



The main source, or even the only source of information coming from space are the photons. Their energy distribution, meaning their colour, and their quantity, which is their spectral distribution shown here in the optical domain from blue to red, inform us on the physical processes responsible for the emission and absorption of the radiation, therefore of the photons, but also on the physical properties of the environment, namely the matter with which the radiation will interact.

- Notes

Summary



Photons

Photons transport Energy

h : Planck constant

$$h = 6.626 \times 10^{-34} \text{ J.s}$$

ν : photon frequency

λ : Photon wavelength

$$E = h\nu$$

Diagram showing the equation $E = h\nu$ with handwritten labels: E is labeled "Energie", ν is labeled "Fréquence", and h is labeled "Moment cinétique".

$$\lambda = c \cdot P = \frac{c}{\nu}$$

Introduction to Astrophysics

As we have just mentioned, light is extremely important in astrophysics, because light carries energy as a wave or as a particle. This is the wave-particle duality. The photons will convey a certain amount of energy which will be quantified. This energy is proportional to the frequency of the photon. And the proportionality constant, which is the Planck constant, has the units of an angular momentum. So in quantum physics, it's the angular momentum that is quantified and thus also the energy of the photons. Obviously the frequency is related, as always, to the wavelength through the speed of light and the period of oscillation of the wave which is 1 divided by the frequency.

Notes

Summary



0m 36s

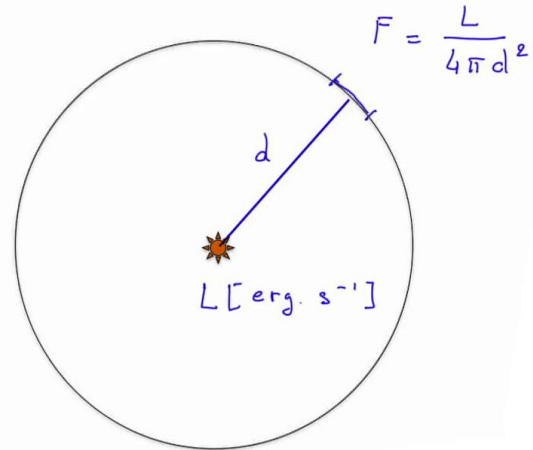
Energies are measured as energy fluxes as many objects radiate continuously with time

$$F_{\lambda}: \text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$$

$$F_{\nu}: \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$$

$$1 \text{ erg} = 10^{-7} \text{ J}$$

F.



Introduction to Astrophysics

The energy is measured per unit of time, so it is actually a power. If a star radiates a certain luminosity L , the brightness will be measured for example in ergs per second, an energy unit divided by a time unit, and that brightness, which we will have here, will be captured at a certain distance from the Earth, here, at a distance d . And we will capture it on a certain surface, so we have here the isotropic radiation of a star with total luminosity L . This radiation will be diluted on a sphere of surface 4π times the distance squared. In the end, what we will receive on the ground, is a certain flux of photons, a certain flux of energy, which will be the original luminosity L of the star divided by $4\pi d^2$. That is what we find here. We have the luminosity, namely the energy, actually the power - energy divided by time - that will be distributed isotropically, on the surface of the sphere which is here, and we only receive a small part of the whole radiation. We will also observe at certain specific wavelengths or frequencies. So to go from the expression of a flux in wavelength units to a flux in frequency units, it isn't enough to replace λ by ν .

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Summary



Energies are measured as energy fluxes as many objects radiate continuously with time

F_λ : $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$

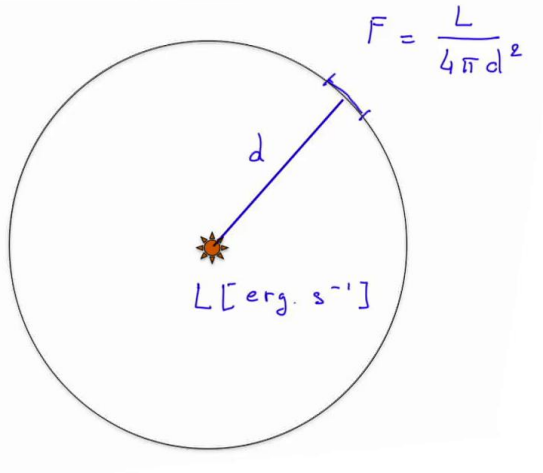
F_ν : $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$

$1 \text{ erg} = 10^{-7} \text{ J}$

$F_\lambda d\lambda = -F_\nu d\nu$

$\lambda = \frac{c}{\nu} \Rightarrow d\lambda = -\frac{c}{\nu^2} d\nu$

$F_\nu = \frac{c}{\nu^2} F_\lambda$



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

$L [\text{erg. s}^{-1}]$

Introduction to Astrophysics

Regardless of the way one measures the available energy in wavelength units or in frequency units one has to have the same result. If I multiply the flux by a wavelength unit or the flux expressed in frequency units by a certain interval of frequencies I need to obtain the same result, in absolute values, since λ and ν vary inversely. Now, we said that $\lambda = c / \nu$. This implies that if I take the differential we have $d\lambda = - (c / \nu^2) \times d\nu$. If we replace $d\lambda$ here, we obtain immediately that $\nu d\nu = (c / \lambda^2) \times \lambda d\lambda$. So the relation between the flux expressed in frequency units and the flux expressed in wavelength units is not totally obvious. There is a slight distortion between the two scales.

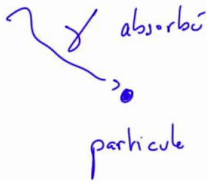
Notes

Summary



Photons: Radiation Pressure

Photons also transport momentum



$$E = \sqrt{p^2 c^2 + \cancel{m^2 c^4}}$$

$$E = p c \rightarrow p = \frac{E}{c} = \frac{h\nu}{c}$$

$$\frac{dp}{dt} = \frac{h\nu}{c} \quad \|\vec{F}\| = \frac{h\nu}{c} \quad \text{Pression de radiation}$$

Introduction to Astrophysics

Photons do not only carry energy: note that energy can be expressed in different ways for the photons. It can be written as $E = h\nu$, but can also be written as the quadratic sum of $p \times c + mc^2$ with the famous mass energy. Now for photons, there is no mass energy but they still have a momentum. Therefore we can write that $E = p$ times c where p is the momentum. Of course, one can reverse the equation and get $p = E/c = h\nu$ (for the photons) $/c$. Now what will happen, is that each time one has for example, a particle of matter or a dust particle, a photon can be absorbed. During the absorption, all the momentum of the photon, - because a photon is always entirely absorbed or emitted - all the momentum of the photon will be transferred here to the particle or dust-particle. So, during the transfer, the dp/dt of the particle is just $h\nu/c$. The whole momentum of the photon will be transferred to the particle, The dp/dt of the particle is a force, whose norm is $h\nu / c$. This force is extremely important in astrophysics. It will play a role in the whole process of star formation through atomic or molecular cloud collapse. This force is called radiation pressure. This force will be generated by a photon flux hitting particles, atoms, molecules, dust particles.

Notes

Summary



4m 10s



The energy distribution of photons can be:

- Continuous
- Discrete (spectral lines)

In most practical cases it is a combination of the two processes.

Introduction to Astrophysics

We have seen that light can transport energy. It can also transport momentum, and transfer this momentum to matter, therefore imprinting force on matter. Now how does the photon spectrum distribute itself in energy? The spectrum, this energy distribution, can be discrete or continuous. In one case, we have a radiation where all wavelengths are present in the spectrum. In the other case, only some wavelengths are present, so discrete lines will form the spectrum. In most cases, astronomical objects will show spectra that are a combination of both types of radiation. The physical processes at play behind these types of emission are not the same, and this is why we can study celestial bodies.

Notes

Summary



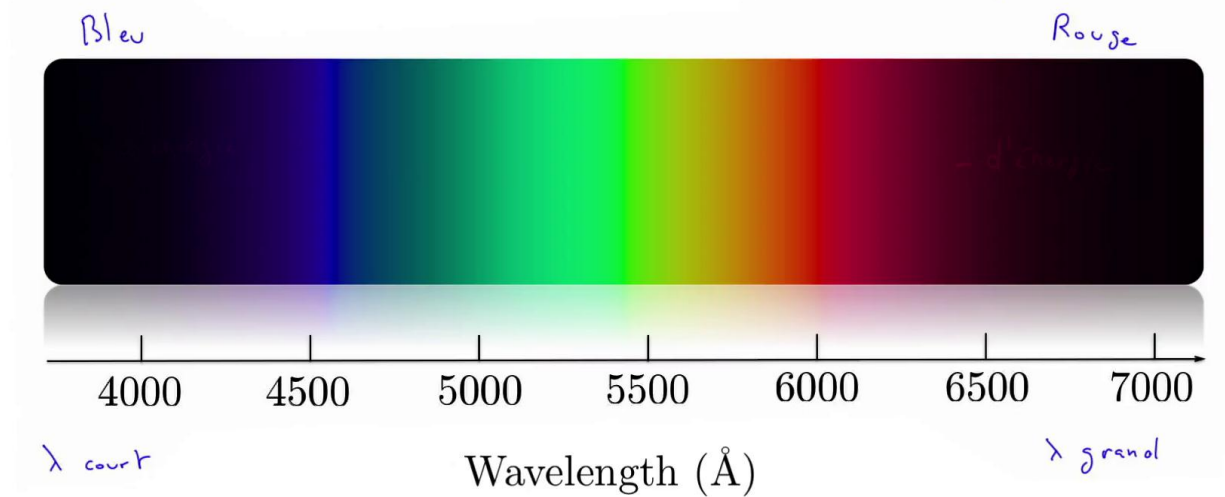
6m 04s

Different Types of Spectra

Continuous spectrum:

the energy distribution is a **continuum**

$$E = h\nu = pc \quad \lambda = \frac{c}{\nu}$$



Introduction to Astrophysics

First of all, continuous radiation: we have here a continuous spectrum. Each photon which has been emitted from blue to red, so here we show only the visible wavelength range, each photon transports an energy $h\nu$, which we can also write as a momentum, and a wavelength which is equal to c/ν so the wavelength and the frequency vary in opposite ways. Here we recognise of course the blue, with the red on this side of the spectrum the short wavelengths, so, small λ , are on this side of the spectrum large λ . It is the opposite for the frequencies. Finally the most powerful phenomena... So, more energy is transported at short wavelengths or at high frequencies. And here, less energy because the wavelengths are larger and the frequencies shorter.

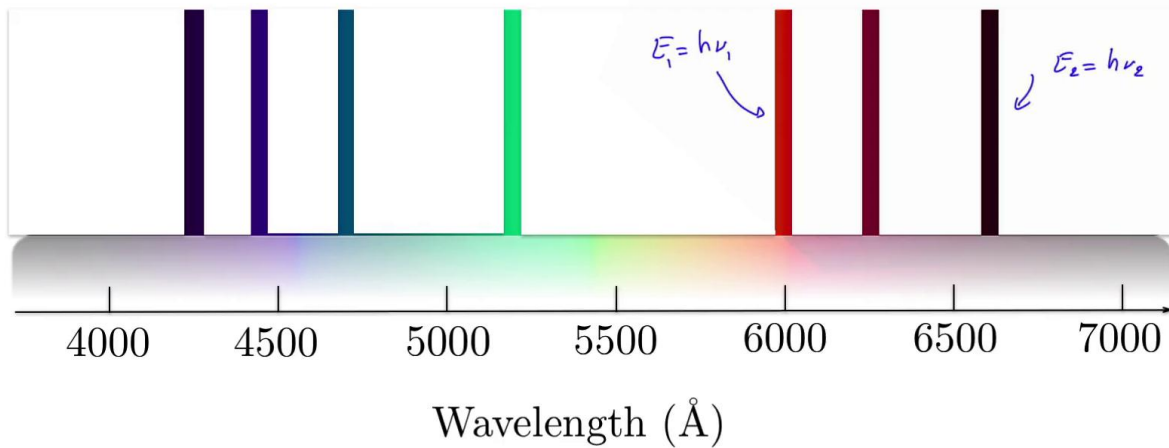
Notes

Summary



Different Types of Spectra

Spectral **lines**: energy distribution is **discrete** (Nuvées atomiques ou moléculaires)



Introduction to Astrophysics

The energy distribution of the photons can be continuous or discrete. This is the case in atomic or molecular clouds where each photon has a well-defined energy. For example here, we have a given photon with an energy $E_1 = h\nu_1$. Here we have another photon with an energy $E_2 = h\nu_2$. This type of radiation is generally present in nebulae, atomic or molecular clouds, excited by ionisation sources, in other words, heating of matter.

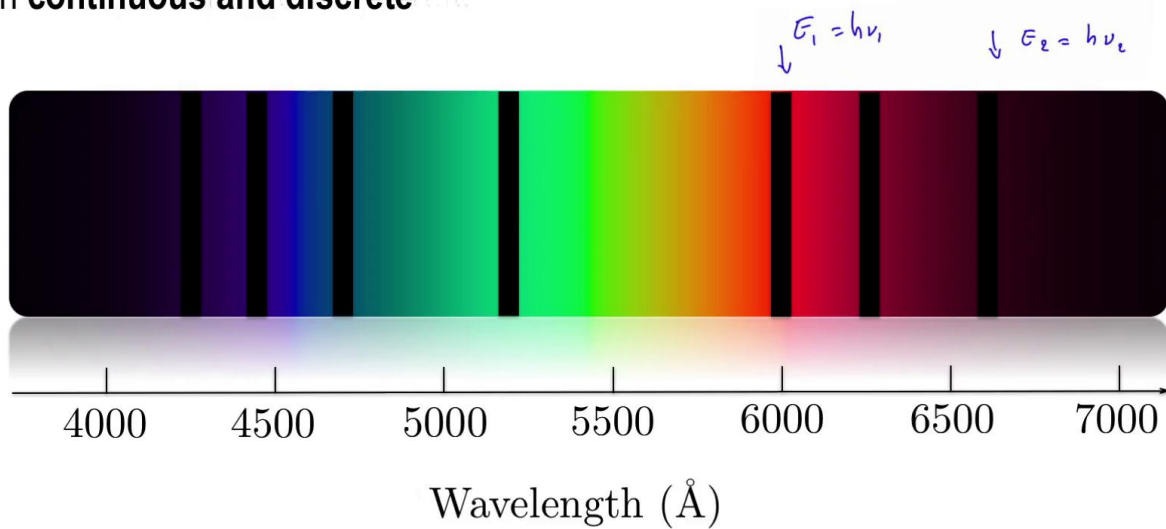
Notes

Summary



Different Types of Spectra

Both **continuous** and **discrete** efe



Introduction to Astrophysics

For example, stars in a nebula. Of course, most of the time we will have a combination of both types of radiation. For example here, we have a continuous radiation which will superimpose itself with a discrete radiation. This happens when a background source is seen through, for example a cold gaz cloud. We will see that later on, where some wavelengths are absorbed. So here, again we have: $E_1 = h\nu_1$ $E_2 = h\nu_2$ where ν_1 and ν_2 are exactly the same frequencies as in the previous slides. because we have the same gas with the same chemical composition, which absorbs the background radiation. So we can easily have a combination of continuum and line spectra where the lines can be in emission or in absorption. Here we show them only in absorption but we could very well have them in emission, as in the previous slide, in superposition with the continuous spectrum.

Notes

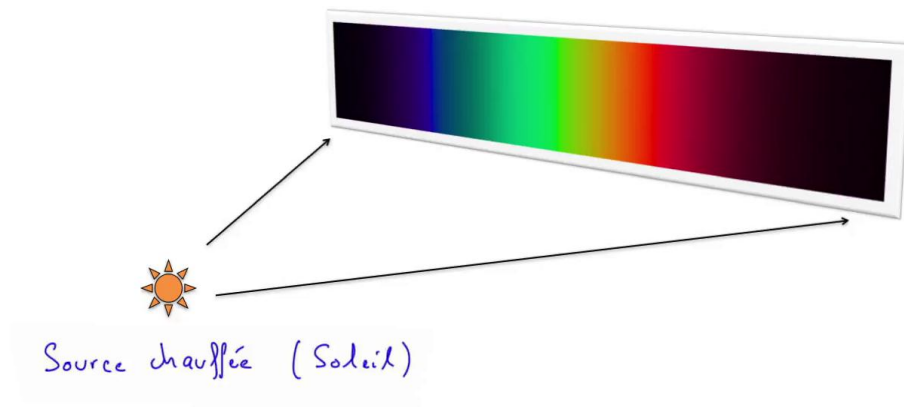
Summary



8m 36s

Different Types of Spectra

Continuous spectrum



Introduction to Astrophysics

Here is a situation where we have a continuous spectrum where we have a heat source, for example the sun or any other star where we have a nuclear radiation source in the center, which will heat up the outer layers and the outer layers will re-emit what we call black-body radiation at all wavelengths, in this case here in the visible wavelength range from blue to red. All stars will show this type of continuous radiation.

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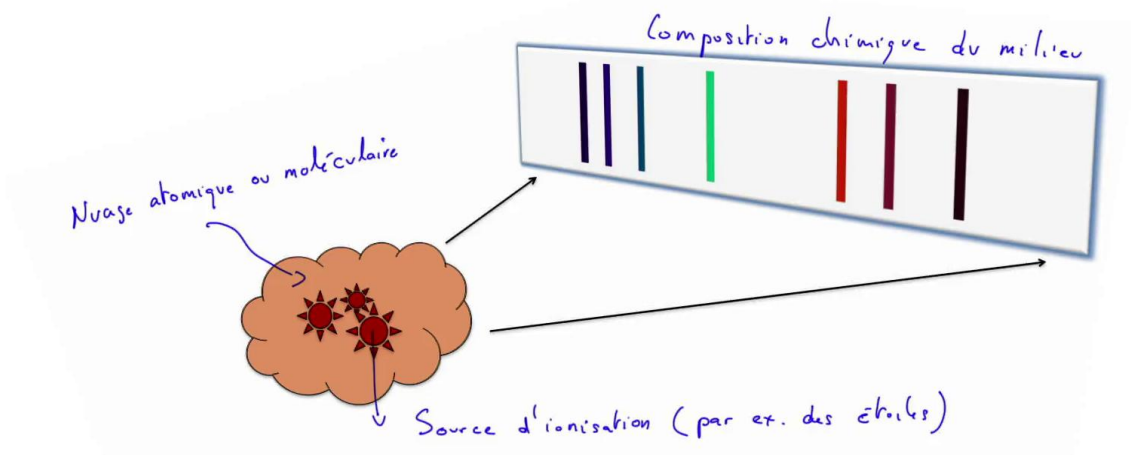
Summary



9m 41s

Different Types of Spectra

Discrete spectrum



Introduction to Astrophysics

Here is now a situation where we have a line spectrum with the monochromatic lines that we have shown earlier at certain frequencies or certain wavelengths. We have a situation where a molecular or atomic cloud is ionised by a source of ionisation here, for example stars. The stars will excite the atomic gas. We will come back to that in the following videos. The gas will be excited by the photons emitted by the stars and, through de-excitation, atoms will emit lines, which will be characteristic of the chemical composition of the gas. The line-spectra inform us of the chemical composition and the physical conditions of the medium: a gas which was ionised, excited by a radiation source such as stars.

Notes

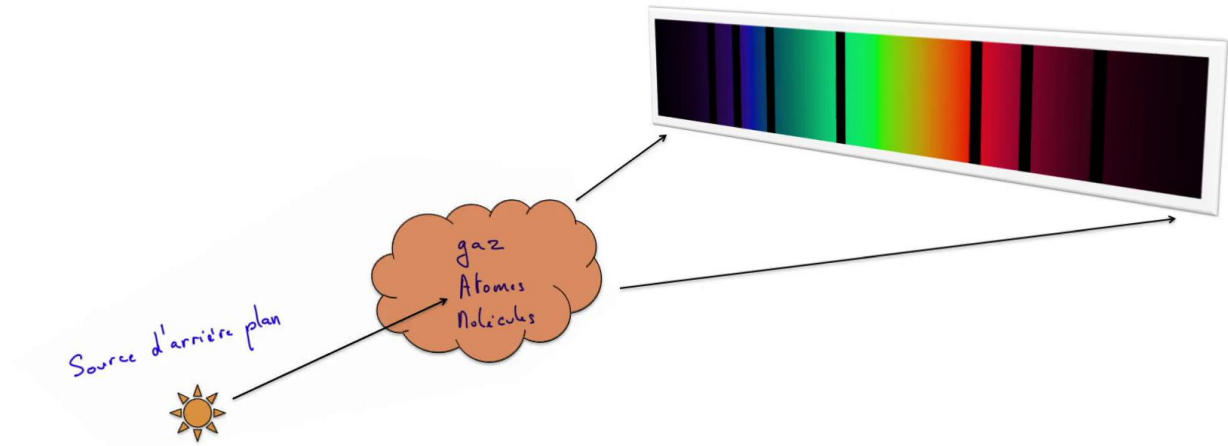
Summary



10m 08s

Different Types of Spectra

Continuous and discrete



Introduction to Astrophysics

We have seen before that most of the spectra are a combination of a continuous spectrum and a line spectrum. Here is a good example. We have here a background source. A hot source, which emits a continuous spectrum. For example a star which emits a black-body radiation spectrum. And on the line of sight, between the background stars and us lies for example a gas with atoms and molecules. This colder gas will absorb light at well defined wavelengths which depend on the chemical composition of the gas. Here again we can learn things thanks to such a spectrum, of the background source but also of the chemical composition of the gas over the line of sight to the background source.

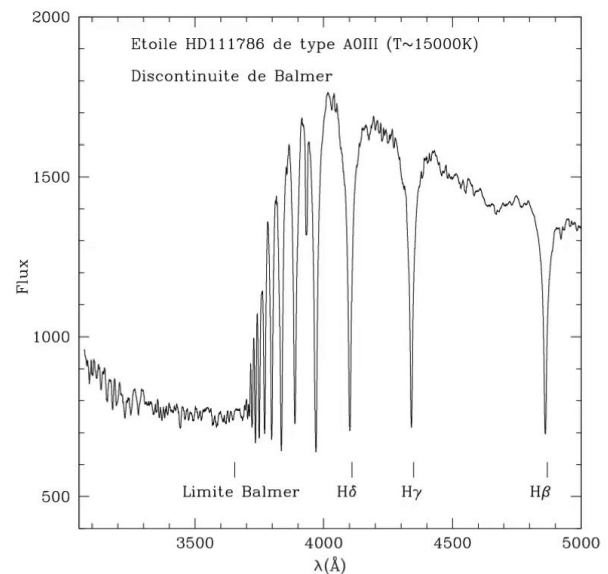
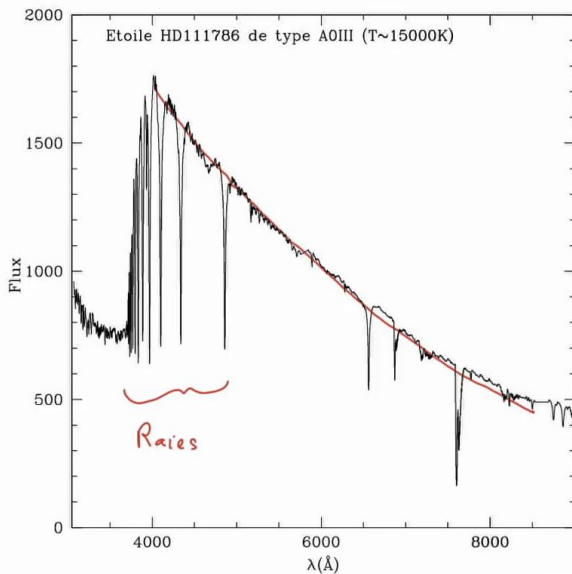
Notes

Summary



11m 07s

Examples of Stellar spectra



Introduction to Astrophysics

Here is a concrete example of a spectrum composed of a continuum and of absorption lines, the spectrum of a star whose name is here. We can see here the surface temperature : 15 000K. Its a hot blue star whose black-body spectrum can be seen here and which also displays a whole series of lines. If we zoom in on the lines here, We can see them here, stretching the wavelength axis we see that there are lots of lines, which here are due to hydrogen in the stellar atmosphere. This is for a star other then the sun.

Notes

Summary

12m 05s



Emission and absorption by Solar Photosphere

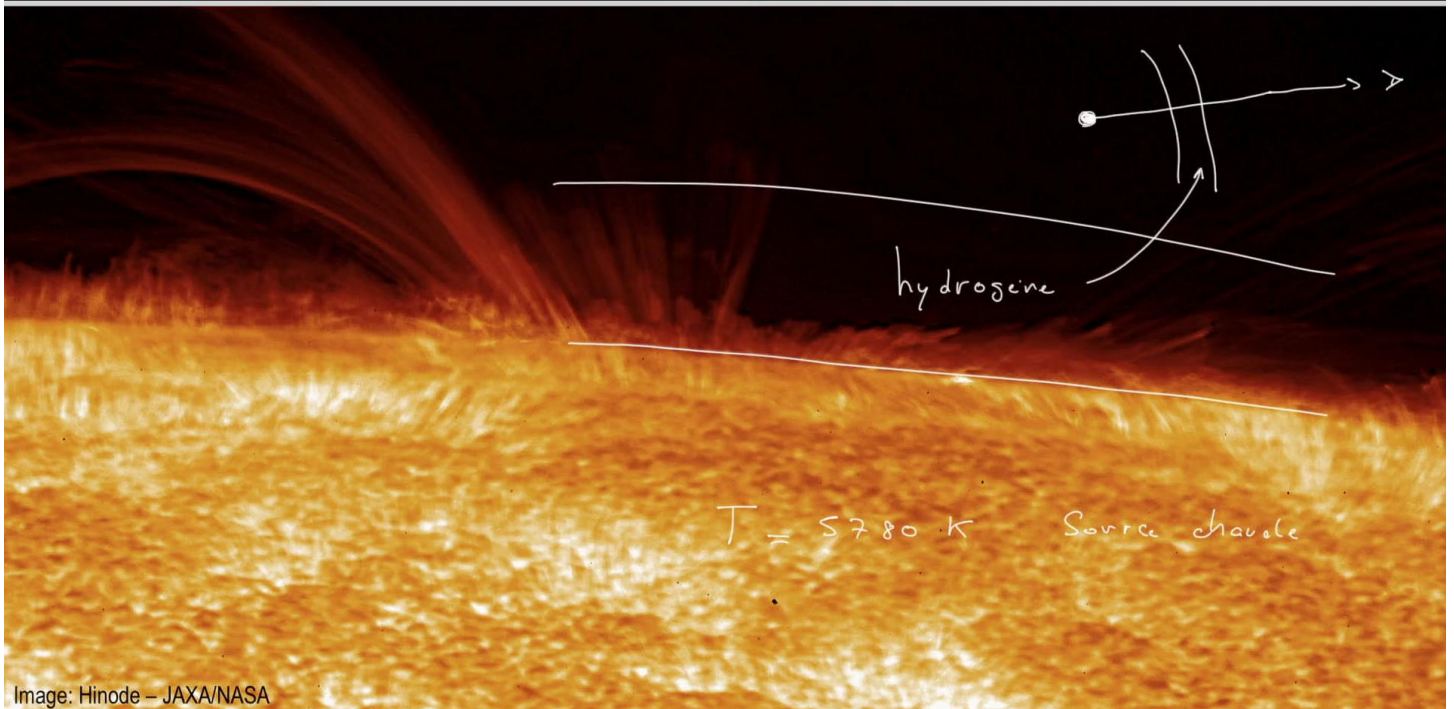


Image: Hinode – JAXA/NASA

Now let's look at what happens in the sun. If one took a spectrum of the sun, what would one have? Well, we have the sun with a surface temperature of 5780K. That is our hot source. The sun, of course, has an atmosphere. So, the sun's surface is here, but let's tell that the upper atmosphere of the sun is around here. This contains hydrogen. So we have here the situation we had before, where we had a hot source, the sun's surface, with light that travels to the eye and then, in between, we have the hydrogen surface, which we have shown here. So we have the sun's core producing radiation due to nuclear reactions which will heat the sun's surface, and the gas in the atmosphere of the sun will form the lines we have seen in the spectrum shown earlier. All stars display this kind of spectrum: a continuum component due to the heating of their surface from the inner nuclear reactions and at some point absorption lines just above their surface due to hydrogen which is cooler than the surface. That said, one can also have emission lines next to the surface if the physical conditions and the temperature of the star are right.

Notes

Summary



12m 46s



- **Black body** radiation
- **Compton Diffusion (Bremsstrahlung)**
- **Synchrotron** radiation

Introduction to Astrophysics

We have seen that light can be distributed into two components, one continuous, and one discrete, i.e. the line spectrum. Let's see in a bit more detail which physical processes can be responsible for the continuous spectra. As we have just seen, the sun or the stars display a black-body spectrum. Let's also look at two other radiation processes which will generally take place in galaxy clusters or in places where a magnetic field is present. For instance, the Compton scattering or Bremsstrahlung-radiation which will take place in ionised gases or synchrotron radiation which takes place when magnetic field lines are present in the interstellar medium, intergalactic medium or around astronomical objects.

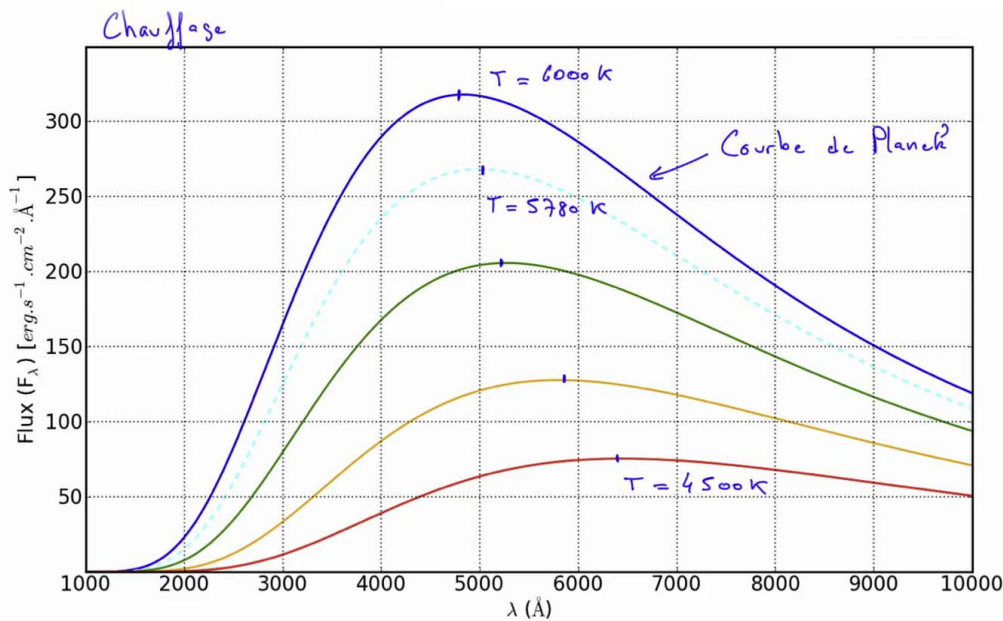
Notes

Summary



14m 19s

Black Body Radiation



Introduction à l'astrophysique

First of all, black body radiation: it is a radiation which is created by a heat source. Stars are excellent black bodies. We will come back to them in the following videos. The spectrum of this black body is a Planckian curve, which depends only on the temperature. The position of the emission peak here, depends only on the temperature. Here we have a black body with a temperature of 6000K. Here we have a black body corresponding to the temperature of the sun : 5780K and there colder and colder stars, down to $T=4500\text{K}$. The colder a black body is, the more in the red its radiation peak will be. We can already deduce, knowing only that a star has a black body radiation spectrum and knowing that the radiation peak will move with the temperature, that a star that radiates most of its light in the short wavelengths, will be bluer than a star which radiates at longer wavelengths and with a lower temperature. So, a hot star will appear blue while a cold star will appear red.

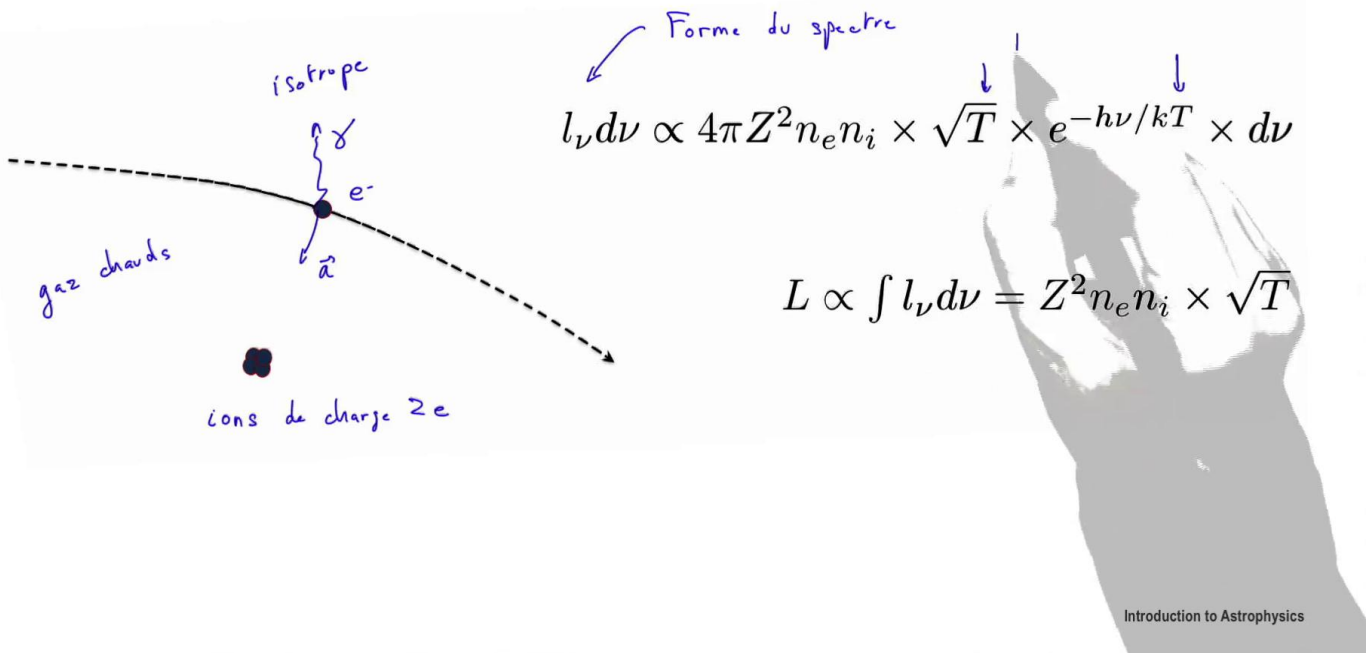
Notes

Summary



15m 07s

Compton Diffusion & Bremsstrahlung



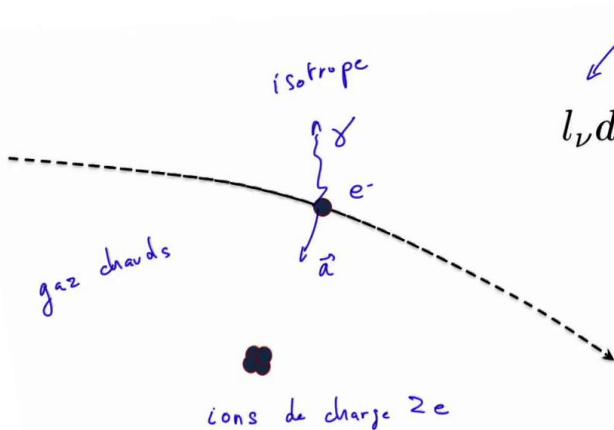
The second type of continuous radiation which can be relevant, especially when we have a hot, ionised gas, is the Compton scattering of electrons in a proton gas, which is actually a plasma. This radiation is also called Bremsstrahlung radiation, or "braking radiation" in German. "Braking" because electrons are accelerated, namely, they will be accelerated by ions with a charge Ze here, and here we have an electron. So each time an electron will move near a proton it will be accelerated and, when an electron moving already at high speed is accelerated, it emits a photon in a random direction. Thus, it is an isotropic radiation. While passing through, the electron loses energy therefore it is slowed down or braked, which is where the name comes from. This is something we meet in hot gases like plasmas. Heat is needed to dissociate atoms, that is, the nucleus from the electrons, to get a gas of ions and electrons, namely a plasma. The shape of the spectrum is given here. We had f_ν f_λ before. Here we rather use the specific intensity l_ν . So this is the curve describing the shape of the spectrum. We can see that we also have a continuous function with an exponential here.

Notes

Summary



Compton Diffusion & Bremsstrahlung



Forme du spectre

Température

$$l_\nu d\nu \propto 4\pi Z^2 n_e n_i \times \sqrt{T} \times e^{-h\nu/kT} \times d\nu$$

$$L \propto \int l_\nu d\nu = Z^2 n_e n_i \times \sqrt{T}$$

La Energie disponible totale : L

Introduction to Astrophysics

Notes

So the temperature of the gas or the plasma is important here. Then we have the density of ions and electrons in the plasma. We can compute easily, by doing an integral over all frequencies, the total available power for all wavelengths, in other words the luminosity of the object. This radiation is isotropic and is relevant to very massive objects where gravitational contraction will heat the gas, such as galaxy clusters. So we will have plasmas with electrons that interact with ions and each time we have an acceleration with a uniform or at least continuous distribution, as soon as we have a continuous distribution of accelerations, we will also have a continuous energy distribution of the emitted photons.

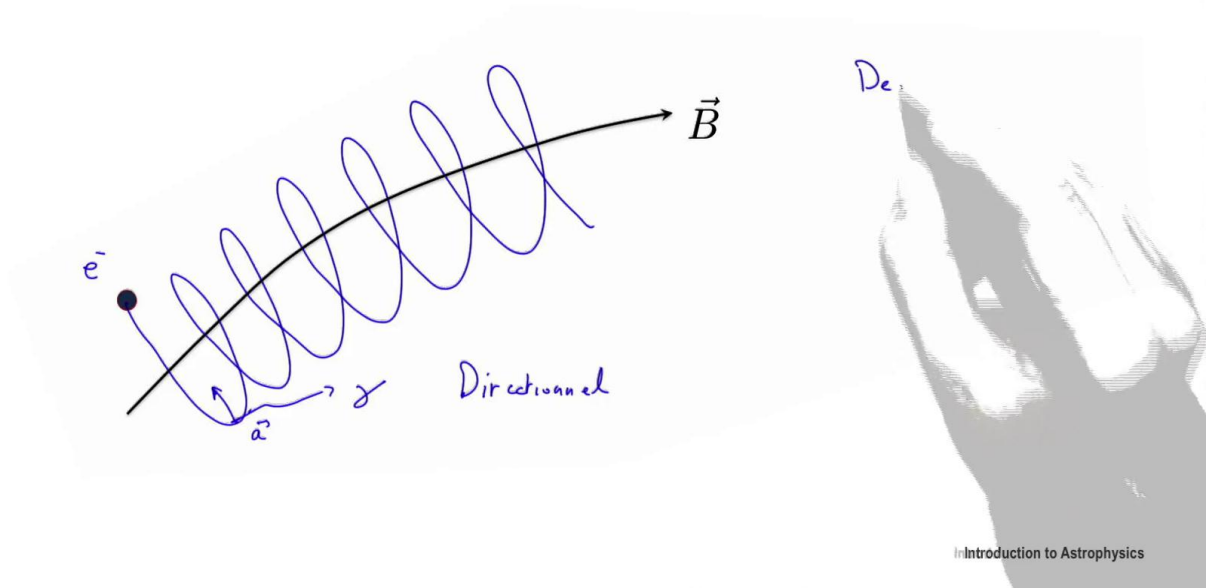
Summary



18m 13s

Synchrotron Radiation

Electrons « spiral » around magnetic fields lines



Therefore, that spectrum is also continuous. And finally, yet another type of continuous radiation, the synchrotron radiation. It is the same type of radiation as observed in particle accelerators. It is a radiation which will cause the particles to slow down. Here we have an electron which starts spiralling around a magnetic field line. Obviously, each time we have a loop like this, we also have a centripetal acceleration and like in the case of Bremsstrahlung radiation we will have emission of photons. But here the photons will be emitted in a well-defined direction because the electrons are channelled by the magnetic field lines. We note that, in the case of Bremsstrahlung radiation, the electrons had to interact with ions. To produce ions, atoms had to separate into electrons and ions and therefore a heat source was needed. Thus, we spoke of "thermal radiation". Here we have a magnetic field that does not need extreme temperatures, and the gas can even be really cold. So one speaks of "non-thermal radiation". In both case, for the Bremsstrahlung and for the synchrotron radiation, we have continuous radiation. In the Bremsstrahlung case, the radiative intensity depends on temperature and electronic density.

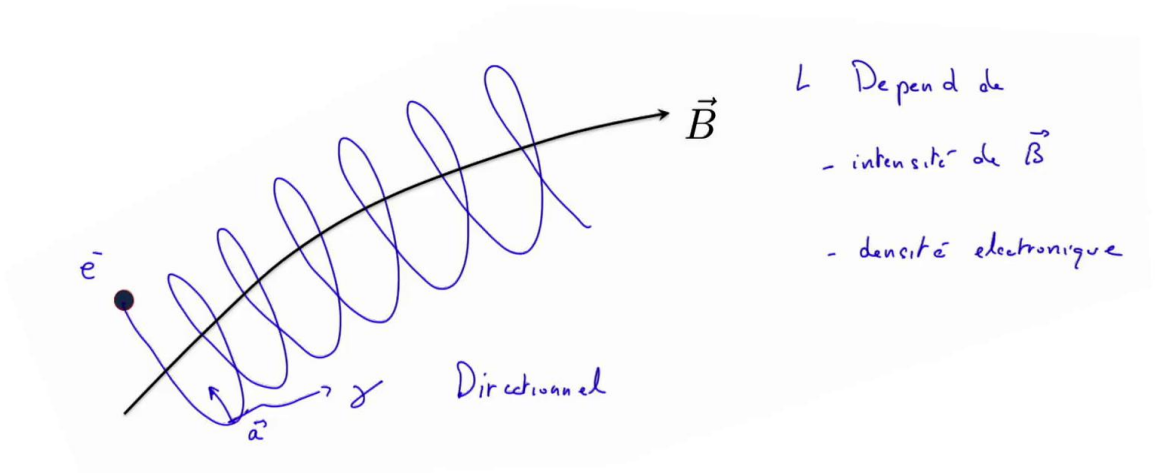
Notes

Summary



Synchrotron Radiation

Electrons « spiral » around magnetic fields lines



Introduction to Astrophysics

Here the radiation depends on the intensity of the magnetic field and electronic density. We have a directional radiation. So if we can observe this type of radiation as a function of the observed brightness, we will get information on the intensity of the magnetic field at that location and on the electronic density.

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Summary



20m 34s

Synchrotron Radiation

Crab Nebula (M1): optical



Images: NASA/ESA/HST/ASU/J. Hester et al.

Crab Nebula (M1): optical + X-ray



Introduction à l'astrophysique

Here on one slide we summarise the various types of radiation and especially the synchrotron radiation. So what we see here are two multi-band images, i.e. observed at several wave lengths, of the Crab nebula: Messier 1 A supernova exploded in 1054, and what we see here are the residues of the explosion. This is an image taken at three optical wavelengths and combined into a single image. And here we have an image where we combine optical radiation and X ray radiation. We note that the nebula looks very different at different wavelengths. What happens at each locations? Here in the optical radiation, if we took a spectrum of the nebula, if we looked at what goes on in these filaments, we would see a line spectrum, in particular hydrogen and helium lines which are the most abundant elements in the stars and also in the remains of supernovas. By studying the spectrum of these filaments, one can even determine their temperature, which ranges from 10 000K to 20 000K and their radial velocity which, measured through the Doppler effect, reaches about 1500km/s.

Notes

Summary



21m 03s

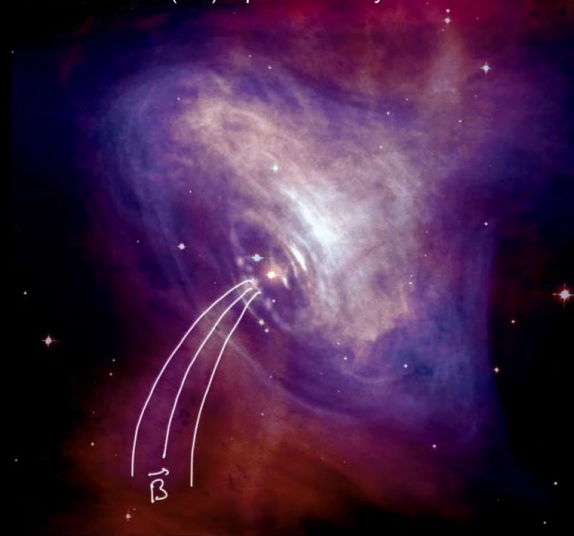
Synchrotron Radiation

Crab Nebula (M1): optical



Images: NASA/ESA/HST/ASU/J. Hester et al.

Crab Nebula (M1): optical + X-ray



Introduction à l'astrophysique

Now, if we look at the image on the right, we have a totally different picture, Especially the radiation, the blue part here which corresponds to the red part in this image, which is the optical diffuse radiation, but we can also see a radiation, here, which is directional. Actually the X-ray radiation is shown here in blue. That is a radiation that is emitted tangentially along the magnetic field lines. We have here a synchrotron radiation, due to a magnetic field created by a pulsar, a residual star which, after a supernova explosion, spins very fast and produces a magnetic field around the lines of which electrons will spiral. Thanks to the study of optical radiation, we can determine the chemical composition of the gas around the supernova and obtain the expansion velocity of the nebula from the observed velocity of the filaments. We also know the chemical composition. Thanks to the X-ray emission, one can determine the plasma density, hence that of the gas of electron and ions, and the intensity of the magnetic field in the nebula.

Notes

Summary



22m 16s



The radiation processes we have just seen are not the only possible ones. Nevertheless, they are the main processes encountered in astrophysics to explain the astronomical objects that we see. They are our main tools to study the universe. In the following videos we will focus on two processes that are especially important in astrophysics. One of them is a continuous radiation, the black body spectrum and the second is the line spectrum emitted by an atomic or molecular gas.

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Summary

