



THE DISTANCE TO THE STARS:

The meaning of photometry
in Astronomy



Network for Astronomy School
Education - International
Astronomical Union



Credits

Written: Beatriz García and Ricardo Moreno Luquero

English translation: Suzana Gelf

Designer: Silvina Perez Álvarez

Graphics: NASE and Wikipedia

Printed by: Albedo Fulldome S.L. Barcelona, España, 2020

ISBN: 978-84-15771-70-8



International
Day of Light

16 May

Prologue

When we imagine the Universe as a whole we must approach concepts related to the measurement of time and the determination of distances. Perhaps we can think that obtaining both magnitudes is somewhat complex and the truth is that from the point of view of natural philosophy these are issues that were resolved step by step, applying the scientific method, using tools that Scientists developed throughout the history of the Astronomy.

The basis of all discoveries is the study of light, which led to the determination of the chemical composition of stars, their movements and evolution, but which also provided the possibility of determining the distances to celestial objects.

Along millennia and from the first proposals to calculate distance using trigonometry, as suggested by Aristarchus of Samos several centuries before our era, to the recognition of current astrophysical "candles", a special type of supernova, researchers found ways to determine the distances that separate celestial objects.

One of the purposes of this publication is to show how it is possible to reach the stars by determining the distances that separate us from them, analyzing the power of the light that we detect on Earth, but it also seeks the recognition of those people who found the way to reach this achievement. Finally, the invitation is to develop the "sense of space" in a finite, but unlimited Cosmos.

Beatriz García

The Light

In classical Greece (3rd century BC), Euclid made the first mathematical study of light in his Optical treatise. He described the rays of light traveling in a straight line, and enunciated the laws of reflection from the mathematical point of view.

Much later, around the year 1000 AD, the Arab-Persian Ibn al-Haytham (Alhazen) (Fig. 1) wrote eight books on Optics, where the first explanation of the rainbow is found. It is one of the first to explain vision not as a ray coming out of the eye towards the object, but the other way around.



Fig. 1: Ibn al-Haytham (Alhazen) was the first to explain the Rainbow with the Optic.

In 1676 the Dane Ole Romer measured the delay and advance of Jupiter's moons by observing them in the part of the Earth's orbit closest and furthest from Jupiter, and interpreted it as the delay of light in travelling that difference in distances. Until the 18th century, the works were almost exclusively geometric optics, with lenses, mirrors and prisms. Stand out Isaac Newton, who treated light as corpuscles, and Cristian Huygens, who treated it like waves.

The first to attempt a quantitative study were Bouguer (1729) and Lambert (1760), who developed concepts and definitions that are still used today. In 1879, Edison and others developed the electric lamp, which emitted light when a conductor was heated. At first the filament was made of carbon, but then it was converted to metal: osmium (1902), tantalum (1905) and tungsten (1906). In the middle of the 20th century other types of lamps appeared: gas discharge lamps, halogen lamps and, more recently, LED lamps.

In the following sections, the scope of the work related to the photometric technique and the determination of power from unknown sources will be described, in order to show how to determine the Sun and, applying the acquired knowledge, to estimate the distance to the stars from their luminosity.

The Photometry

We can produce light in two ways: the first is by heating something very much, for example a solid in incandescent lamps, or a gas in a fire. The second way to produce light is an electrical discharge in an ionized gas, such as in discharge lamps, where mercury or sodium vapors are used. In all these cases, visible light is usually accompanied by infrared and ultraviolet radiation, usually in the form of losses.

The Sun and the stars produce light through a different process: by the fusion of atomic nucleus or nucleosynthesis.

Inside the Sun, energy is created in the core, in a region of very high pressure and a temperature of about 15 million degrees Celsius. Under these conditions, matter is completely ionized. It is neither solid, liquid, nor gaseous, but is in a fourth state of matter called plasma. At the core, these conditions allow for nuclear fusion reactions, in which enormous quantities of hydrogen are transformed into helium. Scientists assume that this is done in two ways: with the so-called proton-proton chain, which is common in moderately massed stars such as the Sun, and with the Carbon-Nitrogen-Oxygen chain, which is predominant in stars with more mass than the Sun.

In both cases, four protons (hydrogen nuclei) are transformed into a helium nucleus, plus positrons, neutrinos and photons in the region of the highest electromagnetic energies (gamma rays). The resulting mass is somewhat less than that of the initial four protons. That lost mass has been transformed partially into energy, according to Einstein's famous equation:

$$E = m \cdot c^2$$

In which m is the mass that is lost and c is the speed of light, 300,000 km/s. In the Sun, every second 600 million tons of hydrogen are transformed into helium, but with a loss of mass of between 4 and 5 million tons, which is converted into energy. Although it may seem like a huge loss, the mass of the Sun is such that it can continue to function like this for billions of years.

Fig. 2: it takes a million years for photons formed in the nucleus to escape into the photosphere.



The photons generated in the nucleus interact continuously with matter, very dense in these areas. The result is a zigzag path (Fig. 2) that delays up to one million years the exit of these photons into space.

This energy is transported out of the Sun by conduction, convection and radiation. When it reaches the surface of the star it leaves it and spreads through space, by radiation, at the speed of light.

The luminosity or power of the Sun is enormous. The transmission of this energy through space can be imagined as if it were made in a bubble that grows larger and larger with distance. The surface of that sphere is $4\pi R^2$. If the power of the Sun is P the energy E that arrives in one second at one square metre at a distance R is:

$$E = \frac{P}{4\pi R^2}$$

For example: at the distance from the Earth the average energy coming from the Sun per second is 1366 W/m^2 , a value measured by satellites in the upper atmosphere, and called the solar constant.

Definitions and units

In the study of light, several basic concepts and definitions are used. Let's see what they are.

The first is the concept of **solid angle** and its unity, the steradian. If in a circle the radian can be defined as the central angle that covers the length of a radius in the circle, in a sphere the steradian (sr) is defined as the solid angle ("in 3D", in the form of a cone) that covers an area of 1 square radius in the sphere. The total of the sphere has 4π steradians and a steradian would be the solid angle with which we see one square meter at a distance of one meter. If on a sphere of radius R we draw a surface of area A , the solid angle it covers would be $\Omega = \frac{A}{R^2}$ (Fig 3):

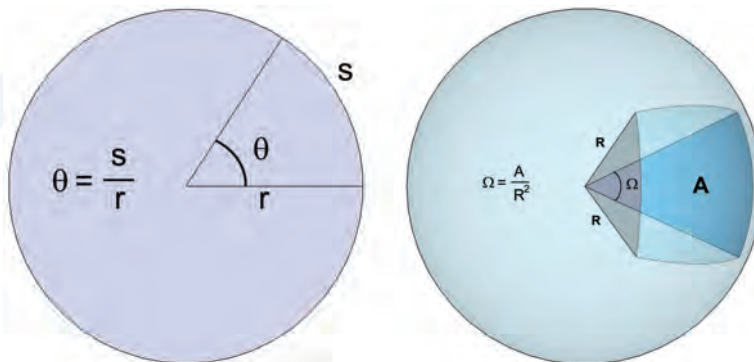


Fig. 3: flat angle in radians and solid angle in steradians.

Another concept is the **power P** of a transmitter. This is the total amount of energy it emits per second. It is measured in watts (W). For example, a 100 W filament bulb.

Some of the energy of an emitter is not visible to the human eye, for example the energy emitted in form of heat or ultraviolet radiation. The **luminous flux F** of a source is the part of the power of that emitter that is visible to the human eye. It is measured in lumens (lm). An ideal source could emit a maximum of 683 lm per W . The real emitters have a lot of heat loss, and they also emit in many colors, which we do not all perceive as the same. This means that a 100 W filament bulb, for example, can have a flow of about 1000 lm .

The light from a point source travels radially outwards in straight lines. The luminous flux included in a given solid angle Ω does not depend on the distance to the source.

Hence the concept of **luminous intensity I_v** of a source: it is the flux per unit of solid angle $I_v = \frac{F}{\Omega}$. It is measured in candela (cd). Although it has a precise definition, a candela is approximately the luminous intensity of a candle. A 100 W filament bulb can have about 100 cd .

To differentiate between luminous flux and luminous intensity, it must be kept in mind that luminous flux is the luminous energy radiated in all directions, whereas luminous intensity is the luminous flux within a given solid angle Ω , which remains constant at any distance from the source.

An old unit of the luminous intensity is the "candle". In 1909, the United States, England and France established the "international candle" as the standard unit, based on the intensity of electric carbon filament lamps. Later it was agreed to call it an international candela, with a cd symbol. According to the definition, if a source has 1 cd of luminous intensity, the luminous flux emitted in a solid angle of 1 steradian is 1 lumen.

When we talk about the greater or lesser illumination that a surface has, we are talking about the **illuminance E_v** , which is the amount of luminous flux that reaches one square meter of that illuminated surface. If the surface has an area of S and a total flux of F arrives, the illuminance of that surface is:

$$E_v = F/S$$

Its unit is lux (lx), which is one lumen per square meter ($1 lx = 1 lm/m^2$). For example, a sports stadium with daylight-like lighting receives about 100,000 lx . The luminous flux is obtained by multiplying the illuminance by the area. So if in the above example the stadium has an area of 5,000 m^2 , we will need to illuminate it with $5 \cdot 10^8$ lumens.

Let us now assume two non-point sources with the same luminous intensity, one of which has a larger area than the other. If you look at them one by one, the smaller one appears brighter to the eye than the other. The brightness is the luminous intensity radiated per unit area of the emitter.

Finally, **luminous efficacy** is the fraction between the lumens produced by the light source and the watts consumed by it. The ideal maximum would be 683 lm/W . If we assume this value as 100%, we speak of **Light Efficiency**. In an incandescent filament lamp, the luminous efficacy can be 15 lm/W and its efficiency 2%, i. e. only 2% of the radiant energy is seen as luminous flux, while 98% of the bulb's power is emitted in the form of heat, mainly. In a fluorescent lamp, the efficiency can reach 100 lm/W , i. e. its efficiency can be around 15% (the other 85% of the energy consumed is not visible). In an LED lamp, the efficiency can be 200 lm/W , and its efficiency can reach 30%, which means that we see 30% of the power consumed.

Day and night vision

The human eye is not equally sensitive to all colours. Under normal conditions, the human eye is more sensitive to light emitted by the Sun, which has a maximum in the green-yellow with a wavelength of 555 nm . Sensitivity decreases rapidly for longer and shorter wavelengths.

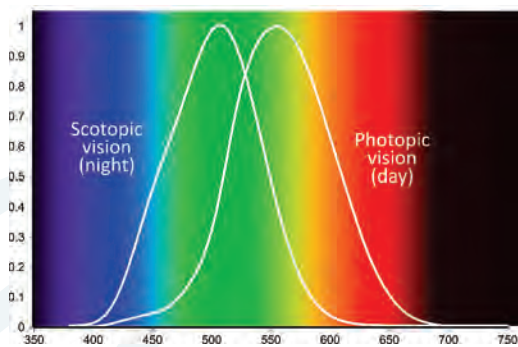
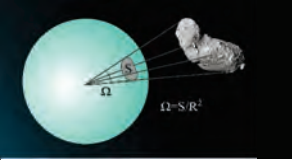

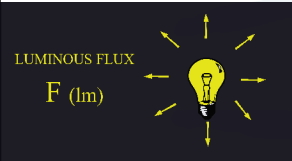
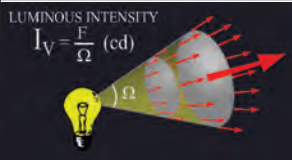
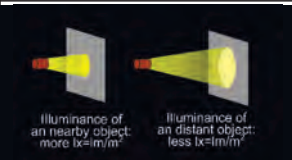
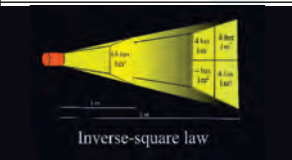
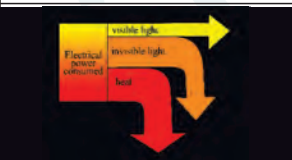


Fig. 4: sensitivity curve of the human eye, day and night.

In addition, the sensitivity of the eye changes during the day and night (Fig. 4). In our retina there are two types of light-sensitive cells: cones, which are sensitive to colour but need a lot of light, as in daylight, and sticks, which are much worse at distinguishing colours but need little light, and are responsible for night vision. When you go from day to night, you go from what is called photopic vision to scotopic vision. This causes the sensitivity of our eyes to recognize the colours of the stars.

To measure the illumination with which we see an object, the watt is not sufficient, because the human eye has different visual sensations with different colours. This is why a new magnitude is needed, the luminous flux, which is measured in lumens. If a source would emit only at a wavelength of 555 nm , which is what the human eye sees best, 1 W would be equivalent to the maximum of 683 lumens. If it also emits at other wavelengths that we see less bright or even do not see, 1 W would be equivalent to significantly fewer lumens.

The following table summarizes the basic physical quantities for measuring light :

Magnitude	Definition	Schema
Solid angle	The solid angle of an object from a given point measures how large that object appears to the observer. The unit is the steradian (<i>sr</i>), represented by the Greek letter omega Ω .	
Power	It is the measure of the amount of electromagnetic energy that emits a radiator per time unit. Measured in watts (<i>W</i>).	
Luminous flux	It is defined as the power emitted in the form of light radiation to which the human eye is sensitive. Its symbol is <i>F</i> , and its unit is the lumen (<i>lm</i>).	
Luminous intensity	Flow emitted per unit of solid angle in a particular direction. Its symbol is <i>I</i> , and its unit is the candela (<i>cd</i>).	
Illuminance	Luminous flux received per unit area. Its symbol is <i>E</i> , and its unit is lux (<i>lx</i>), which is equivalent to one lumen per square metre (<i>lm/m²</i>).	
Inverse-square law	Illuminance decreases with the square of the distance between the focus and the illuminated surface, as the area also increases with the square of the distance. The light intensity and distance from the source are related to this law. This law is only valid if the direction of the incident light beam is perpendicular to the surface.	
Luminous efficiency	It is the quotient between the luminous flux produced and the electrical power consumed. The bigger it is, the better the lamp will be and the less it will waste. The unit is the lumen per watt (<i>lm/W</i>). The theoretical maximum is 683 <i>lm/W</i> .	

Measurement: the Photometer

A photometer is an instrument that measures the amount of light in a given location. Determines the amount of energy per unit of time (the Power) from an unknown source compared to a well characterized source. Today, most photometers use a photoelectric cell, which compares point sources with measurement standards, sets units for the devices used and also allows the construction of a system of magnitudes.



Historically, there are several photometers proposed for comparing light sources. In this work we will focus on that of Robert Bunsen (Fig. 5), a German chemist and physicist who was born in the city of Göttingen where he did his first studies before moving to Paris, Berlin and Vienna. He taught Chemistry at the Polytechnic Institute of Kassel (1836) and at the Universities of Marburg, Breslau and Heidelberg (1852). Convinced of the importance of physical studies for chemistry, he argued that "a chemist who's not a physicist is nothing".

Fig. 5: Robert Wilhelm Bunsen.

Working with Kirchhoff, in 1859 he invented the first methods of spectral analysis, discovering that spectrum lines are characteristic of every chemical element. From the spectroscopic technique, he characterized and isolated caesium from the lepidolite ore and rubidium.

He built many of the devices he needed in his experiments. Perhaps the best known is the lighter that bears his name, but he also invented the oil spot photometer.

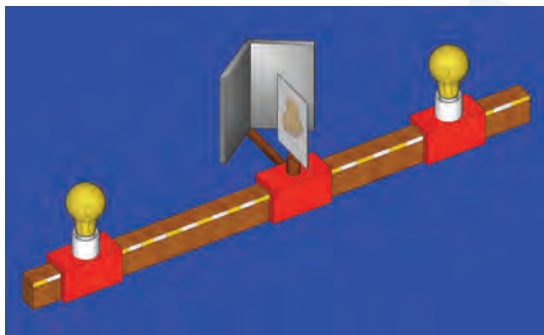


Fig. 6: Bunsen photometer, with a paper and an oil spot. It had two mirrors at an angle to see both sides of the paper at once.

The Bunsen photometer

The photometer invented by Bunsen made it possible to establish the intensity of a light source by comparing it with a light source of known intensity. Two light sources are located at the ends of a measuring tape (Fig. 6). A plain white paper with a small oil spot is placed between the sources. In the stained area, the paper becomes semi-transparent. As you move the paper along the tape measure, moving it away from or closer to the light sources, there comes a time when the stain is barely visible. The photometer that Bunsen built had two angled mirrors to see both sides of the stain at the same time, but it can be dispensed with. In this position, the illuminance that reaches every second the both sides of the paper is the same. The luminous flux will be a part η (the luminous efficacy) of the electrical power consumed, and these lumens are distributed over the entire surface of a sphere of radius equal to the distance from the source to the paper (area = $4\pi d^2$). The flux per area unit is the illuminance in lx: the farther away the less illuminance: thus the greater the area of the sphere. If both sources are bulbs of the same type they have a similar luminous efficacy and in the practice proposed below the equations that should be considered are:

$$Ev_1 = Ev_2$$

$$\frac{\eta P_1}{4\pi d_1^2} = \frac{\eta P_2}{4\pi d_2^2}$$

cancelled: $\frac{P_1}{d_1^2} = \frac{P_2}{d_2^2}$, and solved $P_1 = P_2 \frac{d_1^2}{d_2^2}$

Ev_1 and Ev_2 are the illuminances (in lx) that reach each side of the paper, η is the luminous efficacy of the sources (the part of electrical energy that we actually see), P_1 and P_2 are the electrical powers of the two bulbs, and d_1 and d_2 are the distances from the paper to each light source.

If for example the bulbs are 100 W and 60 W halogen bulbs (Fig. 7 and 8), in the position where the oil stain is not visible it will occur:

$$\frac{100}{d_1^2} = \frac{60}{d_2^2}$$

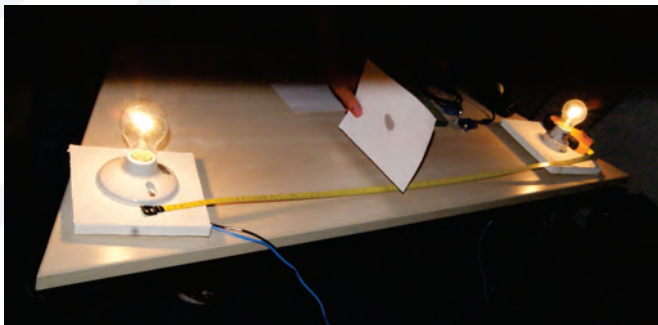


Fig. 7: Bunsen photometer. As the stain looks dark, there is little light behind it, and it should be brought closer to the right light bulb until the stain is not visible.

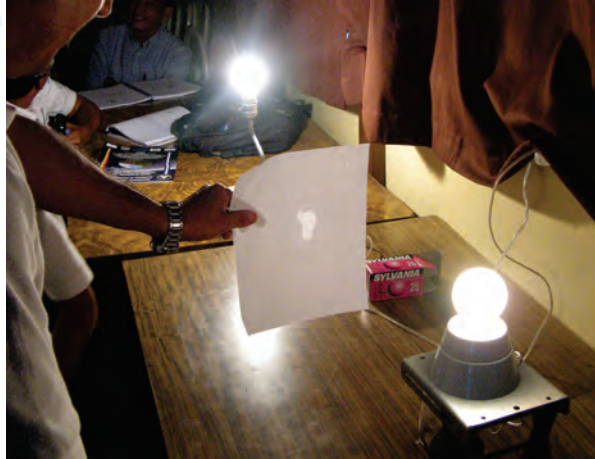


Fig. 8: the oil stain looks shiny; too much light comes from behind, and it should be brought forward until the stain is not visible.

We can do a classroom experience to check the functionality of the oil spot photometer. We will compare a 60W standard bulb with two other sample bulbs, 40W and 100W. To do this, we prepare a chart like the one shown below, so that the student can record the data accurately, including whether the lamp is transparent or the glass is painted and what colour the light it produces is.

Lamp used as a pattern			Lamp used as a sample			
Type of bulb	Indicated power (W)	Distance bulb-paper (m)	Type of bulb	Indicated power (W)	Distance bulb-paper (m)	Calculated Power (W)

Tabla 1: Determination of the power of an unknown source.

Determination of the power of the Sun

The power or luminosity of the Sun is the energy emitted by our star in a second. Using the oil spot photometer, we will calculate its power by comparing it with a 100W bulb (Fig. 9).

On a sunny day, the photometer and a halogen bulb of at least 100W (the more the better) are installed outdoors. The photometer is placed between the Sun and the bulb at a distance such that both sides of the photometer appear equally bright. The distance d_1 , in meters, from the photometer to the bulb filament is measured (Fig. 10).

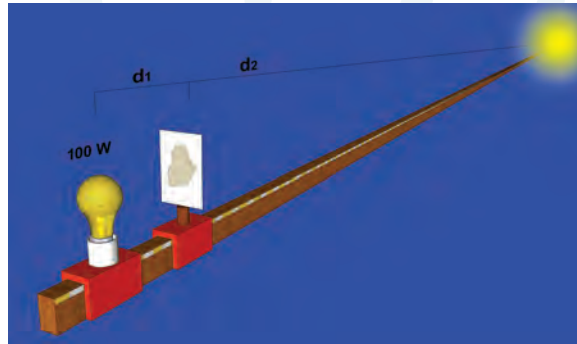


Fig. 9: comparing the power of the Sun with a 100W bulb.

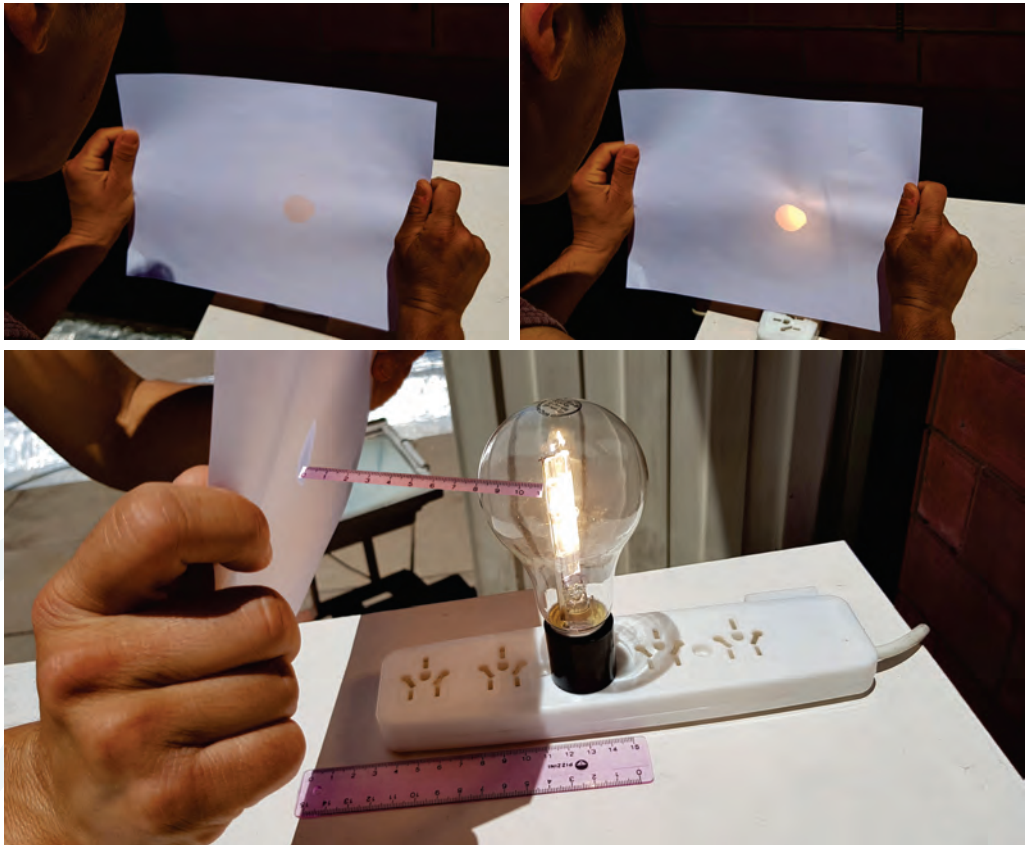


Fig. 10: when the stain is no longer visible, measure the distance from the paper to the filament.

Knowing that the distance of the Sun from the Earth is approximately $d_2 = 150,000,000,000m$ (one astronomical unit), the power of the Sun P_{sun} can be calculated with the same formula as the previous activity, known as the inverse law of squares:

$$\frac{100 \text{ W}}{d_1^2} = \frac{P_{sun}}{d_2^2}$$

Note that the luminous efficiency of the Sun and the halogen bulb are not the same, but the result obtained should not differ much from the actual luminosity of the Sun, which is $3.83 \cdot 10^{26} \text{ W}$.

Determination of the distance to the stars

One of the most important topics in astronomy is the determination of distances. We can say that this physical magnitude was one of the topics in which scientists really showed their abilities, since determining distances to objects that we cannot reach is not a trivial issue.

- Parallax

Perhaps the oldest method of which we have news to determine the distance to the stars is that of parallax, which provides a resource where we apply basic geometry and trigonometry to solve a triangle whose vertices are occupied by the Earth, the Sun and the star whose distance you want to know.



Fig. 11: parallax. The finger appears projected on a different background when observed with the right eye (left) and with the left (right).

To understand the concept of parallax, let's imagine observing a finger of our hand, the thumb for example, on the arm extended first with the right eye (keeping the left one closed) and then with the left, there will be an apparent displacement (Figure 13) . The farther the finger is from the face, the greater the displacement angle. Half of this angle is called "angle of parallax". What we will notice is that the finger appears projected on different backgrounds, there is an apparent displacement of the position of the finger with respect to the background, for example a wall of the room where there are hanging pictures. If we change the distance from the finger to the eye, the angle will change and the farther the finger is from the face, the angle will be smaller. In the case of the stars, it is impossible to notice this apparent displacement by parallax using the eyes. This is achieved by observing the star from two positions of the Earth in its orbit around the Sun, separated by 6 months, as seen in Figure 12. .

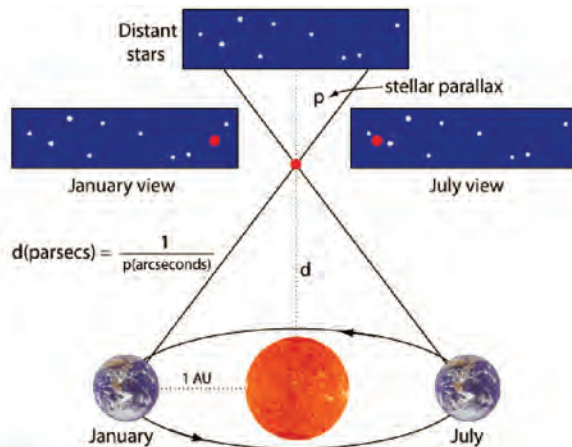


Fig. 12: paralaje estelar. (Crédito: Hyperphysics).

By observing the star for example in January and July (the two eyes), we can determine in the acquired photographs the apparent change in the position of the star (the parallax angle "p"), determine the right triangle Earth-Sun-Star and calculate the distance Star-Sun. This simple but innovative method was proposed by the Greek scientist Aristarchus of Samos about 400 years before Christ!

However, the method has its difficulties, since as the stars are farther and farther away, the angle of parallax becomes very small and impossible to measure.

Finally, this procedure allows defining the distance unit used in astronomy, the "parsec" (pc), which corresponds to the distance for which the angle p is $1''$ (one arc second). This angle corresponds to a linear distance of 3.1×10^{13} kilometers.

If we consider distances, we can understand that a bright and distant source will look weaker than another less powerful and nearby. This characteristic defines the "brightness" of the stars, which is related to what astronomers call "apparent magnitude" and also follows the law of the inverse of the square:

$$\text{Brightness} = \text{Luminosity} / 4\pi d^2$$

The system of apparent magnitudes was defined by Hipparchos from Nicea about 125 years before Christ and it was necessary to wait until 1850 when Robert Pogson proposed the algorithm that relates the apparent magnitudes to the brightness of the stars, a relationship that is logarithmic and whose approach, with few modifications, is still used today by astronomers:

$$m_2 - m_1 = 2.5 \log B_1/B_2$$

where m are apparent magnitudes and B are the brightness, what the eye perceives and is, of course, affected by distance. This mathematical expression is known as Pogson's Law.

To solve the problem of distance, astronomers devised an ingenious procedure. Imagine that all stars are at the same distance, for example $10pc$. In this case, the brightness of each one would no longer be related to its distance, and we could compare the stars to each other by the amount of energy per unit of time the stars produce, which would no longer be affected by the distances.

If we apply Pogson's Law to this case, it would result:

$$M - m = 2.5 \log (P/4\pi d^2) / (P/4\pi 10^2)$$

where M is the magnitude of the star at $10pc$ (called "absolute magnitude"), m its apparent magnitude (that seen by the eye), P the power of the star and d the distance from the star to the observer,

simplifying results:

$$M - m = 2.5 \log (10^2/d^2)$$

solving the logarithm:

$$M - m = 2.5 \times 2 (\log 10 - \log d)$$

finally:

$$M = m + 5 (1 - \log d) = m + 5 - 5 \log d$$

That is, if we know the apparent magnitude and distance, we can determine the absolute magnitude, which is related to the power of the star.

On the other hand, and taking into account the Bunsen's photometer again, if we know the power of the sources, it is possible to determine its distance from the observer.

For distances greater than 20 parsecs, there are other resources in astronomy that allow the determination of distances, all of them related to the study of light from stars.

Once parallax becomes impossible to use, astronomers use a main sequence adjustment process to calculate distances to locations within the Milky Way. To do this, scientists simply compare the apparent magnitudes of stars in star clusters with the absolute magnitudes of the same stars, a measure of the intrinsic brightness of a star (we assume that the absolute magnitude is the apparent magnitude if the star is at 32.6 light years away or 10 parsec). When these values are determined, Pogson's Law can be used to calculate distances. This method has a limit and this is that of the Milky Way. Beyond our galaxy, the methods for measuring distances are related to Cepheid variable stars and type Ia supernovae.

- Cepheid Variables

Variable stars are stars that experience fluctuations in their brightness (in their absolute luminosity). Cepheids Variables (CVs) are special type of variable star, are hot and massive (five to twenty times as much mass as our Sun), their tendency is to pulsate radially and vary in both diameter and temperature. These stars are typically yellow bright giants and supergiants (spectral class F6 – K2) and they experience radius changes in the millions of kilometers during a pulsation cycle.

The most important aspect of these pulsations is that they are directly related to the absolute luminosity, which occurs within well-defined and predictable time periods (ranging from 1 to 100 days). When plotted as a magnitude vs. period relationship, the shape of the Cepheid luminosity curve is very characteristic, it sudden rises and presents a peak, followed by a steadier decline (Fig. 13). The variability in the magnitude is determined by photometric measurements.

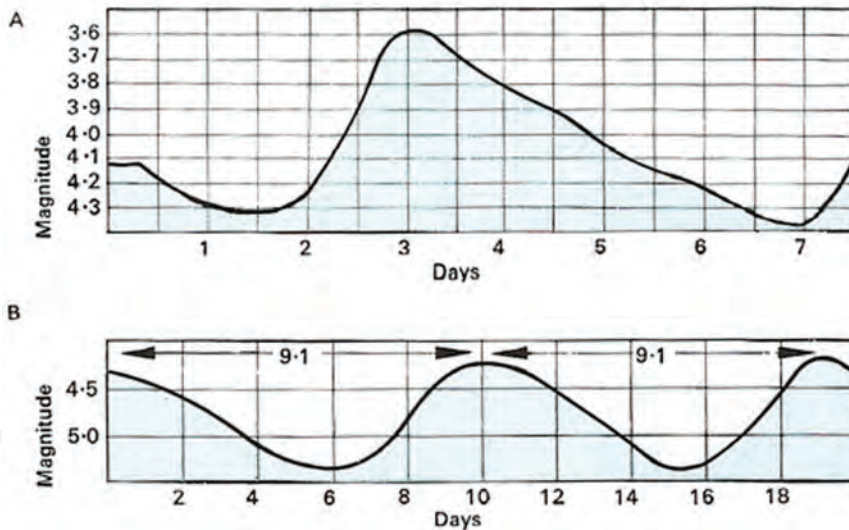


Fig. 13: Cepheid variables are notable for their regularity. Delta Cephei itself has a period of 5.3 days [A]; in comparison the light curve of the southern Cepheid variable Kappa Pavonis with a period of 9.1 days [B]. The shapes of the curves are not identical. Since Kappa Pavonis has the longer period, it is the more luminous. (Credit: David Darling).

The name is derived from Delta Cephei, a variable star in the Cepheus constellation that was the first on this type to be identified. Analysis of this star's spectrum suggests that CVs also changes in terms of temperature (between 5500 – 6600 K) and diameter (~15%) during a pulsation period.



Fig. 14: Henrietta Swan Leavitt.

The first discovered Cepheid was Eta Aquilae, observed on September 10th, 1784, by Edward Pigott. Delta Cephei, for which this class of star is named, was discovered a few months later by the amateur English astronomer John Goodricke.

In 1908, during an investigation of variable stars in the Magellanic Clouds, the American astronomer Henrietta Swan Leavitt (1912) (Fig. 14) discovered the relationship between the period and luminosity of Classical Cepheids. After recording the periods of 25 different variables stars, she published her findings in 1912.

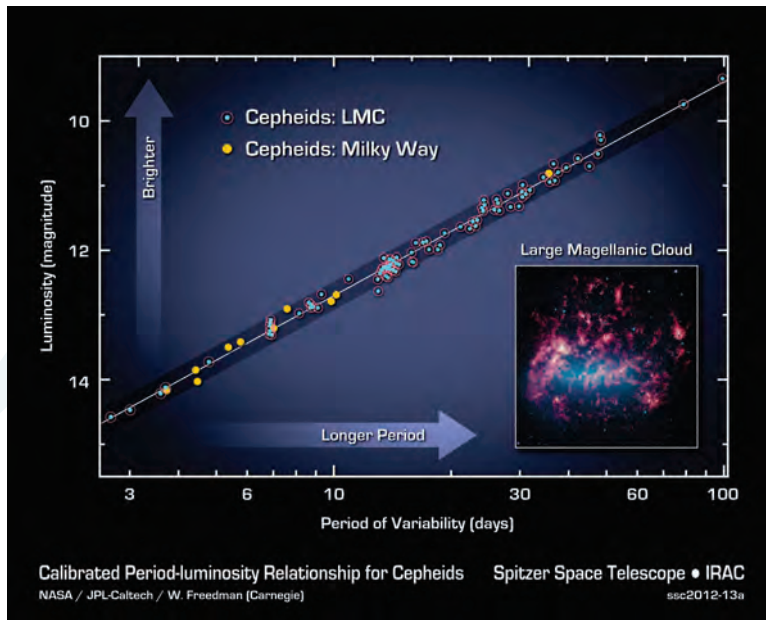


Fig. 15: period-Luminosity Cepheid Variable Stars relationship.

In the following years, several more astronomers would conduct research on Cepheids. By 1925, Edwin Hubble was able to establish the distance between the Milky Way and the Andromeda Galaxy based on Cepheid variables within the latter.

The relationship between the period of variability and the luminosity of CV stars (Figure 15) is very useful in determining the distance of objects in our Universe.

Once the period is measured, the luminosity can be determined, thus yielding accurate estimates of the star's distance using distance modulus equation, which comes from Pogson's Law for the absolute magnitude (M) for one star at a distance d (in parsec), as we shown in the previous section,

$$m - M = 5 \log d - 5$$

Cepheid variables can be seen and measured to a distance of about 6 Mega parsec, compared to a maximum distance of about 20 pc for Earth-based parallax measurements and just over 100 pc for the most recent measurements made by ESA's Hipparcos mission (1993).

- Supernova

Because supernovae are very energetic events, astronomers can observe them at great distances, but very brief: often lasting only days and astronomers must work to detect them before they reach their peak brightness and begin to fade. They are only useful as distance indicators if it is possible to calibrate them - to relate their observed brightness profile to absolute magnitudes.

Supernovae can occur for various reasons and with different intensity. Depending on their characteristics, they are classified into supernovae of type *I* (*Ia*, *Ib*, *Ic*) and type *II* (*IIn*, *IIP*/*IIL*, *IIf*).

Supernovae Ia are the most frequent and are considered as "standard candles" extragalactic. These explosions occur in binary systems when a white dwarf accumulates enough mass to reach the Chandrasekhar limit of 1.44 solar masses, at which time the star collapses in the event we call supernova.

All type Ia supernovae have the same luminosity or absolute magnitude. Therefore, by comparing the relative brightness, or apparent magnitude, of the supernova with its "standard" brightness we can easily calculate the distance at which it is located.

There are aspects in the use of supernovae as indicators of distance that are beneficial, such as their luminosity (it can be observed at very large distances), some supernovae can be modeled as a single star that suffers a violent energy event, to some extent, the properties in general, some supernova explosions do not depend heavily on the chemical composition of the parent, so in some cases we might be able to compare local supernovae with distant ones.

But also, we must bear in mind that these events appear unpredictably and this is the biggest problem, since it does not allow us to organize in advance to observe them with a telescope. In addition, most supernovae become brighter during the 2 or 3 weeks after the explosion, remain bright for 1-3 months and then fade in a year or two. To study a supernova properly, we need to discover it before it reaches its maximum brightness. Finally there are no good examples of these events in our own galaxy since the telescope is used in astronomy. The last supernova that exploded in the Milky Way, and was noticed by humans, happened in 1604: the Star of Kepler. In 1987, a supernova appeared in the Great Magellanic Cloud. It was close enough to detect neutrinos from the explosion on Earth, but no events have been observed since then.

- One experience at the classroom

If we assume that the stars are objects of the solar type (with more or less and even the same mass as the Sun) that are further away from us, we can estimate their distance. We are making the assumption that the stars are of a similar luminosity to our Sun, but in reality there is everything: some are similar, some are much brighter, and some are weaker.

This activity only serves to estimate the order of magnitude of the distances to the stars. We're gonna need to make a little artificial star. It is possible to do this with a flashlight covered with a piece of aluminium foil, from which only a small fraction of the light is allowed to escape, which will be the artificial star. We can use fiber optics from those used for the digital audio connection of TV equipment. They're not expensive, and they sell them in the TV shops. Cut a piece about 5cm long (Fig. 16).

If we do not have fibre optics, we can replace it with a small hole in aluminium foil made with a sewing needle (Fig. 17). To measure the size of the hole, we can put several needles next to each other to complete the 1cm width. The diameter of one of them (and therefore of the hole in the foil) will be 1cm divided by the number of needles.



Fig. 16: artificial star with a flashlight and a piece of optical fiber.

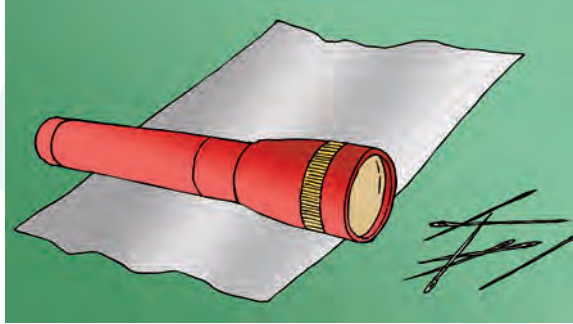


Fig. 17: a fiber optic substitute is a hole in aluminum foil made with a sewing needle.

Now we have to determine the power of the flashlight. It is possible that the bulb is printed with the data of its resistance R . If it is not, we will have to measure it with a multimeter. The voltage V of the batteries is usually printed on them, and if there are several, the voltage of all of them must be added if they are in series, which is the usual thing. From this data, the power of the flashlight is calculated by applying the equation:

$$P_{\text{flash light bulb}} = \frac{V^2}{R^2}$$

You will also need to measure (Fig. 18) the area of the flashlight area $A_{\text{flash light bulb}}$ where the light comes out and the area of the fiber optic section $A_{\text{optical fibre}}$ or the hole made with the needle in the foil. They're all circles with the area:

$$\pi \cdot r^2$$

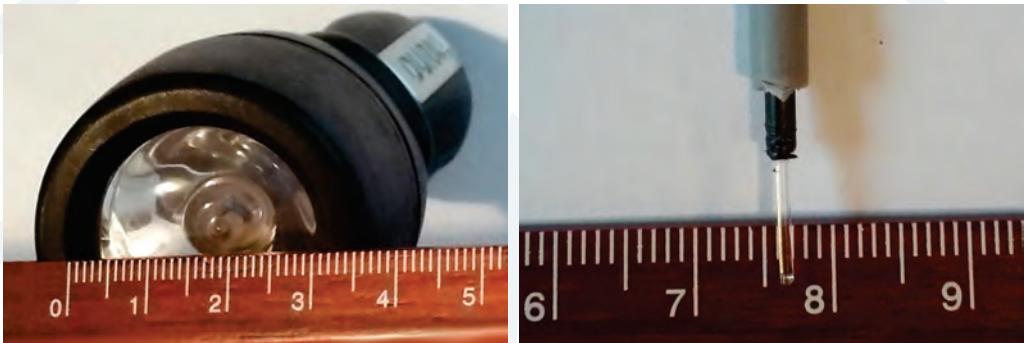


Fig. 18: the diameter of the flashlight and the fiber must be measured. The radius will be half the size.

The power P_1 coming out of the optical fiber will be a fraction of the power of the flashlight bulb. That fraction is the ratio between the area of the circular section of the optical fiber and the area of the flashlight part where the light comes out.

$$P_{\text{artificial star}} = P_{\text{flash light bulb}} \cdot \frac{A_{\text{optical fiber}}}{A_{\text{flash light bulb}}}$$

If the experiment is done with perforated aluminum foil instead of fiber optics, the fraction will be the ratio between the area of the small circular hole, equal in diameter to the thickness of the needle, and the area of the flashlight where the light comes out. .

With this artificial star of known power, you go out at night. With the help of another person, the artificial star is moved away a few tens of meters until it is seen, with the naked eye, with the same brightness as a real star in the sky. The distance to the observer is measured.

The dummy star has a power of P_1 , and was located at a distance of d_1 from the observer. Assuming that the real star has a power similar to that of the Sun ($P_2 = 4 \cdot 10^{26} \text{ W}$) and that it is at an unknown distance d_2 , the above formula can be applied:

$$\frac{P_1}{d_1^2} = \frac{P_2}{d_2^2}$$

and estimate the distance d_2 to the star. Transforming the result to light years, (one light year is approximately 10^{13} km), the result obtained will be a few light years, probably less than the actual distance. The reason for the discrepancy is that most of the stars we see in the sky are actually more powerful than the Sun. But the result obtained from "several light years" gives an idea of its real distance, when compared to the distance between the Earth and the Sun, which is 8 light-minutes away.

Conclusion

Photometry studies light from a quantitative point of view. It allows you to compare light sources and relate them to the distances they are located. This is very useful in Astronomy, as it allows us to study what the stars look like, determining their power or luminosity. In this publication we have reviewed some basic concepts of photometry, explained what the Bunsen's photometer consists of and made it from paper and an oil stain. We have used it to calculate the power of the Sun, and then estimate the order of magnitude of the distance to the stars, analyzing the different methods that astronomers use to determine this magnitude, of fundamental importance to model the universe.

Bibliography

Darling, D., Cepheids Variable.

https://www.daviddarling.info/encyclopedia/C/Cepheid_variable.html

Hipparcos Mission, Overview. Completed in 1993.

http://www.esa.int/Science_Exploration/Space_Science/Hipparcos_overview

Leavitt, H. S., Pickering, E.C, Periods of 25 Variable Stars in the Small Magellanic Cloud. Harvard College Observatory Circular, vol. 173, pp.1-3, 1912.

Ros et al, 14 Pasos hacia el Universo, 2a. Edición, Barcelona, 2018.



Network for Astronomy School
Education - International
Astronomical Union

