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ROBOTS QUE MIRAN AL CIELO

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

UNIT 3:

DISTANCES (2^{nd} part). QUASARS

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Measuring the distance to the stars (Part 2)

In Unit 2 we learned that with the parallax method we can measure the distance to objects that we cannot access. In addition, we found that the maximum distance we can measure with this method does not exceed 100 light-years, which corresponds to the stars in our galaxy closest to the Sun. Beyond that distance the method is no longer useful, so astronomers have had to look for other systems to calculate the distance to the rest of the stars in our galaxy, and even to other galaxies. These alternative methods are based on the brightness of various types of astronomical objects, with certain characteristics. Let's look at some of these methods.

Brightness and distance

When we observe a light from a certain distance, the brightness appears to be lower. Think of two street lamps placed on the street, one next to you and the other one 500 *m* away. The more distant lamp post looks dimmer, although in fact we know they are both the same. This is because the light from a distant object is distributed over a larger area and a smaller amount reaches us. The light is not lost, it is just more spread out.

If we understand why and how decreases the brightness that reaches us as we move away from the light source, then we can calculate how far away a distant streetlight is by comparing it with the one we have nearby. That works for us because we know that both streetlights are the same. And the calculation turns out to be very simple.

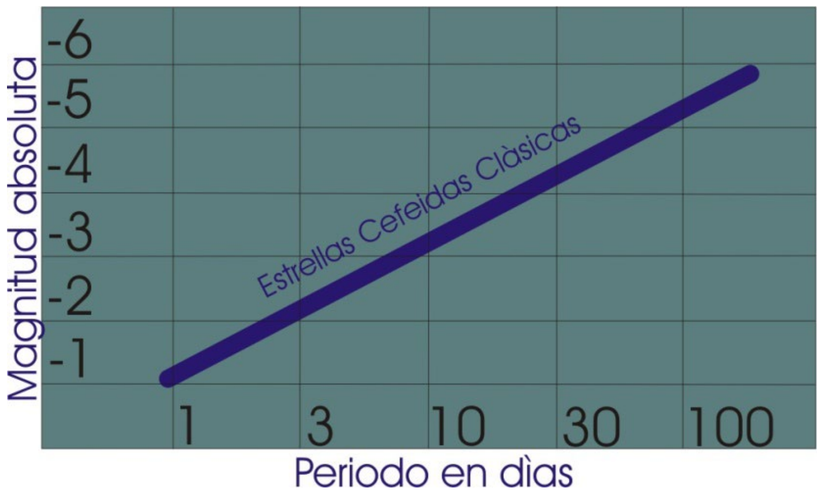
But with stars we have an added complication: we do not know what the original brightness was to compare it with the brightness that reaches us; there are stars that are very faint and others that are very bright, up to 1 million times brighter than the Sun. So, to be able to use the formula that relates brightness with distance, we must first know what the brightness of that star is when it is close. And that is without being able to travel to it. Is there any way?

NOTE: *Brightness measures the amount of light we receive from an object and decreases with the square of the distance. Thus, a star emitting the same amount of light (intrinsic brightness) as another star, but twice the distance away, will appear four times fainter.*

Cepheids

For thousands of years, humans thought that stars were constant and unchanging. But with regular observation it was found that some stars change slowly, increasing and decreasing in brightness: these are the **variable stars**. There are many types of variable stars, but here we will look at one type in particular, the Cepheids. In 1784, at the age of 19, an English astronomer named John Goodricke discovered that the star Delta in the constellation Cepheus was variable. It had a cyclic variation in brightness of only 5.4 days during which the star's brightness increased and decreased again until it regained its initial intensity.

Cepheid variables have a very particular property that was discovered in 1908 by Henrietta S. Leavitt investigating thousands of variable stars in galaxies close to our own, the Magellanic Clouds. She found that the period of brightness variation is related to the **luminosity** of the star. The higher the luminosity of a Cepheid, the longer its period. This is of vital importance, as it provides us with a tool to obtain the intrinsic brightness of distant stars and, therefore, to calculate their distances.



As we said, when we observe a star we can only determine its **apparent magnitude,** which is a measure of its brightness as seen from Earth. But obtaining the **absolute magnitude** of a Cepheid is as easy as observing how it rises, falls and rises again in brightness over several days and thus determining its pulsation period. By comparing these two magnitudes, we can find out how far away the star is.

This method was used to calculate the distance to the nearest galaxies by observing their cepheids. In order to use it, we need to be able to observe the stars that make up the galaxy individually, but this is impossible with distant galaxies. Therefore, in order to measure the distance to the most distant objects in the Universe, we must study other properties of the light that reaches us from them.

The magnitude of stars

The most remarkable aspect when observing stars is their brightness. The Greek astronomer Hipparchus, around 150 BC, classified them by their luminosity in the first known star catalog. He first looked for the brightest stars, measured their position and assigned them the 1st magnitude, as they were the ones that appeared the most prominent. Then he chose the stars that seemed to be about half as bright as the previous ones and assigned them the 2nd magnitude; to those that were half as bright as the previous ones he assigned the 3rd magnitude, and so on until he reached the faintest stars that he could detect with the naked eye, to which he assigned the 6th magnitude.

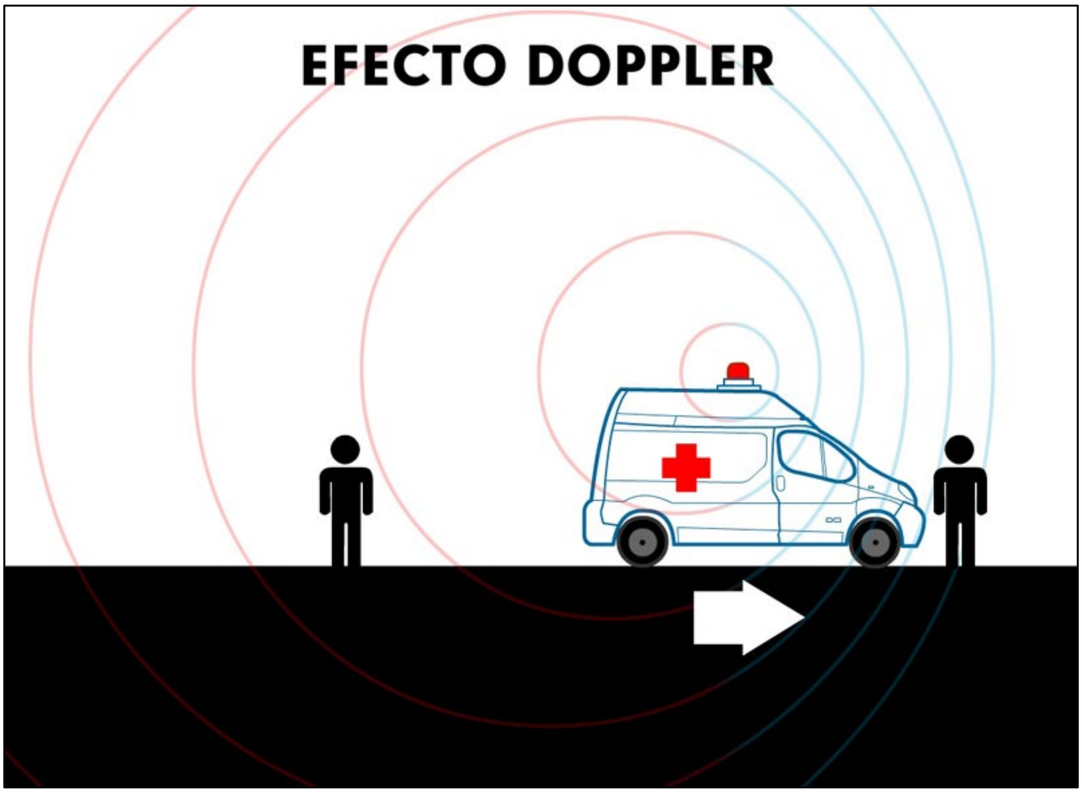
This method, although good, was not entirely accurate, for with the naked eye and without any measuring instrument it could not determine the exact brightness of the stars. But in 1830, John Herschel invented a more accurate method of measuring stellar brightnesses and found that most of the 1st magnitude stars of the Hipparcos series were 100 times brighter than those of 6th magnitude. Thus, the difference in brightness between one magnitude and the next, which had originally been thought to be twice as great, was actually 2.512 times. This is the scale currently used by astronomers.

Herschel discovered that some stars were brighter than those that Hipparchus had called 1st magnitude, so now we have stars of magnitude 0, and even of negative magnitude. For example, the brightest star we can see in the night sky, Sirius, has an apparent magnitude of -1.4.

In order to compare the intrinsic brightness of one star to another, we should do so as if they were at the same distance. By convention we use the distance of 10 *parsecs* as the near distance at which we would see its absolute brightness. Thus, we define **absolute visual magnitude *Mv*** as the apparent visual magnitude that the star would have if it were at a distance of 10 *parsecs*. For example, our star, the Sun, we observe it with a visual magnitude of -26.7, but if we were to place it at a distance of 10 *parsecs*, we would see it with a visual magnitude of 4.9, almost like the faintest stars we see in the sky with the naked eye. That is, the absolute magnitude of the Sun is 4.9.

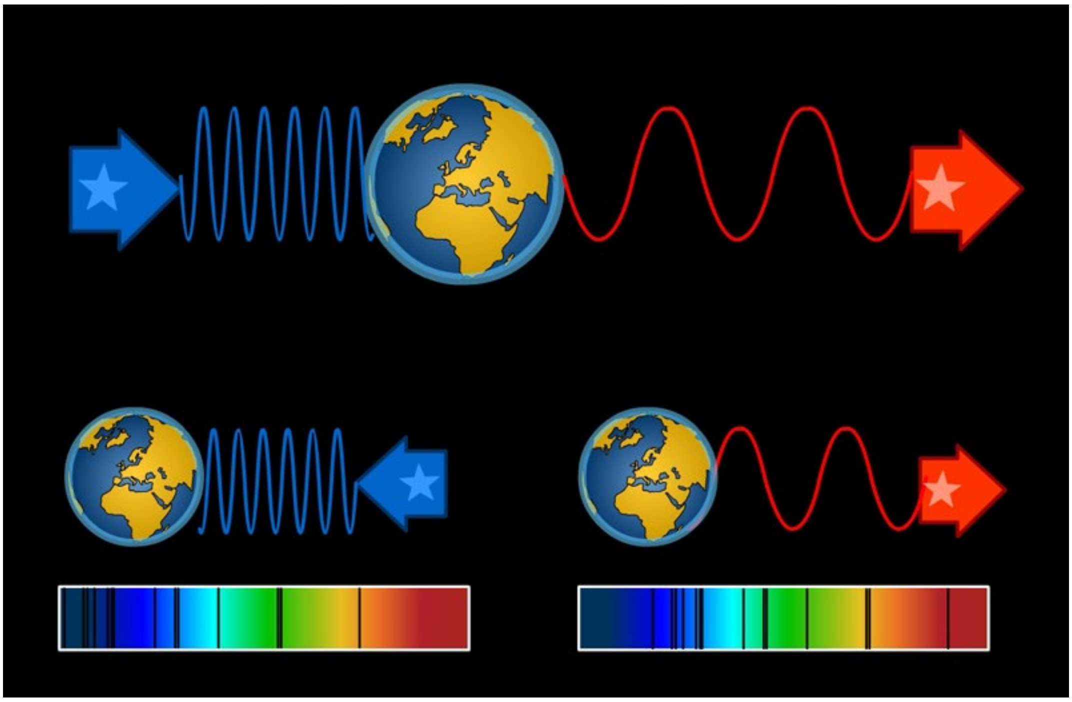
The redshift

When an ambulance moves while sounding its siren, it sounds differently when it is approaching us and when it is moving away. This difference in the sound, due to the movement of the source that emits it with respect to us, is called the **Doppler effect**. While the siren emits at a certain frequency, we perceive it differently depending on whether it is approaching or moving away from us. If it is approaching us, we notice a higher-pitched sound, while when it is moving away, we notice one lower-pitched.



This Doppler effect that we perceive in sound is also detectable in light. When a light source moves at very high speeds with respect to us, we can observe how the frequency (color) of the light we receive changes, becoming bluer as it approaches us and redder as it moves away.

We can determine the speed at which celestial objects (stars, galaxies, etc.) move by observing their spectrum, i.e. by passing their light through a spectroscope that allows us to see the different colors contained in the light and the signatures of the chemical components found in the light source. If these patterns, which we call **spectral lines**, move towards the red color, it means that the light source is moving away from us.

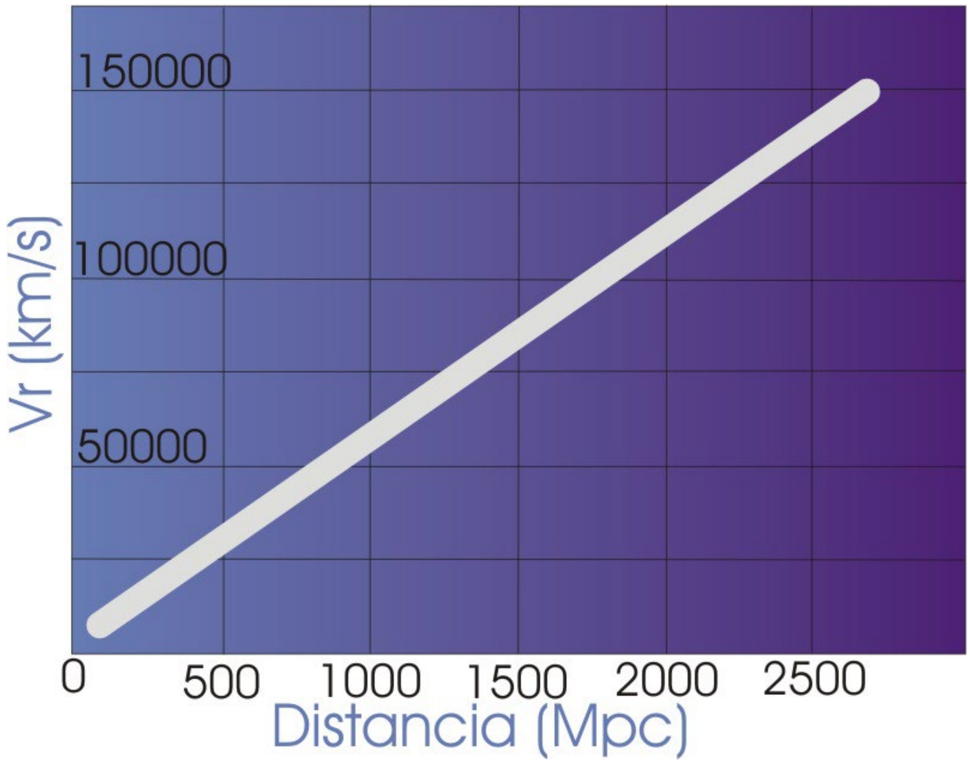


Spectra of a light source approaching the Earth (left) and moving away from it (right). The spectral lines are blue-shifted (left) and red-shifted (right), respectively.

In the case of galaxies, they are moving away from each other due to the expansion of the Universe. The astronomer Edwin Hubble found that the greater the distance to a galaxy, the faster it moves away from us, and he took advantage of this circumstance to measure the distances to galaxies.

Hubble's law relates the distance to a galaxy to its **recession velocity**, that is, the speed at which that galaxy is moving away from us due to the expansion of the Universe. It can be stated as follows: the recession velocity of a galaxy, V_r, in kilometers per second (*km/s*) is equal to the Hubble constant, *H*, multiplied by its distance, *D*, in megaparsecs (*Mpc*, million *parsecs*). Remember that 1 *parsec* = 3.26 *light-years*.

$$V_r = H \times D$$



We can visualize this relationship in a graph in which we plot recession velocities and distances for a number of galaxies. The representative points of the galaxies are distributed along a straight line, showing us that the farther away the galaxy is, the faster it recedes from us.

The best estimates of velocity and distance suggest a value for the Hubble constant of about 70 *km/s/Mpc*. This tells us that for every million parsecs that exist between two galaxies, they are moving away from each other at a speed of about 70 *km/s*. If we can measure the velocity of a galaxy, we can estimate its distance from ours by dividing it by the Hubble constant. For example, the Virgo cluster of galaxies has a recessional velocity of 1180 *km/s*. To find its distance, we divide by *H* and we get 17 *Mpc* (17 million *parsecs*).

QUASARS

Quasars are very distant objects that emit an enormous amount of energy and have a point source appearance, similar to that of stars. Their name comes from quasi-stellar objects.

The first quasars were discovered in the mid-20th century. They were first detected as radio sources in observations with radio telescopes (telescopes that observe in the radio wave range). Using radio interferometers (radio telescopes for calculating the diameter of radio-emitting celestial objects), the angular diameter of the discovered quasars was measured and they were found to have very small angular diameters, much smaller than those of galaxies. When astronomers photographed the regions of the sky containing these radio sources with optical telescopes, they also did not find the image of vast galaxies they expected. Instead, there were small luminous star-like objects. When they obtained the spectra of the first quasars, they found that they had redshifts much larger than that of any previously observed object.

In astronomy, the **redshift** *z* of a spectral line is the difference between the observed wavelength of a line (λ_o) and the one emitted (λ_e), $\Delta\lambda = \lambda_o - \lambda_e$, divided by the emitted wavelength λ_e.

$$Redshift = z = \frac{\Delta\lambda}{\lambda e}$$

It is usual to convert redshift to recession velocity by the relation

$$V_r = c\,z$$

where *c* is the speed of light.

Quasars have very large redshifts due to the expansion of the Universe and therefore also have very large recession velocities. Hubble's law tells us that larger redshifts imply larger distances, which tells us that quasars are the most distant objects known.

But the most important thing about these objects is not only that they are so far away, but that they are visible despite their great distance, i.e., they must be super luminous. For a quasar to be visible as a faint star it must be as bright as a thousand galaxies put together. Even more surprising is that this enormous amount of energy comes from a region that must be less than 1 *light-year*, one hundred thousandth the size of a galaxy. How could such a “small” object generate ten to a thousand times more energy than all the stars in a galaxy? Recall that, in a common galaxy like ours, there may be about 200 billion stars.

The origin of this impressive source of energy can be found in the existence of huge black holes at the center of quasars. **Black holes** are the remains of massive stars (at least 8 times the mass of the Sun) that, after their life as stars, explode as supernovae and their nuclei are compressed so much that their gravity becomes very high, so that not even light can escape from them. Hence the name “black holes”. We can detect them by the effects they produce on bodies in their proximity.

The black hole inside a quasar would contain millions of times the mass of the Sun. All that mass produces an enormous gravity that attracts huge amounts of gas, dust and even stars, which are heated to high temperatures and emit a lot of energy as they approach the black hole. This is why we are able to see these objects at enormous distances from us.

Quasars have been found to show brightness changes on varying time scales, from a few months to weeks, days, and even hours. These rapid changes in brightness indicate that quasars are small, since an object cannot change faster than the time it takes light to travel from one end to the other.

For further information, visit our website: **www.iac.es/peter**

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