Nuclear Astrophysics
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Module - 01
Lecture - 03
Background of Elemental Abundance Curve

Welcome students, to the third lecture of nuclear astrophysics. I hope based on previous two lectures you have got some idea about what I am going to discuss in this course, what are the questions that we will try to answer in this course and what are the expected learning outcomes of this course. It is a union of nuclear physics and astrophysics. So, whatever concepts you have been taught till plus two or in BSc level those will be helpful to you.

The concept of binding energy, the calculation of coulomb barrier of a nuclear reaction, the calculation of Q-value and the basics of nuclear reactions if you are taught and the liquid drop model whose extended version is a semi empirical mass formula which gives the value of binding energy with respect to the mass number and then the disadvantages of liquid drop model were addressed by another model that is a shell model, if you know all these things then it becomes easier to understand this course. In the last class I have discussed few properties of different entities like the Sun which is a part of the solar system, of course which is also a star. Is it population I or population II star? The category under which the Sun can be considered is population I star which has more metallicity and is relatively younger and populations II stars are quite old and their metallicity is very low.

How have we defined metallicity in this course perspective? Elements starting from carbon and beyond carbon they are considered as metals. So, the definition will change when we use the word metal when we come to the astrophysics. Then I have discussed after giving a few numbers about the Sun, the mass luminosity and the sizes of the stars when compared to the Sun.

The temperature of stars ranges from 3000 to 50000 K and then mass ranges from 0.1 to 100 times that of mass of the sun. The luminosity of stars when compared to the luminosity of sun it ranges from 10^{-4} to 10^{6} times of luminosity of sun. So, you can see the small range of the mass and high range of the luminosity.

What is the reason for this? That as I said I will discuss in due course. Then I have discussed a few important properties of galaxy confining myself to the milky way galaxy about 10^{12} stars are there and other properties of this milky way galaxy I have discussed. Then I have discussed the properties of universe, how many stars are there and what is the size and what is the average separation between the stars.

So, ultimately, we have concluded universe is a classic example of ultra-high vacuum. Because the visible matter is occupying only 10^{-25} portion of the universe space, remaining is empty. So, if you consider each star as one rain drop and if you assume the stars are raining then the separation between the stars is about 100 km. So, you can imagine the level of emptiness in the universe.

Though we have 10^{22} stars in the universe and mass number also I have given in the previous slide, we can consider universe as almost nothing because of a huge separation between the stars and universe contains billions of galaxies. So, all these numbers at first instance you may think where from we have got it. Is it some kind of prediction? No, using many types of astronomy related techniques we have got these numbers.

I have discussed different techniques of observational astronomy like optical astronomy, radio astronomy and space astronomy and using telescopes like speed telescope and Hubble telescope, Chandra observatory. So, all these equipment has given information about the number of stars and number of galaxies. So, this was a summary of the previous two lectures. Now in today's lecture let me discuss few important characteristics of the universe.

There are many properties of the universe, the properties which are relevant for nuclear astrophysics I am going to discuss in today's lecture. The list of the general selected properties I have provided in the previous class. How these properties are analysed regarding the universe? Researchers have considered various objects like planets, meteorites, comets, stars and space between the stars. So, people have considered all these types of objects.

And they have measured the energy emitted from those objects and sometimes researchers have analysed the chemical composition of the objects like meteorites. Then the listing of the properties of universe could become possible. And what are the four important properties? Number one, elemental abundance curve and this particular property has been analysed by considering the abundance of elements in solar system and abundance of elements in different parts of the galaxies, in different types of stars and in different regions between the stars which we call as interstellar space. So, by analysing the chemical composition of the elements in all these areas and with all these objects people came up with elemental abundance curve about which we are going to discuss in today's lecture. What are the remaining three topics which I will discuss in the upcoming lectures?

The relation between mass of the star and the luminosity of the star; when people have plotted the mass of the star, how does it look like with respect to the luminosity and temperature of the star? It has given a beautiful insight about the property of the universe. So, that is called as HR diagram. Then by looking at the distant galaxies using the telescopes like Hubble, researchers have analysed the velocity with which these objects are moving with respect to each other and they came up with well-known law called as Hubble’s law. So, that is the third important selected general property of the universe. Then the remnants of the 2.77 kelvin cosmic microwave background which has given a solid argument in support of the big bang hypothesis. So, let us see in today's lecture, salient features of elemental abundance curve.

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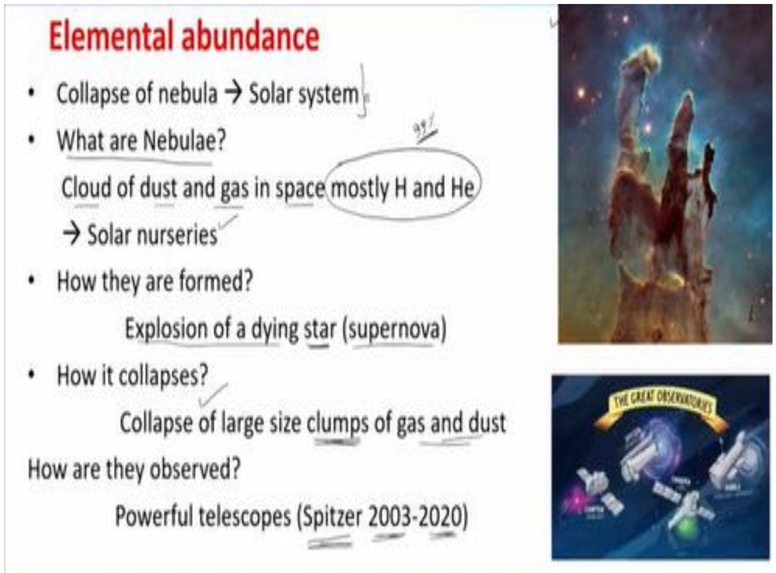

When I say elemental abundance curve what basically I am referring to initially the abundance of elements in the solar system. How solar system has been formed? It is widely accepted that the solar system is formed because of the collapse of nebulae. Now let me spend some time on the salient features of nebula whose plural form is nebulae and what exactly is a nebula and how a nebula can collapse and where it is located, what are the sizes of the nebulae.

So, all these things about the nebulae I am going to discuss briefly now into this lecture before going to the discussion on elemental abundance in solar systems as the solar system is formed because of the nebulae. So, I am taking this opportunity to discuss or to inform something about the nebulae though nebulae is directly is not into the picture when we consider the elemental abundance curve.

But because of the collapse of nebulae, we have this solar system in which the abundance of elements we will discuss whether it can give some beautiful insight about the property of the universe. So, let me start the discussion on nebulae. So, what exactly are nebulae? Nebula is basically a cloud of star dust and gas in space and mostly hydrogen and helium. So, almost 99% of hydrogen and helium, remaining parts are small amount of plasma, basically the ions and electrons.

So, between two stars when interstellar space is considered you will find different types of star dust and gas and that is nothing but nebulae. So, this is a famous photograph and you might have seen this in different books in your childhood. If you have gone through some space related text books or some story books you might have seen this. These towers of dust and gas in the cosmos they are nothing but nebulae.

Now after answering what are nebulae, let me use the word solar nurseries. So, you know the literal meaning of the word nursery. Nebulae which are basically a composition of star dust and gas they are also starting point for the star formation. So, that is the reason why we call these nebulae as star nurseries. So, how nebula can act as a starting point of a star and when I say it is a composition of dust and gas where from it has come and how big it is and how it undergoes collapse!

So, all these things I am going to discuss now. How are they formed basically? See whenever you consider any star at the end of the star life that means before a star dies it will explode many a times which we call as supernova. Supernova is a stage when star reaches a stage of explosion and because of the explosion whatever dust and gas is thrown out of the star that is nothing but nebula which further sometimes can act as a new star.

How does it collapse? Because the nebula consists of dust and gas and this dust and gas they are spread through a large area. However, because of the presence of gravitational force between this dust and gas they will come together and as the dust and gas undergoes gravitational attraction, slowly the size of the cloud becomes bigger and it becomes stronger.

When this entity becomes so big that it starts collapsing and when it undergoes collapse that leads to the formation of things like solar system. So, that is how the elemental abundance in solar system is linked with the explosion of nebula. Here when I say clumps basically clusters of gas and dust when become so big, they will collapse and that is how they become reason for the formation of solar system. How can one observe the nebula?

Of course, by using powerful telescopes, for example Spitzer space telescope which was launched in 2003 by NASA and it got retired in the year 2020. So, it has given large number of photographs from the universe and this has played very important role in observing the nebula which are present between the two stars. And we have Compton gamma rays telescope, spitzer telescope, Chandra observatory and Hubble telescope. So, these are the different facilities which helped us to observe the nebula and stars.

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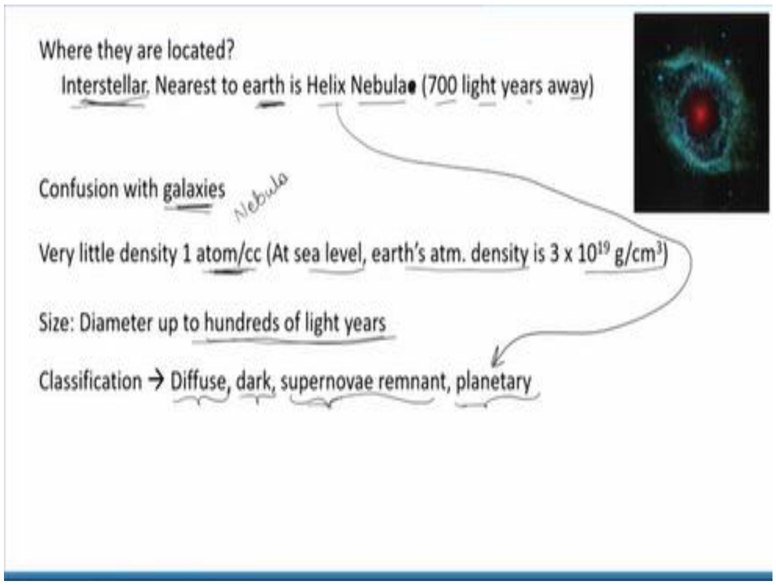

Where are they located? I mean what is the site of this nebula? As I said already interstellar that means between the stars. So, that is why sometimes you can use the word interstellar medium, ISM. Let me take an example nearest to the earth the nebula one can see is called as Helix nebula and the distance is about 700 light years away. This is the photograph of Helix nebula shown in the slide, such a beautiful thing you see it is a blue colour.

So, blue denotes the hotness and red denotes the coolness. Why is so? That I will discuss very soon. So, even if you travel with velocity of light, it will take about 700 years to reach the nearest nebula from earth. So, that is the separation between the nearest nebula from earth. For several centuries researchers have thought galaxies as nebula. So, there is some confusion between which one is galaxy and which one is nebula.

Of course, there is a clear difference between star galaxy and nebula. Now if I provide some information about the density, its density is extremely low less than 1 atom/cc, when you compare with the earth's atmospheric density at sea level it is about 10^{19} gm/cm^3. So, this gives an idea about the density of the nebula. So, all these numbers I am giving for nebula.

What about its size? Not small of course, the diameter is up to hundreds of light years. Depending on the nature of nebulae one can divide into four types. The way nebula behaves with the visible light we can divide into emission and absorption, emission or reflection nebulae which come under this diffuse nebula and then dark nebula because it will stop the light like it becomes opaque. And whatever is other side of the nebula?

It cannot see the light from other side of the nebula because it will stop the light coming from a source. Then from a remnant of supernova if nebula is formed then we call it as the supernovae remnant. So, nebula can also be formed because of the supernova also. Then there is planetary nebula and this Helix nebula is some kind of planetary nebula. So, this is a brief information about the nebula whose collapse gives rise to the solar system.

Now once we have the solar system, of course we would like to see the abundance of elements in the solar system. So, let me start the actual thing that is the elemental abundance in the solar system with this background of nebula.

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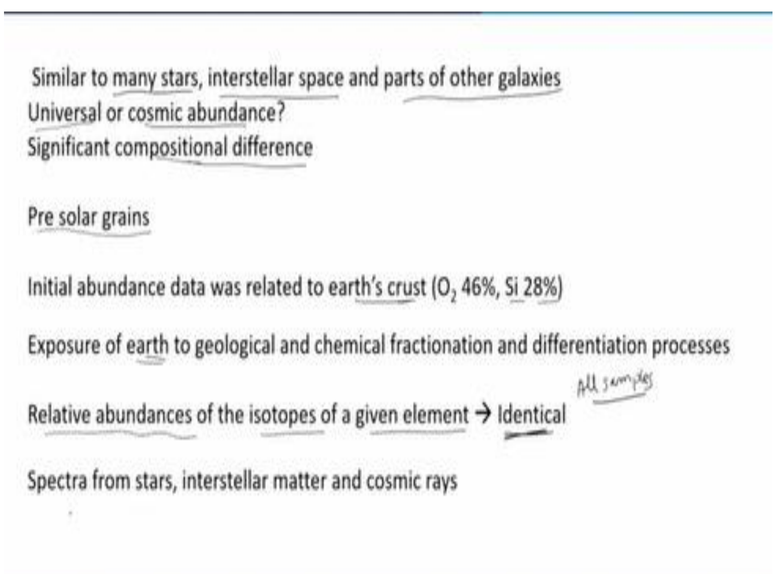

Now if we want to see the abundance of elements in the solar system it is mainly the sun which compresses the most of the mass of the solar system. We can assume that the elemental abundance in sun is similar to that of abundance in many stars and also elemental abundance in interstellar space and parts of other galaxies. So, it is quite common to assume that one can give abundance at the universal level.

So, by analysing the abundance of elements in the sun can we give universal abundance. Because the abundance of elements in the sun can be expected to be same that of in the many types of stars and interstellar space and the different parts of the galaxy. People thought initially that elemental abundance in the sun can be considered as universal abundance. For that when researchers have done a lot of studies some interesting results came out which I am going to list right now.

So, can we get some kind of universal or cosmic abundance? Interestingly the compositional difference is quite significant. Because when researchers have taken pre-solar grains which can be a good source of objects, which cannot undergo chemical and geological fractionation like earth, then one can see the composition whether it is same like that we see in the sun. People have observed quite different.

Initially the data was related to the earth's crust i.e., oxygen 46%, silicon 20%, other elements occupy the remaining 36%. Now because we know that earth has been exposed to lot of geological and chemical fractionation and differential processes, we cannot expect the elemental abundance on earth to be the same as that of the sun. Now it is very clearly known that sun is full of hydrogen, helium. What about earth? That is not the case.

Because earth is continuously getting exposed to the chemical and geological fractionations and interestingly if you see the relative abundances of isotopes of a given element more or less in all samples it is same. The relative abundance of isotopes of a particular element is almost identical in all samples. What does it mean? Isotopic abundance is not very sensitive to geological and chemical fractionation processes.

So, this is one of the important outcomes when people have observed the abundance of elements and also isotopic abundance of a given element. Now when we take the spectra from different objects like stars, interstellar matter and cosmic rays, based on the analysis of the spectra if abundance is calculated then how it looks like.

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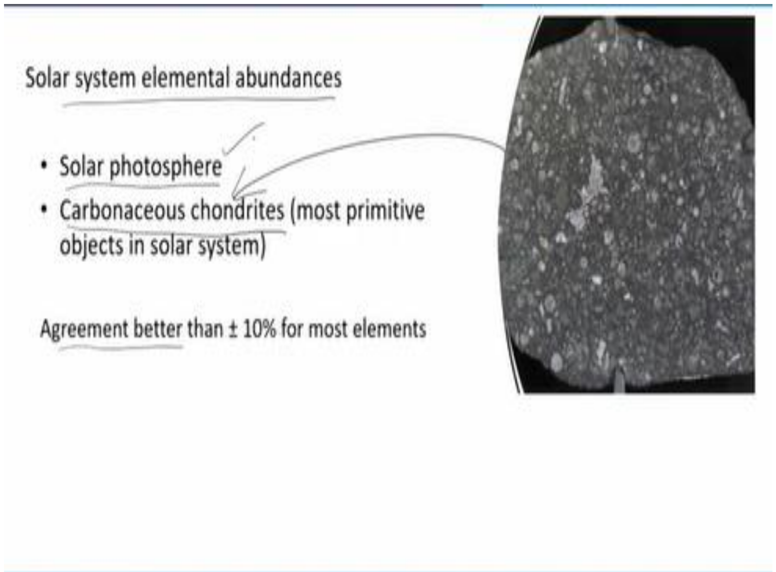

Let me give you some picture. Before that let me give some more information about the solar system elemental abundances. So, researchers have taken two methods, now I am confining only to the solar system elemental abundance. The abundance data was collected based on two things; one is solar photosphere and then one of the important primitive objects in the solar system.

That is carbonaceous chondrites, it looks like this (shown in the slide) which is believed to be one of the oldest meteoroids in the universe. When one considers this kind of object, one can assume that it has not undergone any kind of fractionation processes. So, at that stage you observe the elemental abundance then you see whether it is same as that of solar photosphere or not.

So, interestingly there is a good agreement between abundance curves obtained from solar photosphere and abundance data obtained from these carbonaceous chondrites and the agreement is within 10% for most of the elements. How it looks like?

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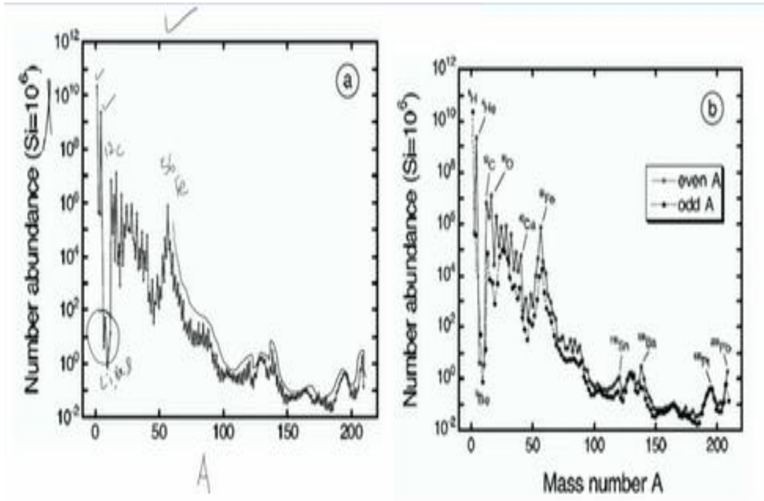

Abundances within a group/subgroup → specific nucleosynthesis mechanism

Let me show you. When we normalize with the silicon and the number of atoms is 2^6 and on the x axis you take the mass number, you can see in the first diagram the most abundant elements are H and He and then you can see a sudden dip in the abundance of Li, Be and B. So, for Li, Be and B the abundances are very low. Why it is so, we have to understand.

Then sudden rising abundance from the ^{12}C, then you see slowly it is decreasing up to mass number (A) say 45, like Ca. Then there is a majestic peak you can see around Fe. After Fe you can see the decrease in the abundance with some ups and downs at specific places. So, this is how elemental abundance curve looks like. Now on the right hand side I am showing you the same abundance curve by separating the abundance of even A nuclides and odd A nuclides.

How it looks like? More or less the same. Interestingly the abundance of nuclides with even mass number is higher than the abundance of nuclides with odd mass number. Are you able to recollect something when I say even and odd type? You must have been taught well while learning shell model and semi empirical mass formula and liquid drop model and correlating the concepts with the binding energy curve, please recollect them.

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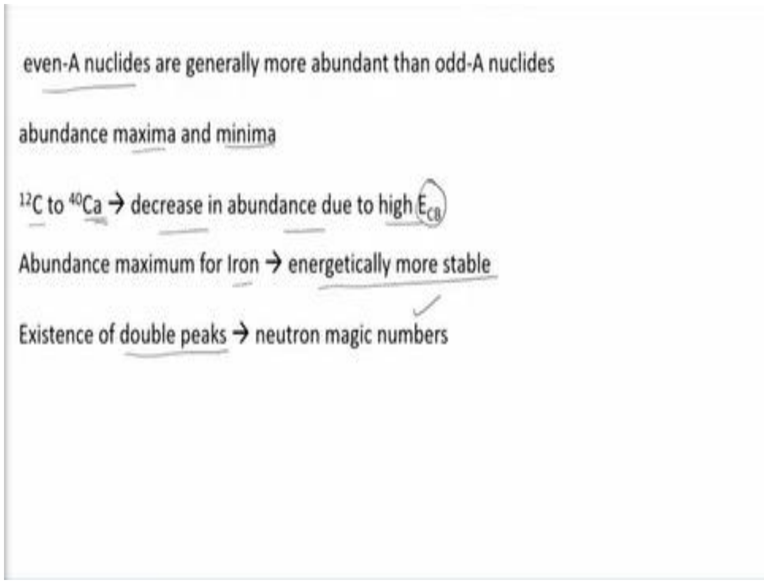

So, as observed in the experimental data even A nuclides are generally more abundant than odd A nuclides and it is not some kind of haphazard observations. The trend is clearly either maxima or minimum at several places and from C to Ca if you see there is a decrease in abundance due to high coulomb barrier. Because you go from low to high atomic number the charge increases which leads to the increase in the coulomb barrier.

So, the increment in the coulomb barrier is leading to the decrease in the abundance in many regions not everywhere. Now at iron why the abundance is maximum? Because it is very clear, energetically this is the most stable element and you also have seen few double peaks after the iron peak, they denotes the existence of neutron magic numbers and please recollect the knowledge of shell model.

So, this neutron magic numbers filling the neutron shells that gives rise to the high abundance, high stability. So, when people have plotted the abundance of elements with respect to mass number and when you get the peaks like this at certain mass number that clearly gives beautiful insight into the nuclear physics part of this nuclear astrophysics.

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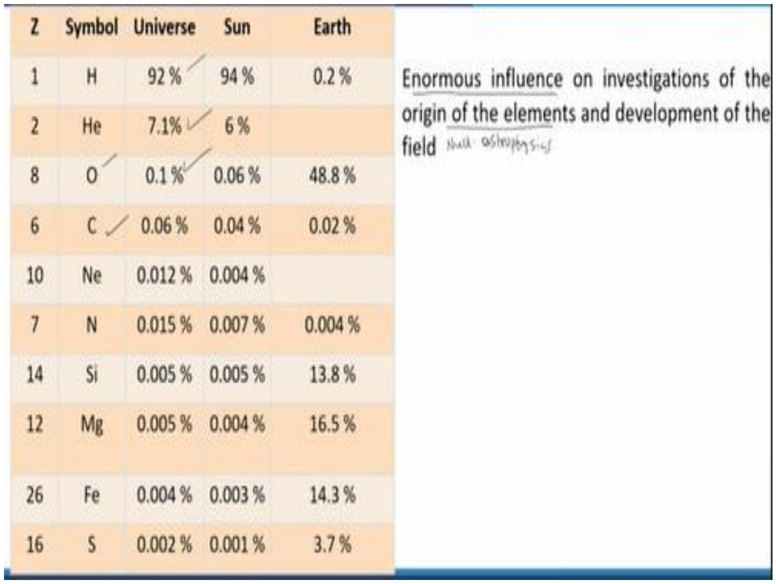

Z	Symbol	Universe	Sun	Earth
1	H	92 %	94 %	0.2 %
2	He	7.1%	6 %	
8	O	0.1 %	0.06 %	48.8 %
6	C	0.06 %	0.04 %	0.02 %
10	Ne	0.012 %	0.004 %	
7	N	0.015 %	0.007 %	0.004 %
14	Si	0.005 %	0.005 %	13.8 %
12	Mg	0.005 %	0.004 %	16.5 %
26	Fe	0.004 %	0.003 %	14.3 %
16	S	0.002 %	0.001 %	3.7 %

This is how the data corresponding to different elements looks like. So, the most abundant element in the universe is H, then He, then not C, it is O. Why is it so? We will discuss after at least 15, 20 lectures and then remaining elements abundances are given here. So, this data had enormous influence on investigations of the elements and their origin and the development of field of nuclear astrophysics.

The data on abundance of elements had immense influence on the investigations of the origin of these elements.

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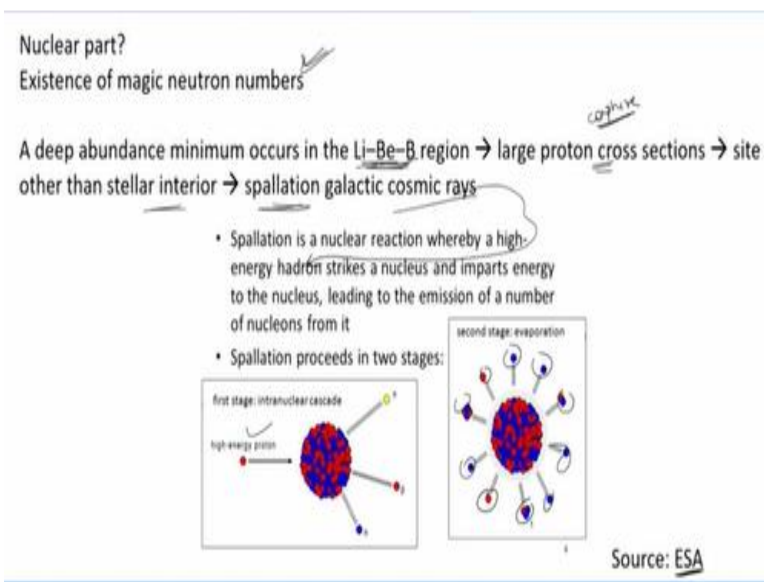

Now can we extract some nuclear related properties from this abundance curve? Let us see, as I already discussed existence of magic neutron numbers. So, this is supporting the shell model and then dip in abundance occurs in Li, Be, B. So, interestingly they have large cross section for the proton capture. They have large proton capture cross section because of that they will be destroyed immediately whenever they are formed in the stars.

Where from they are producing because even though it is less abundant if we consider the scenario within the stars then even that much of abundance cannot be quoted because of their large proton capture cross sections. So, there could be sites other than the stellar interior for these three elements. So, there are few elements which cannot be understood by considering the star as the site.

People had assumed and later it was verified that it is due to the spallation galactic cosmic rays. What is spallation? It is basically a nuclear reaction whereby a high energy hadron strikes a nucleus like high energy proton and because of the impact of this high energy proton on this nucleus and energy transfer to this nucleus, emission of number of nucleons and then evaporation happen. This process proceeds in these two stages.

This is the source of Li, Be and B. So, this has been taken from the European space agency website.

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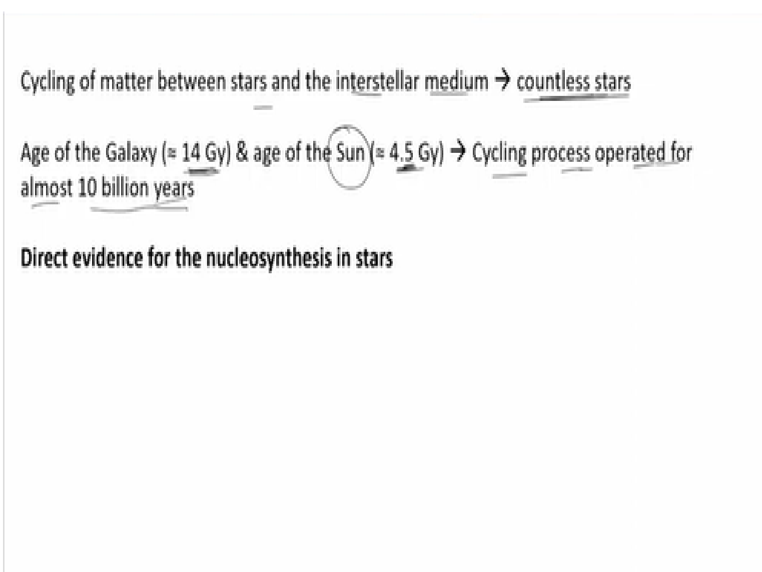

Now let us discuss about the cycling of matter between the stars and the interstellar medium. What do you mean by the cycling? As I said when star is formed, before it dies it will explode and it will throw out the gas and dust. It is settled in between the two stars as some kind of cloud and this cloud can become source of a new star. So, this cycling between the star and the interstellar medium lead to the production of countless stars.

Now let us see some interesting observation. It is known that age of the galaxy is about 14 giga years and the age of the sun is 4.5 giga years. What does it mean? The cycling process operated for almost 10 billion years, cycling process for the formulation of a star like sun it took about 10 billion years. So, this is one of the interesting evidence for the cycling process and what is the direct evidence for the nucleosynthesis in sun and stars that I will discuss in the next lecture.

So, to summarize today's lecture I have discussed some important features of the nebula, their characteristics, where they are formed, how it undergoes collapse and what about its size. Then elemental abundance curve, how it looks like, where are the dips and ups. So, all these things I have discussed in today's lecture and let me continue this topic in next lecture. Thank you so much for your attention.