Nuclear Astrophysics
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Module - 01
Lecture - 04
Evidence of Nucleosynthesis - I

Welcome students, to today's lecture. If you remember what I have discussed in the previous lecture, in this initial part of the course, I am trying to give you an overview of the properties of the solar system, collection of stars and categorization of stars, properties of galaxy and then properties of the universe. After that I have started discussing the selected general properties of the universe.

As part of discussion on selected general properties of the universe which was preceded by the observational astronomy features, I discussed the solar system abundance curve in the previous lecture. What have you understood in the previous lecture? When abundance of elements was studied it was clear that the abundance of elements has more or less a systematic trend.

Initially most abundant elements H, He, they have huge peaks and then sudden decrement in the abundances of Li, Be and B, then the increase in the abundance of C. Then slowly up to Ca the abundance was decreasing. Then after that you have seen a majestic peak around Fe and after Fe the abundance was decreasing more or less continuously.

But even after iron when you have seen the abundance of elements there were few peaks. As I have discussed they correspond to the filling of shells by magic number of neutrons. So, that has given a clear indication that neutron induced reactions play an important role in the abundance of elements in the universe. When I use all these words many times you can ask which nuclear reaction plays very important role in the abundance of a particular element.

It will take some time to reach that stage. If you remember I have listed four important properties of the universe. No. 1: elemental abundance curve, that I have discussed in the previous class. Now with one question related to the solar abundance of elements in the solar system, I will move on to the few more properties of the selected properties of the universe. And what is that question?

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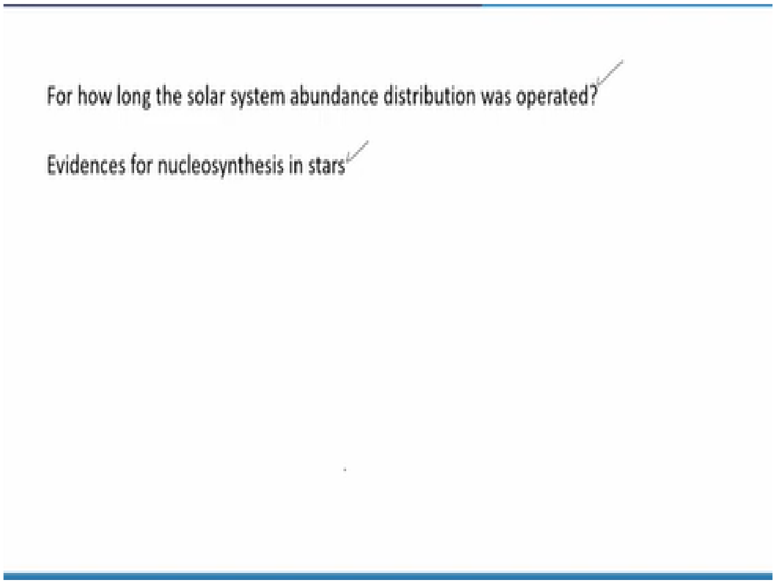

For how long the solar system abundance distribution was operated? I mean can we come up with some time scale for how long the distribution of elemental abundance in the solar system got operated? How to guess that? This I will address in today's lecture in brief. Then I will provide a few evidences for nucleosynthesis in stars. And after that if time permits, I will cover some more selected general properties of the universe.

So, this is going to be the gist of today's lecture. In the last lecture I have fully focused on elemental abundance curve. So, for how long it could have been operated? How to know that? Can you guess? I am talking about the abundance of elements. The distribution we have seen initially H, He they are very high. Most abundant elements in the universe H and then He then comes other elements. Is not it?

For how long the solar system abundance distribution was operated? Let me see how we can address this query.

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Nuclear processes → Liberation of KE → interior source of energy radiated from star's surface

Nuclear processes → alteration of stellar matter's composition → ejection of part of its mass into space → alteration of interstellar medium's chemical composition → formation of new generation of stars

Cycling of matter between stars and the interstellar medium → countless stars

Age of the Galaxy (≈ 14 Gy) & age of the Sun (≈ 4.5 Gy) → Cycling process operated for almost 10 billion years

Nucleosynthesis

Three broad segments:

1. Primordial nucleosynthesis (H, He)
2. Energetic particle (cosmic ray) interactions (Li, Be, B)
3. Stellar nucleosynthesis (C and heavier elements)

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You see it is very clear, the fusion of nuclides into heavier species. So, all of you are aware of the basics of nuclear reaction. Though nuclear reactions are of many types, in general, within the stars it is a fusion reaction. What will be happening in the fusion reactions? Two nuclei, undergoes fusion, then a heavy nucleus will be formed in general and then energy will be released.

The kinetic energy released in the nuclear processes becomes the interior source of the radiation emitted from the surface of the stars. So, what is the interior source of the radiation coming from the stars? It is basically nuclear processes and most of them are nuclear fusion reactions. So, these nuclear reactions which are producing a kinetic energy which is emitted in the form of radiation from the surface of the star, also play role in altering the composition of stellar matter.

Here nuclear processes are playing dual role; first they produce energy. There is no doubt in the fact that the light emitted from the stars or energy from the stars like sun it is purely because of the nuclear processes. Now these nuclear processes they also decide the composition of stellar matter. As part of evolution of the star there are many evolutionary stages that I will discuss in due course.

But for time being you try to understand what I am trying to convey. During different evolutionary stages of star there is always a possibility. and it always happens that some part of the star, some mass of the star will be ejected into the space outside the star during certain evolutionary stages of the star. So, the content, the matter, the mass ejected by the star into the space, means the interstellar medium, constitutes a separate region within the stars.

So, in the interstellar medium when part of the stars content is ejected, what will happen? The presence of part of the star in that interstellar medium because of the ejection by the star, it will change the chemical composition of the interstellar medium. So, there is an alteration in the chemical composition of the interstellar medium. So, you have stars in different places.

Between the stars whatever space is there, in that space one star has ejected some of its part some of its content. And this content is changing the chemical composition of the interstellar medium. So, what does it mean? So, interstellar medium is playing a very important role in the formation of new generation of stars. So, birth of a star from the interstellar medium in which some content of the star is present, in other place is becoming the reason for the formation of a new generation of stars.

Try to understand how one star is giving birth to another kind of star. What are the various physical quantities coming into picture? That we will discuss slowly. So, for time being; please remember the question with which I have started the lecture. For, how long solar system abundance distribution was operated? Can we get some time scale? Can we get some number regarding the duration through which solar system abundance distribution took place?

For that I am starting from the argument that one star which formed because of you know if you start from the very first star after the big bang. During the evolutionary stage part of its mass got ejected into interstellar medium which is becoming the source of new generation of stars. Now as I said the liberation of kinetic energy is becoming the interior source of the energy radiated from the star surface.

And these are the same nuclear processes which changes the composition of stellar matter. As I said ejection of part of its mass into the space will also change the interstellar medium's chemical composition. So, you have new generation of stars. The cycling of nucleonic matter between stars and the interstellar medium, I hope I am clear when I say the cycling of matter between stars and interstellar medium.

This cycling of matter between stars and the interstellar medium leads to the existence of countless stars. Now, if this is the case if large number of stars are occurring because of the cycling of matter between the stars and interstellar medium then it is well known that the age of the galaxy is about 14 billion years, and if you see the age of the Sun 4.5 billion years, it is very clear that the cycling process operated for almost 10 billion years. The difference between age of the galaxy and age of the sun, do you think it makes sense? Think about it. The age of the galaxy is about 14 billion years and age of the sun is about 4.5 years.

It is clear that the cycling process occurring between the stars and the interstellar medium which is becoming the source of another star. Considering that argument in mind it is clear that when I ask you for how long the solar system abundance distribution got operated, it is about 10 billion years. I hope you got convinced with this argument. So, once we are done with the elemental abundance curve in particular solar system abundance curve, let me start the discussion on widely used term in this course. That is nucleosynthesis. What is it? It is the process of formation of nucleus because of various processes which is taking place continuously in the universe. Of course, what is evidence? That we will discuss. I will discuss in today's lecture some of the important evidences. So, the nucleosynthesis that means the synthesis of nucleus, the cooking of elements in the universe can be broadly categorized into 3 types. Number 1, primordial nucleosynthesis; that means immediately after the big bang when quarks and gluons are formed the interaction between them led to the existence of protons and these protons and then some electrons they related to the formation of neutrons. You know neutron when it is in free condition it is radioactive with 10 minutes half-life.

So, when neutrons are available when protons are available you have He also. So, the stage up to which H and He are formed we categorize them under primordial nucleosynthesis. This is the first step in the nucleosynthesis phenomenon. Number 2, energetic particle interactions; because of the interactions caused by the cosmic rays which are high energy protons.

We can see the formation of Li, Be and B. So, we can see the formation of nuclides of atomic number 1, atomic number 2, 3, 4, 5. See the moment we crossed atomic number 2 when we are discussing third and fourth and fifth atomic number elements the reason is completely different. It is no more primordial nucleosynthesis it is because of the cosmic ray interactions. More about this we will discuss in future. But initially I am trying to give an overview about the nucleosynthesis.

How to categorize it? Number 3, all elements beyond boron that is C and beyond C which can be considered under the category stellar nucleosynthesis. So, this paper the stellar nucleosynthesis written by Professor J N Goswami from physical research laboratory, Ahmedabad gives you a beautiful idea about the nucleosynthesis within the universe. Of course, there are many other papers as well.

So, what you have to remember at this stage is stellar nucleosynthesis. I am not discussing much about primordial nucleosynthesis and cosmic ray interactions which are related to the formation of Li, Be and B. For time being let me focus on stellar nucleosynthesis. Why? One of the questions which I have started with in today's lecture was what are the evidences of synthesis of nuclei within the universe? Elements are formed in the universe.

What is the guarantee? What is the proof? What is the evidence that it is because of the nuclear process? Do we have any evidence? Yes, we have many evidences. And I am sure you will be really enjoying after knowing these evidences while learning. Unless you are aware of those evidences through some internet related material or in some text books. But at least I am really excited to share the evidences reported by the researchers regarding the synthesis of nuclei in the universe. Let me start with the first evidence of nucleosynthesis.

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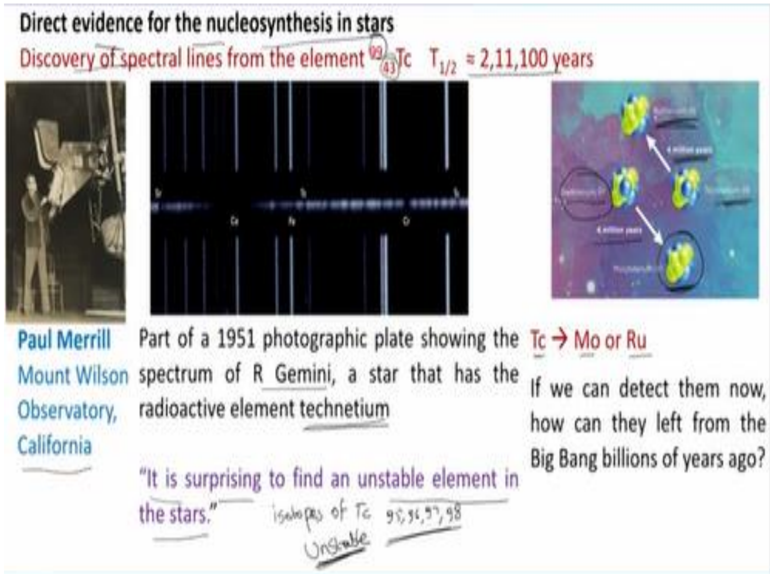

The direct evidence of nucleosynthesis in stars, in 1952 Paul Merrill using a telescope you can see in the photograph in Mount Wilson observatory Pasadena California. What he has done? His studies have given some remarkable discovery and this is the one. In the photographic plate Paul Merrill has shown the signature of an element technetium (Tc). In this part of the photographic plate, you can see Tc, you can see strontium (Sr), you can see Ca, you can see Fe, Tc, Cr and Tc respectively from the right. So, this spectral line was observed from a star which is known as R Gemini and this has the radioactive element Tc. Now if you see this statement with a bit less confidence given by the Paul Merrill that it is really surprising to observe an unstable element in the stars. Of course, you know the difference between stable element and unstable element.

If you come across any element which is unstable, what will happen? It tries to reach to the stable state. How? By radioactive decay depending on the nature of the radioactive element it can undergo via gamma it can undergo via beta decay it can undergo via alpha decay or some other decay processes. At that time researchers have never imagined the existence of Tc in the universe. Why? Listen to me carefully. No isotope of technetium is stable.

We have isotopes of Tc ranging from 95, 96, 97, 98 all are unstable. It was quite clear by the time. So, when I give few statements, you can be bit confused that how can you give this judgments kind of thing? On one hand I am saying Tc is unstable. On another hand I am saying that this spectrum confirms the existence of Tc, based on the spectral line recorded from the light emitted by a star that is Gemini.

So, how people know that technetium has no stable isotope? Remember by the time periodic table came up with most of the elements and one of them was Tc. And using other experimental techniques you know each and every element came into picture in terms of knowledge system. And all these elements how they were formed within the earth's crust? That was the area people were thinking of.

But as I said while giving the historical background of the nuclear astrophysics which is the union of nuclear physics and astrophysics that what could be the source of energy from the Sun? See with that question this field has emerged. The subject which we have opted in this NPTEL to know more about Nuclear Astrophysics and as the name suggested what is the role of nuclear physics in the astrophysics? So, the question with which this whole subject emerged was what is the source of energy from the Sun?

And people came up with different arguments as I said. Though now it appears that I am deviating from the present topic I will come back to the actual topic very soon. So, it was clear that H and He could be the most abundant element in the stars. That was clear from the other observations like recording the spectral lines, when light is falling on some photographic plates or when you develop the image of the photographic plate you measure the emission spectrum and absorption spectrum. So, when people started recording the emission and absorption spectrum suddenly Paul Merrill observed that this is indeed signature from only Tc. How we can say that it is only from Tc? Because the gamma ray corresponding to the Tc unstable nucleus is nothing but the wavelength observed in this spectral line diagram.

So, how it is possible to obtain it as it is an unstable element? Remember unstable elements are not formed in the stars. It is not like that unstable elements are indeed formed in the stars but heavy elements are formed or not that was doubtful. But when Tc was observed then suddenly people tried to think how a heavy nucleus like Tc can show its presence in the spectrum.

Some more information let me share with you. So, the discovery of spectral lines from the element Tc, mass number 99 and atomic number 43 the half-life is 2.11 lakh years. So, what? If technetium can give its signature even after 2.11 lakh years that means it was formed before 2.11 lakh years. That means elemental abundance or when I say nucleosynthesis it is still happening.

And if you see the cosmological scale billion years and compared to this Tc half-life which was observed not million or billion years ago it was just 70 years back. What did it convince? The discovery of Tc line whose half-life is 2.11 lakh years means very recently this Tc was formed. When you compare to this cosmologist scale of billion years it is only 2 lakh years.

So, when we can observe Tc now which was formed before 2.11 lakh years it means the synthesis of Tc is happening continuously. So, this is one of the remarkable evidence for the nucleosynthesis in stars which is happening continuously for the last billions of years. Let me share some more information about this Tc. See ^{97}Tc, if it is formed it can always decay to ^{97}Mo.

As I said already no isotope of Tc is stable. So, including ^{97}Tc which is having about 4 million years half-life it is decaying to ^{97}Mo. The decay is happening not only that, if it is ^{98}Tc its half-life is also 4 million years which is higher than ^{99}Tc half-life. It can decay to ^{98}Ru.

So, one can see that the decay of Tc to Mo or Ru if we can detect them. Now what makes us to think that Tc was formed immediately after the big bang only but not now. So, they cannot be left from the big bang which happened billions of years ago. I repeat when we are able to detect the Tc using the telescopes now how we can say that they left from the big bang billions of years ago.

So, it can decay either to Ru or it can either decay to Mo. And this is a reference I strongly suggest you to go through the paper written by J. A. Johnson published in the journal science in the year 2019. You can see it is a very recent paper. These photographs were taken from this website the conversation.com.

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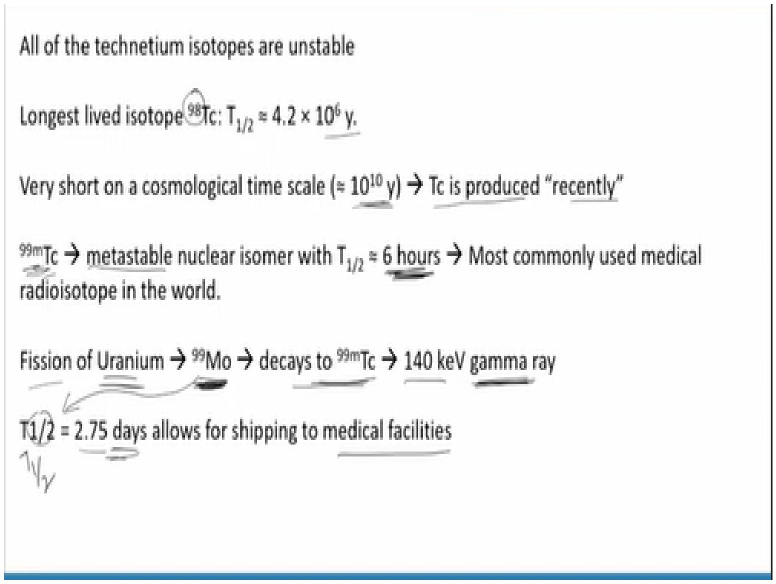

So, as I said all of the Tc isotopes are unstable and the longest lived isotope ^{98}Tc, about 4 million years. Now when compared with the cosmological time scales 10^{10} years we can always say confidently that Tc is produced recently. Let me take liberty to share with you something which is not directly linked with the nuclear astrophysics but something else. I will not take much time.

See in Tc one can observe an isotope called as ^{99m}Tc metastable state. So, what is a metastable state? Metastable state is an excited level whose half-life is more than several seconds. What is so special about it? I believe you are aware that the energy levels of any nucleus they are in discrete, of course, after certain stage there will be continuum. But above the ground state, you have first exited state, second exited state, third, fourth, fifth like that and when transition occurs from one state to another state it occurs within nano, micro or femto and picoseconds. But there are a few nuclear exited levels whose half-life is in seconds, sometimes you may see in hours and days, may be some isomeric states with years. So, this ^{99}Tc has a peculiar state called as 99 metastable state whose half-life is about 6 hours.

That is the reason why this Tc is used in the diagnostic purposes across the world. Most commonly used in medical radioisotope in the world, why? Because this emits 140 keV gamma ray. What is so special about it? It is not very much different from the x-rays. All of you know the x-ray diagnostic equipment. So, in place of x-rays one can use the ^{99m}Tc state and whose half-life is only 6 hours.

So, after a few days it will not be having any impact on the human body. So, health-wise no issue at all. How this ^{99m}Tc state is used or produced in the medical facilities across the world? See, you know the fission of uranium. In plus two you have been taught fission of uranium it gives you lot of fission fragments. One of the fission fragments is ^{99}Mo. And this ^{99}Mo decays to ^{99m}Tc.

The ^{99}Mo has half-life of 2.75 days. So, this much time is sufficient for people to produce ^{99}Mo within the nuclear reactor and ship them to medical facilities. So, it is a topic which is nothing to do with the nuclear astrophysics. But because we are seeing that Tc is a very important discovery which is a strong evidence for the nucleosynthesis, I thought to share with you an isotope connected to Tc which is widely used in diagnostic facilities. So, some more evidences in the next lecture. I hope all of you have got an idea about the direct evidence of nucleosynthesis in the form of discovery of Tc. Thank you so much. See you in the next lecture. Thank you.