Our closest star!

Measuring the astronomical unit through the transit of Venus.

Metadata

General Info

Title: Our closest star!

Short description: Students calculate the astronomical unit using pictures from the transit of Venus in 2004.

Keywords
astronomical unit, Venus transit, parallax, measurement units, distance, space, Sun

Educational Context

Context: Students calculate the astronomical unit using pictures from the transit of Venus in 2004. They learn the three different measurement units of distance in space (astronomical unit, light year and parsec) and they study the parallax method. At the end they discuss about the improvement of technology and its contribution to science, the experimental errors, and the importance of cooperation in science. They reflect on the methods and tools they used.

Age: 15-18

Prerequisites: trigonometry, rectilinear propagation of light, basic information about the Solar System

Lv. Of difficulty 3

Aggregation Level

Duration :3-4hrs

Educational Objective

Cognitive Objectives

- To learn the three measurement units of distances in space, and why they are useful.
- To know for every measurement unit the distance in space that defines it.
- To know the method of parallax and how astronomers use it to measure distances.
- To learn what a Venus transit is and why it does not happen often.
- To learn how scientists of the 18th century managed to calculate the astronomical unit.
- To become familiar with the scale of distances that astronomers deal with.
- To recognize the capability of scientists to adapt some methods (in this case the parallax) to different context and purpose.
- To learn about the existence of experimental errors and that they are part of the process. The errors do not occur because they did something wrong.

Affective

- To understand the importance of cooperation in Astronomy and science in general.
- To understand the importance of technology's evolution in science.

Psychomotor

- To be able to use a pixel ruler software to calculate distances in an image.

Subject Domain

Big Ideas of Science

The Solar System is a very small part of one of millions of galaxies in the Universe.

Subject Domain

Physics

Orienting & Asking Questions

You have definitely caught yourself gazing upon the stars. The sky surrounding our planet is full of stars and other celestial objects.

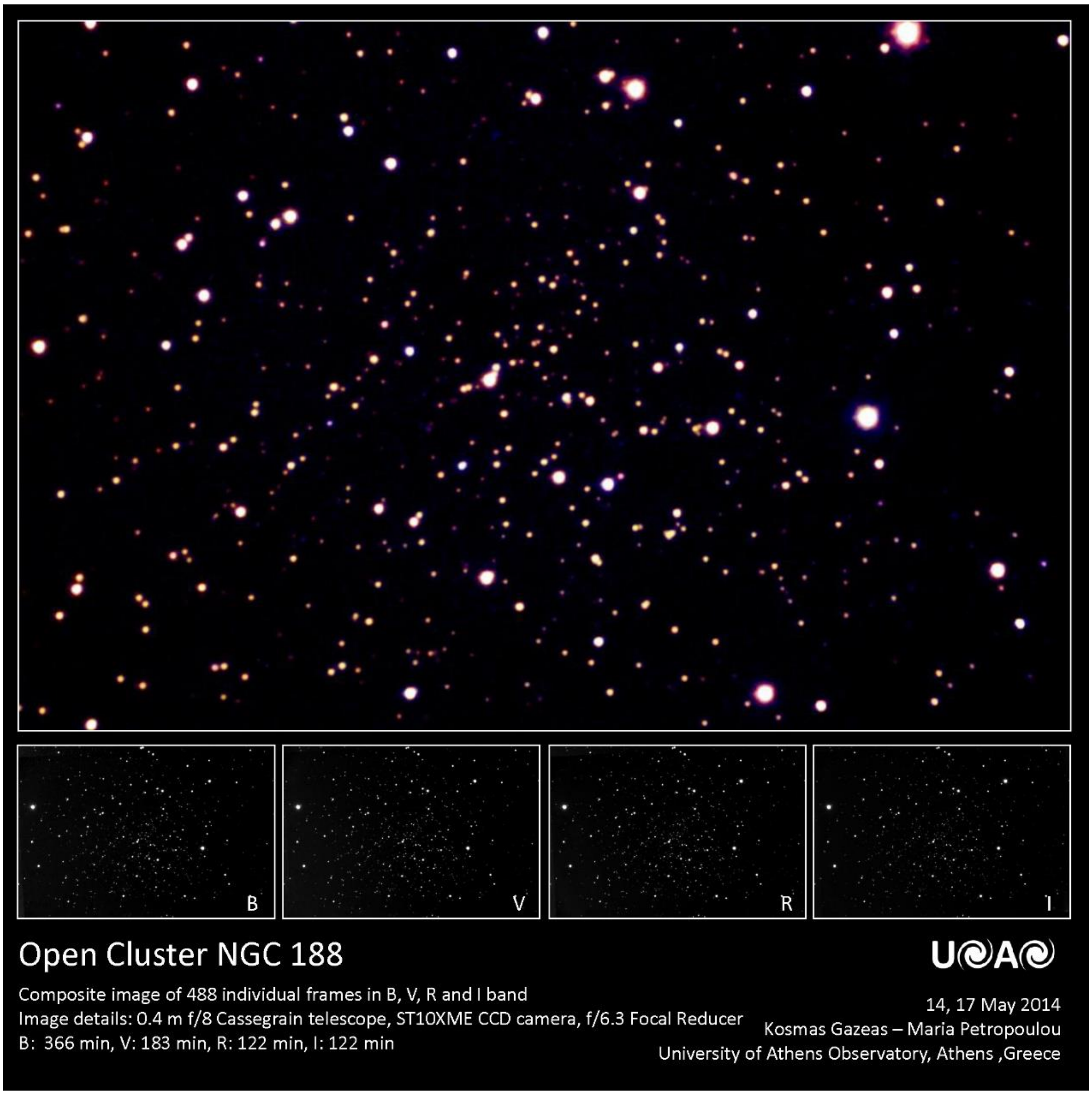
But which star is closest to us?

The Sun of course! So close that its light is preventing us to see other stars during the day.

How close is the Sun to planet Earth and what does "close" mean in terms of space distances? How far away are the other stars we see at the night sky? Write down your thoughts.

How far away from the Earth do you think the Sun is? Can you imagine a way of measuring this distance? Write down your thoughts and discuss them with the rest of the classroom.

If you search on the internet the distance of a star or a planet you can easily find the answer. But how do scientists count these vast distances by looking at the stars? They just have pictures of the night sky…



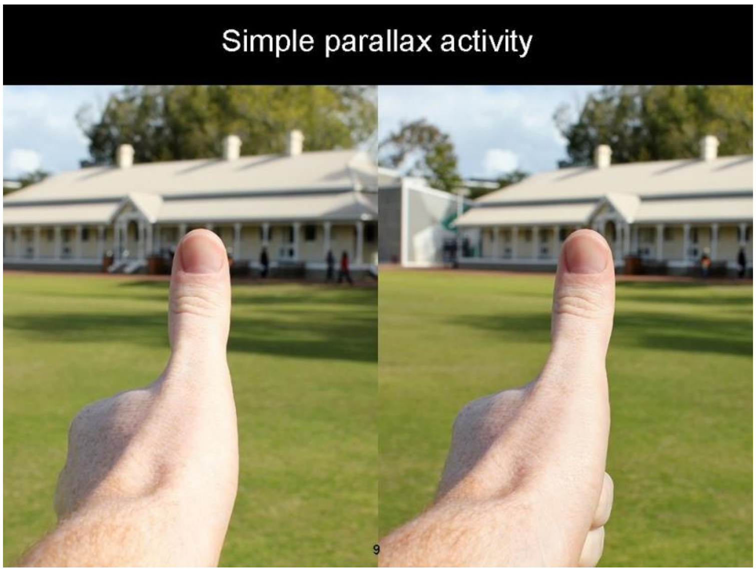
Open Cluster NGC 188

Composite image of 488 individual frames in B, V, R and I band
Image details: 0.4 m f/8 Cassegrain telescope, ST10XME CCD camera, f/6.3 Focal Reducer
B: 366 min, V: 183 min, R: 122 min, I: 122 min

14, 17 May 2014
Kosmas Gazeas – Maria Petropoulou
University of Athens Observatory, Athens ,Greece

Parallax

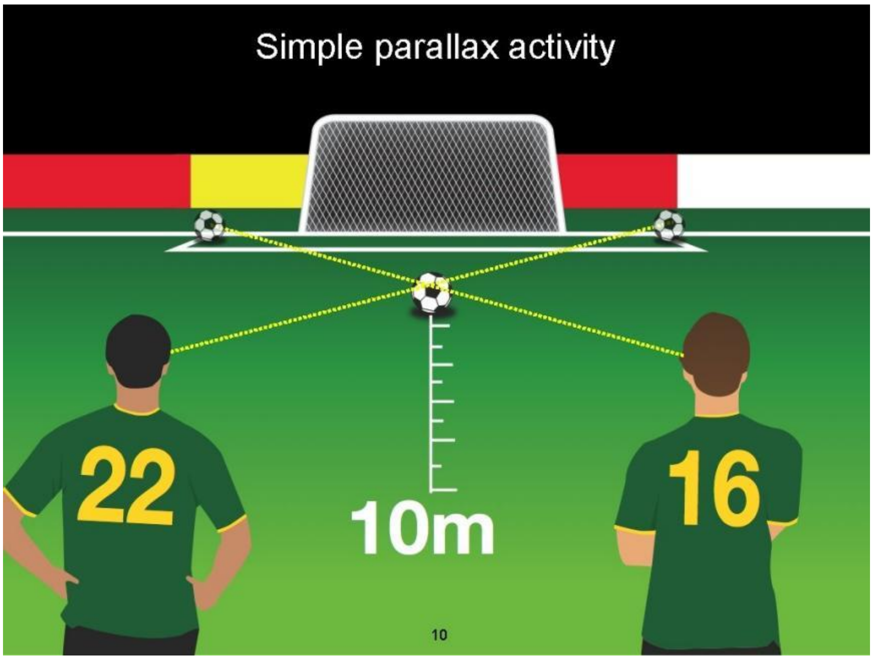
Lift your arm and give a thumbs up to your favorite item or person in the room. Close your left eye. Then open your left eye and close the right one. What do you see? Does anything change? The object or person you chose at the beginning is at the same place when you observe it or him with your right and left eye?


Simple parallax activity

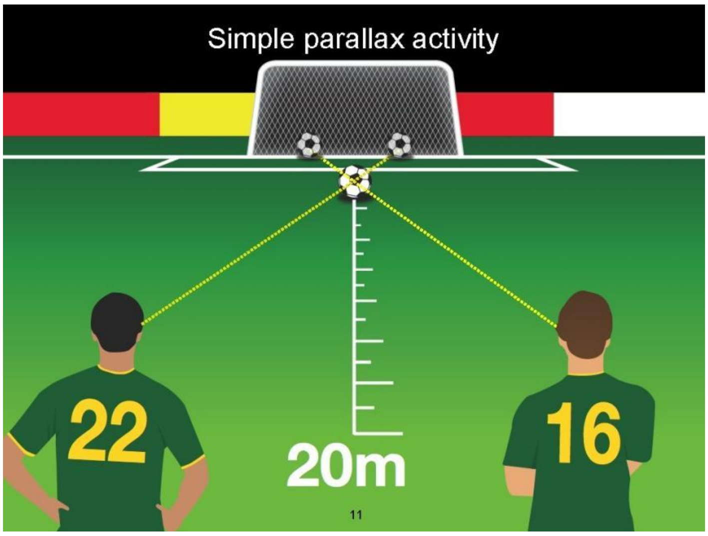
The phenomenon that you observe is called **parallax** and it is used by astronomers to measure distances in space.

Try to do the same thing you did before but with something that is farther away from you. What do you observe? That is correct! Parallax does not work. If we want to use this method for objects that are far away, we have to observe them through bigger angles. Since we cannot move our own eyes away from each other, we must think of something else.

For example, a football player watches the ball which is 10 meters away from him. If he closes his right or left eye the position of the ball compared to the net behind it will not change. The baseline, as it is called, meaning the distance between his eyes, is too small. But another player that is standing next to him, 2 meters away, sees the ball to a different relative position. So, **if we make the baseline bigger, we can use parallax for more distant objects.**


Simple parallax activity

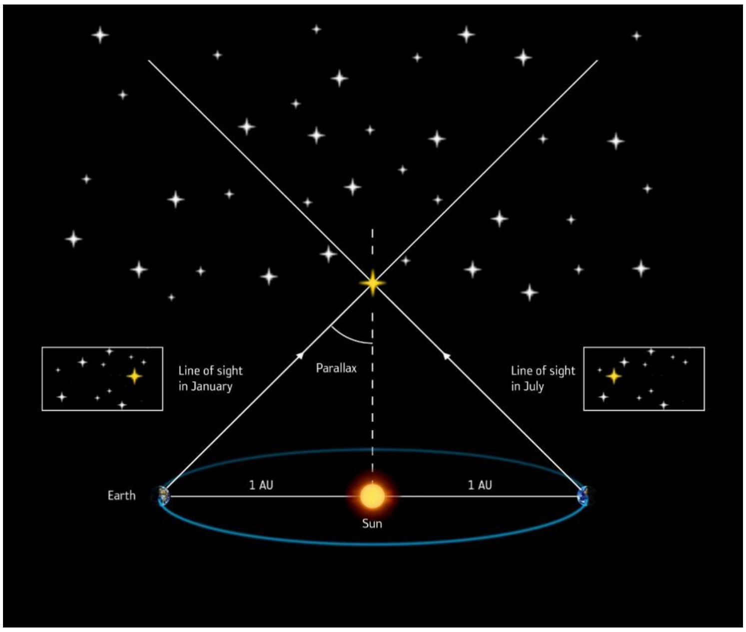
What do you think will happen if we move the ball away from the players? Will it change the position they observe? Why? Write down your thoughts and discuss them with the rest of the classroom.



What do you observe? Is the distance of the object (in this case the ball) related with the distance between the different observed positions?

Astronomers use the same method to count the distance of near stars. Imagine that your thumb or the ball is the star. If you observe the star from different angles, you will see it in different positions compared to its more distant background. But they faced the same problem you did when you tried to use your thumb for more distant objects. They needed a bigger baseline. Can you imagine what baseline they use in order to employ the parallax phenomenon?

One baseline that they use is the Earth’s orbit! By knowing the angle formed by these different positions (called parallax angle), they are able, through trigonometry, to count how far away the star is.



Units

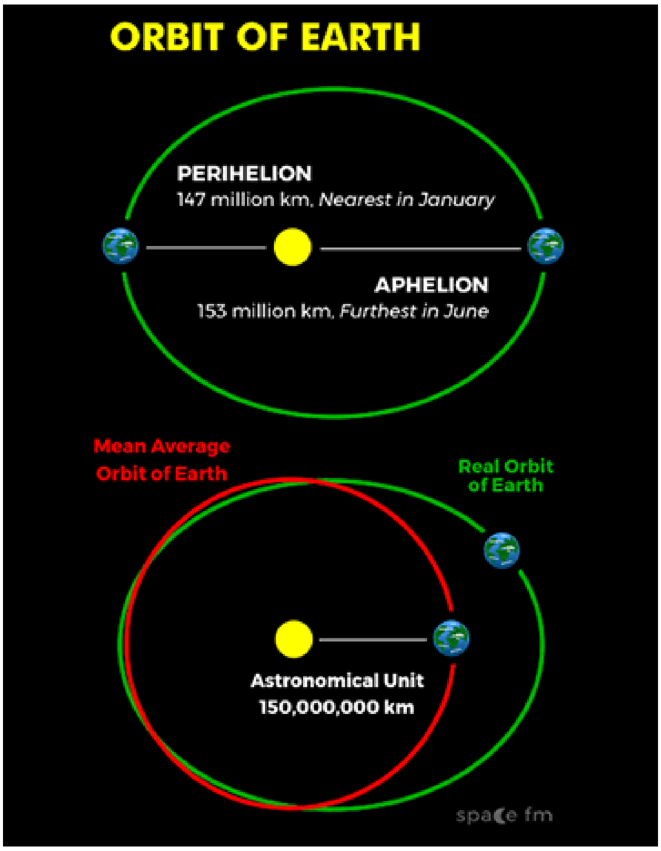
Let's take a moment to think how we measure a distance in our everyday lives. For example, how would you measure the distance between two edges of a table? You would probably use a ruler and the measurement would be in centimeters. What would you do if you wanted to measure a bigger distance? How far away is the kitchen from the living room in your house? How about your school from your home? How far away did you go on your last trip? I think by now you don't still count in centimeters.

In the same way, astronomers realized that it is not practical to count in kilometers even for “small” distances within our Solar System. So, they invented other measurement units. How would you determine such a unit? What distance would you use as reference to count even bigger distances in space? Write down your idea and discuss with the rest of your classroom.

In astronomy scientists use three different measurement units. Let's take a look on every one of them.

- Astronomical Unit (A.U.)

  This unit was inspired from our Solar System. It is the distance of the Earth from the Sun. Because of the Earth's elliptical orbit around the Sun their distance is not constant. So, in order to define the Astronomical Unit, scientists used the mean distance between the two celestial bodies.



- Light Year

The need for another unit other than the astronomical unit came up when Friedrich Bessel measured the distance of a nearby star (named 61 Cygni) and found it equal with 660.000 astronomical units! Imagine how big this number would be for distant stars if we expressed their distances from Earth in astronomical units. Scientists needed a significantly larger measurement unit.

It is called light **year,** but it measures distance! It is defined as the distance that light travels in space within a year. By knowing the speed of light (300.000 km/s) it is easy to calculate how far it goes during an Earth year concluding that 1 light year is approximately equal to 9.3 trillion kilometers.

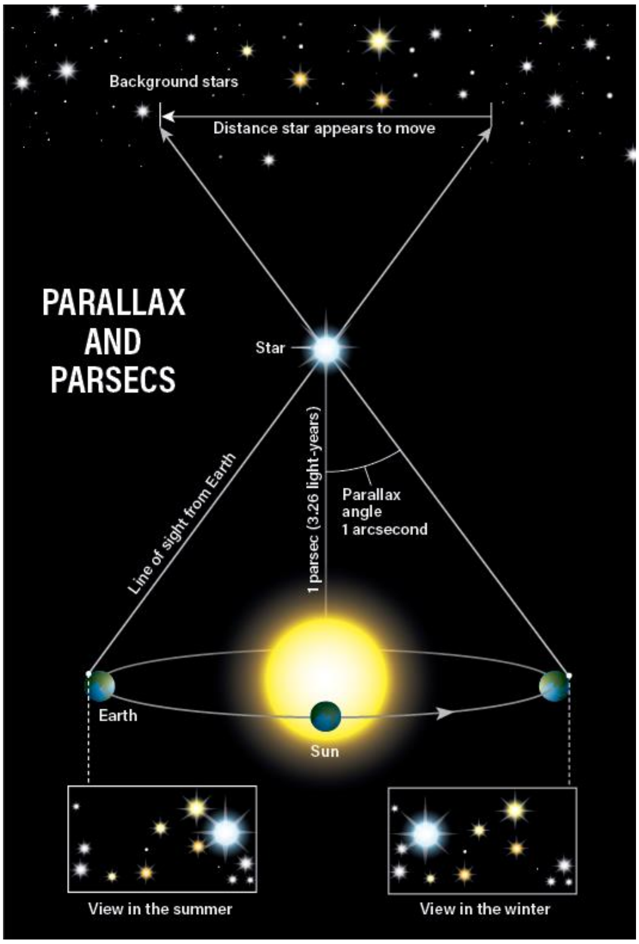
$$U = \frac{dx}{dt} \rightarrow C = \frac{dx}{dt} = \frac{1\ light\ year}{1\ year} \rightarrow 1\ light\ year = C * 1\ year$$
$$= 300.000 \frac{km}{s} * 31.104.000s = 9.3\ trillion\ km$$

Therefore 1 light year is equal to 62.000 astronomical units! Imagine that the light of our nearest star (the Sun) needs only 8 minutes and 20 seconds to travel 1 astronomical unit and reach our planet. Wait a second… That means that when we look at the Sun, we see the light that was emitted by it 8 minutes ago. So, we actually see the Sun as it was 8 minutes ago. We can see the past!

By looking through a telescope at a galaxy hundreds light years away from the Earth, we see how that galaxy was hundred years ago, before we were even born. It is like using a time machine! Scientists observe the sky, analyze the light that arrives to Earth and study the past…

- Parsec

Parsec is an even larger unit based on the method of parallax. When a star presents annual parallax equal to one arcsecond (equal to 1/3600 of a degree, which means that it is a really small angle), its distance from the Earth is equal to 1 parsec. 1 parsec is also equal to 3,26 light years or 206.265 astronomical units.

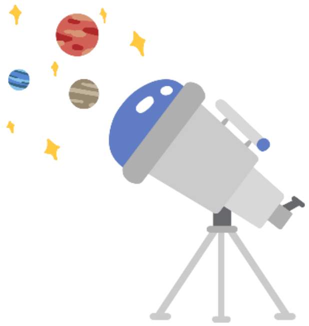


Hypothesis Generation and Design

Generation of Hypotheses or Preliminary Explanations

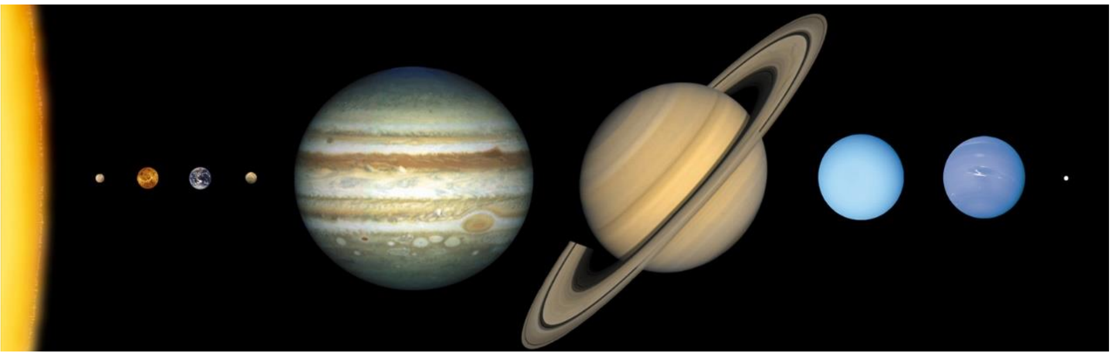
Scientists did not just invent these new units. They connected them with a known measurement unit of distance, the kilometer. Otherwise, measuring in astronomical units, for example, would be pointless because everyone would wonder how big an astronomical unit is. But how did they do that? You already saw how astronomers connected light years with kilometers through the speed of light. Can you imagine how astronomers of the 17th and 18th century figured out how many kilometers away is our closest star, the Sun?

They used parallax! Imagine that you are an astronomer of the 18th century and you want to measure the distance of the Sun using parallax. How are you going to do that? You need a distant background to see the parallax of the Sun, meaning the swift of its positions when you observe it from different angles. But the Sun, as you know and as we mentioned before, is so bright that we cannot see other stars in the background. So, how will you adapt the parallax method in this case?



What if we use the Sun as the distant background? In that case we need another celestial body between the Earth and the Sun to measure its parallax using the solar disk as a background. But what does exist between the Earth and the Sun that we could use?

We can use the other planets of our Solar System that are between the Earth and the Sun!



Scale in our Solar System (size and distance):

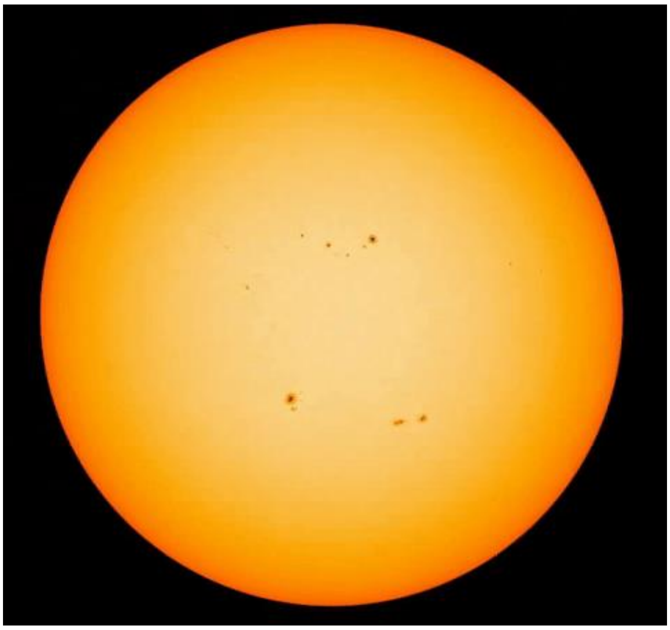
https://www.youtube.com/watch?v=DMZ5WFRbSTc

Those are Mercury and Venus. Since the background of the parallax is the Sun, we will measure the angular distance of different positions of the planet on the solar disk. There are different positions because of parallax which means that we need to observe the planet from different angles creating a baseline. But what baseline do you think we should use? What baseline would be big enough and what did scientists of the 18th century do?

Just like astronomers did back then, you can use the distance between two different places of the Earth as your baseline. That means that you need two observers in two different spots of the Earth observing the phenomenon at the same time, preferably as far away from each other as possible in order to have a big baseline.

Design/Model

The phenomenon of Venus (or Mercury) passing in front of the solar disk and appearing as a black spot is called transit. A Venus transit is a beautiful but rear phenomenon. Why is it rear? How often does Venus pass between the Earth and the Sun and how can we use this to measure the astronomical unit?



Orbits of Earth and Venus and why a transit of Venus is a rear phenomenon:

https://www.youtube.com/watch?v=hUhLod8pDhU

How to observe the phenomenon, its history and reference to its use for the measurement of the astronomical unit:

https://www.youtube.com/watch?v=SkRMJWjhvoQ

Venus transit:

https://www.youtube.com/watch?v=f6QooEtDVSU

How did scientists of the 18th century calculate the astronomical unit in kilometers? By observing a Venus transit from different parts of the Earth they used trigonometry to calculate the astronomical unit.

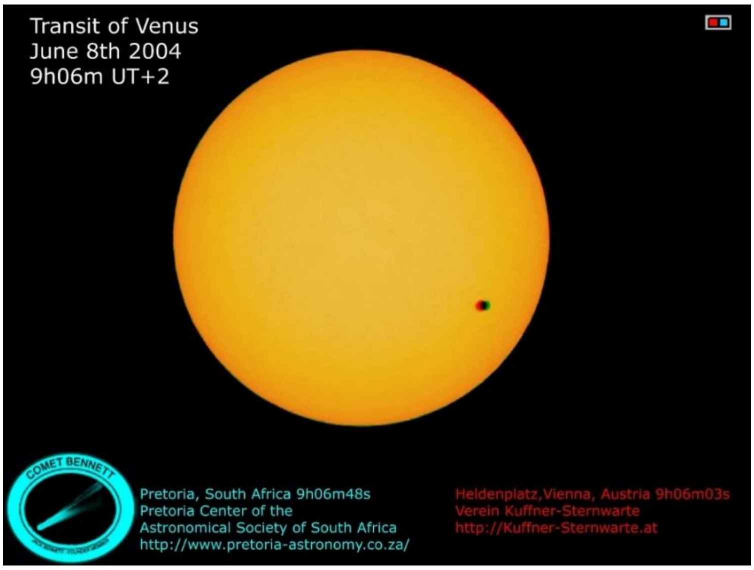
Though other astronomers had this idea before, Edmond Halley (yes, the known comet was named after him) was the one that advocated most successfully about the importance of these events. By using his influence at the time, he wrote a paper calling astronomers to travel across the globe and observe the phenomenon. This way he initiated an unprecedented international scientific effort where at least 122 observers in 62 separate stations took part.

Become an 18th century astronomer and calculate the distance of the Earth from the Sun!

With what criteria would you choose the cities from which you would use photos of the Venus transit? Remember that you want a big baseline to see the parallax.

Therefore, we need locations that have different geographical latitudes. Another thing is that the transit of Venus is not observable by the entire surface of the Earth. That happens because some locations do not face the Sun during the transit, meaning that for them the transit happens during the night so they cannot look at the Sun.

In this course we will use real images that astronomers took during the 2004 Venus transit. More specifically images from South Africa and Austria were combined to make Venus's parallax more obvious. You can see the picture that was created bellow and download it because you will need it later. You can also find the picture here https://www.eso.org/public/outreach/eduoff/vt-2004/photos/images/vt-photo-01-kspc.jpg



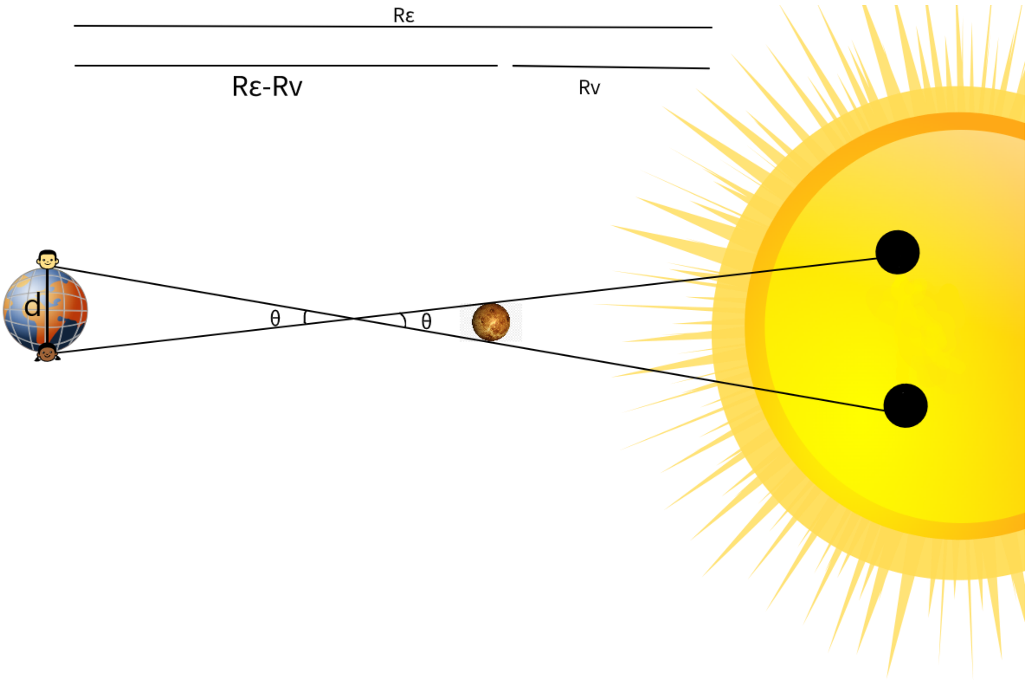
In the following image you can see why observers in different places of the Earth see Venus in different positions of the Solar disk creating the phenomenon of parallax and compare it with the experience you had when you used your thumb. Can you match the parameters for each case?

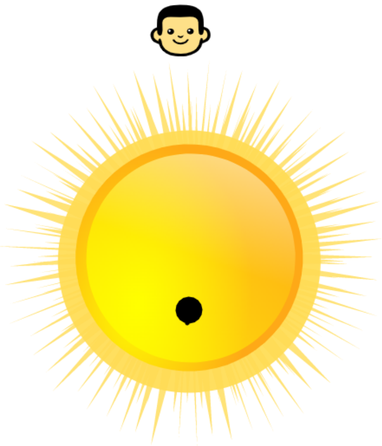
Thumb→

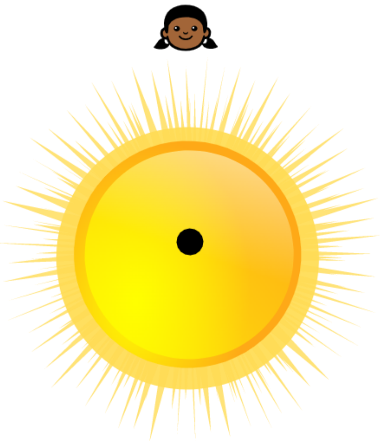
Eyes' distance→

Arm length→

Thumb -> Venus
Eyes' distance -> d (Earth's diameter)
Arm length -> Rε-Rv (Venus's distance from Earth)



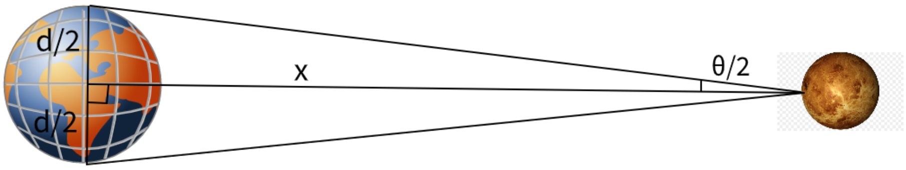




Thanks to Kepler's 3rd law and his work, the analogies of the Solar System were known far before the 1761 and 1769 Venus transits. That means that the distance of every planet from the Sun was known in relation to the astronomical unit (the distance of the Earth from the Sun). More specifically they knew that R_V is equal to 0.723 au. Therefore:

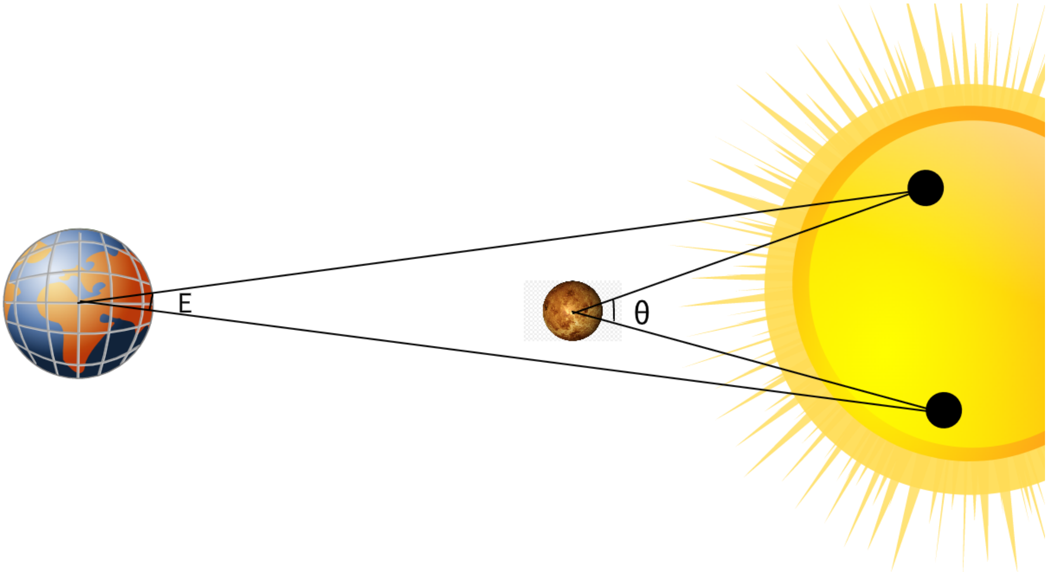
$x=R_E-R_V \rightarrow x=1au-0.723au \rightarrow x=0.277au \rightarrow 1au=x/0.277$

All you must do is calculate x. For that purpose, you need to measure the angle θ from the pictures of the astronomers' observations, calculate d and apply some trigonometry. The trigonometry needed for measuring x is the calculation of a tangent.



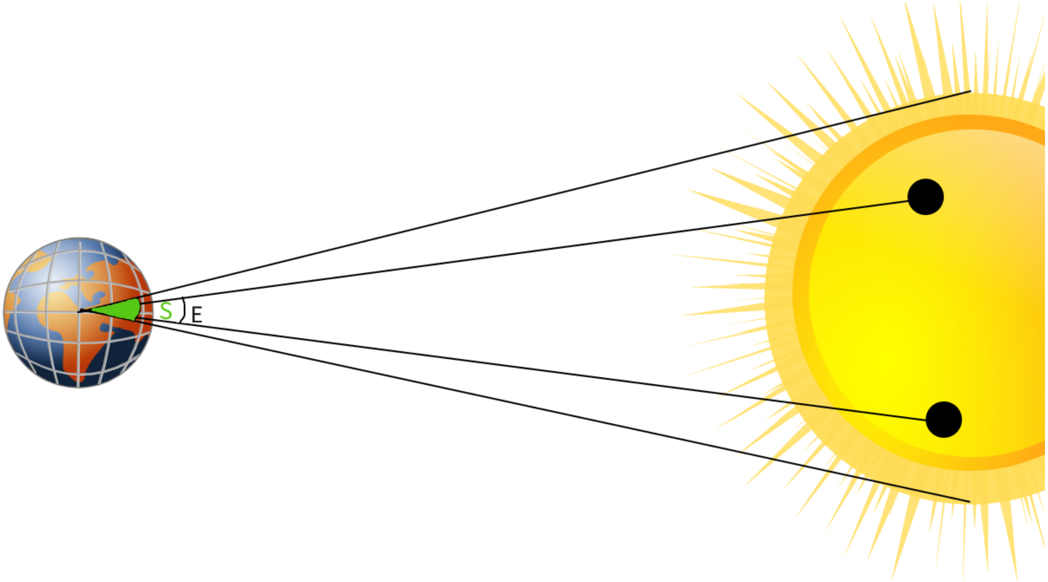
$$tan\frac{\theta}{2}=\frac{\frac{d}{2}}{x}\rightarrow x=\frac{d/_2}{tan\,\theta/_2}$$

To measure angle θ from the images and calculate the astronomical unit, like astronomers did in the 18th century, we will use one more time Kepler's 3rd law. That is because the angle of the positions as seen from Earth is not equal with the angle of the positions as seen from Venus.



According to Kepler's 3rd law the angle between the two positions as seen from Venus (which is the parallax angle θ) is equal with the angle E which is the angle between the two positions as it is observed by Earth divided by 0.72.

$$\theta = \frac{E}{0.72}$$



We know that the diameter of the Sun, when observed from the Earth (angle S), is equal to 0.5 degrees. Each degree is equal with 60 arcminutes and each arcminute is equal to 60 arcseconds (just like the hour). So, 1 degree is equal to 3600 arcseconds and 0.5 degrees (Sun's diameter) is equal to 1800 arcseconds. This way we can compare the distance between the two observed positions with the diameter of the Sun through the observers' images. By knowing that the diameter of the Sun is 1800 arcseconds we can calculate angle E in arcseconds.

Planning and Investigation

Plan Investigation

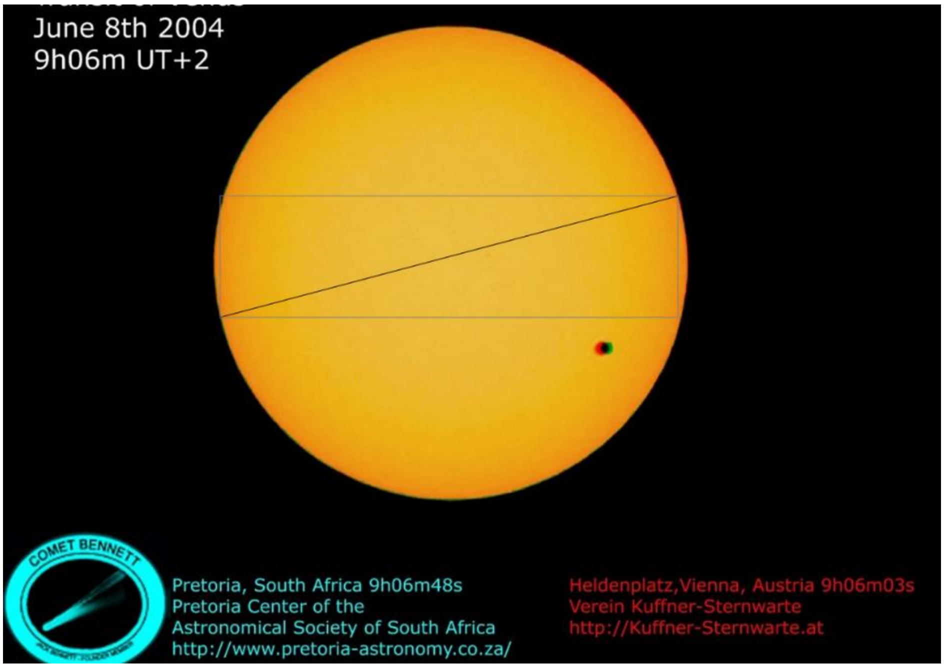
But how can we measure E? We are going to use a software called online pixel ruler. You can enter it here https://www.rapidtables.com/web/tools/pixel-ruler.html

Instructions for using this tool are written within the website.

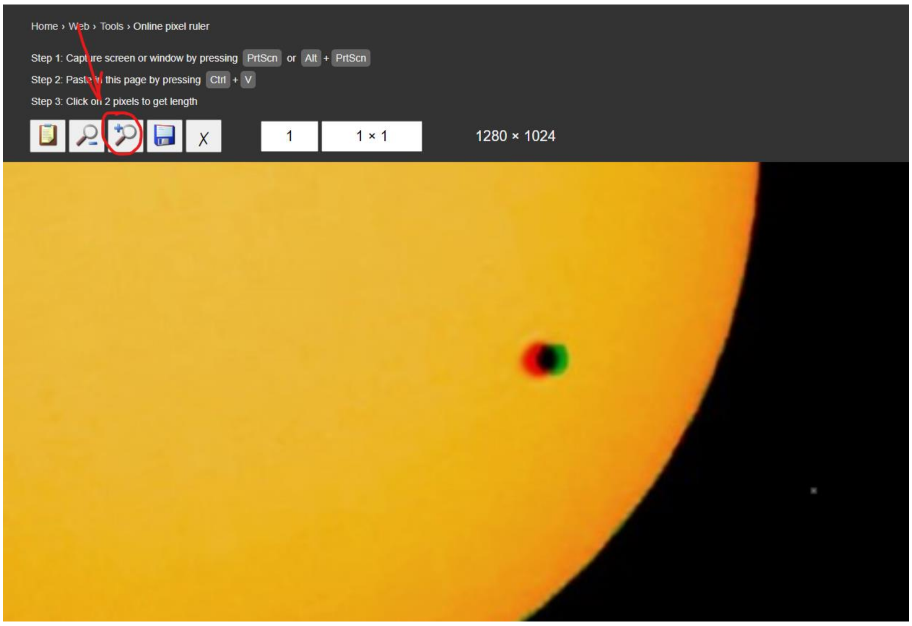
1. First you capture your screen or window by pressing PrtScr or Alt+PrtScr
2. Then you paste the image in the pixel ruler page by pressing Ctrl+V
3. Finally you click on two points of the image to get their distance in pixels

Perform Investigation

1. Open the image that you downloaded with the Venus transit.
2. Press PrtScr.
3. Return to the online pixel ruler and press Ctr+V.
4. Measure the diameter of the Sun.



5. Zoom in to the two shadows of Venus.



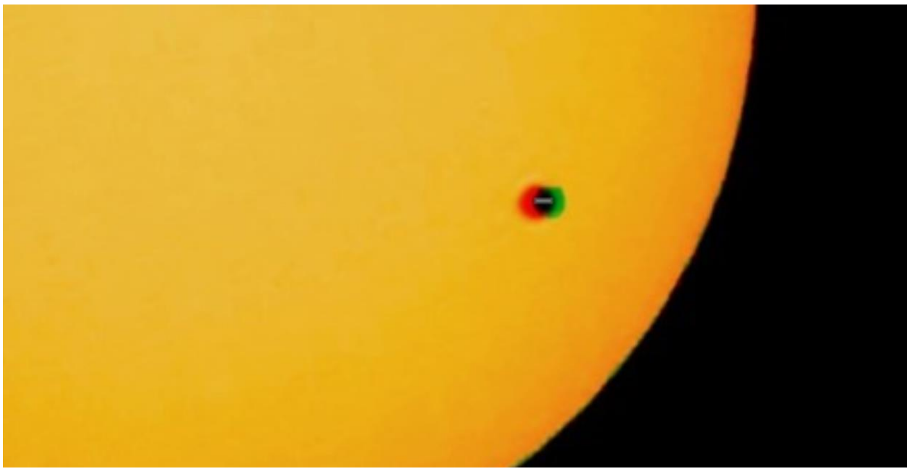
Home › Web › Tools › Online pixel ruler

Step 1: Capture screen or window by pressing PrtScn or Alt + PrtScn

Step 2: Paste in this page by pressing Ctrl + V

Step 3: Click on 2 pixels to get length

6. Measure the distance between the two positions of Venus.



Write down your measurements in the following table.

Distance	Measurement(pixels)
Sun's diameter	
Venus positions' distance	

Analysis & Interpretation

Since you had not defined a scale for the image, the measurement you have is in pixels. That is not a problem because you know how many arcseconds is the diameter of the Sun. Therefore, by comparing the two measurements, you can calculate the distance between the two positions of Venus (angle E) in arcseconds.

$$\frac{Sun's\ diameter\ in\ pixels}{Venus\ positions'\ distance\ in\ pixels} = \frac{1800}{E} \rightarrow E = \frac{1800 * Venus\ positions'\ distance\ in\ pixels}{Sun's\ diameter\ in\ pixels}$$

Write down your result.

E=................

So, by using the formula from Kepler's 3rd law you can calculate the angle θ. Write down your result.

$$\theta = \frac{E}{0.72}$$

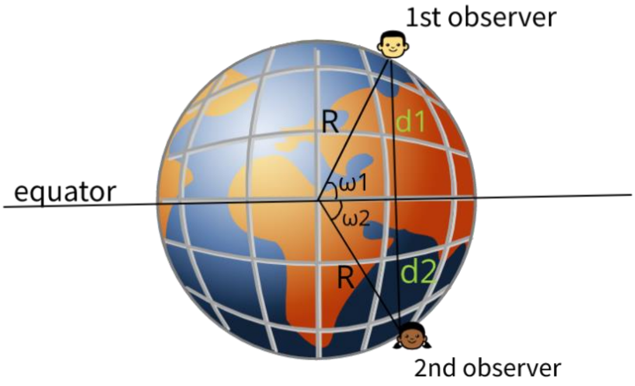
θ=.............

The other distance you must calculate is d, which is the distance of the two observers. To do that you will use trigonometry. All you need are the Earth's radius and the observers' latitudes.

Earth's radius: 6371 km

Heldenplatz, Vienna, Austria latitude: 48.21 degrees

Pretoria Center of the Astronomical Society of South Africa latitude: -26.2 degrees



$\sin\omega_1 = d_1/R \rightarrow d_1 = R*\sin\omega_1$

$\sin\omega_2 = d_2/R \rightarrow d_2 = R*\sin\omega_2$

$d = d_1 + d_2$

R: Earth’s radius

ω : geographical latitude

Write down your result.

d=............

Now you can go back to the formula we discussed before and calculate x.

$$tan\frac{\theta}{2} = \frac{\frac{d}{2}}{x} \rightarrow x = \frac{d/2}{tan\,\theta/2}$$

Write down your result.

x=...............

Finally, you can use x to find how many kilometers is the astronomical unit.

1au=x/0.277

Did you find it? How many kilometers is the astronomical unit according to your measurements? Write down your result.

1au=................................

Conclusion & Evaluation

Conclude and communicate result/explanation

Write down a brief text about the work you have done. Explain why the measurement of the astronomical unit is important and the steps you followed to measure it. Include the discussions that took place in your classroom.

Evaluation/Reflection

1. Compare your result with the results of your classmates. Why did your classmates find different numbers? Since you had the same data and you followed the same directions shouldn't you have the same outcome? Write down your thoughts and discuss in the classroom why this happens.
2. Would an astronomer of the 18th century be able to measure the astronomical unit by himself? Why is cooperation important in science and in general? Can you think of other examples where cooperation was useful in Astronomy, other science fields or everyday life? Write down your thoughts and discuss this topic in the classroom.

During this discussion, the educator's goal is to introduce the experimental errors to the students, presenting them as part of any experiment. The reasons of their existence can be also explained as well as methods for their minimization.

In this section it is important to highlight some parts of the Nature of Science such as the cooperation of scientists and its importance in order to reach a conclusion or conduct an experiment. Another fact is that they do not always agree with each other.

3. What do you think was the most interesting part of this exercise and what did you find less interesting? Write down your thoughts and discuss this topic in the classroom.

4. Do you feel that you learned more about Astronomy, distances in space and the way astronomers work? Write down your thoughts and discuss this topic in the classroom.

5. Do you feel that you learned a new software or mathematical tool? Write down your thoughts and discuss this topic in the classroom.

6. Do you think you can use the same scientific method in only one context or can it be applied for multiple cases? Write down your thoughts and discuss this topic in the classroom.

During this discussion the main target is to highlight the capability of scientists and scientific methods to be applied in different contexts with different goals, just like the adaptation of the parallax method that students did during this course. Another example in Astronomy is the many ways photometry is used and the images are analyzed to conduct research on different celestial bodies.

Consider other explanations

The data from the Venus's transits (1761 and 1769) were combined and analyzed by the French astronomer Lalande who calculated the astronomical unit equal to 153 ±1 million kilometers. This result is surprisingly close to today's known number of 149,597,871 kilometers.

Compare your result with the results of the 18th century and today's known value. How did scientists manage to have such an accurate measurement? What do you think? Discuss this topic with the rest of the classroom.

After the Venus's transits, other methods were used to improve the accuracy of the astronomical unit's measurement and calculation. Some of them are the parallax measurement of the near-Earth asteroid 433 Eros and the radar measurements of the Venus's and Mars's distance from the Earth. During this discussion the educator could refer to technology, its use in science and the contribution of the technological evolution in our understanding of the world.