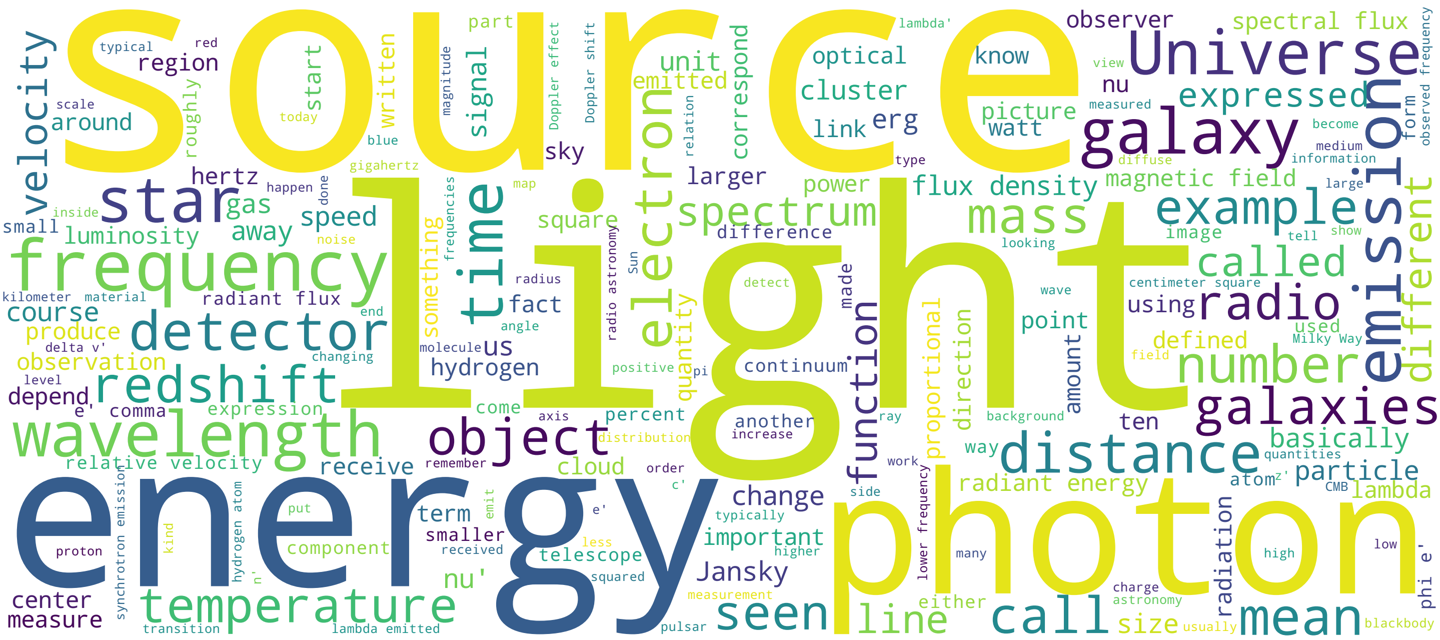
Photon Propagation

The Universe At Radio Wavelengths

Jean-Paul Knieb



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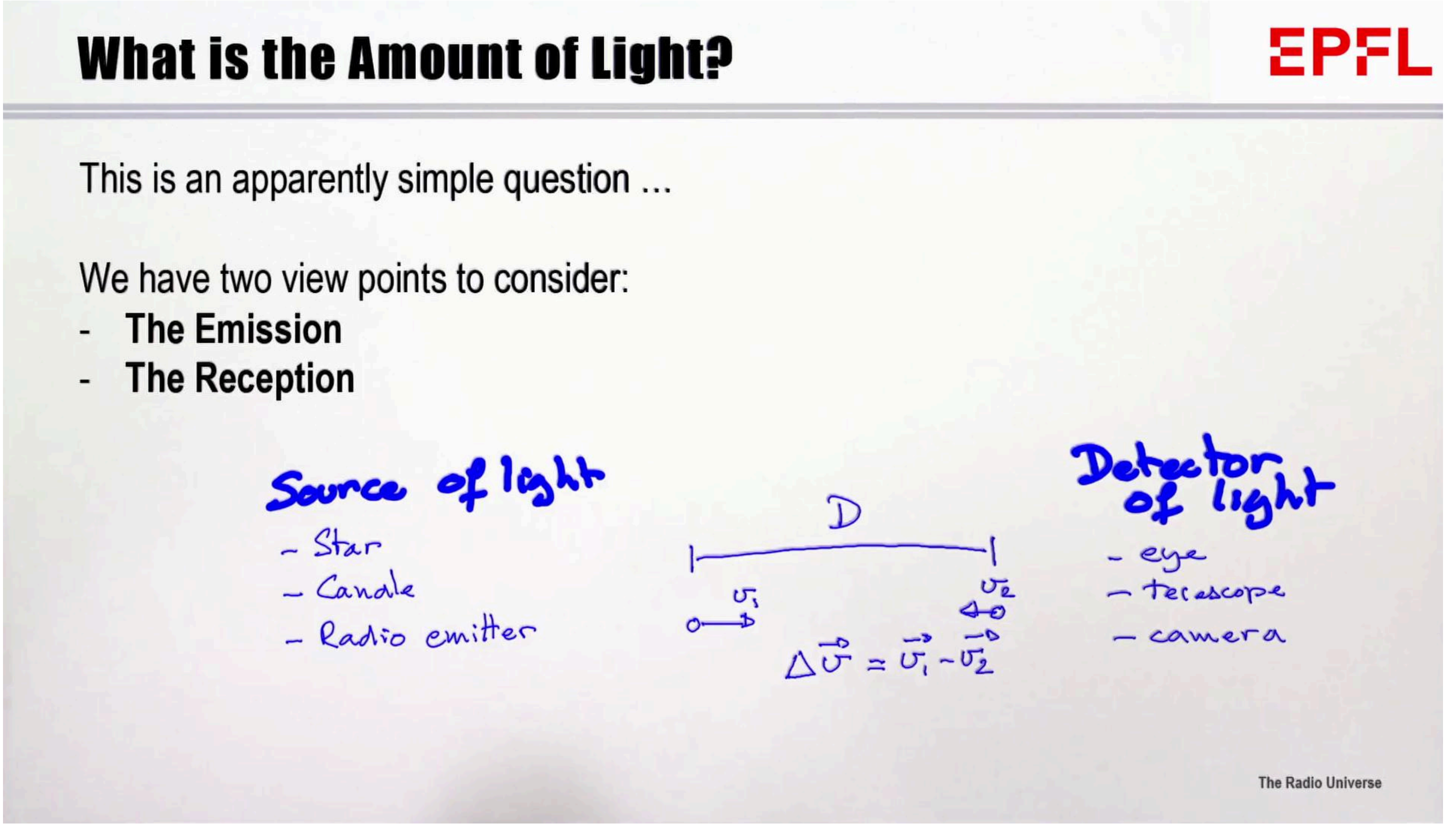
Video

We have seen that the photons are considered as the light particle but can also be understood as a wave carrying the electromagnetic energy. This duality between particle and wave can explain the different properties of the light in terms of diffraction and refraction. Now we will explore some of the basic properties of the light addressing the following questions. What amount of the light do we measure? Are the light flux changes with distance? What is the Doppler effect? How to explain the blue and redshift? And what can we learn from this? We will conclude that the study of the light we receive from a distant source can teach us about the distance between the source and the receptor and the relative velocity between them.

Notes

Summary

0m 05s

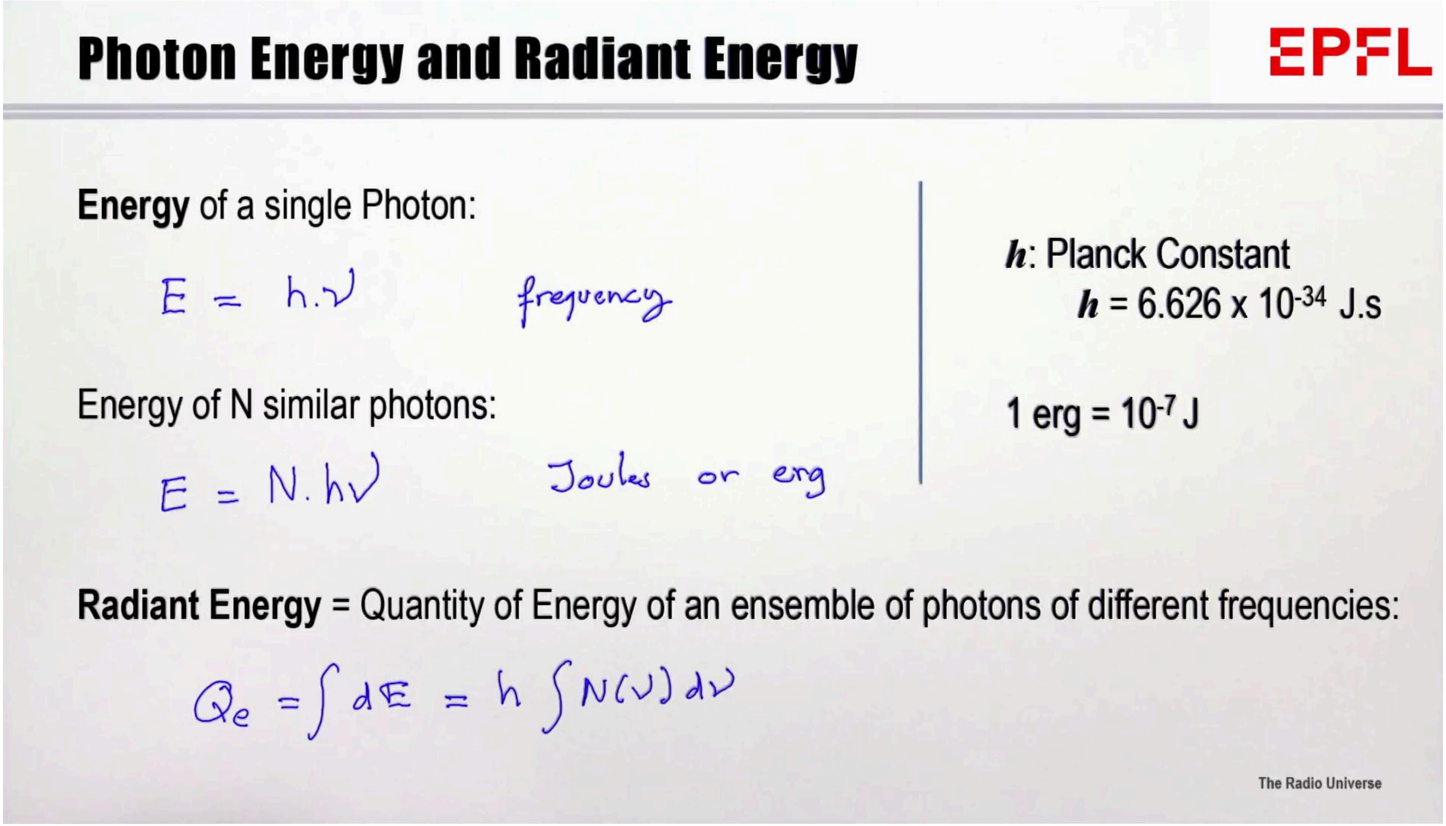


An important question when we talk about photons and energy and light is what is the amount of light? This is an apparently simple question but maybe that's not the case. First, we have to consider two viewpoints. We have the point of the emission of the light and we have the point of the reception of the light. Let's start with the source of light. So let's see we put the source of light here and over there we have the detector of light. So the source of light could be, for example, a star, it could be a candle or it could be a radio emitter. As for the light detection, we could have our eye, we could have a telescope or we could have like a camera. Between the source and the detector we have a given distance between the source of light and the detector. Furthermore, this my source of light and my detector may have a velocity. For example, here I have 'v1' for the source of light and have 'V2' for the receptor. What is really important is the relative motion. So that's the difference delta 'v' of 'v1' minus 'V2'. Well, we have to think this is a vector. Okay. So what's really important is the relative vector. Okay. And, of course, what is mostly important is the relative vector along the distance.

Notes

Summary

1m 01s

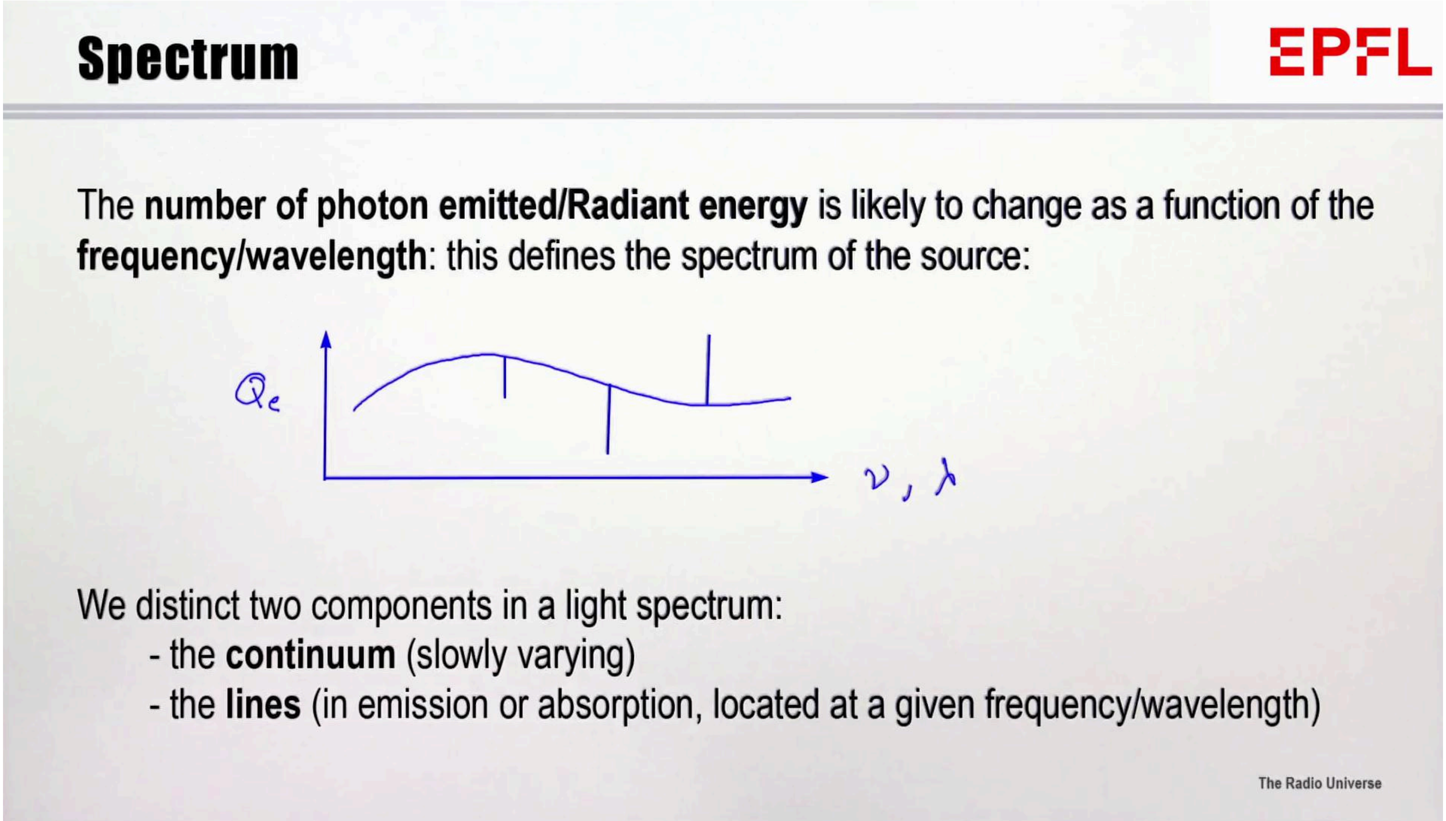


Now we have to define what is the quantity of energy or also called the radiant energy, of the light emitted or received. So first let's define the energy of a single photon. The energy of a single photon is given by 'E' the energy and this is equal to 'h' time nu. 'h' is the Planck constant and it express as a number of joule time second and nu is the frequency. The frequency is expressed in number of hertz or one over the number of seconds. The energy ‘E’ is units is defined in either joule or erg and one erg is equal 10 to the minus seven joule. Now let's have a look at an ensemble of photons and to start with let's suppose they are all similar. So each photon would have the same energy. So let's take 'N' similar photons so the energy of these photons is 'E' equal 'N' times 'h' nu. And, of course, this is expressed also in joules or in ergs. Now we try to be more broader and just define the radiant energy as the quantity of energy of an ensemble of photons which may have, of course, different frequency. So let's define this radiant energy as 'Qe'. This energy 'Qe' is basically equal to the integral of 'dE', the element of energy. This is also equal at ‘h’, the Planck constant, times the integral of 'N nu', the number of photons with frequency nu, d nu. So here we have the radiant energy. That's the quantity of energy given either by the source or received by a receiver.

Notes

Summary

3m 11s

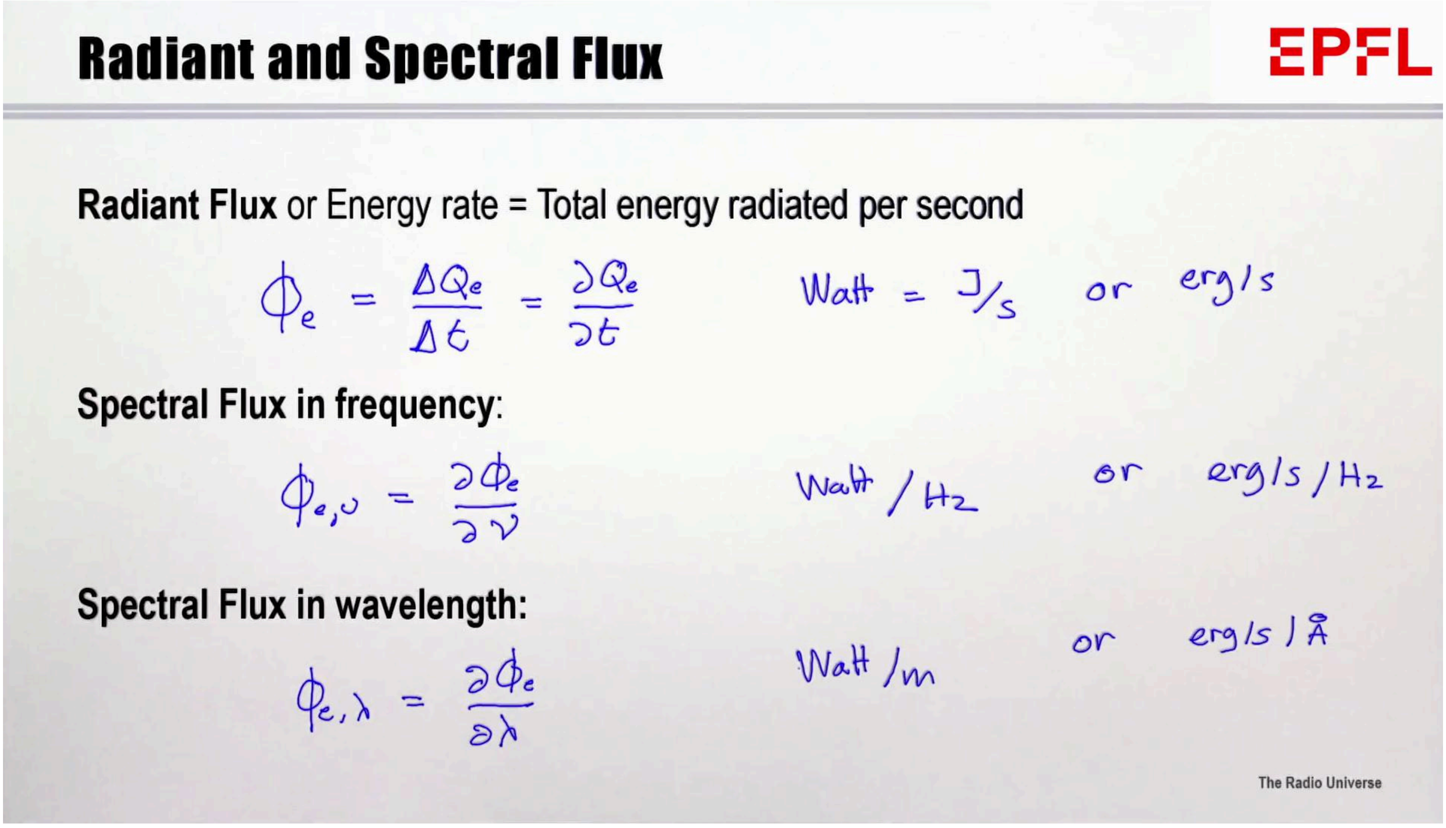


Now let's have a look of the number of photon emitted that is the radiant energy and this radiant energy, as we've seen, will depend on frequency of wavelength. So we can define the spectrum of the source. So let's put that in a diagram. First, let's define the axes. On the y-axis we have 'Qe', the quantity of energy the radiant energy. On the x-axis we have either nu, the frequency, lambda, the wavelength. The radiant energy will be a function of either the frequency of the wavelength and could have this form. In the spectrum we can have a continuum which is slowly varying and we can also see some lines. The lines can be seen in emission or they can be seen in absorption against the continuum. Those lines are located at given frequency or given wavelength and they are due to transitions between different state of different atoms.

Notes

Summary

6m 01s

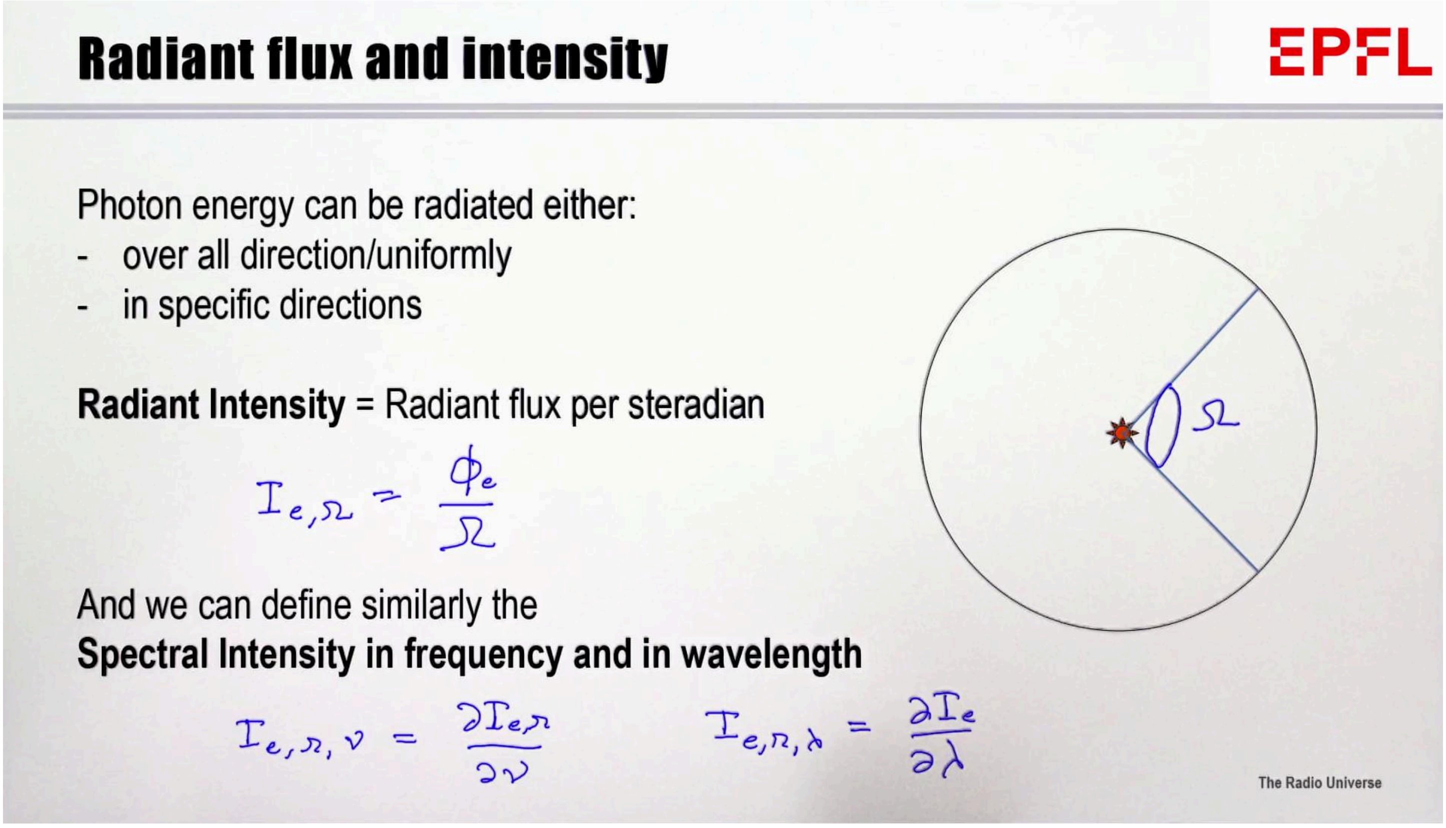


Let's continue to further more definition. A star is constantly emitting energy so what is important is not only the radiant energy but is the radiant flux or the energy rate. That is, what is the total energy radiated per second. We define a new quantity which we call radiant flux or energy rate which we write phi of 'e' and phi of ‘e’ is equal to the quantity of energy, for example, received in a given of time delta 't'. We can also write it as 'dQe' over 'dt'. This, of course, is expressed in watt which is number of joules per second or equivalently we can use the unit erg per second. This radiant flux here is irrespective of frequency of wavelength. So we have to we can define a spectral flux in frequency. This is written phi 'e' comma nu and this is equal to 'd phi e' over 'd nu'. As for the units, this will be watt per hertz or erg per second per hertz. Similarly we can define the spectral flux in wavelength. This is phi 'e' comma lambda and this can be written 'd' phi 'e' over 'd lambda'. As for the units, this is given in watt per meter or in erg per second per angstrom.

Notes

Summary

7m 30s

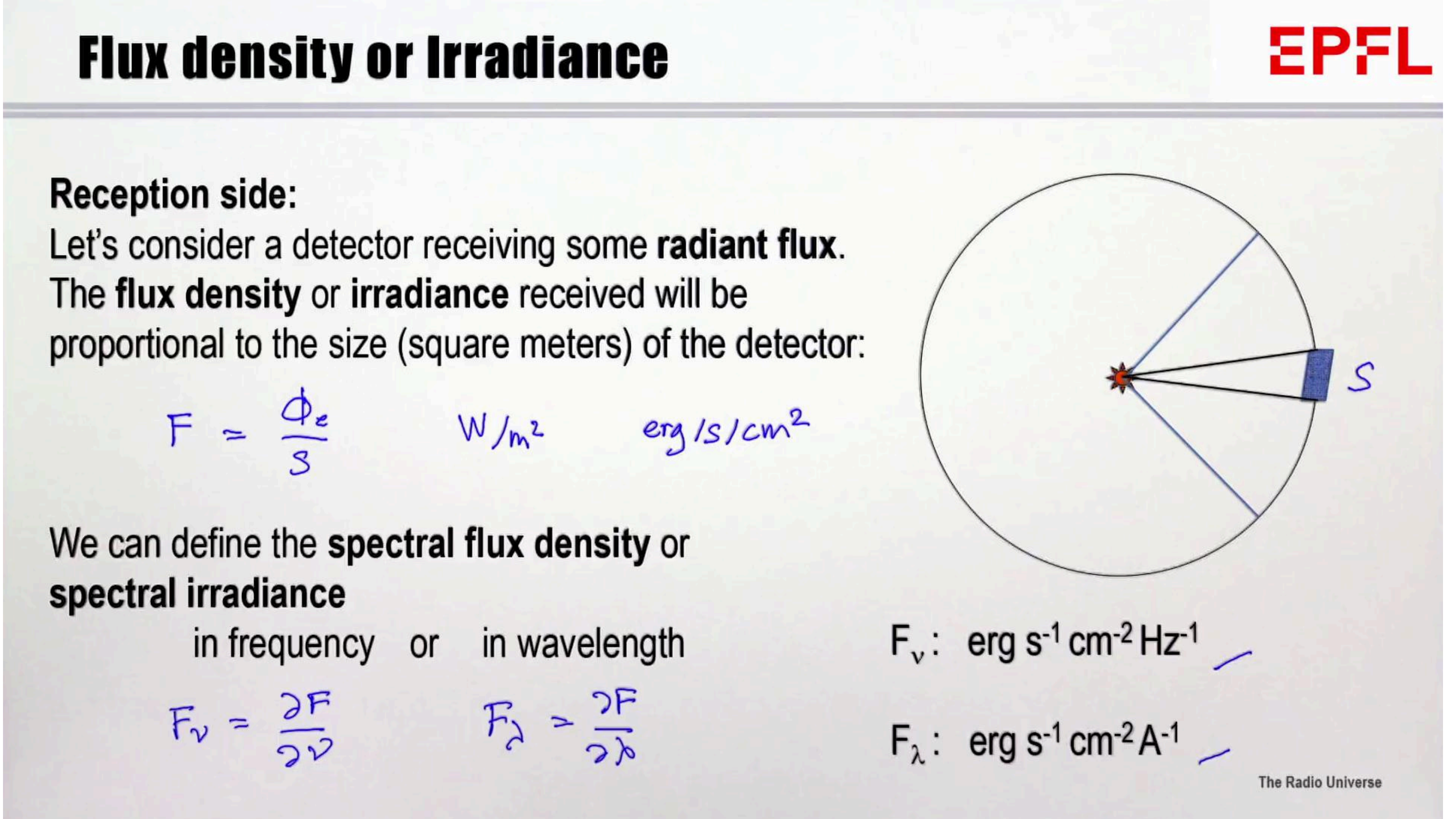


Now we have defined the amount of energy but now let's look at the propagation of that energy by the source. So the photon energy can be radiated either over all direction, that is uniformly, or that can be also radiated in specific direction. So we can define the radiant intensity which is just the radiant flux per steradian. So the radiant intensity 'e' of 'e' comma omega is defined as phi 'e', the radiant flux, divided by omega, the angle in which the energy is radiated. Similarly we can define the spectral intensity in frequency. This is just 'I' of 'e' comma omega comma nu and this is written 'd I e omega' divided by 'd nu'. And we can also have the spectral intensity in wavelength. This is 'I' of 'e' comma omega comma lambda and this is just 'd I e' over 'd lambda'.

Notes

Summary

9m 34s

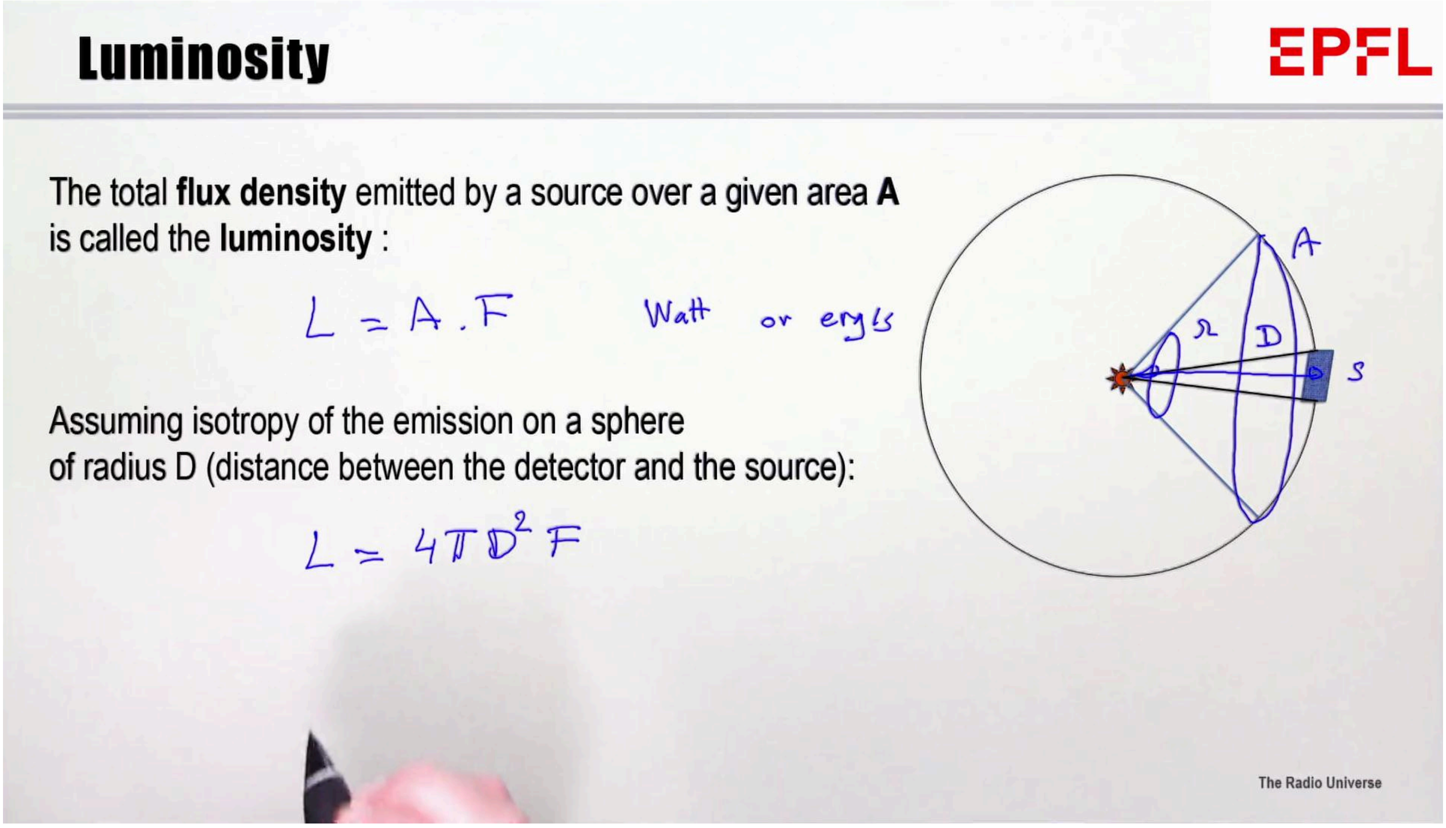


So let's consider this detector with a surface area of 'S' and this detector will receive some radiant flux emitted by the source. What will be received is what we call the flux density or irradiance. And this number will be proportional to the size of the detector. Okay. The larger the detector the more flux we will receive. So the flux density received. We call it 'F'. and this is just proportional to phi 'e' divided by the surface 'S'. This will be expressed in watt per square meter or alternatively, in erg per second per centimeter square. Again this is a total energy respective of the wavelength of the frequency. So we can define the spectral flux density or spectral irradiance as a function of frequency. This is 'F nu' and this is equal to 'dF' over 'd nu' and the spectral flux density in wavelength, this is written ‘F lambda' and this is equal to 'dF' over 'd lambda'. The units are a bit complex. 'F nu' the spectral flux density in frequency is expressed in erg per second per centimeter square per hertz. As for the spectral flux density in wavelength, this is expressed in erg per second per centimeter square per angstrom.

Notes

Summary

11m 06s



Now we've seen the quantities both from the emission side and both from the reception side. Now we have to make the link between the source and the detector. For this we will define the total flux density emitted by a source over a given area 'A'. This quantity is called the luminosity. The luminosity is written ‘L’ and is equal to 'A’, the area in which the flux is going through, times 'F', the flux density emitted by the source. So the unit for the luminosity are expressed in watt or in astronomy usually we use erg per second. So we have our source. We have our detector. This defines the solid angle to which the light is emitted and that would correspond to the area for which we receive the emission or we could receive the emission. Our detector here has a smaller area and is called 'S'. And the link between the source and the detection detector is separated by a distance which we call ‘D’. So assume isotropy of the emission on the sphere of radius ‘D’ make the link between the luminosity and the flux received which is ‘L’. The luminosity is then equal to four pi D-square, the surface of the sphere, times the flux 'F'. We can return this equation and write the flux as a function of luminosity.

Notes

Summary

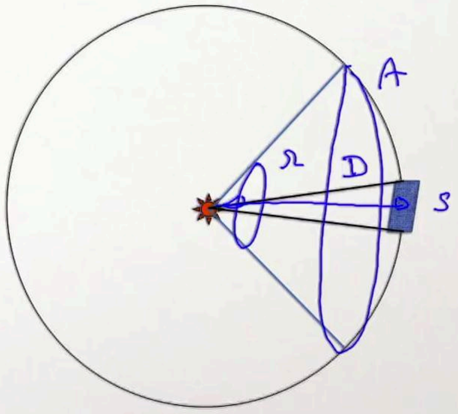
13m 07s

Luminosity

EPFL

The total **flux density** emitted by a source over a given area **A** is called the **luminosity** :

$$L = A \cdot F \qquad \text{Watt or erg/s}$$



Assuming isotropy of the emission on a sphere of radius D (distance between the detector and the source):

$$L = 4\pi D^2 F$$

$$F = \frac{L}{4\pi D^2}$$

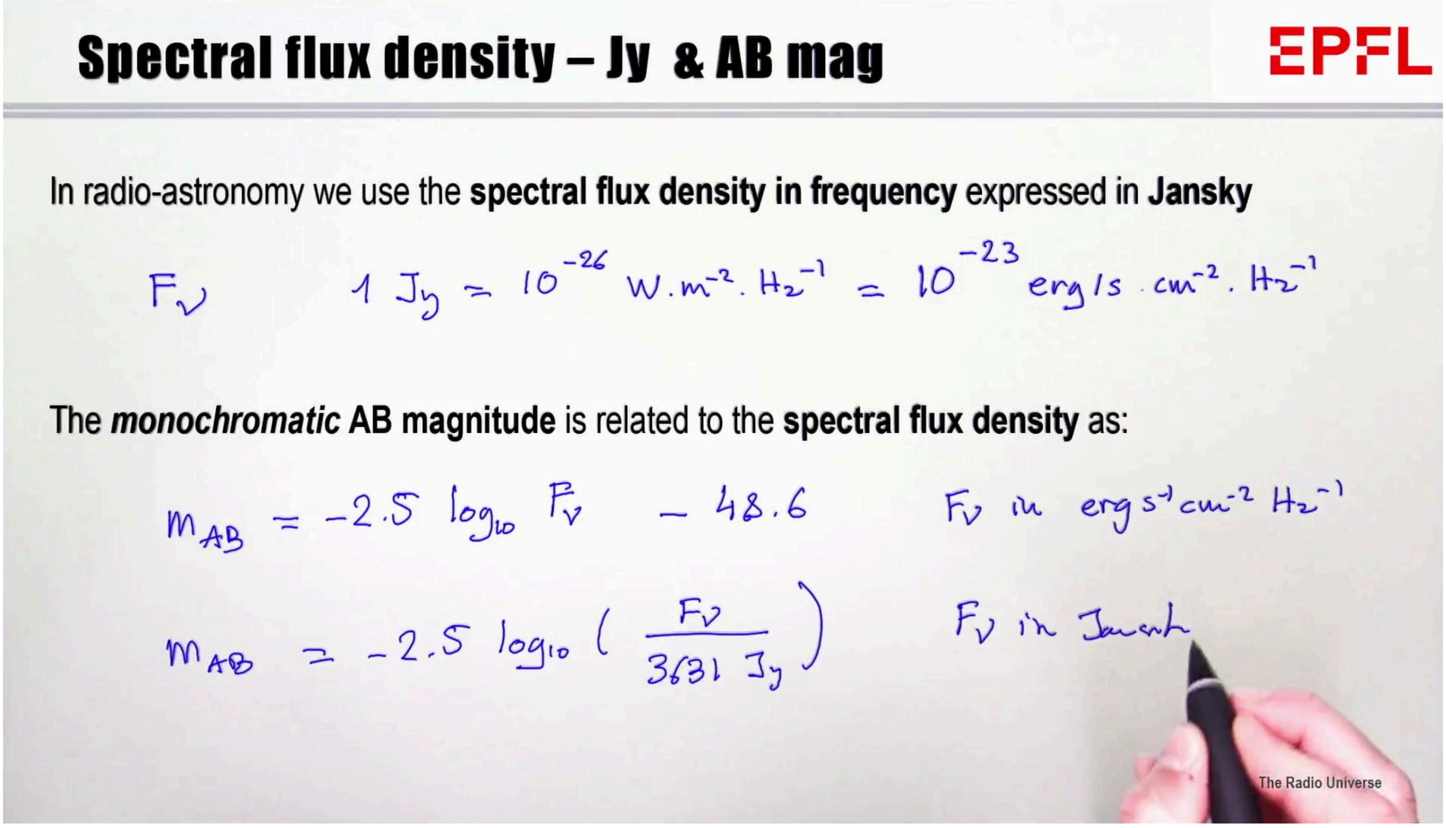
The Radio Universe

The flux is then equal to the luminosity divided by four pi D-square. So the further away is the source of the emission, the smaller will be the flux received and the flux will go as one over D-square, the distance to the source.

Notes

Summary

15m 18s



Now let's have a look at what we use in radio astronomy. We have a special unit that is being used. It's called the Jansky. The Jansky is linked to the spectral flux density expressed in frequency, that is, the spectral flux density in frequency 'F nu'. And we have defined the Jansky to be one Jansky can be written as 10 to the minus 26 watt per meter square per hertz. If we use more traditional units from astronomy this is expressed as 10 to the minus 23 erg per second per centimeter square per hertz. So the Jansky is something that is commonly used in radio astronomy. We can make the link between the flux expressed in Jansky to the magnitude usually used in optical astronomy. We can define the monochromatic AB magnitude and we can link it to the spectral flux density. The relation is the following. The magnitude AB, 'M AB' is equal to minus 2.5 log ten of 'F nu' minus 48.6. Here we have expressed 'F nu' in erg per second per centimeter square per hertz. We can expand the magnitude AB as the function of 'F nu' expressed in Jansky then we have 'M AB' equal minus 2.5 log ten 'F nu' divided by 3,631 Jansky. Here ‘F nu’, of course, is expressed in Jansky.

Notes

Summary

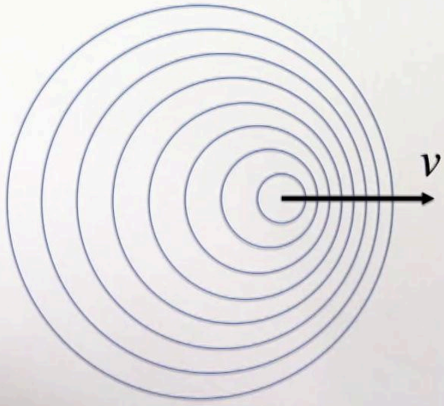
15m 39s

Doppler Shift

EPFL

The **Doppler effect** or **Doppler shift** is the **change of the frequency or the wavelength** due to the **relative velocity between the source and the observer**.

Example: the change of the sound pitch of the ambulance coming to you and going away from you.



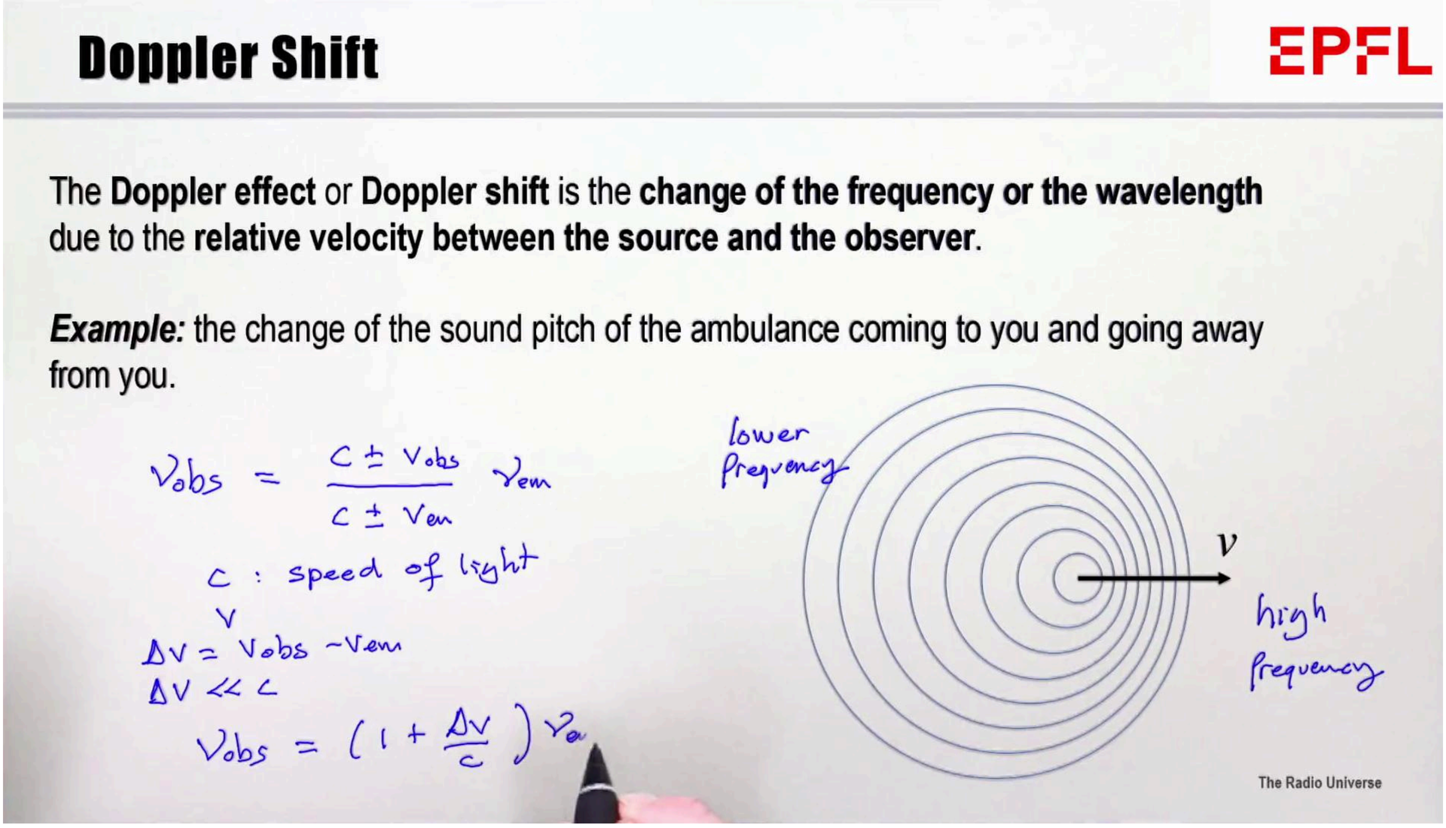
The Radio Universe

So we have made the connection between the quantity of energy emitted and the quantity of energy received and we've seen that depends on the distance. But we have another important parameter to take into account as we explained in the beginning is the relative velocity difference between the source and the detector. This relative velocity if non-zero will produce what we call a Doppler shift. This is also called the Doppler effect and it basically the change of frequency or the wavelength due to that relative velocity between the source and the observer. I'm sure you've seen that in everyday life. In fact, the change of the sound of pitch of the ambulance coming to you and going away from you is something you are aware of. If the ambulance is coming toward you the pitch will be higher frequency. If the ambulance is going away from you the pitch will have a lower frequency. So let's have a look at this cartoon. Here we have an object that is moving away in one direction to velocity 'v' and this object is emitting light. Light is particles but it's also wavelength so as time goes by the light is propagating in the medium and the circle here show the propagation of the light coming from the source.

Notes

Summary

17m 53s

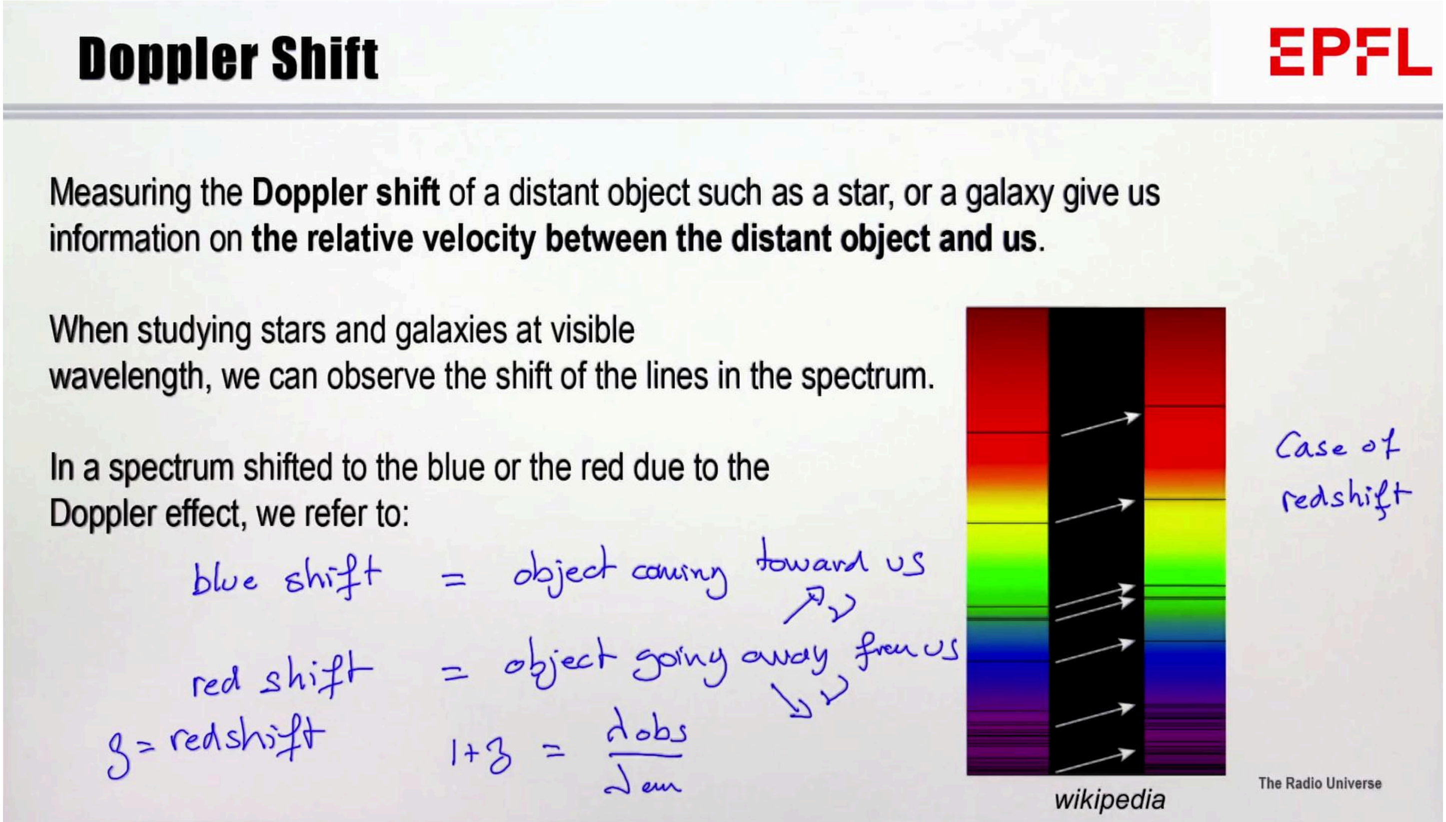


As we can see in the picture, here we see that we have a relatively high frequency, that is, we have many cycles on the given distance. On the other side we have lower frequency when the source of light is going away from you and we have the same number of cycle but over a much larger distance. So we can define the observed frequency and we can link it the observed frequency to the emitted frequency depending on the speed of the source and the speed of the observer. We can demonstrate that the observed frequency is related to the emitted frequency with this relation so we have nu-obs equal equal the ratio of 'c' plus or minus v-obs divided by 'c' plus or minus v-em times the frequency of the emission. ‘c’ in this case is the speed of light, 'v' is the velocity either of the observer or the emitter and what is important is the difference delta 'v' which is the difference between the observer velocity and the emitter velocity. If we have the difference in velocity which is much smaller than the speed of the light then we can express nu-obs, the frequency seen by the observer as one plus delta 'v' over 'c' times nu emission.

Notes

Summary

19m 43s

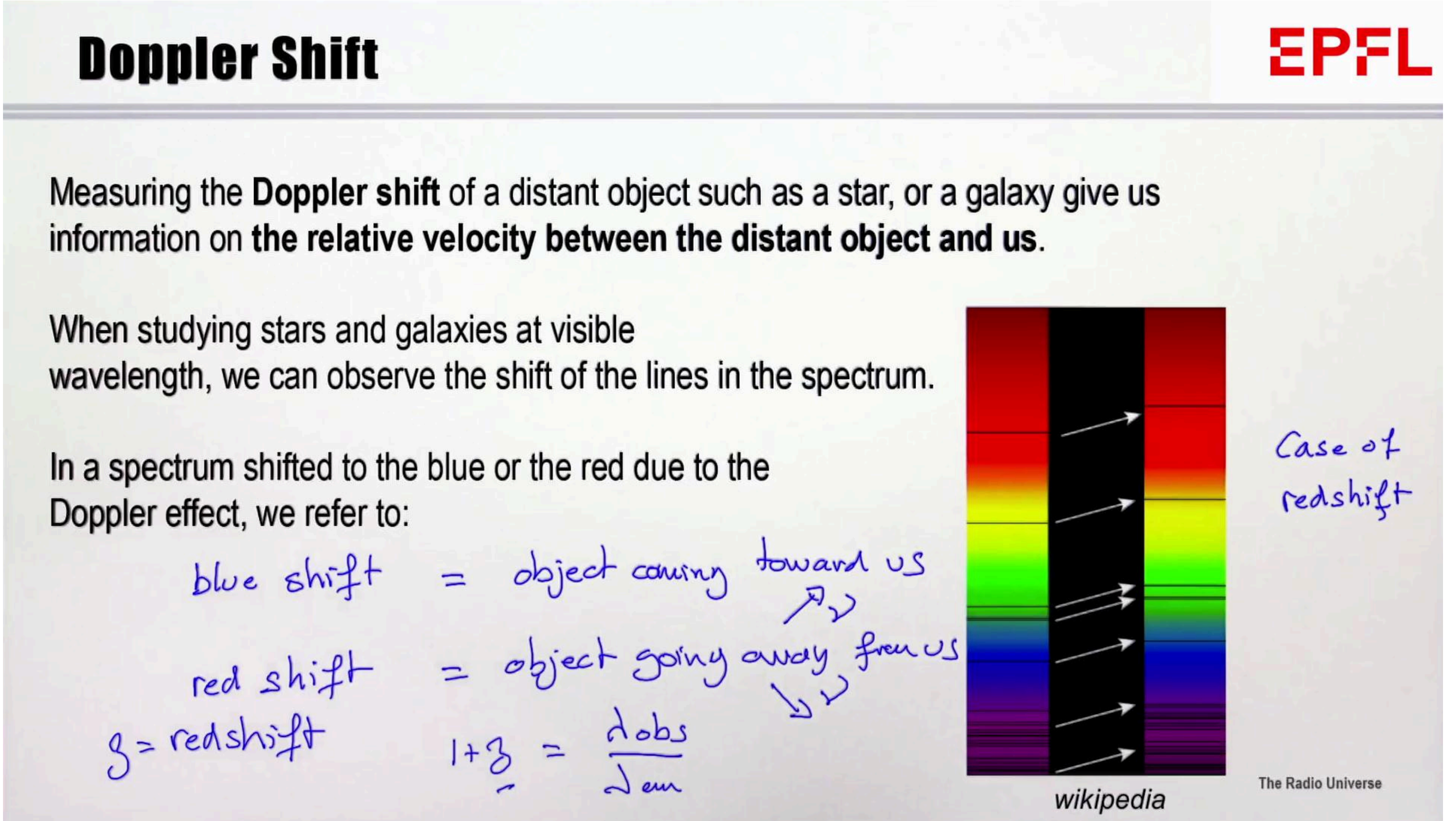


So the Doppler shift inform us of the relation between the observed frequency and the emitted frequency as a function of the relative motion. So measuring the Doppler shift of a distant object like a star or a galaxy give us that information about the relative velocity between that distant object and us. So we have been studying stars and galaxy at visible wavelengths and we have observed shift in the spectrum. As an example, here we have a spectrum that would be the emitted spectrum and that would be the observed spectrum and we see that there is a shift of the line going toward the redder wavelength. That's what we call the case of a redshift. So the spectrum can be either blue or redshifted to the Doppler effect. So we refer to a blueshift in the case of an object coming toward us. That is a higher frequency. Or a redshift, that means an object is going away from us and that means a lower frequency. Because of that we have defined a unit which is called the redshift in astronomy and we write ‘z’ the redshift and we define in such a way that one plus 'z' equal lambda-obs over lambda emitted. So, for example, if there's no velocity if there's no redshift then 'z' equals zero and then we have lambda-obs equal lambda emitted.

Notes

Summary

21m 41s

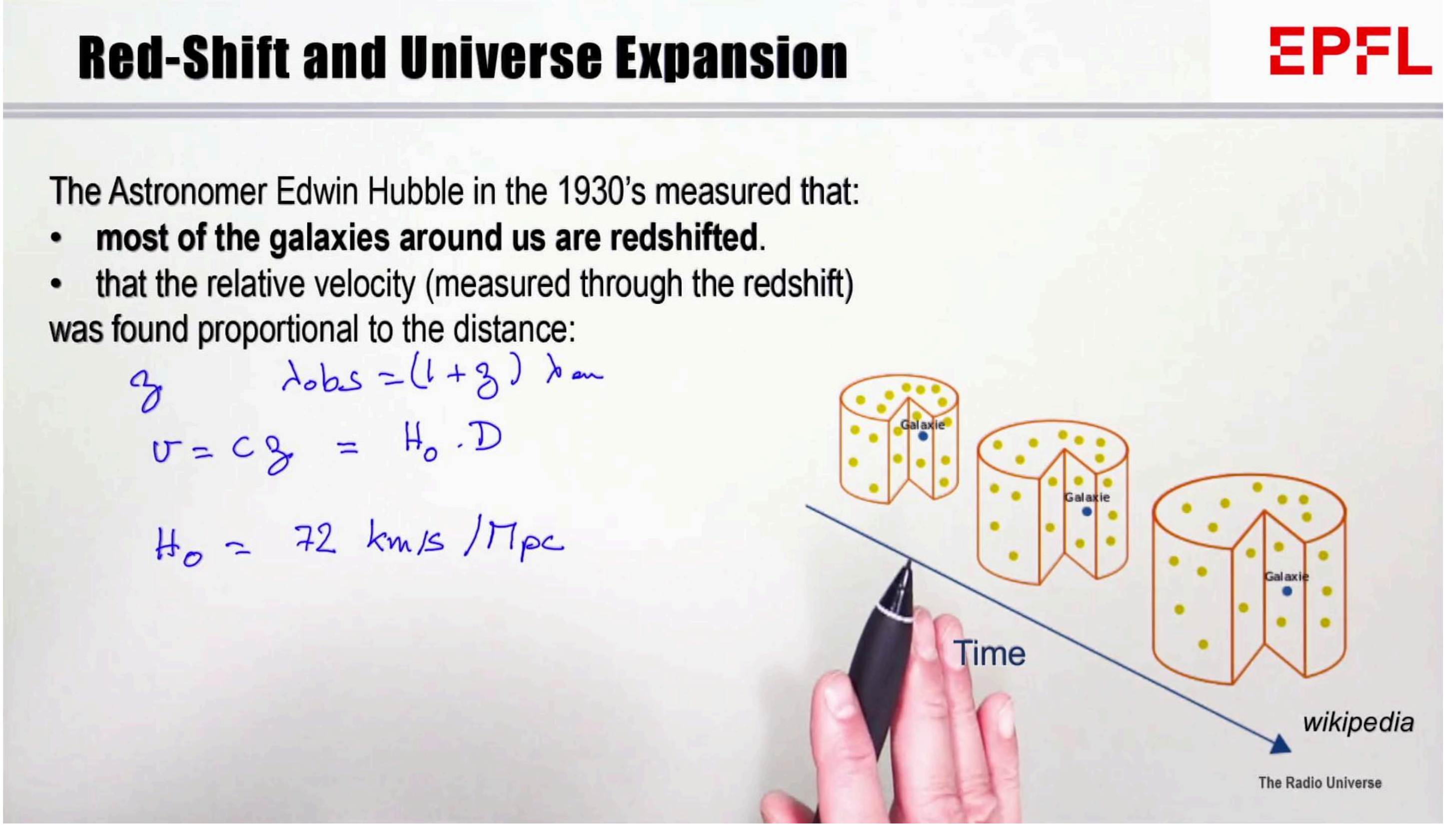


If we have a redshift, 'z' is positive and that means the lambda observed is larger than the lambda emitted. So a galaxy which has a positive redshift will have larger lambda-obs compared to lambda emitted. That will mean it will have a lower frequency.

Notes

Summary

23m 48s



In astronomy there's a special link between redshift and the Universe and more precisely, the Universe expansion. Indeed, the astronomer Edwin Hubble in 1930s measured that most of the galaxies around us are redshifted and that the relative velocity which is, of course, measured through the redshift was found proportional to the distance. So now let's recap. 'z' the redshift. The observed lambda of a given line is written as one plus 'z' lambda emitted. So that means if 'z' is positive the wavelength is larger and that means the object is going further away from us. We can relate the velocity 'v' equal 'c' time 'z', the redshift, and Hubble have shown that this velocity is proportional to the distance. So we can write 'v' equal 'H-not' times 'D'. 'H-not' is the Hubble parameter. As of today, we measure 'H-not' to be 72 kilometers per second per megaparsec. So the typical distance between two galaxies of the order of one megaparsec so it means that because of the expansion of the Universe those two galaxies are going away from each other at 72 kilometer per second. We can describe the expansion of the Universe a bit like of a cake where we have grains of grapes that represent the galaxies in the cake and the cake is the Universe.

Notes

Summary

24m 20s

Red-Shift and Universe Expansion

EPFL

The Astronomer Edwin Hubble in the 1930's measured that:

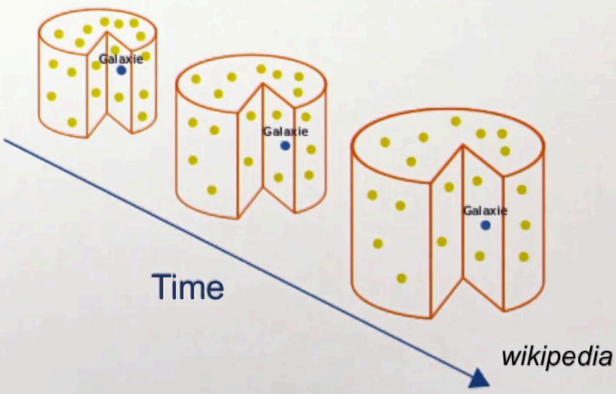
- **most of the galaxies around us are redshifted**.
- that the relative velocity (measured through the redshift)

was found proportional to the distance:

$z \qquad \lambda_{obs} = (1+z)\,\lambda_{em}$

$v = cz = H_0 \cdot D$

$H_0 = 72 \text{ km/s /Mpc}$



As time goes by, the Universe is expanding and what is changing is the distance between the different galaxies as the function of the Universe expansion. So the size of the galaxy is not changing but the distance between the galaxies are changing as the Universe is expanding. And we could have done this measurement because we have measured the redshift that is the change between the lambda of the emission of the source and the lambda observed in our detector.

Notes

Summary

26m 22s

Photons may have different frequencies thus different energy. For example, blue light is more energetic than red light. As the number of photons emitted depend on the frequency, they collectively define a spectrum. A spectrum has two components; a slowly varying continuum and emission or absorption lines. We have introduced a number of quantities that define the amount of light emitted by a source and the amount of light that a detector received. These quantities have specific units as they are corresponding to different measurements. For example, the flux density received depends on the source luminosity divided by the square of the distance to the source. Finally, we have seen that the Doppler effect will blue or redshift the source spectrum depending on the relatively velocity between the source and the observer. We can conclude that the light received give us measurement on the source properties. With this background in the following videos we will be able to take a closer look at concrete example of source emission in terms of continuum and line emissions and also explore the radiation transport.

Notes

Summary

27m 17s