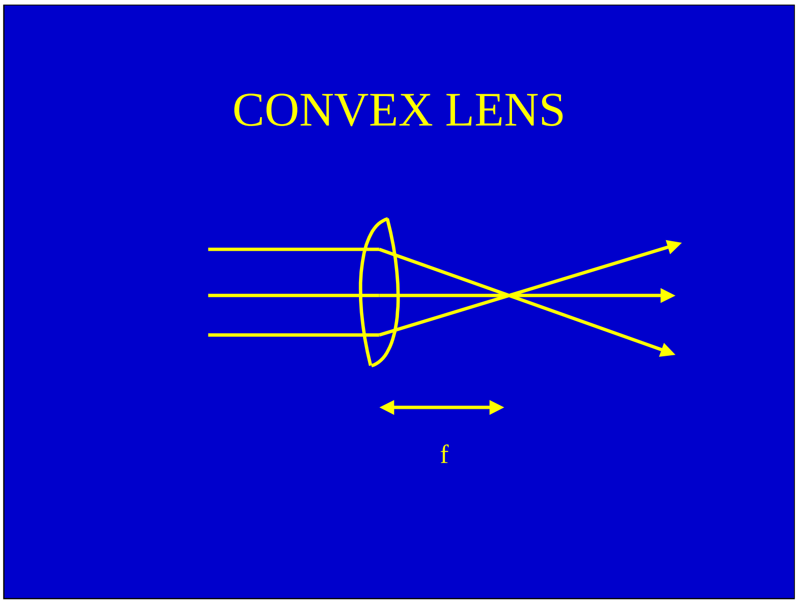
GALILEO

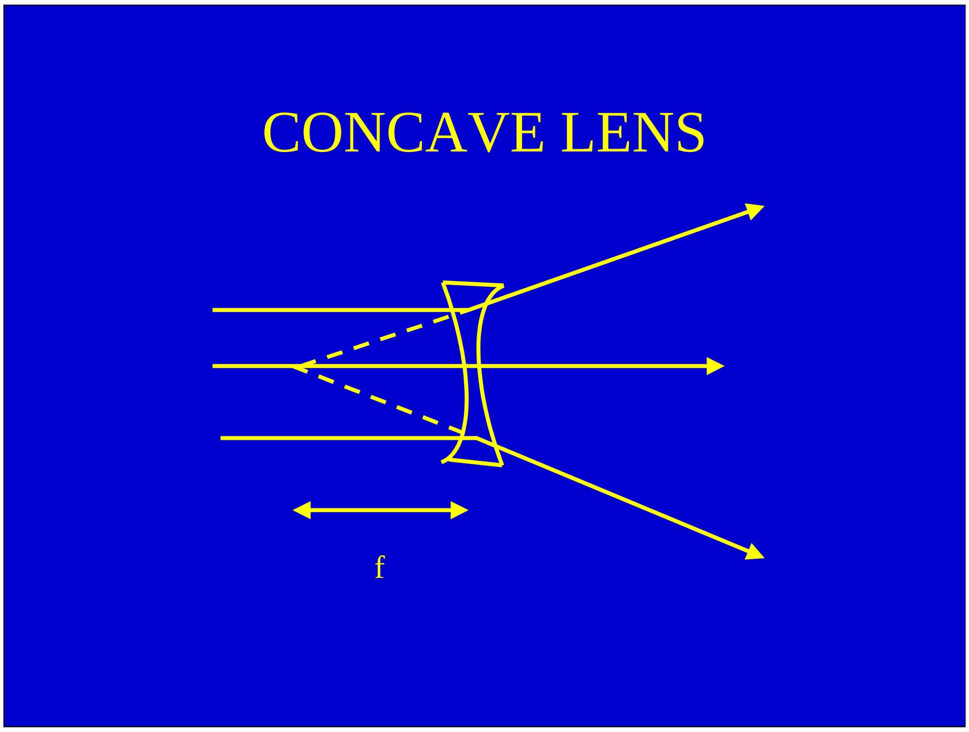


When light travels from one medium to another at an angle to the interface, it often changes direction. This is called refraction. Lenses have curved surfaces that have been shaped carefully so as to manipulate beams of light and to form images. A convex lens is thicker in the middle than the edges. It focuses a parallel beam of light more or less to a point a distance f away from the lens. f is called the focal length of the lens. An image formed to the right of a convex lens is called a real image since the light actually passes through it. This is the kind of lens far sighted people need to correct their vision.

A lens with a shorter focal length is regarded as being stronger than a longer focal length lens, and is also generally more difficult to make.

The lenses in our eyes are convex. Their focal lengths can be varied about 10%, with a muscle, allowing us to focus on objects a range of distances away.

The light rays drawn above follow the same paths if their directions are reversed. So light rays passing through the focal point on one side of a lens are focused parallel on the other side.

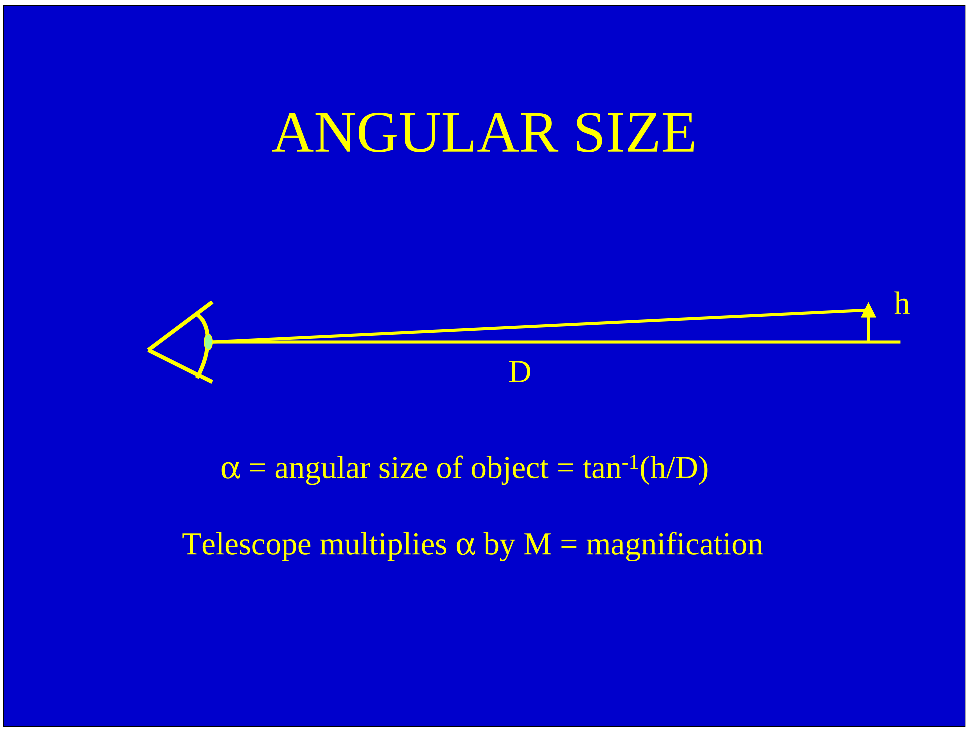


A concave lens is thinner in the center than the edges. This is the kind of lens near-sighted people need to correct their vision.

The focal length of a concave lens is regarded as being negative since parallel light diverges upon passing through it, appearing to have come from a point in front of the lens. If an image is formed to the left of a lens it is called a virtual image since the light to the right of the lens did not actually pass through it. Nevertheless you can see this image if you place your eye to the right of the lens.

Just as for the convex lens, the light rays shown would follow the same paths if their directions were reversed.

This is all we need to know to understand the Galilean telescope.

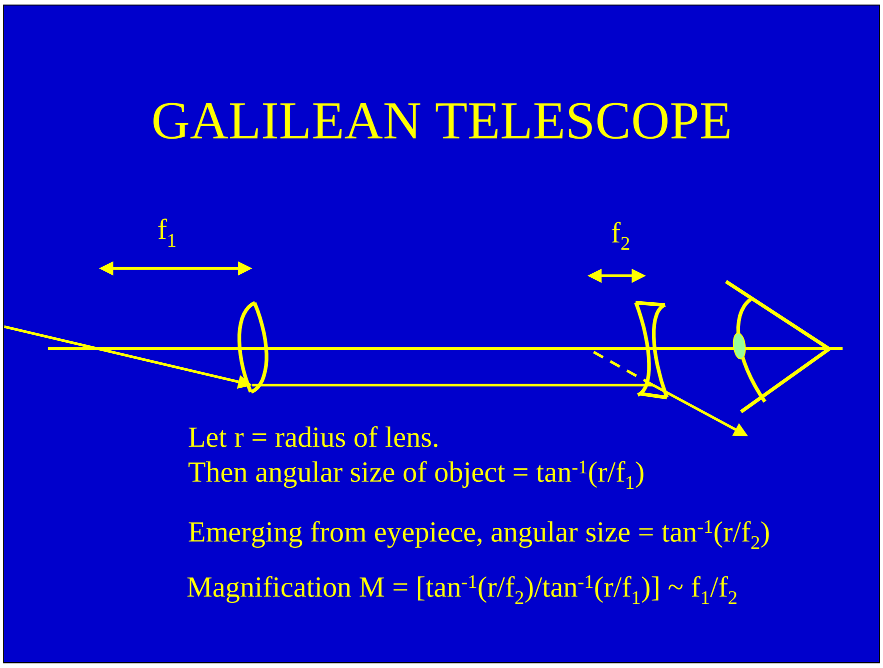


We characterize a telescope by its power, or magnification. Typical binoculars have a power of 8 – 10. That means they make distant objects appear to be 8 – 10 times closer than they really are. How do they do this?

When we look at a distant object it has a certain angular size. Our eye then focuses an image of the object onto our retina. The larger the object is the bigger its image will be. What really counts is the angular size of the object, not its actual physical size. Large objects far away have a small angular size and so appear small to us.

The angular size of a tree of height h and distance D away is $\tan^{-1}(h/D)$. For small angles the arc tangent function is proportional to the ratio h/D and in fact is equal to 57*(h/D).

What a telescope does is increase the angular size of an object (making it appear closer) using its arrangements of lenses. Let us see how this works for the Galilean telescope.



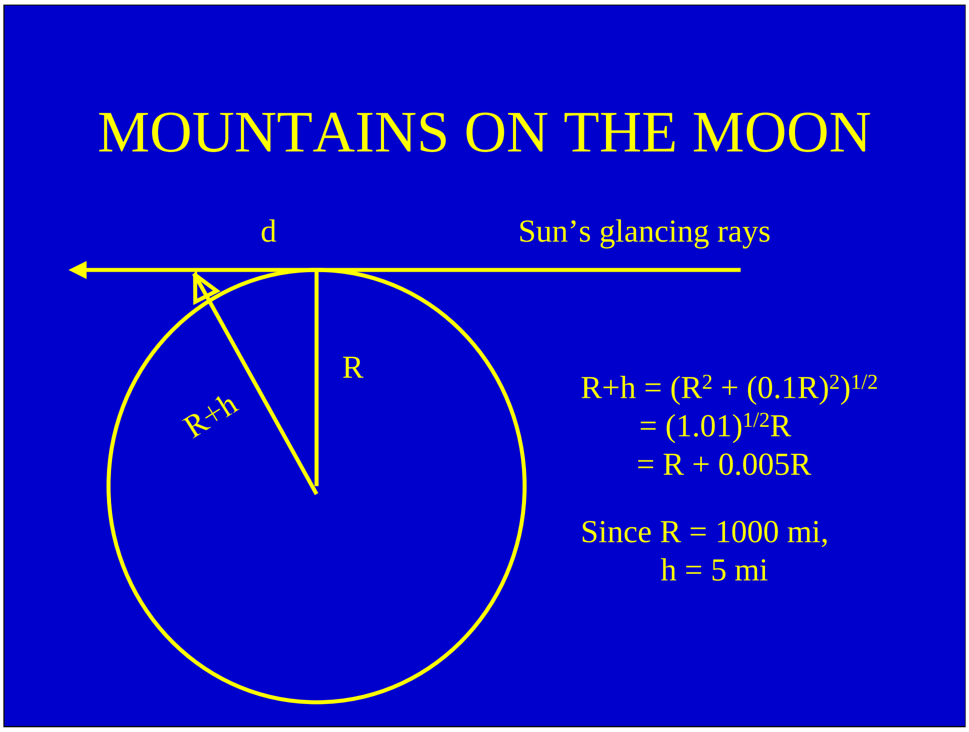
A Galilean telescope consists of a tube holding two lenses at its ends. The one facing the object being viewed is convex, and weak (i.e. has a large focal length). The other, the eyepiece, is concave, and stronger, with a shorter focal length.

Let us follow a single ray of light as it enters the telescope. We can choose any ray so let's select one for simplicity. We know that if a ray crosses the axis of the telescope at a distance from the first lens equal to its focal length, it will be focused parallel to the axis on the other side.

If we let r equal the radius of the lenses, then the angular size of the object we are looking at is $\tan^{-1}(r/f_1)$ which for small angles is equal to $57(r/f_1)$. Here we assume the axis of the telescope is aimed at the base of the object, and its top is just captured by the outer edge of the first lens.

This ray parallel to the axis is turned into a diverging ray by the eyepiece, and all similar parallel rays will appear to have come from the focal point to the left of the eyepiece. The angle between the ray and the telescope axis is now equal to $\tan^{-1}(r/f_2)$ and is equal to $57(r/f_2)$ for small angles.

So we see that the angular size of the object has been multiplied by $M = (r/f_2)/(r/f_1) = f_1/f_2$. The magnification of the telescope is just equal to the ratio of the two focal lengths. What Galileo wanted was a weak convex lens and a strong concave lens. The latter was the more difficult challenge to make. The telescope he used to make the observations reported in Siderius Nuncius had a magnification of 20.



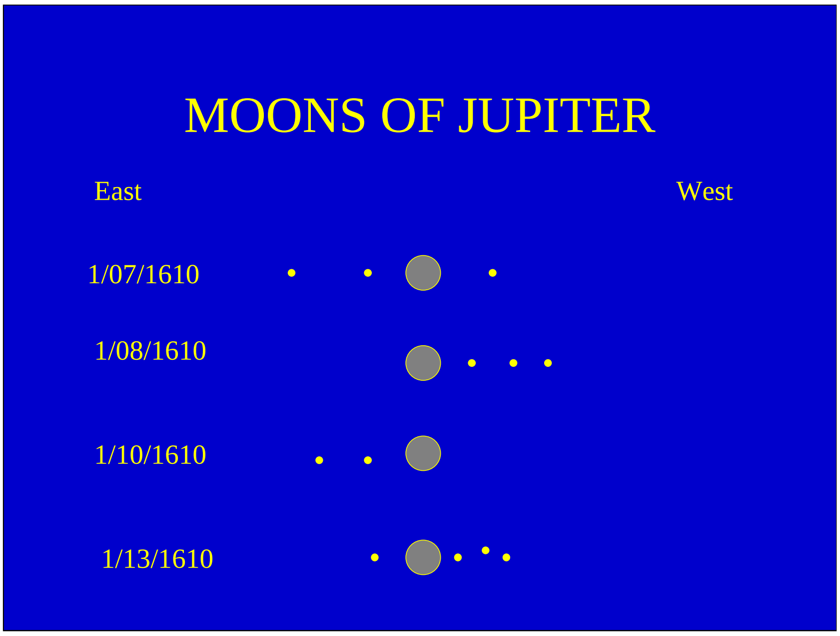
Galileo saw bright spots extending into the dark (unilluminated) part of the moon, and dark spots well into the bright (illuminated) part. If the moon were a perfect sphere, the dark and light regions should be separated by a uniform, somewhat fuzzy line.

Suppose there is a tall mountain of height h in the above diagram. Such tall mountain peaks will continue to intercept the sun's rays well after surrounding lower areas are dark. Galileo estimated he could see bright spots extending about 10% of the moon's radius into the dark region. Then from the above diagram, we only need the Pythagorean theorem:

$$R+h = (R^2 + [0.1R]^2)^{1/2} = (1.01)^{1/2}R = R+0.005R$$

So h = 0.005R. Since Galileo knew the radius of the moon was about 1000 miles (as determined by the ancient Greeks), he had found that the highest mountains on the moon are about 5 miles tall.

He had the impression that the tallest mountains on Earth are about 1 mile high, so he announced that Moon mountains are higher than those on Earth. This may in fact be the case, since he may not have seen the highest mountains there.



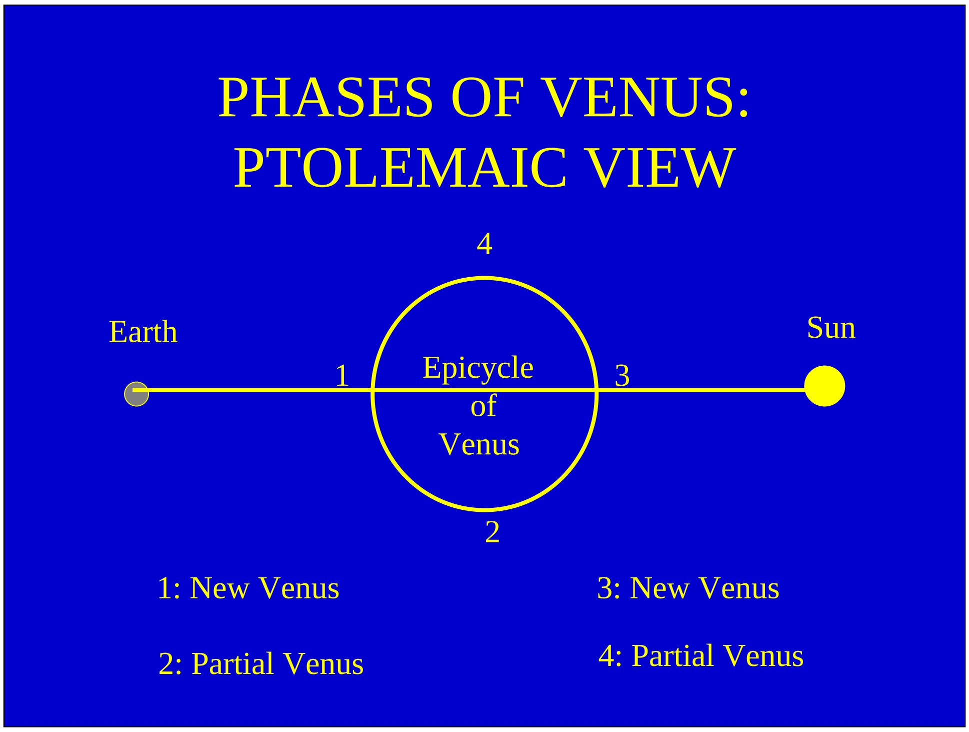
Galileo’s 20 power telescope was probably best suited to making observations of the Moon it being so close, and full of fuzzy features. His next major target became Jupiter in early 1610. At that time Jupiter was in opposition, so as close to Earth as it gets, and fully illuminated. Looking south toward the ecliptic, he saw it beautifully displayed on 1/07. He was surprised to see near it three small but bright stars in a row and lined up along the ecliptic. He thought they were three of the fixed stars that just happened to be near Jupiter.

At that time Jupiter was in retrograde motion, so when he again looked the next night he expected to see it farther to the west of the three fixed stars. Instead it was to the east of all three. He thought perhaps the almanacs were wrong and Jupiter had resumed its proper motion towards east.

When he saw Jupiter again on the 10th, there were only two small stars, both to the east. And on the 13th he saw four small stars. By this time he had to conclude that the group of four move around Jupiter as the Moon moves around Earth. Galileo was clearly very excited about this as can be seen from the number of sketches he shows in Siderius Nuncius.

He watched the group long enough to show that the little stars accompany Jupiter both in its retrograde and direct motion, leaving no doubt that they accompany it.

An immediate conclusion is that there is more than one ”center” in the universe. This clearly shakes the foundation of the Aristotelian doctrine that the Earth is the one and only center.

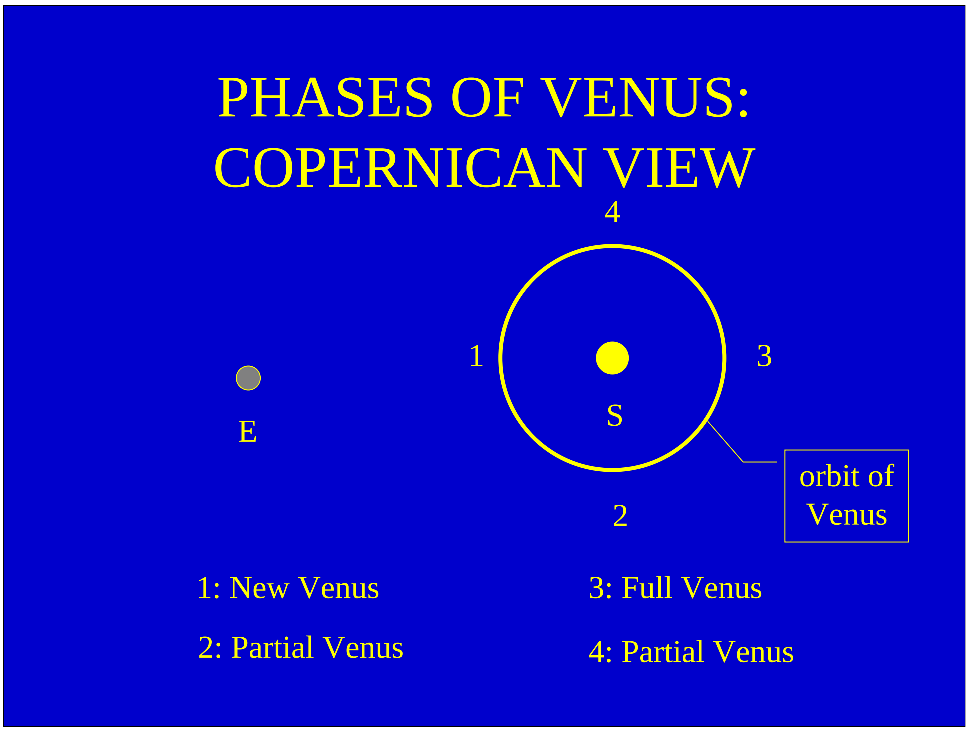


By the autumn of 1610 confirmations of Galileo's observations of the Moon and Jupiter had been reported by others, and the telescope was on its way to general acceptance. Galileo did not rest on his laurels – he announced a new major discovery regarding Venus that was to be the smoking gun that killed the Ptolemaic system.

Naked eye observations could reveal the positions of the planets in the sky, but the telescope could show something more: the shape of the appearance of the planet.

According to the Ptolemaic model as sketched above, Venus remains between the Sun and the Earth at all times. This means that a Full Venus is not possible. When it is nearly lined up with the Sun, we cannot see Venus at all. Only when it appears on one side or the other does it become either the evening or morning star, and should then have a crescent shape. At greatest elongation Venus is the brightest object in the heavens, and should appear as a fuller crescent.

In the fall of 1610 Venus appeared in the evening sky and Galileo had an improved telescope with fewer aberrations. He then made a determined effort to observe its shape over time. The reason was that the Copernican model predicted a different sequence of shapes than the Ptolemaic model.

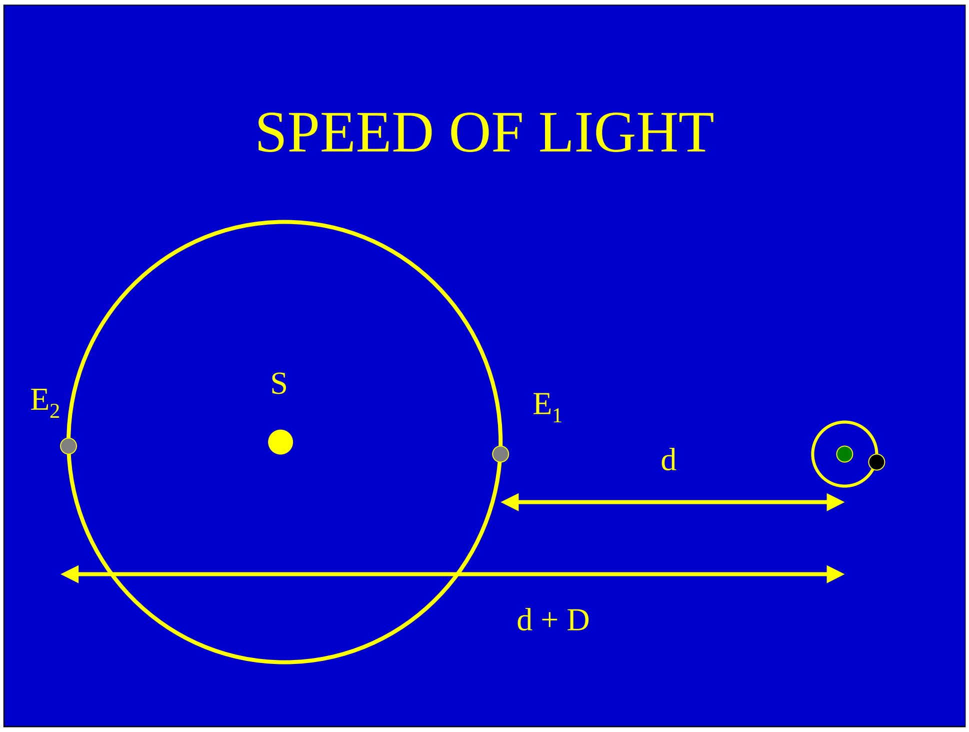


According to the Copernican model, Venus goes behind the Sun from Earth and so should appear full as it enters or leaves that region. In the fall of 1610 just after the sun set, it should appear as a round disk, then gradually develop a crescent shape as it moved farther from the Sun.

Galileo saw Venus as a round disk in October of that year, but was unsure of the result because of aberrations. Maybe it was a crescent but was smeared to a round shape. He did not know the resolving power of his telescope.

To establish credit for the discovery but to save himself embarrassment in case it was false, Galileo sent a letter to the Tuscan ambassador in Prague which included an anagram. The anagram, properly unscrambled, read “The mother of love emulates the figures of Cynthia.” Venus is the mother of love, and Cynthia is the Moon. Cynthia, or Artemis, was a Greek goddess associated with the Moon. This means that Venus has a full set of phases like the Moon. (The above code was of course in Latin).

By December Galileo had seen Venus develop into a crescent shape and could reveal his discovery. No version of the Ptolemaic model, and there were several, could account for his observations. It was only a matter of time before astronomers had to abandon the Ptolemaic model.



Here we see a view of Earth, Sun, and Jupiter with one of its moons. The Earth is shown in two diametrically opposite positions. The motion of Jupiter's moon is so precise that after enough data is collected and analyzed, astronomers can predict months and years in advance when the eclipses of the moon behind Jupiter will occur.

In 1676 Ole Romer, a Danish astronomer announced to the Academy of Sciences in Paris that the eclipse of one of Jupiter's moons, expected on November 9, would be exactly 10 minutes late. When the Royal Observatory in Paris confirmed this prediction, everyone wanted to know the basis for it. Romer explained that the delay was due to the finite speed of light. It takes light about 16 minutes to cross the diameter of Earth's orbit. This was the first measurement of the speed of light and although not terribly accurate, it did establish that the speed of light is finite although large. The modern value is 300,000 km/s.

The first laboratory measurement of the speed of light was accomplished 300 years later when the technology needed to measure very short time intervals had been developed.