

STELLAR SPECTRA

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Abstract

This Workgroup consists of an approach to stellar spectrum theory. Stars emit radiation in all frequencies, yet as our atmosphere has a high extinction in almost all non visible wavelength's we shall only consider experiments about the visible spectrum.

The workgroup will have a sequential theoretical presentation, mixed up with continuous experimental demonstration of all concepts presented. These demonstrations indicated in text, will consist of simple experiments that teachers can produce in class when introducing subjects like polarisation, extinction, blackbody radiation and continuous spectrum, line spectrum, sunlight spectrum and Fraunhofer lines.

Construction of simple spectroscope will also be done.

Introduction

Star continuously emit energy that spreads as a spherical surface throughout space. The energy is transported as radiation. Radiation is associated to electromagnetic waves that travel through space with oscillating electrical and magnetic fields in space at a speed of 299 793 kilometres per second. A perfect linearly polarised electromagnetic radiation would have a profile like the one presented in Figure 1.

Stellar radiation doesn't normally have a preferential polarisation. But some light might be polarized. Oriented polarisation of light can be explained to students using a *Polaroid* sheet. We can see that the light is polarised by placing another *Polaroid* sheet next to the first one and looking to the light passing through it. When the two *Polaroid* sheets have similar polarisation orientations (light will pass through them) or perpendicular polarisation orientation (light will be block and the sheets will be obscured) (Demonstration 1-Figure 2).

As known, electromagnetic radiation can present different types of wavelengths or frequencies that are usually grouped in different types as shown in Figure 3.

Frequency, wavelength and light speed are related to each other by the expression

$$\nu = \frac{c}{\lambda} \quad (1)$$

where ν is the frequency, c is the speed of light and λ is the wavelength.

Though stars emit in all wavelengths we will make the major part of our approach to stellar spectrum using the visible, infrared and ultraviolet wavelengths, because except for radio frequencies those are that our atmosphere is transparent to (Figure 4). Therefore they are the best ones for experimentation.

Stellar Radiation

It's common knowledge that stars are nuclear reactors where huge amounts of energy are permanently being produced. The energy is transported to the surface in the form of photons. Photons are "light" particles responsible for electromagnetic radiation that have a quantified energy of value

$$E = h\nu \quad (2)$$

where E is the energy of the photon, h is Planck's constant ($h=6,626 \times 10^{-27}$ J.s= $6,626 \times 10^{-27}$ erg.s) and ν is the frequency of the electromagnetic radiation associated with the photon.

Photons that leave the stellar photosphere are responsible the spectrum that can be detected. Therefore to understand the spectrum one needs to understand all phenomena related to the production of light since its nuclear generation until it leaves the star's atmosphere.

Opacity

The energy associated to a photon takes about 1 million years to reach the surface. This might seem strange, but not if we think about the density of the core and stellar interior. Radiation is produced in the core in nuclear reactions, where mass is converted to energy according to Einstein's equation

$$E=mc^2 \quad (3)$$

On the journey to the surface photons continuously interact with matter of the dense stellar interior. Successive absorptions and emissions determine the path of photons since their generation in the core. Some times emission sends the photons closer to surface, other times it sends it backwards. So after a million years the energy produced in the core, usually as a gamma ray, finally reaches the surface in the form of one or more photons (recall that the fall to fundamental state of excited particles many times occurs in several steps producing several photons). Absorption's and emissions occur in a very big number since the photon generation until it reaches the photosphere.

When it reaches the photosphere it is radiated to the exterior without further interactions for most of the wavelengths.

The core and the inner parts of the Sun are opaque (optically thick) to all radiation wavelengths and its atmosphere is transparent (optically thin). A gas may be optically thin or optically thick according to the fact that it absorbs the photons crossing it. As an example, our atmosphere is normally optically thin to visible wavelengths. Yet, on a foggy day, you won't see far, so it is optically thick. But optically thin doesn't mean invisible. For instance one can use an overhead projector to prove that the flame of a burning candle is optically thin to visible light projecting the candle's shadow with an overhead projector on a wall (Demonstration 2, Figure 5). The candle will appear, but not the flame. The flame is therefore optically thin to the wavelengths of the projector.

Blackbody Radiation

During the long period the photons stay inside the stars they are thermalized, which means that the photons that are emitted will not have their initial wavelengths. Instead, they will have a distribution of intensities of emitted radiation that obeys a Planck curve, which is only dependent of temperature by Planck's law. For each frequency we will have

$$I_v = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} = B_v \quad (3)$$

$B_v = \text{blackbody intensity}$

where h is Planck's constant, ν is the frequency, k is Boltzmann's constant ($1,34 \times 10^{-16}$ erg/K), c is the speed of light in vacuum, and T is the thermodynamic temperature.

We say it radiates like a blackbody. The distribution of blackbody intensity as a function of the wavelength is given in Figure 6.

All optically thick objects are blackbodies and they have a maximum wavelength ($\lambda_{\max}$) for emission of radiation associated to their temperature that can be determined by *Wien's displacement law*

$$\lambda_{\max} = \frac{0.290}{T} \quad (cm) \quad (4)$$

where T is the thermodynamic temperature. Examples of optically thick astronomical objects are the stars (except for their atmosphere and corona), the planets, asteroids, etc.

Almost all things on Earth radiate like blackbodies. For instance, the common human being radiates like a blackbody. It absorbs ultraviolet and visible light during daytime. Yet, as known, if one wishes to see the radiation emitted by him, one should seek the infrared region with the devices that military use. That is because all energy absorbed by the human being is thermalised and then emitted according to Planck's law close to a maximum infrared wavelength of $9.4 \mu\text{m}$ given by Wien's law (considering a temperature of 37°C (310 K)). Blackbody radiation is the explanation why observing an incandescent lamp or an incandescent hot object with a spectroscope will allow us to see a continuous spectrum associated to blackbody radiation (*Kirchoff's 1st law*) (Demonstration 3).

Since the stellar atmosphere is optically thin, the blackbody radiation will be determined by the temperature of the photosphere. In the Sun's case (around 5800 K) so its blackbody radiation should have a maximum wavelength at about 5000Å, as shown in Figure 7. Also shown in Figure 7 are the ultraviolet and infrared absorptions due to Earth's atmosphere as consequence of what has been presented with Figure 4.

Curiously the human eye has evolved to have a curve of visibility that is quite consistent with the visible curve of sunlight that gets to Earth's surface (Figure 8). Note that due to atmospheric extinction the light curve of sunlight reddens near sunset, and so does human eye visibility curve.

The concept of extinction can be demonstrated with an overhead projector leaking only a small beam, filling a tall glass with small portions of very diluted milk; the bigger the column of milk is, redder will be the light that gets to the wall, since blue light is preferentially scattered (Demonstration 4, Figure 9).

Absorption Spectrum

When we have a hot atomic gas, it emits a line spectrum (*Kirchoff's 2nd law*)(Demonstration 5) associated to the emission of photons due to electronic transitions from a higher state to a lower state of energy.

If the gas has those emission lines due to transitions between to electronic states, then obviously it can absorb the same energy doing the opposite transition. Then if the gas is put between an incandescent source and a spectroscope, the gas will absorb those same lines from the continuous spectrum of the incandescence source (*Kirchoff's 3rd law*)(Figure 10) .

This is what happens in the stellar atmospheres. The gas of the stellar atmosphere will absorb the frequencies associated to the spectral lines of the elements present in its composition. It will then emit the radiation but not all in the same direction (some is even emitted backwards). The frequencies associated to the atomic absorption by the elements of the atmosphere appear like dark lines over the continuous spectrum. Composition of the stellar atmosphere can be made with students using simple cases like the one presented in Figure 11.

The stars can be classified according to the spectra which they produce. About 95 per cent of the stars can be put into classes which are labelled O, B, A, F, G, K and M, according to special characteristics of the spectra. For example, in type A stars the lines representing hydrogen are prominent, whereas in type G stars the lines representing calcium are strong and the hydrogen lines are considerably weaker.

The order of the classes given above is also the order of the surface temperature of the stars, the ones of type O having the highest temperature. It is also generally the order of absolute magnitude of the star.

Building a small spectrometer

Use of a simple spectrometer allows us to see the difference in the continuous part of stellar spectra and can easy allow us to show our students the lines of the solar spectrum. You can also show your students other sources using diffraction gratings or

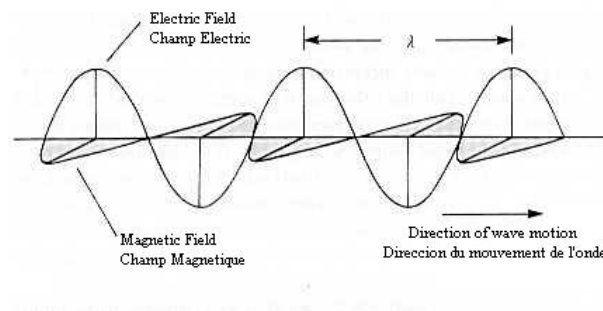
spectrometers, like incandescent lamps, fluorescent lamps, neon lights, LEDs, mercury lamps, low pressure and high pressure sodium lamps or even white computer screens.

We will try to mount the spectroscope that J.Waxman (1984) described in. *Astronomy*. Cambridge University Press, pp 320-323. We can see the general aspect and the model of the window and wavelength graduation Figures 12-13.

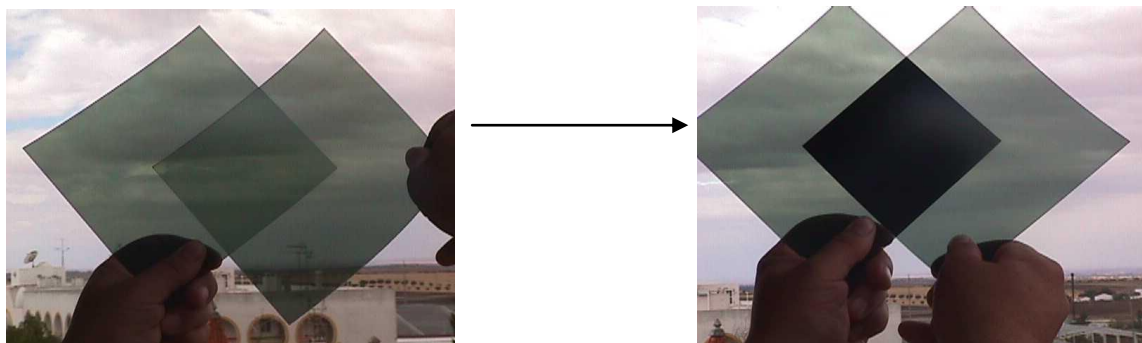
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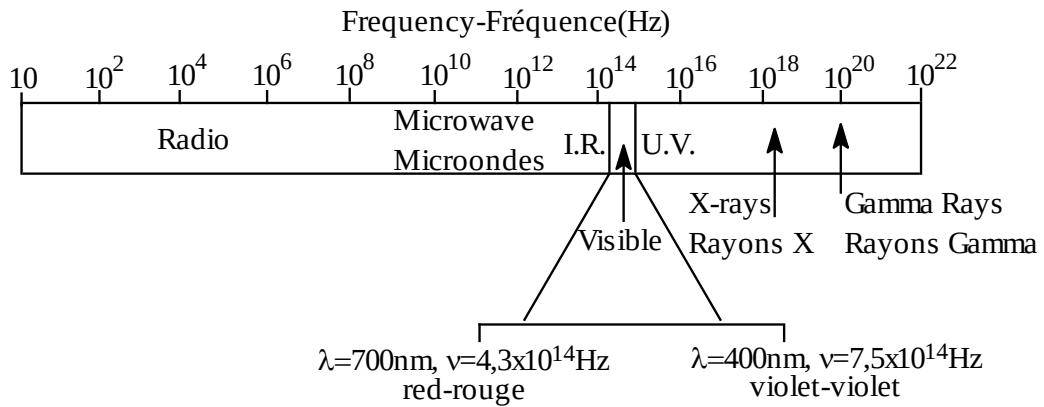
FIGURES



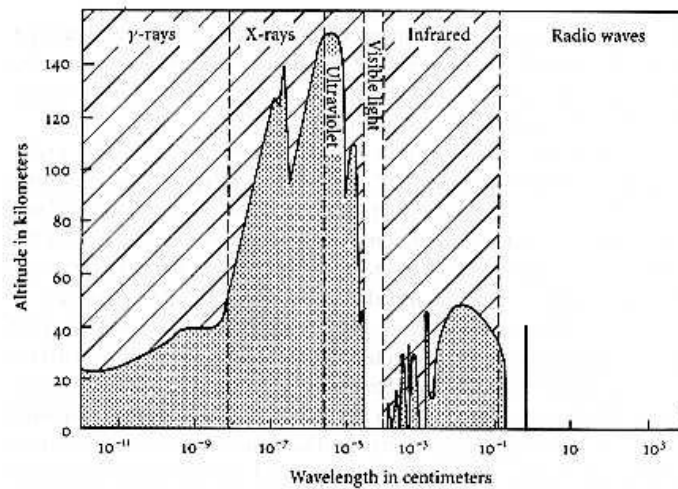
1 - Electromagnetic wave. Onda electromagnética.



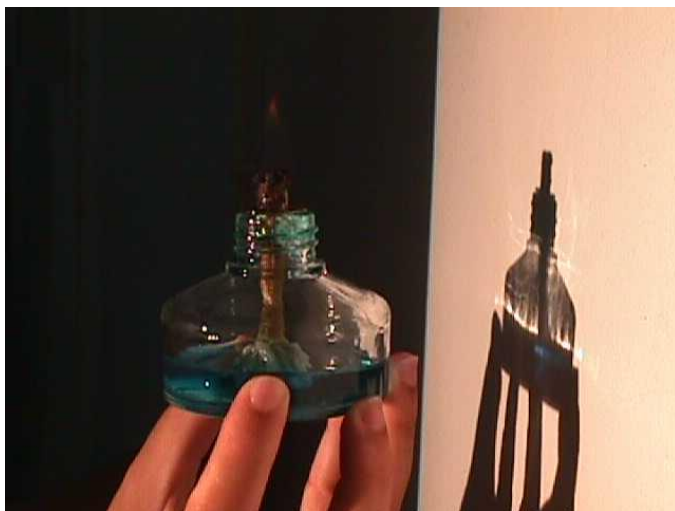
2 – Polarization demonstration. Demonstração da polarização da luz.



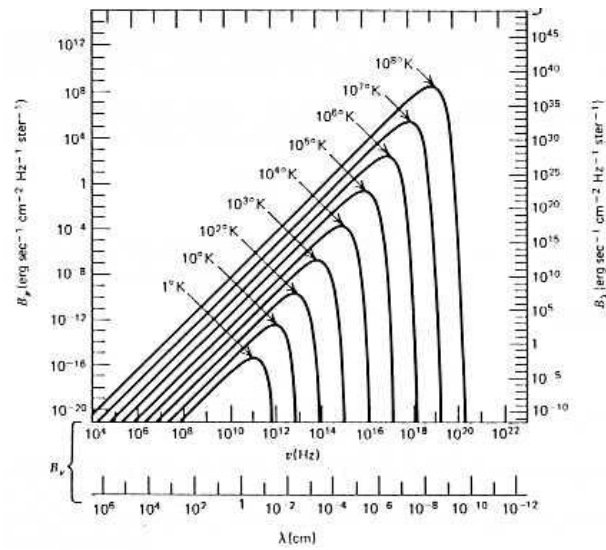
3-Electromagnetic Spectrum. Espectro Electromagnético



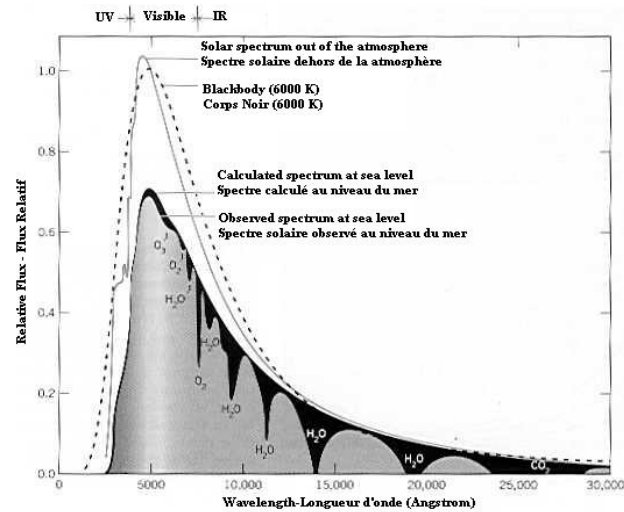
4 -Transparency of earth's atmosphere to the diferente Wavelengths(Credit: Lang,1995).
Transparência da atmosfera da Terra nos diferentes comprimentos de onda (Crédito: Lang,1995).



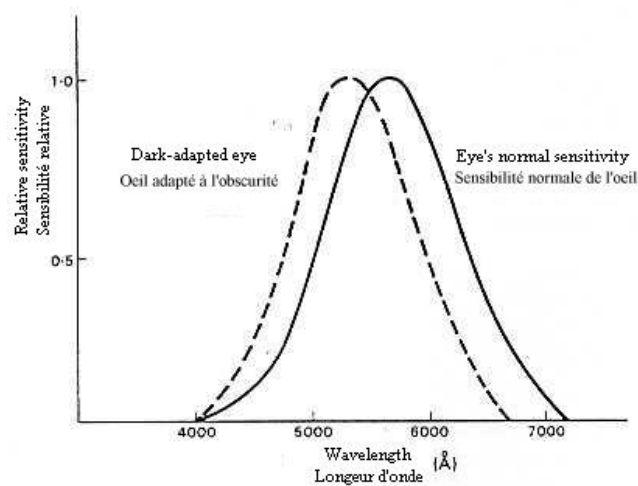
5 – Optically thick and optically thin. Opticamente fino e opticamente espesso.



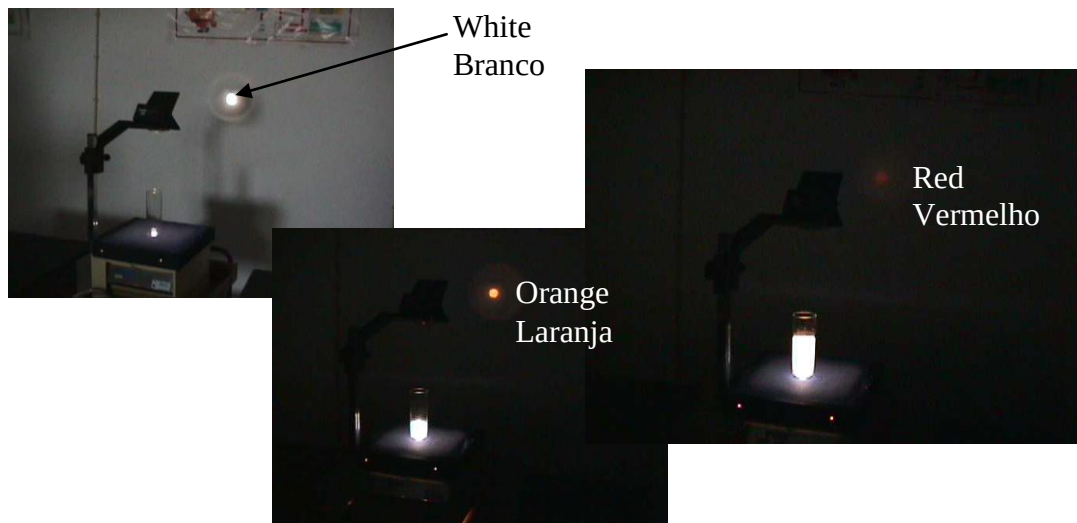
6 - Planck curves at different temperatures. Curvas de Planck a diferentes temperaturas (adapted from Rybicki & Lightman, 1979).



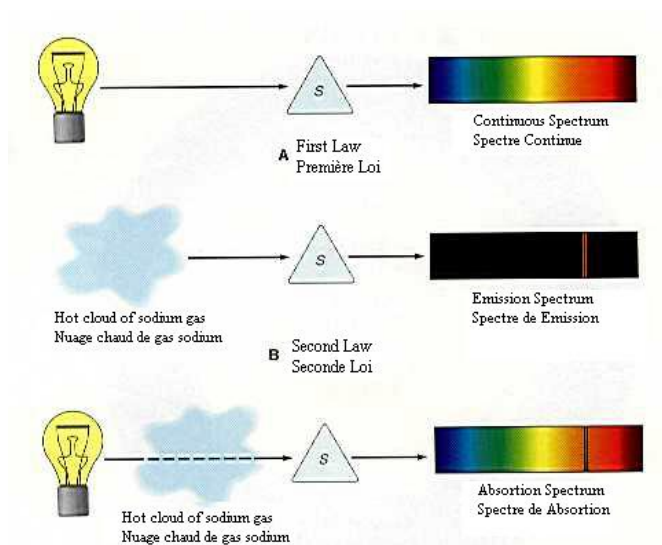
7 - Solar Spectrum. Espectro Solar. (Zeilik, 1997)



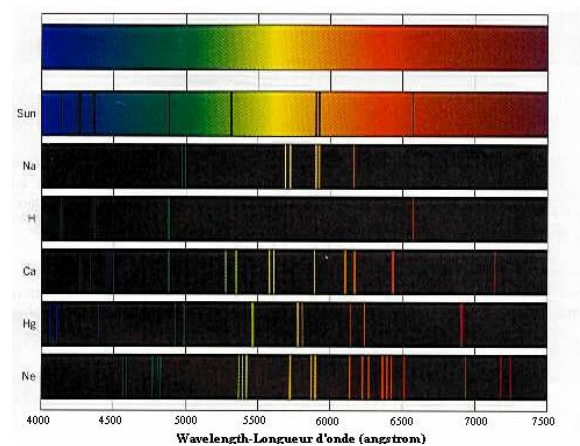
8 - Human Eye's sensitivity to the various wavelengths. Sensibilidade do olho humano a diferentes comprimentos de onda.



9 – Scattering and Extinction. Dispersão e Extinção.



10- Kirschhoff's Laws. Leis de Kirschhoff.



11 - Low resolution spectrum of continuous emission spectrum, sunlight and several emission spectrums of elements. Espectro solar de baixa resolução e espectros de alguns elementos (Zeilik,1997).

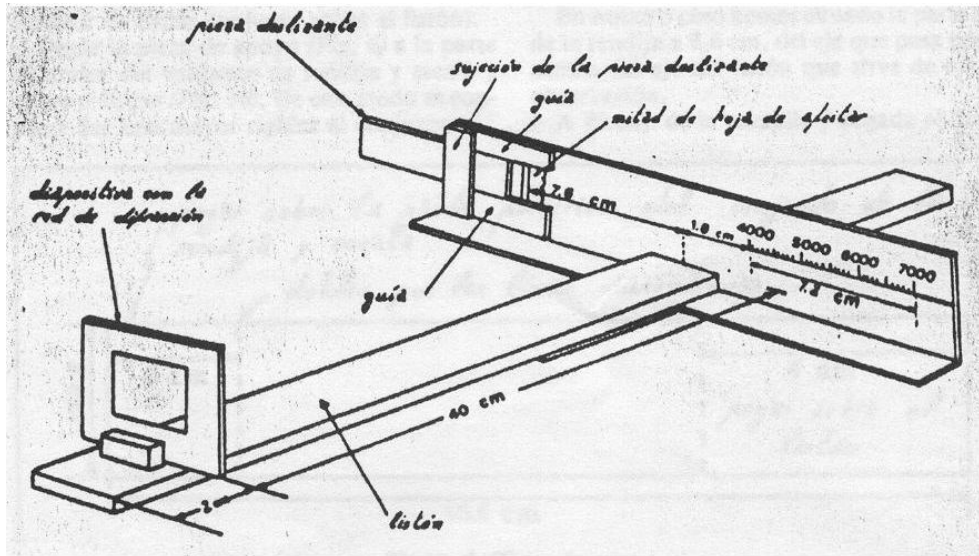


Figure 12

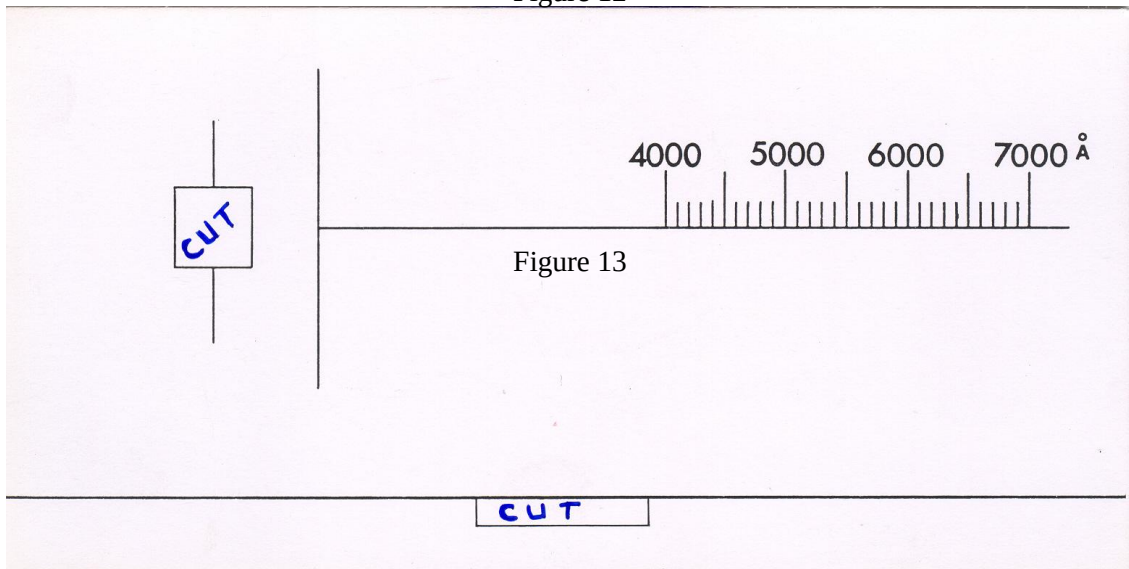


Figure 13