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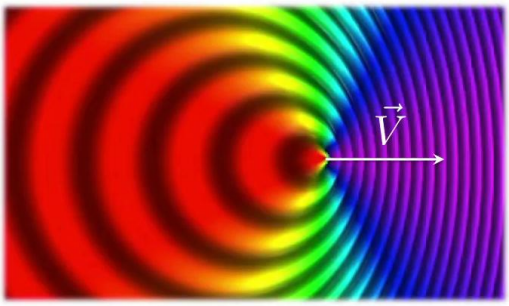
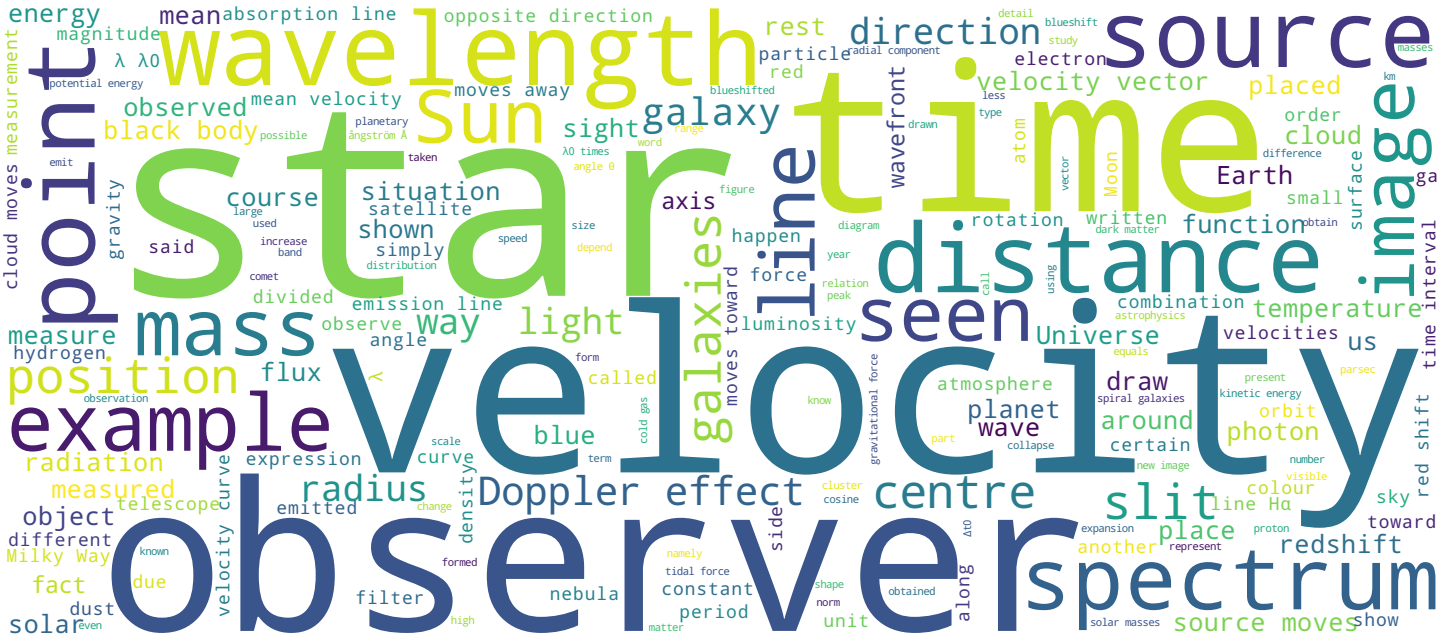


Image: wikipedia

Doppler-Fizeau Effect in Astrophysics

Introduction to Astrophysics; Chapter 3.1

Frédéric Courbin



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Video

EPFL

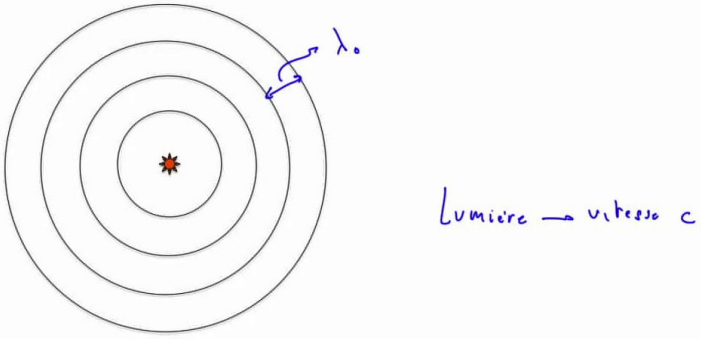
The Doppler-Fizeau is one of the most invaluable tools in astrophysics. It allows a direct measurement of the velocity of stellar objects and so enables the study of their movement. When used along with the Viriel theorem or the Kepler's laws, both bringing in the velocities, it also allows indirect measurement of the masses of celestial bodies. It concerns the effect of the combination of velocities when a source moves with respect to the observer. The wavelength of the emitted wave, it may be sound or light, decreases if the source moves toward the observer, and thus we observe blueshift. The wavelength increases if the source moves away from the observer, in this case redshift is observed. One can see here a moving light source and a representation of the perception of wavelength by the observer. When the source moves forward, the wavelength is compressed and the light seen by the observer is bluer. While moving in the opposite direction, the wavelength increases and so it is seen redder, redshift is observed.

Notes

Summary

0m 04s

Doppler-Fizeau Effect



Introduction to Astrophysics

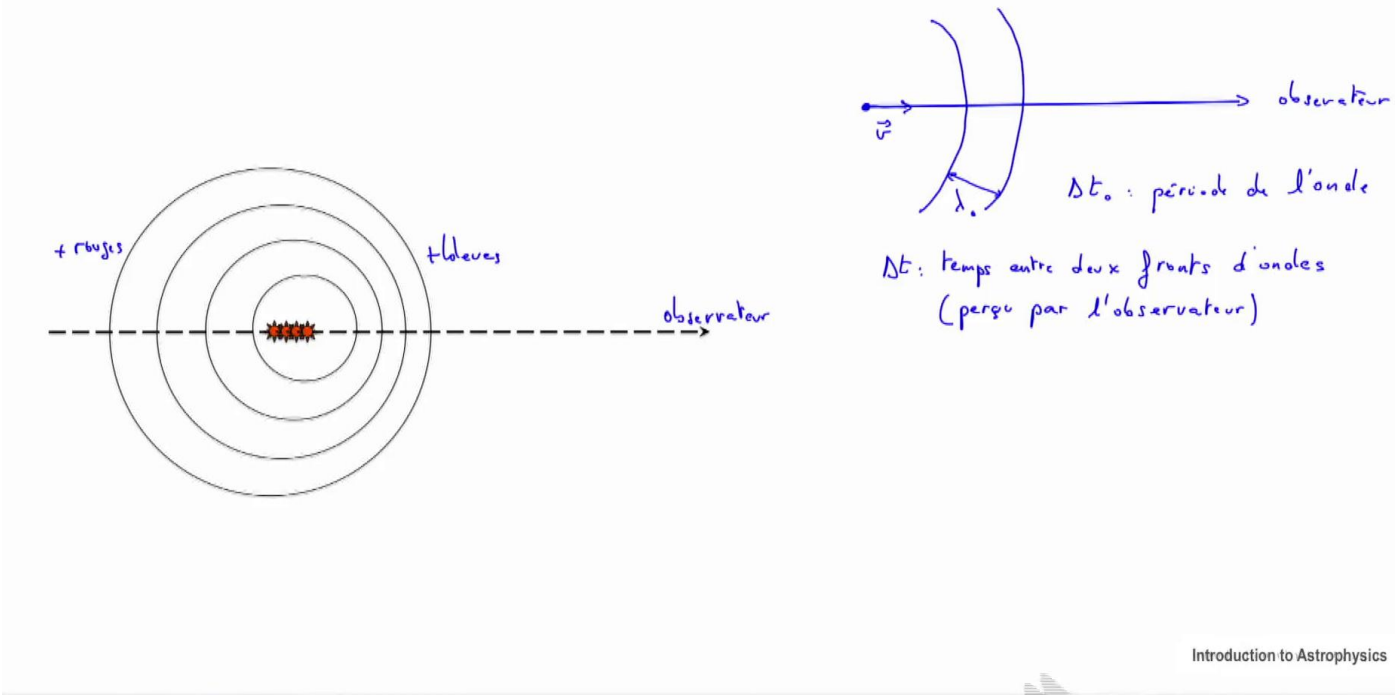
How does the Doppler effect work? Considering at first a source at rest. It was just said that the Doppler effect is due to the combination of movements, the combination of velocities, so the velocity of wavelength propagation and the velocity of the emitting source. Here we have a source at rest emitting a spherical wave with some speed c and wavelength lambda zero (λ0). λ0 is shown here, so wavelength is the pulsation of the wave. In the case of the light, the velocity is equal to c.

Notes

Summary

1m 14s

Doppler-Fizeau Effect



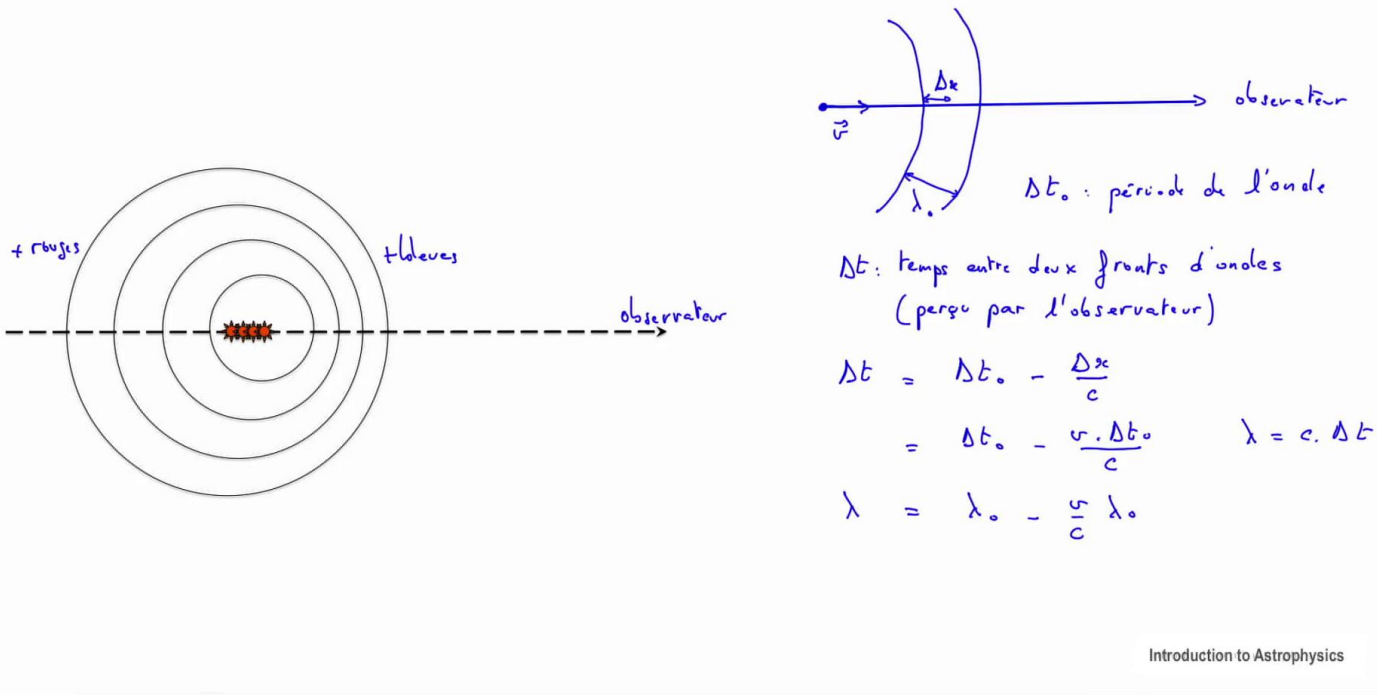
Now, what is happening when the source moves? Here we have a wavefront that was emitted at the time when the source was in this place. The source will continue to emit the wavefronts while moving forward. While this wavefront was emitted, this one was propagating, and so on. Here we arrive at a situation in which the wavefronts were emitted in the same way as when the source was at rest but are combined with the velocity of the source. It can be noticed that the wavefronts are closer to each other toward the observer and further from each other in the opposite direction. How does it work? Here the wavelengths will appear bluer and here redder. Now, let's draw the axis representing the direction of the observer and the source with some velocity v. Then, the source emits the wavefronts so we can draw one here and another one over here. Wavelength emitted by the source at rest, will be called λ0. Now we consider Δt, the time interval between two wavefronts seen by the observer. What will be this time interval? Obviously, if the source is at rest Δt is equal to Δt0, which is also the period of the wave. We can say that Δt0 is the period of the wave, the period of the wave at rest.

Notes

Summary

1m 52s

Doppler-Fizeau Effect



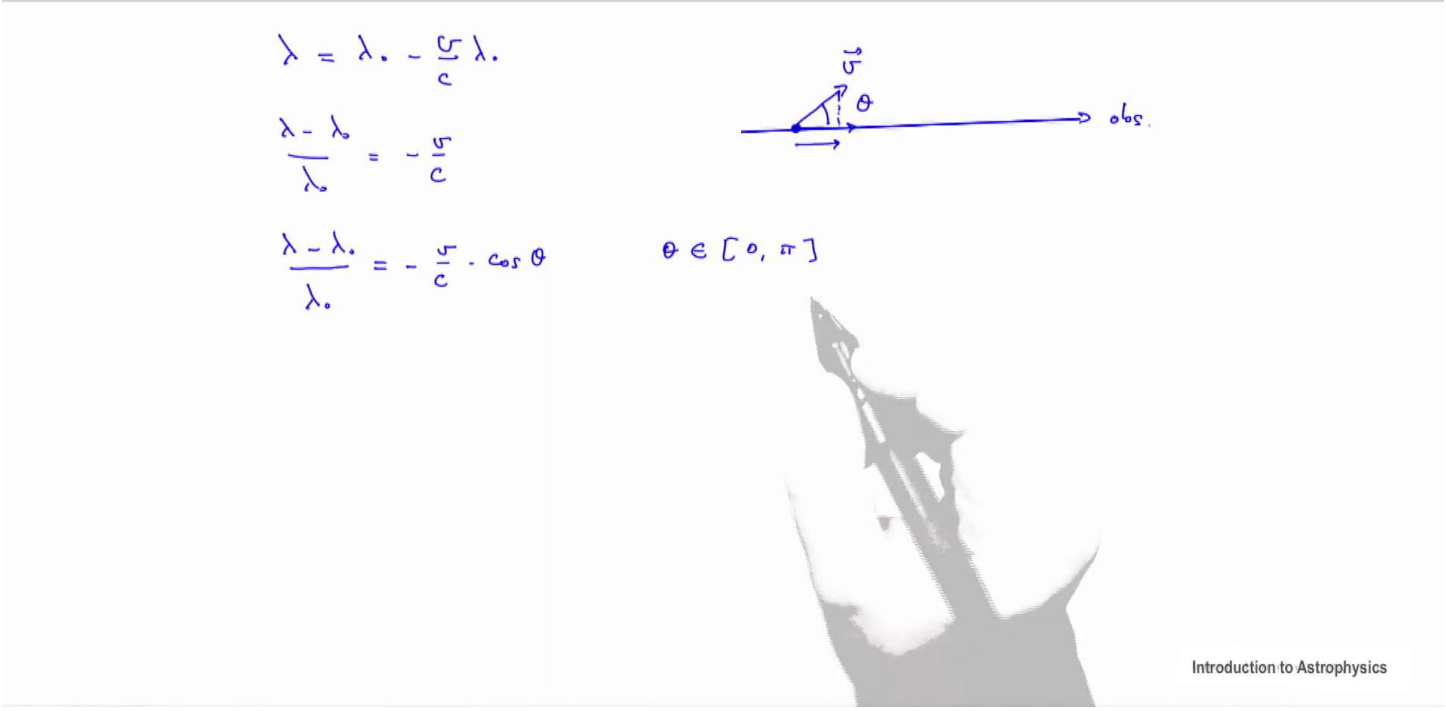
The relation between those two time intervals is Δt = Δt0 if nothing moves. But if the source is not at rest, during the time Δt0 it will move a given distance Δx continuously emitting wavefronts. Finally, the time separating two wavefronts seen by the observer will be equal to Δt0 minus another time interval that is equal to the time needed for the source to move with the velocity v a distance Δx that is shown here. Of course, the velocity of the wave is c. Now, one just has to rewrite Δx as vΔt0 which is the distance the source moved during the time that separates two wavefronts at rest with the velocity v. Obviously, it is divided by c as the wave is propagating with the speed of light in the case of the electromagnetic waves. We also have that λ= cΔt, so it suffices to divide the whole expression by c to obtain that λ, the wavelength seen by the observer, is λ minus v/c λ0. This is the expression for the Doppler effect that combines the wavelength in the reference frame of the source, so, what the source sees while emitting the wave, and the wavelength seen by the observer. Here the case of the source moving toward the observer was presented, but if the source moves away, the sign changes here for +, so we would be in the situation where the wave propagates in a direction opposite to the observer.

Notes

Summary

3m 38s

Doppler-Fizeau Effect



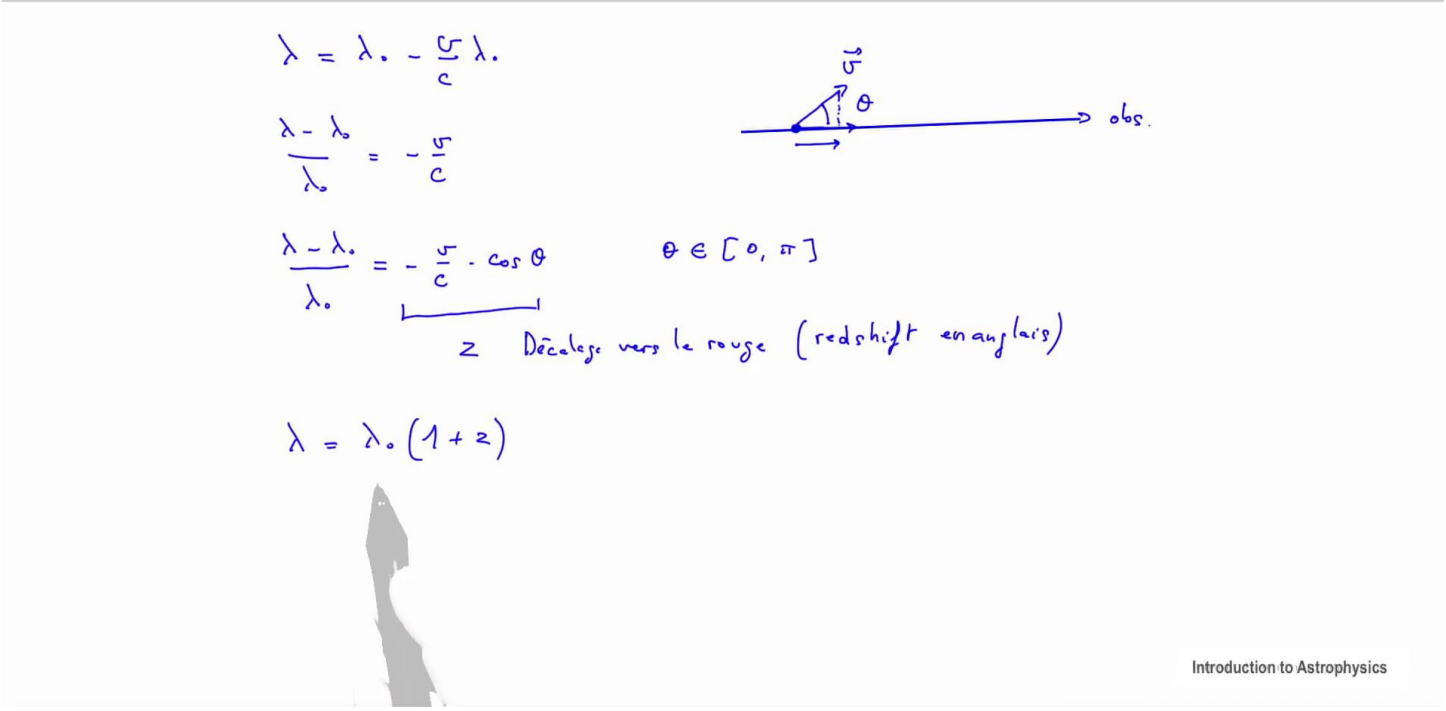
The expression for the Doppler effect can be written in several different ways. In the previous slide it was written in this way. The minus sign is due to the fact that, as was seen in the figure which was just drawn, the source moves toward the observer. The plus sign appears if the source moves away from the observer. It should be noted that the sources do not always move in the same direction as the line of sight to the observer. Let say the observer is in this place. In one situation the source can go in the direction of the observer, but there can also be the case in which the source moves in the other direction. Let this be the velocity vector, the angle θ is the angle between the line connecting the source with the observer and the velocity vector. What counts in this case is the velocity of the source along the line of sight - the velocity that is projected on the line of sight. So in fact the full expression for the Doppler effect Is $\Delta\lambda/\lambda$, or $\lambda - \lambda 0/\lambda 0$, equals minus v over c times the cosine of the angle between the velocity vector and the line of sight connecting the source to the observer. Clearly, θ takes the values in the range from 0 to π.

Notes

Summary

5m 35s

Doppler-Fizeau Effect



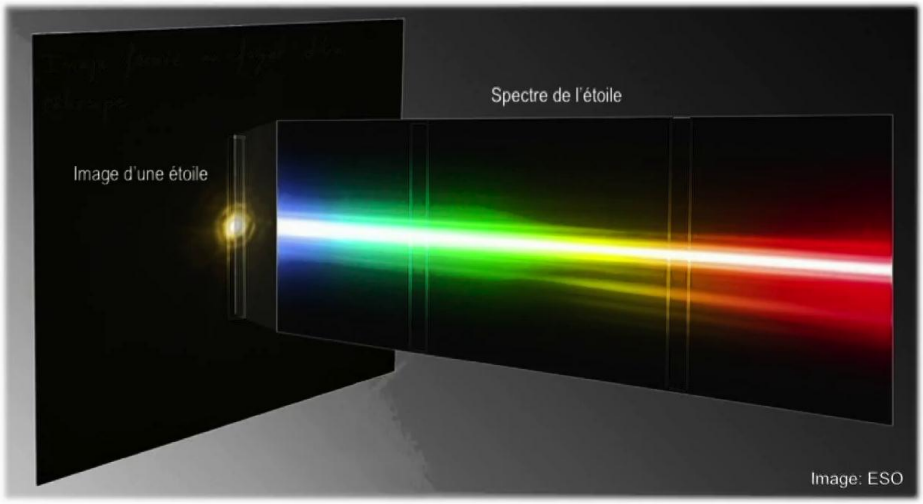
The redshift is often written as z The redshift is often written as z and relates for example to the cosmological redshift. The expression for the Doppler effect can be written in more compact way as λ = λ0 times (1 + z). If the velocity or the redshift of the source is known, one can relate the observed wavelengths to the wavelengths emitted by the source as if it was at rest.

Notes

Summary

6m 56s

Doppler-Fizeau Effect: Measurement



Introduction to Astrophysics

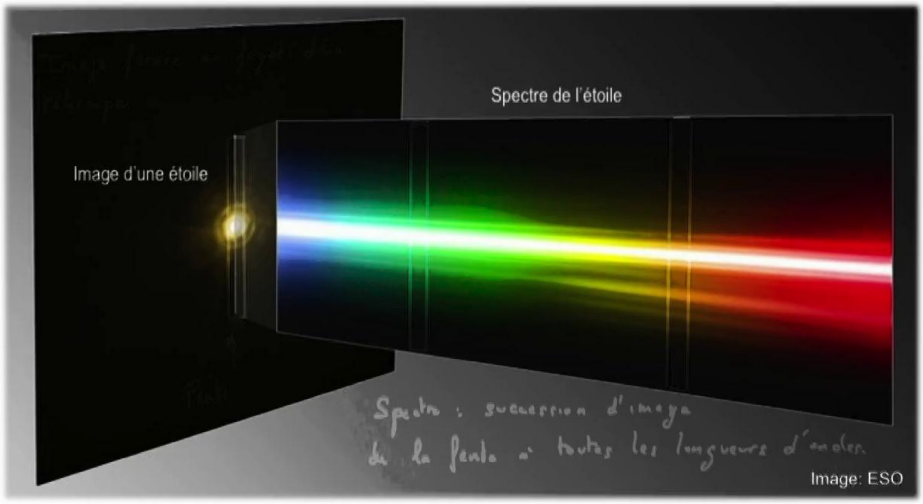
We have already defined the redshift, but how in practice the redshift is measured ? or the blueshift is measured ? Speaking of colours, one can see here an example of the spectrum, the image of a star as seen with a telescope. The image, instead of being directly recorded with the CCD camera or another detector, is divided into many parts from which one is selected. In fact, in focal plane of the telescope a mask is placed in the shape of the slit, as shown here. The image if the slit can be observed with a prism or a diffraction grating. In this way the image of the slit can be observed over the whole range of wavelengths. So the spectrograph works in such a way that the image is formed in the focal plane of the telescope, then a part of this image is selected. Here the star is seen as a point so the light is dispersed from the blue to the red part of the spectrum, as illustrated in the figure. If the observed object was an extended light source, there would be a spectrum like this one at all the points of the slit. So what the spectrograph does is to create an image of the slit at all wavelengths. Here we would have the slit seen in green light, and in this place the image of the slit can be drawn at the wavelengths toward the red part of the spectrum.

Notes

Summary

7m 37s

Doppler-Fizeau Effect: Measurement



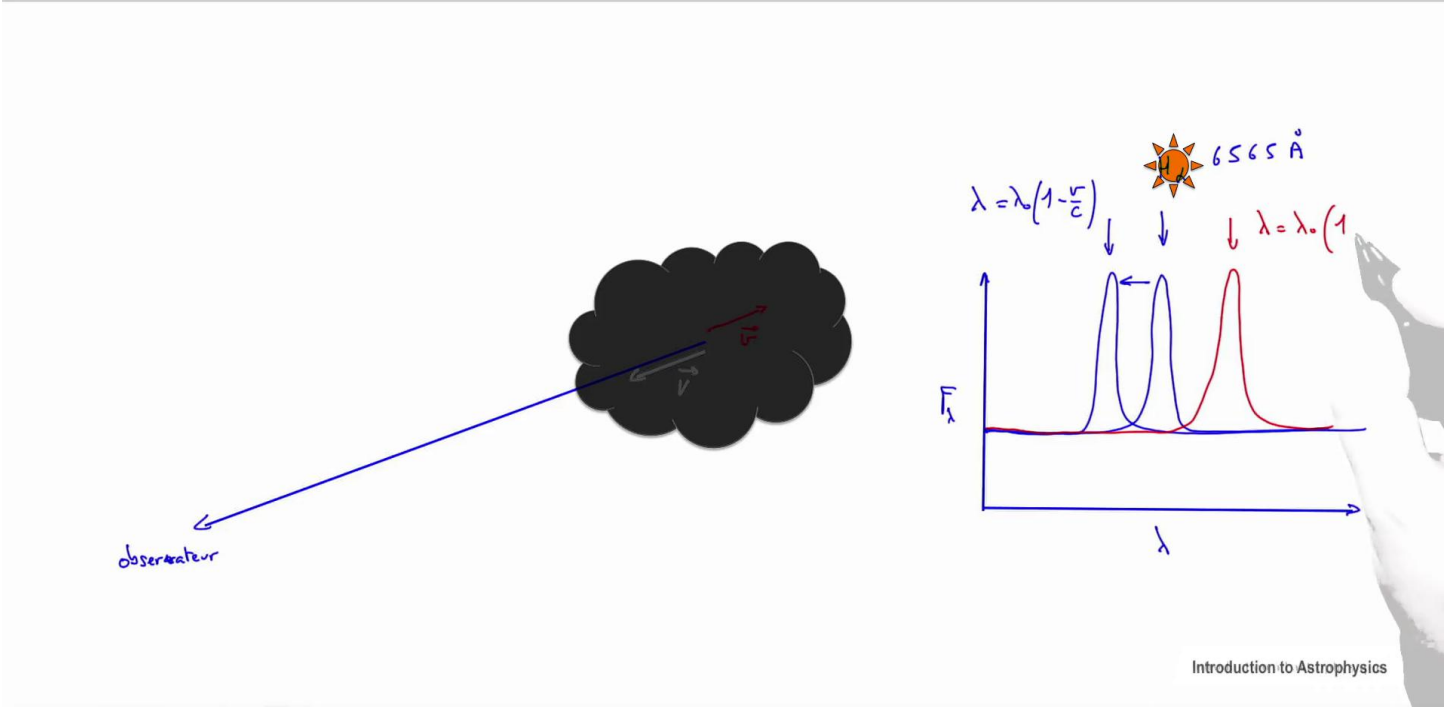
The idea behind this is to create the image of the slit at all wavelengths. The slit is placed here, the image of the slit is created. The spectrum is the combination of the successive images of the slit.

Notes

Summary

9m 02s

Example of a Gas Cloud in Motion



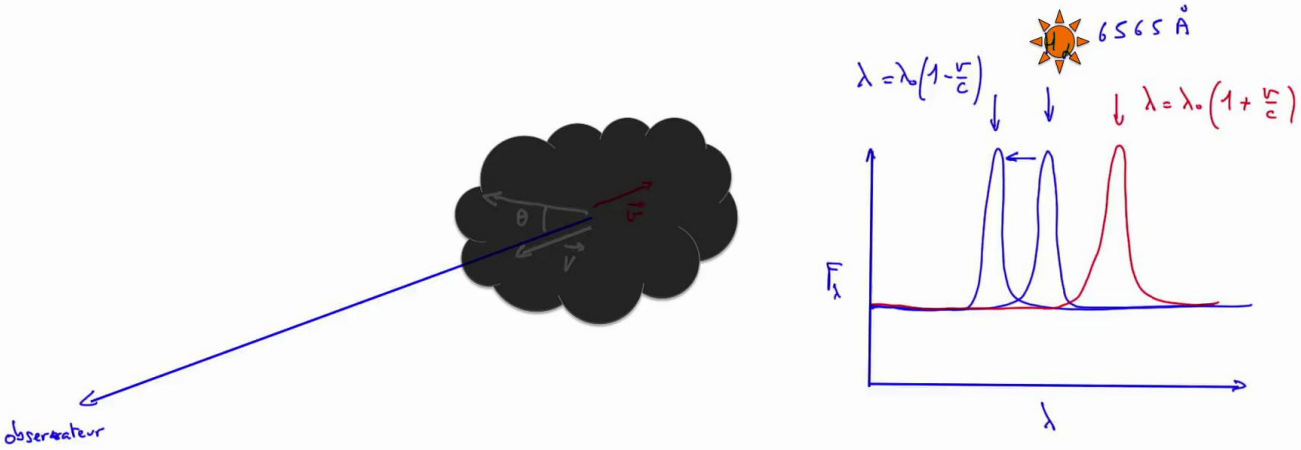
Once we have the spectrum, how the redshift can be measured in practise? As an example we show a nebula or a gas cloud emitting emission lines. This gas cloud moves for example in the direction of the observer that is placed here. In this situation the cloud has some velocity towards the line of sight to the observer, let it be the velocity v. In this case a blueshift is expected to occur. Let's draw the spectrum of this object. We place two axes and draw a simple spectrum that is just an emission line. On the y axis we have the flux Fλ, and the x-axis corresponds to the wavelength. If we consider this simple spectrum composed of one emission line, for example the hydrogen line Hα at 6565 ångström (Å), what will happen to this line ? In this case we have a blueshift so the line shifted toward the blue will be seen here and in this case the wavelength of the line will be λ =λ0 times 1 minus v/c. Conversely, if the velocity vector is in the opposite direction, so, when the source moves away from the observer, then we observe a red shift and the spectrum shifts toward red and will be seen in this way. The redshifted line will have the wavelength of λ= λ0 times 1 plus v / c.

Notes

Summary

9m 16s

Example of a Gas Cloud in Motion



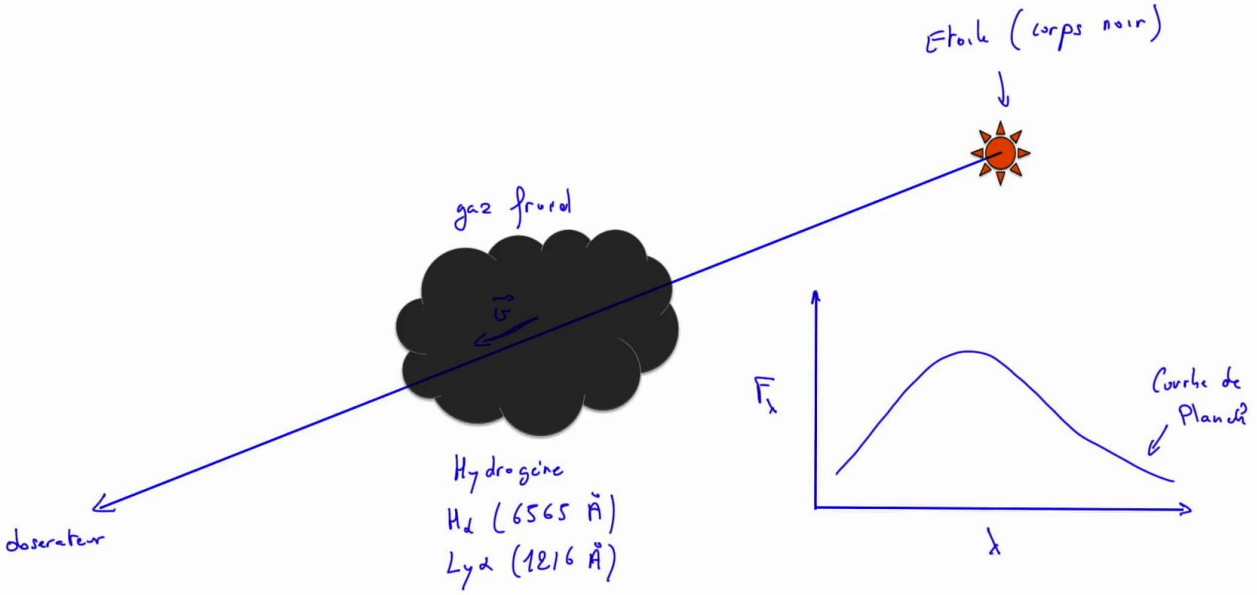
So in this case the cloud moves toward the observer. If the cloud moves in a different direction than along the line of sight to the observer, we can choose for example this direction, one has to multiply the velocity v by the cosine of the angle θ.

Notes

Summary

11m 12s

Example of a Gas Cloud in Motion



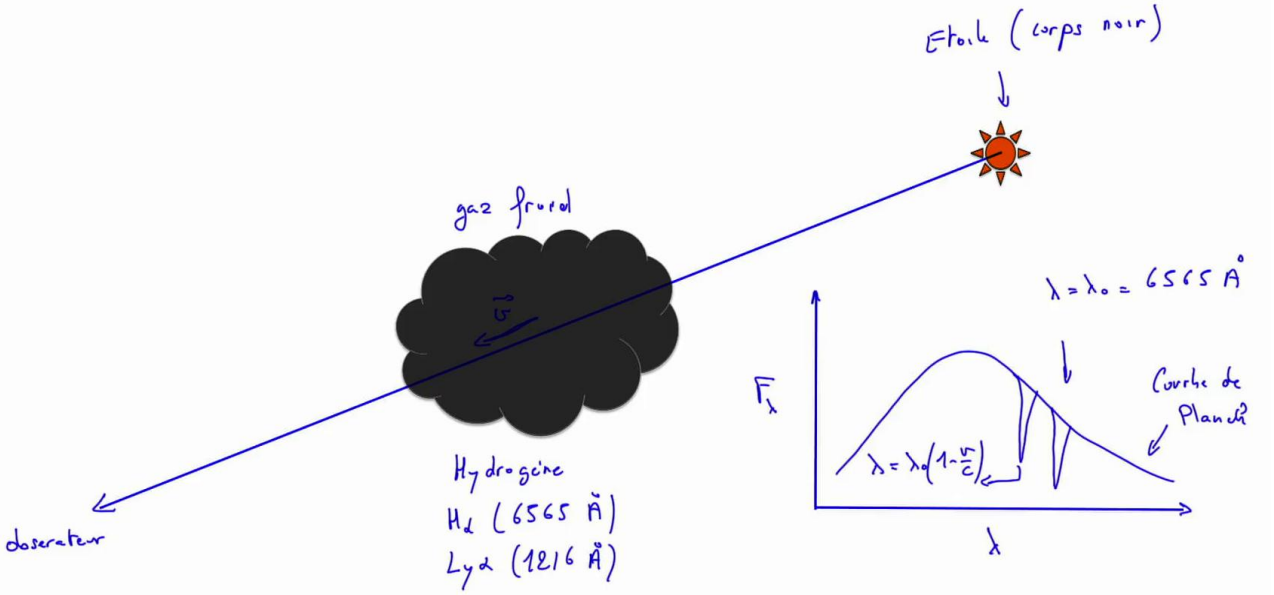
We have just seen an example of a cloud emitting a line, in our case the line Hα. Now, we can look at the situation in which there is an absorption line. Obviously, Doppler effect applies also in this case. Here we have a star whose spectrum is that of the black body. The light of the star passes through the cloud composed of cold gas and propagates toward the observer. The cloud of cold gas contains atoms, for example hydrogen but it can also include other atoms. We can have for example the line Hα that we have just seen with the wavelength 6565 ångström (Å), so the optical line, or a line of the Lyman series - Lyman α, at 1216 ångström (Å). We have the situation in which there is a cloud of cold gas that absorbs light, creating an absorption spectrum seen superposed with the spectrum of the star. Firstly, we draw the velocity vector of the cloud and the spectrum, as before the y axis corresponds to Fλ, x axis to λ. We could also have Fν, ν if we would like to present the spectrum in a different way. This is the curve representing the black body spectrum, the Planck spectrum, as an example it could be the spectrum of the Sun at 5780 K.

Notes

Summary

11m 31s

Example of a Gas Cloud in Motion



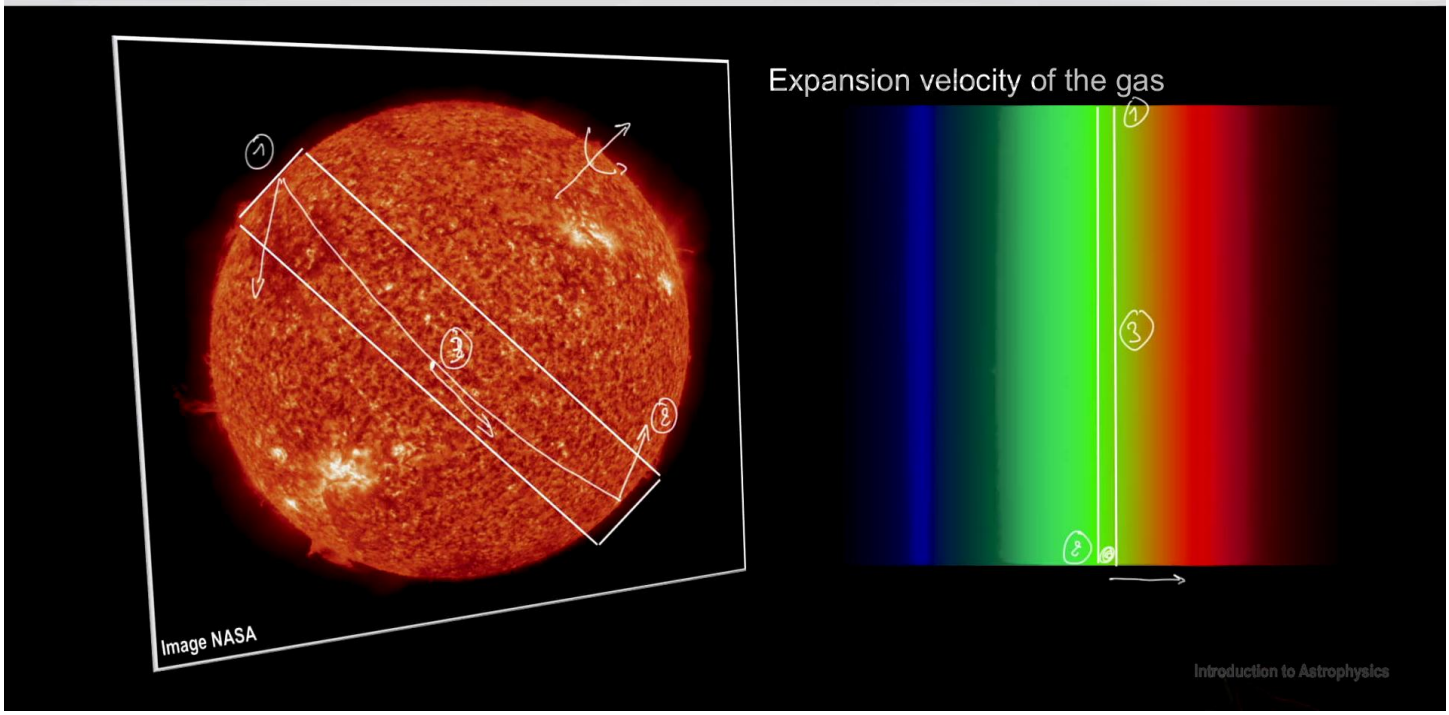
What will be observed depends on the velocity of the cloud: if the cloud is at rest, an absorption line, for example the line Hα, will be observed at λ equal to λ0 =6565 ångström, as v = 0. If the cloud moves toward the observer the line will be blueshifted and the same absorption line will be observed but toward the blue part of the spectrum. In this case λ = λ0 (1-v/c). As we have seen, the Doppler effect applies for the emission lines, as well as for the absorption lines.

Notes

Summary

13m 15s

Doppler-Fizeau Effect: Measurement



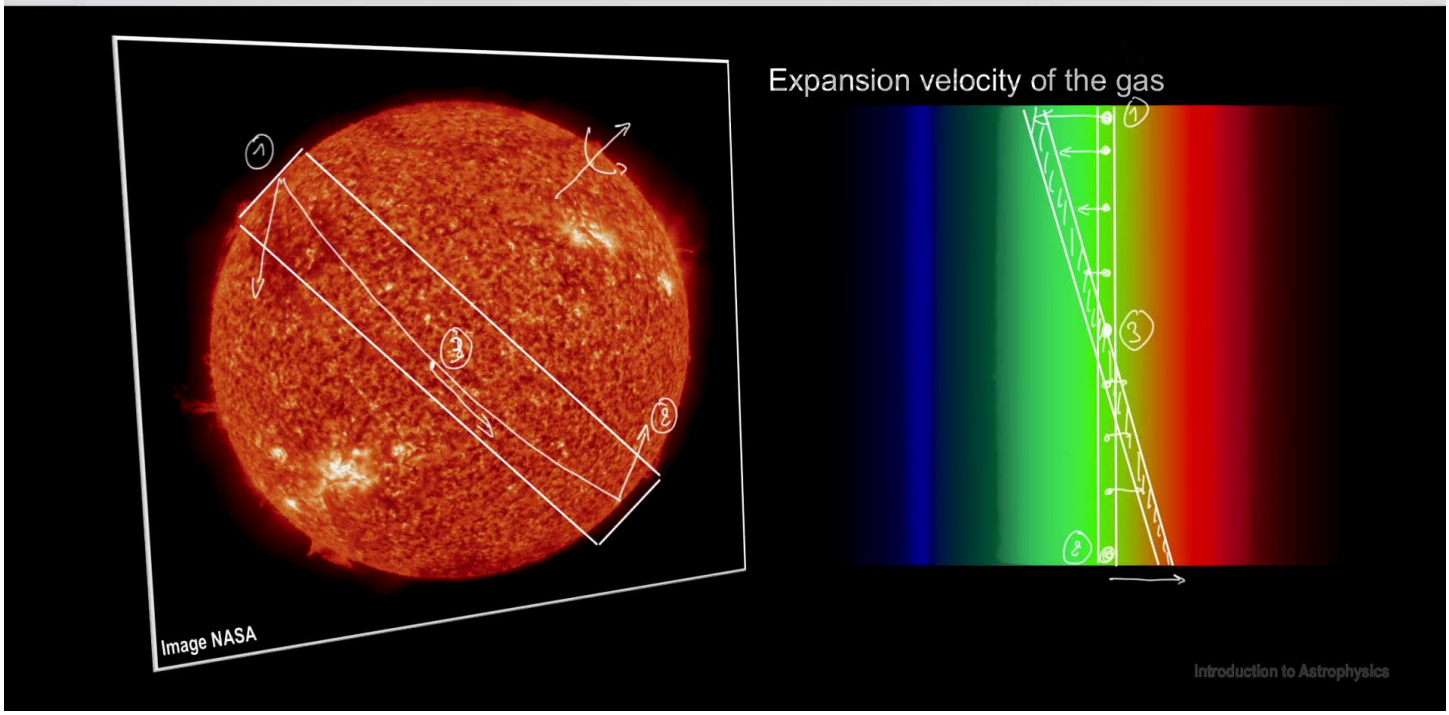
Now we will see in details how the Doppler effect can be used. As an example we take the case of the rotation of the Sun or of the stars in general. We draw the rotation axis of the Sun and the solar equator. Then, we can take the solar spectrum by placing the slit in this way in order to select a piece of the Sun. Here, the slit is drawn quite large on purpose. In this position, at the border of the Sun, the velocity vector is directed toward the observer, it will be at position 1. On the equator, the velocity vector is tangential, this will be position 3. In this place the velocity vector has the opposite direction than at position 1, it can be called position 2. It was said that the spectrum is the image of the slit at different wavelengths. We will represent it in this image; drawing the slit thicker than before and selecting a line that would be in the green part of the spectrum. Then we will look at the points 1, 2 and 3 on the slit. The point 3 is in this place, the point 1 in the upper part, and the point 2 is here. We can see that the point 2 is moving away from us so the point that is in this place will be redshifted.

Notes

Summary

14m 06s

Doppler-Fizeau Effect: Measurement



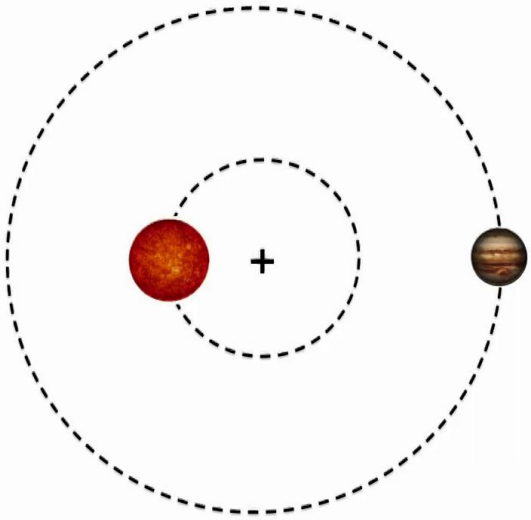
The velocity at point 3 does not have a radial component so this point stays in the same place its wavelength being equal to $\lambda = \lambda 0$. Point 1 is moving in our direction so it will be blueshifted. One can imagine the series of points for which the redshift will be measured. There are different velocities so in this place the points are blueshifted. In this way, a new image of the slit can be seen when all the points are shifted in such manner. If the wavelength at rest is equal to $\lambda 0$, once shifted, all the wavelengths $\lambda 0$ will be placed on the new image of the slit. Consequently, all the emission or absorption lines of the Sun will be seen inclined in the spectrum. Obviously, if the star was rotating in the other direction the new image of the slit would be tilted also in the opposite direction.

Notes

Summary

15m 43s

Search for exoplanets



- Distance étoile - planète faible
- Contraste lumineux étoile - planète très grand

→ Très difficile de voir directement une exoplanète

Introduction to Astrophysics

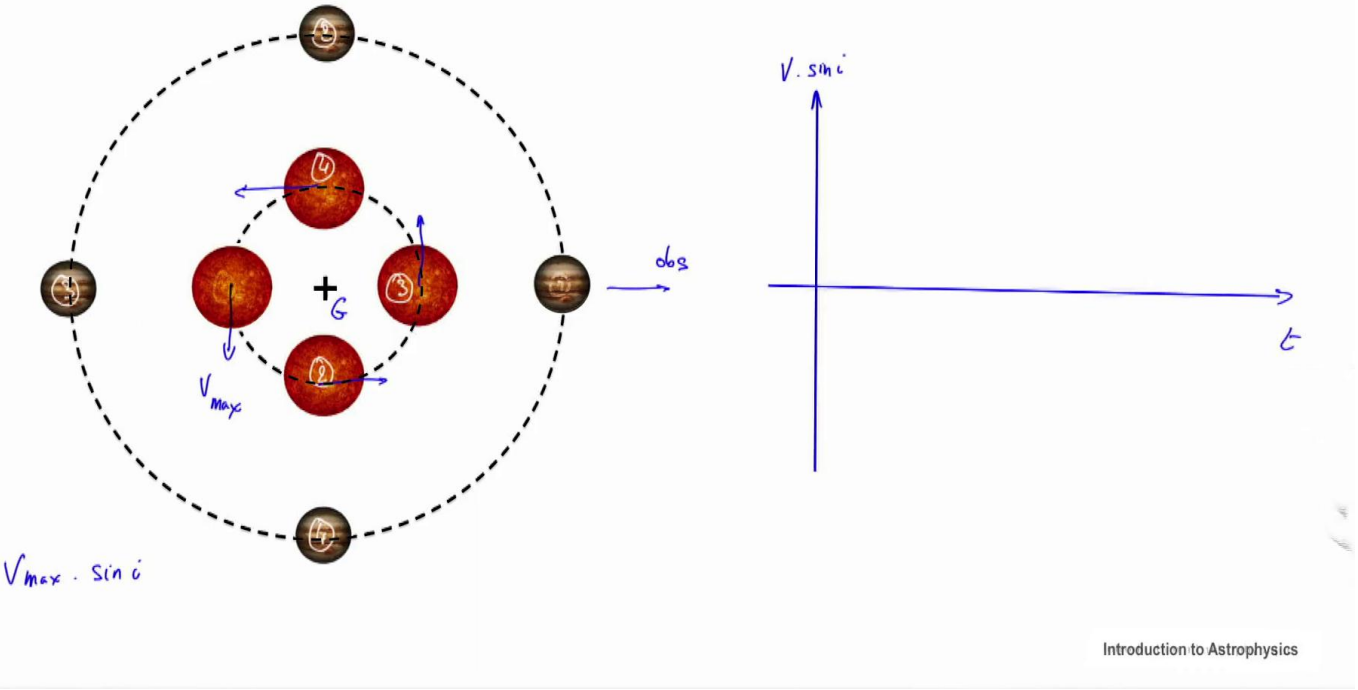
Now let's look at an important application in astrophysics, namely the search of the exoplanets using the measurement of the radial velocities of the stars that host a planetary system outside the Solar system. It is not an easy task because the distance between a star and a planet is small, and the luminosity contrast between those two is generally very high. The contrasts can reach tens of magnitude, in some cases even more. So it is difficult to directly detect an exoplanet with direct imaging around the host star.

Notes

Summary

16m 52s

Search for exoplanets

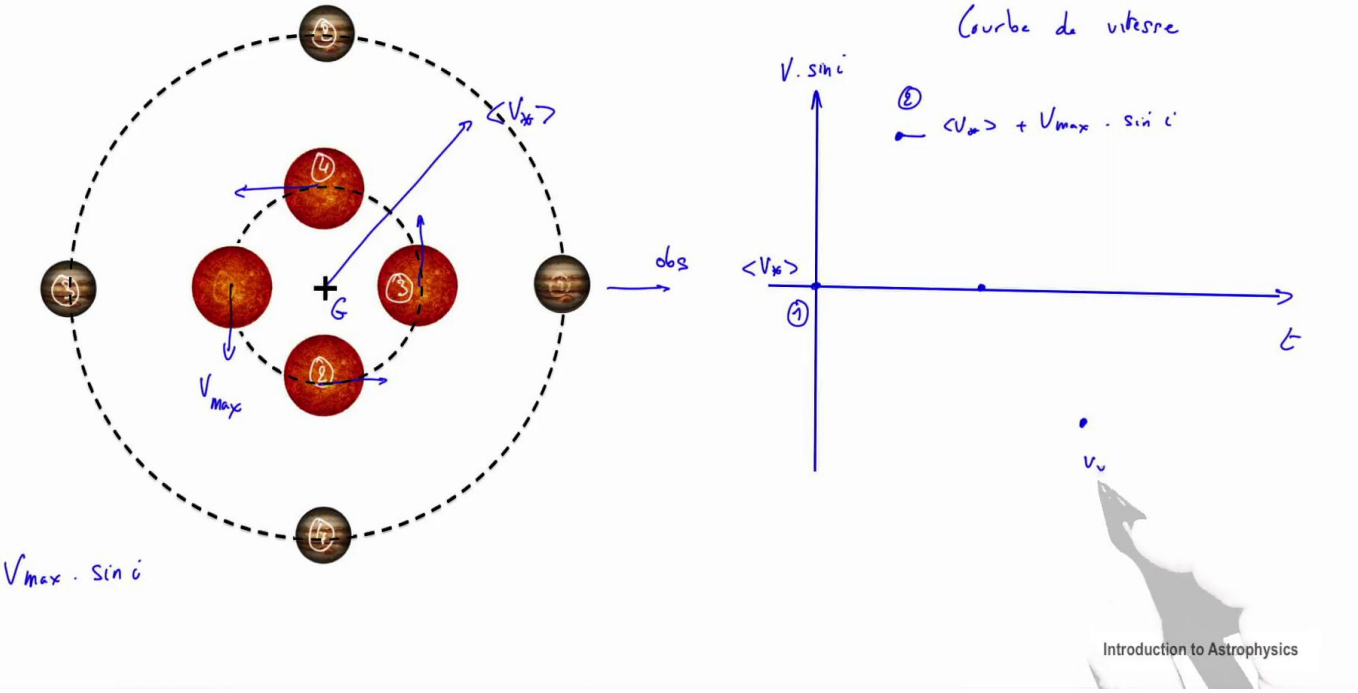


Let's see what happens when the planet rotates about the centre of mass of the star-planet system. Representing a few positions during the planet's rotation, and drawing what is happening at each position; Here is the star and its planet are at position 1. In this place we mark the centre of gravity of those two objects, here position 2 of the star and the corresponding position of the planet. At position 3 the planet is here, while for position 4 here. Of course each time the velocity vector at positions 1, 2, 3 and 4 is equal to vmax. One has to pay attention, to the fact that the velocity is equal to vmax times sinus i, which is measurable with spectroscopic measurements, on account of the inclination of the planetary orbit with regard to the plane of the sky. This is the direction to the observer. When the spectrum of the system is available it is only the star that is visible and not the planet. Those are the oscillations of the star's velocity that will be detected around the centre of mass of the star-planet system. Let's draw this situation. The important data can be obtained from the star's spectra taken at regular intervals. The velocity will be presented on the y axis, so v sin i, as a function of time.

Notes

Summary

17m 34s



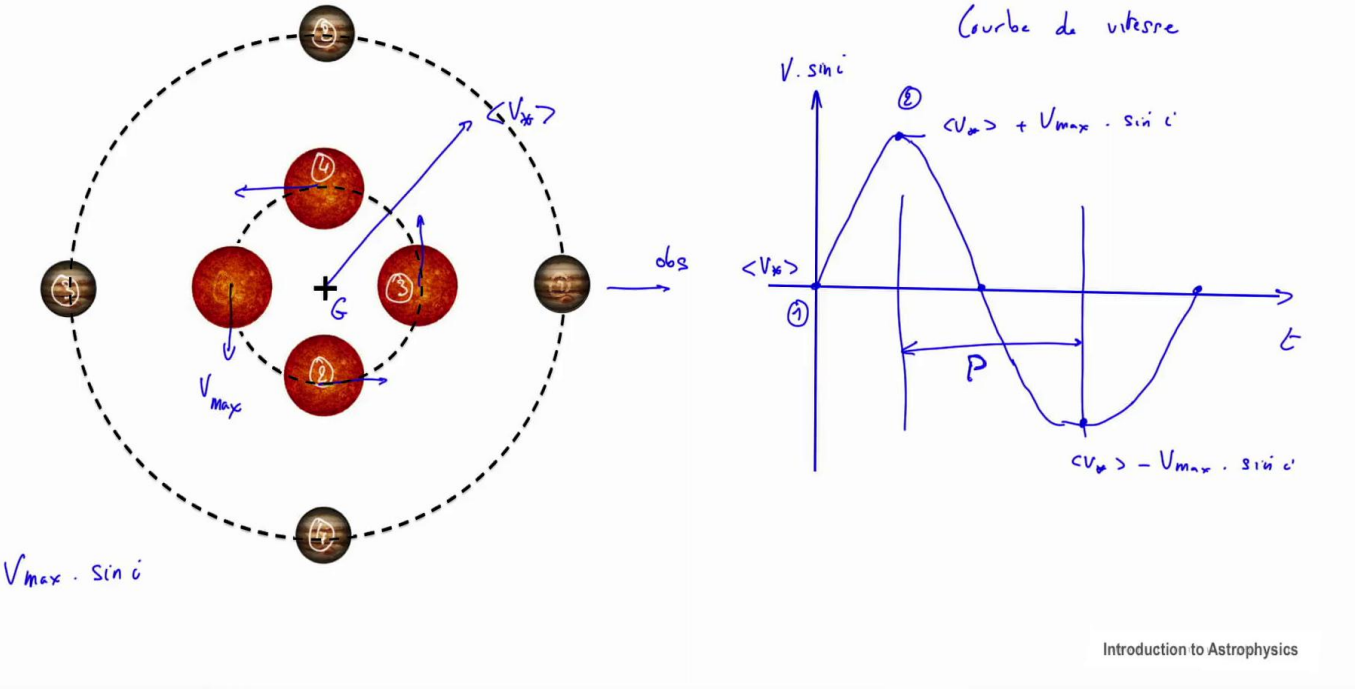
This curve is called the velocity curve. Obviously, the stars in the Galaxy have some velocity so we need to centre the axis on the mean velocity of our star in the Galaxy. This velocity is typically equal to some tens or hundreds of km/s. The mean velocity can be represented in this way with an arbitrary direction. This vector represents the mean velocity of the star in the Galaxy, so the velocity of the centre of mass of the system. The star rotates about the centre of mass, and we can put the data coming from the different positions on the diagram. Starting with position 1: if the observer is here, there is no radial component of the velocity and no change observed with respect to the mean velocity. On the contrary, for position 2 the velocity vector is radial with respect to the observer, and a point corresponding to this position can be placed here. This velocity is equal to v mean +v max sin i. Position 3 corresponds to position 1, with the difference that this point is obtained further in time. As before, the velocity is equal to the mean velocity because of the lack of the radial component. Position 4 is similar to position 2 but the velocity vector has the opposite direction so on the diagram the point should be placed on the other side.

Notes

Summary

19m 33s

Search for exoplanets



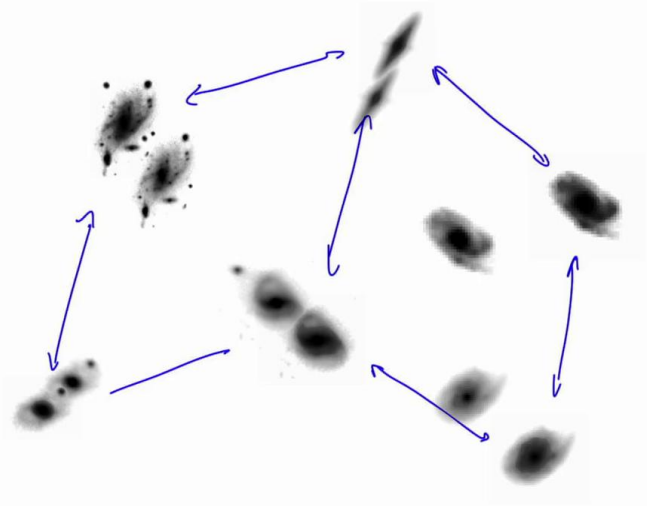
The velocity in this case is equal to v mean minus v max times the sine of the inclination. By connecting the points we obtain the velocity curve which is obviously periodic. So what we can measure directly is the rotation period of the star around the centre of gravity which is equal to the rotation period of the planet around the centre of gravity, as we are in the frame of the centre of mass of the system. That kind of curve, the velocity curve of a star, suffices to deduce the period of rotation of the planet and the maximal velocity of the star rotating around the gravity centre.

Notes

Summary

21m 06s

Hubble Law: Expansion of the Universe



$V_{galaxie} = H_0 \cdot d$

$\downarrow$ Doppler $\quad$ $\downarrow$ module de distance

Introduction to Astrophysics

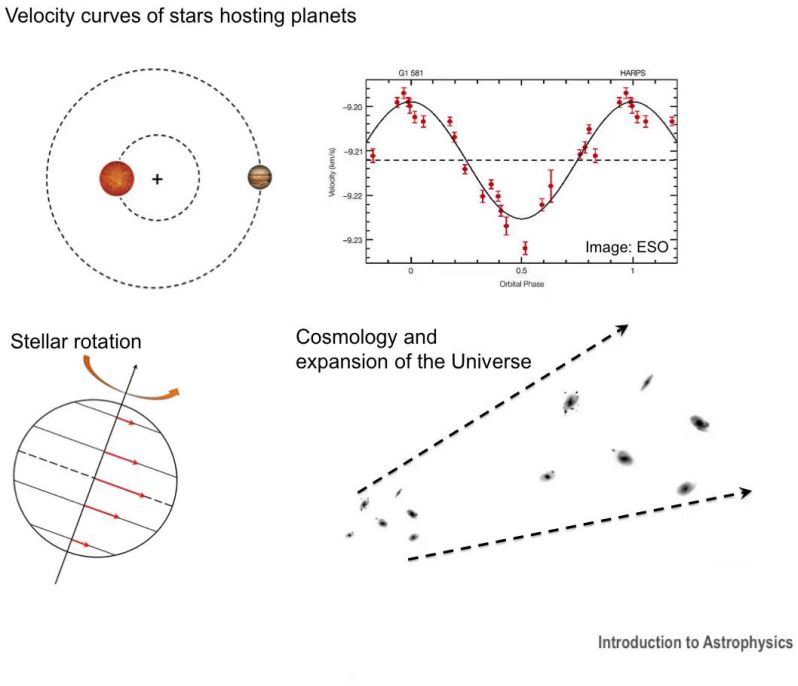
This was another important application of the Doppler effect. At last, the Hubble law, so we do now a drastic change in spatial scales and enter into the domain of cosmology. As the Universe expands, the distances between the galaxies, schematically presented in the figure, will increase with time. Because of this expansion so, after some time the galaxies have moved away from each other. The metric expanded and all the arrows drawn here on the image become larger. Due to the increased distances, if the observer was placed in one of those galaxies he/she would observe the other galaxies moving away. The Hubble law relates the velocity of galaxies that move away, this velocity being completely radial with respect to the line of sight to each galaxy. so the velocity of these galaxies is proportional to the distance between the galaxies. These velocities of the galaxies are measured using the Doppler effect, the distance, as it will be seen later, is measured with the distance modulus. Then, the proportionality constant can be deduced.

Notes

Summary

21m 54s

Doppler-Fizeau Effect



As we have seen during this lecture, the Doppler-Fizeau effect has lots of applications in astrophysics: from the search for exoplanets using velocity curves of stars hosting planets, to the rotation of stars and to the measurement of the temperature of the interstellar medium, or to the measure of the rate of expansion of the Universe using the recessional velocity of galaxies. We will get back many times to the Doppler effect during this course. It is worth mentioning that each time a theoretical model, an idea or a concept predicts velocities, the practical way of measuring them will be by using the Doppler effect.

Notes

Summary

23m 06s