told you about globular clusters which have around a million stars they are very compact and you saw in the picture that they lie outside the plane of our galaxy.

They are distributed in a kind of spherical fashion, outside the plane of our galaxy (()) (05:42) and these globular clusters you can guess that they have old red stars, the reason should be clear because the disk the star formation is taking place in the disk of our galaxy. The globular clusters are there all over, so they have, they were formed at certain time after which there is no star formation taking place.

So the old, the young stars, bright stars would have bright blue stars would have burnt themselves out very fast whereas the old, the small low-mass stars which are also red remained, they have a long life. They burn their fuel slowly right. But these, there is another class, these are the globular clusters and we shall come back to globular clusters again as we go along in cosmology they also are very important in cosmology.

But we have another kind of cluster which you see these are open clusters. So these are loose collection of stars which are believed, which are actually believed to have formed which and there is evidence that these stars formed together. So gas cloud collapsed and in that process many stars are formed together. So they could have hundreds to thousands of stars. So this picture here shows you the prominent, very prominent open cluster in our own galaxy and you can see this in the sky, it is very prominent.

So you will see it is called Pleiades. So it looks like a region on the sky of the sky where there are more stars than the rest of the region okay so this is called Pleiades. So we look up any sky chart and identify Pleiades in the sky, you can see it and I think you can see it right now also, at night, if you go out at night Pleiades.

It is an open cluster. Now you can use, so the main, I am not going to go exactly historically how the distance ladder was established, I shall try to give you an idea of the distance ladder with some indication as to how it was established. So one possibility one what you could do is, you use the parallax distance method to find the distance to some open cluster okay. So you then have some open clusters which whose distances are known okay.

So for example with Hipparcos, it has been the distance to the nearest open cluster which is called Hyades as we determined using, it has 300-400 stars and that a very accurate distance determination has been possible using this satellite Hyades and it gives an estimate of 40.34 parsec, that is the nearest open cluster okay. That is the current, I mean current most precise possibly the current most precise value. But historically also and this is one approach and people would have taken.

So you use the parallax method to find the distance to an open cluster okay. And then you can look at different open clusters which the other open clusters may be further away so the distances will be unknown okay. So you had these observations of open clusters, these are stars that groups of stars and each group was formed all the stars in a single group was formed together. So that is an open cluster. Now, what you do is you do a main-sequence fitting to the open clusters.

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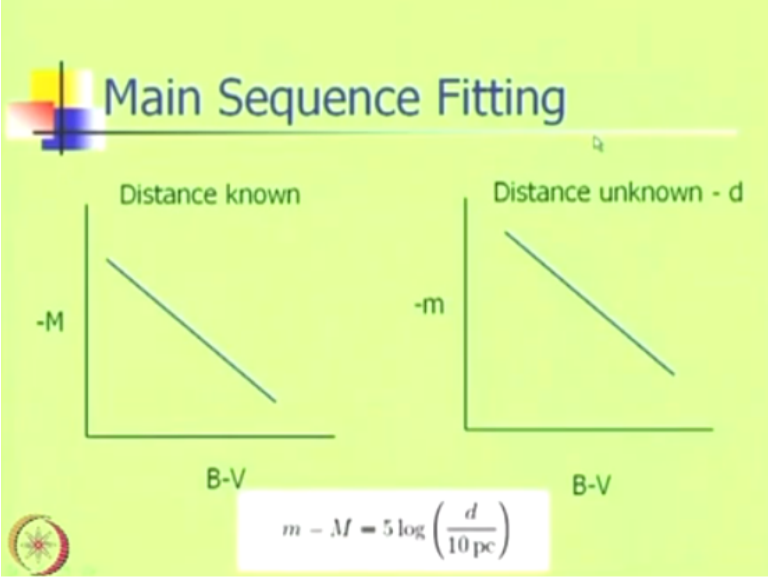

$$m - M = 5 \log \left(\frac{d}{10\,\text{pc}} \right)$$

So let me explain this idea to you. We have seen that the bulk of the stars, they are that you see will be in a stage where they are burning hydrogen and they lie on a curve in the HR diagram called the main sequence. So if you have an open cluster whose distance is known you can then measure the magnitudes.

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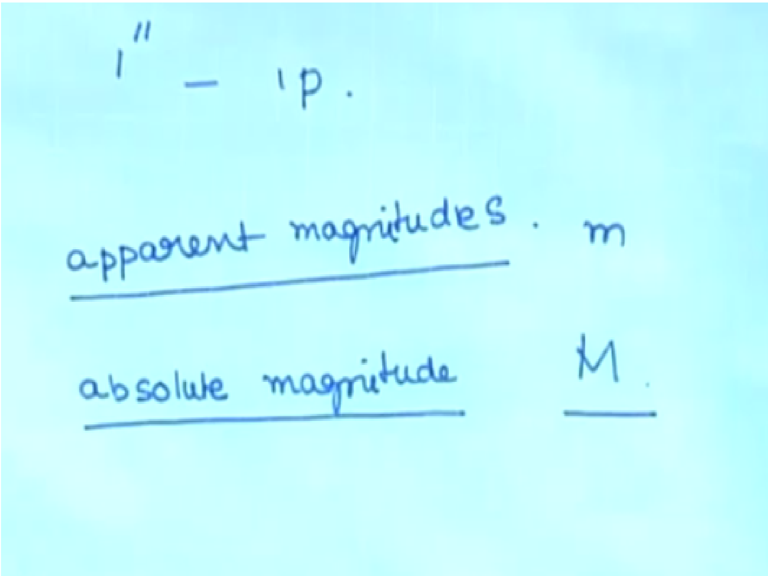

The apparent magnitudes of these stars in that open cluster, apparent magnitude is log of the flux and since the distance is known you can determine the absolute magnitude. So the apparent magnitude is m and the absolute magnitude is M. Since the distances, distance to the open, you have some open cluster whose distance is known you can then determine the absolute magnitude.

So the absolute magnitude tells us about the intrinsic brightness of the stars. The apparent magnitude is only the apparent brightness which will change with distance. The further away it is, the less will be the apparent brightness and the magnitude will be more because the magnitude increases if it gets fainter okay. So you have a known an open cluster whose distance is known from this you can determine the absolute magnitude and the colour. Color does not depend on the distance so you can determine this curve okay.

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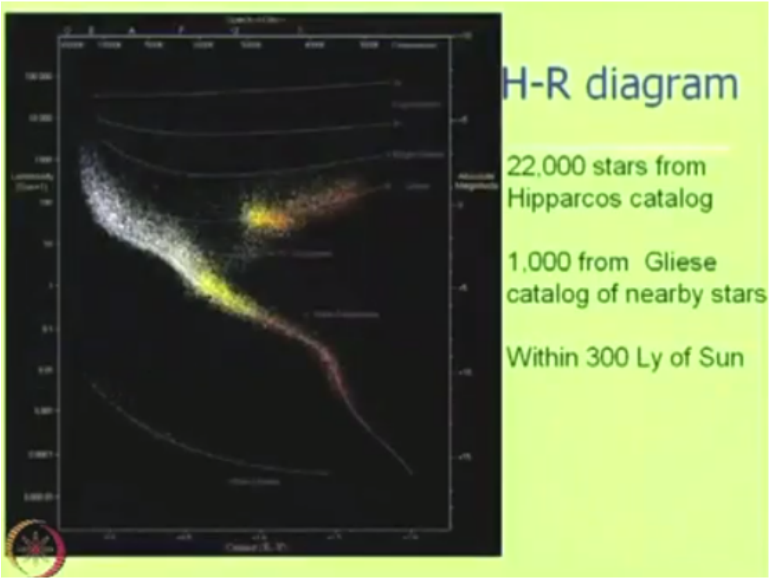

So this you get something like this. This is a large collection of stars for which the distances are known the distances for the only stars were determined by Hipparcos. Earlier on before this satellite was launched, you would have had less stars but to start to for this distance ladder to work, you need to know for the main sequence fitting to work, you need to know a collection of stars whose distances are known, whose distance is known.

So open cluster is one such thing, you determine the distance to one of the few of the stars you know the distance to that entire thing okay. So then you can plot in this HR diagram with the absolute magnitude on the y axis okay. Next what you do, you identify other open clusters for which the distances are not known. Again you will find that the bulk of the stars lie on the main sequence but now you do not know the absolute magnitude, you only know the apparent magnitude.

So you have the HR diagram for both an open cluster whose distance is known and an open cluster whose distance is not known. And the physics of the HR diagram is the same. So it is the same thing that should be there in both of these. So you can now relate the apparent magnitude of these stars to the absolute magnitudes. If you want these 2 curves to be identical, so from there you can determine the distance to the open cluster.

So this is how you, the first step take the second step in the ladder. So the first step is that you determine distances using parallax and once you have the distance from parallax to an open cluster, you can now determine distances to more open clusters by doing the main-sequence fitting. So you can now determine distances and you can see open clusters.

And parallax method works only in the neighbourhood of the solar system but you can see open clusters further out. So using this you can get distances to objects which are further out. That is the second step. So you are now able to go a little further so you are able to go 2 distances where you can see open clusters.

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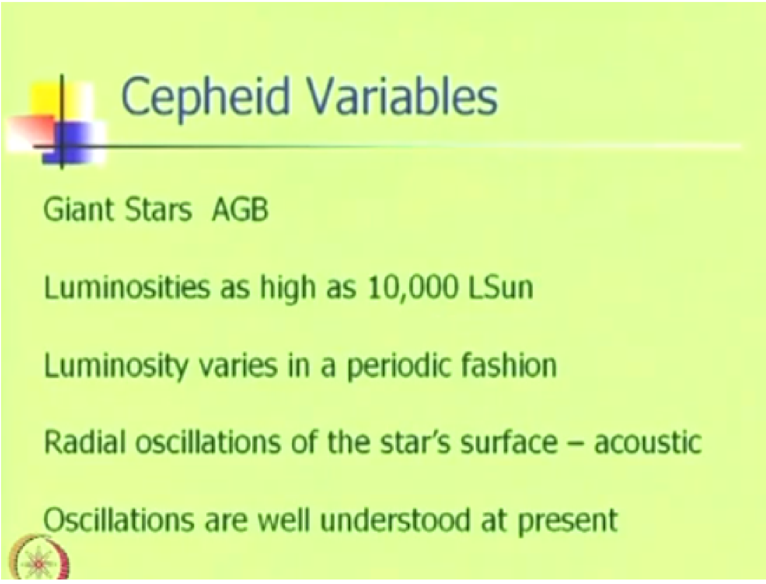

The next step is a very crucial step. So for cosmology, so this previous step is again restricted inside our own galaxy. You cannot go outside, you cannot see open clusters in other galaxies. You cannot use this to determine the method to the distance to globular clusters also okay. But the next step is very crucial so the next step depends on a certain kind of stars called Cepheid variables.

These Cepheid variable stars are giant stars. Possibly they are believed to lie in the asymptotic giant branch in the HR diagram and their luminosities could be as high as 10,000 times the luminosity of the sun. So we have the HR diagram here. So these are stars which lie somewhere in the giant has a giant branch somewhere here okay. And they have this characteristic that the luminosity varies as a function of time, it does not have a constant luminosity.

So the luminosity shows periodic pulsation, periodic variation okay. It does not go to 0, not like a pulsar, a pulsar just which is off. This has periodic variation. There are fluctuations in the luminosity which are periodic and it is now understood that these periodic variations occur because of some radial oscillations of the star surface. So the star has an instability. The surface of the star has a some instability due to which you have radial oscillations on the surface of the star.

The surface of the star basically oscillates. It increases and decreases and you know that the luminosity depends on the radius so if the surface of the star, if the radius of the star increases and decreases, the radius goes up and down, up and down then the luminosity will have pulsations variations and these are acoustic modes. So these are like sound waves basically some acoustic modes on the star.

So the star is made up of some gas. These are like sound waves in that gas okay and the physics of these oscillations are now well understood. So one can actually write down equation and one has a good understanding of the physics of this. So remember we have studied stars.

In our study of stars we assume that they are in hydrostatic equilibrium but there you can always ask the question that you have this star in hydrostatic equilibrium what happens when you disturb it okay and these are stars where if you disturb it then the surface will actually oscillate okay. These oscillations are well understood. So you take the same fluid equations and then solve it for the disturbance. So you have some radial modes of oscillation in these stars.

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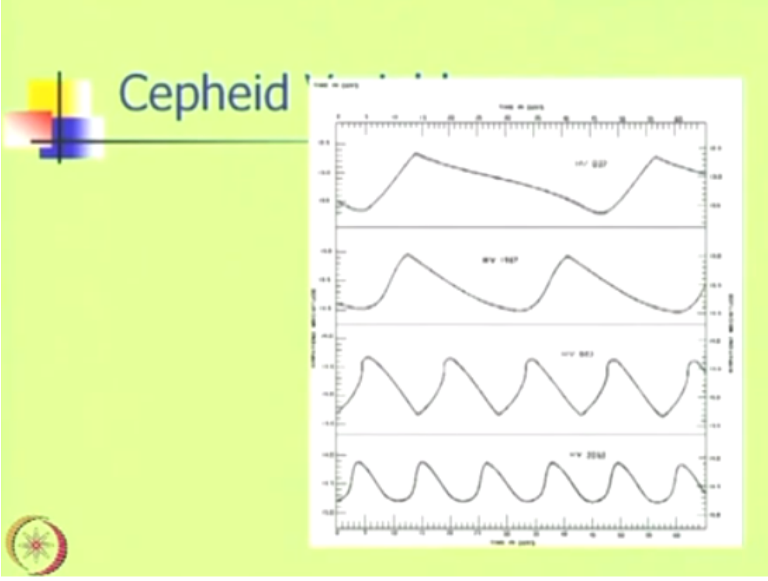

And this picture shows you the kind of oscillations that you have in the luminosity okay. So these time period here, here is of the order of days okay so you have such a period. So the luminosity here is oscillating. So you could have shorter period and longer period. The time scale here is in days okay and this is 5 days, 10 days, 15 days etc okay. And you can have things which have short period and long period.

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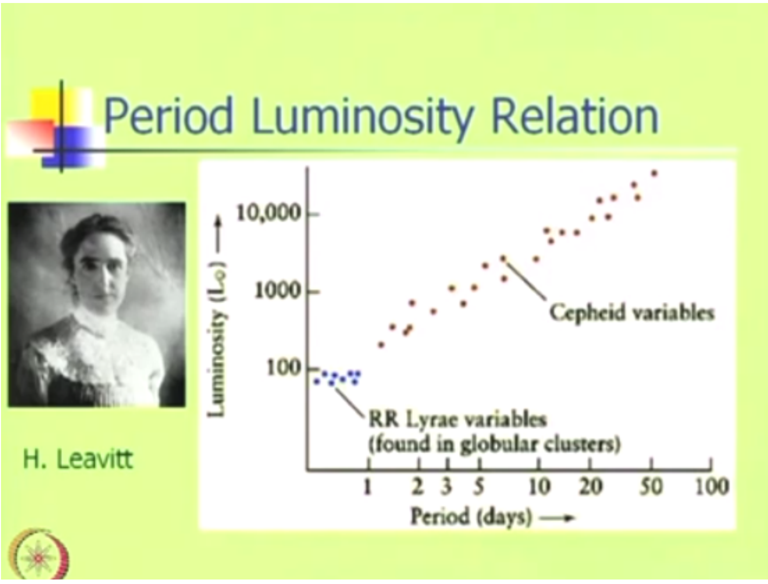

Now the crucial step in this was made by a lady astronomer, Henrietta Leavitt and she discovered that there is a relation between the period and the luminosity of these Cepheid variable stars. That is the crucial step okay. So she discovered Henrietta Leavitt, discovered that there is a relation between the period of the variation, so you can see here the period is in days and the luminosity in units of solar luminosity of the star.

So the more luminous a star, the longer the period of the oscillation. So if you look go back to the picture that we were seeing, these are more luminous stars larger period and these are less luminous stars right. Now this is very useful and because you see a star. You see these Cepheid variables are very bright stars first of all. So you can see them 2 very large distances, that is one big advantage okay.

And the second thing is you see the star and you see that its luminosity is now pulsating varying with time, so you can measure the period and the period will not be changed and depending on the distance. The flux will be different right. So you cannot tell how intrinsically bright the object is but you can tell definitely what the period is that is easy to measure.

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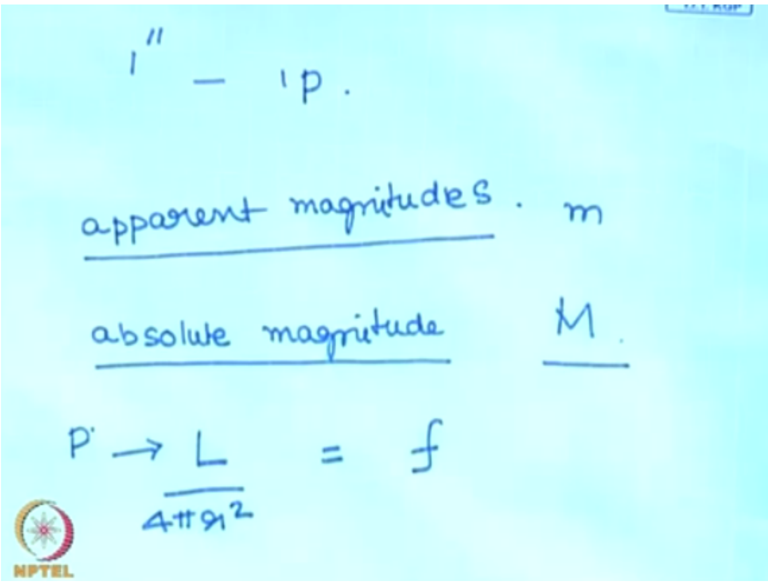

Now once you know the period of the star so you know that you measure the period and from the period, from the luminous period-luminosity relation from this relation period-luminosity relation, you can get the luminosity and sitting on earth you can also measure the flux. Flux is the amount of radiation coming per unit energy, power per unit area that you receive and these 2 we know are related that luminosity by 4 pi R square.

So if you can measure the period and the flux which you can measure from here, from earth, you can then determine the distance to the star okay. Now it is possible that there is extinction in route so the flux may be diminished but then you can use observation that different wavelengths as I told you extinction causes reddening so one can correct for the reddening and determine what the extinction is and correct.

So basically you can correct for the extinction and get an estimate for the distance okay. So the way this okay. There are, let me just tell you mention another thing. There are another kind of star called RR Lyrae variables which have a different period luminosity relation which also are variable stars. So one should not confuse between RR Lyrae and Cepheid variable.

The period-luminosity relation are different okay. These are not so bright RR Lyrae in the initial days there was some confusion but then people figured it out. So what is the next step in the distance ladder. The next step is that you have distances to open clusters from fitting the main sequence then you, in this process you try to find, you find open clusters whose distances can be determined by main sequence fitting, also inside which you have Cepheid variables okay.

So once you have open clusters which contain Cepheid variables, you can then calibrate this period-luminosity relation because you need to know the luminosity of at least 1 or 2 points to determine the calibration of this curve otherwise you will just have a relation between the flux and the period okay. Believe the luminosity and the period but you will not know the distances.

So you need to know the distances for to determine the calibration of this curve right. You need to have a few Cepheid variables for which the distances are known and this can be done by identifying Cepheid variables in open clusters whose distances can be determined by main sequence fitting okay and now so you can only the main the open cluster business will take you only up to some distance.

You have to find within that distance you have to find open clusters which have Cepheid variables in them and determine the period-luminosity relation. Once you have done that you can use the period-luminosity relation to now find distances further away because Cepheid variables can be seen to larger distances okay so that is the third step in the distance ladder. So Cepheid variables are the thing which allowed people historically and even now which allows us to go beyond the our own galaxy.

So you can see open clusters in our galaxy, you also have Cepheid variables in our galaxy so you can calibrate the curve and then you can go beyond that using Cepheid variables. So Cepheid variables were used to determine the distances to the globular clusters which did a crucial role in determining the structure of our own galaxy okay, that is the first thing.

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Second thing is that Cepheid variables were also used to determine the distance to one of the nebula that were seen in the sky. I had mentioned earlier that before we knew that our galaxy has a certain size and that there are galaxies outside, people observed that in addition to stars there are also nebulae which are seen in the sky, what is the nebula I had mentioned this, a star is a point in the sky, you cannot measure its dimension.

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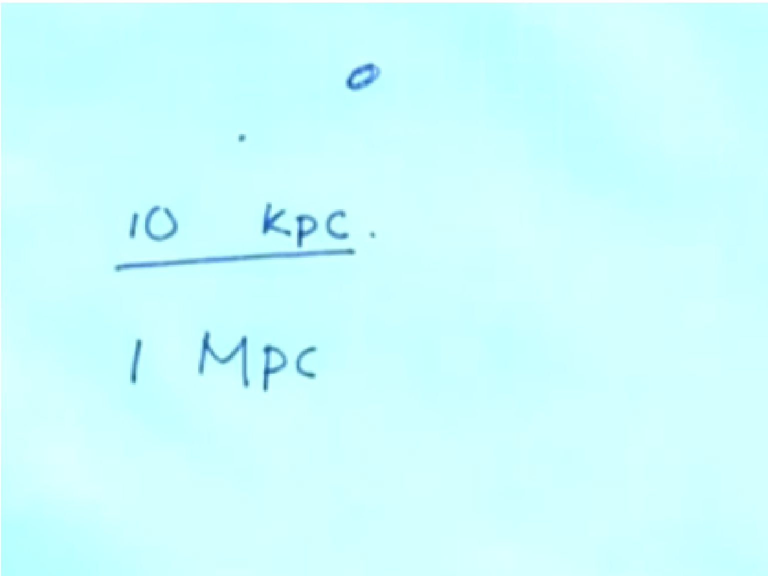

A nebula is a hazy thing like this. That is how it will appear okay, it will be a hazy thing and the question was are these nebulae inside our galaxy or outside. It is well known that there are some nebulae inside our galaxy like the Orion Nebula. It is essentially some gas where star formation is taking place okay. But the question was are all the nebulae inside our galaxy or outside.

So once the Cepheid variable method was fixed it was possible to measure, to identify a Cepheid variable in one of the nebulae, in the Andromeda constellation and determine the distance and the distance turned out to be much larger than the distance the size of our galaxy.

The size of our galaxy, I have told you is of the order of 10 kilo parsec. The distance to Andromeda turned out to be, this Andromeda nebula turned out to be much larger which clearly established that this Andromeda nebula is not part of our own galaxy, it is something outside okay.

This was the first, so the Andromeda galaxy so it is better to call it the Andromeda galaxy because the Andromeda galaxy is another galaxy just like our own galaxy. It is the nearest full-fledged spiral galaxy like our own. There are the large magellanic cloud and small magellanic cloud but I have already mentioned that these are satellites of our dwarf galaxies which are satellites of our own galaxy.

The nearest full-fledged galaxy is the Andromeda galaxy and the distance to Andromeda was determined using Cepheid variables and it was established that these nebulae are outside our own galaxy so it was established that there are galaxies like our own galaxy outside. We are not the only galaxy in the universe okay and this is the currently accepted value.

So this Andromeda nebula is at a distance of 778 kilo parsec of the order of 1 Mpc. So our galaxy has a size of the order of 10 kilo parsec and the Andromeda galaxy is at the at a distance of around 1 Mpc which is obviously outside our own galaxy okay. So this was a very crucial step.

(Sir that means we determine the distance of the Andromeda galaxy by) by identifying a seafood variable there. Once you know seafood variable there, you can measure its period and you once you know the period, you know the luminosity, you can measure the flux. If you know the flux and you have you know the luminosity you can get the distance. So that is the basic idea.

So for Andromeda this was done and it turned out to be much more than 10 kilo power of the order of tens of kilo parsec okay. Now if you look at the galaxy and take the light from a galaxy, so now we know that there are these objects outside our own galaxy which are also which were seen in the sky as nebulae and they are also galaxies just like our own galaxy. If you take the light coming from a galaxy and put it through a spectroscope you get a spectrum of a galaxy.

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So this shows you the spectrum of a galaxy. Now people who are experts in spectroscopy can identify spectral lines, so they can tell you which line is what okay. So this shows you one such image and one such picture.

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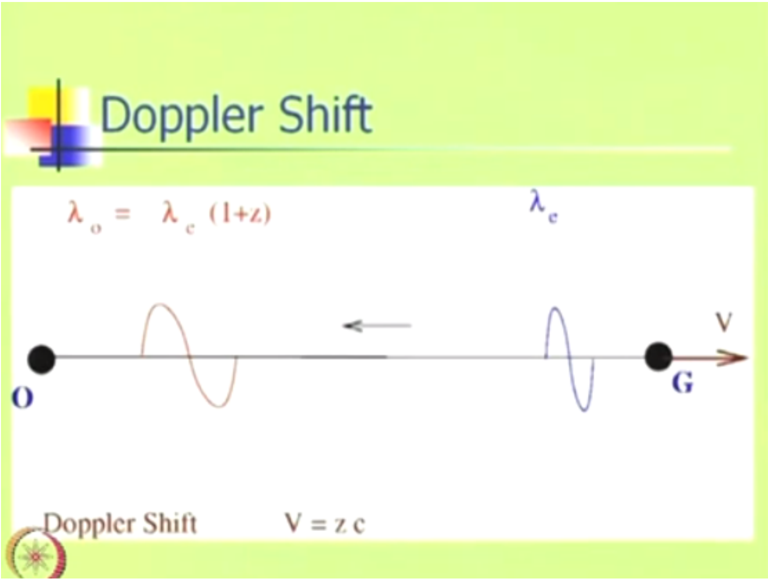

And once you have identified the lines, we know Doppler shift, I mentioned it in the last class also. So suppose you have a hydrogen line or a calcium line, if you do the experiment on earth, if you measure the wavelength of that line on earth you will get some value. So if the line is emitted from a distant galaxy, it also will be emitted at the same wavelength okay, Lambda emitted.

And if the galaxy is moving away from us then the wavelength will be increased, when it so the wavelength that the observer will see if the source, if the galaxy is moving away from the observer, the observer will see the same light at a different wavelength which is larger and it is larger by a factor of 1+Z where Z is related to the velocity to the speed with which it is moving away in this fashion.

So Z=V/C and this is called this phenomena is called red shift. So essentially, if the source is moving away from the observer you will have an increase in wavelength and this is what is called red shift. If the source is moving towards the observer, the wavelength will go down and this is called blue shift and this is quantified by this number Z okay because we shall now be using red shift and very frequently.

So it is better that everyone understands what we are talking about. So when people measured the spectrum of when the astronomers measured the spectrum of galaxies, they found that they could determine so you could basically determine the velocity with the speed of the galaxies by measuring the spectrum. So all that you have to do is identify a line and see at what wavelength you are observing it. And compare it with the wavelength, it with the wavelength that you know that the line is emitted okay.

Well this is a spectral nature of the galaxy okay. Now you do not ask me details of why it is like this okay. Then you look at the mechanism by which the radiation is produced. So we will not go into that their main aim here was to just show you that there are spectral lines in the radiation of a galaxy which can be identified and once you have identified it you can determine the speed with which the galaxy is moving whether it is moving away from you or towards you okay.

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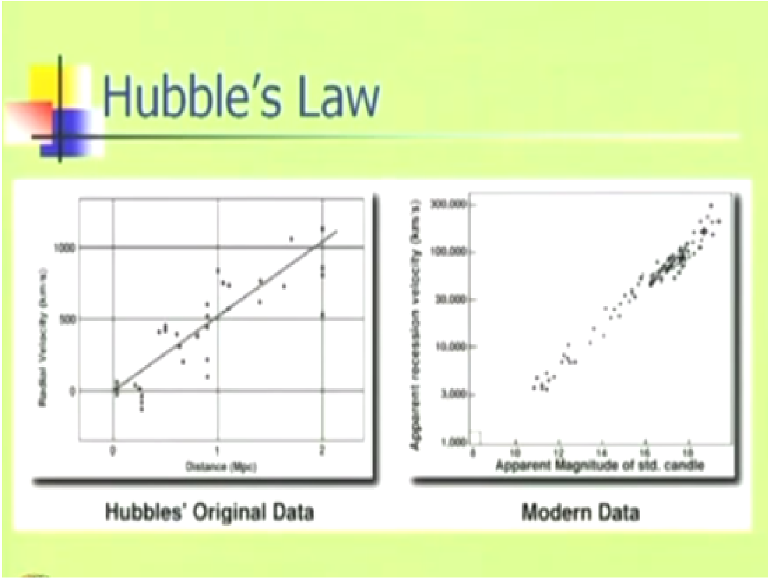

And the American astronomer Edwin Hubble made this very remarkable discovery. It is on this discovery that all of our understanding of cosmology rests. So the discovery that he made was that the galaxies on the average are moving away from us. So what he found was that you on the average the galaxies all have red shifts. There are very few blue shifts okay that is the first thing.

Though I should mention that the Andromeda galaxy is actually moving towards us. So it is being blue shift. It is blue shifted okay but on the average the galaxies Hubble found were all moving away from us that is the first thing. Second thing was that not only are the galaxies moving away from us but if you plot the velocity with which the galaxies are moving away from us against the distance to the galaxy, he found Hubble at least found that there is a straight can fit a straight line through it.

So essentially the galaxies are moving away from us with a speed that is proportional to the distance that is what Hubble found okay. That is how he interpreted his observations. So Hubble, what Hubble did was he determined distances. There were 2 very important things. One is determining distances, this was done through the Cepheid variables. The other thing was to determine the velocity, the speed which was done through red shift measurements.

So through the spectrum okay. So you have to take galaxies identify Cepheid variable stars, determine the distance, then you look at the spectrum identify spectral lines from there you get the speed and Hubble made this remarkable discovery that the galaxies on the average are moving away from us with the speed that is proportional to the distance. This goes by the name of Hubble's law okay.

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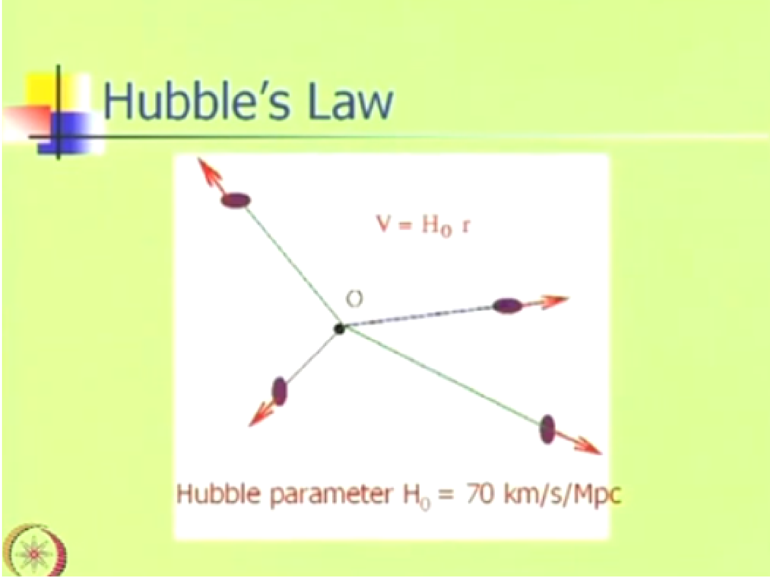

And this picture illustrates what Hubble's law implies. So Hubble's law, Hubble's discovery implies that all the galaxies, so these are the galaxies different galaxies and the observer sitting here, so we are seeing that the galaxies are all moving away from us with a speed that is proportional to the distance. So V = some constant x R and this constant goes by the name of the Hubble parameter H okay.

And it at present it is believed that the value is 70 kilometers per second per megaparsec okay. We write it as H naught in cosmology. So in cosmology it so happens that the Hubble parameter can actually evolves with time okay on the cosmological timescale and H naught refers to the present value of the Hubble parameter which was what Hubble measured because he measured it sitting here and looking at nearby galaxies and he found.

The value Hubble obtained was different okay but current observations indicate that the Hubble parameter has a value 70 kilometers per second per megaparsec. Hubble obtained a much larger value because of problems in the C feed calibration of the period-luminosity relation of the Cepheid variables but we will not go into the all those details.

The crux of the whole thing is Hubble found that the galaxy is on the average are moving away from us with the speed proportional to the distance the constant of proportionality between the speed and the distance is called the Hubble parameter H naught. And at present it is believed current observations indicate it has a value of 70 kilometers per second per megaparsec.

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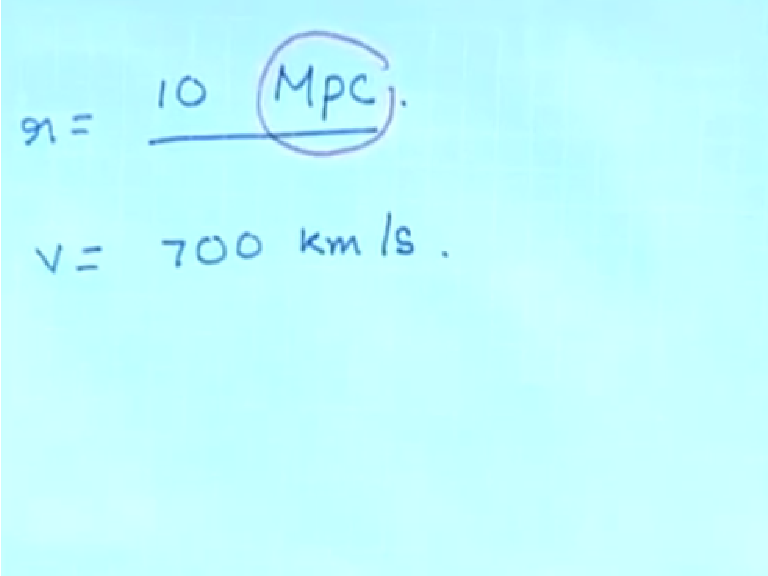

So what this implies is that if I look at a galaxy which is 10 Mpcs away then it is moving away from us with a speed, we expect it to be moving away with a speed 700 kilometers per second okay. That is the implication very simple. This is what it implies. A point to note here is that the length scales that we are talking about has changed.

When we were talking about the solar system, you are working in terms talking in terms of astronomical units then we moved on to parsecs for objects around the solar system and then kiloparsecs for the galaxy. Now we are going into the realm of the entire universe cosmology and the units that we shall be dealing with our Mpc 10 to the power 22 meters, 1 parsec is 10 to the power 16 meters. So 10 to the power 22 meters okay.

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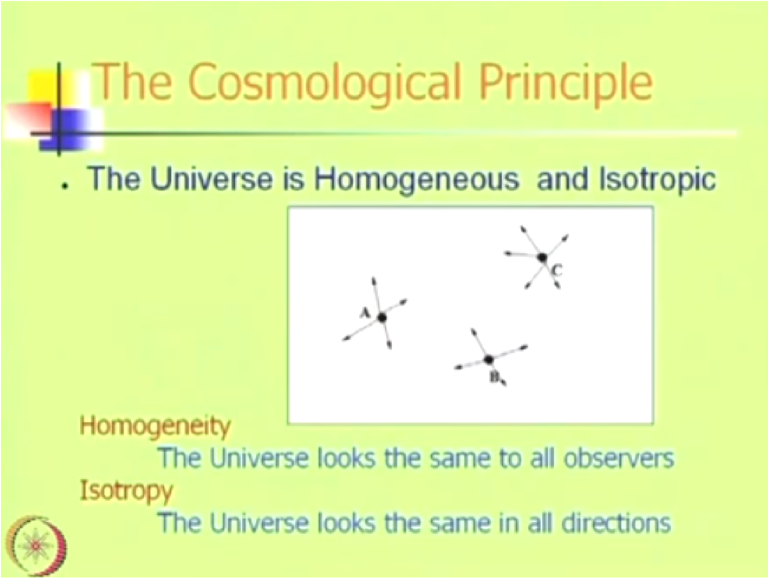

Now at around the same time, so this was around 1920's at around the same time physicists Einstein and his collaborators, Einstein had proposed they were working on theoretical things Einstein had proposed the general theory of relativity in Europe. He was in Europe at that time. He had proposed the general theory of relativity it was known and they were now trying to apply the general theory of relativity to describe the entire universe.

General theory of relativity you may be aware is a theory for gravity and it describes gravity in terms of the curvature of space-time and Einstein and collaborators were trying to now develop a model based on the general theory of relativity which could be applied to the entire universe and something that refers to the entire universe is basically cosmology the science of the if you want to study the entire universe as your system then what we we have gone then we are then in a realm of a subject called cosmology okay.

So they were trying to develop a theory for the entire universe based on the general theory of relativity and to make such a theory you need to make certain assumptions right. Just the theory of gravity will not tell you what the universe entire universe is doing, you need to make certain assumptions. The same theory of gravity after all describes the earth and the sun, the moon around the earth etc right.

So you need to make certain assumptions about the system. So when they wanted to make a model for the entire universe they thought what are the assumptions that we can make which are applicable to the entire universe and if you remember early Greek astronomer Greek scientists philosophers they had proposed the model for the universe where the center of the universe is on earth.

And later this led to a lot of trouble tragic things because of this human of earths and geocentric point-of-view, anthropocentric point of view and again you remember galaxies we found, initially people found that the center of the galaxy was on sun, was sun was near the center of the galaxy later it turned out to be completely wrong okay but that possibly was not known to them at that time or may be it was does not matter.

But they wanted to avoid making such mistakes. So the question is then where does one put if you want to model the universe do we have a where does one put the center of the universe if at all you have such an idea. So they wanted, basically they wanted to avoid introducing any such concept and they took a point of view that the universe is has no center it is homogeneous and isotropic.

These assumptions, these 2 assumptions go by the name of the cosmological principle and the entire theory of cosmology is based on this cosmological principle okay. So it is a theoretical assumption. So what does only we mean by this, so the assumption is that the universe is homogeneous and isotropic. So let us just look at a picture of a part of the universe.

Please do not make the mistake of thinking that this is the entire universe. In this picture, I have tried to show you a part of the universe. If you assume that the universe is homogeneous what it means is if you have observers located at different points. Homogeneity means that all points are equivalent. If I have a fluid water which has homogeneous density it means that the density of water is the same everywhere.

Similarly, when I say that the universe is homogeneous what it means is that the universe appears exactly the same to all observers irrespective of where they are located. So if A is an observer located here and B is an observer located here and C is an observer located here. If the universe is homogeneous, it implies that what this observer sees and this observer sees and this observer sees should be exactly identical okay.

So wherever you go in the universe you should see exactly the same thing because it is homogeneous. There is no preferred position. Essentially, it means that there is no preferred position. All positions are equivalent. There is no center okay. The certain assumption is that of isotropy. Isotropy means that all directions are equivalent. So if I sit at one point and now look at different directions.

So let us consider an observer A and this observer looks in different directions then the observer if the universe is isotropic you expect to see exactly the same thing okay. So this is what we mean by isotropy. There is no preferred position there is no preferred direction. So let me give you examples more familiar examples of homogeneity and isotropy because these are very important concepts in cosmology.

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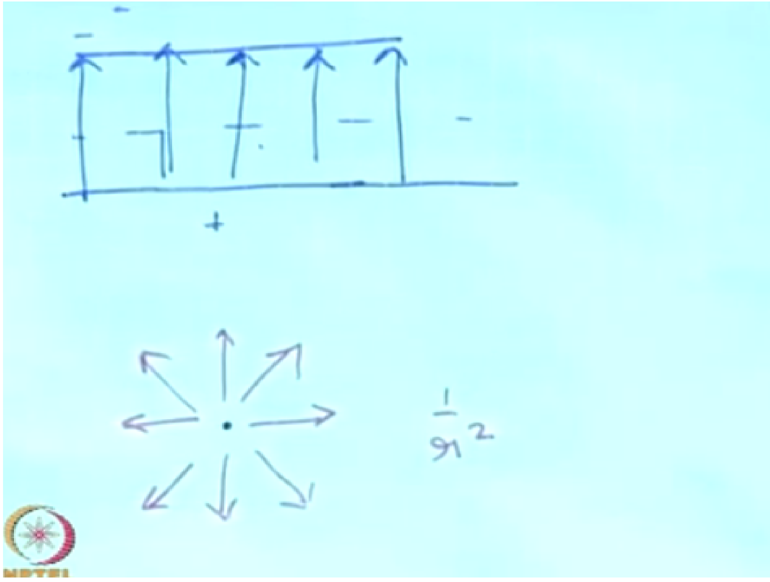

So homogeneity for example if you remember you would have studied the electric field inside a capacitor and if you take the idealization that your capacitor plates are parallel and infinite then the uniform the electric field inside, if this is positively charged this is negatively charged then the electric field inside is going to be everywhere the same like this pointing upwards.

So the electric field inside is homogeneous. It does not depend on the distance from the plate. It does not vary as I go from here to here because the plates are assumed to be infinitely large okay. So this is an example possibly familiar example of homogeneity okay and isotropy the electric field due to a point charge it goes out radially in all directions equally in all directions this is isotropic but not homogeneous because it falls as 1/r square.

This is homogeneous but not isotropic because there is a preferred direction. Our universe is both homogeneous and isotropic. That is what was assumed. This so this is what is the cosmological principle. Now this is the cosmological principle. If you now take the cosmological principle.

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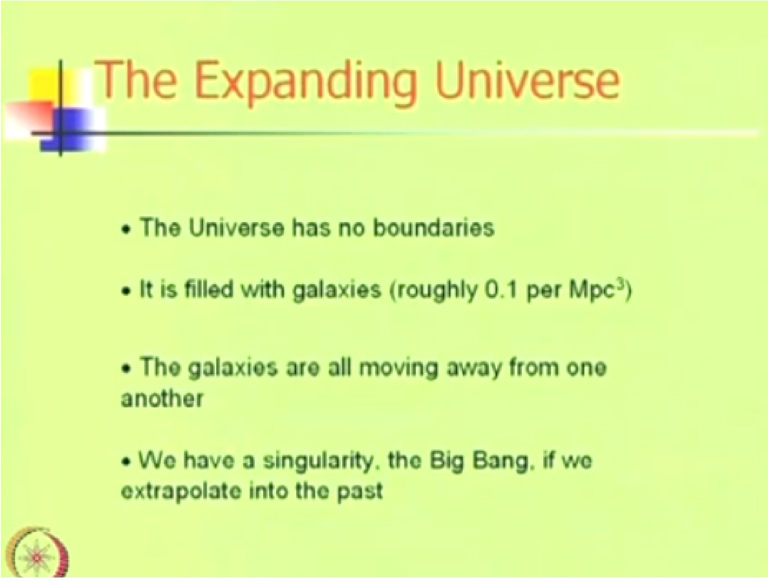

And so we take the cosmological principle and try to fit it with the fact with the observation made by Hubble. So Hubble observed that for an observer sitting over here Hubble observed that the galaxies are all moving away from us and we now try to okay so if you now take Hubble's observation that the galaxies are all moving away from one another and also the cosmological principle that the universe is homogeneous and isotropic.

These 2 things together and lead to a picture which where the universe is expanding. So let us try to understand this picture. How do we have an universe which is both well which is consistent with both the Hubble's law of expansion and the cosmological principle. The first thing that you have to realise is that if the universe is homogeneous and isotropic there can be no boundaries.

And just imagine if my universe had boundaries. So just imagine that this is my universe there is nothing outside. So here in my universe has boundaries. If my universe has boundaries then an observer located near the boundary will see something different from an observer located in the center. Not only that it will not be isotropic because in one direction you will see the boundary in another direction you will see the universe okay.

So it is quite clear that if my universe is homogeneous and isotropic there can be no boundaries okay. So it could be either infinite that is the simplest possibility or it could be a finite space without boundaries which is a little complicated to visualise so let us not go into that. We shall possibly come to that later. Just imagine an infinite universe with no boundaries okay.

So our universe then is infinite. It has no boundaries okay. That is the first thing. So the first thing in our picture is that we have an infinite universe. The next thing is that we see that the universe around us is filled with galaxies okay. So around us the neighbouring universe there are galaxies, we see the Andromeda galaxy and we see other galaxies beyond that.

So the universe around us is filled with galaxies and so if I go elsewhere in the universe since the universe is homogeneous I will see again galaxies. So we the way you imagine it now is that you have an infinite universe and the entire universe is filled with galaxies. The average spacing between the galaxies is a possibly is around so density okay. The density of the galaxies is around 0.1 per megaparsec.

So the typical spacing is somewhat less than 1 Mpc more than 1 Mpc, somewhat more maybe around 2, little more 2 Mpc okay. So the density is 0.1/Mpc cube average, I am giving some value okay, some typical value. So you have galaxies throughout the entire infinite universe with roughly the same density of around this value. That is the picture.

So you have an infinite universe and the infinite universe is filled with galaxies okay. Now sitting on earth, sitting on in our galaxy rather sitting in our galaxy we see that all the other galaxies are moving away from us. So the only way you can have this consistent with the homogenous and isotropic thing picture is that the galaxies are all moving away from one another okay.

It is not that they are moving away just from us. The galaxies the entire universe is filled with galaxies and the galaxies are all moving away from one another. If you have this picture then you can make a coherent image of the universe which is both consistent with the Hubble's law of expansion and homogeneity and isotropy.

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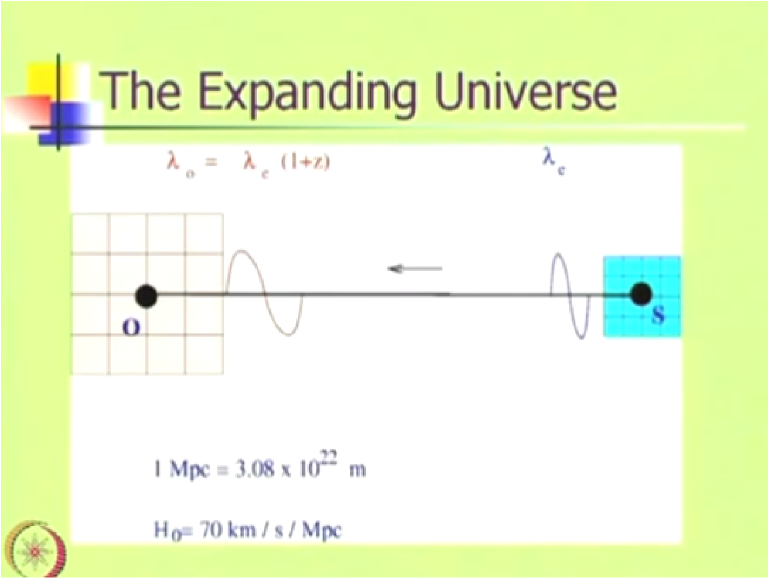

Let me illustrate this with a picture, so just imagine a part of the universe like this. This is a part of the universe and just imagine that I have put a grid in that universe. The grid spacing like a graph paper okay and the grid spacing and let us say is 1 centimeter or whatever one unit okay. So it is a graph paper which I have put in that part of the universe, I have divided it into cells and this spacing is one unit.

And I have a galaxy sitting at each of these point in the grid point okay. So it is a graph paper and I have a galaxy sitting at each of these grid points like a crystal okay and my entire universe is actually filled with such things, not only that this, the entire universe is filled with galaxies like this. So such thing fills my entire universe okay.

Now at a later time what happens that these galaxies are moving away from one another. So at a later time the same part of the universe will look like this. So what has happened is that the distance between these galaxies has increased. It was one here maybe it has now become 2 okay. So the galaxy is continue to sit at these grid points. They have all moved so it is like a graph paper.

I have changed the units of the graph paper. The same graph paper was, the graph paper was the units were originally 1 centimeter and now after some time they become 2 centimeters. So what has happened is that the entire universe is filled with galaxies and the intergalactic spacing has increased okay. So the intergalactic spacing is essentially this graph spacing and the universe is expanding so though even now the intergalactic spacing is going up.

If you go back into the past the intergalactic space this spacing of the graph paper or the distance between the galaxies was less and if you keep on extrapolating this backward in time what you find is that there comes a time when this spacing actually becomes 0 okay. We shall work out the dynamics but there comes a time when this spacing, if you extrapolate it backwards so it they are nearer and nearer and you extrapolate it backwards and you find that there is a time when these facing between all the galaxies become 0.

So the entire universe has collapsed to a point. This is a singularity which is referred to as the Big Bang okay. In our discussion, the Big Bang is not a very crucial things. We shall not discuss much about it because not much is known. The only thing that you need to remember is that the whole thing becomes singular okay. So I hope the picture of the expanding universe is clear.

So you visualize it as an infinite universe which is filled with galaxies and the galaxies are all moving away from one another. So if you extrapolate it backwards they were closer to each other and if you extrapolate it sufficiently back in the past, they were all at the same point which is the same. So the entire infinite universe was at one single point which is the Big Bang okay.

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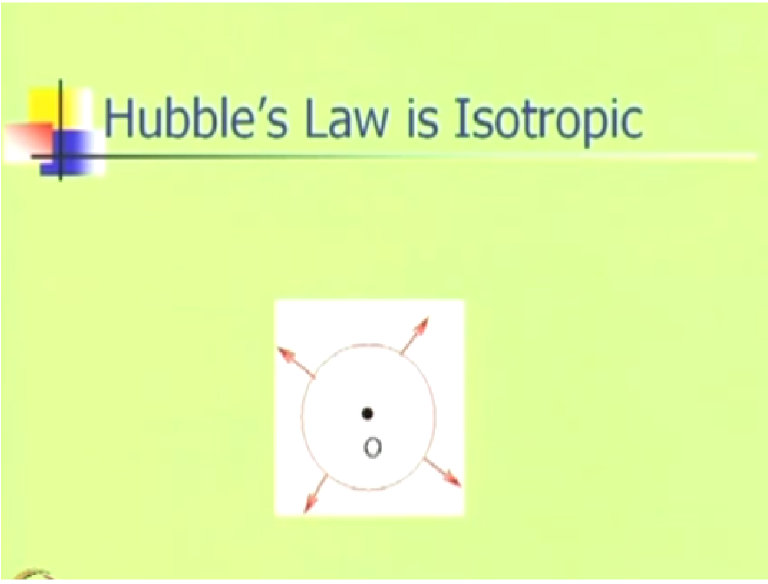

Now let me now just convince you that the Hubble law of expansion that we see is actually consistent with homogeneity and isotropy. So Hubble's law basically what we see is that the galaxies are all moving away from us with a speed proportional to the distance. So all the galaxies that lie on a sphere will move away from us with the same speed. So it is isotropic that is obvious.

Now what is not that obvious easily is that the Hubble law of expansion is homogeneous okay. One can do the exercise in 3D. It is not very difficult. I will just require a vector version of what I will do here. I will do this in one dimension and try to convince you that the Hubble's law of expansion is actually homogeneous okay.

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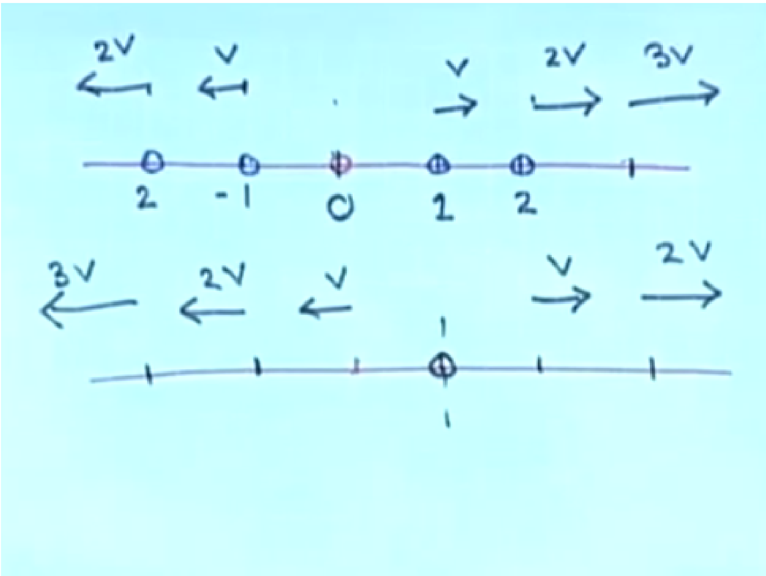

So what is the Hubble law of expansion, we will do it in one dimension. So consider a one-dimensional universe just for argument and there is an observer sitting here, I am the observer and a distance one away this is 1, this is - 1 and this is 2. These are distances in different directions and there are galaxies at these distances. So I am a galaxy, I am sitting on a galaxy located here and there is a galaxy located at distance 1 away and a galaxy a distance 2 away etc.

And I sitting here, I observe that this galaxy is moving away with a speed which is 1 x H naught, this galaxy will be moving away from me with twice the speed because the distance is more. So the speed also of this galaxy is 1 in some unit because all the galaxies are moving. Hubble's law is basically that all the galaxies are moving away with the speed proportional to the distance.

So this will be moving away with some speed V then this will have 2 V, this I am at rest I am sitting here. A galaxy here will be moving away with the speed V, the galaxy here will have a speed 2 V, a galaxy here will have a speed 3 V etc okay and what we want to prove is that for an observer located somewhere else that observer will see exactly the same thing.

So let us consider an observer who is sitting not at this galaxy. The observer is not sitting here but sitting here instead. So if an observer is sitting here then the observer who is sitting on a galaxy here that observer will also be moving with the same velocity with the velocity V. Now consider an observer who is moving with the velocity V and sitting here what will that observer see.

So you have to now transform the velocity also. If you transform the velocity, you have to subtract V from all of them. If you subtract V from all of them you will find that this observer will now be at rest. This observer will be moving with speed V. This will be moving with speed to 2 V. The original observer will be moving away with speed V, this will be moving with speed 2 V. This will be moving away with speed 3 V. So irrespective on of which galaxy you sit on, you will see exactly the same Hubble law of expansion I hope it is clear.

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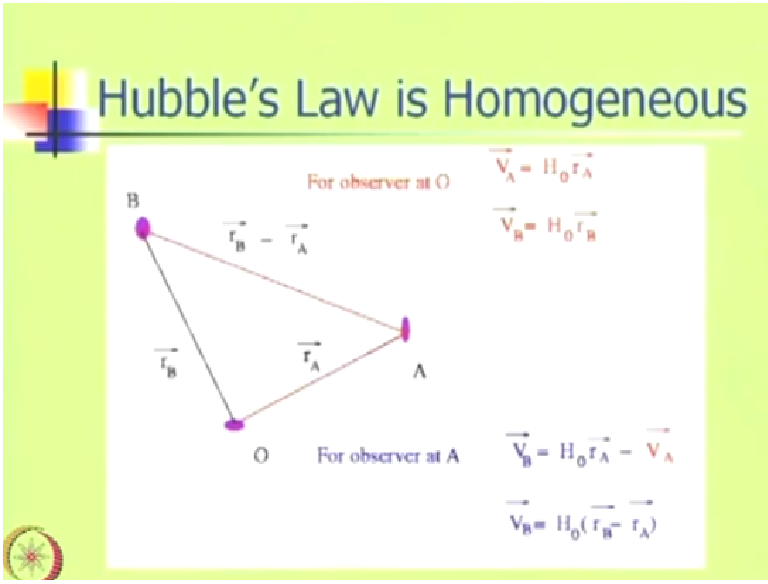

Now, one can do a 3 dimensional generalization of this it is not very difficult. All that you have to do is replace these scalar additions with vector additions. One can even do a more generalization of this, one can use special relativity to do the law of addition of velocities and show that the Hubble's law is consistent.

See I have used the Galilean law of transformation, one can even do special relativistic version of this and also show that the same thing is true okay. So the Hubble's law and the cosmological principle basically give us a picture of the universe which is homogeneous isotropic and expanding. Let me bring today's lecture to a close here. We shall learn more about the expanding universe in subsequent lectures.