Nuclear Astrophysics
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Module - 02
Lecture – 07
H-R Diagram

Hello students, welcome to the discussion on evidences of nucleosynthesis. Let me take a quick recap of the previous lecture in which I have discussed more evidences for nucleosynthesis like the measurement of light curves from supernovae, the decay of ^{56}Co before reaching ^{56}Ni, how supernovae theoretical models predicted the light curves and experimentally there was a good agreement.

In the last lecture I have also discussed one of the fascinating problems in Nuclear Astrophysics that is how mass numbers 5 and 8 can be bridged. The gaps at mass number 5 and 8 can be bridged based on the concept of triple alpha process. Do you remember the last lecture's ending part where I have shown you chart of a few nuclides and there were no stable isotopes for the mass number 5 and 8?

And that is where the fantastic contribution from Hoyle came, who predicted that it is because of the resonance at around 7.7 MeV level in ^{12}C leads to the production of ^{12}C. If the fusion between alpha and ^{8}Be does not happen around the Hoyle state then the observed abundance of ^{12}C could not be explained. So, that is where we have seen it is a two-step process.

That two-step process which has led to the production of ^{12}C could answer the question, one of the important questions in this course that is how to understand the gaps at mass number 5 and 8. After this in today's lecture we are going to discuss one more important selected property of the universe that is how one can see the variation of luminosity, temperature, density and color of stars in the universe.

The name of this selected property of the universe is H-R diagram. In today's lecture we will see some more features, let us start. Let me discuss second important selected property of the universe. First important selected property was elemental abundance curve. Second one is H-R diagram. You might have seen in internet about this H-R diagram. What does it tell us, how is it helpful to us?

The objective of this course is to understand the nucleosynthesis that means how elements are formed in the universe and the second objective is the energy produced from stars. What is the reason behind the production of energy from the stars? And it is very clear that it is a nuclear reaction which is playing vital role in the production of energy from the stars. So, it is quite natural to understand the properties of the stars.

So, how to understand the properties of the stars? There are various types of stars, is it possible to categorize the stars based on their intrinsic properties? So, Hertzsprung and Russell these two researchers independently what they have done is following which is very interesting.

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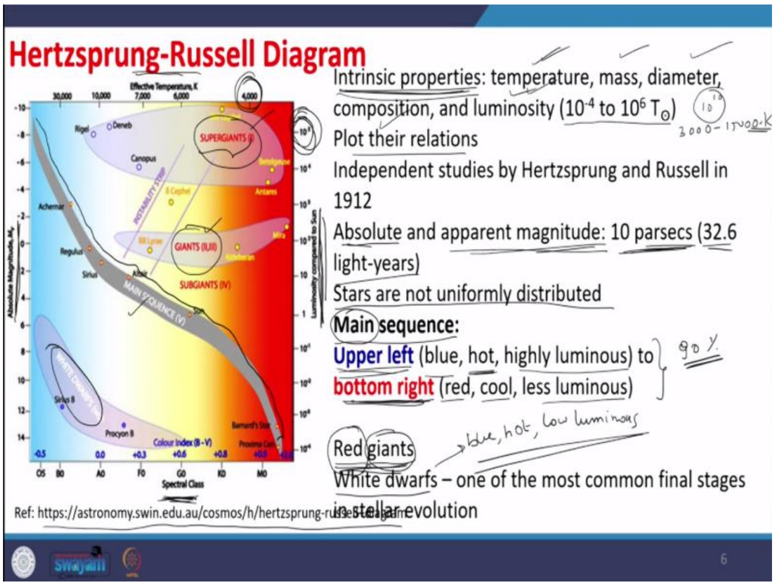

In order to understand the properties of the stars you need to correlate the intrinsic properties of the stars and when I say star, it is an entity having large number of nuclides. It is some kind of plasma you can say. Each star has its own temperature, mass, size, chemical composition and luminosity. Here you need to remember the luminosity is ranging from 10^{-4} to 10^{6}, about 10^{10} difference, whereas the temperature is ranging from 3,000 to 50,000 K.

So, Hertzsprung and Russell what they have done independently is, experimentally whatever luminosity was measured they tried to plot with respect to the temperature or color of the star. So, what is this color? I will give you more details in coming slides.

You take a star, measure its luminosity that means energy emitted per unit time and its temperature, then you plot the variation of luminosity with respect to temperature then you see how stars are arranged. Initially people expected they will be distributed uniformly throughout the region of this luminosity versus temperature plot, but surprisingly it has given totally a different kind of scenario.

What is that see here. Luminosity when compared to sun on y axis and x axis spectral class that means color. What is the meaning of this color? What it corresponds to I will discuss in the next class and absolute magnitude on the y axis left hand side and effective temperature on the x axis. So, this kind of diagram you may not have seen very frequently, but it is quite possible when one wants to correlate four properties in the same diagram, they can plot like this.

They can consider quantity like this. More details can be obtained from this diagram, in any source of the Nuclear Astrophysics text book this kind of diagram can be seen. Because I found it more colorful I took it from this website. So, what is so specialty about this diagram? The relation between these quantities like luminosity, temperature mainly, of course in this list I have not included the magnitude and spectral class because mainly luminosity in the y axis and on the x axis temperature I have denoted.

When these people have plotted these relations and independently studies were done way back in 1912, you see by the time nuclear reactions and all those studies were not very clear, simply the data of stars were available like what is its temperature, what is its color, what is its mass, what is its density. From the spectral analysis from the light emitted from the star people have measured the spectrum and from that spectrum using some mathematics and some techniques they have measured the quantities like temperature, mass, luminosity all those things and Hertzsprung and Russell they have taken those values and they have plotted and here I am using a word absolute magnitude.

See experimentally when we measure it is basically apparent magnitude, to convert into absolute magnitude from the apparent magnitude people take the help of parsecs. So, 10 parsec is equal to like 32.6 light years. I am not going into the details of the conversion of apparent to absolute magnitude. Anyway, the important features are following.

Stars are not uniformly distributed throughout the region of temperature and luminosity. Stars are not uniformly distributed. Personally, it reminds me that the distribution of mass of an atom before the discovery of Rutherford how people used to think. The mass is distributed throughout the atom Thomson Plum Pudding Model. The moment Rutherford did the famous alpha scattering experiment then people got convinced atomic mass is not distributed uniformly throughout the atom.

But it is concentrated at the center of the atom that is called as nucleus. 99.91% of the mass is concentrated at the center of the atom. Coming back to this star business the stars having different luminosity, different temperatures; they are not distributed uniformly throughout the region as expected, but majority of the stars they are following a narrow sequence, called as main sequence.

In the diagram main sequence is starting from the blue color on the left side, very hot, high temperature, high luminous upper left. So, the stars which are emitting blue that means they are very hot high temperature around 30,000 K and high luminous star.

Majority of the stars are distributed from upper left to bottom right. So, for your convenience upper left I have denoted with blue color and bottom right I have denoted with red color. The stars in the bottom right their color is red, in terms of temperature they are cool and in terms of luminosity it is less luminous and the majority of the stars, around 90%, are lying between these two.

Is it not very interesting? 90% of the stars they possess luminosity and temperature in the main sequence and not only that there are stars not only on the main sequence, remaining around 10% of the stars are clustered into several groups like one group is red giants. As the word says it is in the red region, as of the size it was very large in volume. So, you can see in this diagram giants and if you go above this there is the cluster of super giants.

Red giants are hot but color is red, luminosity is very high, temperature is less. Above that you have super giants who have very high luminosity like 10^5, temperature very less like 4,000 and color red. How these red giants are formed? I will discuss that in detail in coming lectures. For time being the purpose is to show you that stars are not distributed throughout the whole region of luminosity versus temperature plot, but they are grouped into several clusters.

One of the main clusters is main sequence, another is giants and super giants they are red in color and then we have white dwarfs they are blue and hot, but low luminous. So, stars are clustered into three major categories number one main sequence. Number two red giants and super giants then number three white dwarfs. If you have say 100 stars, 90 are in main sequence and out of remaining 10 some are in red giants and super giants and remaining are white dwarfs. So, what does this tell us? In order to understand the construction of the star if you want to model the star, how star is forming this could be something common, but what is happening after the death of the star.

That can go to white dwarfs, that can go to red giant. So, this evolution of star to understand, H-R diagram proved to be one of the excellent tools in the Nuclear Astrophysics. For better understanding let me give you some numbers in terms of luminosity and temperature.

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Star Type	Color	Approximate Surface Temperature	Average Mass (Sun = 1)	Average Radius (Sun = 1)	Average Luminosity (Sun = 1)
O	Blue	over 25,000 K	60	15	1,400,000
B	Blue	11,000 - 25,000 K	18	7	20,000
A	Blue	7,500 - 11,000 K	3.2	2.5	80
F	Blue to White	6,000 - 7,500 K	1.7	1.3	6
G	White to Yellow	5,000 - 6,000 K	1.1	1.1	1.2
K	Orange to Red	3,500 - 5,000 K	0.8	0.9	0.4
M	Red	under 3,500 K	0.3	0.4	0.04 (very faint)

See star type, sometimes you can see O star, B, A, F, G, K, M these kind of codes are given and as for color it could be blue or blue to white the transition white to yellow, orange to red and red finally. Corresponding to each color the surface temperature approximately ranges from 25,000 to 3,500.

Earlier I have given you 3,000 to 50,000 K range. Here I am showing up to 25,000 Kelvin. Average mass when compared to the sun, it ranges from 0.3 to 60 and near sun, it is orange to red and white to yellow. Compared to sun the average radius is 15 times in the upper left and 0.4 times in the bottom right.

In terms of sun luminosity, it is about 1.4 million times for stars in the upper left region and 0.04 times that of sun in the red, cool and the low luminous lower right region. This table gives an idea regarding the numbers for temperature, mass, radius and luminosity and whenever you see this kind of codes it denotes the color code in H-R diagram. How this H-R diagram is going to be useful for us, let me give you some calculations.

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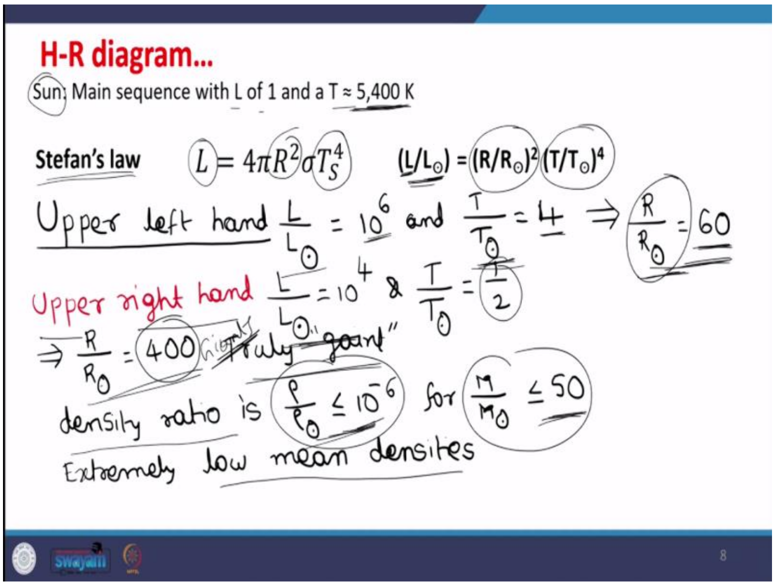

Sun has luminosity of 1 we can consider and whose temperature is 5,400 Kelvin, we have to have some reference and assuming the black body radiation the Stefan's Law tell us the luminosity is proportional to fourth power of the temperature. So, this is playing an important role in understanding the construction of the stars.

Let me take the help of this Stefan-Boltzmann law, which is, $L = 4\pi R^2 \sigma T_S^4$. Now if I go for ratio of luminosity of star with respect to luminosity of sun it looks like, $(\frac{L}{L_\odot}) = (\frac{R}{R_\odot})^2 (\frac{T}{T_\odot})^4$. In the upper left hand region if the $L/L_\odot$ is 10^6 and $T/T_\odot$ is about 4 then $R/R_\odot$ is 60. So, one can find out the size of the star if luminosity is known, temperature is known. That is the beauty of H-R diagram. I found a star, I do not know its radius, I do not know its size, no need to measure the size directly this H-R diagram gives you direct tool to measure the size of the star. So, the size of the star can be measured if you can measure the luminosity of the star and the temperature of the star. Let me discuss more about this. In upper right hand side for red giants say $L/L_\odot$ is 10^4 high luminous of course, low temperature that is the reason I have written $T/T_\odot$ as 1/2. This gives radius very high 400 times of that of the Sun, It is truly giant. Keep H-R diagram with you otherwise these numbers will be confusing to you.

$R/R_\odot$ is 60 only for upper left hand region. From this can we find out the density ratio? Of course you can find out the density ratio. It is less than or equal to 10^{-6} if the mass ratio is 50. So, if you know the mass ratio and if you know the radius from the H-R diagram you can get the idea of $R/R_\odot$ and from the mass you can find the density ratio.

See extremely less density, very low mean density for upper right hand, for red giants. So, how this red giants stars can be formed from the star and the main sequence star? And main sequence can become white dwarf or it can become super red giant. When it can happen? Which kind of nuclear reaction is playing important role in it? Those things I will discuss in another part of the course.

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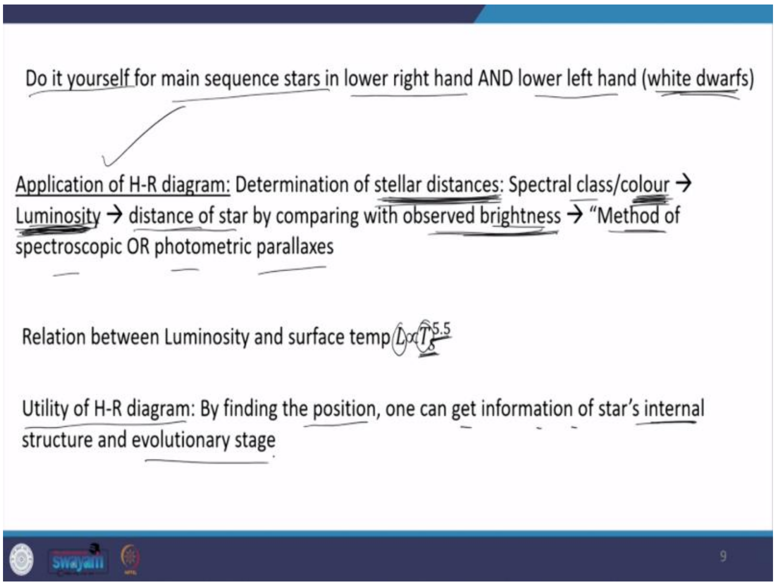

So, for remaining main sequence stars please do it yourself especially in lower right hand and lower left hand that is for the white dwarfs. I have done only for the super red giants please do it for the white dwarfs, take the values of $L/L_\odot$ and $T/T_\odot$ accordingly. Now one of the important applications of this H-R diagram is following.

If I want to measure the distances between stars there is an interesting indirect method, what is that? On earth you measure the spectral class or color. Do you remember earlier in the table I have given you spectral code O, K, M, J like that. So, you measure the spectral class or color, from that you find out the luminosity from H-R diagram. Once you know the color of the star you can go for the luminosity. Once this luminosity is known with observed brightness one can go for the distance of the star by comparing with the observed brightness. This is called as method of spectroscopic or photometric parallaxes. This is one of the important applications of the H-R diagram and let me complete this topic of H-R diagram by giving you a mathematical relation between luminosity of a star and a temperature of a star. It is given as $L \propto T^{5.5}$.

So, the utility of the H-R diagram is by finding the position of a star one can get the information of the internal structure of the star and how star will evolve. The stellar evolution is one of the important objectives of this course. How star will evolve? It will go to red giant or it will go to white dwarf? It is easy to guess if you understand the H-R diagram. So, in these two lectures I have provided few more important evidences of nucleosynthesis i.e., detection of neutrino and one important facility also I have shown you in Japan; number two, another strong evidence i,e,. decay of ^{56}Co with respect to which people have calculated the light curve of the supernovae and they are in good agreement with the experimentally measured the light curves of the supernovae.

Then I discussed H-R diagram. What is this H-R diagram? When Hertzsprung and Russell independently have taken the data of temperature of a star and luminosity of a star and plotted, the plot is known as H-R diagram. The conclusion is that stars are not uniformly distributed throughout the region of luminosity and temperature, in fact 90% of the stars they are lying on a very narrow region called as main sequence and remaining stars are located in giants, red giants and white dwarfs and the utility of this H-R diagram I have tried to explain with the help of some numbers. One can find out the size of the star if you know the value of $L/L_\odot$ and $T/T_\odot$. I hope you have got some idea about the H-R diagram. Two more important selected properties of the universe I will discuss in the next lecture. Thank you very much for your patience. Thank you.