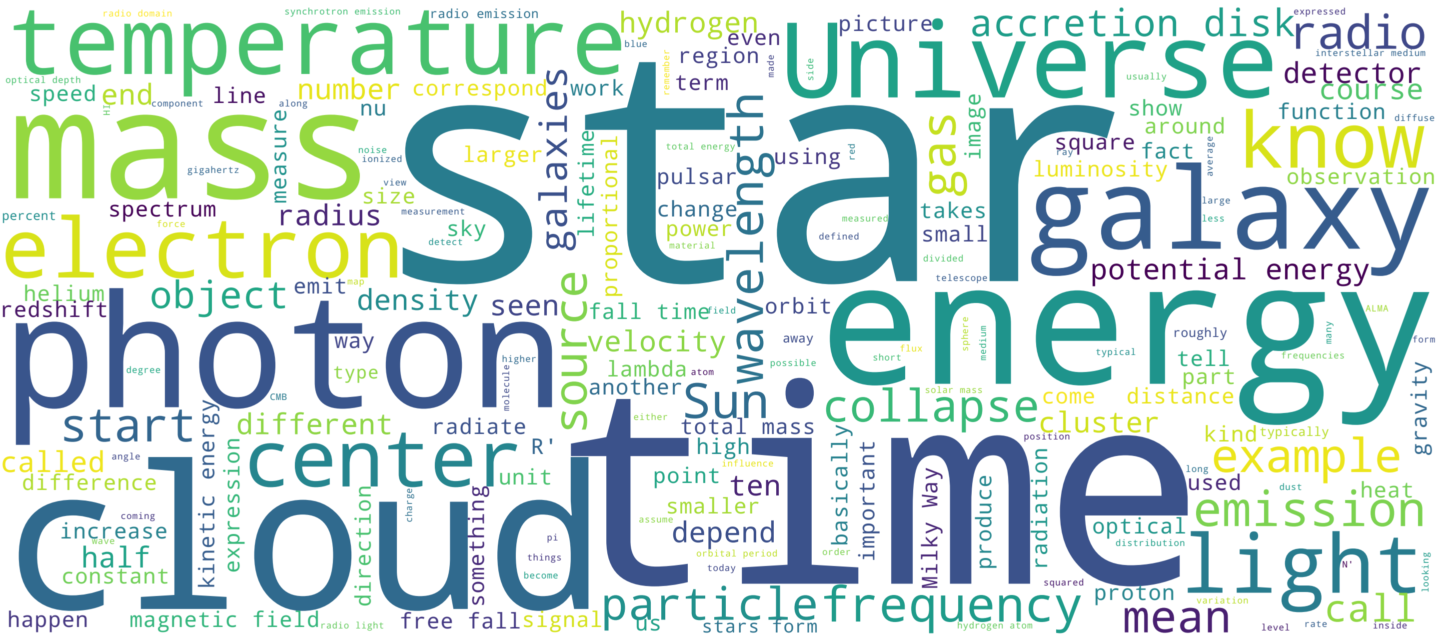
Stellar Formation

NGC 604: stellar formation region

Image: NASA/ESA - HST

The Universe At Radio Wavelengths

Frédéric Courbin



Search MOOC

Video

We have seen in the previous videos what is the radio emission of galaxies. Galaxies are composed of nebulae, composed of stars. Stars don't radiate much in the radio domain although they emit some radio light as the Sun but the Sun is really nearby seen from far away stars don't emit much radio light.

Notes

Summary

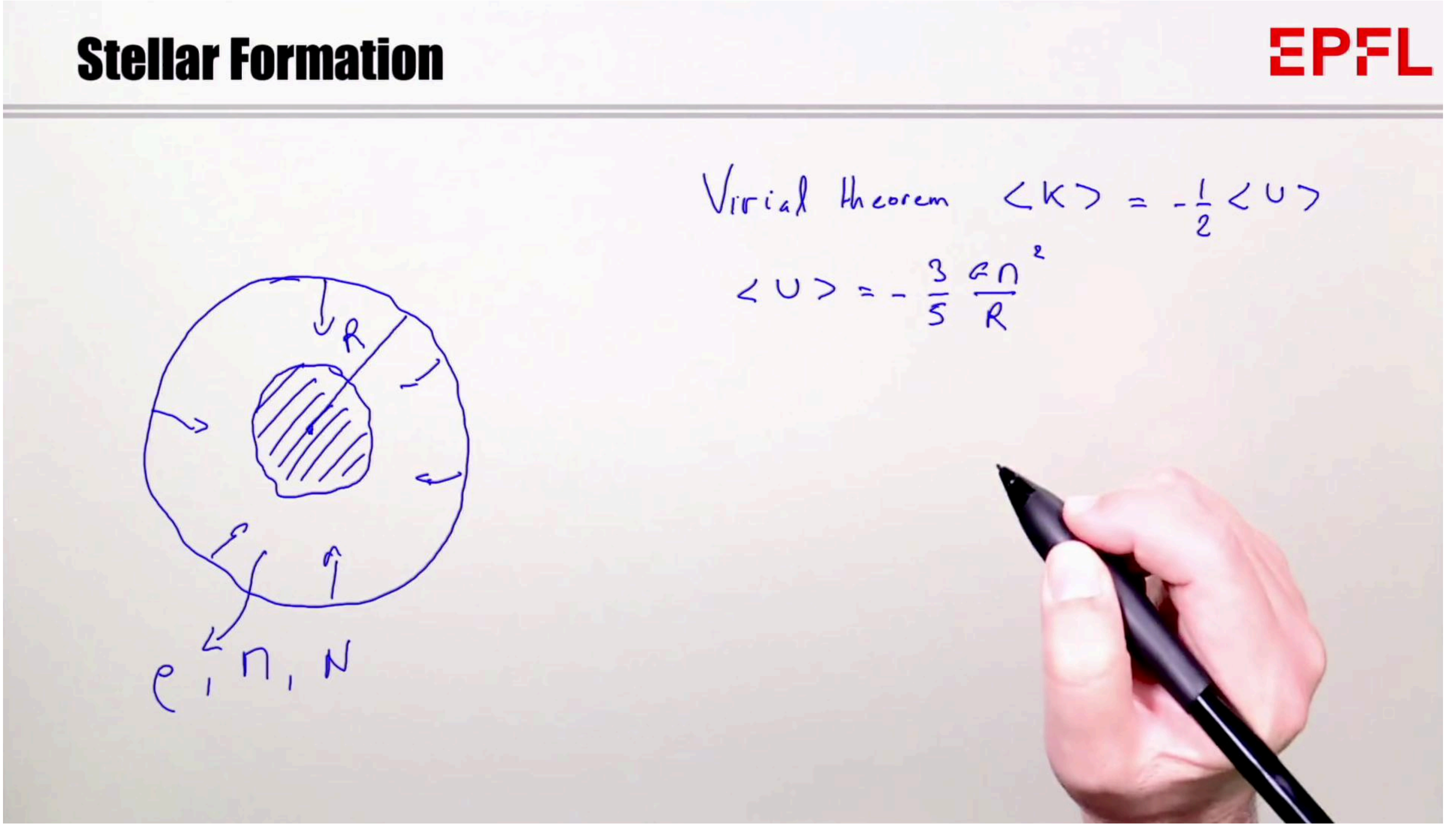
0m 05s

Still it's very interesting to see how stars form. How they may illuminate, for example, the accretion disk where planets will form later around stars and this will radiate in the radio domain but let's see first how stars form from the collapse of nebulae of recycled material in the interstellar medium and how they start the nuclear reactions that power them all along their life.

Notes

Summary

0m 24s

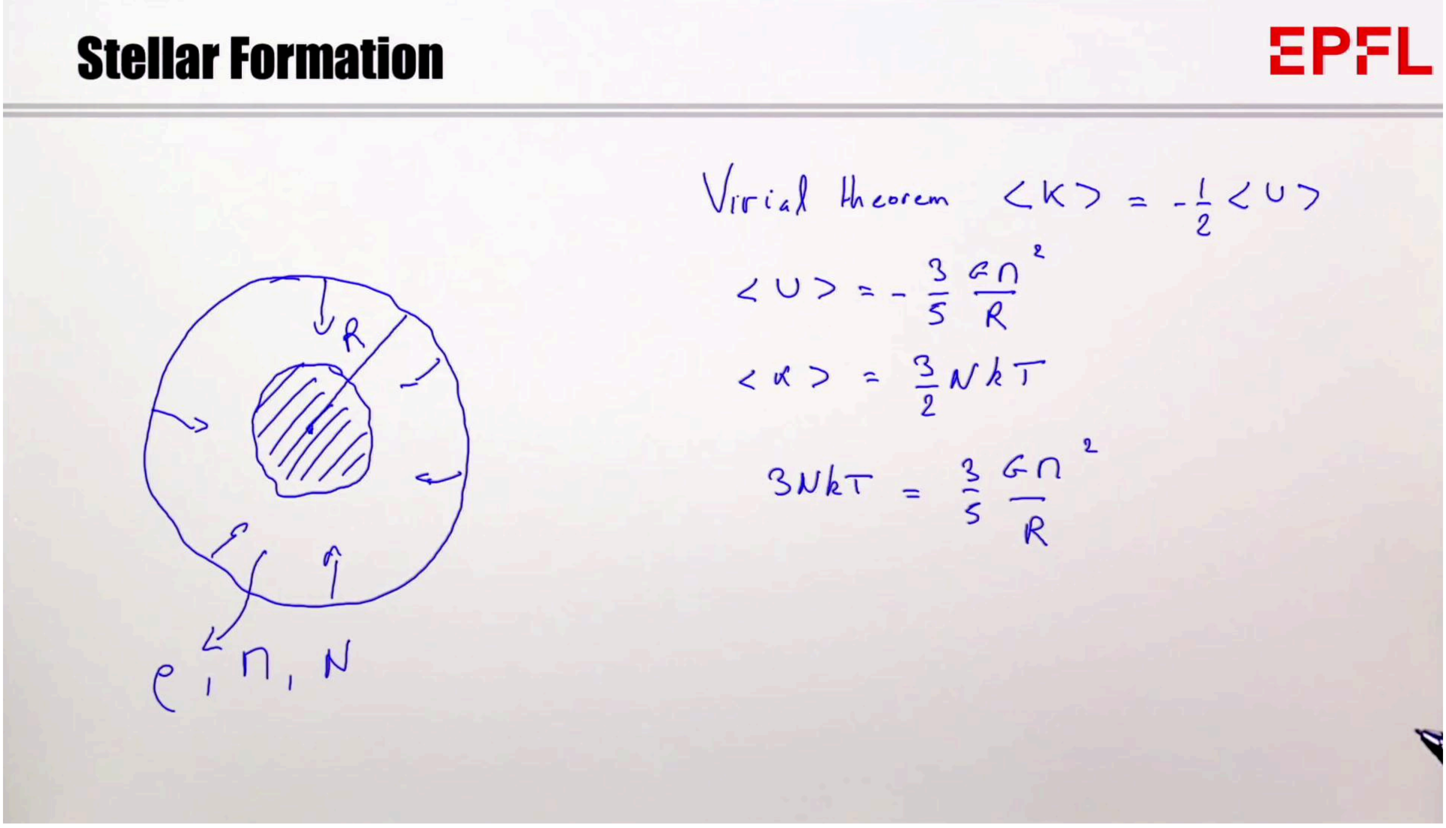


So how does stellar formation works? So stars form from clouds of gas. They can be spherical or slightly different and then the gas starts to collapse under the influence of the gravitational force. We start with some radius 'R' and at some point, you know, the cloud will be smaller and then the temperature will increase in the center and then up to the point where nuclear reactions will start. So how does it work? So let's start with a simple cloud, you know, toy model with a density rho that will take constant all across the cloud. The total mass of the cloud will be 'm' so that will be the total mass of the star in the end and now in this cloud there is a number of particles, atoms, molecules and that's the total number of the molecules inside the cloud of some radius 'R'. Now for a self-gravitating system you may all know the Virial theorem that tells you that on average with time the kinetic energy is minus half of the potential energy. Now what's the potential energy? So for a sphere you can show and we'll just assume it here can show that it's minus three fifth of 'G' 'm-square' over the radius of the sphere.

Notes

Summary

0m 52s



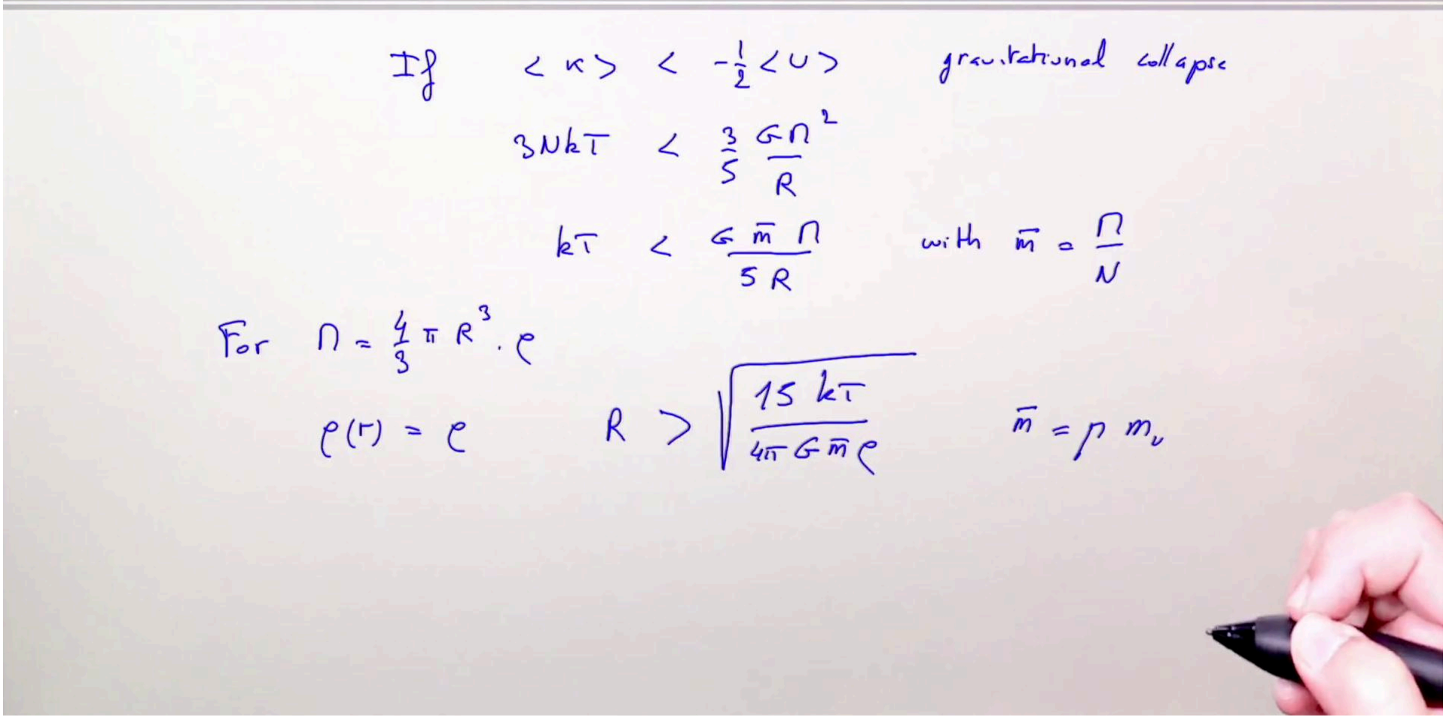
And then for a gas, the kinetic energy will be three halves of 'N' so that's one-half 'kT' per degrees of freedom and there are three dimensions so there are three degrees of freedom and 'N' particles so that's three 'N' degrees of freedom. And then, you know, you just equate the two parts of the equation and get three 'NkT' equal three fifth of 'G' 'm-squared' over 'R' so the minus half factor here has disappeared in the equation.

Notes

Summary

2m 29s

Jeans Mass and Radius



Now if the kinetic energy doesn't compensate for the gravitational energy, the potential energy so we are in this situation where 'k' is smaller than minus half of the potential energy then we'll observe a gravitational collapse. And then the cloud will start to contract. So let's rewrite this equation. So that's three 'NkT' that's smaller than this so that's from the previous slide and then if we rearrange the term, we end up with where now we have defined the mean mass of the particles in the cloud. So that's just the total mass divided by the number of particles. And then if we assume also the simple relation that the mass is the volume of the cloud times the constant density so here we take rho of 'r' equal 'r' so density is constant then we invert this equation and end up with 'R' larger than square root of '15 kT' over four pi 'G' 'm' rho. And if you want you can express the mean mass of the particles as the mean molecular mass times the atomic unit of mass so that's the mass of a proton.

Notes

Summary

3m 10s

Jeans Mass and Radius

EPFL

$$R_{Jeans} = \sqrt{\frac{15\, kT}{4\pi G \bar{m} \rho}} \quad \text{with} \quad \bar{m} = \mu\, m_u$$

$$R > R_{Jeans} \rightarrow \text{collapse of cloud}$$

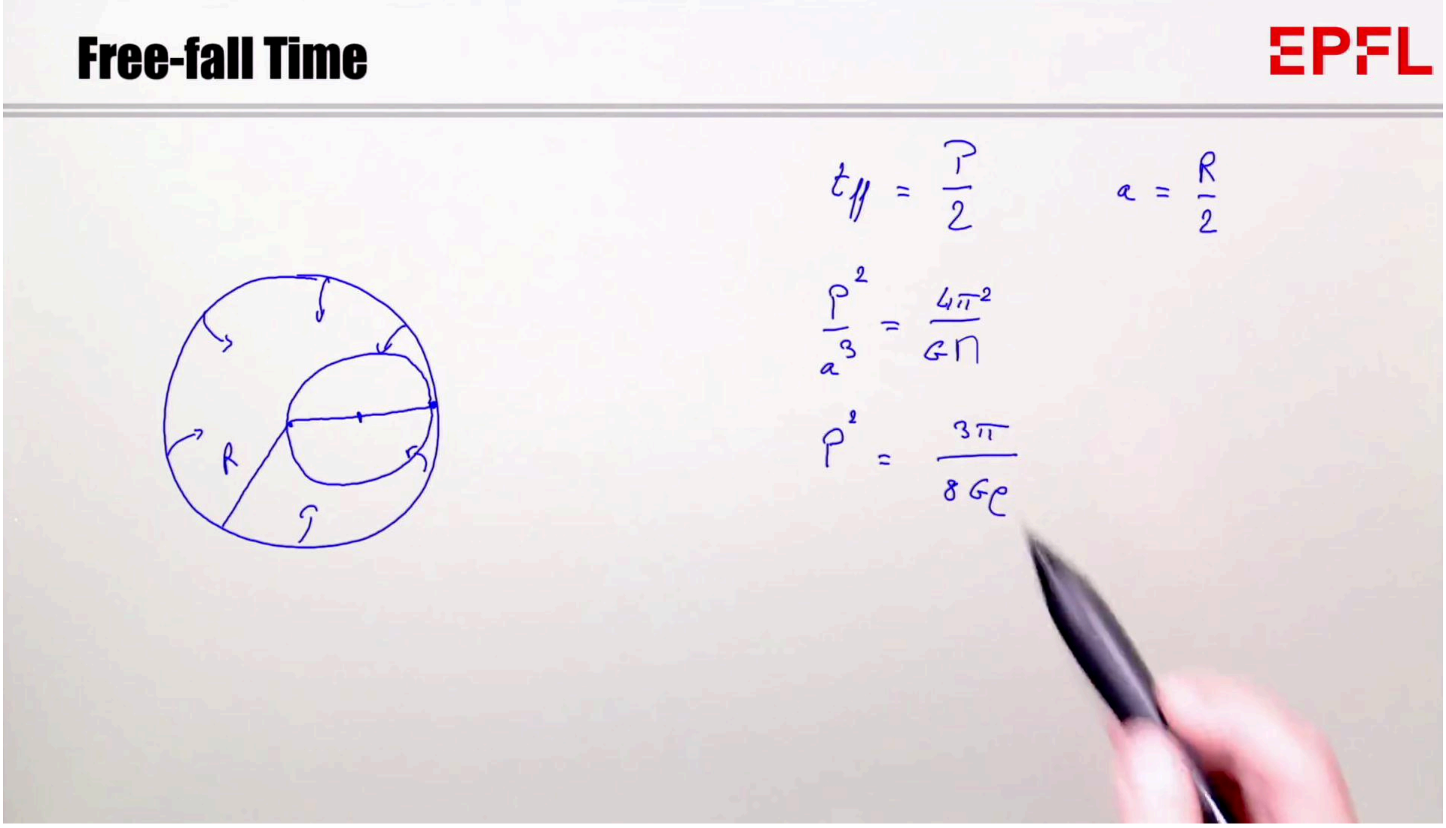
$$\text{Similarly} \quad M_{Jeans} \qquad M > M_{Jeans} \rightarrow \text{collapse}$$

So now the condition we have is the condition for collapse on the radius and that's called the Jeans radius and that radius is again. So that's, in fact, the minimum radius after which a given cloud of gas with some temperature 'T', some constant density rho will start to collapse. So if the radius of the cloud is larger than the Jeans radius then we have the start of a collapse of the cloud. Now similarly, one can define also the Jeans mass so it's just using the same equation and the same assumptions as before and that's the mass above which a given cloud will collapse. So for a constant radius and increasing density and, therefore, increasing mass after the Jean mass then you also have a collapse of your star or at least of your cloud. So that's mostly the conditions to start forming a star. Why this because if you start collapsing a cloud then the temperature in the center will increase.

Notes

Summary

4m 43s

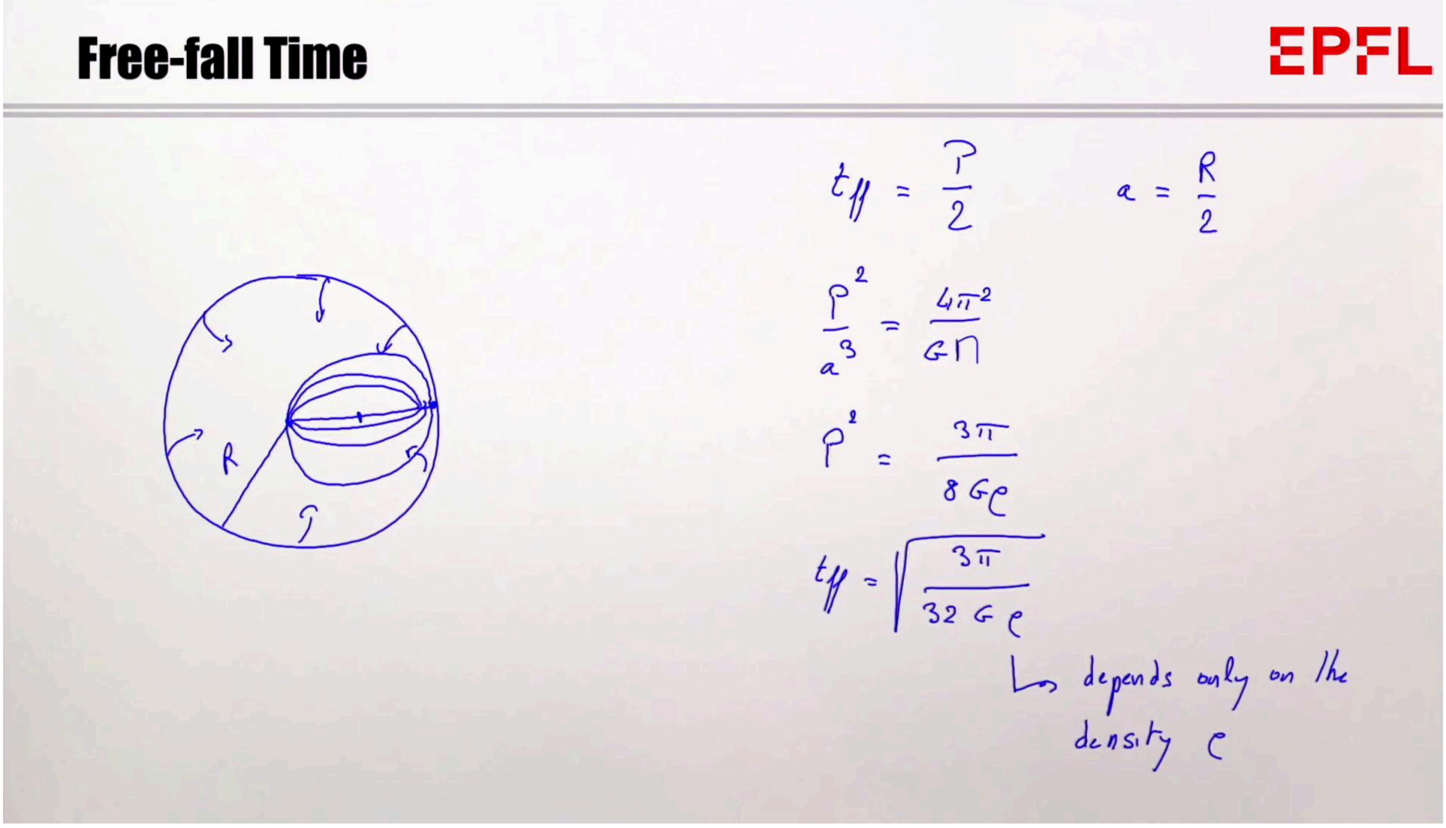


So we said after a given mass or after a given radius we can have a collapse of a cloud of gas. So here is the cloud of gas. It still has some radius 'R' and then we want to know how much time it takes for all the particles at the edge of the clouds to reach the center. That's called the free-fall time so how long it takes to go from here to the center. Now one way of computing this is to consider that particles are in on an orbit which radius is half of 'R' and then we can use the Kepler law. So imagine you have a particle here in orbit around this center. It will take one period, one orbital period to do one round, of course, and it will take half the orbital period to go in the center. So that's how we define the free-fall time as half of the orbital period of that orbit which semi-major axis is 'R' over two. So it takes half an orbital period of an orbit which semi-major axis is half of the radius of the cloud and that's a very nice way of seeing things because you can use the third Kepler's law that tells you that 'P' squared over 'a' cube equal four pi 'G' 'm' where 'm' squared is the total mass of the cloud and then you just replace 'P' and you replace 'a' and you end up with 'P' squared equal three pi over eight 'G' rho and then your free-fall time if you replace so you divide this by two.

Notes

Summary

5m 55s



‘a’ is already replaced in the formula then the free-fall time is simply three pi over 32 'G' rho where rho is constant. And very importantly this depends only on the density and it doesn't depend at all on the total mass of the cloud, for example, it doesn't depend on its radius so it's all about how dense the mass is and you also see that in the calculation, I could have used very well an orbit like this or very elliptical orbit or an even more elliptical orbit or even a straight line just because the third Kepler's law doesn't depend on the ellipticity of the orbit that you consider. So that's a fairly easy way to compute the free-fall time of self-gravity in cloud under the influence of nothing else than its own gravity.

Notes

Summary

7m 46s

Free-fall Time

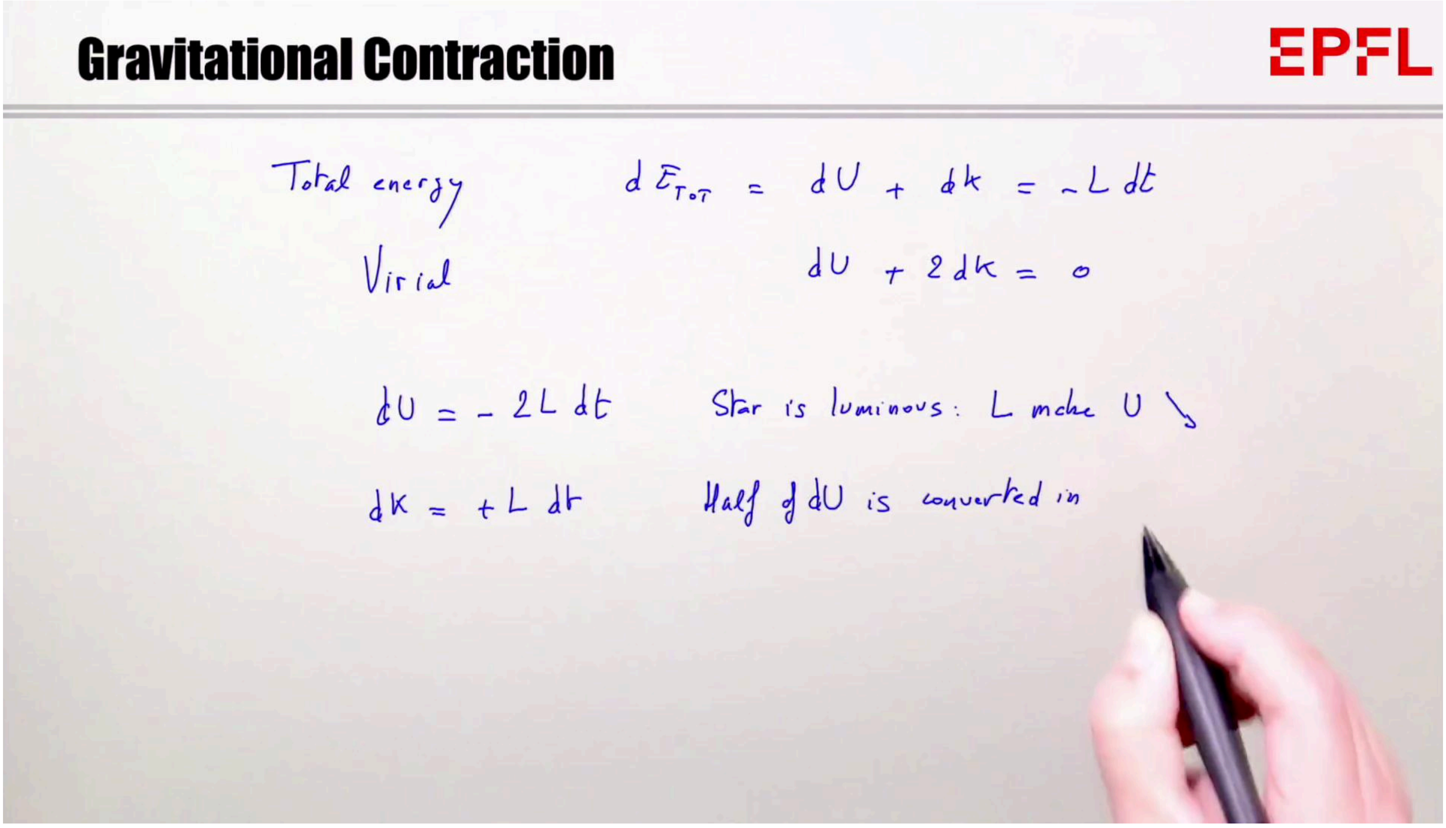
	Density (kg.m^{-3})	t_{ff}
Universe	10^{-27}	10^{11} years
Galaxy	10^{-21}	10^{8} years
Interstellar Medium	10^{-21} / 10^{-17}	10^{5} / 10^{8} years
Solar System	10^{-12}	1000 years
Sun	1400	1800 sec

Now here is the result in numbers. So I told you the free-fall time depends only on the density of your cloud so that's in kilograms per cubic meter and that's very rough and, of course, mean numbers across objects of different special scales and that's the free-fall time. So if you take now extreme scales from the whole Universe with the mean density of typically ten to the minus seven kilograms per square per cubic meter then the free-fall time is about ten to the eleven years which is actually longer than the age we believe the Universe has which is about thirteen ten to the nine years. For a galaxy with a lower density then, of course, this time now goes as square root of one over the density so it's ten to the eight years. For some cloud in the interstellar medium, that can be very long as well ten thousand years to a few million years for the solar systems, you know, the larger density and it's typically 1000 years and for the Sun then where the density is extremely high then it's just half an hour. So that's surprising number but that's really the free-fall time so the time it takes to collapse just under the influence of the gravity of the cloud not balanced by any other type of force.

Notes

Summary

8m 37s



Now what happens during the collapse? So we have the total energy of the cloud and this total energy will, in fact, change. So it's the sum, of course, of the variation of potential energy plus the variation of kinetic energy and we know that stars radiate at some luminosity and that's the energy they lose as a function of time. Per unit time they lose minus 'L'. So that's the total energy of the star and then we also have the Virial theorem that we can apply to the star and that one tells you that the variation of potential energy plus twice the variation of kinetic energy is on average in time equal to zero. So this is true for a self-gravitating system and this is true all the time. The star radiates light and, therefore, lose energy. Now if you solve this simple system of two equations, you end up with 'dU' equal minus two 'L dt' and you also end up with 'dK' equal plus 'L dt'. So what does it mean? It means that the radiation from the star makes 'U' decrease. So the star or the protostar cloud gas is luminous and then 'L' makes 'U' decrease so you radiate luminosity, you lose potential energy. That's why you have this minus sign here. And that equation tells you that half of that is converted in kinetic energy.

Notes

Summary

10m 01s

Gravitational Contraction

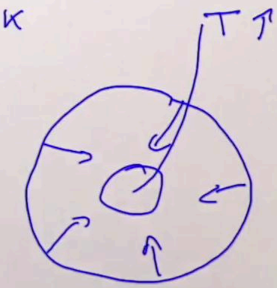
Total energy $\quad dE_{TOT} = dU + dK = -L\,dt$

Virial $\quad dU + 2\,dK = 0$

$dU = -2L\,dt \quad$ Star is luminous: L make U ↘

$dK = +L\,dt \quad$ Half of dU is converted in K

Contraction → heating → radiation pressure



So if the star like the cloud lose potential energy and gain kinetic energy it means it convert enough gravitational energy into heat. And, therefore, contraction also implies heating. And, therefore, you will start to radiate more and more photons from the center of the protostars and that will create radiation pressure. So you have your star. Gravity makes it shrink collapse then you have an increase of temperature in the center and, therefore, you start to have photons emitted away from the center because of the gravitational heating. The conversion of 'U' into 'K'. And these photons will kind of balance the gravitational collapse and that's why the Sun, for example, didn't collapse in half an hour but in a much longer time scale because gravity is balanced by the radiation pressure due to the contraction of the cloud under the influence of its own gravity. So the gravity produced heat and at the same time it makes the star shrink slower.

Notes

Summary

11m 42s

Life Time

$$t_{life} = \frac{U}{L} = \frac{3}{5}\frac{GM^2}{R} \cdot \frac{1}{L}$$

Helmholtz - Kelvin time

For $M = 1 M_\odot$ $\quad t_{HK} \sim 10^7$

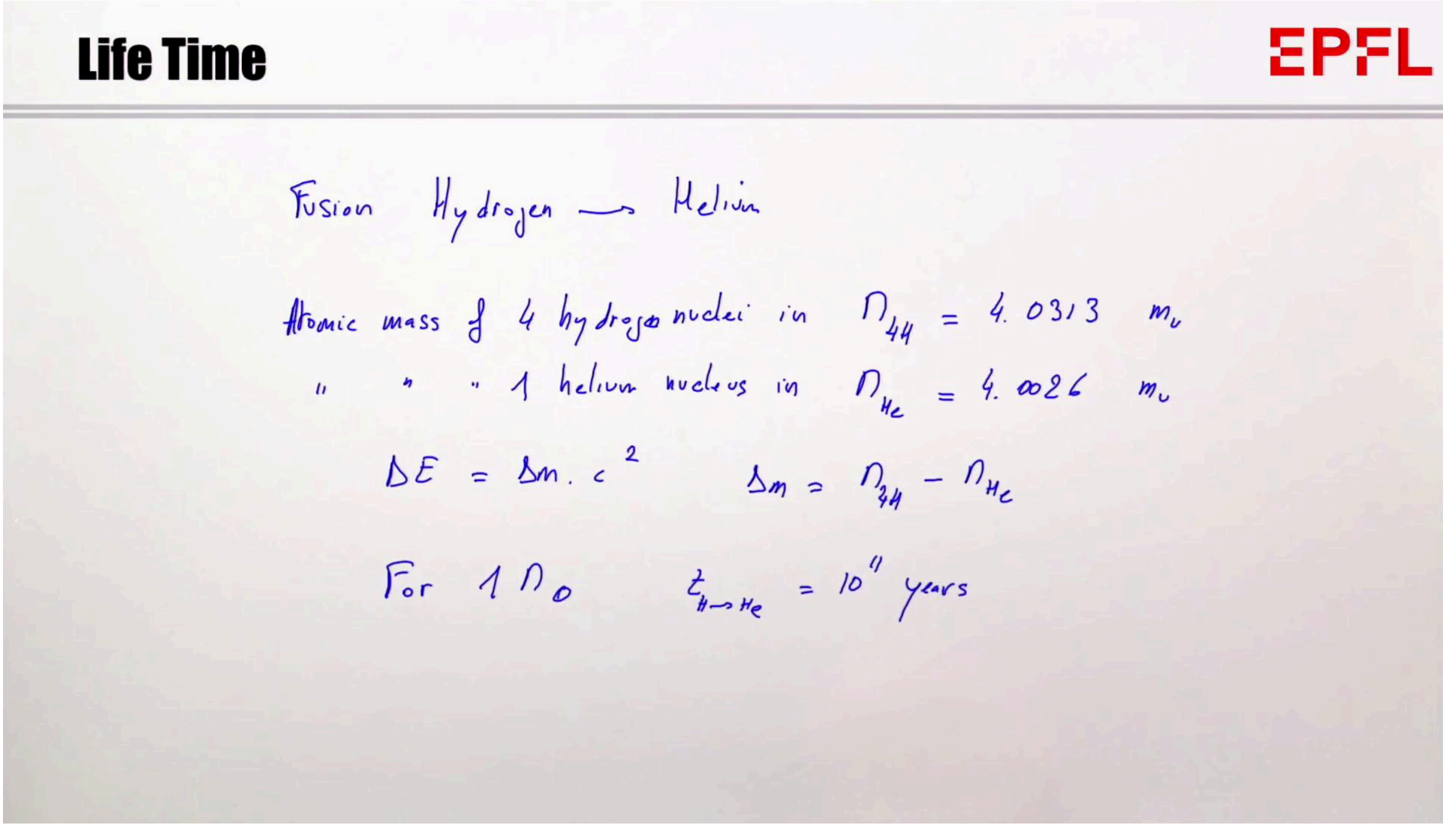
1000 x too short

Now the energy of the star seems to come from its potential energy so what about computing its lifetime. Lifetime can be approximated by potential energy divided by the rate to which you lose the energy or you convert it into heat and light and that's the luminosity of the star. So that assumes that the only source of energy in the star is gravity, potential energy. Now for a sphere we have seen that the energy is this and then you just divide by the luminosity of the star. So we know the luminosity of the Sun. For example, we know the mass of the Sun. It's one solar mass. Therefore, we can compute this lifetime. That's also called the Helmholtz-Kelvin time and that's the time it takes to convert all the potential energy into light or heat. Now for 'm' equal one solar mass then this Helmholtz-Kelvin time is about ten to the seven years and that happens to be a thousand times too short. We know that the lifetime of the Sun is about ten billion years so obviously, the source of energy in the Sun is not only gravity.

Notes

Summary

12m 49s



So the source of energy of the Sun is not only gravity still gravity has to do with powering the Sun because it will heat the center of the Sun and at some point the temperature will be so high then you can fuse hydrogen into helium. So one possible source of energy for the Sun or stars is the fusion of hydrogen so nuclei of hydrogen into helium and then the energy that make the hydrogen fuse into helium will be released in the medium and so in the inside the star and power the star. Now the atomic mass of four hydrogen nuclei is so the mass plus four of four hydrogen nuclei is 4.0313 proton masses. Now the atomic mass of one helium nucleus is mass of the nucleus is 4.0026 proton masses and, of course, you all know Einstein relation or the difference of energy is the difference in mass times 'c' squared where this delta 'm' is the difference in mass between these two things, between the mass, well, the conversion in energy of the mass of four hydrogen atom well, hydrogen nuclei, sorry, and the mass of an helium nuclei. And now again if you do the calculation for one solar mass then the time to burn helium, hydrogen into helium into the thermonuclear sense is ten to the eleven years and that's more or less the lifetime of the Sun or at least compatible with the lifetime of the Sun.

Notes

Summary

14m 08s

Life Time

EPFL

Fusion Hydrogen → Helium

Atomic mass of 4 hydrogen nuclei is $M_{4H} = 4.0313\ m_u$

" " " 1 helium nucleus is $M_{He} = 4.0026\ m_u$

$$\Delta E = \Delta m \cdot c^2 \qquad \Delta m = M_{4H} - M_{He}$$

For $1\ M_\odot$ $\quad t_{H \to He} = 10^{11}$ years

So hydrogen into helium is indeed a very good candidate and we know now that is the process to produce energy in the center of stars as soon as the temperature is above one typically one million kelvin. And this temperature is reached by the initial gravitational collapse of the star. So the collapse of the star will make hydrogen burn into helium and that's how the star will live all along its life.

Notes

Summary

16m 01s

So we have now seen how stars form, how they collapse, how they form from a cloud of gas, how the temperature increase in the center and how they start the nuclear reactions and with this, of course, they will radiate visible and infrared light. They won't radiate much of radio light but around the stars there is usually some residual material accreting on the star and this and the star will, of course, heat this material and the material will radiate blackbody radiation usually seen in the very far infrared and, in fact, also in the radio. So, for example, with ALMA with a submillimeter array ALMA, you can do very precise interferometric maps of accretion disk around stars.

Notes

Summary

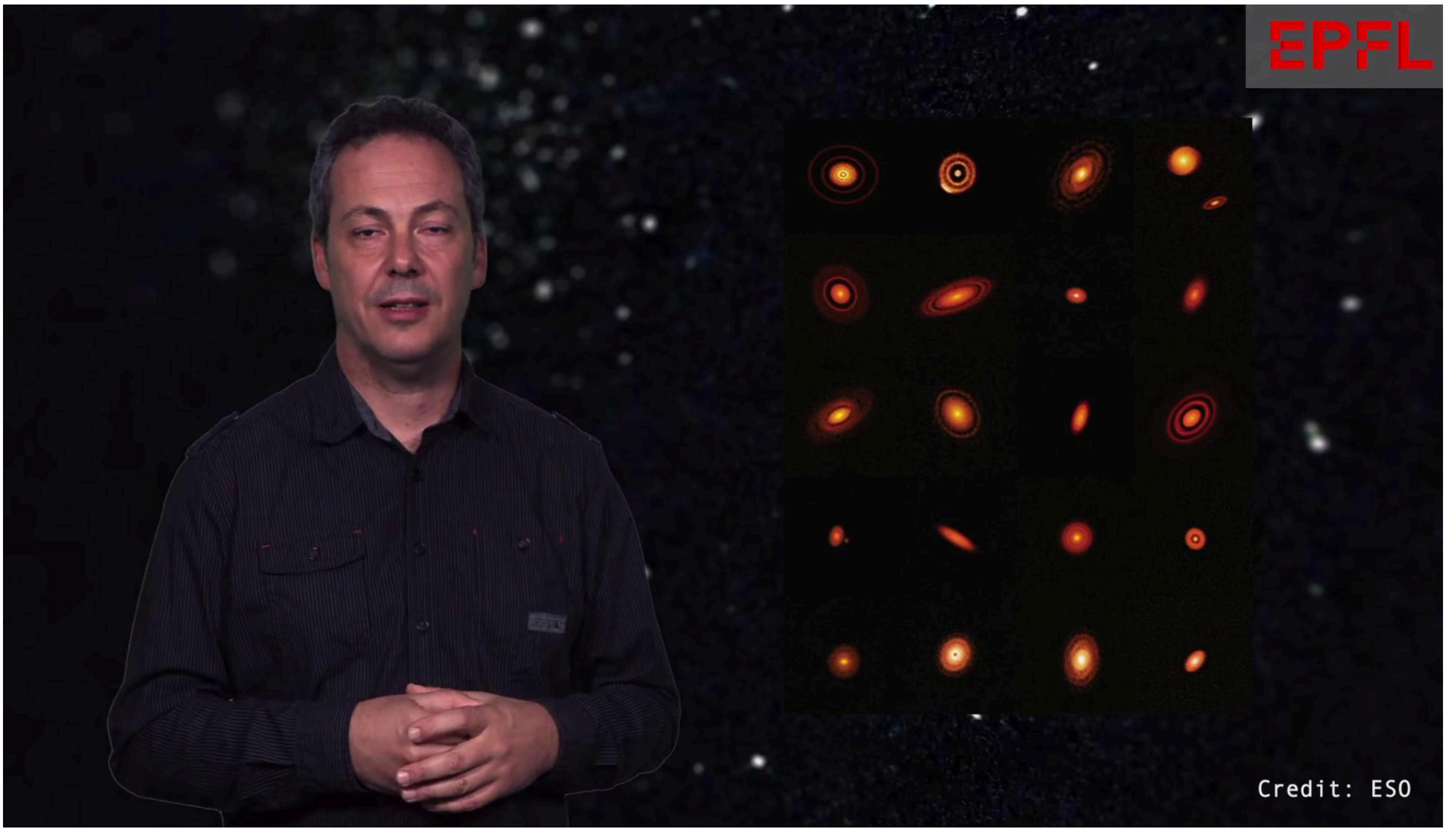
16m 31s

So that's an artist view of an accretion disk but the next image, this one, is real images of an accretion disk.

Notes

Summary

17m 15s



A various accretion disk in the nearby Universe, in the Milky Way but with ALMA we can start to resolve the accretion disk. So we don't see the star in the radio almost nothing of the star but what you see is the material around the star and you see also some rings around dark rings in this accretion disk because planets form in these rings and they kind of clean the dust that is seen in the radio domain at some positions at some orbital periods. So that's how stars form. How they interact with the accretion disk and with radio observations even if you don't see the stars you see them, in fact, when they are dead. You will see other videos when dead stars emit radio light due to synchrotron emission, due to the magnetic fields of the what remains of the star. So that's in supernovae, in pulsars but when a star is living, is alive so when it burns so by definition when it burns its hydrogen into helium, it doesn't really get much of radio emission. Still the star will illuminate the accretion disk and the accretion disk will radiate in the infrared and in the radio and, therefore, with ALMA the submillimeter array, you manage to see the tiny accretion disks around stars so that's protoplanetary disk with planets forming around a star.

Notes

Summary

17m 22s