Nuclear Astrophysics

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Module - 02

Lecture – 08

M-L Relation, Hubble's Law and Echo of Big Bang

Welcome back to the lectures on Nuclear Astrophysics. In the previous lecture what I had discussed with that let me do a quick recap then I will discuss some more points in today's lecture.

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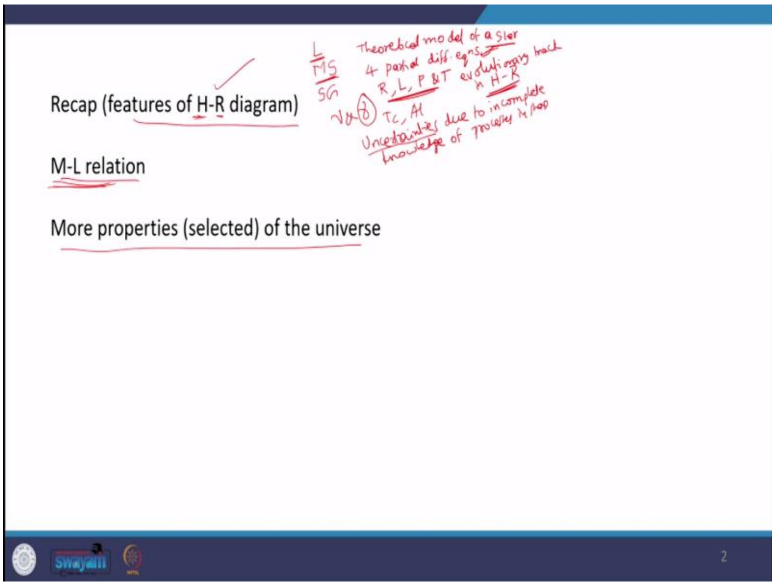

So, what I discussed in the previous lecture is main features of the H-R diagram. You have seen how the data obtained regarding the stars in terms of luminosity and temperatures have been plotted and what are the important outcomes of this H-R diagram. Luminosity is not constant it varies from one star to another star and we also have seen that most of the stars are grouped into a cluster called as main sequence.

We have seen why certain stars appear only in specific regions of the H-R diagram and one more thing which I missed in the previous lecture is any theoretical model of a star can be constructed by solving a set of four partial differential equations. If one wants to construct theoretical model of a star one needs to solve four partial differential equations for radius, luminosity, pressure and temperature because these equations describe the structure of a star as a function of the distant from the center and also as a function of time and the time sequence of such solutions of these equations represents an evolutionary track in H-R diagram.

Already I have told many times that energy is generated by nuclear reactions and gravitational contraction and more I will discuss in detail in coming slides and how energy is lost. The generation of energy is because of the nuclear reactions and how these nuclear reactions are happening?

I will discuss in detail after sometime in the same lecture, but how energy is lost from a star. One of the entities which takes away the energy by not depositing within the star is neutrino because it is very weakly interacting and I have discussed in one of the previous lectures that it is the detection of neutrino which is useful tool as evidence of the nucleosynthesis in stars because neutrinos are the byproducts of nuclear processes.

So, the energy is produced because of the nuclear reactions and how these nuclear reactions are happening? Because of the conversion of gravitational contraction into thermal pressure. When nuclides are coming close to each other because of the gravitational contraction there will a be situation when this gravitational contraction leads to the creation of thermal pressure.

This thermal pressure initiates the nuclear reactions which further produce nuclear energy and how the nuclear energy is lost? As I told one of the important reason is the escape of neutrinos from the star. What are the other features I have discussed in the previous lecture as part of the H-R diagram? Not only neutrinos, but also sometimes gamma rays can escape from the stars.

Greater the total mass of the star, greater is the temperature and pressure in the core of the star and faster energy is generated and a greater luminosity. This I will discuss in detail in today's lecture and in stellar model, the modeling of a star that means a stellar evolution model calculations there are uncertainties due to incomplete knowledge of certain nuclear processes in stars like mass loss, energy transport, rotation in magnetic fields and remember that impact of this uncertainties associated with this nuclear physics on energy generation and nucleosynthesis is one of the important challenges in the complex puzzles in Nuclear Astrophysics. So, what I want to say is that if you consider the uncertainty in the calculation of energy produced from star the main reason is the uncertainty in the nuclear quantities like energy levels.

What are the spins and parities and nuclear reaction rates, nuclear cross sections all those things I will discuss in detail. The point which I would like to highlight is following. The uncertainties in nuclear physics processes leads to the uncertainties in the estimation of energy generation from the stars because there is an uncertainty in the quantities related to the nuclear physics.

I hope this should be sufficient to have a feel about the significance of nuclear physics in understanding the stellar evolution. So, whenever you have been taught nuclear physics earlier in plus 2 or in B.Sc. if you have done the binding energy curve and simple concept of nuclear reaction, nuclear fission and Q value of a nuclear reaction those are the values which are playing extremely important role in the calculation of energy generated from the stars.

What are the points I am going to discuss in today's lecture which I was supposed to discuss in previous lecture that is mass and luminosity relation and some more selected general properties of the universe. So, let me see in this lecture how much I can cover.

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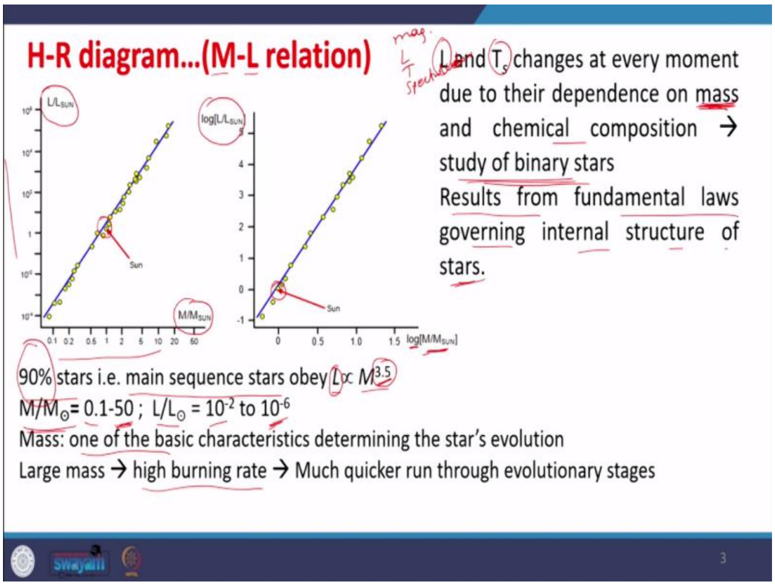

In H-R diagram if you see what is the relation between mass (M) and luminosity (L) it is not directly given there. What quantities we have in H-R diagram are magnitude, luminosity, temperature and spectral color, but if I plot $L/L_\odot$ and $M/M_\odot$ and see how it varies for all stars whose data is available then you can see the location of sun pointed in the slide and you see the scale is the logarithm scale.

It means if you take the logarithm value of $L/L_\odot$ and this logarithm value of of $M/M_\odot$ then also you will get a linear relation and in this way of representation. So, the luminosity and temperature which I have discussed in previous lecture they are changing at every moment due to their dependence on the mass of the star, less mass, less luminosity (most probability) and temperature is also changing.

The mass is continuously changing. So, when you want to find out the change in luminosity and temperature it is not constant for a star, it is not constant throughout the different timings. So, it strongly depends on the time because the moment energy starts generating from the star the chemical composition also is undergoing change. So, keeping this in mind we can say that the most basic parameter which we have to consider is mass.

That is how the mass and the luminosity relation is important to understand where you can see that it is a linear relation and studying the chemical composition in mass can be done by studying the binary stars (two stars bonded because of the gravitational attraction) and this M-L relation results from the fundamental loss governing the internal structure of the stars because we are considering the variation in mass and chemical composition which is further leading to the change in luminosity and temperature.

Now 90% stars that means mainly main sequence stars they obey this kind of relation, $L \propto M^{3.5}$. Now this tentative number you have to remember, not for all stars, but yes stars lying on main sequence and the mass is varying with respect to the sun's mass like 0.1 to 50 already I have discussed earlier and $L/L_{\odot}$ is ranging from 10^{-2} to 10^{-6} for these stars.

As I said mass is one of the basic characteristics determining the evolution of a star large mass means you can easily expect burning rate is very high. So, when mass of a star is high, there is more material for undergoing burning and what is this burning basically? It is the reaction between the nuclides and this is caused by the thermal pressure as I said. So, more mass, more burning and quicker the mass of the star undergoing destruction.

So, the lifetime of a heavier star in terms of mass will have less lifetime because more mass, more burning processes, more burning rate and less lifetime of the star and when star reaches to the final dying stage it may go to the giants or it may go to the white dwarfs and that is part of H-R diagram.

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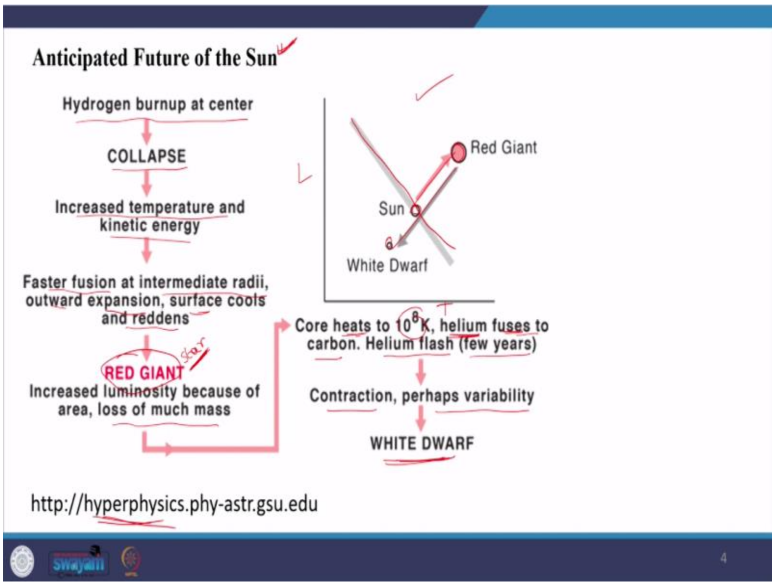

So, this is some interesting diagram I have taken from this website hyperphysics. I think all of you are aware of this, anticipated future of the sun. Right now hydrogen burning is taking place at the center. Once it undergoes collapse because of the increase in temperature and kinetic energy one can have faster fusion at intermediate radii, outward expansion in the outer region, and cooling at the surface and then it becomes completely red and it reaches to the red giant stage. Now you might be having some idea about the location of red giant star in H-R diagram and once it becomes red giant the luminosity will be more because of the area and mass will be very less compared to the original one and this leads to the heating of the core to high energy like 10^8 K.

Then helium will fuse to the carbon and then flashes of helium will occur after few years then the contraction perhaps with some variability will become white dwarfs. So, this is some kind of anticipated future of the sun. In terms of diagram we can see sun is here (refer to the corresponding slide) and initially it will become red giant and finally it will come to the white dwarf. What is this diagram? So, this is nothing but H-R diagram, luminosity versus temperature or spectral color. So, this is some interesting diagram which explains the anticipated future of the sun and all of you might be aware that already sun has lost half of its age. It passed half of its tenure.

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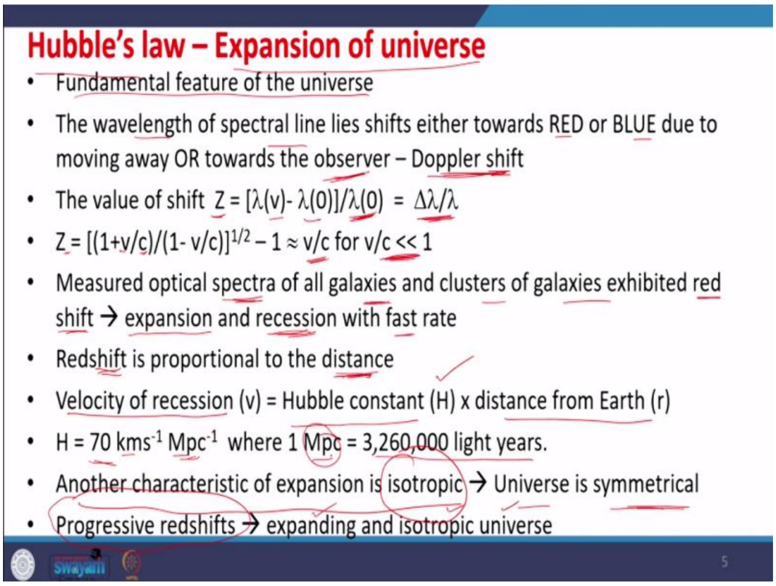

Another property of the universe is Hubble's law all of you might be aware of the essence of Hubble's law so I will not take much time. Why I am discussing this topic Hubble's law. See I have started discussing after optical astronomy and radio astronomy, all those astronomy techniques. I am putting in front of you salient features of the selected properties of universe.

So, initially I discussed elemental abundance curve and then I have discussed H-R diagram and as an extension of H-R diagram I have shown you mass-luminosity relation, but remember when you try to understand the H-R diagram please do not forget to do those numerical which is by taking different values of $L/L_\odot$ and $M/M_\odot$ to calculate the values of the size i.e. radius and density if masses and from M-L relation how to get the information of the luminosity if mass is known and vice-versa. So, all these things please look into it carefully. Now third general property which is very important is Hubble's law. So, what is the essence of Hubble's law? You are very well aware so quickly let me present some salient features of the Hubble's law which supports the concept of expansion of the universe.

So, this is the fundamental feature of the universe, Hubble's law. See when you record those spectrums of stars the wavelength of the spectral line shifts either towards red or blue because with respect to observer the star is either moving away from or coming towards the observer and you know this is well-known Doppler shift (Z). This shift mathematically is given by, $Z = \frac{\lambda(v)-\lambda(0)}{\lambda(0)} = \frac{\Delta\lambda}{\lambda}$; where $\lambda(v)$ is the wavelength in the laboratory frame and $\lambda(0)$ is the wavelength in the rest frame. This Z is in terms of velocity of light and velocity of the star with respect to which it is coming towards the observer or going away from the observer. If you calculate Z it is more or less equal to v/c if the ratio is much less than 1.

$$Z = \left(\frac{1+\frac{v}{c}}{1-\frac{v}{c}}\right)^{1/2} - 1 \approx \frac{v}{c} \text{ for } v/c \ll 1$$

When researchers have measured the spectra of star's light and this stars are basically from all kinds of galaxies or clusters of galaxies, every spectrum has exhibited red shift there is no blue shift. So, it is very clear that the expansion is taking place beyond any doubt and the velocity with which it is moving away from the observer it is recession which is happening with not slow rate, but in fact with fast rate.

This shift in the wave length that is red shift is proportional to the distance between the source and the observer. Now how to find the velocity of the recession? It is proportional to the distance from the Earth on which we are doing this measurement there is a proportional to constant which is called as Hubble constant and at present the calculated value of the Hubble's constant is about 70 $kms^{-1}Mpc^{-1}$ where 1 Mpc = 3260000 light years and another interesting characteristic of the explanation is its nature of isotropic and this says that universe is more or less symmetrical. These are some of the salient features as part of Hubble's law which is supporting the idea of expansion of the universe. So, this is one of the important selected property of the universe.

It is very important to analyze the red shifts in order to understand the isotropic nature of the universe and also expansion of the universe. Then after elemental abundance curve, H-R diagram and Hubble's law let me briefly discuss one of the most fascinating property of the universe, the detection of 2.7 K radiation whose temperature is 2.7 Kelvin. So, what are the salient features let me present in this slide.

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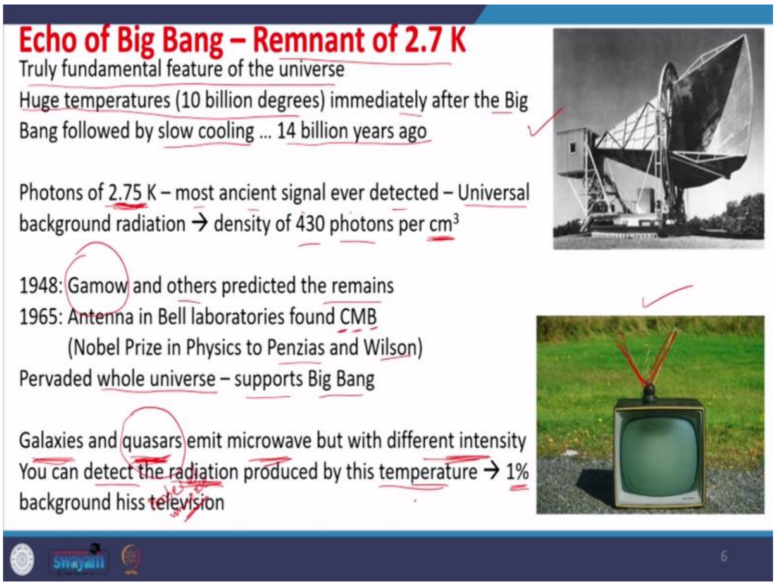

Like Hubble's law it is also a fundamental feature of the universe. Initially when big bang happened there was a huge temperature of 10 billion degrees immediately after the big bang, of course slow cooling happened. All these things started around 14 billion years ago. Now the detection of photon, whose energy is corresponding to temperature of 2.75 K has been designated as most ancient signal ever detected.

This is given as UBR Universal Background Radiation and the density of these photons of 2.75 K is about 430 photons/cm^3. Do you remember the contribution of Gamow if you have been taught the alpha decay process who proposed that it is a quantum mechanical tunneling process because of which alpha particle can come out of a nucleus?

In 1948 the same Gamow had predicted the existence of this photons of very less energy which can give idea about the remnants of the big bang, echo of the big bang that is remnant of the 2.75 K radiation. Not only Gamow some others also predicted the remains of this radiation and the antenna in bell laboratory found this Cosmic Microwave Background because it is in the region of microwaves because of which Noble Price in physics was awarded to Penzias and Wilson. This pervaded the whole universe and this provided a strong supporting feature to the big bang.

What are quasars? Basically they are the strong radio source. They are very much away from the Earth, beyond many galaxies. Quasars are also designated as the probes of the universe. So beyond this I will not discuss because I have to discuss the role of nuclear physics in the Astrophysics I hope you understand. So, for typical astrophysics concepts you can go through another course or you can go through many textbooks available in the market. So, the quasars which are the strong radio sources, they emit microwave.

But the intensity is different because when I say microwave radiation that is Cosmic Microwave Background is assigned to the 2.7 K which comes into the region of microwaves if it is an electromagnetic spectrum. This 2.75 K corresponds to the wavelength in microwave regions. Quasars and galaxies also emit microwaves. So, why researchers are saying this 2.75 K are coming from the distant away like 14 billion years ago because of the change in the intensity.

So, it is not like the 2.75 K in the microwave region they are coming only from the echo of the big bang. No, they are coming from different sites as well, but one has to look into the intensity as well, the intensity of the microwaves coming as echo of the big bang is different from the intensity of the microwaves emitted by the quasars and galaxies.

So, this clearly distinguishes the remnants of 2.7 K which is the echo of big bang. Interestingly one can detect this radiation of 2.75 K from the echo of the big bang produced by this temperature as 1% of the background hiss television. More details you can find out in the internet, but this antenna of hiss television can catch this background.

So, let me quickly summarize all these aspects of the Astrophysics which is basically trying to explain the universe. Observing the universe comes into the category of astronomy and explaining universe comes into the category of Astrophysics. Then I will start the role of nuclear physics. So, let me quickly summarize in a different way in these two slides.

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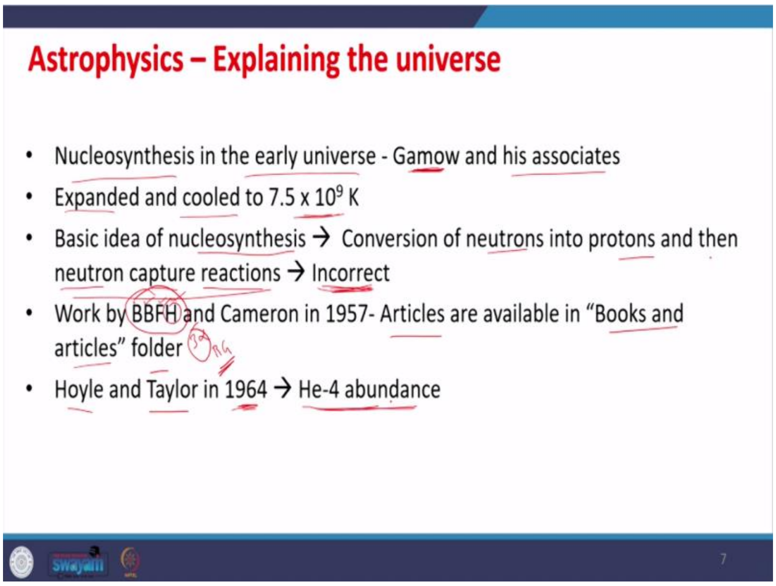

So, Gamow and his associates predicted the nucleosynthesis in the early universe. Even though energy is not sufficient for the fusion to happen based on quantum mechanical tunneling synthesis of nuclides can happen and the expansion formed by the cooling of the universe to the temperature of 10^9 K and basic idea of nucleosynthesis is conversions of the neutrons into protons and then neutron capture reaction.

This was the earlier idea, but later it has been proved to be incorrect. It is not the neutron capture reactions which are causing the formation of elements starting after hydrogen. Basically they are the result of charger particle capture reaction not the neutron capture reactions of course I will discuss in detail in coming slides and please do not forget to go through the papers of Cameron and B^2FH.

What is the importance of Hoyle's work? I have discussed in the most previous lecture triple alpha reaction which is the source of energy from red giants. Anyway, the articles whose first page I have shown you in one of the earlier slides they will help you in getting the papers of this B^2FH and also the Cameron. Hoyle and Taylor in 1964 found out the abundance of helium, which was the important milestone in astrophysics. Then it comes out that it is clearly known that from the elemental abundance curve and the detection of gamma rays from ^{26}Al and ^{99}Tc that gamma rays are coming from the distant places. So, it is because of the nuclear reactions and what kind of nuclear reactions are this? They are the thermonuclear reactions because these reactions are induced by the temperature caused by the surroundings.

And who is contributing to this temperature production, the gravitational contraction which is happening continuously when nuclides are coming together after certain stage gravitational contraction is creating some kind of thermal pressure and this thermal pressure is causing the nuclides to undergo nuclear reactions that is the reason we call these nuclear reaction as thermo nuclear reactions.

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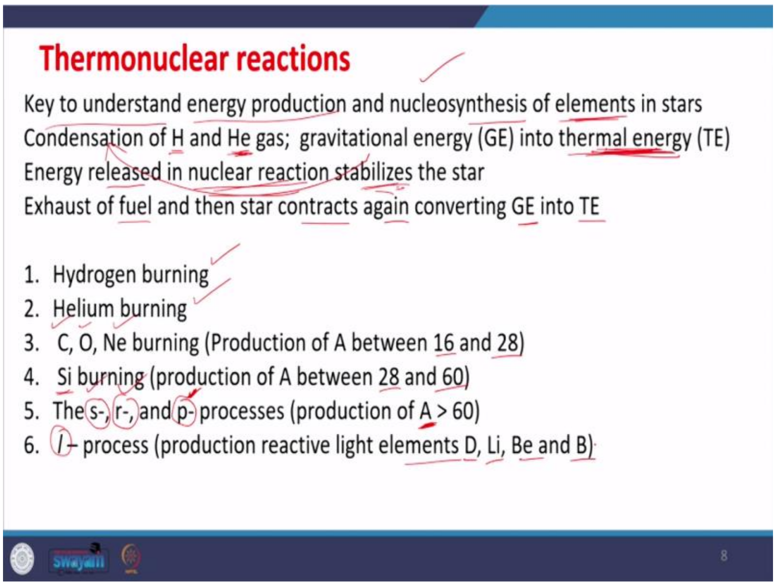

So, the understanding of this thermonuclear reactions is very important to know the production of energy from the stars and to understand the synthesis of elements in stars. So, what are the thermonuclear reactions and its properties all those things we will start discussing right now. From this I must say the actual part of the course has started because what is nuclear physics' role in the Astrophysics starts from the discussion on thermonuclear reactions which is a key to understand the production of energy from the stars and also the synthesis of elements in the stars.

And as I said initially when protons are formed and because of the protons and neutrons fusion when helium is formed the condensation of this hydrogen and helium because of the gravitational energy that gravitational energy which is causing the condensation that means contraction of hydrogen and helium gas is leading into the production of thermal energy.

This thermal energy is causing the nuclear reactions to take place and the energy released from those nuclear reactions stabilize the star for long time in general. The stability of the star is because of the energy released in nuclear reactions in stars and because of the amount of chemical composition available the exhaust of fuel happens.

Then the contraction of stars happens again converting the gravitational energy into thermal energy and various stages are available, like, first the hydrogen burning, then the burning of helium and then burning of carbon, oxygen and neon which leads to a production of elements whose mass numbers are between 16 and 28 and then burning of silicon which causes production of the nuclides whose mass number is between 28 and 60.

After silicon burning we have more than 60 nuclides having mass number more than 60 they are because of three processes called as s-process (slow neutron capture), r-process (rapid neutron capture) and p-process (proton capture). These have very least role playing, but have their own importance in understanding the nucleosynthesis, but coming to the energy production s-process and r-process play very important role.

Then there is one process called as l-process which is important to understand the production of reactive light elements like deuterium, lithium, beryllium and boron. So, students in this lecture what I have discussed are M-L relation and mass of the stars is proportional to the luminosity to the power of 3.5 in case of stars lying on the main sequence.

Then I have discussed the other features like Hubble's Law and remnants of 2.7 K that is echo of the bang and I have summarized the astrophysics which is trying to explain in the universe and I have just started discussion on thermonuclear reactions, more properties about the thermonuclear reactions in the next lecture. Thank you very much for your attention, see you soon.