Nuclear Astrophysics

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Module - 01
Lecture - 02
Properties of Galaxies and Universe

Welcome students to the second lecture of nuclear astrophysics. I hope you got some idea about the framework of this course, which I have discussed in the last lecture. Let me take a quick tour of the content which I have covered in the last lecture. So, the subject nuclear astrophysics, a union of nuclear physics and astrophysics tries to explain how elements are synthesized in universe, based on the knowledge of nuclear reactions.

And the energy produced from stars at different stages, what is the role of nuclear physics to answer this question. So, these two are the important goals of nuclear astrophysics and I have listed a few questions, then I have provided some historical background which goes like following.

The sum of the masses of the constituent nucleons is bit higher than the mass of the nucleus, the difference is called as binding energy. That has motivated people to think that, if at all energy can be released from a nucleus, maybe energy from the sun is because of the nuclear reaction. And the fusion of H into He and whatever energy is released, that could be the source of energy from the sun, that was the proposal.

But the major challenge was, do you remember? The energy available was not sufficient to initiate a nuclear reaction, because it is much lesser than the coulomb barrier. The energy required for crossing the barrier, when two nuclei having charges are present in the nuclear reaction. I am not talking about the neutrons as one of the entities, where there is no point of any coulomb barrier.

It was Gamow who proposed that, even though the energy available is less than the coulomb barrier, based on quantum mechanical phenomenon that is tunnelling process, nuclear reaction can indeed take place. But for that, it is very important to have large amount of the matter and that led to the statement that, there is a huge amount of H and He in the Sun, of course most of it is H.

Then, I have given some brief information about the observational astronomy which we categorized into optical astronomy, radio astronomy and space astronomy. The biggest advantage of space astronomy is that, it will get rid of all the problems because of the weather and atmosphere; and it is atmosphere which absorbs the large part of the electromagnetic spectrum coming from the stars.

So, how can we lose it? So, that problem can be circumvented by placing the instruments and telescopes in the balloons, sometimes in rockets and satellites and in the space laboratories and the future developments are based on neutrinos and gravitational waves. While discussing the observational structure in the cosmos, I have given a few numbers regarding the properties of the Sun.

What is the mass of the Sun, density, luminosity, surface temperature? All those things I have discussed. Then I went for collection of stars, there we have seen the luminosity of the stars, ranges from 10^{-4} to 10^{6}, whereas the mass ranges from 0.1 to 100. Why? There is a huge change in the luminosity, when there is a small change in the mass that we have to understand in due course.

Then, I have introduced a term metallicity; that means metals. In astronomy, this word is used referring to the presence of elements starting from carbon and we have categorized stars into population I and population II stars. Population I stars are young in terms of age and they have high metallic content and sun is part of population I star. Old stars and stars having less metallic content comes under population 2 stars.

And frequently we are going to use this terminology, population I and population II. So, up to this I have discussed in the previous lecture. Before entering into the actual nuclear aspect of the astrophysics, I am trying to provide this background, where I am trying to give you a basic idea of the astronomy that is observed features of universe, which I have been discussing and I will take some more time into this lecture.

Then the physics part; astrophysics that is explaining the universe. Observational part of the universe that is astronomy and explaining the observation features that is astrophysics. These two are the things I am spending some time on in these two or three lectures. Let us, continue today's lecture with the metallicity of stars.

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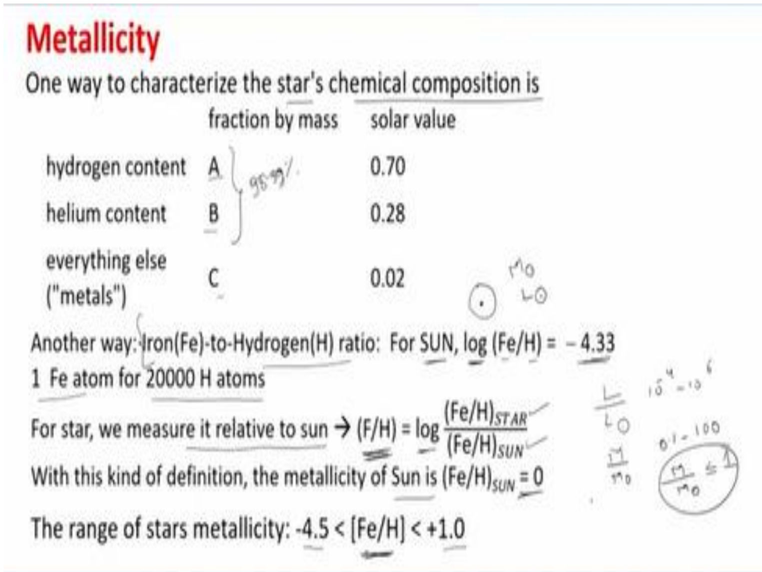

One way to characterize the star's chemical composition is by mass fraction, in the slide H content is denoted as A and He content as B and if you go for C, everything other than H and He content. A and B contains about 98 to 99% sometimes people say it is more than 90%. Another way to characterize the star's chemical composition is Fe to H ratio. Why Fe? This is the most stable element, which is evident from the binding energy curve.

So, taking it as a reference Fe to H ratio, if we see for the logarithmic value of the ratio of Fe to H ratio is - 4.33. That means one Fe atom for every 20000 hydrogen atoms. So, there are two ways to characterize the chemical composition of stars and second way is iron to hydrogen ratio.

The first way is the traditional way that is H content, He content and everything else. And for stars we measure the metallicity that means the chemical composition relative to the sun. So, this is how one can measure the chemical composition relative to sun. So, with this kind of definition of course the metallicity of the sun is 0.

So, it is important how the definitions are being used in different contexts. With this kind of definition if we see, the iron to hydrogen ratio, the metallicity ranges from - 4.5 to 1. So, whenever I code this kind of ranges, I want you to remember the other numbers also; $L/L_\odot$ ranges from 10^{-4} to 10^6; mass ranges from 0.1 to 100 though most of the stars are either comparable or equal to the mass of the sun and above this they are very rare and above 100 the stars have not been identified, which I have discussed in the previous lecture.

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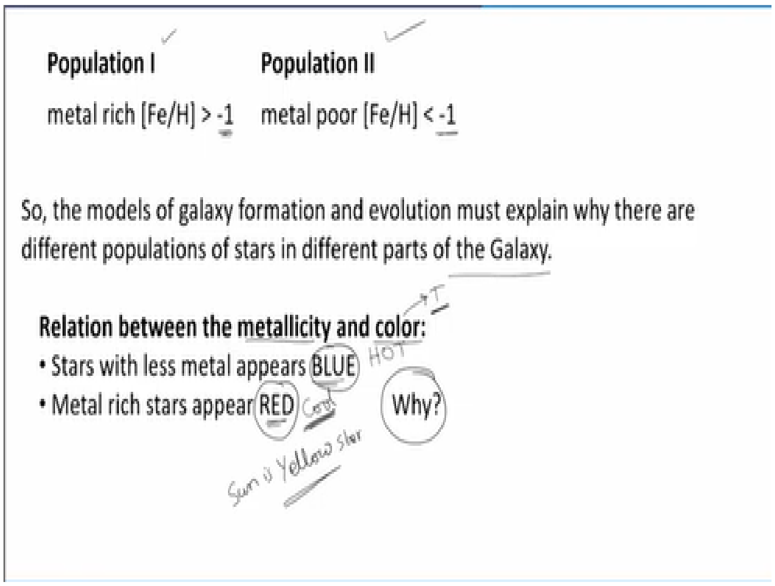

And as I said population I and population II stars, like this we can categorize. In terms of metallicity, some qualitative numbers earlier were given to you. Now, let me provide some quantitative information about population I and population II stars. The stars which are having Fe to H ratio greater than -1 they come under population I and less than -1 come under population II.

So, while modelling the formation of galaxies and the evolution of galaxies, which is a collection of stars one has to explain why there are different population of stars in different parts of the galaxy. When we try to model the universe, which is the collection of galaxies and galaxy is a collection of stars, it is important to include this aspect of metallicity.

Now what is the relation between the metallicity of the stars and the colour of the stars, which is directly linked with the temperature of the star. So, it is very well known that stars with less metal appears blue and stars appearing blue are very hot, whereas, the stars which appears red are considered cool, why? This we have to answer slowly. So, please think about this question, in this slide I have tried to correlate the colour of the star.

What about the colour of the sun? It is yellowish. So, sun is a yellow star. There are stars hotter than the sun, they appear in blue; stars cooler than sun, they appear in red, why? Is there any relation between the colour of the stars and the metallicity? And the metallicity in this context, I am using the definition Fe to H ratio. So, this question you have to remember and try to answer, based on the information given in due course.

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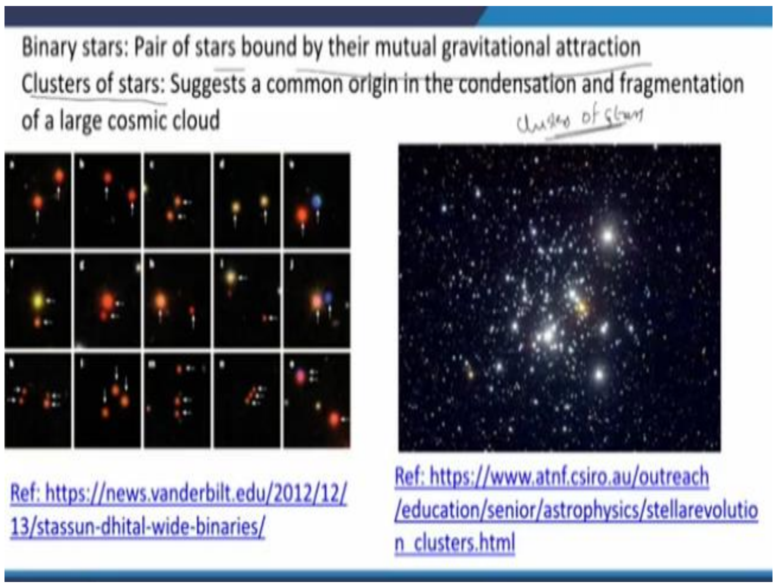

So, stars when we discuss, in general stars are binary in nature under the influence of gravitational force, the stars are bound to each other and of course they will rotate; and the pair of stars bound by their mutual gravitational attraction. We call them as binary stars and some photographs you can see in this slide. Other than binary stars, you can also come across clusters of stars, which suggests a common origin in the condensation and fragmentation of a large cosmic cloud, so the 2nd photograph shows clusters of stars. There are many types of stars, whose categories we will discuss in next slides.

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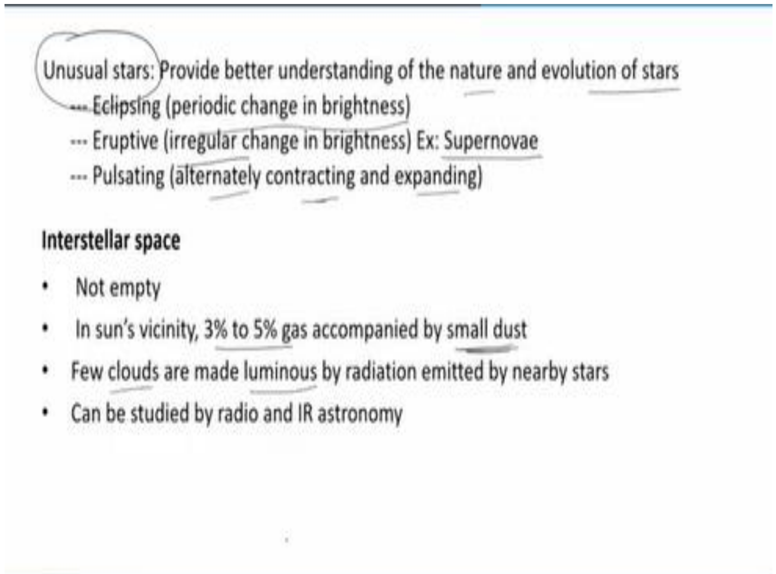

Like unusual stars, when we say unusual in what sense we are using this word. Stars live for millions and billions of years by producing energy constantly throughout their life and they will die in different ways. But there are a few stars which deviate from this kind of procedure. Those stars are can be categorized into unusual stars.

So, they provide better understanding of the nature and evolution of stars, which can be categorized into following types. Eclipsing stars, which are known for the periodic change in brightness. Eruptive stars, the change in the brightness is not periodic but quite irregular like supernova, which is the last stage of the star after explosion when it happens. And then pulsating stars, they contract and extracting expand alternately.

So, as the word suggests literally, they are pulsating stars in the sense of expansion, contraction alternately. So, after discussing about the sun, that means solar system and then the stars let me go into the interstellar space. So, with this information you can see it is not empty, the space between the two stars is not always empty, earlier please recollect one statement I have given. The nearest star when we take the sun is about four light years away.

But this space between stars is not many times empty; you will see it is filled with something to its certain extent. For example, if you take the sun vicinity, 3 to 5% of the gas is accompanied by a small dust. And you can also see many photographs related to stars and galaxy, you will see few clouds between the stars they are quite luminous, they are luminous because of the light coming from the stars and falling on this dust.

So, whenever you come across a luminous cloud, that luminosity is because of the falling of the light from the star nearby it. The interstellar space mainly these clouds, they can be studied by radio and infrared astronomy.

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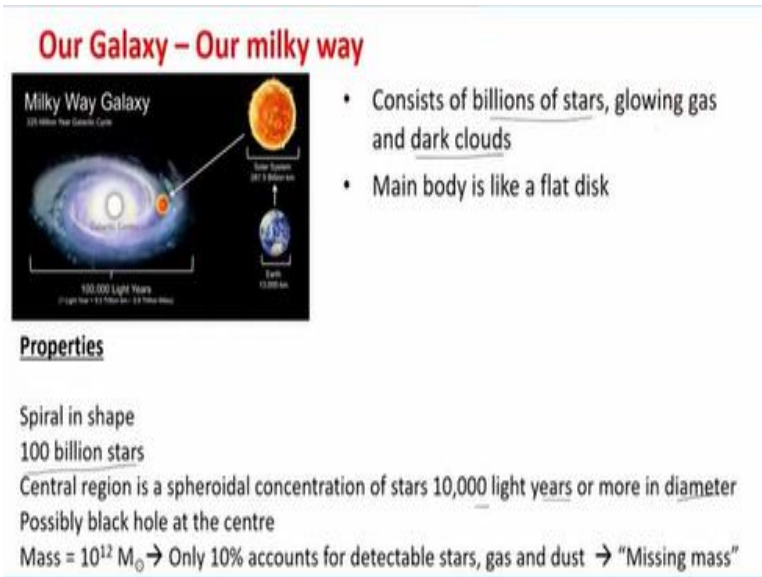

Now, after discussing solar system, stars and interstellar space let me go to the next higher level, that is galaxy. Galaxy contains millions and billions of stars. Let us start with the galaxy in which, we reside that is milky way galaxy, it has been named as milky way galaxy, unlike people think sun is not at the centre of the milky way galaxy. It is away from the centre and some numbers are given here.

Diameter of the solar system is 287 billion km and that of earth is 13000 km and the diameter of milky way galaxy is expected to be 1 lakh light years. Now, you can always ask, where these values are coming from? Is it really some kind of prediction? No. The studies of the stars and collection of stars and galaxies using observational astronomy based on the facilities available on earth and space like Hubble telescope.

When, studies have been made with all the parts of the galaxy and all the parts of the universe, these numbers came out. So, a galaxy, our galaxy consists of billions of stars I have said and glowing gas and dark clouds they are present inside the galaxy. And if you see the collection of the stars in this galaxy, it is like a flat disk. What are the properties of this galaxy, some numbers let me try to give, in terms of shape it is spiral.

Around 100 billion stars are there in the milky way galaxy. Literally, people have counted the number of stars; it is about 100 billion stars in our milky way galaxy. The central region is a spheroidal concentration of stars, like 10000 light years or more in diameter. Whereas, the whole diameter of the milky way galaxy is about 1 lakh light years.

Evidence is growing regarding the existence of black hole at the centre of the galaxy. Now, even Nobel prize has also been given for the existence of black hole. Though I am not going into the details of it, you might be interested to know more, you are suggested to go through the books on astronomy. So, this course is all about the role of nuclear physics in understanding the properties of the stars, synthesis of elements and energy produced in the stars, which make the universe.

What is the mass of our galaxy? It is about 10^{12} times the mass of the sun and only 10% accounts for detectable stars, gas and dust. What is the remaining 90%? That is the mystery that is missing mass. What I am trying to convey is that, when you detect and measure the stars and the interstellar space, which is consisting of gas and the dust it amounts 10% of the mass, which was estimated using other methods.

So, not only one method is available to find out the mass of the galaxy. One traditional method is that, physically what you see in the galaxy that is the stars and interstellar space, there are some clouds and gas and some dust, you measure the mass of them and sum of their masses should be equal to the mass of the galaxy, but it is not the case. Only 10% of the mass of the galaxy is coming from the masses of physically seen entities.

What about the remaining 90%? This is the missing mass and we have no clue about it to a reasonable level, this is quite interesting, is not it? Now, after discussing the properties of the sun, which is the basis of the solar system and then collection of stars and then galaxy, which is a collection of stars mainly and then coming to the collection of galaxies, that is universe. So, like a galaxy contains billions of stars, universe contains billions of galaxies.

I am sure the numbers which I am going to provide in this slide will be quite interesting for you.

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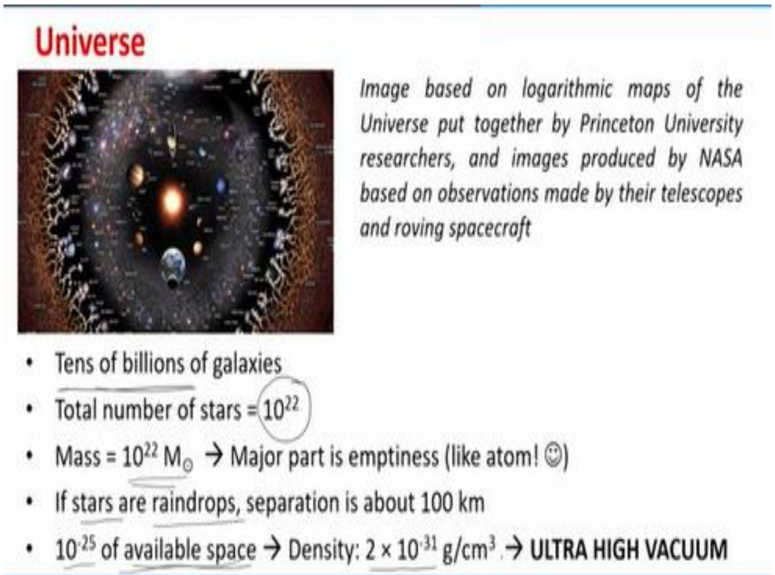

So, some image based on logarithmic maps of the universe put together by the researchers from Princeton university and also images produced by NASA based on observations made by the telescope and roving spacecrafts. Is not it very beautiful, the universe's picture? It has been proved that the number of galaxies is about tens of billions in the universe and the total number of the stars in the universe is about 10^{22}.

So, using observational techniques people have counted the number of stars in the universe, it is about 10^{22}. What is the mass of the universe? 10^{22} times mass of the sun. What about the mass of the milky way galaxy? It was about 10^{12} times mass of the sun. If you go to collection of galaxies that is universe, the mass of the universe is about 10^{22} times the mass of the Sun.

The interesting thing is that, though we say the mass is 10^{22} times the mass of the Sun, the space between the stars and galaxies is so huge that, when we see the physical universe, it looks like almost empty. Like most of the atom is empty like most of the universe is empty. What a beautiful correlation, is not it? Inside the atom you know the size of the nucleus, less than 0.1% of the size of the atom and around the nucleus when we say electrons are orbiting, most of the atom is empty.

Similarly, for the universe though the mass is 10^{22} times mass of the Sun, most of the space is empty. So, let me give you some numbers. If we consider, stars as rain drops, how many stars are there in the universe? As per the data available 10^{22} stars are available. And if you assume stars as rain drops, the separation between these rain drops is about 100 km.

Now, can you imagine a separation of 100 km between two rain drops, when you see the rain? No. If that is the case you see there is no rain at all, if there is a distance of 100 km between two raindrops, is not it? So, the stars and galaxies they occupy 10^{-25} part in the universe. So, whatever space available in the universe only 10^{-25} is occupied by the galaxies.

So, the density if you see it is about 10^{-31} gm/cm^3. So, universe is a classic example of ultra-high vacuum. What is the unit of vacuum? Nothing but of pressure, torr. May be, in some experiments you have seen the values of the vacuum; where you try to create the vacuum using some pumps. For example, using rotary pump you can achieve 10^{-2} to 10^{-3} torr.

Then if you go to diffusion pump you can achieve 10^{-6} torr, then you go for iron pump, molecular pump, crayo pump, then you can go for maximum 10^{-12} kind of thing. The classic case of ultra-high vacuum, where it is? We are inside it, the universe. So, I am sure you have enjoyed these numbers related to the universe. What have we understood from this?

Starting from the sun and from the of stars and then about the galaxy and then universe, we have seen the numbers of the stars and then masses, their luminosities and various other features, when we discuss observational structures in the cosmos. Where is nuclear physics inside it? Till now I have not touched on the nuclear part, which is basically the essence of our course astrophysics.

But this background is important to understand the role of nuclear physics in stars. Let me start other topic after discussing the salient features of universe, galaxy and the solar system.

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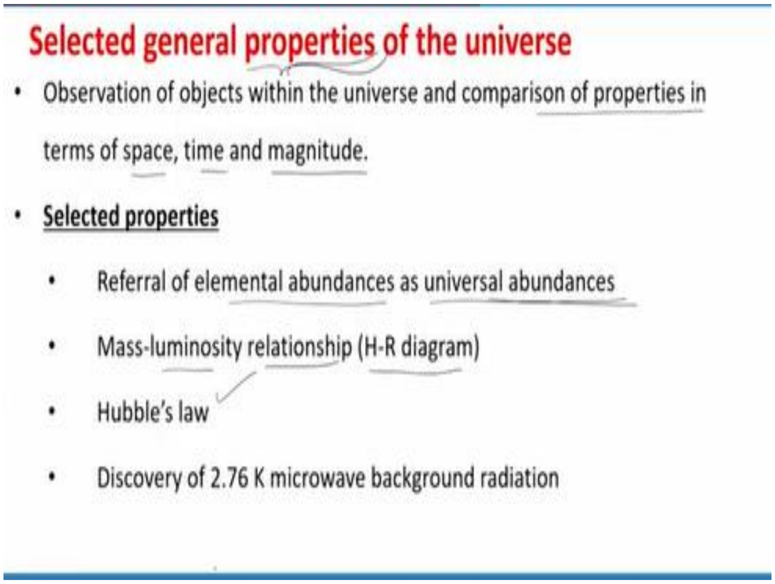

We have seen some numbers regarding the galaxies, number of stars and the density, available space, distance between the galaxies and ultimately ultra-high vacuum of the universe. There are a few beautiful and interesting properties of the universe, which I am calling as selected general properties of the universe. When I say selected general properties, how these properties have been analysed? Where from we got the information about these properties of the universe?

Whatever objects are there within the universe, you do some kind of measurements. Based on the observations from the measurements, you compare the properties in terms of space, time and magnitude. The evolution of universe became possible, only based on the observation of objects within the universe and comparison of the properties of these objects in terms of mass, in terms of space, time and the magnitude.

Then, once you compare the properties of these objects in these terms, that give you information about the properties of the universe, because universe is composed of these objects. So, that is the thing which I am trying to convey in this slide. What are the selective properties made here? Elemental abundances, referral of elemental abundances as universal abundances. So, many elements are in our surroundings.

How those elements are formed? What nuclear reactions are responsible for formation of those elements? And if we see the abundance of those elements. You know not all means, of course you know very well that not all elements have equal abundance on earth, not only in earth inside the stars also the abundance of elements is not uniform. But does it possess any kind of trend, when we see the elemental abundance curve, we will discuss more.

So, that has been obtained only after the comparison of properties of the objects based on many measurements. If you see the mass of the stars and luminosity of the stars, is there any relationship between them or not? So, by doing many measurements lot of observations on all parts of the galaxy, that means all stars inside one galaxy, when you measure the mass of each star and luminosity of each star, then when you plot mass versus luminosity, can there be a beautiful or interesting feature outside out of it? That is called as H-R diagram. So, this is another important selected property. So, when you see the abundance of elements, that gives one important property to the universe. When you see the relation between mass and luminosity, that gives another property to the universe and when you see the distance galaxies using telescopes, we get another property that is Hubble’s law.

So, Hubble’s law is another important selected general property to the universe and last but not the least, the observation of 2.76 K remnant of photons, because of the cosmic background radiation. This is something called like a capstone for the hypothesis of big bang. So, in the next lecture I am going to discuss each and every property I have mentioned here. What are the properties?

Elemental abundance curve, H-R diagram, Hubble’s law and 2.7 K remnant photon remnant, which has given a thorough proof for the big bang hypothesis and age of the universe. Of course, beyond this there are some more like causes and other things, but we will not discuss. I hope you have enjoyed today's class. To summarize today's lecture, I have provided the metallicity of the stars, how population I and population II stars are separated from each other.

Then I have discussed the properties of solar system, stars, galaxy and the universe and I have started discussing selected general properties of the universe. In the next lecture these four selected general properties of the universe, I will discuss in detail. Thank you very much for your attention.