ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

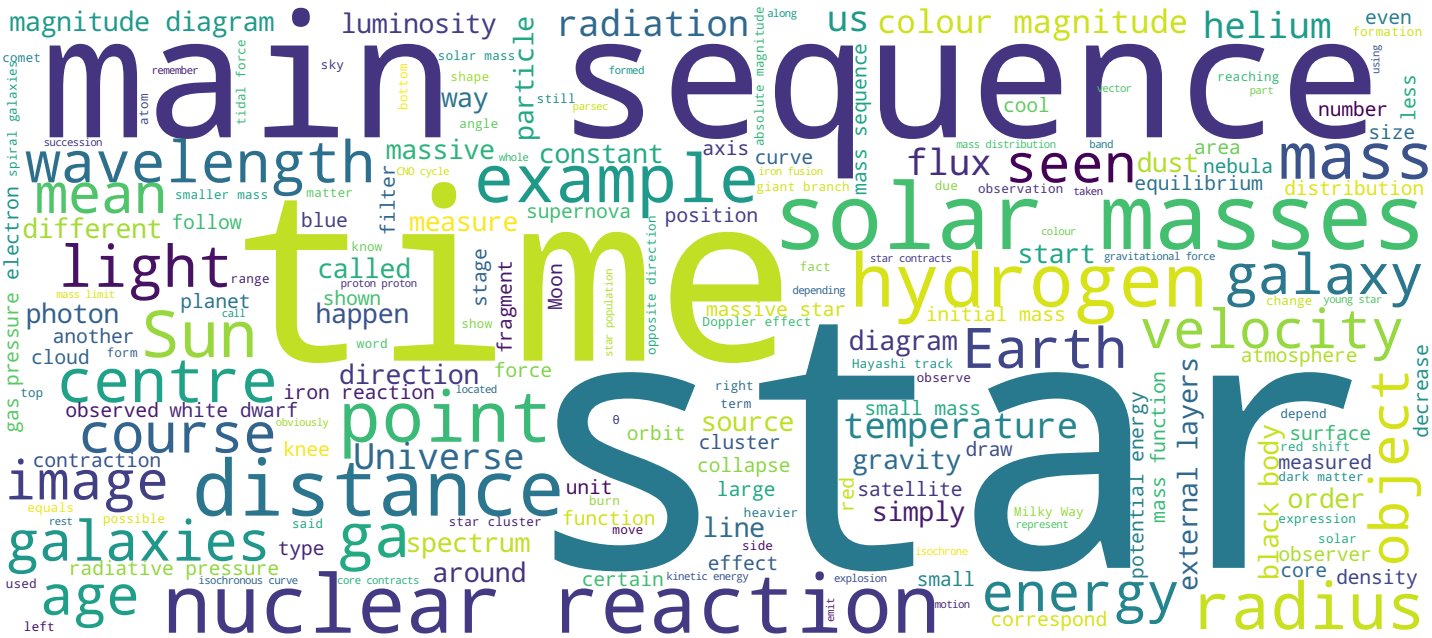
Different stages of stellar evolution

Images: NASA, ESA, ESO

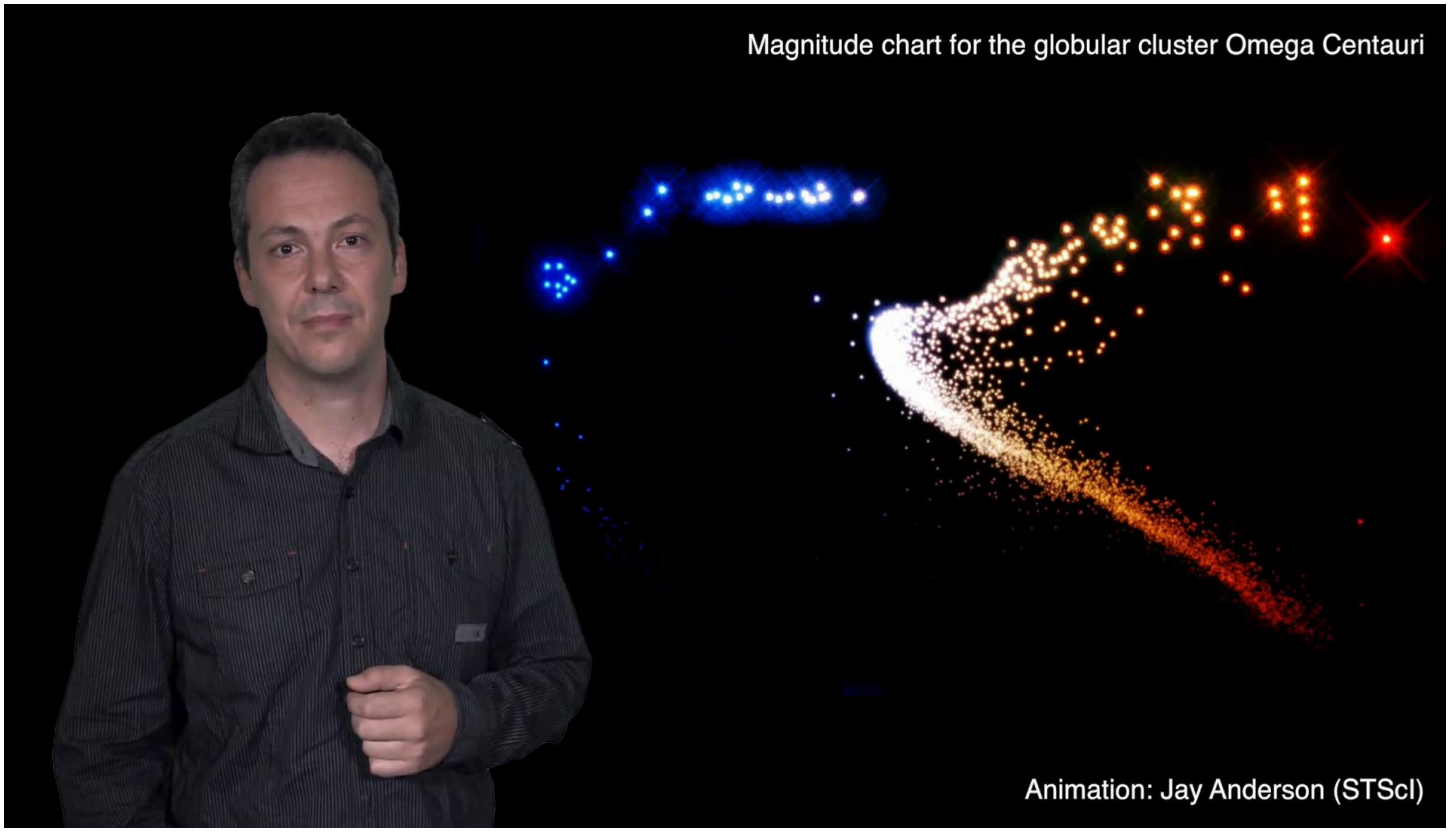
Stellar Evolution: How Stars Live and Die

Introduction to Astrophysics; Chapter 5.3

Frédéric Courbin



EPFL



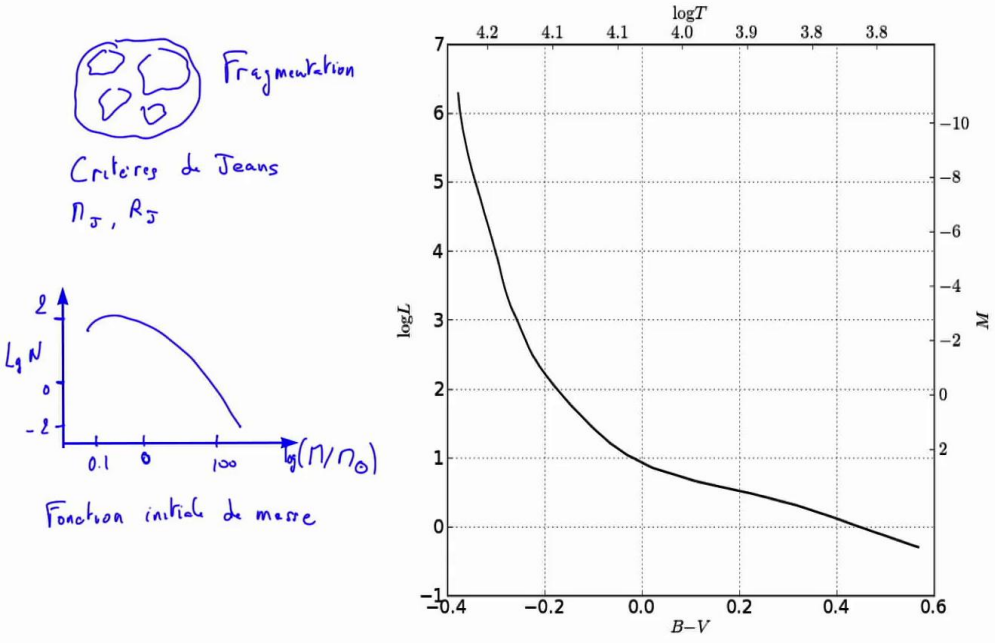
We have introduced the HR diagram, the colour-magnitude diagram and we have seen where each type of star is located in it depending on its mass, luminosity, colour and size. In what follow we will see in a very simplified manner how stars evolve in the diagram during their life, how they are born, how they burn their hydrogen into helium and how they eventually die, depending on their luminosity and their initial mass.

Notes

Summary

0m 05s

Hayashi Sequence



Introduction to Astrophysics

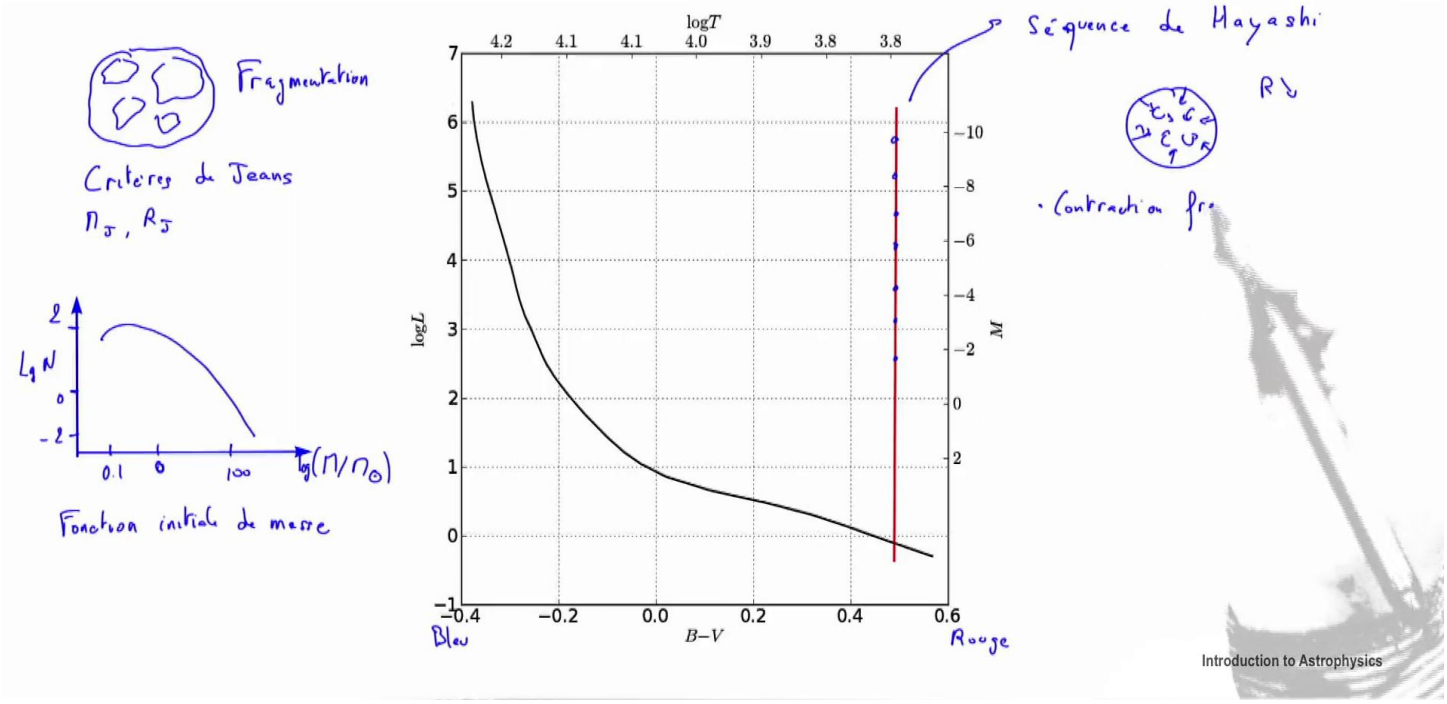
How do stars form ? By fragmentation of a cloud of dust and gas. We have here a cloud which fragments into several pieces the size and mass of which obey some distribution. The cloud fragments and the resulting pieces have to meet Jeans' criteria : you remember that, in the previous chapter, we had introduced Jeans' mass and Jeans' radius. If the fragments are large or massive enough, they may collapse and contract. The initial clouds have some mass distribution that we can represent on a log/log scale here. The curve has usually this shape and is called the initial mass function. This initial mass function gives the distribution of nebula fragments in units of solar masses. We have on this axis the decimal logarithm of the number of fragments. This point is more or less two, here is the 0 and here is minus 2. There are many fragments of small mass and a few fragments of large mass. We have here more or less 0.1 solar masses, here are 100 solar masses and finally here is the 0 since it is a logarithmic scale. The zero corresponds to one solar mass. Most stars weigh roughly one solar mass. This is the initial mass function, giving the mass distribution of the fragmenting clouds.

Notes

Summary

0m 33s

Hayashi Sequence



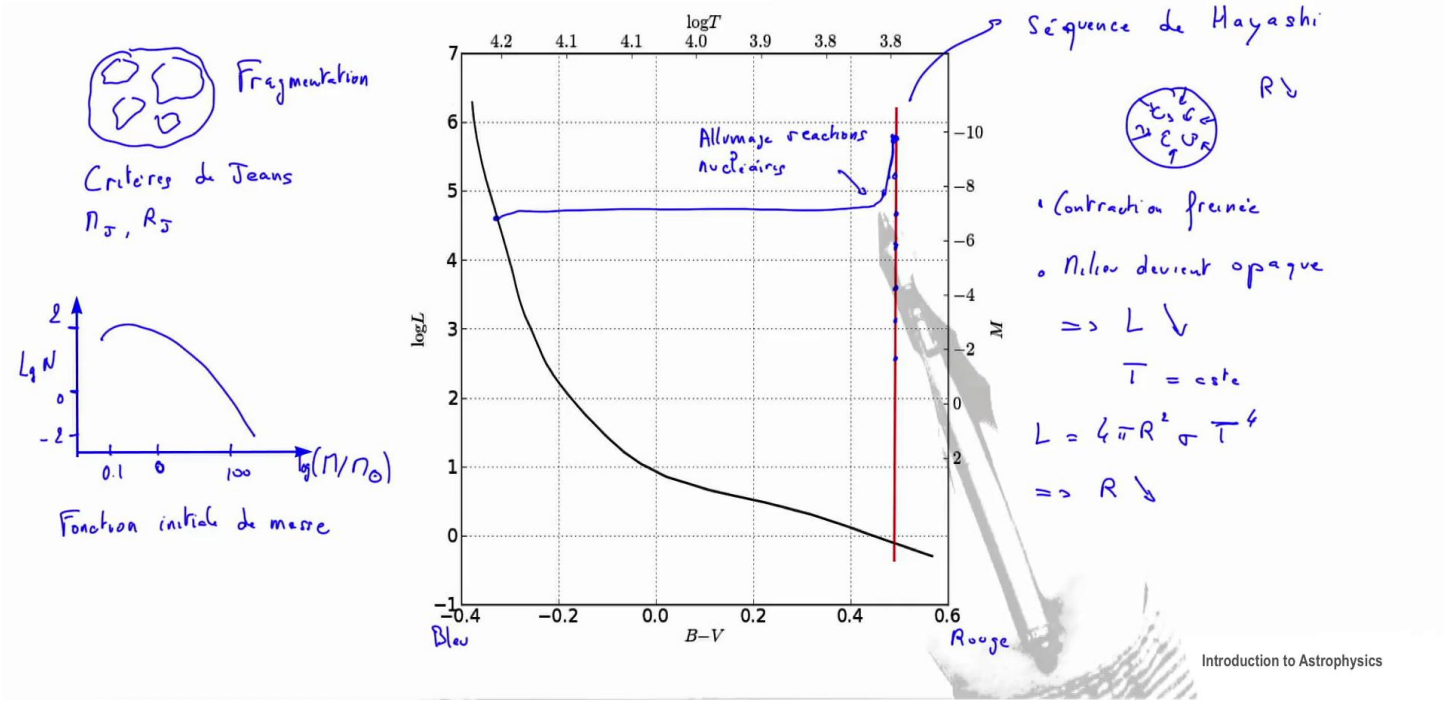
These fragmenting clouds appear in the colour-magnitude diagram along a roughly vertical sequence that I schematize here. This sequence is called the Hayashi track. This sequence is isothermal, everything is at the same temperature. We have here the log of temperature, the log of luminosity, the absolute magnitude is represented here and decreases upwards, therefore the luminosity increases upwards. Here is the colour index with rather blue stars in this area on the left and red stars over there. The nebula fragments will spread over the Hayashi track. Their mass distribution is given here and they are distributed along this line. Imagine here, on various locations, various stars with different masses which are actually protostars. At this stage, stars are convective. The motion at the centre of the star is turbulent, going in all directions. The material inside is mixed and the star contracts. At this stage there is not any nuclear reaction yet. Remember that according to the Virial theorem, if the radius decreases the temperature of the core increases and it will do so until igniting the nuclear reactions. At this point the contraction is slowed down.

Notes

Summary

2m 28s

Hayashi Sequence



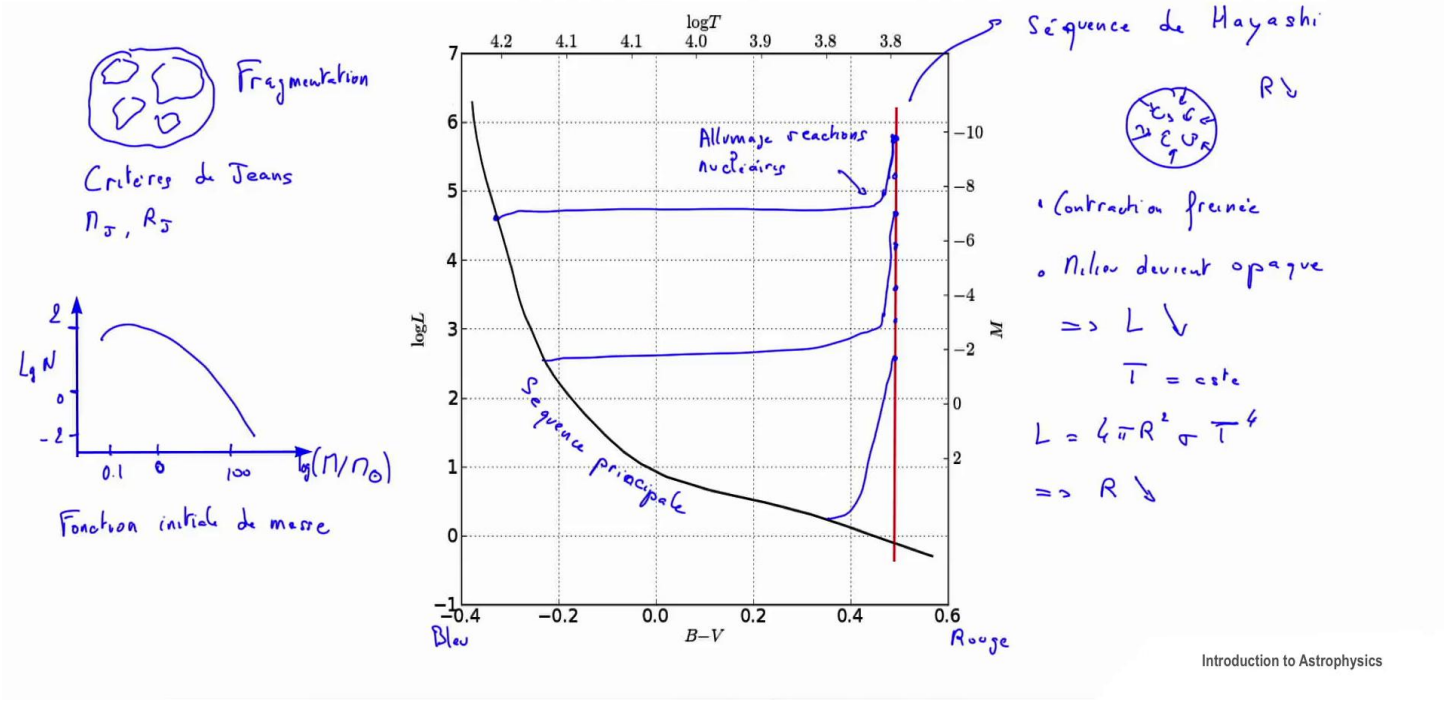
The contraction is slowed down by two phenomena : radiative pressure due to photons emitted by the contraction of the star and the internal heating of the star, and of course the gas pressure due to the turbulences. When the star contracts, it becomes more and more opaque. The medium becomes opaque which means that the luminosity decreases. The Hayashi track is an isothermal curve, which means that during the contraction T stays constant. Remember that $L = 4\pi R^2 \sigma T^4$. L decreases while T is constant and all other quantities but the radius are constants. Therefore R decreases. The star's luminosity decreasing at a constant temperature implies that the star is contracting. While the external temperature stays constant, the star is contracting but the temperature increases in the centre up to the point of starting nuclear reactions. For each star, with here a massive one as an example, the star's luminosity decreases when it contracts and the nuclear reactions start. When the nuclear reactions ignite, the star increases in temperature until reaching a position on the main sequence. So on this point we have the start of nuclear reactions.

Notes

Summary

4m 05s

Hayashi Sequence



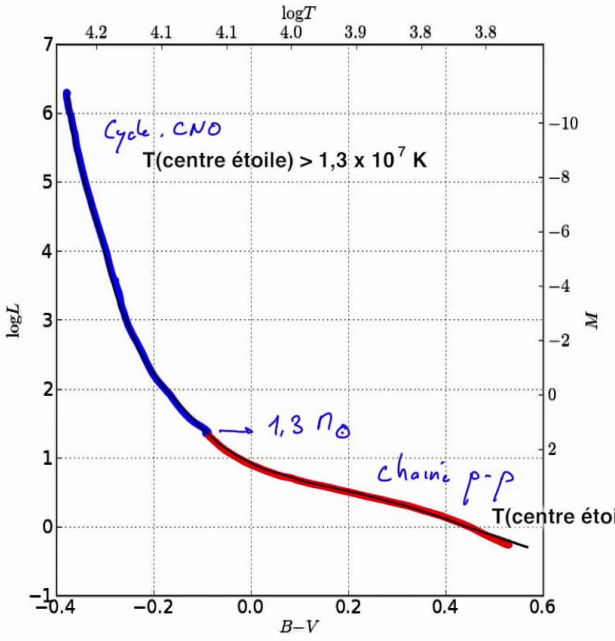
Of course at the start of nuclear reactions the temperature increases very quickly until reaching an equilibrium between the radiative pressure of the photons, the gas pressure and the gravity. The ignition of nuclear reactions is as fast as the star is massive. A star of small mass will drop slower along the Hayashi track before moving to the main sequence. Stars of even very small mass tend to migrate, to start very slowly their nuclear reactions. We see that we left from a mass sequence defined by the initial mass function and we reach another mass sequence, which is the main sequence. The heavier stars are at the top and the lighter stars at the bottom.

Notes

Summary

5m 55s

Fusion of Hydrogen into Helium



Introduction to Astrophysics

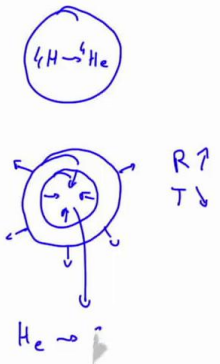
What happens once on the main sequence ? Stars burn their hydrogen. We have thus nuclear reactions of fusion of hydrogen nuclei into helium nuclei. This can happen in two different ways with a more or less complicated reaction chain. The limit between the two possible reactions is at 1.3 solar masses. Over 1.3 solar masses, stars burn their hydrogen into helium following the CNO cycle. Under 1.3 solar masses, we have the proton-proton chain. Contrarily to what the name suggests, the CNO cycle produces neither carbon, nitrogen nor oxygen. The proton-proton chain involves essentially protons. but the outcome of both reactions is the fusion of four hydrogen nuclei into one helium nucleus. The CNO cycle requires higher temperatures than the proton-proton cycle. We have therefore a limit in temperature which corresponds of course to a mass limit. What is really important to remember is that when a star is on the main sequence, it burns its hydrogen into helium. This is what stars do during the longest part of their life. On the main sequence, there is an equilibrium between gas pressure, radiative pressure and gravity. In the star, there is hydrogen burning into helium and emitting photons in all directions. Then there is the gas pressure. And finally in the opposite direction there is the star's own gravity which tends to make it collapse.

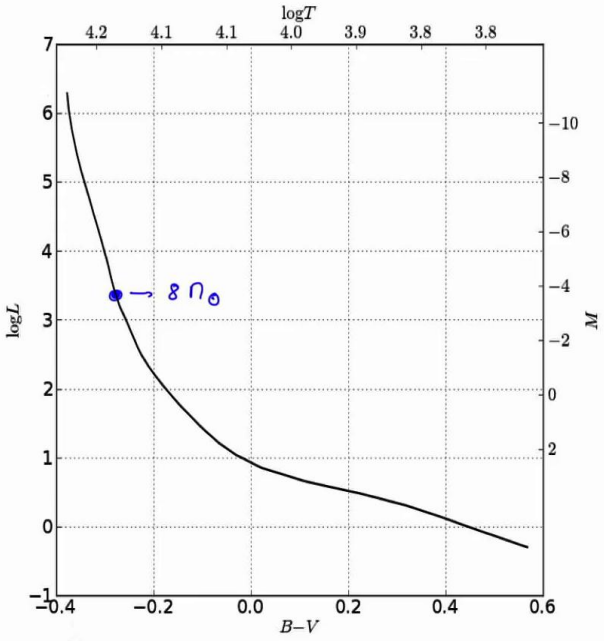
Notes

Summary

6m 47s

Evolution of Massive Stars





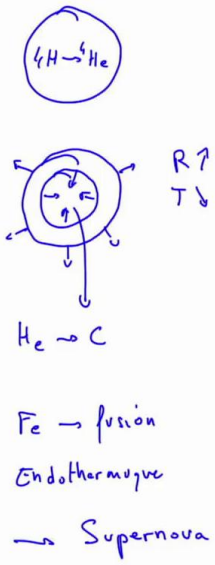
What are the phenomena occurring in stars when they are on the main sequence ? There are nuclear fusion reactions along the whole main sequence with different kinds of reactions depending on the mass being above or below 1.3 solar masses. Another important limit is at 8 solar masses. We will see that this limit determines how the stars die. Let us consider a star on the main sequence and heavier than 8 solar masses. The star is burning its hydrogen into helium. I draw here this star. It burns hydrogen into helium and is in a state of equilibrium between pressure and gravity. Once the fusion of hydrogen stops, both gas and radiative pressure decrease and gravity wins. Two things happen at this stage. First the star cools down and second the external layers are ejected. The core will in turn contract and the external layers expand Now two things happen. First, the radius of the star increases. At the same time, the external layers cool down, T decreases and the star becomes redder. Meanwhile the core warms up. Heating continues until igniting the next nuclear reactions. The core of the star begins to fuse helium into carbon.

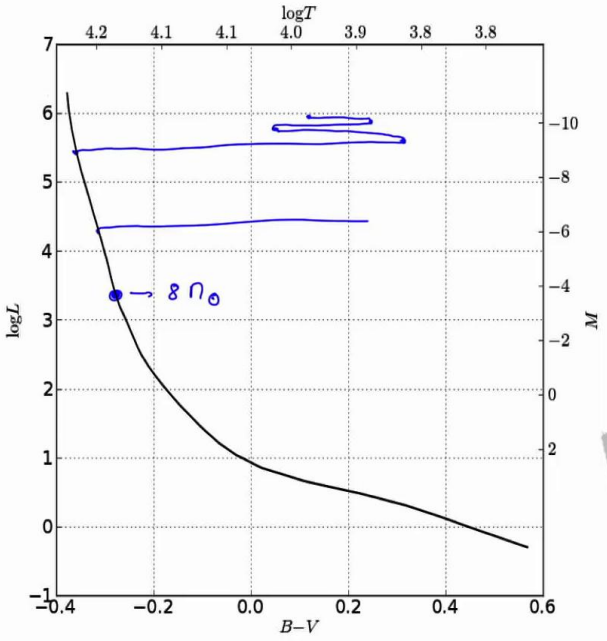
Notes

Summary

9m 05s

Evolution of Massive Stars





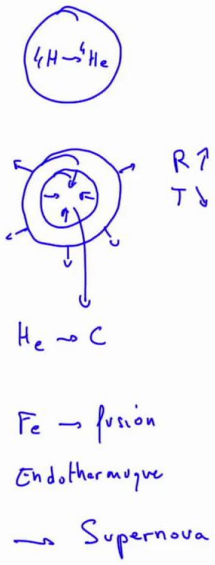
While the star is still on the main sequence, the hydrogen reactions stop, the stellar radius increases and the surface temperature decreases. This means that a star tends to move to the right of the diagram to the domains of lower temperatures and redder surface colours. Another star here will follow the same pattern. For a very massive star, the core contracts and starts the reaction fusing helium into carbon. This happens roughly in this area. At this stage the star obviously warms up and we have therefore a "knee" in direction of hot temperatures. There is a succession of nuclear reactions. We have the burning of helium into carbon. When this reaction stops, the star moves again to the right of the diagram and the next reaction starts, etc. Each reaction is shorter in time than the previous one. After a while we reach the reaction of iron fusion. The iron fusion reaction is endothermic rather than exothermic. When the iron reaction starts in the core of the star, not only there is no emitted photon and no pressure directed outward but there is also energy absorption. The star will therefore quickly collapse and eventually releases a supernova.

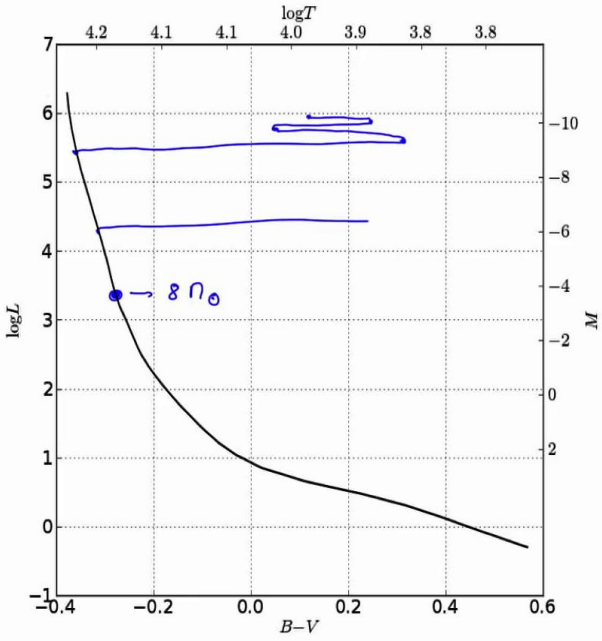
Notes

Summary

10m 56s

Evolution of Massive Stars





M > 8 M⊙

- Succession de reactions nucleaires
- Contractions du coeur
- Fe endothermique

→ explosion

→ Formation d'un trou noir ou d'une étoile à neutrons

Introduction to Astrophysics

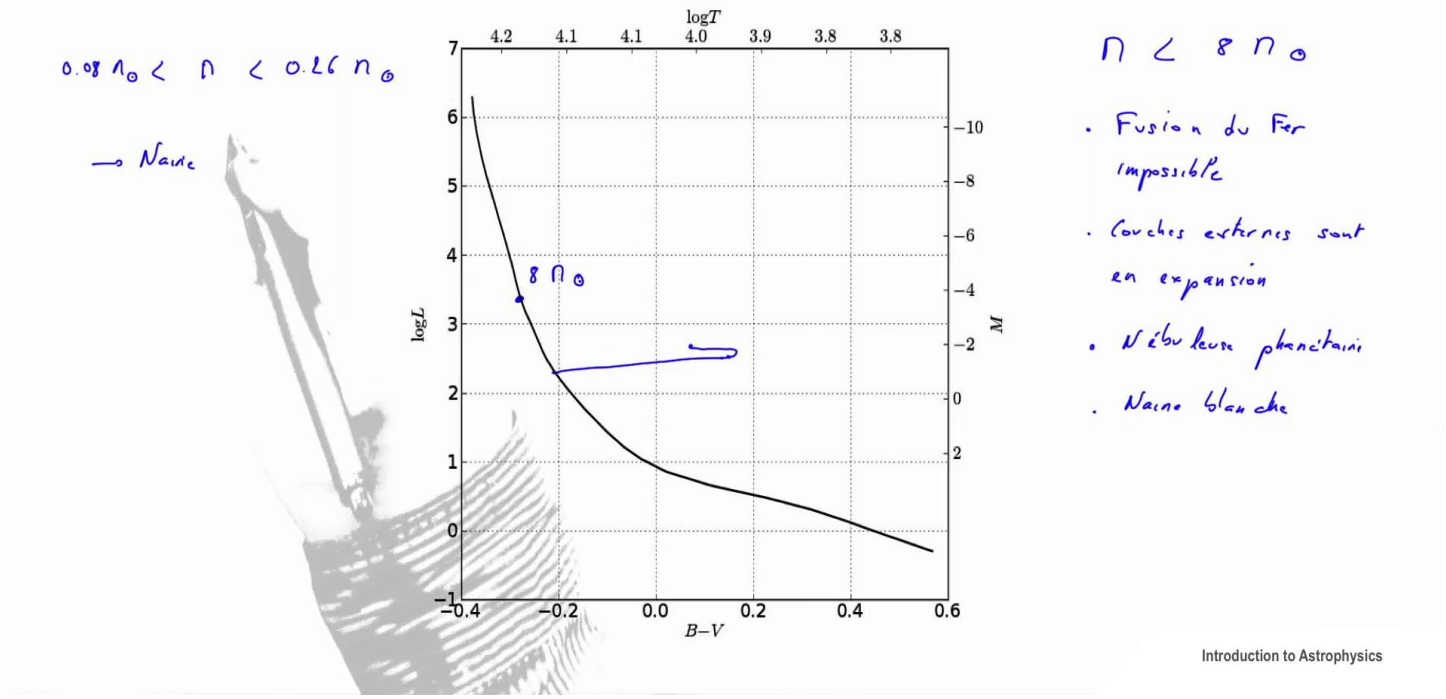
For stars heavier than 8 solar masses there is a succession of nuclear reactions. There is a succession of nuclear reactions and core contractions until reaching the endothermic iron reaction and thus the explosion of the star. Beyond 8 solar masses all stars follow such a trajectory. They become giants and zigzag. The number of zigzags, namely the number of distinct nuclear reactions depends on the mass. And we have then an explosion into a type II supernova. If the star is originally extremely massive, there may remain after the supernova explosion a neutron star or a black hole.

Notes

Summary

12m 32s

Evolution of Low-Mass Stars



What happens for stars of smaller mass ? The mass limit is 8 solar masses. What happens now for stars below 8 solar masses ? Actually it is more or less the same thing as before. Stars evolve into giant stars and cool down to a certain location on the colour-magnitude diagram. They first get redder. Then the external layers inflate and the core contracts probably up to start a new nuclear reaction but without going all the way to the iron reaction. Iron fusion is not possible because the mass of the star is too small. Other reactions than hydrogen and helium burning can then start but without going to the iron reaction. What happens is that the external layers inflate and the core contracts. The external layers are expanding. As for the core, it contracts until it cannot ignite the following nuclear reaction and the star simply dies. The external layers turn into a planetary nebula with at its centre a dead star, a white dwarf that radiates simply as it cools down. There are also stars with an even smaller mass. There are other mass limits : 0.08 solar masses and 0.26 solar masses. Those are stars that form directly into white dwarves from the protostellar cloud with a mass in this range, and do not form from the cloud left by a massive star dying into a white dwarf.

Notes

Summary

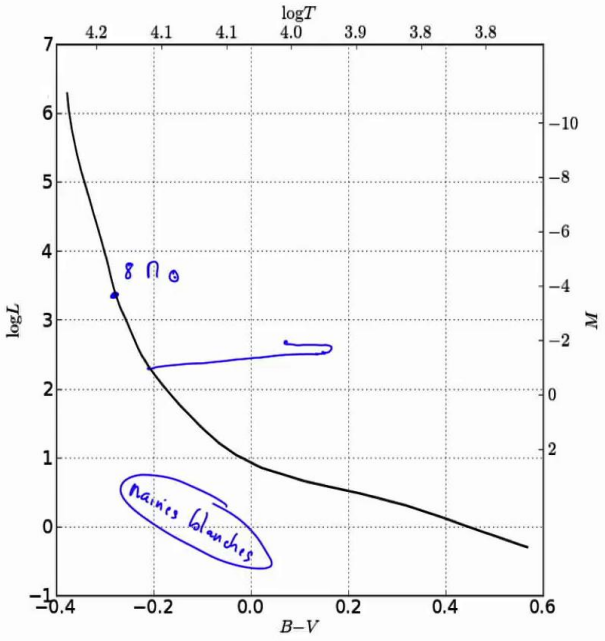
13m 34s

. $0.08\,M_\odot < M < 0.26\,M_\odot$

→ Naine Blanches

. $M < 0.08\,M_\odot$

→ Naine brunes



$M < 8\,M_\odot$

. Fusion du Fer impossible

. Couches externes sont en expansion

. Nébuleuse planétaire

. Naine blanche

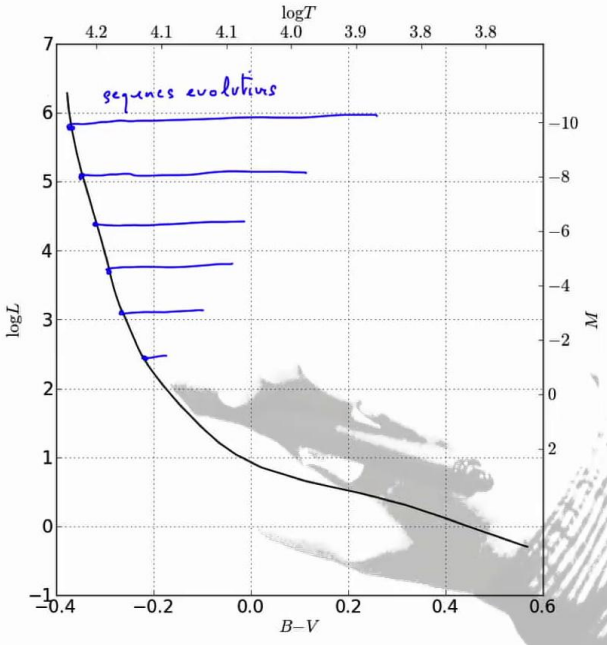
We have thus a white dwarf, which is located roughly here on the colour-magnitude diagram. If the mass is even smaller than 0.08 solar masses the mass is not large enough to start nuclear reactions and we witness the formation of a brown dwarf. Such a star shine only under the effect of its gravitational contraction which is what we saw in the slides about the Kelvin-Helmholtz time scale There is simply a conversion of potential energy into radiation as the star contracts very slowly under the effect of its own gravity. But there is not any nuclear reaction.

Notes

Summary

15m 21s

The Age of Stellar Clusters



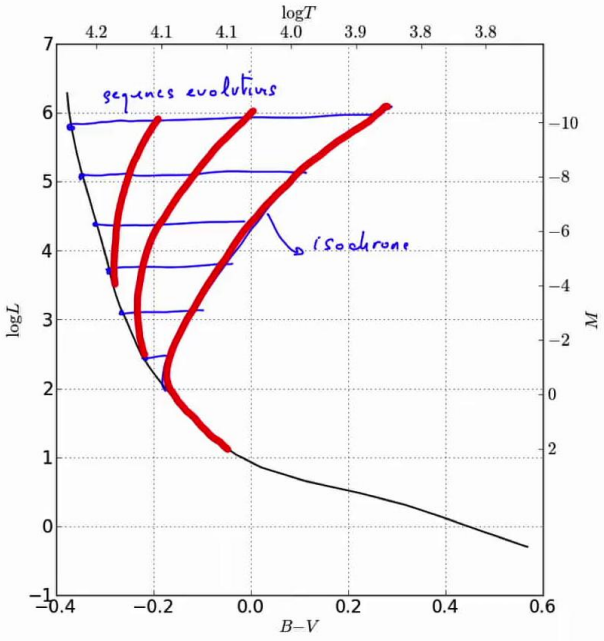
Etoiles brûlant l'hydrogène d'autant plus vite qu'elles sont massives

Let us now see how the colour-magnitude diagram can be used to date a star population. A star population is simply a bunch of stars, for example a globular cluster that we saw several times during the course, or an open cluster and these stars are all formed at the same time. Stars are distributed along a mass sequence, the main sequence. Stars on the main sequence are burning their hydrogen. Be attentive that the more massive a star is, the faster it burns its hydrogen. In other words, a star will leave the main sequence quicker all the more massive it is, the higher they are on the main sequence. We have what are called evolutionary tracks. Stars will evolve and reach different locations on the diagram, more or less like that. I draw shorter and shorter tracks simply because they cool down : a star of smaller mass ignites the nuclear reaction following the hydrogen to helium one faster than other stars. We have evolutionary tracks that look like that, I am not drawing them exactly. We have then these tracks here. The most massive stars leave the main sequence very quickly. Stars with a slightly smaller mass leave it a bit afterwards and so on and so forth.

Notes

Summary

16m 04s



Etoiles brûlant l'hydrogène d'autant plus vite qu'elles sont massives

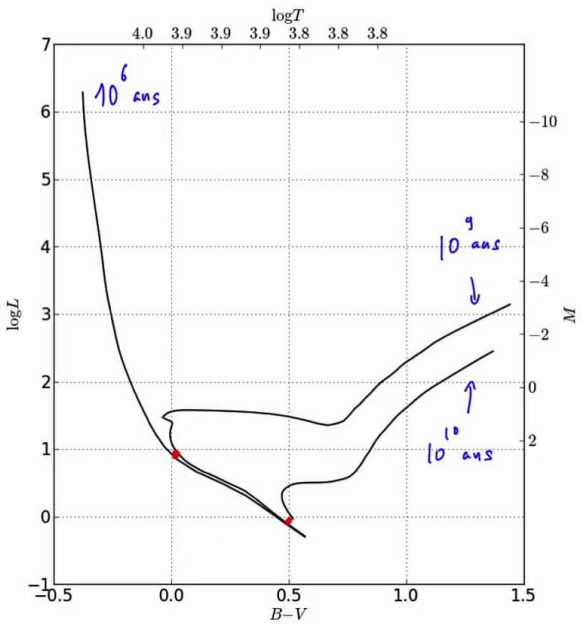
If I link all these points I have what is called an isochronous curve, which as the name suggests links stars with all the same age. I can here draw an isochronous curve like that. You see a knee on the isochrone. There are stars leaving the main sequence, having the required mass to soon leave the main sequence. I may also have another isochronous line such as this one, and so on. The higher the knee, the smaller this distance and the younger the cluster is. If it follows the main sequence the cluster has an age of 0 and stars are starting to migrate towards the giant branch, doing so as fast as they are massive. Of course, the lower the knee on the main sequence is, the older the cluster is.

Notes

Summary

17m 43s

The Age of Stellar Clusters



Introduction to Astrophysics

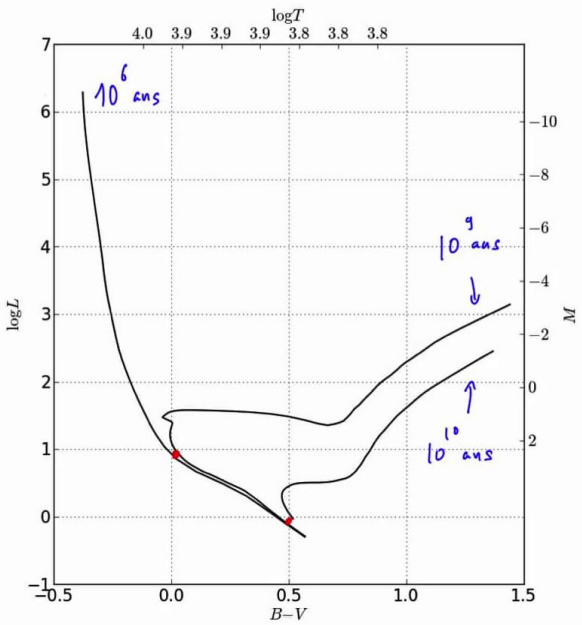
Here are a few examples of isochronous curves. This one is the isochrone we had on the previous diagram which corresponds to the main sequence of very young stars, of the order of 10^6 years old. Here is the isochrone for 10^9 years and another one for 10^10 years, namely 10 billion years, almost the age of the Universe. Notice that on a 10^9 years old isochronous line there is not any star at the top of the diagram any more because all these stars have disappeared. They had a large mass and burned all their hydrogen. They were probably more massive than 8 solar masses and have therefore all exploded. 10^9 years afterwards, there is no more star of this kind left on the colour-magnitude diagram. The remaining stars on this sequence have smaller masses. Here is the giant branch. Some stars are still on the main sequence and are still burning their hydrogen but the more massive ones have moved to the giant branch. If we wait a little more, there subsists only stars with a very small mass on the main sequence. Almost all stars have evolved toward the giant branch. This way, just by looking at the location of the knee, one can know the age of the cluster, simply because the age of the cluster is the age of the stars leaving the main sequence.

Notes

Summary

18m 50s

The Age of Stellar Clusters



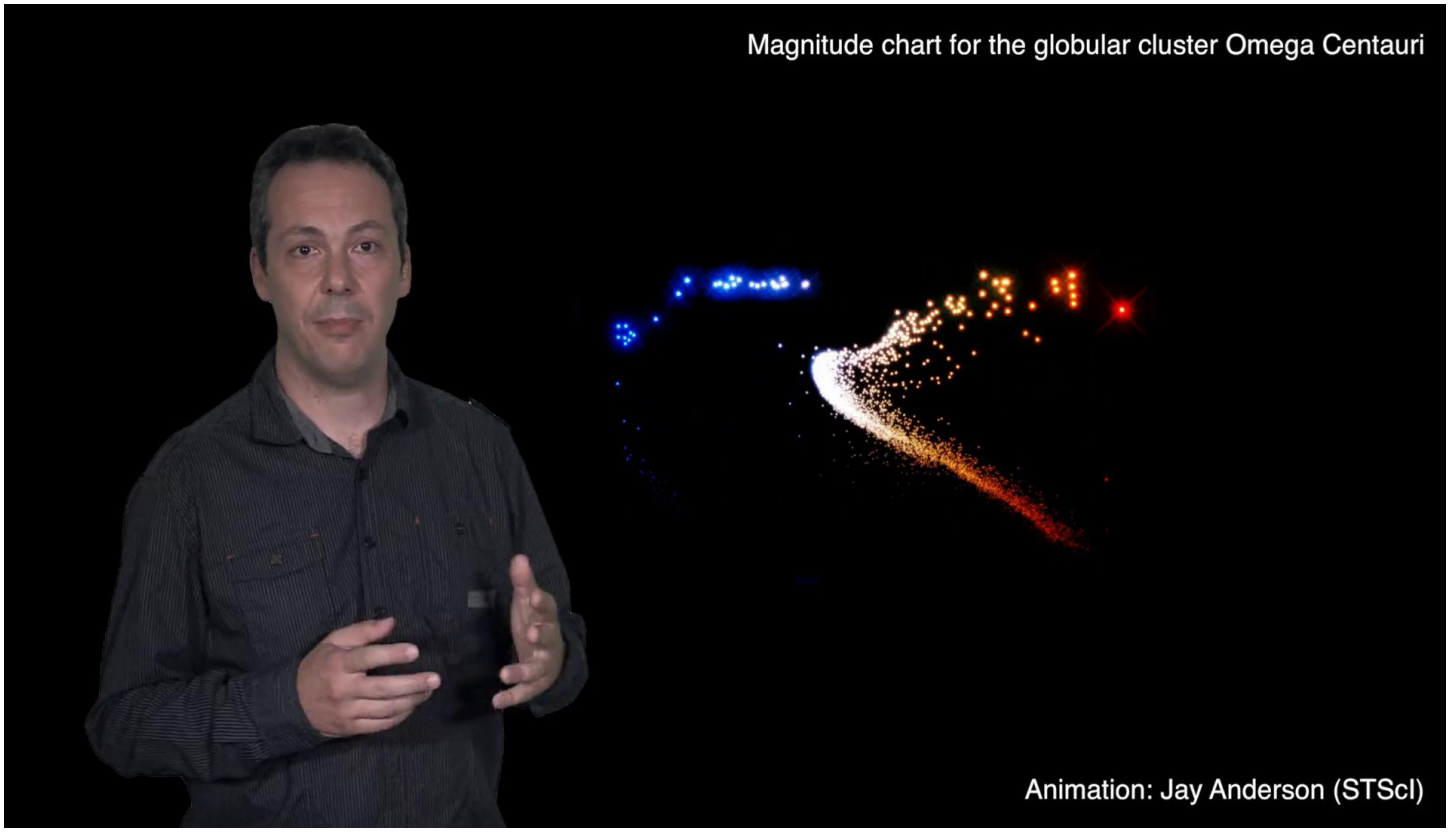
Introduction to Astrophysics

Thanks to colour-magnitude diagrams and by assuming that the sequences we observe here come from a star population of the same age, one can date the age of star clusters. Either very young star clusters, 10^6 years here or star clusters that can have ages of the order of the age of the Universe.

Notes

Summary

20m 08s

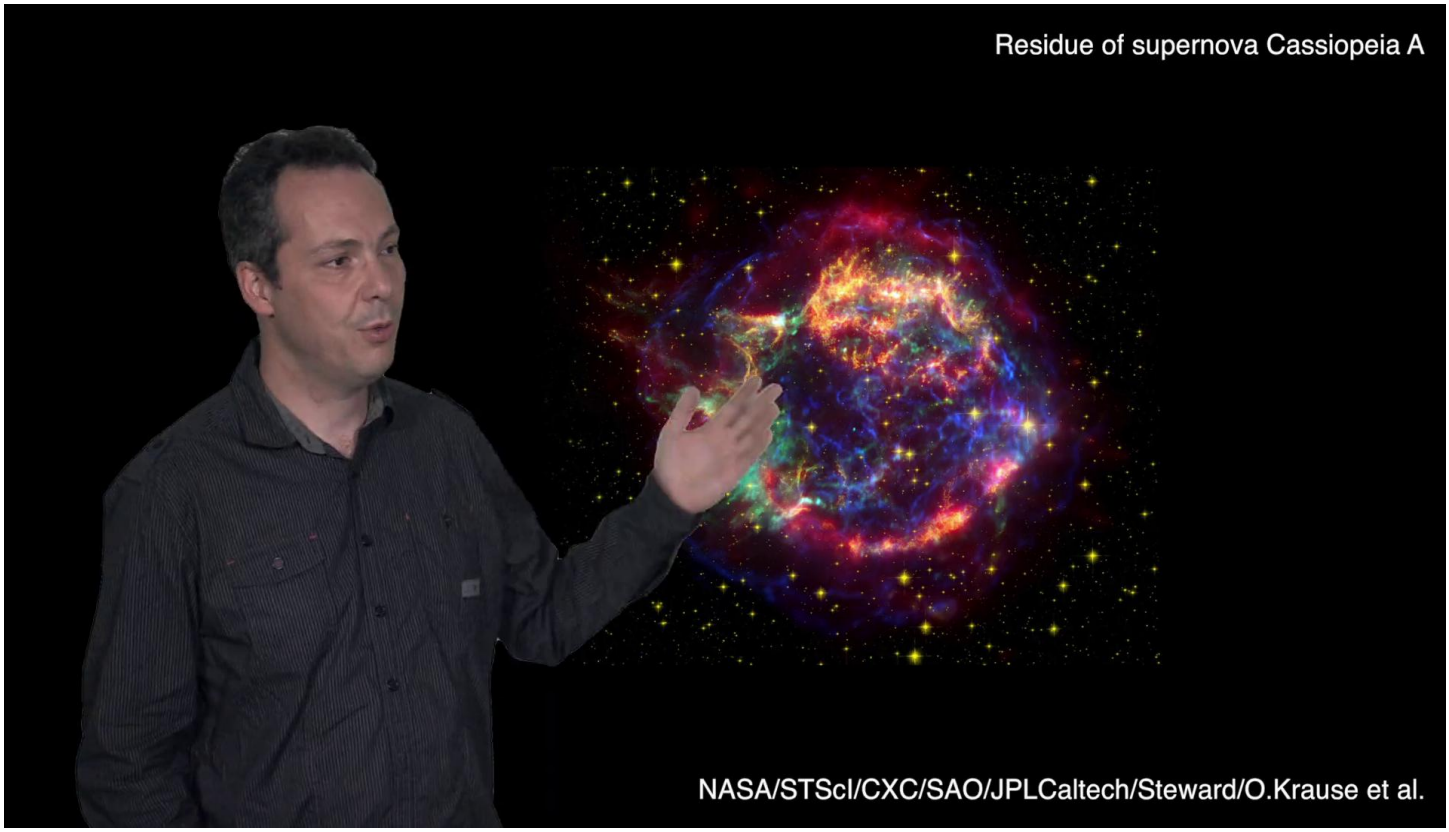


To summarize, stars form from the fragmenting of a gas and dust cloud. They collapse and this collapse warms up the centre of the protostar up to the point of starting the reactions of nuclear fusion of hydrogen into helium. They spend most of their life burning hydrogen into helium. At this stage, they are located on the main sequence we talked about several times, which is a mass sequence with the most massive stars at the top and the least massive stars at the bottom.

Notes

Summary

20m 31s

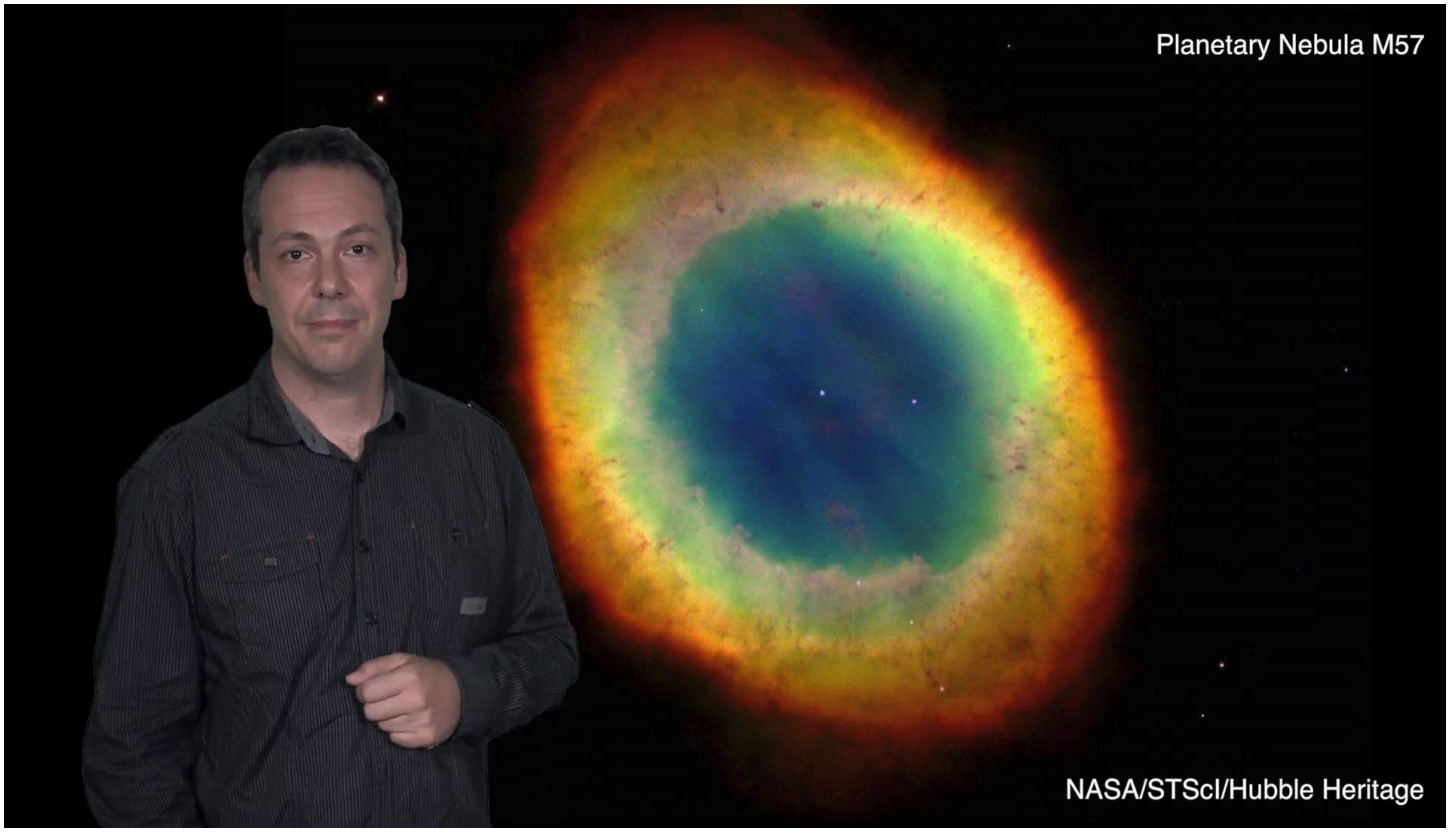


Once the hydrogen has been consumed, the equilibrium between the gas and radiative pressure outwards and gravity in the opposite direction is broken. The core of the star tends to collapse while the outer layers expand and the star becomes therefore a giant star. At this stage, it undergoes a succesive series of contractions and ignitions of nuclear reactions that each produces heavier and heavier elements. If the star is beyond 8 solar masses, it explodes in a supernova, a remain of which we see here in the background.

Notes

Summary

21m 03s



If the star is below 8 solar masses such as our Sun with one solar mass, it produces a nebula such as the nebula Messier 57 that we have already seen in the first chapter, at the center of which rests a white dwarf. Finally, stars with very low masses, less than 0.08 solar masses, remain as red dwarves or brown dwarves at the bottom of the colour-magnitude diagram and they will keep shining for billions of years.

Notes

Summary

21m 46s