Astrophysics & Cosmology

Prof. Somnath Bharadwaj
Department of Physics and Meteorology
Indian Institute of Technology – Kharagpur

Lecture – 23
Galaxies

Welcome in the last class, we discussed the HR diagram and how we can show the position of the star on the HR diagram and how we can infer considerable information from this. Today, we are going to study the evolution of stars and much of the knowledge about the evolution of stars comes from solving the equations that govern the state of a star. So you take the equations that govern the state of a star and solve them.

Now this is a very tricky business and it can be computationally very intensive because the chemical composition changes and if you look at the evolution of stars one also has to deal with situations, which are not always in equilibrium. So it is a very complicated thing, it can be a very complicated thing. So I will briefly give you some idea about the evolution of a star, some of the results that people have obtained about the evolution of a star. Stars form by the collapse of gas clouds in the interstellar medium okay that is how stars form.

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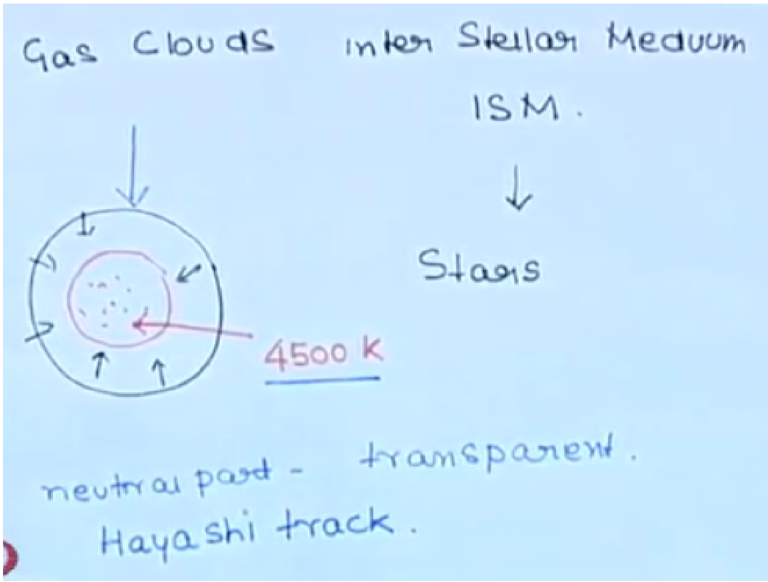

So you have gas clouds in the interstellar medium, the IS, which is also referred to as the ISM and these gas clouds collapse to form stars. Now when a gas cloud collapses, so just imagine this is a gas cloud and it is collapsing as it collapses the temperature is going to rise and after a certain amount of collapse the temperature in the center, in some central region is going to be adequately high is so that the hydrogen gets ionised.

So this part, the temperature is adequately high. It is around 4000. So in the interior in this part it is around 4500 Kelvin. It may be more inside but this is the temperature at which hydrogen starts to get ionized so it may be more inside but at the surface of this region it is around this much 4500. Now when you look at this cloud from outside, so if you are looking at this cloud from here the neutral part is transparent.

The neutral part it is largely transparent. Neutral gas can only absorb at certain specific frequencies or wavelengths, which correspond to the atomic transitions. For other frequencies or wavelengths, they do not interact with the radiation at all okay. So it is largely transparent. So if you are looking from here, you will not see these neutral parts where it is cooler.

When you reach the ionized part you have Thomson's scattering and the optical depth is going to reach unity. The part of the star that you will see is essentially this around 4500 Kelvin okay. So as the gas cloud collapses, during the collapse you will see a surface of this temperature more or less. This constant temperature, the temperature inside may go up, but you will not be looking into it because it becomes optically thick quite fast.

So these are represented, so the track of a cloud that is collapsing to form a star is represented on the HR diagram by what is known as a Hayashi track. So he was the Japanese scientist who work these out. So it follows what is called the Hayashi track. On the HR diagram let me draw that.

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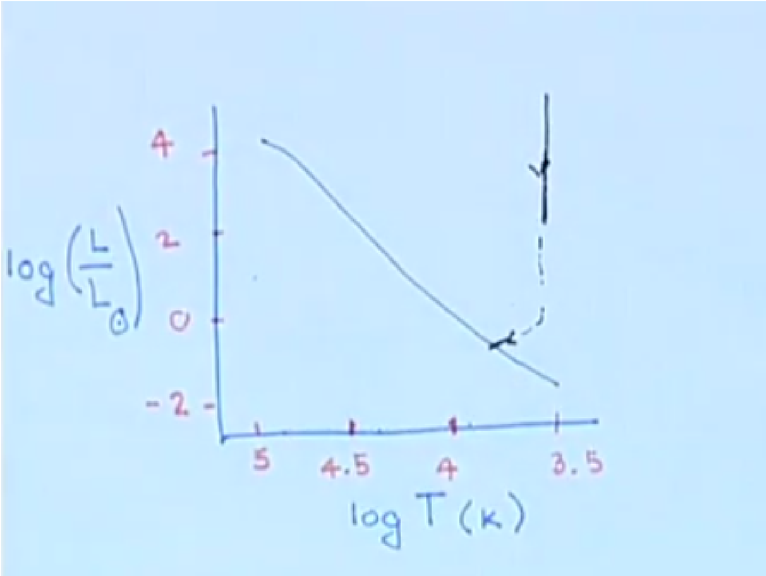

So the log we are going to plot an HR diagram. In this diagram, we will plot the log of the temperature in Kelvin. This is going to be in Kelvin and along the y-axis we will plot the log of the ratio of the star to the solar luminosity, luminosity to the solar luminosity. So L is the luminosity of the star and this is the solar luminosity. This is the diagram we are going to use the HR diagram.

Observationally you cannot directly determine these, you would have used the colour and the absolute magnitude, but here we are going to draw this theoretical HR diagram, which is equivalent okay. And let me put the axis so we will start from 3.5 and we will go up to 5. So 3.54, 4.5, 5 okay. So this is going to be 4 okay. So that is the temperature range and the luminosity range is going to go from -2 so, which is a hundred times fainter than the sun and it is going to increase in intervals of 2.

So this is going to be 0 this will be 2 and this will be 4. So this is where the sun would be, this is hundred times brighter than the small luminous than the sun. This is 10,000 times more luminous than the sun. We have seen that it goes up to the luminosities can vary from roughly hundred times fainter than the sun to 8*10 to the power, so roughly 10 to the power 5 times brighter than the sun.

So it will be up will go up to five okay. So this encompasses the entire possibility roughly okay. So the Hayashi track the temperature remains a constant at a value around 4500, which corresponds to 3.6 in this log scale okay. So a Hayashi track will look something like this. The luminosity will keep on decreasing the temperature will not change okay. A gas cloud, which is forming a star as it collapses will move at a it will go down at a constant temperature that is the surface that you are looking at okay.

The interior temperature may be higher. So in the HR diagram we plot the surface temperature the effective temperature. So the Hayashi track is going to come like this straight down okay. Now let me draw the main sequence. The main sequence as it collapses what is going to happen is that the temperature in the center and the density in the center is then going to become adequately high that the hydrogen starts burning, the nuclear reaction starts and it is going to form helium.

So that once that will lead us to the stable age main sequence configuration. So let me also draw the main sequence over here. The main sequence I have told you is a line that goes like this and the temperature of the sun we know is around 5800 Kelvin so somewhere over here. So the main sequence is a line something like this, may not be exactly a straight line but for our purposes we shall take it to be a line something like this okay.

So as the gas cloud that is collapsing approaches the main sequence depending on the mass of the gas cloud, it will turn left and reach the appropriate point on the HR diagram. So the more massive or the more luminous stars will be somewhere here, the less massive will be here so depending on the mass of this cloud it will go down like this and then it will turn left and assume the correct position appropriate position on the HR diagram okay. That is the stable equilibrium position. So these are the Hayashi tracks.

There will be different tracks for different masses. This part will be roughly the same but it will reach a different part on the HR diagram, go and settle at a different part in the HR diagram. Now stars once they are in the HR diagram in the main sequence okay sorry. This is the main sequence so it will approach the main sequence and go and settle into a different point on the main sequence.

Once it reaches the main sequence that is the stable hydrogen burning configurations stars will remain there form time periods, which vary.

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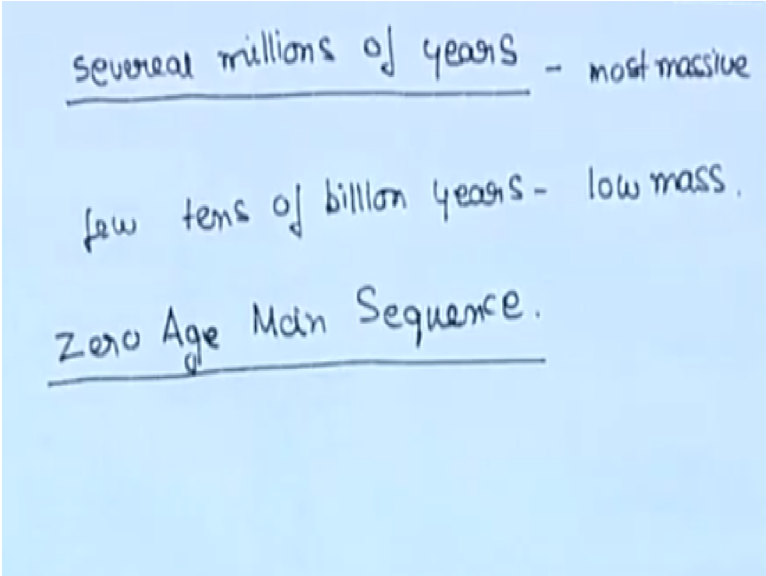

So the least, the most massive stars could spend several millions of years there, in that stable configuration burning hydrogen. These are the most massive stars whereas the low mass stars could spend few tens of billions years. These are the low mass. So the lifetime on the main sequence where it is burning hydrogen and varies a more massive star is more luminous that you can see from here, it burns away its hydrogen rather fast whereas a less massive star burned its hydrogen slowly its luminosity is low and it lives a long life.

And the lives vary from several million years to few tens of billion years. They remain on the main sequence steadily in a steady state okay. And they burn hydrogen it is a stable configuration, that is the configuration for, which we wrote down the equations several classes ago and that is the stable hydrogen burning configuration.

Now once the star burns out all the hydrogen, it is then that the Stellar evolution again starts off okay. Well strictly speaking, it is not so. Let me make that point clear. The position that the star comes to initially when it joins the main sequence, when it goes and reaches the main sequence is what is called the zero-age main sequence.

This is where the core is made up of the composition of the interstellar medium cloud from, which the star was formed. Now as it burns hydrogen the composition changes. It still continues to burn hydrogen but the composition changes and there is a small shift in the position on the main sequence as a consequence of this okay.

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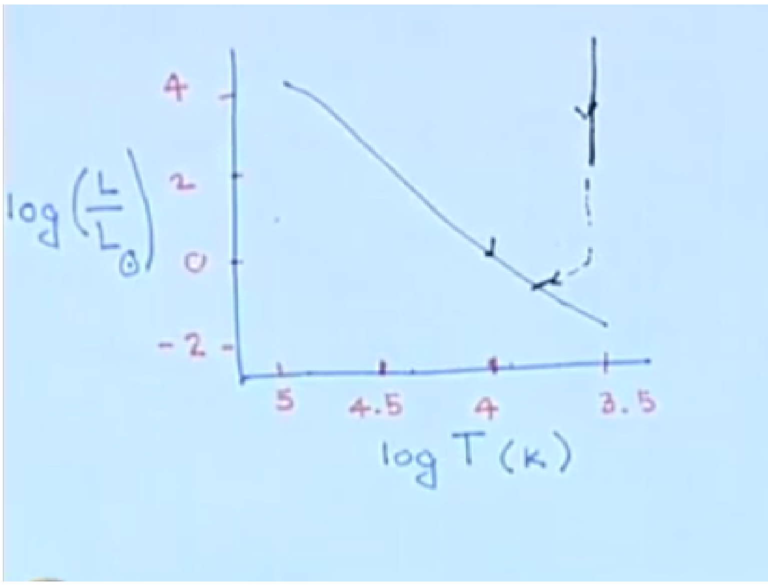

And let me indicate this on the diagram. So let us for example, look at the evolution of the sun, which is somewhere over here. The sun it moves slightly up as a consequence of this okay. So when it joined the main sequence, it would have been somewhere here and as a consequence of the hydrogen burning in the center in the core the chemical composition changes and it moves slightly up.

Now the question is what happens when it has exhausted all the hydrogen at core okay that is the next stage. So the star spends a large part of its life there and then it has exhausted all its hydrogen in the core and it is left with a core that is largely inert made up of helium.

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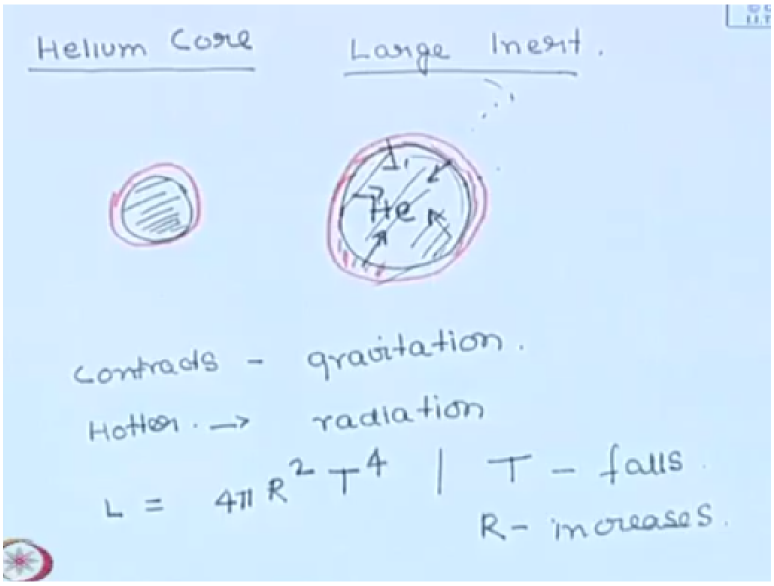

So after it has burned its hydrogen, it is left with the helium core and the helium core is largely inert to start with okay. So we have a helium core, which is largely inert. So this is the helium core in the center and there is a shell of hydrogen being burnt, still being burnt outside it. Hydrogen burning is still in progress in a shell outside it okay. So there is a shell like this where hydrogen burning is still in progress.

Now as time progresses, this hydrogen burning shell, it burns out more of the hydrogen into helium so this gets bigger, core gets bigger and the shell also gets shifted to an gross okay. So this is what happens. Now the next thing that happens is that this core now contracts right. There is nothing to support it. There is no energy source in the center so this core now contracts due to gravitation. And as the core contracts it gets heated up okay.

So now the core, so this is the helium core, this is helium. Core is expanding is increasing in size because the hydrogen shell is burning more and more hydrogen into helium so that keeps on increasing but this whole thing contracts because of gravity gravitational collapse okay. And as it contracts, so this whole thing now contracts due to gravitation and as it contracts due to gravitation what happens is it gets hotter.

So the core is contracting it is getting hotter and it emits radiation also in this process, it gets hotter and it emits radiation this is simple virial theorem okay and this, as it contracts and gets hotter the hydrogen burning at the edge of the core also goes up okay. So the whole thing contracts and the radiation from here this gets hotter and the radiation from here blows out the outer envelope okay. So the outer envelope, the outer part there is more energy being generated.

There is energy being released from the center, more energy because it contracts, which if you have in a star if you have more energy being generated at the center we know from virial theorem that it will expand. If a star loses energy it contracts, if a star gains energy it expands. This we have learned this in the virial theorem. So when the center when the core actually when this thing collapses due to gravity collapses now, it gets hotter emits more radiation. The entire star as a whole will expand.

So the outer part of the star expands and it expands so much that the luminosity actually increases considerably. The luminosity goes up considerably. Due to the expansion the temperature falls of the surface but the radius increases dramatically. And as a consequence what happens that the outer part so let me draw a picture again.

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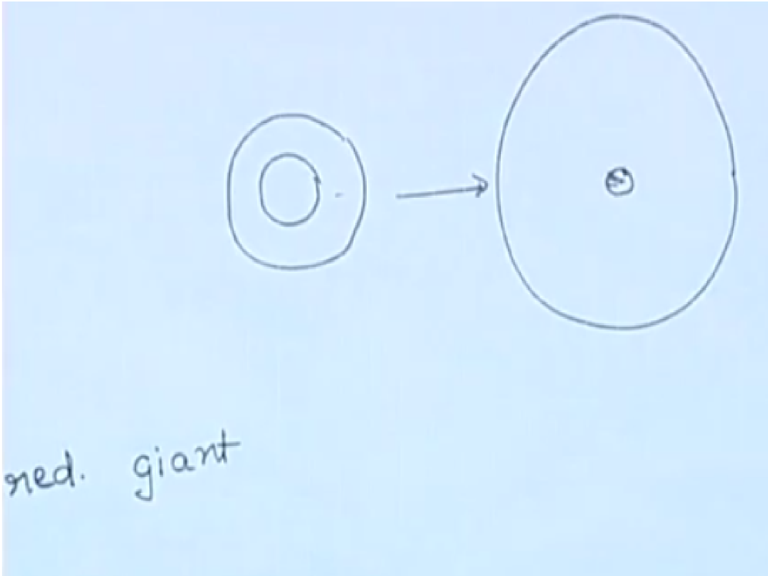

So the core of the star, this is the core this was my star, the helium core collapses it becomes smaller contracts gravitationally it gives out more energy so the outer part of the star increases in radius. The rest of the star increases in radius okay. So it becomes now much larger the temperature of these regions falls.

But the total, the rate increase in the radius is so large that the fall in the temperature is compensated by the increase in the radius more than compensated and the luminosity goes up. And so this star now becomes what is called a giant, red giant. Red because it has become cooler and a giant because its radius has gone up and its luminosity also has gone up.

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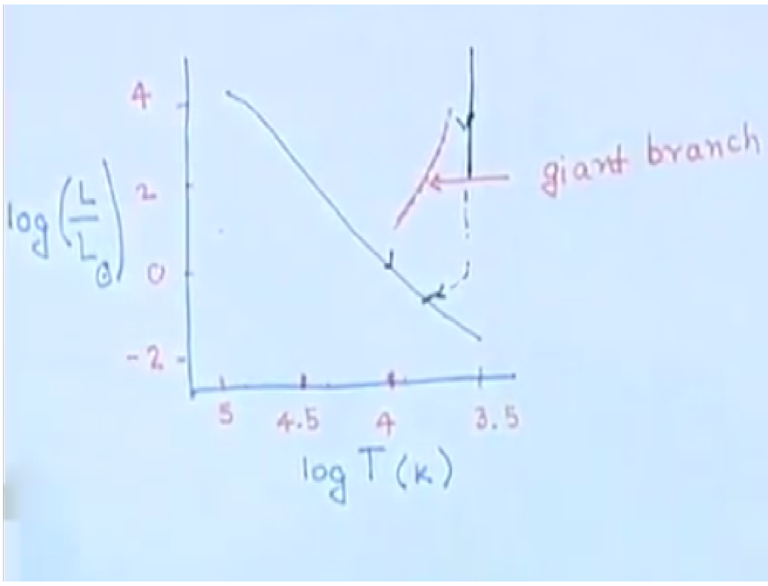

So this now lies on a part of the HR diagram that looks like this this. This is a red giant okay and this, so the star leaves the main sequence and becomes a red giant. The inner part of the star has collapsed, the outer part as its part has expanded and it has cooled but it has expanded so much that its luminosity has gone up okay. so this is what is called the giant, the red giant branch, hydrogen outside this is the giant branch, not just the shell the rest of the star.

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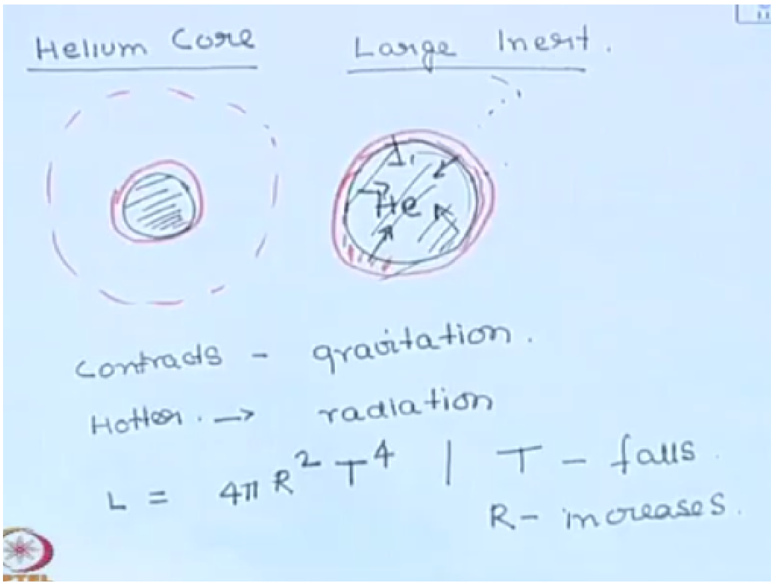

The hydrogen shell is what is burning over here but this whole thing is embedded in the rest of the star okay, that is what expands. This part just contract with collapse, no it does it is a part of the initial cloud this is, I am just drawing the core okay. This is a part of the whole star the star is some bigger okay. So we remember that in the star in the main sequence a hydrogen burning only occurs at the center at the core.

So it is in the core only that the hydrogen gets converted into helium okay. Energy is generated only in the center of the star not through the entire star okay. So the core gets converted to helium at the edge of this helium core you have hydrogen and that hydrogen is sufficiently hot so in a small shell there is hydrogen burning and this thing keeps on increasing in size because the hydrogen burns and gets converted into helium.

But in addition to that it collapses gravitationally because the helium is inert. There is no more fusion going on yeah. It is increasing in size yeah. No, the helium core is still increasing in size, the mass of the helium is still increasing but the radius is contracting. Well it could have been but it is the mass that is increasing basically. The helium mass is increasing because the hydrogen keeps on burning at the edge, which is what I have tried to show over here.

Yeah but the helium mass keeps on increasing, hydrogen burning still continues in the shell and increases faster because the hydrogen burn this when it contracts physically, see one is the mass, the mass in the helium keeps on increasing. The hydrogen and the shell keeps on burning. So the whole thing if it contracts the burning occurs faster, the temperature goes up the burning occurs faster. So the conversion to helium occurs faster because of the contraction okay.

That keeps on going on but the outer part of the star because of the increased production in energy that expands the outer part of the star that expands and it becomes a giant. So the this part the mass is possibly still increasing, the mass is increasing. Oh there will be some stage over there I do not know the exact figure okay. That will depend on the mass of the star etc okay. So it becomes a red giant. Now the core keeps on contracting and as the core contracts its temperature.

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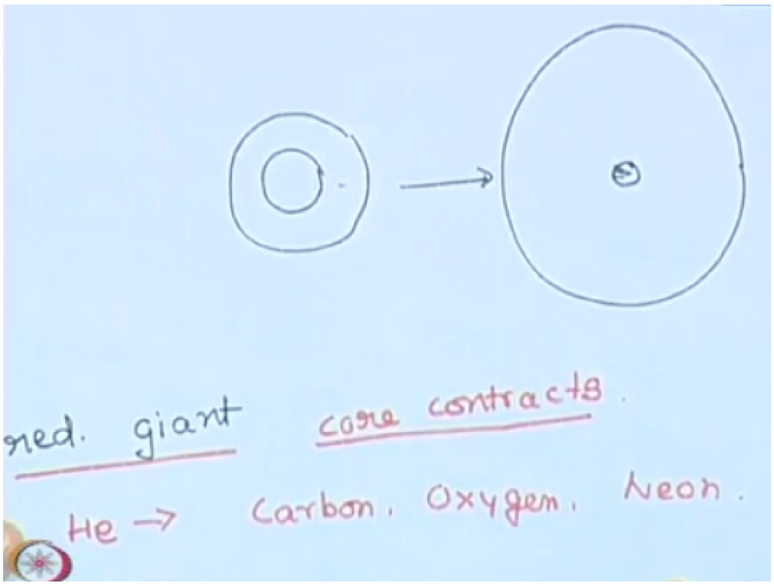

So inside the red giant the core contracts and as the core contracts, the helium core contracts as it contracts the temperature and density go up and finally in the temperature and density are adequately high that helium again nuclear burning starts. Helium now gets converted to carbon and oxygen and also Neon okay. So nuclear it contracts the core keeps on contracting and it gets hot and dense enough so that nuclear fusion starts again. Now burns helium to carbon oxygen and some amount of Neon.

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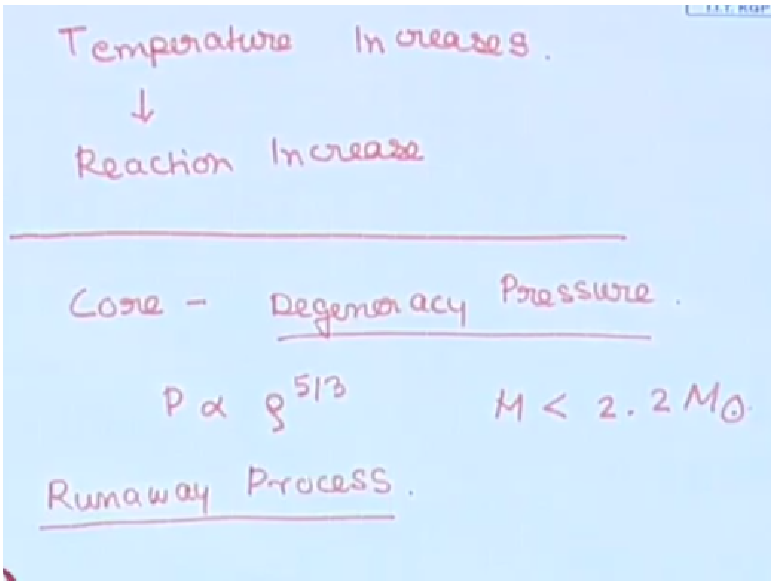

Now remember you would expect that once the energy starts getting produced in the center, the temperature will increase. If the temperature increases, the reaction rate will increase. If the reaction rate increases more energy will be produced. If more energy is produced in a star the star will expand. If the star expands then the temperature will go down right and there is a negative feedback in stars, which maintains it in equilibrium, we have discussed this, which prevents this reaction to become a kind of runaway process and cause an explosion.

But there you would expect the same thing to happen for the core also that which is contracting if it contracts then the temperature goes up, the reaction goes up. If the reaction goes up it will again generate more energy, which will cause it to expand there will be an equilibrium position. This you expect it to happen for the core also but what happens is that the equation of state of the core is different.

The core is supported by degeneracy pressure, by electron degeneracy pressure. What is degeneracy pressure, so if the energy levels, if you have fermions you cannot put all the fermions in the same energy level. You have to fill up to a certain level okay. And if you the pressure that arises because you have to stack the subsequent particles at higher and higher energy levels, there will be a minimum energy and minimum pressure that will be there even at low temperatures okay.

So this is the pressure that supports the core in the helium core. This pressure would be there even at 0 Kelvin because just because the system is made up of fermions you have electrons whose pressure supports it okay. So here the pressure is not dependent on the temperature it just depends on the density and it scales as the density to the power of 5/3 okay. So this is the pressure that arises just from the density.

So if you increase the density the subsequent electrons that you add will have to go to higher energy levels and these will hire energy electrons will contribute more to the pressure okay. So this is what is known as degeneracy pressure. So here the pressure is independent of density. So for masses of star, which are < 2.2 solar masses, the core is supported by degeneracy pressure.

If the core is supported by degeneracy pressure then if the star contracts and the temperature and the reaction rate goes up. The pressure will not change because of the increase in the energy production, the energy production increased energy production will cause the temperature to go up.

This will not affect the pressure and this negative feedback mechanism does not work over here. So here it will keep on contracting. So you have what is called runaway process. So the helium reaction keeps on increasing dramatically and you end up with what is called a helium flash.

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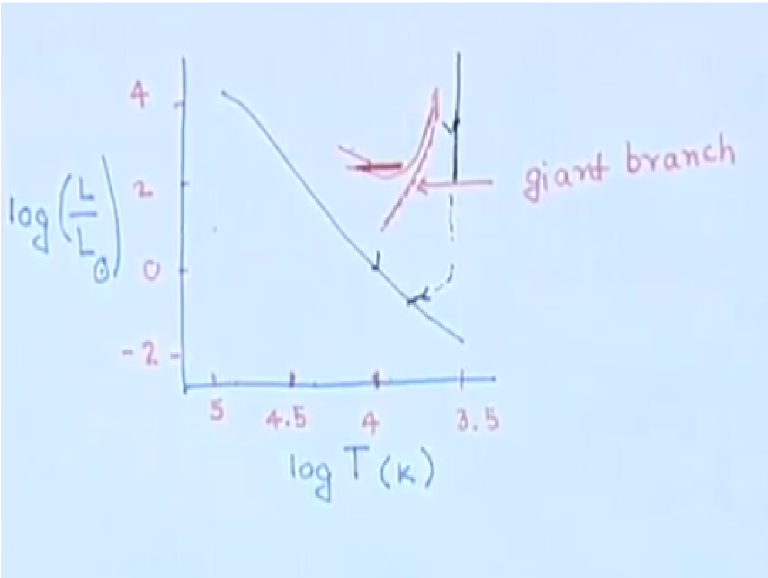

The helium process burning becomes a runaway process you end up with what is called a helium flash over here. The helium burning becomes a runaway process okay. After this the star goes into another state, which is called the horizontal branch. The horizontal branch is a state, which is analogous to the main sequence except that you now have helium burning at the center.

So it goes into something called the horizontal branch like this okay. It is analogous to the main sequence except that you now have, I am just drawing what will happen to the sun other stars will have similar evolutionary tracks okay. So you reach a state you go into an equilibrium state where you have helium, it is an equilibrium state just like you had a hydrogen burning equilibrium state. Here also you have an equilibrium state where and the it is called the horizontal branch.

So masses more than this you do not have the helium flash, mass is less than this you have an helium flash. The reaction for mass is less than this becomes runaway and then it goes into an equilibrium state for mass is more than this, you do not have that runaway state, it straight away goes into an equilibrium state.

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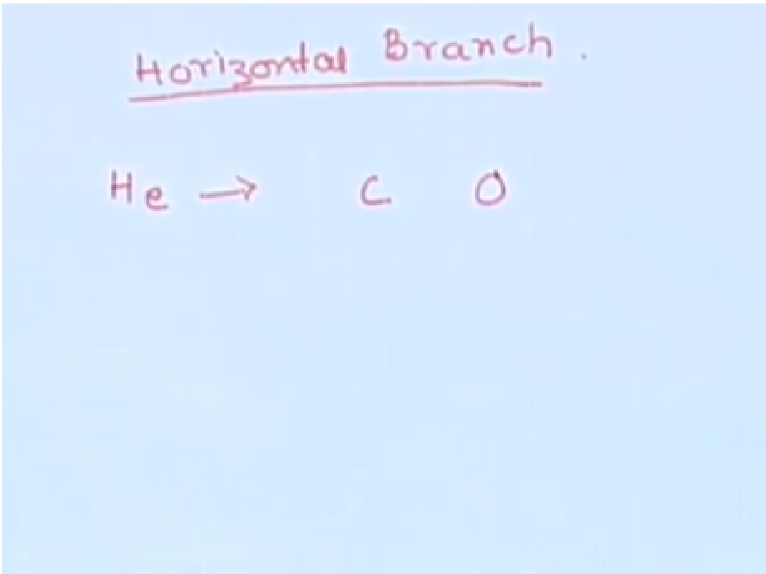

And you go it goes the star goes into what is called a horizontal branch okay. So in this horizontal branch what happens, in this part of the stellar evolution what happens is that helium gets burnt as I have mentioned earlier. Helium gets burnt into carbon mainly carbon and oxygen okay.

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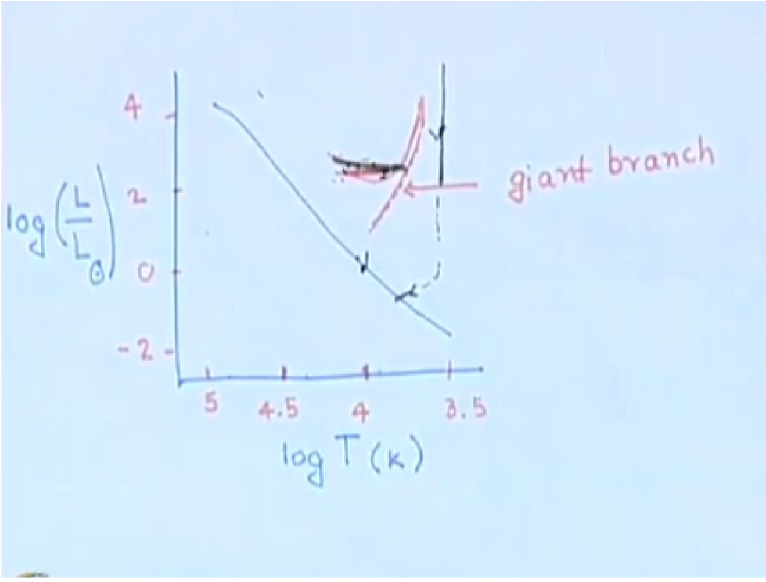

So here you again you have a stable situation over here. So it is called the horizontal branch something like this and there is a spread. So if I start with the solar mass there is a spread over here, it will not be exactly, if I take 2 stars of the same mass and start from here it will not be exactly the same.

They will not lie at exactly the same point in the horizontal branch. This is because in this giant phase, the stars lose mass as winds, stellar winds okay. Mass is ejected and there will be a spread in values. So if you look at the whole collection of stars there will be a big horizontal branch possibly over here okay.

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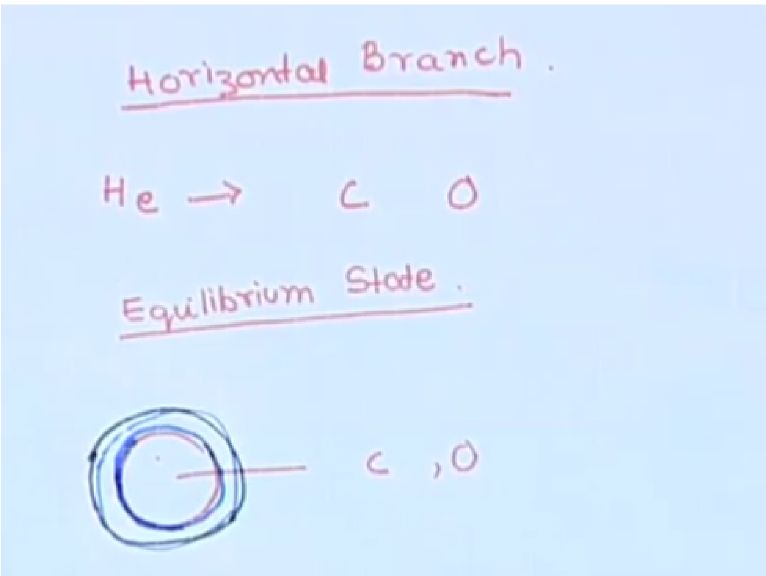

It is another, it is an equilibrium state the horizontal branch is an equilibrium state just like the main sequence where the star is supported by helium burning, which in the main sequence was supported by hydrogen burning. You now have a star supported by helium burning okay. So, now you have this helium burning star in this horizontal branch. And at the, when all the helium is burnt out it remains there for some time.

And then when all the helium is burnt out what happens is that you have a core, which again is inert and is made up of carbon and oxygen. Outside this code you have a shell where helium burning is still going on and beyond this you have a shell of helium and beyond that you have a shell where hydrogen burning is still going on okay. This is the structure of the core of the star and outside that you possibly still have hydrogen left. So this is what happens at the end of the horizontal branch.

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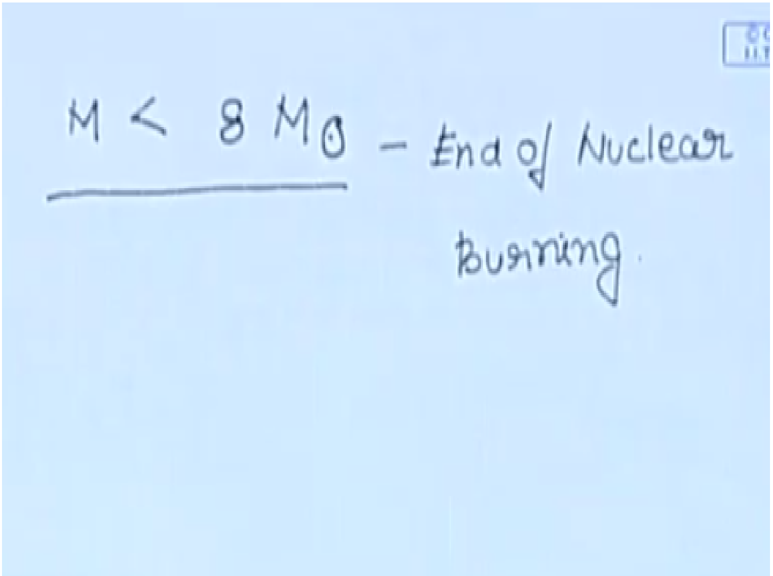

Now for stars, which are < 8 solar masses, if your star is < 8 solar masses, the sun for example, this is the end of nuclear burning no more nuclear burning proceeds beyond this. So for stars less than this, this is the end of nuclear burning.

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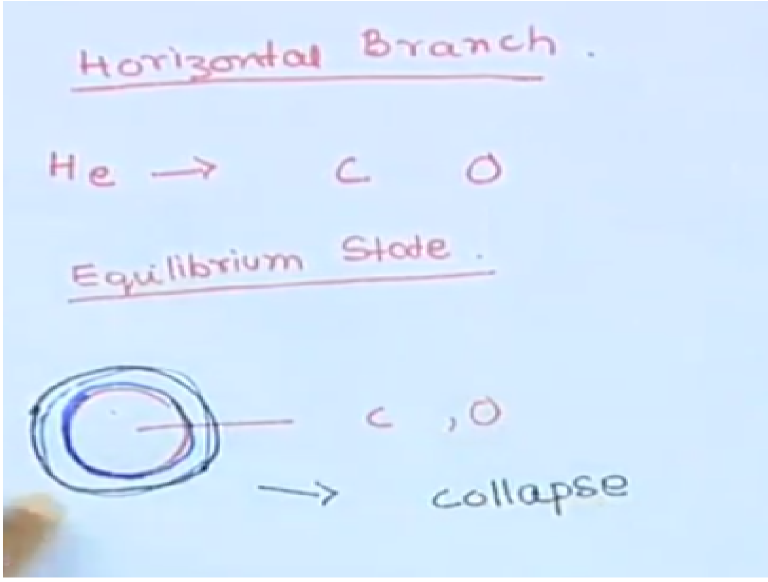

And what happens over here is that this core will now collapse. It will due to gravity and again as it collapses due to gravity, it will get heated up by straightforward virial theorem and it will emit more and more energy and this energy, which is, the increased source of energy will cause the outer parts of star to become bigger.

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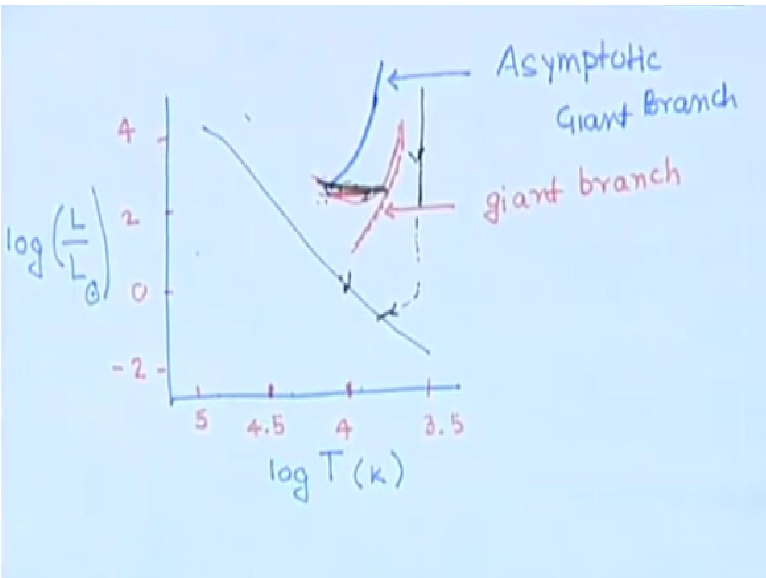

And you will go into a second giant phase called the so there will be a second giant phase called the asymptotic giant branch or the second giant asymptotic giant branch.

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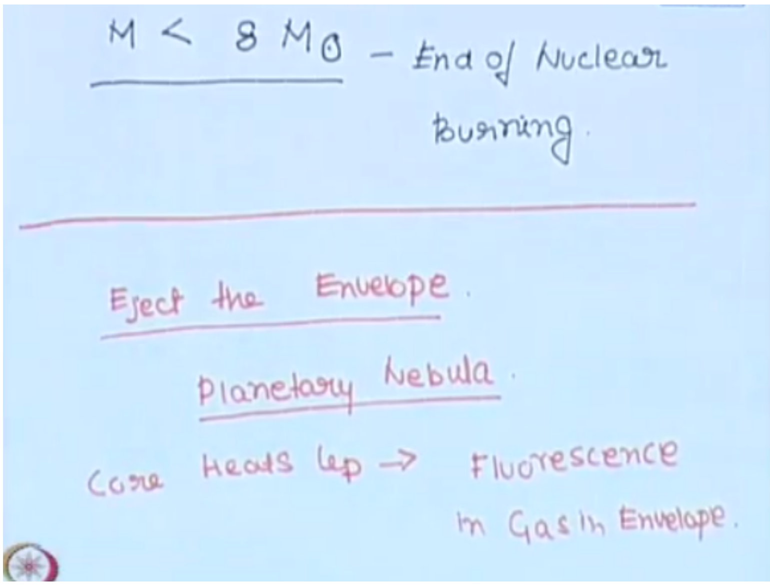

And then the energy from the interior on the core is adequate to eject the envelope. So the core keeps on collapses becomes smaller and smaller and it ejects the envelope forming what is called a planetary nebula, it is a very beautiful objects seen on the sky. The interior the core heats up tremendously, core gets heated tremendously and the radiation the photons from the core fall on the envelope and cause fluorescence. They cause fluorescence in the gas in the envelope.

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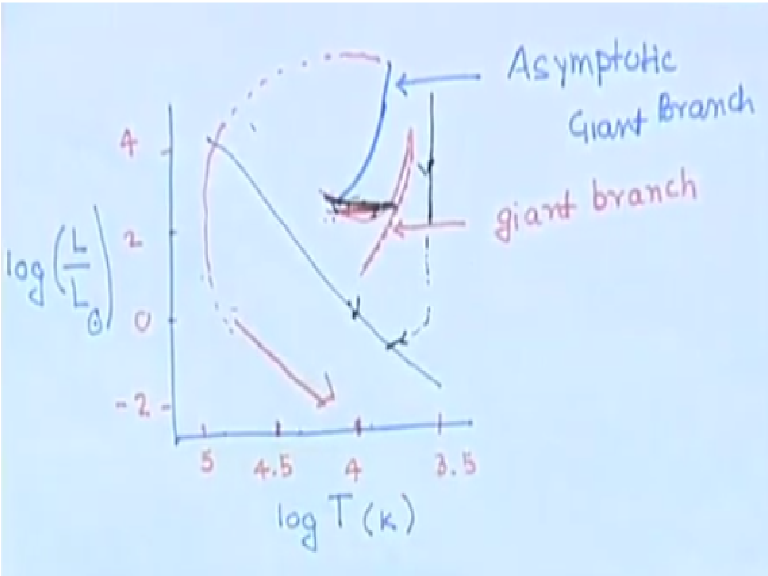

So the track in the HR diagram looks something like this. This will go quite fast so okay and then it will go into a state over here slow evolution, which is the white dwarf, the core so what you have left after the envelope is blown out is a core. The core is a white dwarf.

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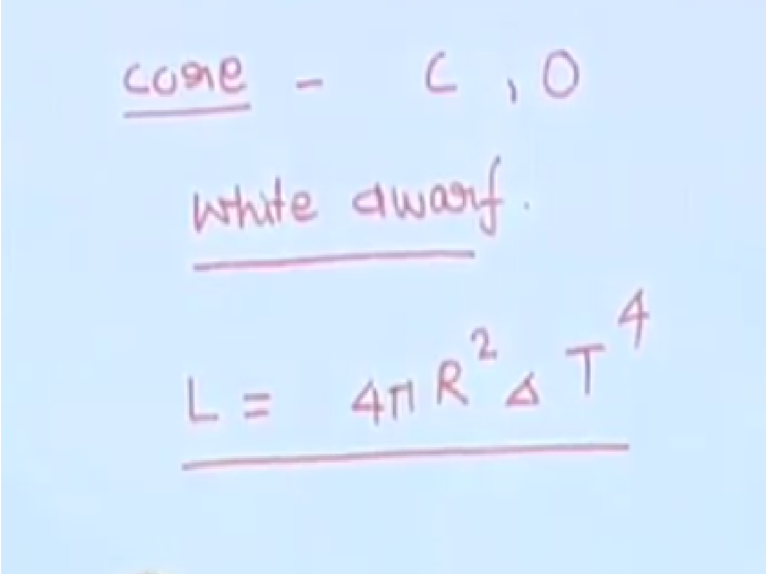

The core remains, it is essentially made up of carbon and oxygen. This is a white dwarf, it is extremely hot because of the gravitational collapse and its track is basically determined it loses energy L is = 4 Pi R square sigma T to the power 4. So it loses energy and due to the radiation from the surface given by this, it is extremely hot but it is very compact and as a consequence of the loss of energy it moves along a track like this, these are the white dwarfs.

So you will see the white dwarfs in this part of the HR diagram. They are very hot stars but they are extremely low luminosity and these are the cores, which have been left behind after stars like the sun or < 8 solar mass have exhausted all their fuel gone through all these phases and then have become planetary nebula and finally they end up as white dwarfs.

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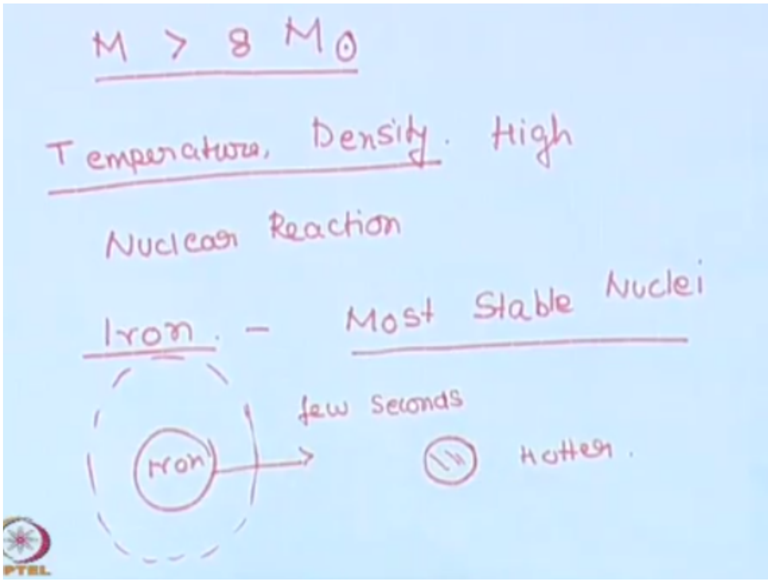

Now what happens to stars, which are more massive than eight solar masses. Now in these stars you let me go back and do the picture what happens to these stars. In these stars you have a core of carbon and oxygen. Now these stars when they collapse when the core collapses, when the core is contracting again the temperature and the density are adequately high.

So you can again start nuclear fusion. In these smaller stars you do not, the temperature, the core of the star once you reach carbon and oxygen when it collapses the density and the temperature do not reach values adequately high for nuclear fusion to occur further. Here this is not true, the temperature and density is adequately high for further nuclear fusion to occur so more nuclear reactions occur.

So you have nuclear reactions going on forming heavier and heavier elements. Finally you reach iron. Iron is the most stable nuclei. Iron nuclei are the most stable, so the binding energy per nucleon is maximum in iron. These are the most stable nuclei and in thermal equilibrium, you cannot form nuke elements, which are heavier than iron. The whole synthesis of elements stops at iron.

So you can form elements, which are less heavy than iron but finally you reach iron and you cannot form anything heavier than that okay. So you end up with iron. So at the end of nuclear fusion you have a core, which is made up of iron. You have burned everything and finally you end up with an iron core and there will be an envelope of other elements in the region where these iron, the reaction to iron could not have formed.

This is the most stable nucleus. So it is a big, all the elements that we see around us, every element here present on earth present anywhere heavier than hydrogen helium and maybe some small amounts of lithium etc they were all produced in stars by these nuclear fusion processes that we discussed okay. But you can only produce up to iron by these processes.

So it was a big problem, how do you produce elements, which are beyond iron for example lead and many other uranium all these very heavier atoms nuclei okay. You cannot produce them in any equilibrium, thermal equilibrium process. That in thermal equilibrium you will go to the most stable state, which is iron. So once you form the iron core there you, nuclear reaction you cannot have fusion any more, nuclear fusion will not get you any further.

You cannot get any more stable nuclei. Now once you form this iron core, this core now collapses, gravity due to gravity right, so it collapses it will become smaller and smaller and in the process it will get hotter also. Now when this collapse occurs this entire collapse occurs in a few seconds. So this whole thing occurs in a few seconds beyond iron, once you reach iron, the whole thing has burned out, burnt and reached iron.

There is no more nuclear fusion going on at the center then the whole thing collapse collapses due to gravity. There is no energy source over here it collapses gravitationally and it gets heated up. The whole thing occurs in a few seconds. It collapses rapidly okay and when it collapses rapidly, there is enormous heat generated.

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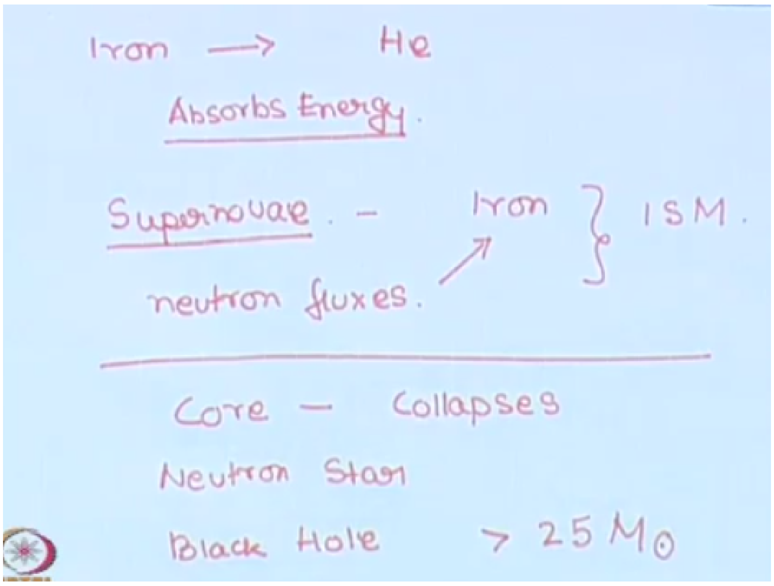

And here what happens is that the iron again goes up breaks up into helium and in the process it absorbs this is an endothermic reaction. Iron is the most stable nuclei, I have already told you that. So in the process it absorbs energy despite all of this, the inner part gets tremendously heated and it generates, it radiates and there is also neutrinos. There is a so in this collapse there is the tremendous nuclear reaction where it gets converted into helium and there are neutrinos okay.

So this is what is, which are emitted there is tremendous amount of radiation also emitted and you have a supernovae, the envelope is blown out. The interior collapses and the envelope energy is generated, which causes the envelope to blow out. Taking away large parts of the elements including the iron and all else away out of it okay. There are large neutron fluxes during this and the neutron impinges on the iron to produce the heavier elements.

And all of these are ejected into the interstellar medium, which then forms the material on, which the next generation of star formation occurs. The core, the core of this whole thing collapses to form either a neutron star depending on the mass or a black hole and masses more than 25 solar masses, it is believed and go straight away and form a black hole.

So in a neutron star what happens is that all of the iron gets converted into helium and finally everything gets converted into neutrons okay. A black hole we shall something if we get time we shall discuss it but main point is that the entire thing collapses to get smaller and smaller and very high dense object.

Before we finish, I should point out and you have a supernovae, the outer envelope gets blown out. Its luminosity goes up tremendously because of the increase in the radius and you will see a very bright object in the sky and you have what is called a supernovae. Now the entire thing occurs in a few seconds and a full computational simulation. So you want to calculate everything on a computer you put all the equations that we have been discussing in a computer and you want to solve it.

The computational power to do this does not exist as yet okay. So there are simplifications, which people have done and these are the some of the, I have told you about some of the results, which people have obtained using these okay. Because things are changing tremendously fast over a few seconds you have to solve the entire set of fluid equations the transfer of radiation there are enormous neutrino flux also there is an enormous neutrino flux etc okay.

So let me just summarise briefly in today's class I have tried to give you a picture of what, how these stars evolve and stars they form from gas clouds, they evolve along the Hayashi track. They reach the main sequence and after the main sequence they go into the giant branch then they go into the horizontal branch.

Then you have a second asymptotic giant branch and after that the evolution is highly dependent on the mass of the star below eight solar masses you have the white dwarfs being formed above eight solar masses, the star explodes in a, it burns, the core burns you get elements beyond carbon and oxygen and finally it explodes in a supernovae and depending on the mass again you either end up with a neutron star or a black hole.