Messages in the light of the stars

Colour, temperature, chemical composition and movement of a star

Network for Astronomy School Education - International Astronomical Union

CREDITS

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THE ELECTROMAGNETIC SPECTRUM

Electromagnetic waves are a periodic variation of two fields, electric and the magnetic, which is transmitted in space without need for a material medium, as it happens with the sonic wave. Light is a type of electromagnetic wave, with a frequency f and a wavelength λ that the human eye can see. But there are many other electromagnetic waves, with other frequencies. The set of all these waves is what we know as electromagnetic spectrum, which is shown in Fig. 1, in increasing order of frequencies (and decreasing of λ).

Although there are no clear limits, the spectrum is usually divided in regions whose waves have a similar behaviour: radio, microwave, etc. The picture shows some objects of the size of the wavelengths in those regions: building, insects, atoms, etc.

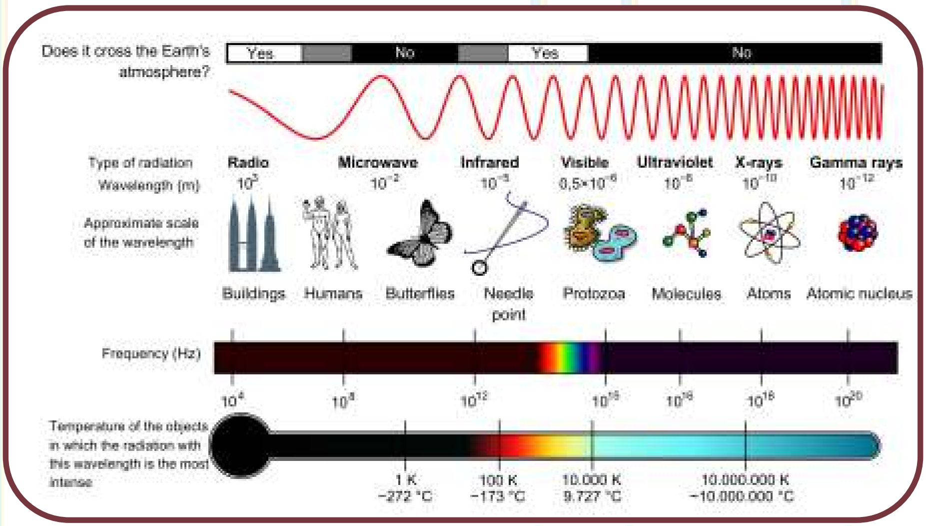


Fig. 1: The electromagnetic spectrum.

DETECTION OF THE ELECTROMAGNETIC ENERGY

Our eye is a marvellous optical detector with which the human being was born, but it is only sensitive to a small region of the electromagnetic spectrum which goes from the red, with wavelength of about 750 nm, a frequency of $4\cdot10^{14}$ Hz and little energy, passing for the orange, yellow, green and blue, until reaching violet, with smaller wavelength, about 400 nm, higher frequency, almost $8\cdot10^{14}$ Hz and with the highest energy inside the visible spectrum.

Beyond red and violet exist other waves not visible to the human eye, with an energy that gives us information about the processes in which they are generated. To be able to study them, it is just necessary to have the suitable detector.

For example in Fig. 2, the Sun appears in different wavelengths, most of which are not visible to our eyes. These photographs were made by special detectors sensitive to these wavelengths, and the colours are simulated, except for the image in the visible.

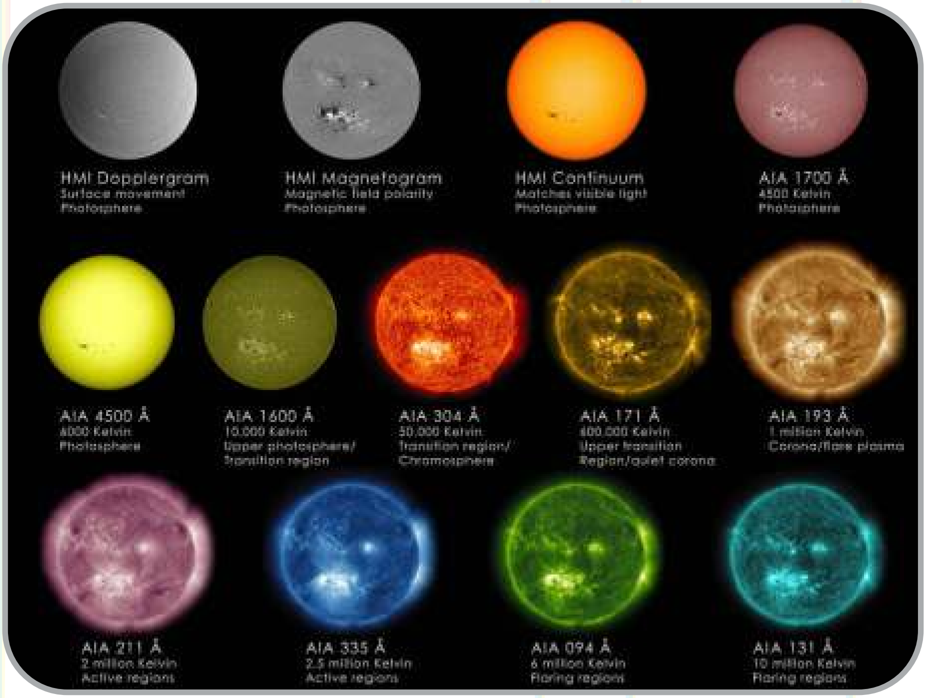


Fig. 2: The Sun in different wavelengths. Credits: NASA/SDO/GSFC.

The stars – the Sun is one of them – emit in many wavelengths, also in the visible, by the violent processes that take place in them and by its high temperatures. But in the Universe there is also much colder matter, for example nebulas and clouds of interstellar material, which do not emit visible radiation, but in wavelengths of less energy, such as infrared, microwaves and radio waves, and we can observe them in those wavelengths, if we have the suitable detectors.

Studying the Universe in all regions of the electromagnetic spectrum, what the astronomers call “multi-wave observation”, allows us to have a much more precise image of its structure, temperature and energy, and to be able to build better models of its evolution.

Fig. 3 shows the centre of the Milky Way, our galaxy, photographed by the space telescopes Spitzer (infrared), Hubble (near-visible infrared) and Chandra (x-rays). In each of them you can see objects and details that in other wavelengths are not seen.

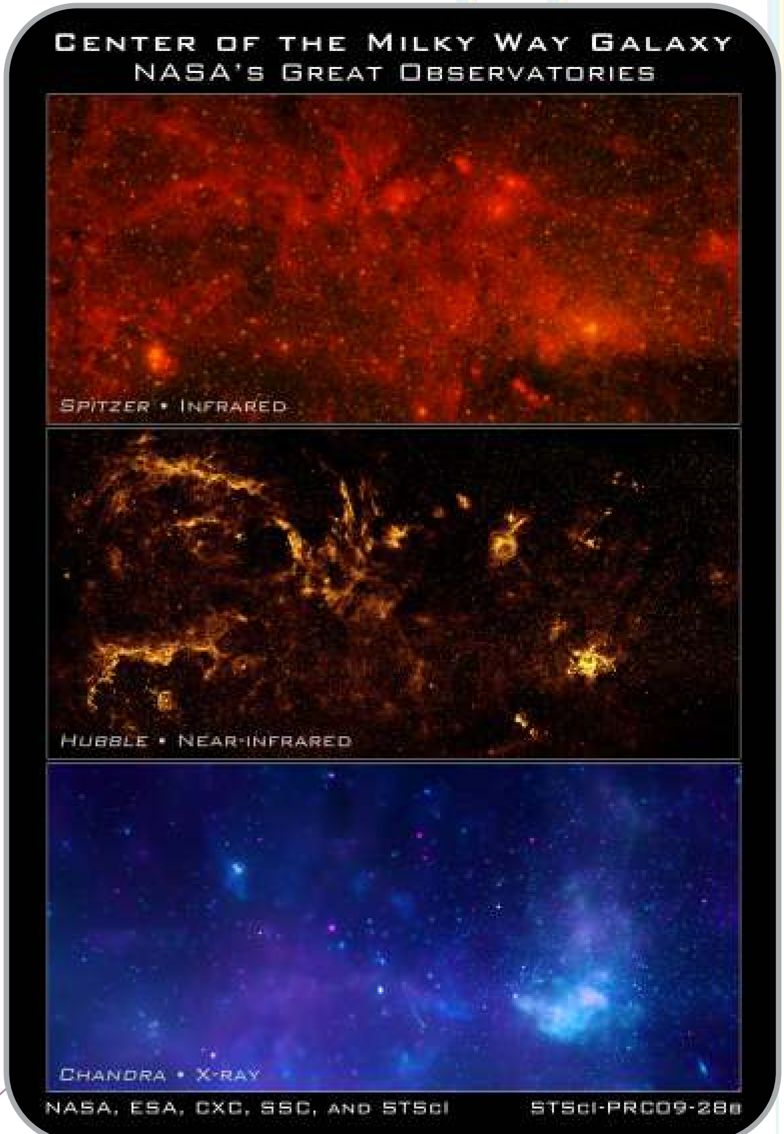


Fig.3: Centre of our galaxy observed with camers sensitive to infrared, visible and x-rays.

DETECTION OF INFRARED WITH A PHONE

When we talk about detecting infrared radiation we certainly think of the night viewers that are seen in the movies, and which are not accessible to anyone. Let's see a more economic and easier procedure to detect that radiation.

The remote controls that we use to turn on the TV or any other electronic device have an infrared LED to communicate with the device. When we press a key, our eyes do not see that the LED turn on, and yet it has emitted infrared radiation.

Most of the cameras of our mobile phones have a chip sensitive to the near infrared (which is close to the visible), which allows us to take photos even if there is little lighting.

Fig. 4: Remote control switched off and switched on.

If we look at the remote control with our eyes directly, we will not notice any difference between switched on and switched off, but the camera of our phone does capture the difference (Fig. 4).

PRODUCTION OF SPECTRA: LAWS OF KIRCHHOFF AND BUNSEN

Any object, for example a piece of metal, emits light if it is heated sufficiently. A gas can also emit light when it is heated, as in a flame. We even can produce light by putting gas between two plates with a strong difference of electrical potential, as in a fluorescent bulb. The emitted light is not the same in each case, it contains a lot of information about the object that produced it. Its study constitutes the Spectroscopy.

That the light can be decomposed in a characteristical set of colors by passing through a prism or a lens is already known from the Xth century. In this epoch the Arabian Wise Alhazen related the rainbow to the water drops suspended in the atmosphere and the sunlight. In the XVIIth century Newton and Huygens studied the continuous spectrum of sunlight passing through a prism.

The German Joseph von Fraunhofer invented in 1814 an instrument called spectroscope, with which he analyzed sunlight and discovered in it up to 570 fixed dark lines that today still bear his name (Fig. 5).

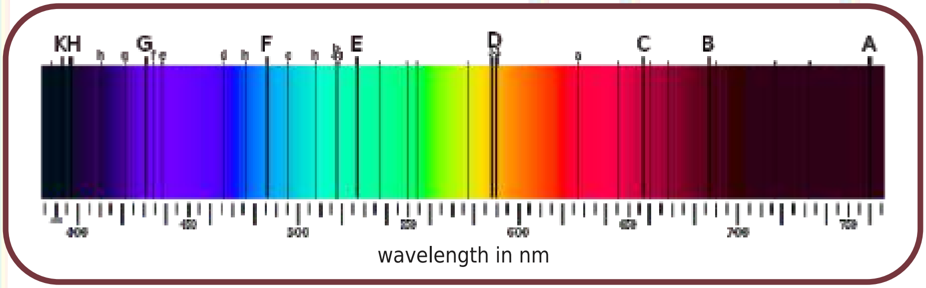


Fig. 5: Fraunhofer lines.

It was Gustav Kirchhoff and Robert Bunsen (Fig. 6), in the mid-nineteenth century, who analyzed the light of the flames produced by various chemical elements when they burned, and observed lines of colours characteristic of each chemical element.

One day, while working in the German town of Hamburg, there was a fire several kilometers away. They used the spectroscope to analyze the flames that could be seen in the distance, and they discovered a double yellow line similar to the one they had observed when burning sodium in their laboratory. It turned out that the building that was burning was a salting factory, with abundant deposits of sodium chloride.

Fig. 6: Kirchhoff and Bunsen.

If they could detect sodium in the flames of a fire, they proposed to study the "flames" of the Sun, to see its composition. What they observed was a continiuous spectrum with some black stripes. Upon analyzing it, they realized that the double bright yellow line of the sodium spectrum was in the same position as the double dark line of the spectrum of the Sun that Fraunhofer had discovered in 1814, and that was called "line D". Kirchoff and Bunsen correctly interpreted it by saying that the coldest gases in the solar atmosphere were catching lines of the light of the Sun, the same lines of the spectrum that they were emitting when the same gas was heated. Thus if the spectrum of the Sun had the dark line D in the yellow zone, this meant that the Sun's light was passing sodium in the gaseous state in its way to the Earth.

They had discovered that the sodium was in the Sun's own atmosphere, without need to go there. In the same way they detected other chemical elements in the Sun's atmosphere.

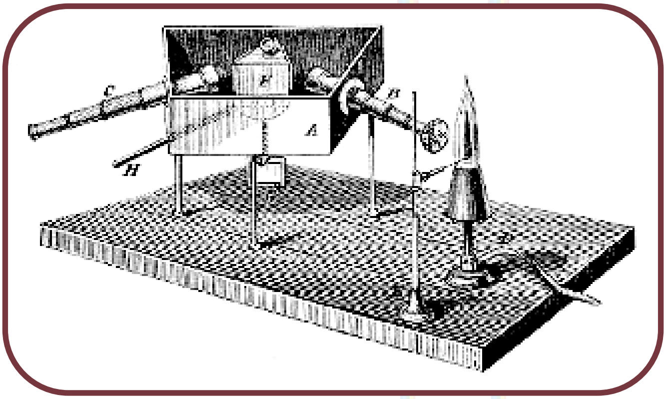


Fig. 7: Spectroscope of Kirchhoff and Bunsen.

THE THREE LAWS OF SPECTROSCOPY

Kirchhoff and Bunsen proposed three laws on which the spectroscopy is still based (Fig. 8):
Law 1: An incandescent solid radiates a continuous light spectrum, at all wavelengths. A liquid or a very dense and hot gas behaves equally.
Law 2: A tenuous gas, when heated, emits light only at certain wavelengths, producing an emission spectrum that depends on the chemical composition of the gas.
Law 3: If the light of an incandescent solid crosses a colder gas, the spectrum is continuous with superposed dark lines, which is called absorption spectrum. In the same gas, the lines of the absorption spectrum and those of the emission spectrum coincide.

These laws can be applied to the light that comes to us from the stars. These celestial objects are made of gas at high pressure and temperature, which makes it be in a fourth state of the matter called plasma. The interior of the star is very dense, and behaves like a solid that radiates light in accordance with the first Law, presenting a continuous spectrum. The external layers are at less pressure and temperature, and in the outermost area it behaves like a tenuous gas much colder than the interior, in the case of the Sun it is only 5780 degrees Kelvin, compared to several million degrees of the core. Therefore, according to the third Law, the most external gases produce absorption lines. Studying the spectrum of the light that comes to us from the star, we can deduce the chemical composition of the gases in the atmosphere.

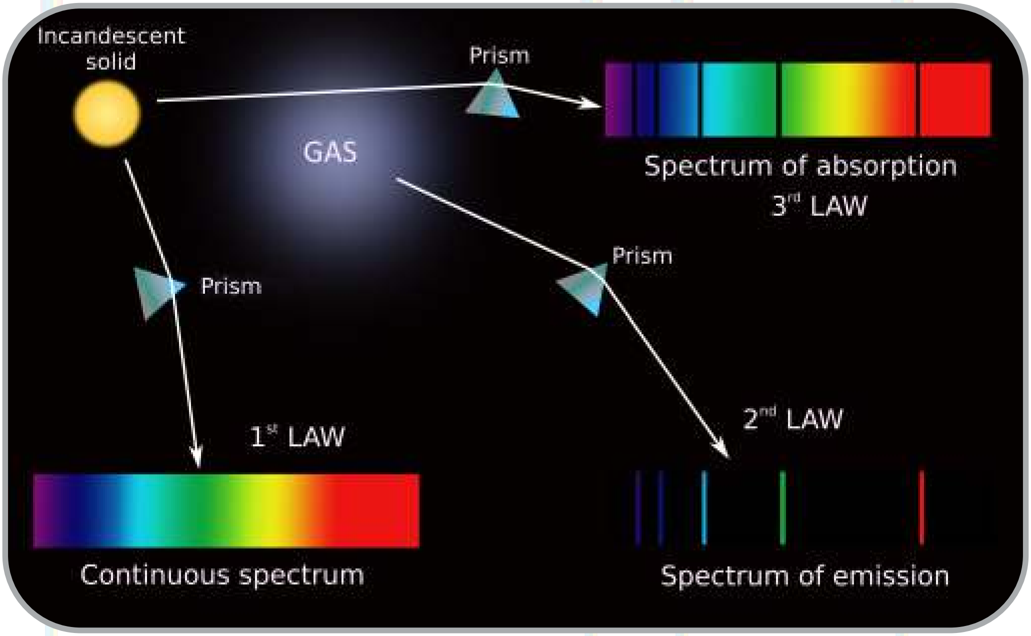


Fig. 8: Laws of spectroscopy. Types of spectra.

BUT: WHY THERE ARE THOSE LINES?

The explanation of the spectral lines came from the hand of the Quantum Mechanics. In 1913 Niels Bohr proposed a model for the atom, with orbitals that had quantized energy levels, as in floors. This meant that electrons could jump from one orbital to another by emitting or absorbing a fixed amount of energy that depended on the orbitals, but they could not stay half-way. With each quantized jump, an energy photon h·f was emitted or absorbed (h is called constant of Planck, $6.63 \cdot 10^{-34}$ J·s, and f is the frequency of the photon).

If the energy was quantized, the f also. Each line of the spectrum was produced by a jump between orbitals (Fig. 9): if it was a more external orbital absorbed a photon, and if it fell down to a more inner orbital with less energy, it emitted a photon. Those possible jumps are specific to each chemical element.

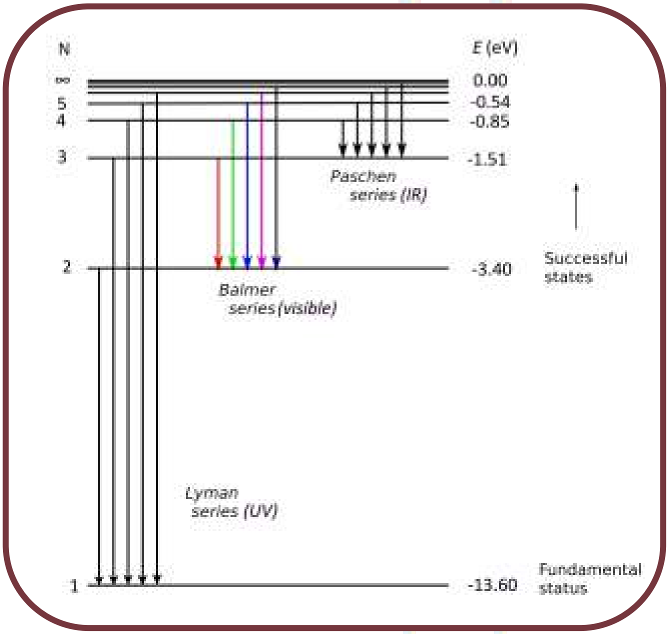


Fig. 9: Energy levels of the Hydrogen atom, with some transitions that produce the spectral lines.

CONSTRUCTION OF A SPECTROSCOPE WITH A CD

Let's see how to build a simple device with which we can decompose the light of a light source, like a light bulb or a candle, and even measure the wavelengths of the colors that are seen.
If the bulb is with filament (halogen) the spectrum is continuous, formed by all colours. If the bulb contains gas (fluorescent tubes, low-energy bulbs and of streetlights) the light contains only certain colours. To separate the colors of light, we need a prism or a diffraction grating. In this case we will use a diffraction grating that form the lines on a CD.
The CD must be plated by the face that is not recorded, it must not be printed, nor be white or of another colour. With strong scissors we cut a piece radially.
It is necessary to detach the metallic layer of the CD. For this we can use adhesive tape, previously scratching the surface (Fig. 10).

Fig. 10: Removing the metal layer of the CD with adhesive tape.

To build the spectroscope, we must make a paper photocopy of the template of Fig. 13, and cut it out, including the the trapezoidal window. The graduated scale does NOT have to be cut. We make a thin slit in the line near the graduated scale, and assemble the box leaving the black part inside (Fig. 11), and sticking the flaps. In the hole left by the trapeze, we paste the piece of CD that we have prepared, which must be somewhat larger than the window (Fig. 12).

Fig. 11: Cut and assemble the spectroscope, leaving the black part inside.

Fig. 12: You have to paste the piece of CD in the window where you look.

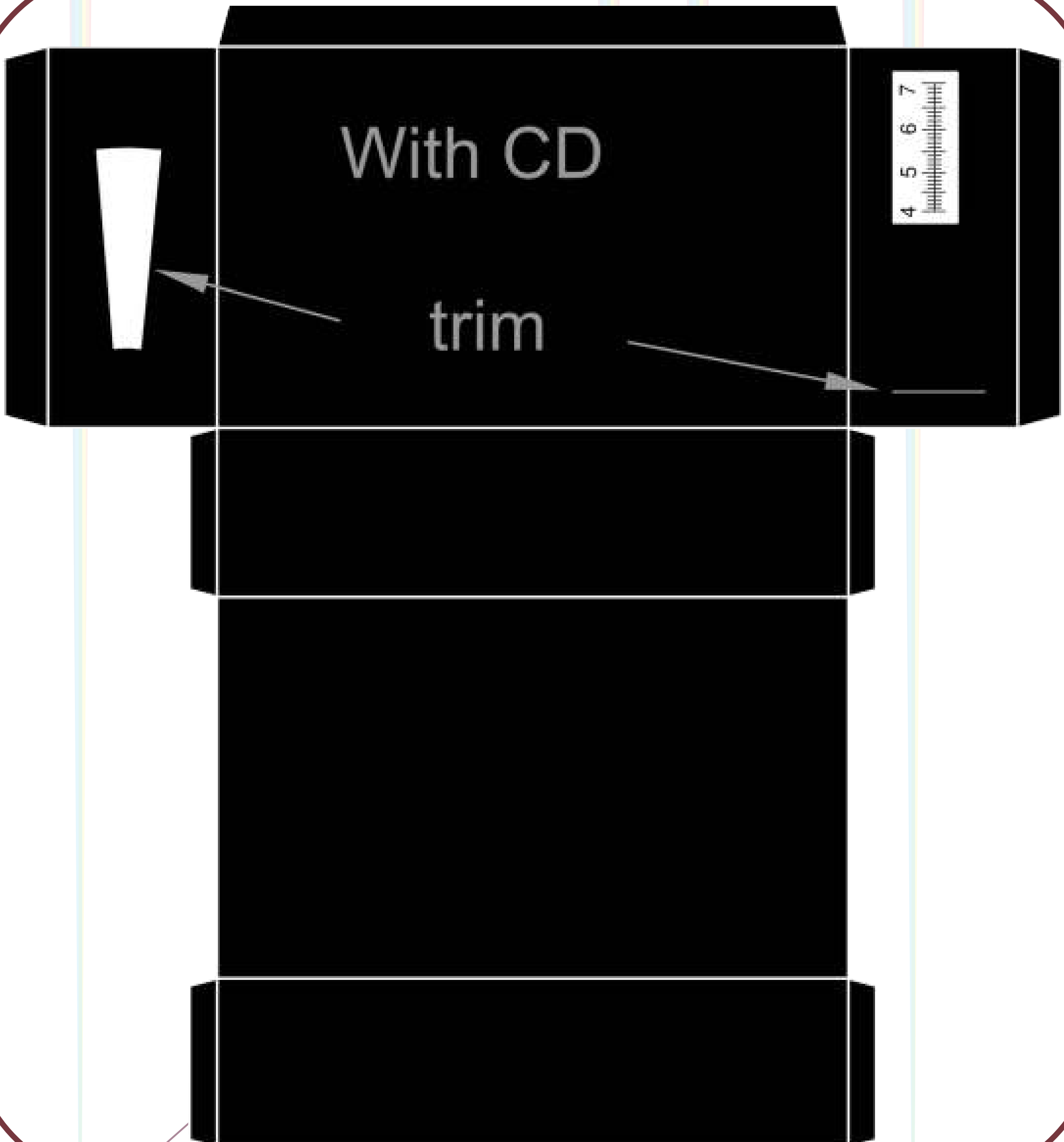


Fig. 13: Template for the spectroscope with CD.

Now let's place ourselves in a dark room, with only one lamp on. We take the spectroscope and look through the window that has the piece of CD, directing the slit of the box to the lamp. We move the slit to the left, (therefore no longer aligned with the lamp), until we see clearly a few colors on the scale. They are the emission lines of the gases that contain the bulb. The scale is graduated in hundreds of nanometers, that means the mark 5 indicates 500 nm ($500 \cdot 10^{-9}$ m). The thinner is the slit, the more accurately we will be able to measure the wavelength of the streaks.

With energy saving lamps and fluorescent tubes, the spectrum is of lines, with a particularly intense green (mercury). With LED bulbs the spectrum is almost continuous, although there are some areas that are missing. You can look at streetlights, both orange (sodium, with an intense yellow double line) and white (mercury vapor). Traditional incandescent and halogen bulbs offer a continuous spectrum, but if they have a power regulator you can see that when they illuminate very little, they hardly have blue. Some examples can be seen in Fig. 14.

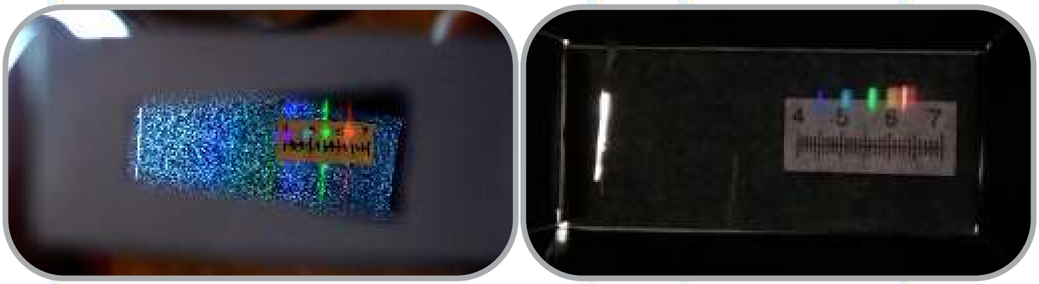


Fig. 14: Spectra of emission lines of a flourescent lamp. You see the spectrum lines and you can measure their wavelength.

Fig. 15: Experience with teachers in Colombia (left) and in Nicaragua(right).

CONSTRUCTION OF A SPECTROSCOPE WITH A DVD

DVDs have more line density than CDs (in the CD there are 650 lines / mm, and in the DVD the double, 1300 lines / mm). If we use a DVD like diffraction grid, the colours will be further separated, and the precision in the measurements will be greater. But we must use another template, the one in Fig. 18. In the DVD there are two plastic layers, one metallic and one not, which is the one that we will use. To separate them the adhesive tape is not necessary as in the CD, it is enough to bend a bit the cut piece, and they separate easily, as it is seen in Fig. 16.

Fig. 16: Folding the piece of DVD separates the silver part of the used grid.

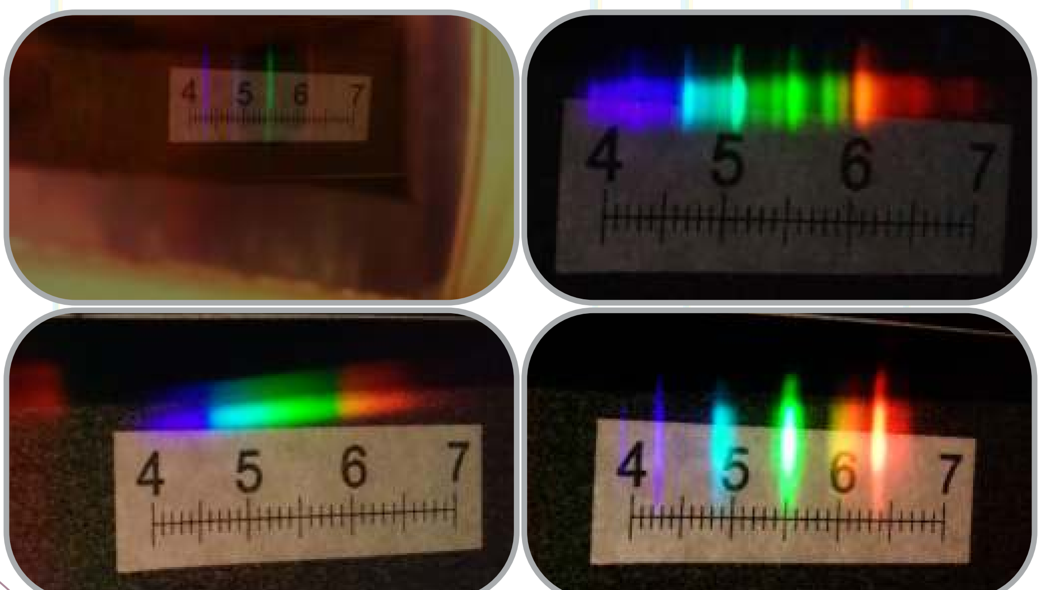


Fig. 17: Spectra of various street lamb bulbs, with the DVD spectroscope.

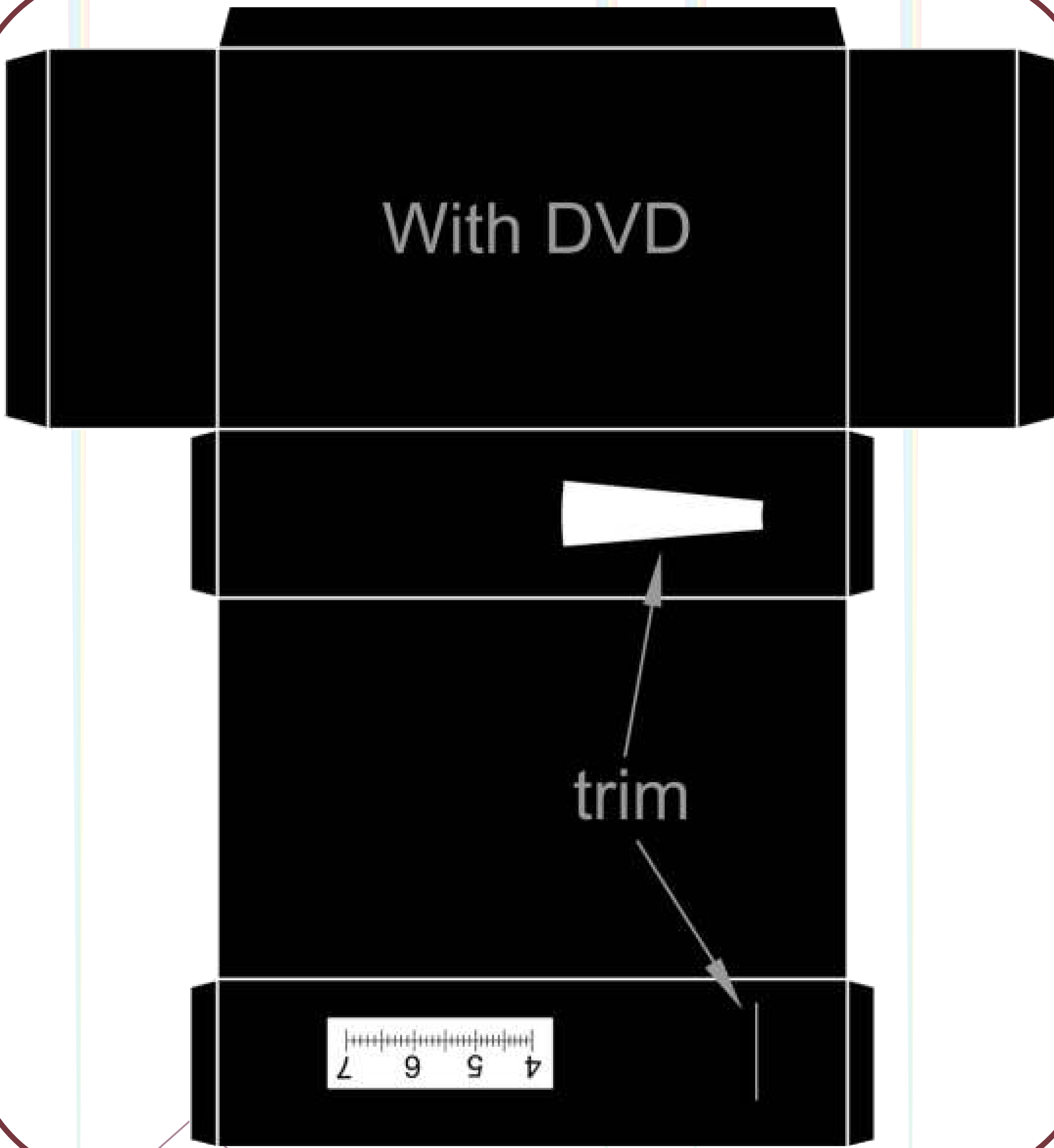


Fig. 18: Template to use with a DVD.

CONSTRUCTION OF A SIMPLER SPECTROSCOPE

It is possible to build a simpler spectroscope, without scale and therefore without being able to measure the wavelengths, with a small carton, for example of medicines, of a book, etc. One of the faces where it opens, a thin split is made in the center, and on the opposite side cut out a window (Fig. 19). Paste the piece of CD or DVD in the window. Close the box and look across the window, directing the slit towards a source of light. The spectrum of colours must be seen to right and left (Fig. 20). If it is not seen, move the box to the left or right, until the spectrum appears.

Fig. 19: Spectroscope with a medicine box and a piece of CD. It is simpler but we cannot measure wavelengths.

Fig. 20: Spectrum example with a medicine box.

LAW OF WIEN

We have seen that a solid sufficiently hot produces light in all wavelengths, with a continuous spectrum. If we measure the energy that it emits in each wavelength, we will see that it is not the same, but it follows a diagram like the one in Fig. 21, called a blackbody diagram, with an emission maximum in $\lambda_{max.}$

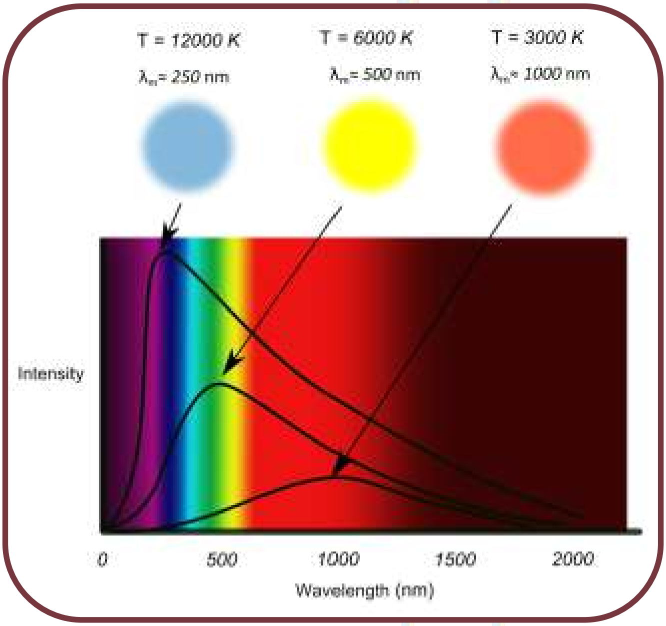


Fig. 21: Blackbody curve and its relation to temperature.

Let's suppose that we have a light bulb with a light regulator, and a photometer with a set of filters with which we can measure the energy of each wavelength. We start with very little illumination of the filament, and we see that the maximum emission is in the red. If we increase the temperature of the filament, the maximum will turn to yellow, then green, blue and even beyond the visible, every time with shorter wavelengths. Wien proved that the product of temperature T and λ_{max} is constant and equal to 2,897·10^{-3}, a constant that bears his name:

$$\lambda_{max} \cdot T = 2{,}897 \cdot 10^{-3} \text{ m} \cdot \text{K}$$

For example· the Sun emits its maximum energy in the green region· with a λ_{max}= 500 nm = 500·10^{-9} m· With Wien's law we can deduce that its surface temperature is T = 5794 K. The yellowish colour of the Sun comes from the combination of all the frequencies in which it emits. Other stars emit more in the red, which means that their surface temperature is lower. And others emits most of their energy in the blue or even further away· which means that they are very hot and the colour that comes out is bluish·

AND WHY ARE THERE NO GREEN STARS?

There are red, yellow, orange and blue, but no green stars. Why?

Let's think about a star with low surface temperature, for example 3000 K. As you can see in Fig. 21, there will be a lot of red radiation, and little of the rest of visible colours, so we will see it at this colour. If we increase the temperature, there will be also orange and yellow radiation. The sum of these three colours gives to the star a red - yellowish tone. If we increase the temperature more, it also emits green. This colour, when mixed with red, gives yellow (see Fig. 22), so the star is still yellow. With more temperature, the star also emits blue, and the sum of yellow, green and blue gives white, therefore the colour of the star will be white, reaching to a white - bluish if the temperature is very high.

And the green star? It is never seen, because this colour is in the middle of the visible spectrum, and a star that emits its maximum radiation in this colour, will always emit also in red and blue, which sum gives yellow or white.

We can reproduce the colour of the stars using three lanterns. The experience works better if you remove the parabolic mirror that the lanterns have next to the bulb, and put a tube of black cardboard. At the end of the tube you have to put a transparent paper filter of blue in one, green in another and red in the third one.

Let's start by lighting only the red lantern. It would be the light of a low temperature star. Let's light the green lantern and mix the two lights: it gives us yellow. They would be the stars of medium temperature, which are seen of a colour that goes from orange to yellow. If we turn on the blue lantern and mix its light with the previous ones, it gives us white, which would be the colour of a high temperature star. If the temperature increased, there would be more intensity of blue, and the star becomes white - bluish.

You can increase or decrease the intensity of a colour by moving that lantern away from the screen.

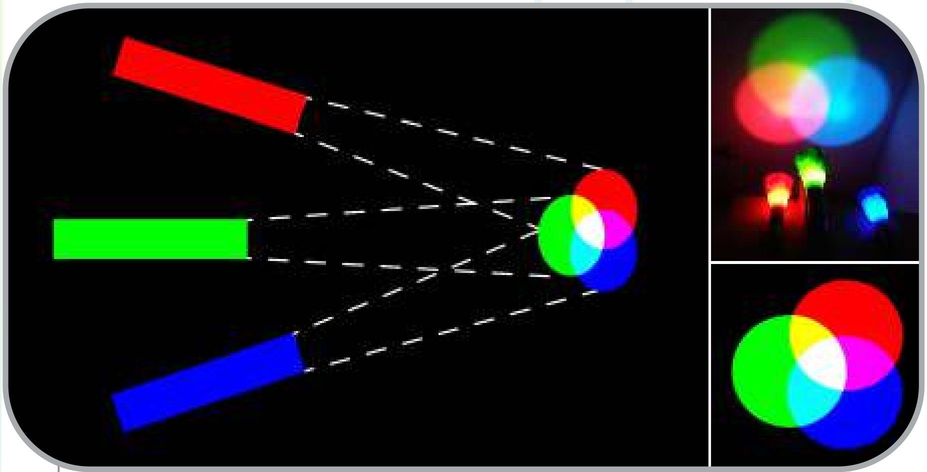


Fig. 22: With three coloured lanterns you can simulate the colour of the stars.

THE STELLAR SPECTRA AND THE SPECTRAL CLASSIFICATION

At the beginning of the 20th Century a group of astronomers working at the Harvard University, sat the bases of the spectral classification that we keep on using today.

These astronomers, led by Annie Cannon, found a relationship between the colours of the stars, their surface temperature and their spectra. They put the stars in certain groups of similar colour, temperatures and spectra, which they called O, B, A, F, G, K, M. The stars of higher temperature are those of type O, bluish, and those of less temperature are M, reddish.

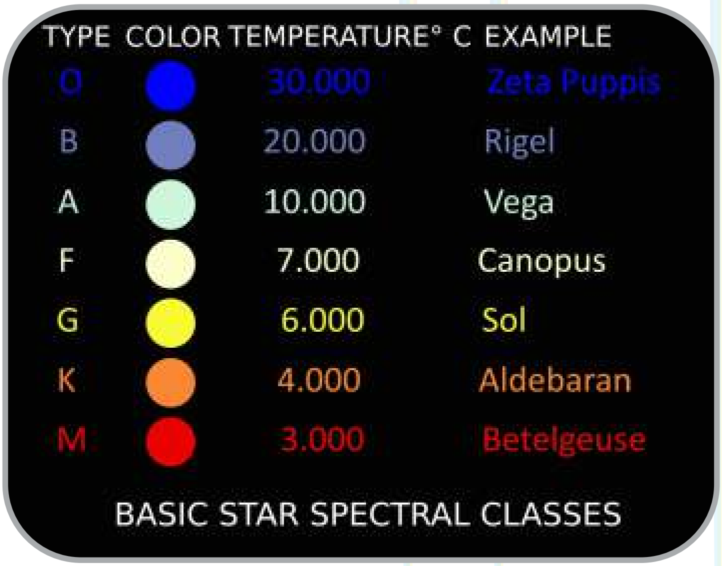


Fig. 23: Types of stars, with their colours and temperatures.

Later each of these types of stars was subdivided. In Fig. 24 you can see the spectra of the types of stars, correlated with the surface temperatures. The characteristic spectral lines of each type are also observed, which represent chemical elements in the atmosphere of the objects. This spectral classification is one of the great achievements of Astrophysics.

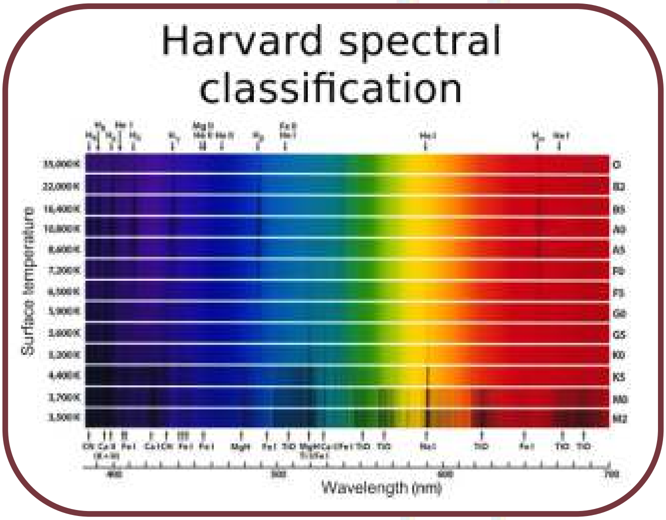


Fig. 24: Harvard spectral classification.

SPECTRA AND EXTRASOLAR PLANETS

If a star approaches us, its spectral lines move towards the blue, and if it moves away from us, they move towards the red. This displacement is called Doppler effect, and it is greater the greater the velocity of the object is. By accurately measuring the position of the lines of the light spectrum of a star, and comparing them with those obtained in the laboratory, we can know if the star approaches or moves away from us, and at what speed. If it is a binary system, in which two stars turn around their centre of gravity, and we know the distance at which they are, we will be able to know also their masses.

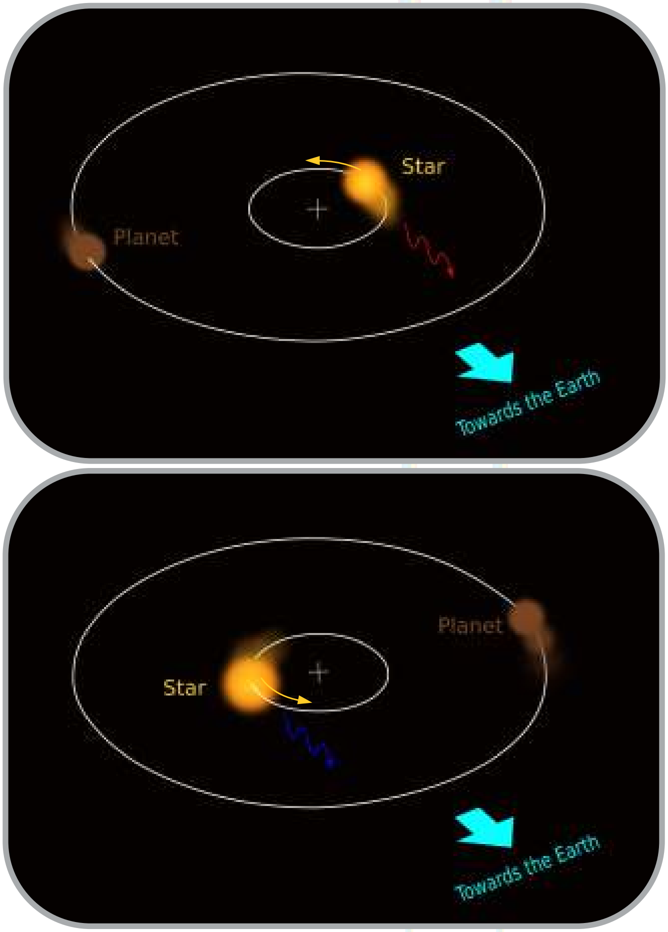


Fig. 25: Doppler effect on a star with a planet.

Most of the well-known extrasolar planets have been discovered thanks to the Doppler effect (Fig. 25). These are very big and dark planets, not directly observable, but detectable when you see that the light of the companion star has an alternating shift towards the red and towards the blue.

CONCLUSION

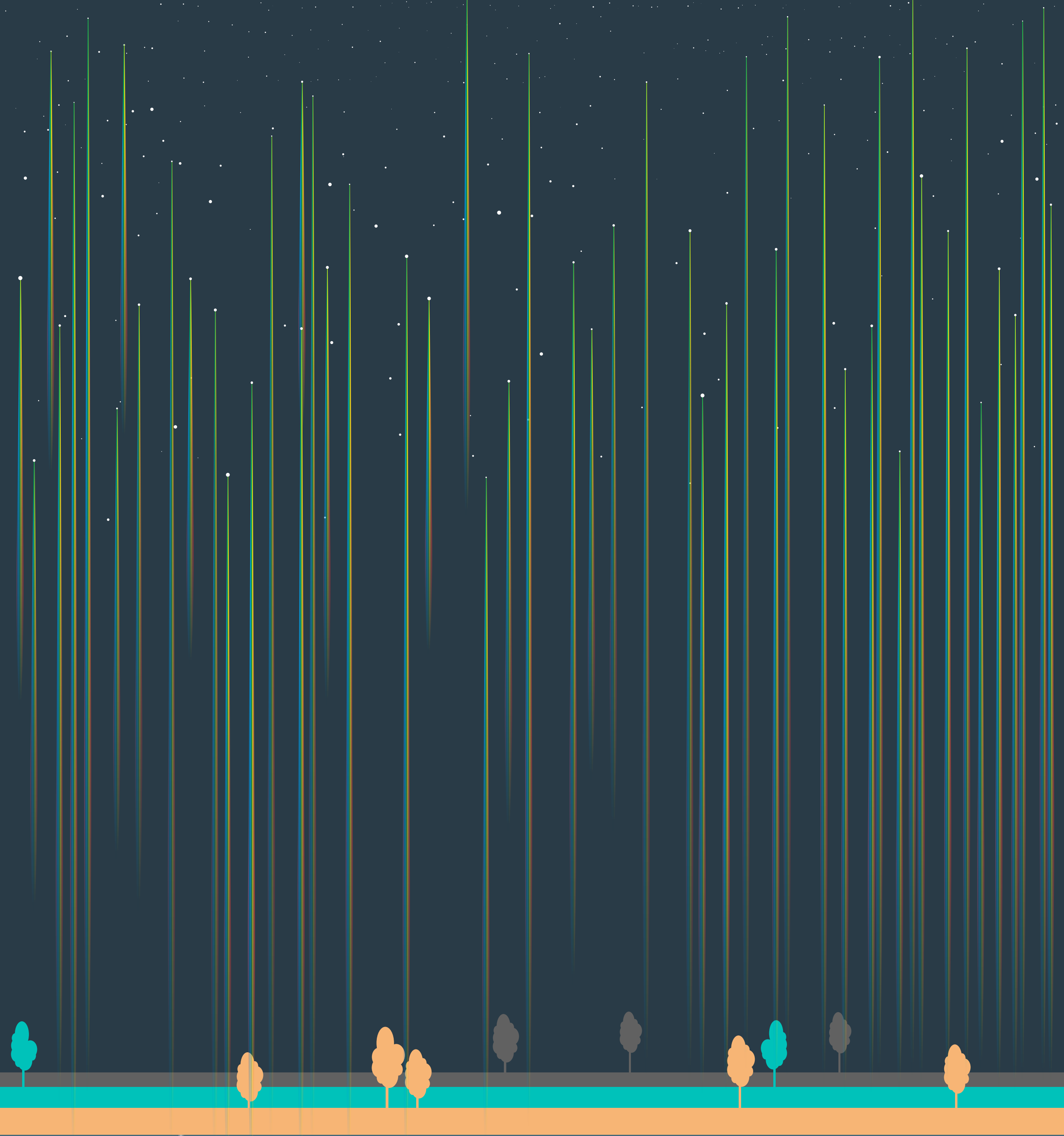
The stars are at enormous distances, but we have seen that to know how they are and what happens in them is not necessary to go there. In the light that they send to us there is a message that contains a lot of information if one can read it properly.

By analyzing the spectrum of the light from a star, we can know what they are made of, its surface temperature, or even if they have big planets around them. Applying other physical laws, astronomers also deduce many other things: the radius of the star, its evolution in time, what processes are going on, etc.

In this publication, in addition to explaining the fundamentals of the spectra, we have reproduced on a small scale and with some simple materials some of these works of the Astronomy professionals, which can be used for the teaching of this science.

BIBLIOGRAPHY

- 14 steps towards the Universe. NASE. Ed. Antares, Barcelona 2018.



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