The Universe in my pocket

TUIMP
No. 15
THE UNIVERSE IN MY POCKET

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Astronomical distances cannot be measured with a ruler or a tape. One needs tricks. The Greek astronomer Eratosthenes, the first to estimate the radius of the Earth 2200 years ago, used the ingenious idea of comparing the inclination of the Sun's rays between Syene and Alexandria.

Soon after, in Alexandria, Aristarchus of Samos had a clever idea to measure the distance to the Moon. He measured the duration of a lunar eclipse by the Earth. This allowed him to estimate that the diameter of the Earth is three times that of the Moon (actually 3.7 times) and hence to deduce the diameter of the Moon, using Eratosthenes' size for the Earth. Knowing the Moon's diameter and its angular size, he could calculate its distance.

As for planetary distances, in 1573, when Copernicus proclaimed that the Earth revolves around the Sun (see the figure at left), we only knew the ratios of the distances from the Sun to the planets Mercury, Venus, Mars, Jupiter and Saturn, rather than their absolute distances.

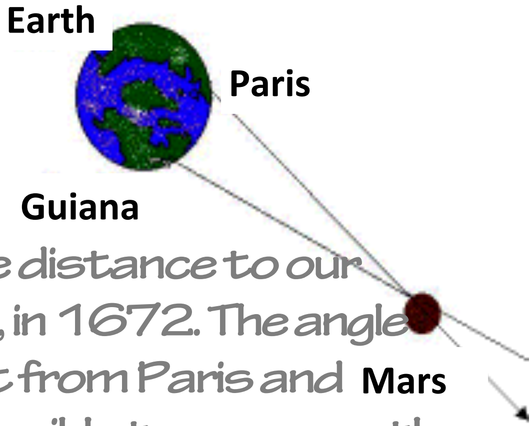
Distances in the cosmos

The ancients knew how to estimate the radius of the Earth and its distance from the Moon (see opposite page), but not its distance from the Sun, of 150 million km. This distance is called the Astronomical Unit (AU).

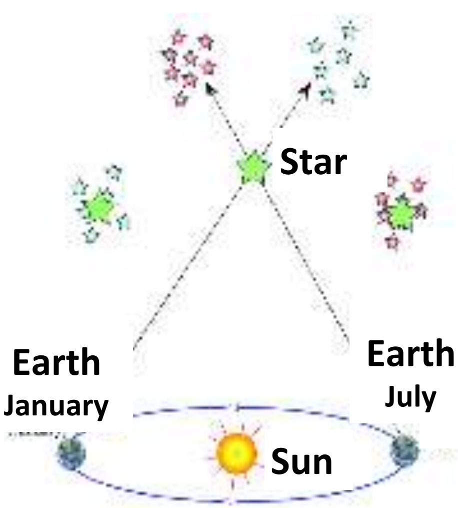
At the time, people thought the Sun was closer than this. They also thought the stars were more distant "suns", but they did not realize just how far away the stars are, so that their light takes many years to reach us. For this reason, we use as a unit of distance the "light-year" (l.y.) which is the distance traveled by light in one year, or 9.46 billion km!

Today's observations give us access to ever greater distances - up to millions of l.y. away - thanks to large terrestrial telescopes and to space-based telescopes on satellites.

For planets within our solar system, the size of the Earth allows us to obtain two different lines of sight. This technique was used to measure the distance to our neighbor, the planet Mars, in 1672. The angle between the lines of sight from Paris and French Guiana made it possible to measure the distance to Mars, and thus to obtain the distance to the Sun. Because we already knew the ratios of the distances from the Sun to Mars and the Sun to Earth, knowing the Earth-Mars distance allowed us to calculate the Earth-Sun distance.



A nearby star is projected against a background of distant stars assumed to be at infinity. Then, six months later, the star is seen on a different stellar background. In this case the base of the triangle formed by the two lines of sight is the diameter of the Earth's orbit around the Sun, not the diameter of the Earth, as in the 1672 measurement.



By observing the same star from two different places, we obtain a triangle whose base and two angles are known, thus allowing us to know the distance to the star.

The "parallax" is the vertex angle of the triangle whose base is the radius of the Earth's orbit.

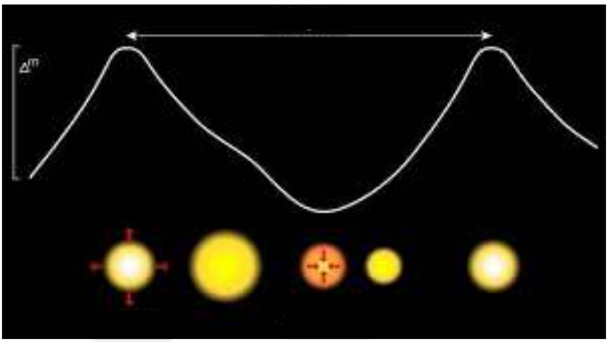
The nearest star, Proxima Centauri, is 4.2 l.y. distant, which implies a parallax of only 0.74 arcseconds ("). In 1838, Friedrich Bessel made the first parallax measurement: 0.3" for the 61st Swan Star. Shortly afterwards, the 0.12" parallax of Vega was measured and also that of α Centauri. Others followed, but astronomers were limited by telescope sensitivity.

The European satellites Hipparcos, in the 1990's, and Gaia, today, have measured millions of parallaxes.

Fig. 51. Miss Henrietta Swan Leavitt, staff member, 1902-1921.

At the beginning of the 20th century, the American astronomer Henrietta Leavitt (1868 - 1921), observed that certain stars have a variable brightness with a regular period (see figure below). She first observed these stars in the Cepheus constellation, so they are called Cepheid Variables. She later observed similar stars in our neighbor galaxies, the “Magellanic clouds”. Their brightness period depended on the stellar luminosity, which could be calculated by assuming that all the stars were at the same distance as their host galaxy.

Although her boss, Edward Pickering, tried to discourage her, Henrietta persisted and detected nearly two thousand Cepheid Variables and was able to deduce the proportionality between period and luminosity. She died before she knew how important her discovery was.



Star light reaches us weakened by a factor equal to the square of the star's distance. This would be a way to determine their distance if we knew their luminosity.

This is why the discovery of Henrietta Leavitt was so important. Variable stars of the type she discovered in the constellation Cepheus and in the Magellanic clouds are also found in other galaxies. The period of their variation indicates their luminosity, and so we can infer their distance.

Such stars can be detected today at distances up to 80 million l.y. using the Hubble Space Telescope, launched in 1990.

Our Galaxy, visible on a clear night as a milky path on the sky, is 103,000 l.y. long. Our Sun lies about 27,000 l.y. from the galactic center (ESO photo).

The Andromeda Galaxy, visible to the naked eye in the northern hemisphere as a diffuse spot, lies at a distance of two million l.y.

Galaxies are grouped into clusters containing hundreds, sometimes thousands of galaxies, at distances of hundreds of millions of l.y. (ESO photo).

Nebulae and galaxies

In 1900, the existence of galaxies other than our own, the "Milky Way”, was not yet known. "Nebulous" light spots were observed and thought to be objects inside our Galaxy.

This assumption was challenged by Heber D. Curtis in 1920 in the "great debate" between him and Harlow Shapley.

But the question of whether these "Nebulae" belonged to our Galaxy remained open until it was possible to determine their distances, thanks to the cepheid method, and later by means of spectral line shifts (see Tuimp 2) obtained by analyzing star light through prisms or gratings.

At left, the Mount Wilson telescope with which Edwin Hubble made his observations. In 1929 Hubble showed that the speed of galaxies increases with their distance from us. Hubble was not the first to think of such a relationship. In fact, Father Georges Lemaître, a Belgian astronomer and cosmologist, had already suggested that the galaxy redshifts were proportional to their distances.

The "Hubble-Lemaître constant", which tells us how much the speed of recession of the galaxies increases with every Mpc of distance from us, was first estimated to be about 500 km/s per Mpc (1 Mpc = one million parsecs, with one parsec being 3.26 l.y.), but since the 1950s, much better estimates give a number between 50 and 100 km/s per Mpc. It is presently estimated to be 73 km/s per Mpc, with an uncertainty of 2%.

However, data from the Planck satellite, based on a cosmological approach, give a value of 67.4 ± 0.5 km/s per Mpc.

Redshift

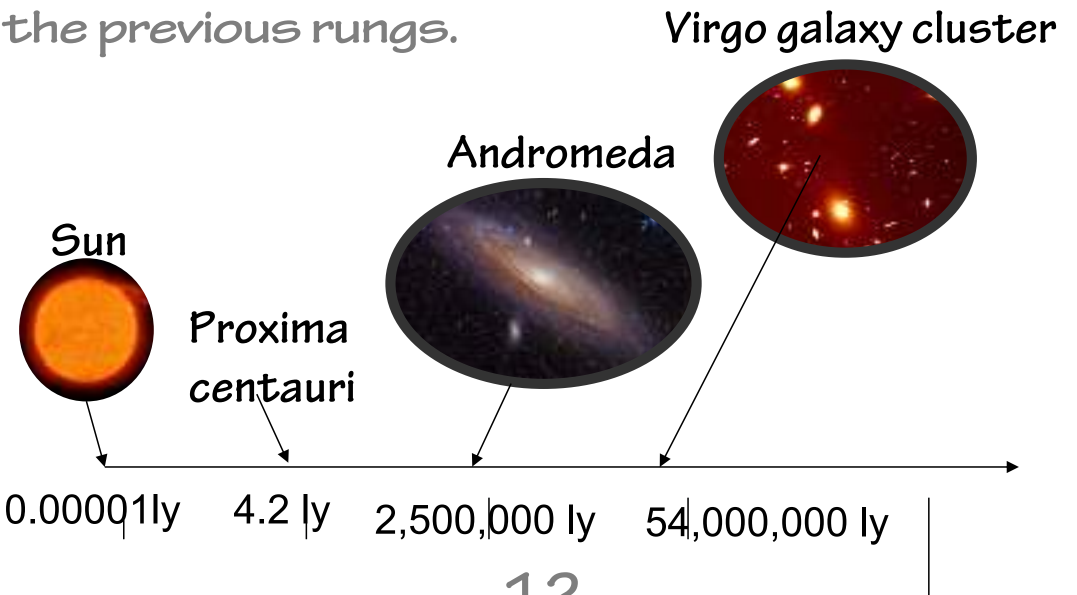
Spectral analysis of star light reveals dark lines due to the absorption of light by chemical elements present in the outer layers of the stars. (see Tuimps 2 &10)

In 1914 Vesto Slipher noted that the dark lines observed in galaxy spectra were shifted towards the red. This shift was interpreted as a "Doppler effect": the frequency of the light wave, and therefore its color, is modified by the speed of the source. This effect is similar to that affecting the sound of a horn which is higher pitched when the vehicle is approaching and lower pitched when it moves away. Redder light has a lower frequency so it indicates a speed of retreat: galaxies seem to be "fleeing" from us!

In 1929, Edwin Hubble estimated the distances of 46 galaxies using the Cepheids they contained and showed that their redshifts increased with their distances.

The distance from the Moon, the start of our journey to the fringes of the Universe, is better known today thanks to lasers, which send flashes of light, reflected by mirrors placed on the Moon during Apollo missions. We thus obtain a very accurate measurement of the distance of our satellite, and therefore of the distances of the other planets of the Solar System.

Beyond, one uses a succession of methods: First the parallaxes, then the Cepheids. Further away, where Cepheids cannot be distinguished anymore, more luminous objects are used, such as supernovae of type I. This succession of methods is the cosmological "distance ladder", with each rung of the ladder based on the previous rungs.



Galaxies flee faster if they are further away. By generalizing this relation, well-established and accepted by the scientific community after 1929, the redshift in turn becomes a measure of distance for more distant objects in which one can no longer observe Cepheid Variables or even Type I supernovae.

As a matter of fact, astronomers do not use the light-year as the unit to express the distances of the most distant galaxies or quasars, but simply the redshift. This redshift is denoted by the letter z, and its value corresponds to the fractional change of wavelength in the observed spectrum.

The redshifts of most of the galaxies in the Virgo cluster lie between 0.5 and 1 while the redshift of the most distant galaxy known so far is 11.09.

Quiz

Suppose we have a spaceship capable of traveling at one tenth the speed of light...

How long would it take to reach:

- The Sun?
- Proxima Centauri?
- Vega?
- The Andromeda galaxy?
- Galaxies from the Virgo cluster ?

Answers on overleaf

Answers

How long would it take to reach:

- The Sun: 80 minutes
- Proxima Centauri: 42 years
- Vega: 250 years
- The Andromeda galaxy: 25 million years.
- Galaxies from the Virgo cluster: 540 million years.

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This booklet was written in 2020 by Christiane Vilain (from Paris Observatory) and revised by Grażyna Stasińska (Paris Observatory) and Stan Kurtz (UNAM, Mexico). Sadly, Christiane passed away while this booklet was being processed.

The image on the first page of this booklet is an artist's representation of the Gaia satellite, which has measured millions of distances to stars and galaxies.

(Credit ESA)

To learn more about this series and about the topics presented in this booklet, please visit http://www.tuimp.org

Translation: Stan Kurtz