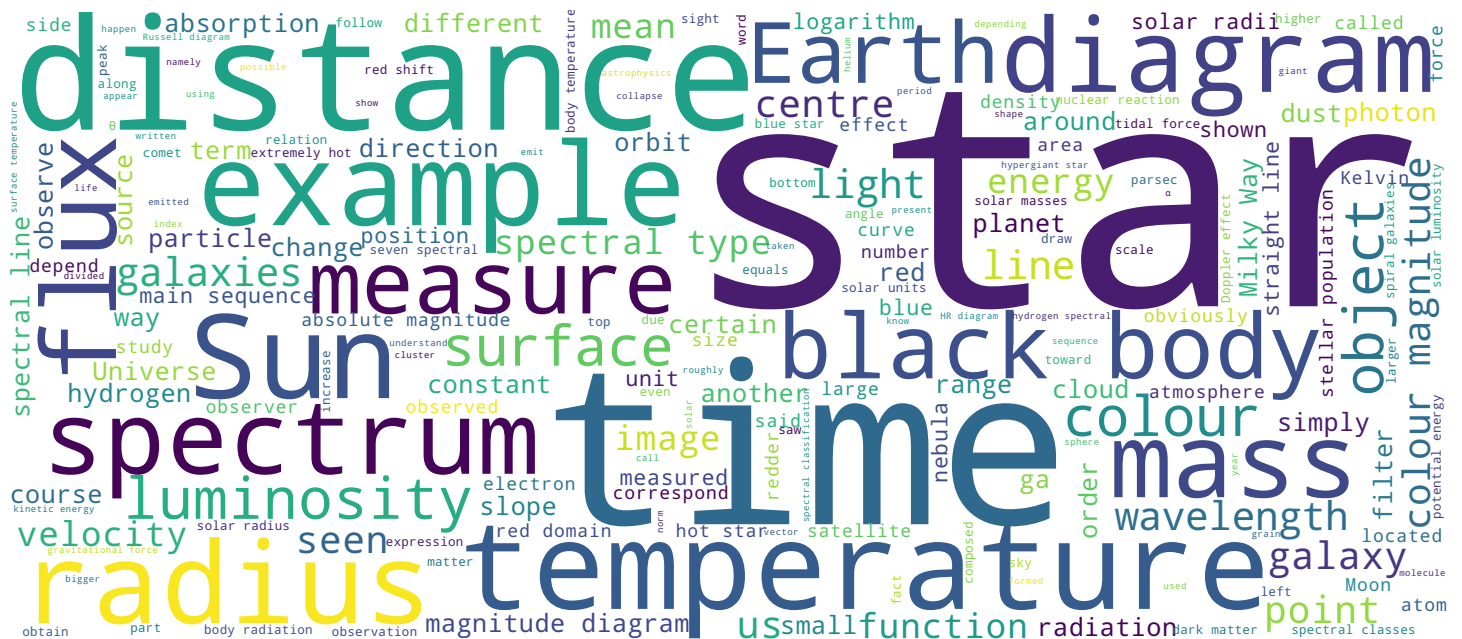
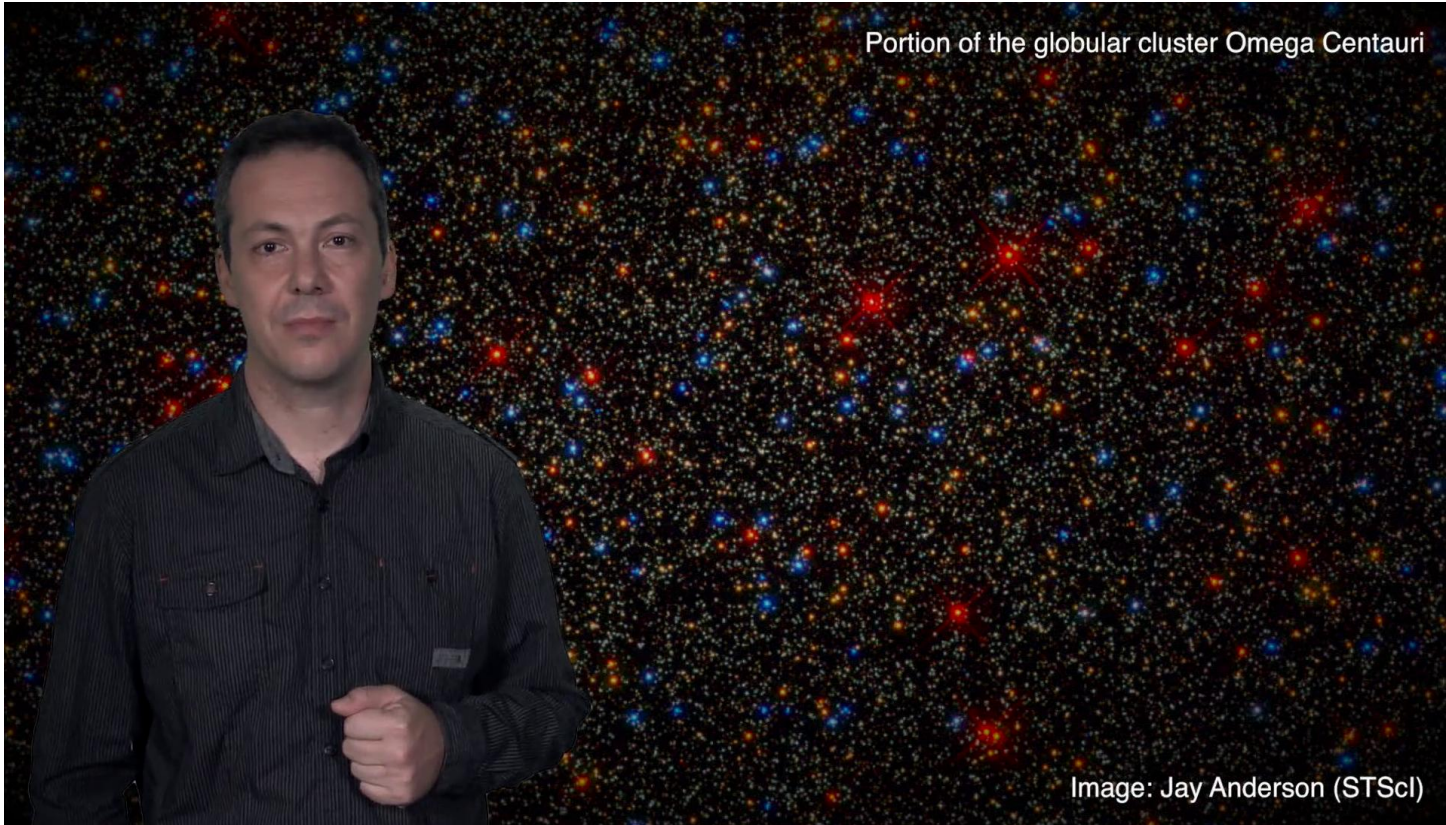


Hertzsprung-Russell diagram

Animations: NASA, ESA, and J. Anderson, R. van der Marel,
G. Bacon, and M. Estacion

Frédéric Courbin





Portion of the globular cluster Omega Centauri

Image: Jay Anderson (STScI)

Once formed, the stars shine thanks to the nuclear reactions in their core. The energy produced is transported to the surface, which in turns warms up and reemits black body radiation. We will see in what follows how one can classify the stars depending on their luminosity and on their colour, which is actually depending on the black body temperature. This video describes the stellar spectral classification and introduces an essential tool for astrophysicists : the Hertzsprung-Russell diagram.

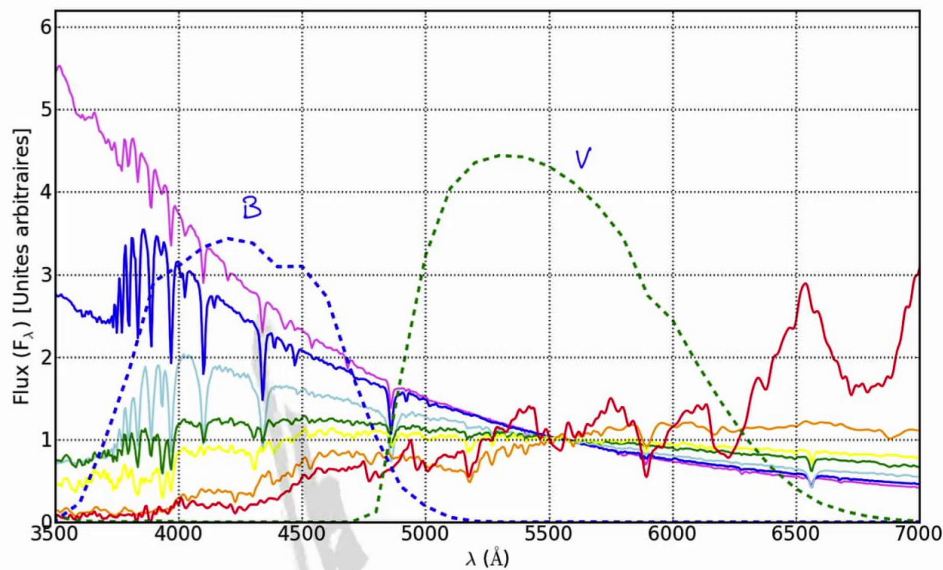
Notes

Summary

0m 05s



Spectral Classification



Introduction to Astrophysics

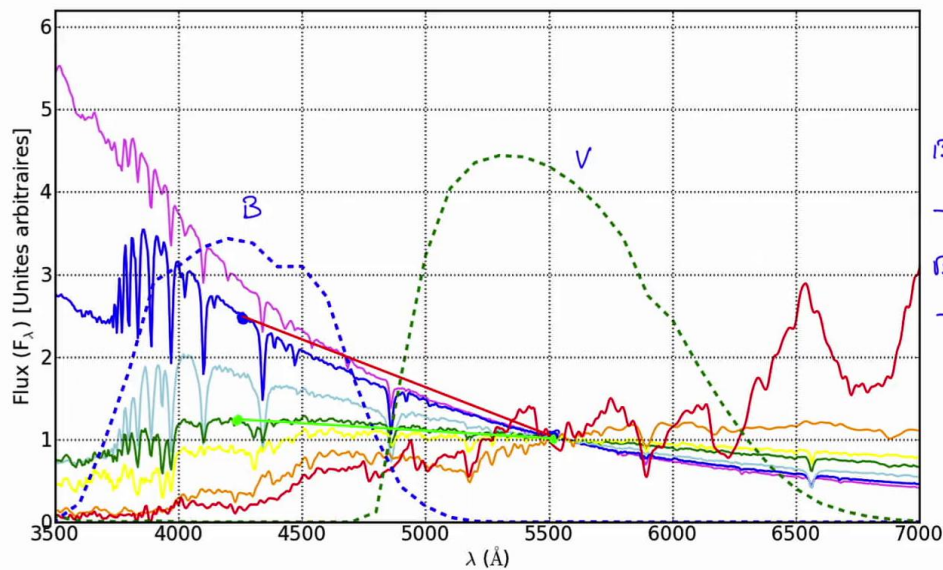
Let us now see how to classify the stars. The main difference between stars is their temperature. This temperature determines the colour of the stars. The stellar classification is therefore a spectral classification mainly linked to the surface colour, the surface temperature of stars. Here are all known kinds of stars. There are seven different spectral types, each with its temperature. Here is for example an extremely blue star with a black body radiation at 40'000 Kelvin so an extremely hot star, among the hottest that exist. As such it has a much higher flux in the blue part of the spectrum - here is the blue, and here is the red. Conversely, if we take a cold star such as this one with a black body temperature of more or less 3000 Kelvin, the spectrum is much redder. There is more flux on the red than on the blue side of the spectrum. Between the two we have stars similar to the Sun. The Sun, with a temperature of about 5780 K, is a star with a mainly yellow spectrum. To measure the colour of stars we use colour indices. We usually use the B and V filters in the optical domain and we then measure the slope of the spectrum as a function of the colour index.

Notes

Summary



Spectral Classification



Introduction to Astrophysics

Each time the temperature of a star changes we have a change in the slope of the spectrum and also several spectral lines such as these ones. We see the hydrogen spectral lines for example as well as molecular bands appearing in colder stars. Depending on the star's temperature its colour changes and the absorption or emission lines in its spectrum also change. How do we measure the slope of the spectrum? We have already seen this. I take the star with a blue spectrum as an example. If I measure the flux at the centre of the B filter bandwidth and the flux at the centre of the V filter bandwidth, I can measure the slope of this spectrum thanks to these two values. We have then some slope, which is blue since there is more flux in the blue than in the red domain. If I now take the green star on this figure, I have a first measure in the B filter and a second one in the V filter and I get then a much more horizontal spectrum slope. The star is thus less blue, simply because its temperature is lower than for the previous star. The B - V index is therefore an indicator of the spectral type and it is this index that will appear later in the colour magnitude diagram. If B - V is large then we have a red star and if B - V is small we have a rather blue star.

Notes

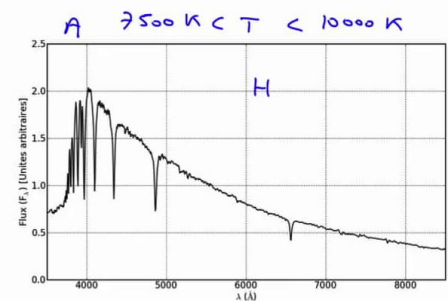
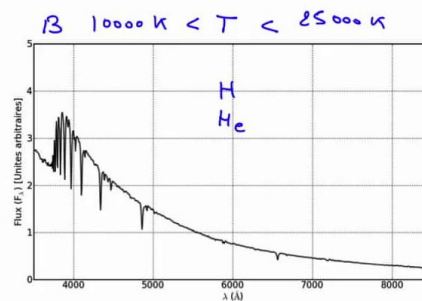
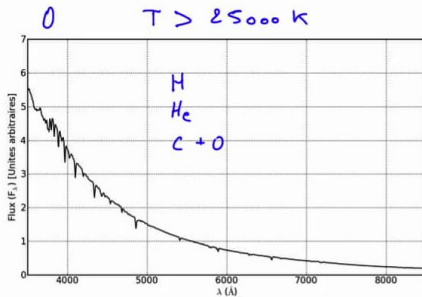
Summary



2m 21s

Spectral Classification

Classification de Harvard . Types spectraux : O, B, A, F, G, K, M $\xrightarrow{\quad\quad\quad}$ T diminue



Introduction to Astrophysics

The spectral classification is based as the name suggests on spectra. There are seven spectral classes at the basis of the Harvard classification. In the Harvard system, we have spectral types named as : O, B, A, F, G, K and M. We have seven letters to indicate seven spectral types. From one side of the scale to the other, the temperature decreases. We typically go from 40'000 degrees here down to 3 000 Kelvin here. Here are a few examples of spectral types : O, B, and A, the first three spectral types corresponding to the following temperatures. This is the range in temperatures. Each spectral type has different features. In each case we have hydrogen here but depending on the temperature the spectral lines are stronger or weaker. In very hot stars we also have helium lines, and here as well. And here there isn't helium anymore. If the star is extremely hot we can also see lines of species with a much higher ionization energy such as carbon or oxygen. The depth at which the lines form depends on two things : the rate, the number of ionising photons emitted by the star and the recombination rate, for example in the case of hydrogen the recombination of protons and electrons.

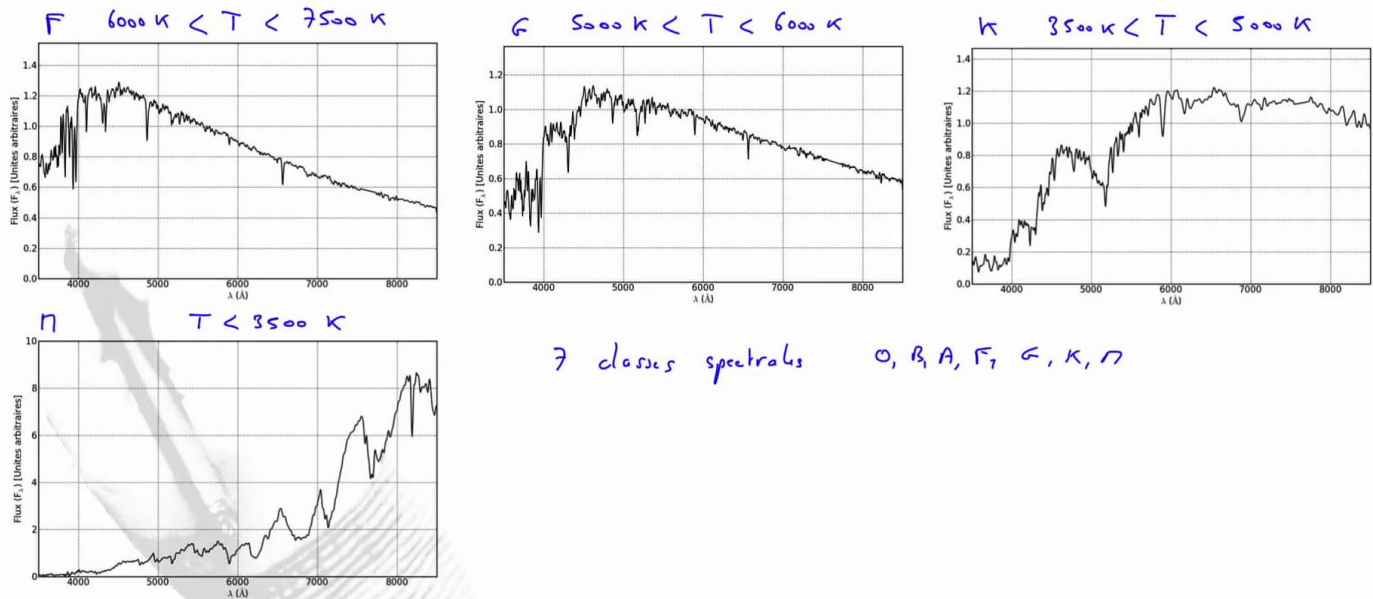
Notes

Summary



4m 07s

Spectral Classification



Introduction to Astrophysics

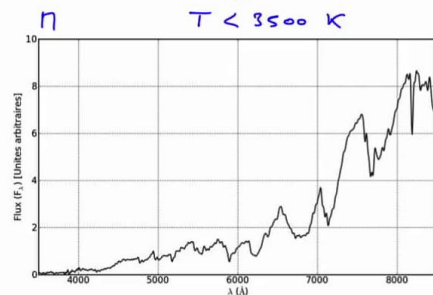
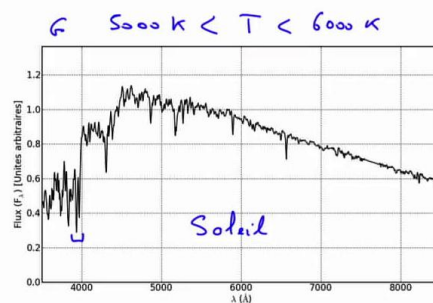
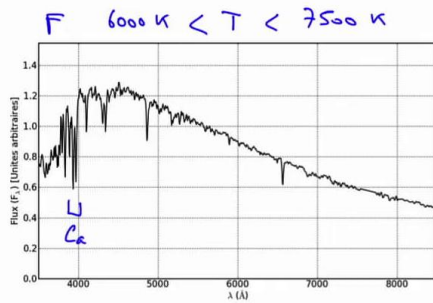
In the case of an extremely hot star, the rate of emitted photons, the flux of ionizing photons is much higher than the proton-electron recombination rate per unit of time. This means that contrarily to what one may think, the hydrogen spectral lines are formed less deep than for a colder star where there are much more atoms so more electron-proton pairs able to reabsorb light and create the hydrogen spectral lines. Each spectral type has of course its own temperature. When we go toward the red domain, toward colder temperatures, the black body peak is translated toward the red domain. Here the peak is at 4000 angstrom, here it is shorter than 4000 angstrom and finally the peak here is far outside of the diagram. Stars become therefore redder and redder when going toward the M spectral type. We have here O, B and A stars. Let us now consider the other spectral types, F, G, K and M. In this case the temperatures are in the following range. As said before, there are seven spectral classes and here are the four last ones. O, B, A, F, G, K and M. We see the black body peak moving toward the red domain as temperature decreases. We also witness other features.

Notes

Summary



Spectral Classification



7 classes spectrales O, B, A, F, G, K, M
10 sous-classes 0, 1... 9
7 classes de luminosité Ia, Ib, II, III, IV, V, VI
Exemple Soleil G2V

Introduction to Astrophysics

For example there are here some metallic lines such as calcium lines. They also appear here. The Sun is by the way a star in the temperature range of 5 000 - 6 000 Kelvin, therefore a G star with 5780 Kelvin. As the surface temperature of the star gets colder, we notice molecular bands. Molecules are therefore broken at high temperatures. When the temperature of the star decreases, molecules will absorb light and produce wide lines. They are actually composed of a great number of very narrow lines which we cannot distinguish due to the limited instrumental resolution. We see here several bunches, each made of a large number of molecular lines. Hence stars with cold temperature feature spectral lines typical of molecules. There are seven spectral classes, and there are also ten subclasses. We have ten divisions between two letters, ranging from 0 to 9. In addition there are seven luminosity classes reflecting essentially the radius of the stars. There are the Ia and Ib luminosities, II, III, up to VI (roman numerals). We will talk about their meaning later. For example, the Sun is a G2 V star. G for the temperature and 2 to split the temperature interval into ten finer intervals. The Sun is thus at 5780 K. V (roman numeral) is the luminosity class of the Sun, which corresponds to the class of 80% of stars.

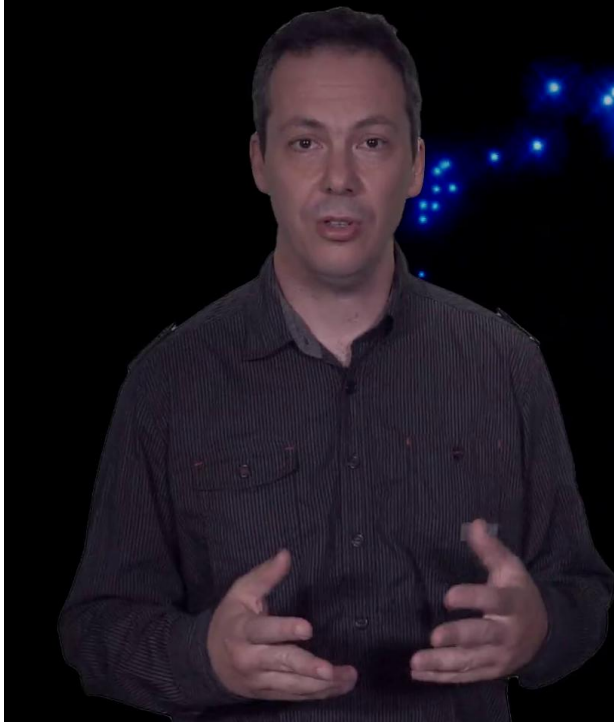
Notes

Summary



7m 59s

Magnitude chart for the globular cluster Omega Centauri



Animation: Jay Anderson (STScI)

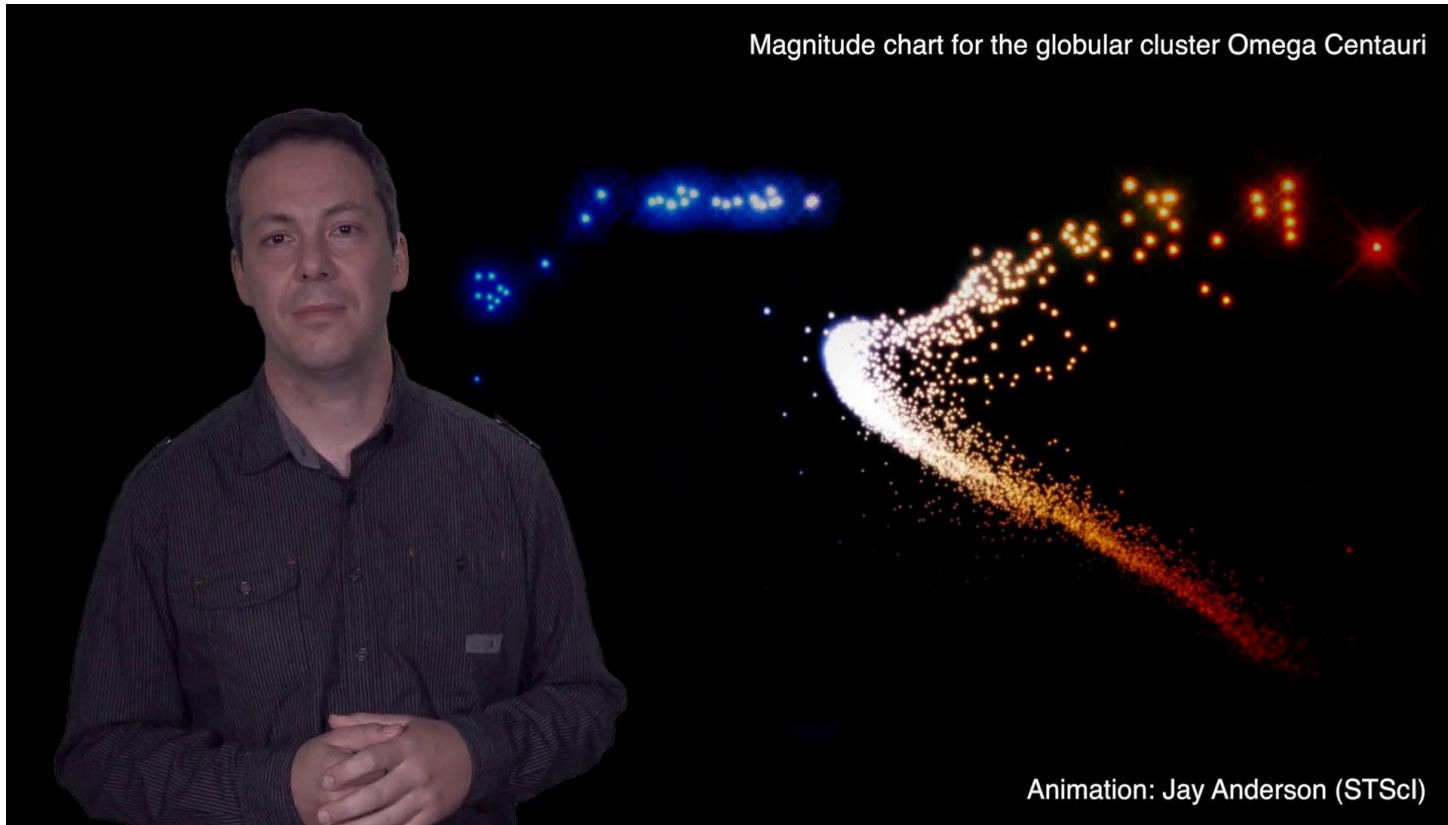
We have just seen that stars can be classified in terms of luminosity and temperature, the latter being at the origin of their colour. It is as such logical to build a diagram showing both quantities and corresponding stars. We are going to do this for the Omega Centauri globular cluster. We first sort the stars by colour, moving blue stars to the left side and red stars to the right side of the diagram. This actually corresponds to sorting them by temperature, with blue hot stars to the left and red cold ones to the right. It simply illustrates Wien's displacement law for a black body spectrum. We now sort them by luminosity and put the faint stars, with a high magnitude, at the bottom of the diagram, and bright stars with small or even negative magnitudes for the brightest at the top of the diagram.

Notes

Summary

10m 16s





The resulting diagram is called the Hertzsprung - Russell diagram, or HR diagram. As you notice, stars are not randomly distributed across the diagram but instead follow a well defined sequence which we will now see. What kind of stars are on the diagram, where are they located and what are their physical parameters ?

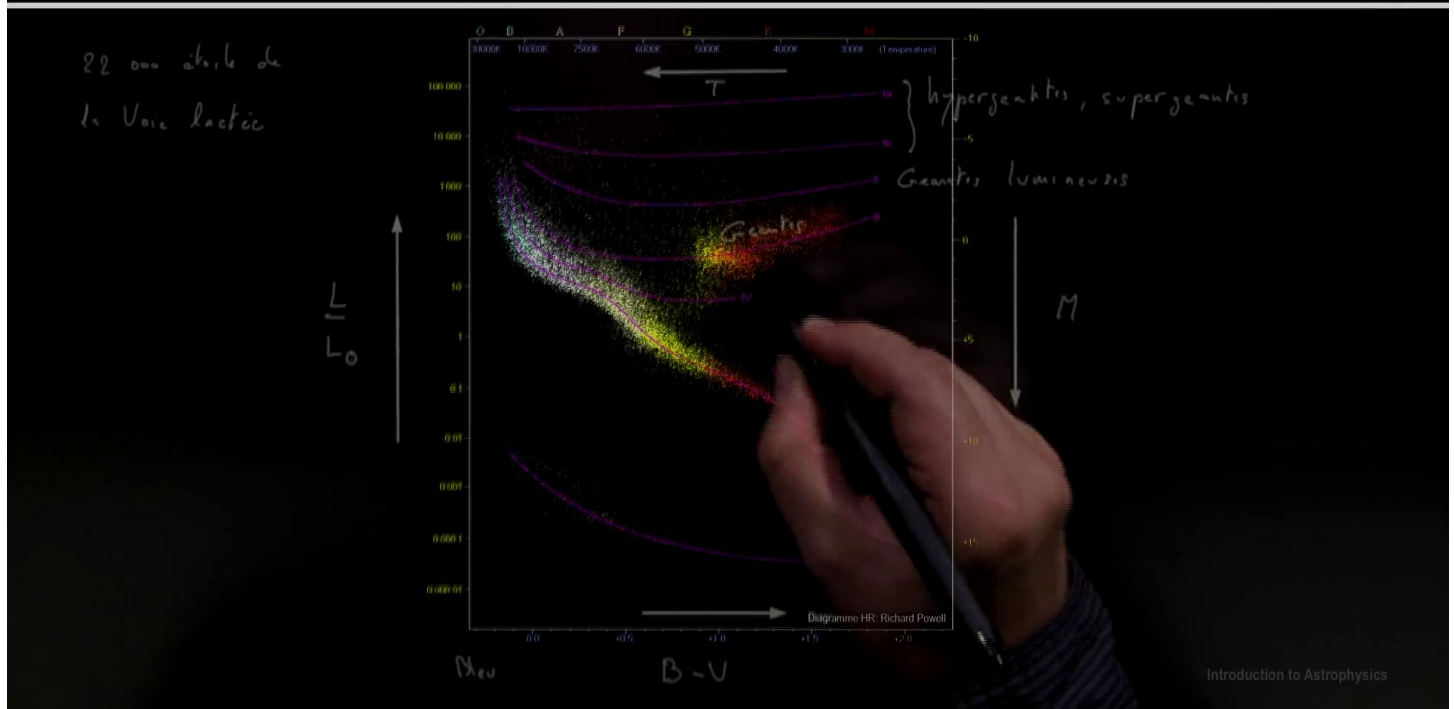
Notes

Summary



11m 11s

Hertzsprung-Russell Diagram



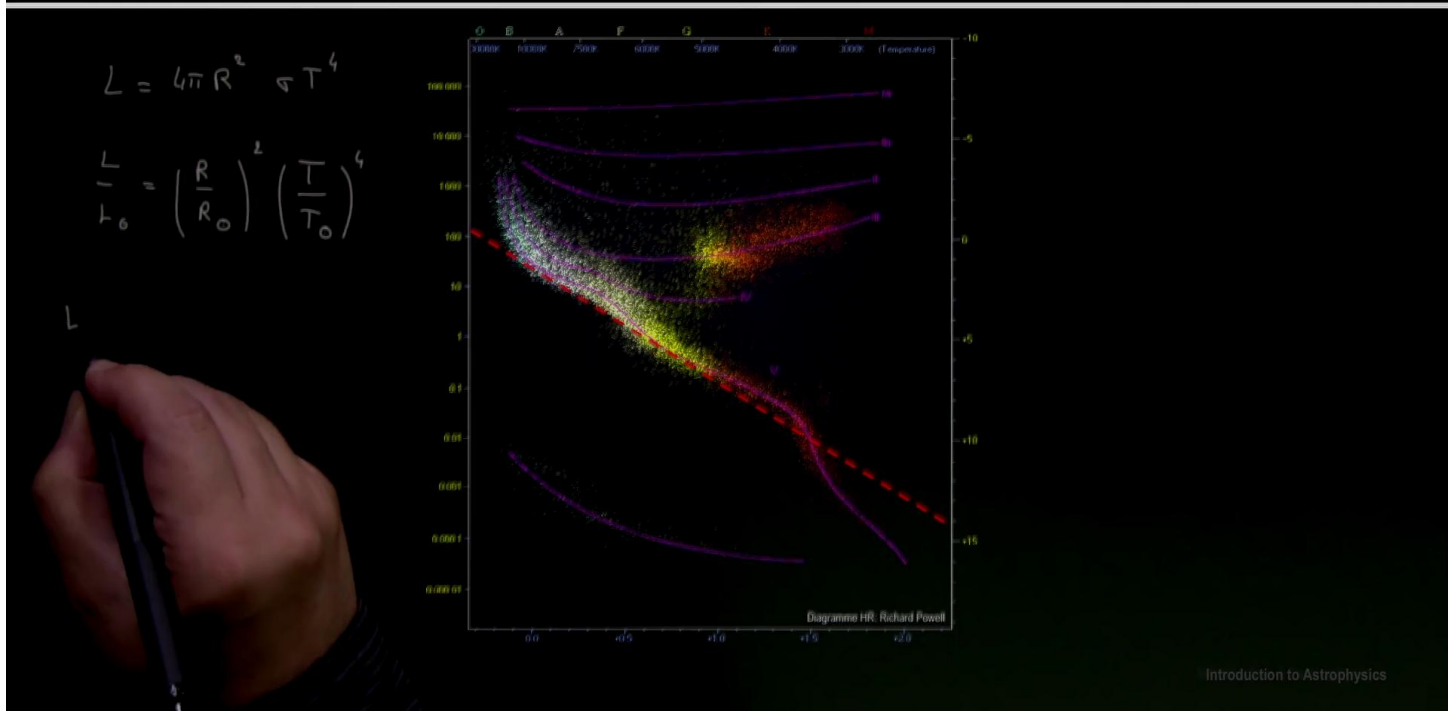
Here is a colour-magnitude diagram, a Hertzsprung - Russell diagram for 22 000 stars of our Milky Way. We have four axes on this diagram. We see at the top the spectral classes, O B A F G K and M, ranging from the hottest temperatures, around 30 - 40 000 Kelvin to the lowest, about 3 000 Kelvin. We will draw the different axes. We have at the bottom an axis representing the colour, B-V for example with the lowest values to the left and the highest to the right. Red colours are on this side and blue ones are here. A blue colour means a high black body temperature. Therefore the top axis showing the temperature varies in the opposite direction to the bottom axis. We have here temperature increasing in this direction. The luminosity axis increases in this direction. Here is the luminosity of stars in units of solar luminosity. In the opposite side we have the axis of absolute magnitudes which increases downwards. The absolute magnitude is the apparent magnitude a star would have if it was located at a distance of ten parsecs. The diagram shows several classes of luminosity. We have here very big and bright stars, hypergiant and supergiant stars. Here are the the bright giants, the giants and the subgiants.

Notes

Summary



Line of Constant Radius



Introduction to Astrophysics

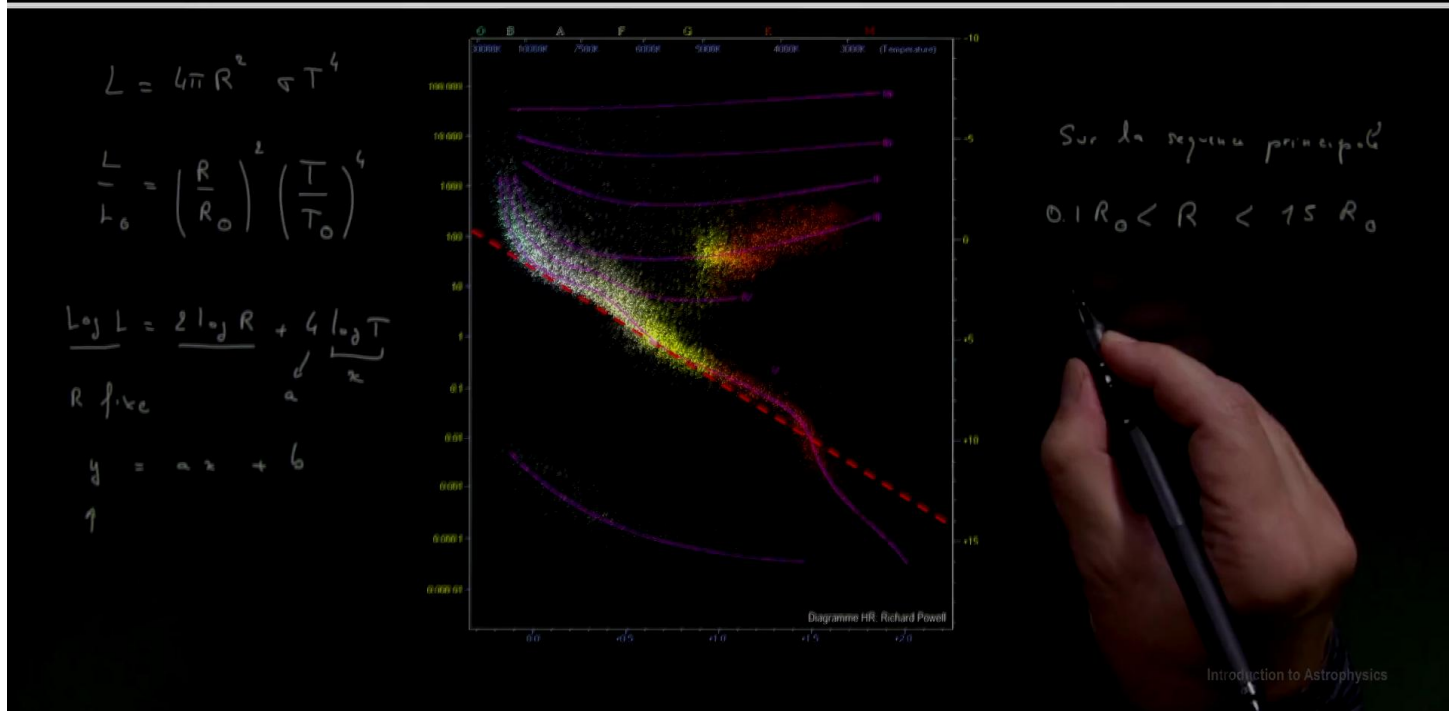
80% of stars are actually on this sequence called the main sequence. Stars burn their hydrogen into helium during all their life on this sequence. It is hence a mass sequence called the main sequence. We have at last the sequence of dwarves. White dwarves are located in this area of the colour-magnitude diagram. We have 22 000 stars of the Milky Way. 80% of stars are located here and the stars which became giants are in this area of the colour-magnitude diagram. We can also draw iso-radius contours on the diagram. We already said that the higher we are on the diagram, the bigger the stars. To understand this, remember that the luminosity of a star depends on its surface. R is the radius of the star, and it is multiplied by σT^4 . This can be rewritten in terms of solar units. We have L over the solar luminosity and here remains the squared ratio of R over the solar radius since both 4π and σ vanished. The same holds for the temperature if one divides by the corresponding solar quantity. We have such a relation that we can turn into a logarithmic one. I do not rewrite each time the solar units.

Notes

Summary



Line of Constant Radius



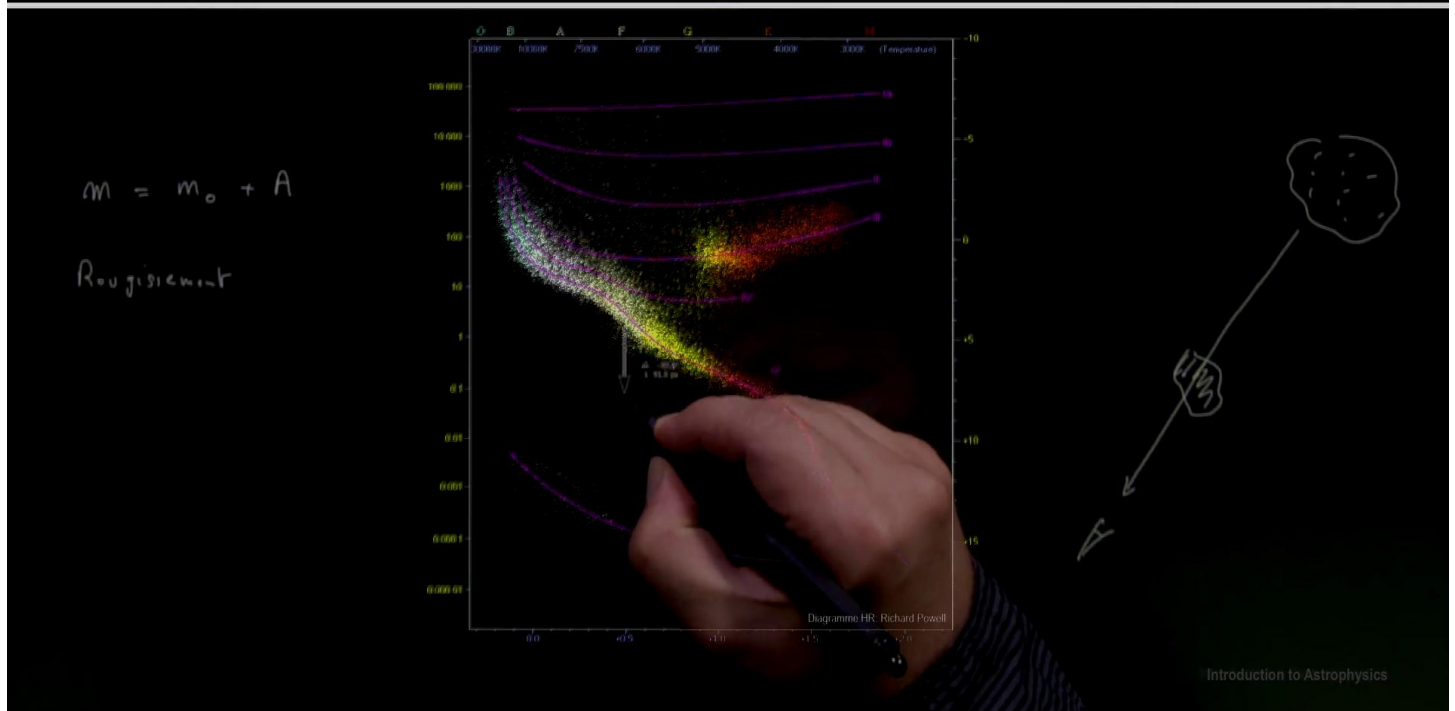
We obtain that the logarithm of L is twice the logarithm of R plus four times the logarithm of the temperature where of course everything is written in solar units : solar luminosities, solar radii and solar temperatures. If R is constant we have the equation of a straight line in a log-log scale : a function which behaves like $y = ax+b$ where y is the logarithm of L , b is twice the logarithm of R , which stays constant since R has a fixed value and here is x , with the constant a in front. This is simply the equation of a straight line in the HR diagram, in the colour-magnitude diagram. This straight line is drawn here and here is the position of the Sun. Now let us change the value of the radius. Here we have one solar radius, one solar luminosity and one solar temperature. When R changes, the value of the parameter b changes as well, therefore the y -intercept point of this line changes. We are translating our line towards the top or the bottom of the diagram. By the way, since we are talking about stellar radius, in the main sequence along this straight line, typical radii range between 0.1 solar radii up to 15 solar radii. It is not the same thing for giant or hypergiant stars.

Notes

Summary



Effect of Interstellar Absorption



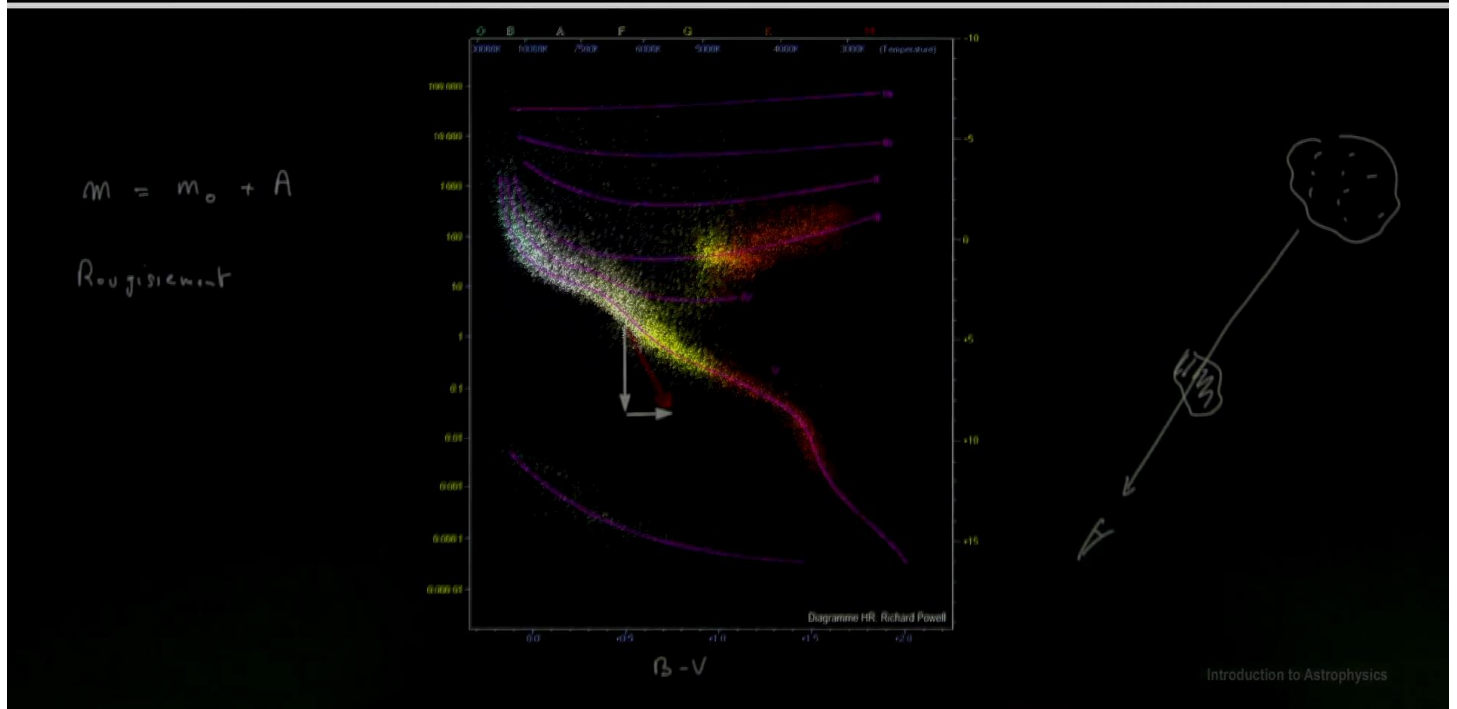
If we consider the whole range of radii for all stars, then the range is obviously much wider and we can reach up to 1000 solar radii for hypergiant stars. On the other hand, dwarf stars can have 1/100th of the solar radius. The range of radii, therefore, spans five orders of magnitude from one extreme radius to the other extreme. A note on the effect of interstellar absorption in a colour-magnitude diagram : Remember that the observed magnitude of an object is the intrinsic magnitude plus some absorption, the positive sign is because, after absorption, a star appears less bright than its real magnitude, so the magnitude will be larger and for that reason we add a positive quantity. We saw that this absorption coefficient depends on the colour : the absorption does not only cause an increase in magnitude but also makes the stars appear redder, as we saw in the chapter on the interstellar medium. If we take the example of this diagram with a stellar population corresponding to a star cluster - this diagram shows the Milky Way, but let us suppose that we observe a homogeneous stellar population, a star cluster - that we observe from Earth with dust clouds in-between, then the diagram will be shifted downwards.

Notes

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Effect of Interstellar Absorption



The sequence is shifted downwards but also reddens, which means that we have a reddening vector in the direction of increasing B-V. In conclusion, the diagram is shifted along a diagonal reddening vector. We therefore have to be cautious on the conclusions of the study of a stellar population when we obtain such a colour-magnitude or HR diagram because it can be affected by reddening on the line of sight of the star we are observing.

Notes

Summary

18m 18s



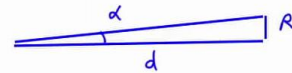
Stellar Sizes

f : flux reçu sur Terre à une distance d

F : Flux à la surface d'une étoile de rayon R

$$f = F \cdot 4\pi R^2 \cdot \frac{1}{4\pi d^2}$$

$$f = F \cdot \left(\frac{R}{d}\right)^2 \quad \alpha = \frac{R}{d}$$



Pour une hypergéante à $d = 200 \text{ pc}$, $R = 1000 R_{\odot} \rightarrow \alpha \sim 0.02''$

Introduction to Astrophysics

A last word on the radius of stars. We said that we can draw isoradius straight lines in the colour-magnitude diagram. We will see here that the radius cannot be directly measured. To understand this, we can look at the flux received on Earth from a star at a distance d and compute this flux as a function of the flux on the surface of the star with a radius r , the luminous flux. The two fluxes relate as follow: the observed flux is the intrinsic flux times the surface of the star times 1 over a sphere of radius d . We then deduce that $f = F (R/d)^2$. R/d is simply the angular radius of the star, the subtended radius of the star at some distance. We have here the radius of the star, the angle α and the distance d . Considering a hypergiant star at a distance of 200 parsec, a very close star with a radius of 1000 solar radii, we get that α is roughly equal to 0.02 arcsecond. 0.02 arcsecond is approximately half the size of the smallest visible detail by current telescopes. It is therefore totally impossible to observe the surface of another star than the Sun. The Sun is the only star on which we see surface features.

Notes

Summary





The colour-magnitude diagram is an incomparably precious tool to characterize stellar populations from the simple measurement of colour and luminosity, the colour being linked to the temperature. Be attentive however that the diagram is valid only if all the objects in it are at the same distance from us, in other words if we show the diagram in terms of luminosity or in terms of absolute magnitudes, namely the magnitude brought to an arbitrary distance of ten parsec. In the next video we will see how stars move in the diagram in the course of their life. It is a whole domain of astrophysics : the study of stellar evolution.

[illegible]

Summary

