Nuclear Astrophysics

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Module - 01
Lecture - 01

Historical Background, Observational Astronomy, Properties of Sun and of Stars

Hello students welcome to the course nuclear astrophysics. It has 20 hours lectures. So, you can see there are 40 files each of about 30 minutes with plus or minus 5 minutes. I hope you have seen the syllabus of this nuclear astrophysics course. It talks about the specific features of the union of nuclear physics and astrophysics. Some of you might have opted for nuclear physics separately.

Of course, till plus two the basics of nucleus have been taught to you. So, the basics of nuclear fission, when it comes to nuclear reactions you might be aware of. You also might be aware of astrophysics. So, if you have been taught the nuclear physics and astrophysics separately then this course is really going to be helpful, even if most of you have not taken astrophysics course as part of your curriculum it is perfectly all right.

Because, the basics of nuclear reactions is going to help you to understand this subject. So, when you have opted this course, what are the questions which you try to understand? From this course what are the things that you are expecting to understand and what are the questions that comes to your mind? So, let me float a few questions to start this course. Since time immemorial it is quite fascinating, in the night when you see before sleeping, completely moon day or completely moonless day, you see different beautiful pictures in the sky. Based on those stars and galaxies sometimes, if they are seen through telescope, across the world in different civilizations lots of beautiful stories and fascinating narratives you can find in the literature. But of course, humans being a curious entity always try to understand the properties of this stars and earth; and with that how elements are formed in the universe, how universe has evolved, what the steps involved in synthesis of elements are and evolution of the stars and galaxies also. So, this beautiful photograph in the slide should give an idea about the interesting aspects of nuclear astrophysics. These are some of the questions which I am trying to put here to start with in this course.

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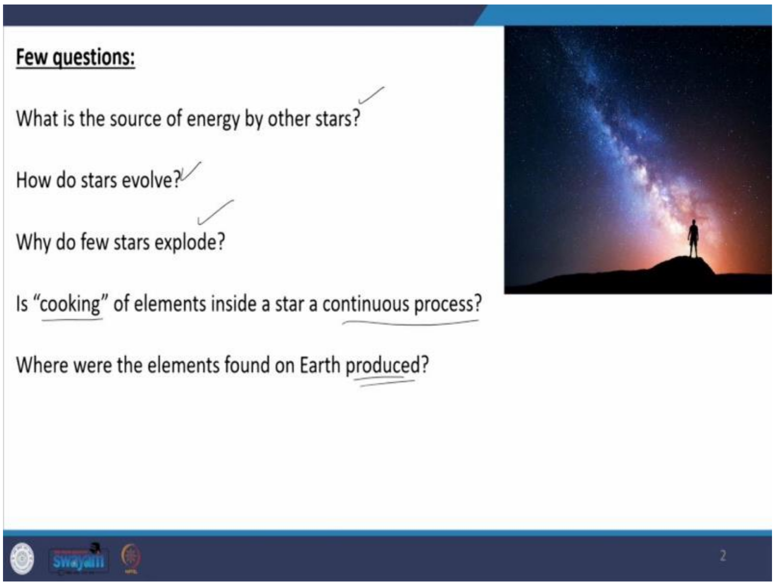

So, what are those questions? It is well known that a star like the Sun emits immense amount of energy. What is the source of energy emitted by the stars other than the sun? And how does stellar evolution happen? Is there any relation between the mass of the star and energy emitted by the star and also, the size of the star? Will there be binary stars only or can there be a cluster of stars?

When a star will die, in how many ways it will die? What is the starting point of a star? So, how stars do evolve? Why only a few stars undergo explosion? These are the questions that we will try to understand in this course. When I use the word cooking of the elements, it must be clear to you, that a lot of elements are synthesized within the star. Is it a continuous process or discontinuous process?

Where were the elements found on earth produced? So many elements we see in our surroundings. How are they produced? What is the main reason behind it? And what is the relation with nuclear physics when we try to understand the origin of the elements that we see in our surroundings?

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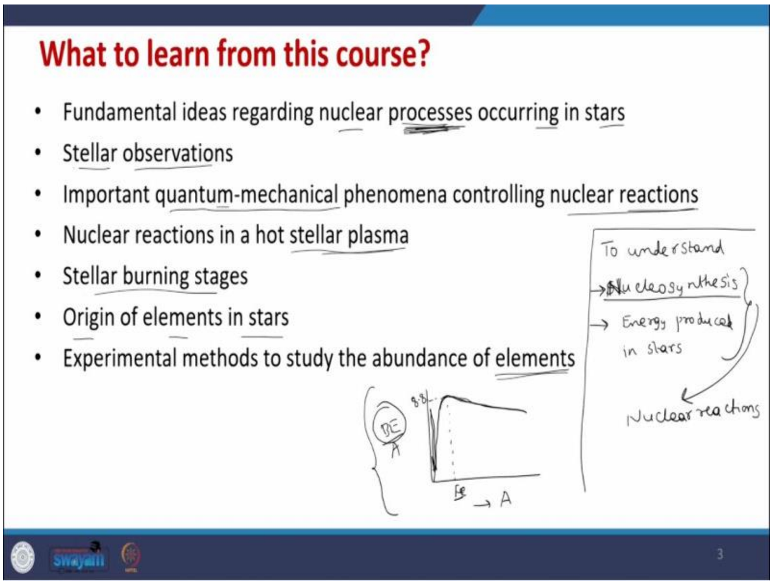

So, what are the things that we are trying to learn from this course? The fundamental ideas regarding nuclear processes occurring in stars. In this line I have given one of the important points of this course that inside the stars whatever things are happening, they are basically nuclear reactions. So, what are the fundamental ideas regarding the processes linked with nuclear physics which are occurring inside the stars?

What are the observations one can make from the stars? So, first one is about nuclear processes which are occurring inside the stars, second is observations of stars and here we are going to see the role of quantum physics and important quantum mechanical phenomena which control the nuclear reaction. These are what we are going to understand from this course.

At certain stage a star becomes very hot: and what kind of nuclear reactions do take place inside the hot stellar plasma? Are there any stages for the burning of a star? While undergoing evolution in how many stages a star will evolve and what is the basis for categorizing the burning stages of stars? That we will try to understand in this course.

What is the origin of elements in stars? How elements are produced in the stars? Finally, I will try to discuss and I will try to provide a brief overview of experimental aspects of nuclear astrophysics so that we can understand the energy produced from the stars and also the synthesis of elements within the stars. So, one can summarize the goal of this course as to understand nucleosynthesis.

What is nucleosynthesis? A process in which, nuclear reactions take place. The transformation of one nucleus from another nucleus takes place continuously. So, this process is called as nucleosynthesis and this is one of the major goals to understand in this course. And second energy produced in stars. How to do the calculations? The basis for these two is nuclear reactions.

So, what are the prerequisites for this course? You should recollect the knowledge of nucleus that has been taught to you till plus two, that is, the energy emitted from a nucleus when another particle reacts with it. Recollect the knowledge of nuclear fission process. When thermal neutron reacts with ^{235}U nucleus it forms ^{236}U and it explodes into fragments. We call it as fission process. That requires, understanding of nuclear reactions between two entities.

Recollect the knowledge of binding energy curve. When you plot the binding energy per nucleon versus mass number then how does it look like and what is the concept of binding energy? What is the concept of Q-value of the nuclear reactions? So, these are the things that you have to remember so that this course will be much easier to understand. Also, the basics of alpha decay, beta decay and gamma decay will be certainly helpful to you. Before taking this course, if you have done some experiments that will be like value addition. So, let me draw the well-known binding energy curve when you plot binding energy per nucleon. What is binding energy?

It is the energy required to assemble nucleons into one nucleus or the energy required to break the nucleus into constituent nucleons. Some kind of tentative diagram is shown in the slide. The peak is at 8.8 MeV per nucleon and this corresponds to ^{56}Fe. And there are also some kind of peaks one can see at H, He then Li, B up to Fe. After Fe binding energy per nucleon decreases slightly. This binding energy curve is going to help you in understanding various nuclear reactions and various features of nuclear astrophysics.

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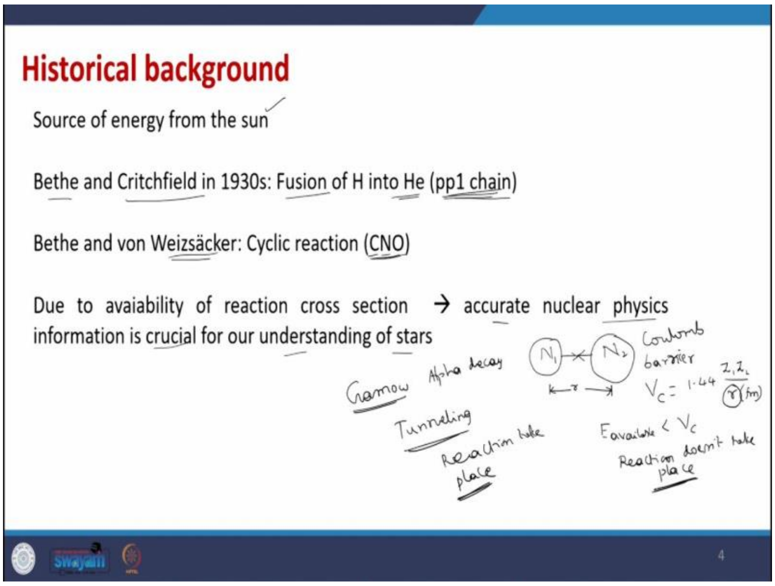

Let me start with the historical background of this subject nuclear astrophysics. When people tried to understand what could be the source of energy from the sun, this was the thought based on which this field of nuclear astrophysics started. In 1930s around in 1936 Bethe and Critchfield have proposed fusion of hydrogen into helium. Later it has become part of a process called as pp1 chain.

Bethe and Weizsacker came up with a cyclic reaction unlike a chain reaction in pp1, including C, N, O, which we call a CNO cycle. Due to availability of reaction cross section based on the availability of facilities accurate nuclear physics information became crucial for understanding the stars. Aston in 1910 or 1920 observed that He as an entity has mass slightly greater than the sum of the masses of constituent nucleons.

That also can be considered as one of the starting points. And then when Cockcroft using the isolator performed experiment then it has given better idea about the nuclear reaction. The major problem with the challenge faced by people is following.

When you have nucleus 1 having some protons and neutrons and nucleus 2 having some protons and neutrons and they try to react with each other, it has to cross a barrier called as coulomb barrier, then only a reaction can happen. That was the understanding at that time.

The coulomb barrier can be given as $\frac{1.44\, z_1 z_2}{r\ (\text{fm})}$, r is the separation between the two nuclei. So, if the energy available is less than the coulomb barrier then reaction does not take place. That was the understanding at the same time when Gamow proposed alpha decay. It was clear that, when a particle which wants to come outside from inside the nucleus like alpha particle or a charged particle wants to go inside a nucleus though energy available is less than the coulomb barrier, because of a quantum mechanical process called as tunnelling with which all of you are aware of, a reaction can take place. The stellar temperature corresponding energy is less than the coulomb barrier. So, people thought how reaction can take place, but, it is the quantum tunnelling process which made people to get convinced that there must be huge amount of hydrogen and helium within the sun and because of the quantum tunnelling process the reactions might be taking place and the energy is coming out of the stars including sun. So, it is the quantum tunnelling process which convinced the people that reaction can indeed take place inside the stars even though the energy available is less than the coulomb barrier.

So, this had prompted people to go beyond their hesitation that how reaction can take place, then things evolved very fast after the particle accelerator initially started by Cockcroft and Walton. So, this historical background tells us that the curiosity to understand the energy emitted from the sun was instrumental in the evolution of this nuclear astrophysics course. And later it is a quantum mechanical process which made people to get convinced that yes indeed reactions can take place.

Astronomy is about observation of the universe and astrophysics is explaining the universe. Astronomy deals with the observation of universe and astrophysics is explaining the features of this observations. So, after providing this historical background, let me take some time to explain some basic features of the astronomy though it is not directly linked with the nuclear astrophysics but broadly it is linked with the subject of nuclear astrophysics.

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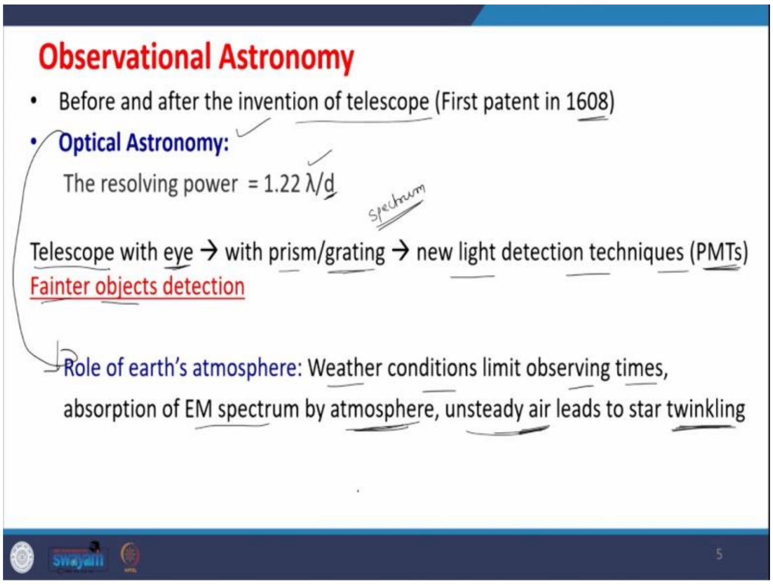

So, in this observational astronomy we can easily divide the time before and after the invention of telescope. The first patent was filed in the year 1608, and we can divide into optical astronomy, radio astronomy and space astronomy. Under optical astronomy if you see, the naked eye was replaced with the telescope in which we have a lens and the light falling on the lens is focused on to a point so that we can get an image. The resolving power is given by $\frac{1.22\lambda}{d}$ where λ is the wavelength of the light and d is the distance. After the invention of telescope at the focus still people are using the naked eye, even though eye can detect the various wavelength but it is not possible to store the data, eye cannot store the data and it is not possible to see the fainter objects. Then we have prism and grating, this has provided information about the chemical composition of the sources from which light is falling on the telescope.

So, it is basically the recording of the spectrum with the help of prism or grating and the analysis of this spectrum has given information about the chemical composition of the objects which are emitting the light. Now, even prism and grating used with the photographic emulsions are suffering from some problems, because of the inability to identify much fainter objects.

Then the new light detection techniques are based on photo multiplayer tubes or silicon photo multipliers. Nowadays people are using many advanced photo sensors which made possible the detection of fainter objects. The major challenges in this observational astronomy especially in optical astronomy you can easily expect the weather conditions which limit the observation times and the atmosphere which absorbs the most of the electromagnetic spectrum.

Turbulence in air leads to the star twinkling. So, these are the challenges in the optical astronomy.

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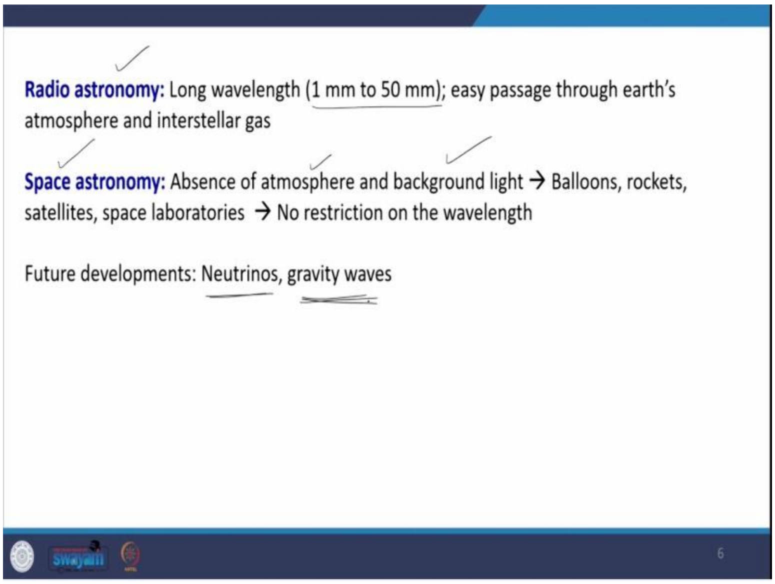

Then coming to another type of astronomy that is radio astronomy where you deal with the long wavelength 1 mm to 15 mm; easy passage through Earth's atmosphere and interstellar gas. So, because of the ability of radio waves to pass through the different conditions, when it comes to the weather, it made possible even in the day or in the night to do the measurements in this radio astronomy.

But of course, the absorption of large part of electromagnetic spectrum by the atmosphere cannot be avoided even in radio astronomy. Larger the aperture of the lens you can see the brighter object. So, the brightness of the object at the focus of the lens is proportional to the aperture of the lens. So, researchers across the world they try to build large and large size telescopes.

But still, they are suffering from the problem of absorption of larger part of the electromagnetic spectrum by the atmosphere. Then, we can go for space astronomy because the ability to put the instruments: the telescopes or detectors, in space made possible to get rid of the problems that arise due to the atmosphere which is absorbing lots of large part of the electromagnetic spectrum and the background light any time it can be done.

And there is no problem of the unsteady air and there is no condition on the observation times as well. So, one can go for balloons. You might be aware of that there is a balloons facility in India at TIFR, Tata Institute of Fundamental Research balloon facility in Hyderabad ,where one can put the instruments within the balloon and take it to some height and collect the data. So, above the surface you can go to some distance.

One can use the rockets and one can put the instruments inside the satellites which can collect the data and in space laboratories using telescopes and other instruments one can collect the data. So, the advent of space astronomy has made possible the study of the universe by absorbing the wavelength of all types of ranges which are there in the universe. So, the astronomy we can categorize mainly into space astronomy, radio astronomy and optical astronomy.

These are all basically observational features. In upcoming time we can expect astronomy based on neutrinos. Why neutrinos are important? Because, if you remember β^- decay or β^+ decay that has been taught to you. Neutrinos are very difficult to detect and sun emits large number of neutrinos. The fusion of hydrogen and helium cause the emission of these neutrinos.

The detection of neutrinos and gravity waves can help us to understand the evolution of universe in a better way. So, these are the neutrinos and gravity waves which can take this field of astronomy to next higher level.

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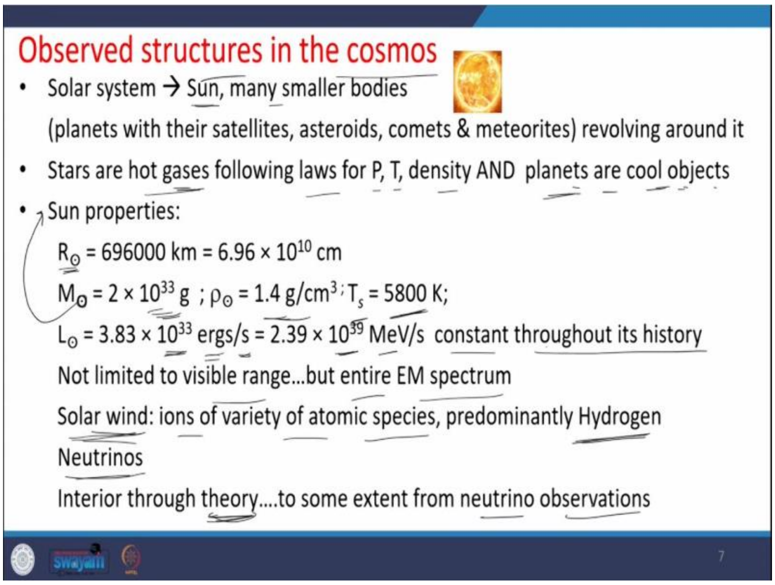

If you see the observed structures in the cosmos, let us start with the solar system which contains the sun and also many smaller bodies, you can see planets with their satellites, you can see asteroids, comets and meteorites revolving around it. Stars are nothing but hot gases, they follow the laws of pressure, temperature and density and planets are cool objects while stars are hot gases. Stars can be categorized into hot gas entities whereas planets are cool objects. Let me give you some quantitative details about the properties of the sun, about 7 lakh km if you see the sun radius and mass of the sun is about 10^{33} gm and the density is about 1.4 gm/cm^3 and the surface temperature of sun is about 5800 K.

So, from now onwards in this course whenever you come across a circle with a dot at the centre, that denotes sun; because when we deal with the mass luminosity (that means energy emitted by star per unit time) we always try to say in terms of mass and luminosity of the sun. So, this symbol is going to travel with us throughout this course.

Luminosity is about 10^{33} ergs/s; in terms of MeV it is 10^{39} MeV. You can imagine the amount of energy emitted by the sun. The energy emitted by the sun per unit time is found to be constant throughout the history of the sun. Of course, the wavelength of the light coming from the sun is not limited to only visible range but entire electromagnetic spectrum and we are also aware of solar wind. It basically consists of ions of variety of atomic species predominantly hydrogen. Many times solar wind also gives some important information about the nuclear reactions taking place within the sun and also neutrinos, one of the important quantities coming from the sun in a good number.

The understanding of interior of the sun till now we are able to do only based on some solid theoretical arguments to some extent from the observation of the neutrinos. Why interior of the sun can be understood only from theory why not by the experimental observations? Because as I said the sun is full of H, He and the reaction between proton and proton is proved to be impossible at least with the available technology.

So, because experiments cannot be done when it comes to the reaction between two protons the interior of the sun can be understood only based on some solid theoretical arguments and partly by observing the neutrinos.

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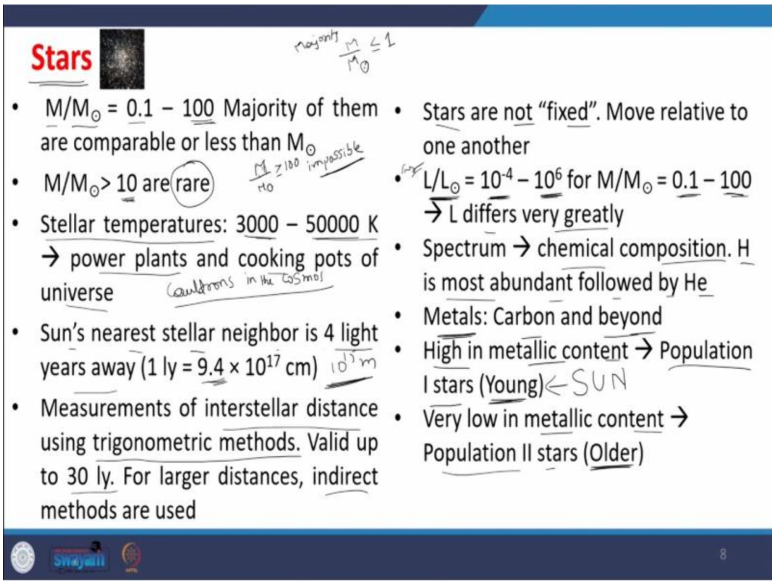

So, after discussing the solar system in the observational structure of the cosmos let me go into stars. Earlier, I have discussed only about one star that is sun. Here I am going to discuss about the stars. What you would like to hear regarding the stars? How many stars are available and what is the mass range of stars? What is the range of the luminosity of the stars and how they are related to the mass and luminosity of the sun?

So, let me provide some kind of quantitative information in the next slide. To give you an idea about the observational structures in the cosmos, starting from the sun in the solar system then I am going to collection of stars. If you see the range of the mass of a star divided by mass of the sun ($M/M_\odot$) it is ranging from 0.1 to 100. Though majority of them are comparable or less than mass of the sun i.e., $M/M_\odot \leq 1$ for majority of the stars observed.

And if, you take mass of the stars which are greater than the sun maximum by 10 times they are rare and $M/M_\odot \geq 100$ is not observed till now. They have not been identified, who? Stars whose masses are 100 times higher than the mass of the sun they have not been identified till now. So, this information on the mass of the stars is very important in this course.

Who decides the mass of the star? And when the mass of the star will change? What is the upper limit of the mass? What is the role of nuclear physics inside it? So, that is what we try to understand in this course. As of now I have given information about the mass of the stars when compared to the mass of the sun, of course this is also a star. If you go for the stellar temperature, it ranges from 3000 to 50000 K.

That is why we call them as power plants and also cooking pots of the universe, based on which you can see one of the important references of this course Cauldrons in the Cosmos. Rodney and Rolf's authors, Cauldrons in the Cosmos is one of the standard textbooks in the field of nuclear astrophysics other than Nuclear Physics of The Stars that is written by Iliadic. Now, if you see sun's nearest stellar neighbour, it is about four light years away.

One light year is about 10^{15} m, see the separation between the stars. So, when we consider the sun, its nearest neighbour is about $4\times9.4\times10^{15}$ m that means 4 light years away from the sun. So, you can imagine the separation between the stars in the universe, at least in our own galaxy.

How interstellar distance is measured? When I say the nearest neighbour is 4 light years away from the sun, it is measured by standard trigonometric method that survivors use even on earth to measure the distances. But this survivor technique is valid only up to 30 light years. For larger distances some indirect methods have to be preferred. Now it is very clear to us that stars are not in fixed position.

They are relative to one another under the influence of gravitational force. If you see the data of luminosity $L/L_\odot$ it ranges from 10^{-4} to 10^{6} whereas mass range is 0.1-100, the temperature range is 3000-50,000. So, $L/L_\odot$ is quite large.

It is about 10^{10} whereas the mass ranges you see only 1000. So, why is so much difference in the luminosity range when there is less range in the mass? This is a beautiful relation between the mass and luminosity of the stars. So, L differs very greatly and if you see the spectrum of the light emitted by the stars as I said earlier it provides information about the chemical composition.

It has clearly established beyond any doubt that H is the most abundant element followed by the He in the stars. We use the word metals in the case of stars when carbon and beyond elements starting from carbon are present in the star, if they are more we can say metallicity of the star is more. So, carbon and elements beyond carbon, we term them as metals in this field of astronomy.

And we can categorize into two types of stars; population one stars which have high metallic content and we consider them as young stars and stars which are having low metallic content they are called as population 2 stars and they are quite older and sun belongs to population 1 star. More about the structure of the cosmos in the next lecture. To summarize today's lecture we have seen the historical background of the nuclear astrophysics.

What we are going to learn from this course that is how nuclear synthesis happens inside the stars and how the energy production in the stars can be understood. These two are the important goals of nuclear astrophysics. Then we have seen the salient features of observational astronomy that is optical astronomy, radio astronomy and space astronomy. Then we have discussed some observation structure in the cosmos. We have seen important properties of the sun and the stars.

Then I will go beyond the stars that is galaxy and then the universe. What are the properties? I will try to convey in terms of some numbers. Hope you have enjoyed this first lecture and I am hopeful that also you will also enjoy upcoming lectures. Thank you very much for your patience.