

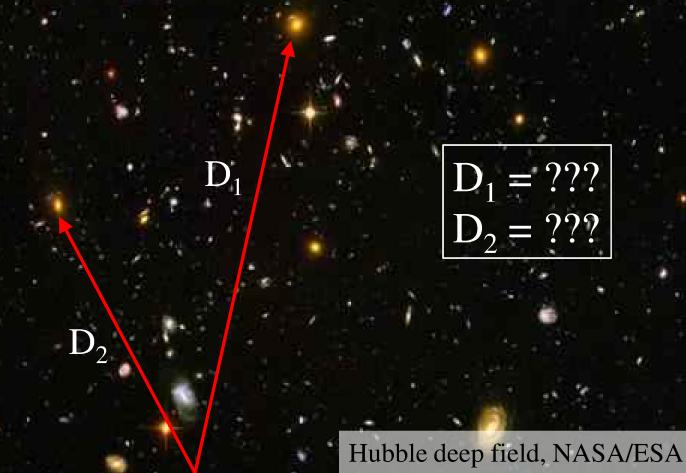
Astrometry is the study of positions and movements of celestial bodies (sun, moon, planets, stars, etc.).

It is a major subfield of astronomy.

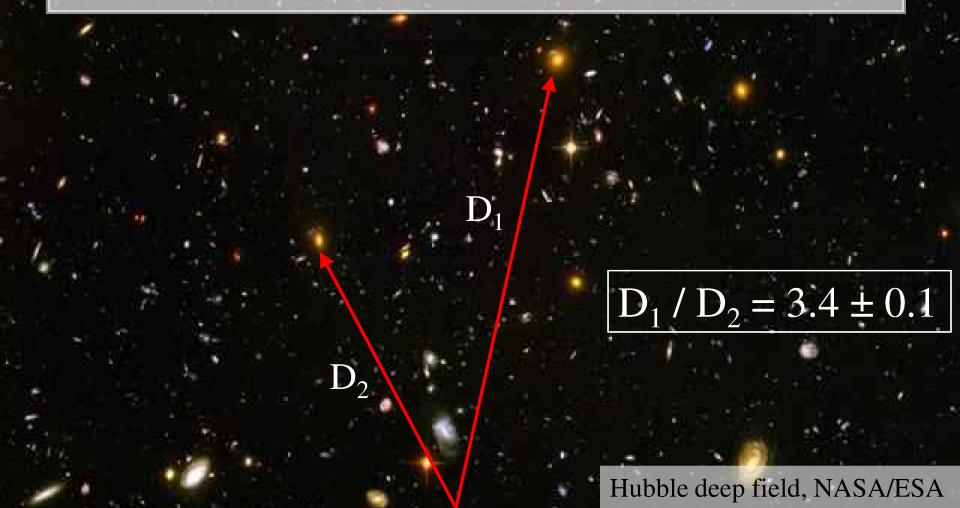
Typical questions in astrometry are:

- How far is it from the Earth to the Moon?
- From the Earth to the Sun?
- From the Sun to other planets?
- From the Sun to nearby stars?
- From the Sun to distant stars?

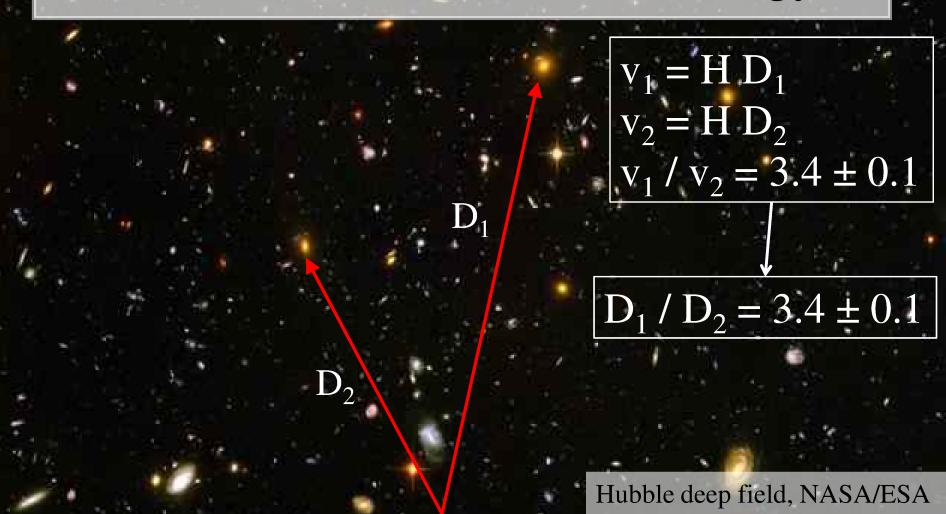
These distances are far too vast to be measured directly.



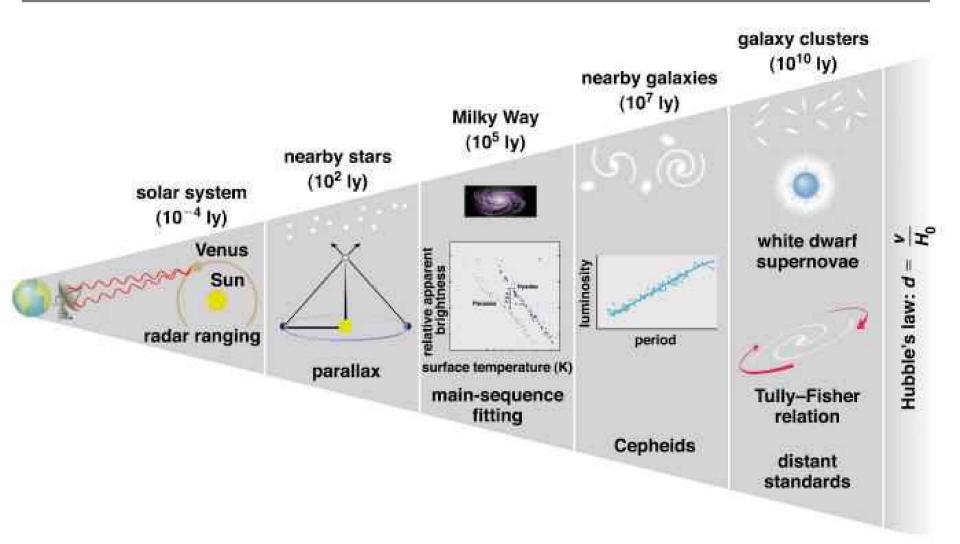
Nevertheless, there are several ways to measure these distances indirectly.



The methods often rely more on mathematics than on technology.

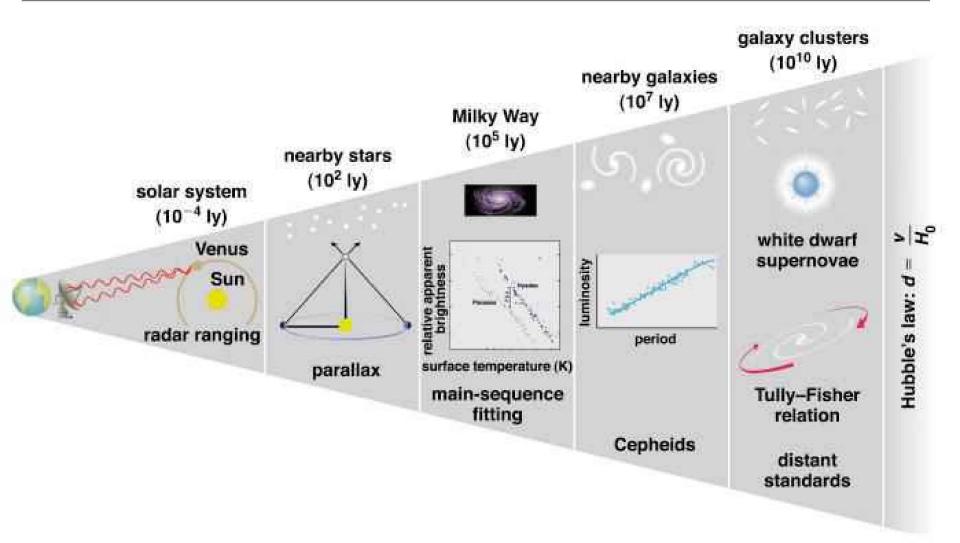


The indirect methods control large distances in terms of smaller distances.



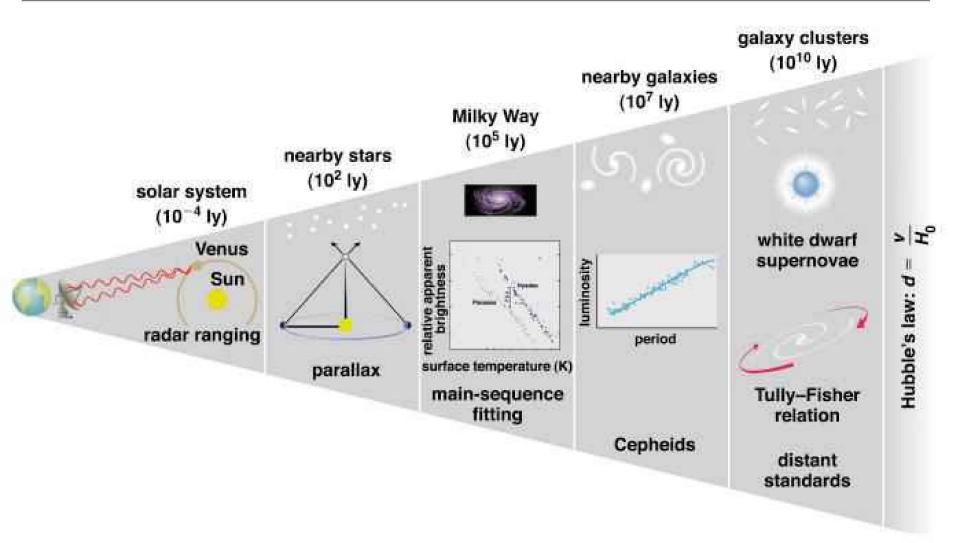
From "The Essential Cosmic Perspective", Bennett et al.

The smaller distances are controlled by even smaller distances...



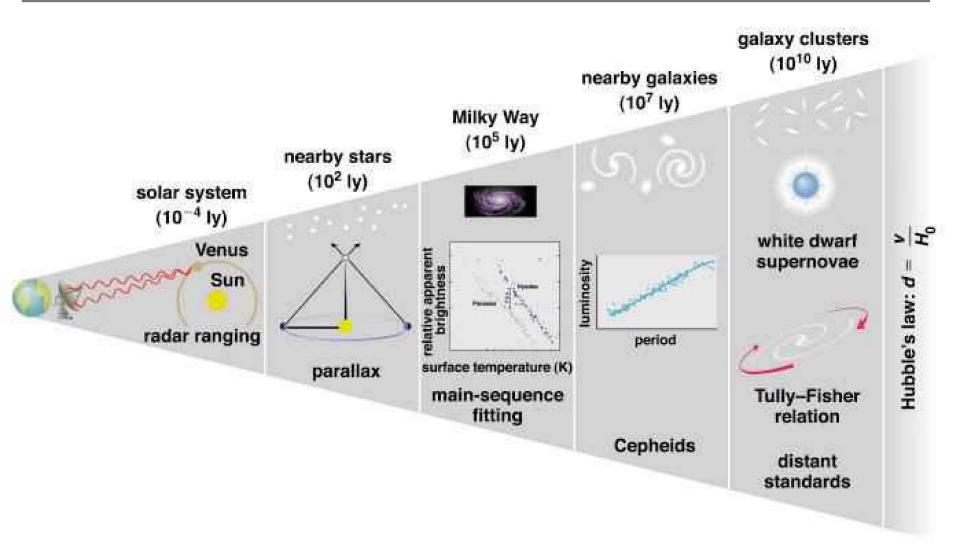
From "The Essential Cosmic Perspective", Bennett et al.

... and so on, until one reaches distances that one can measure directly.



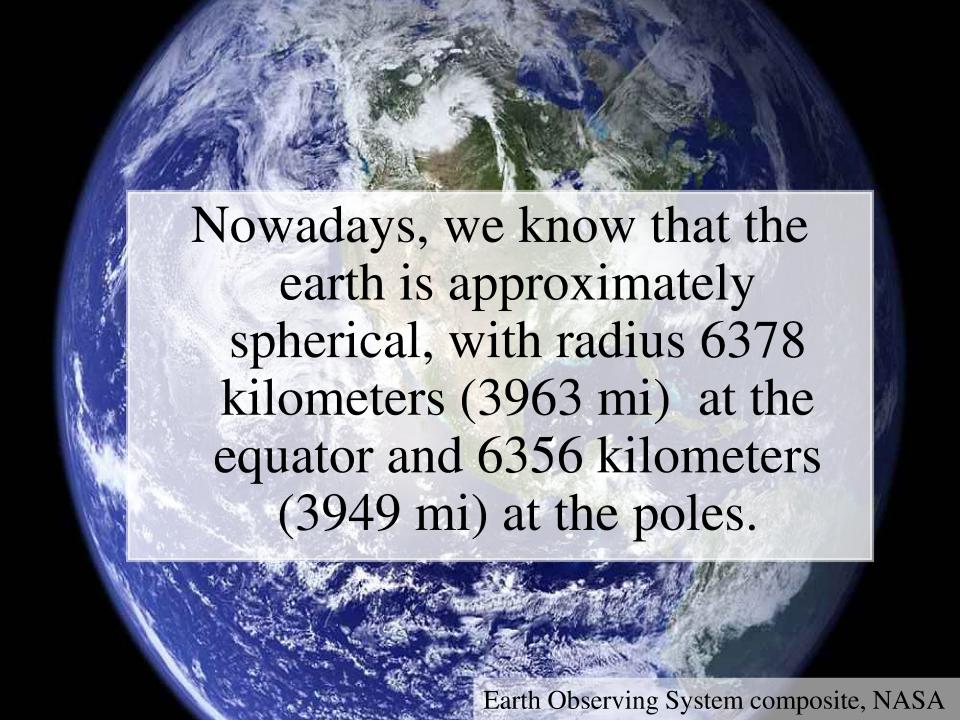
From "The Essential Cosmic Perspective", Bennett et al.

This is the cosmic distance ladder.

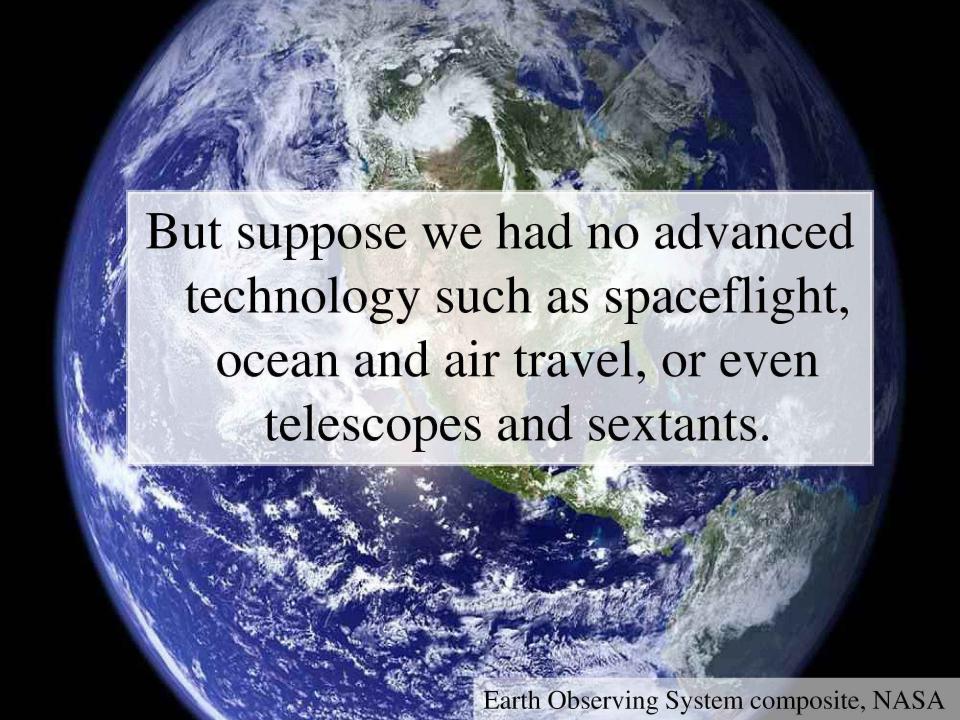


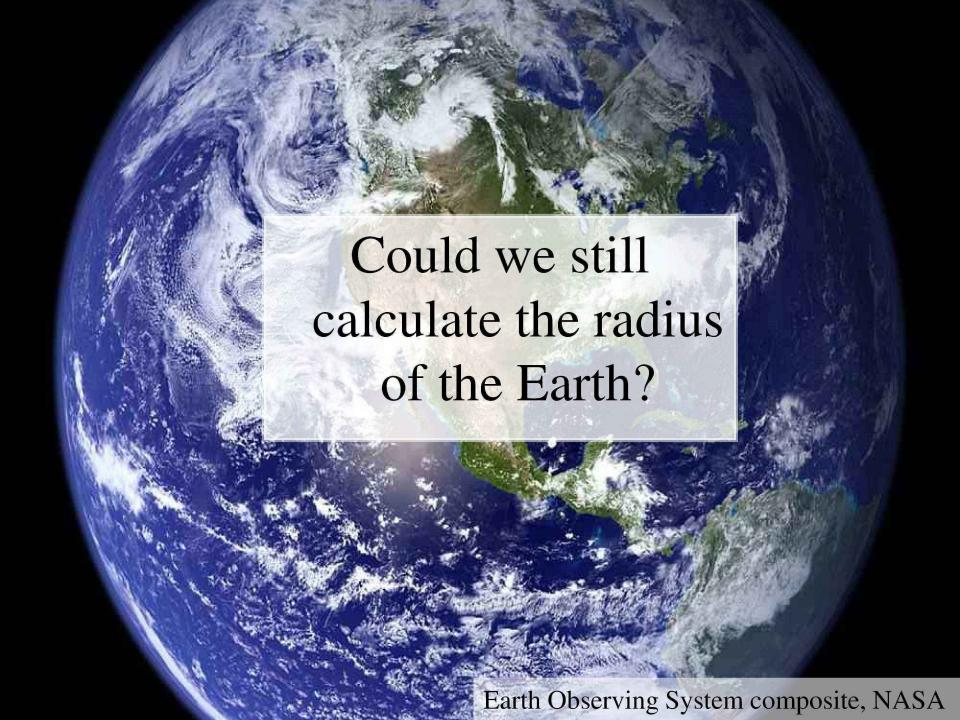
From "The Essential Cosmic Perspective", Bennett et al.



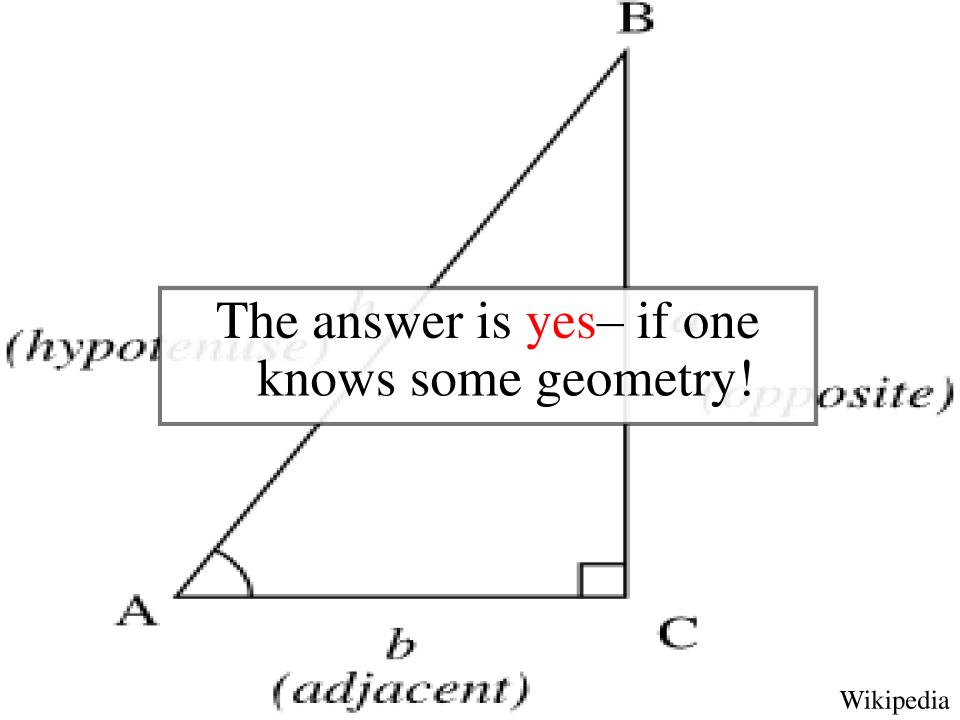


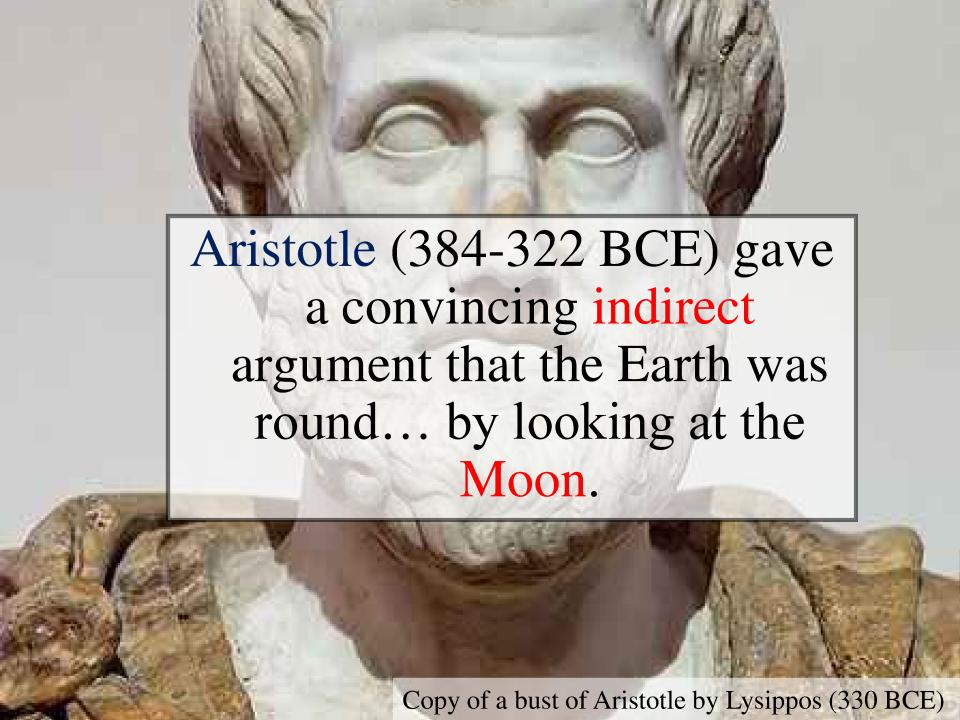




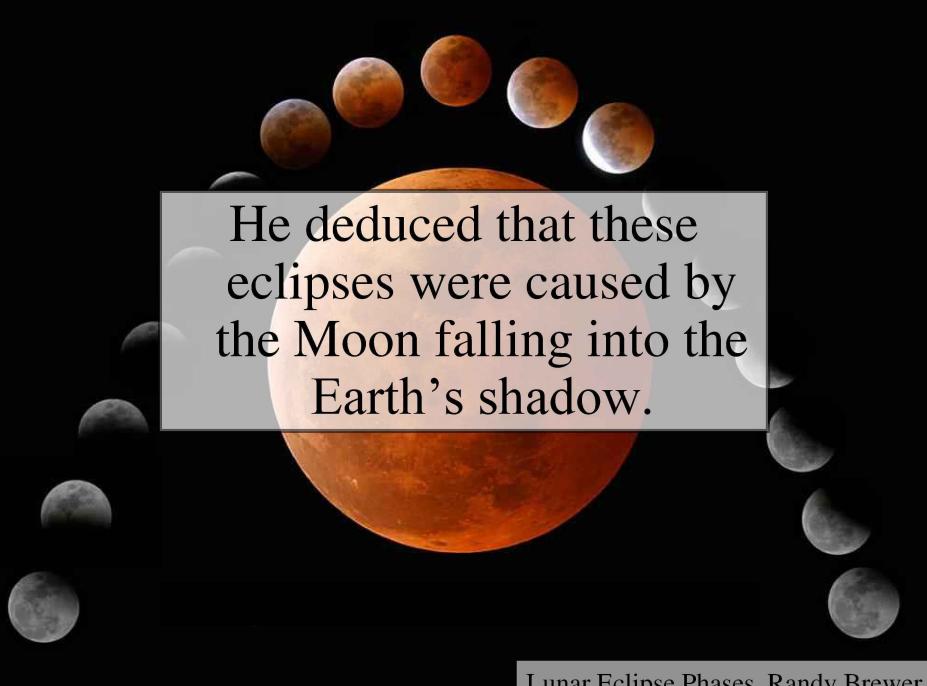


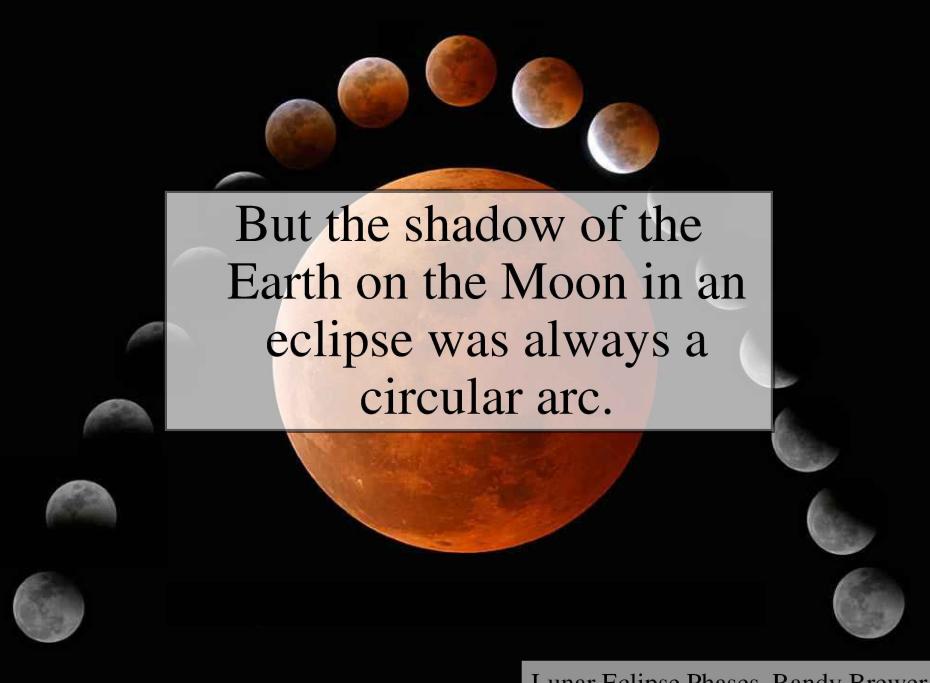


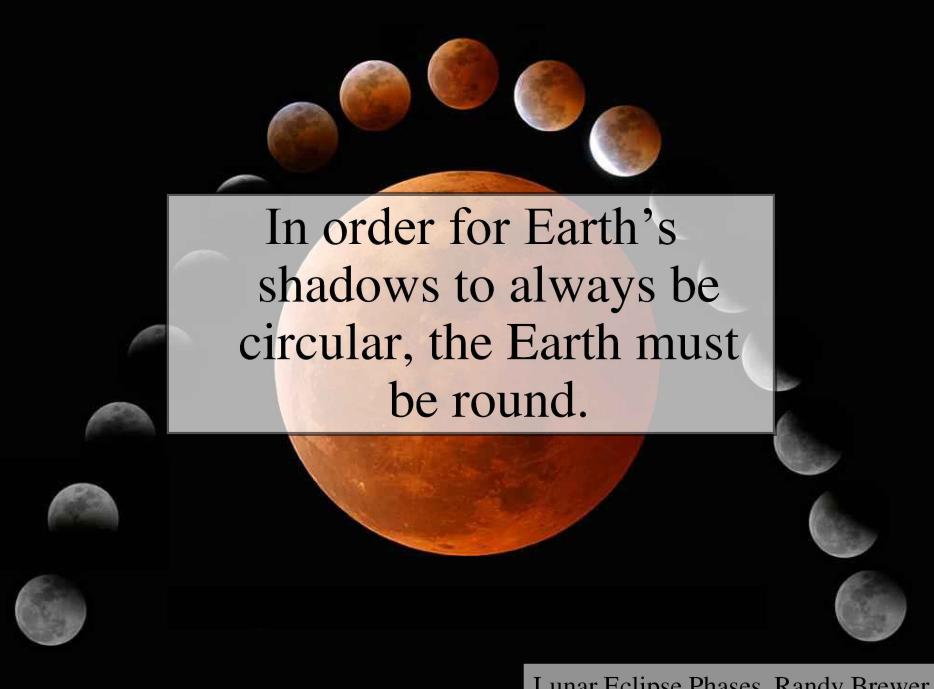


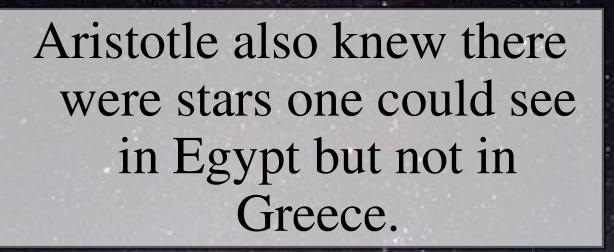




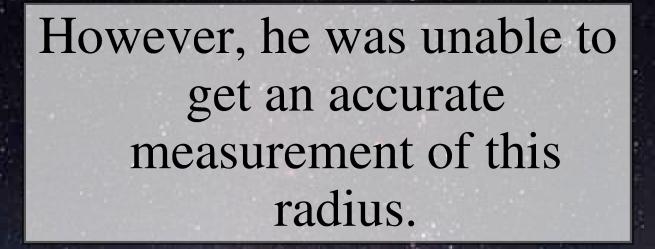


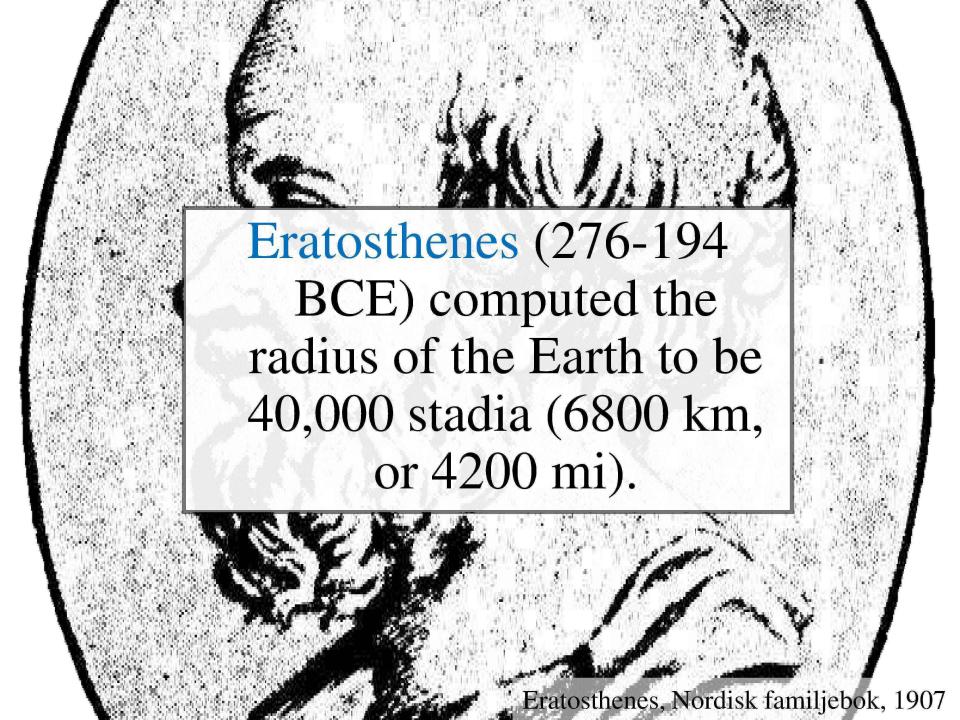


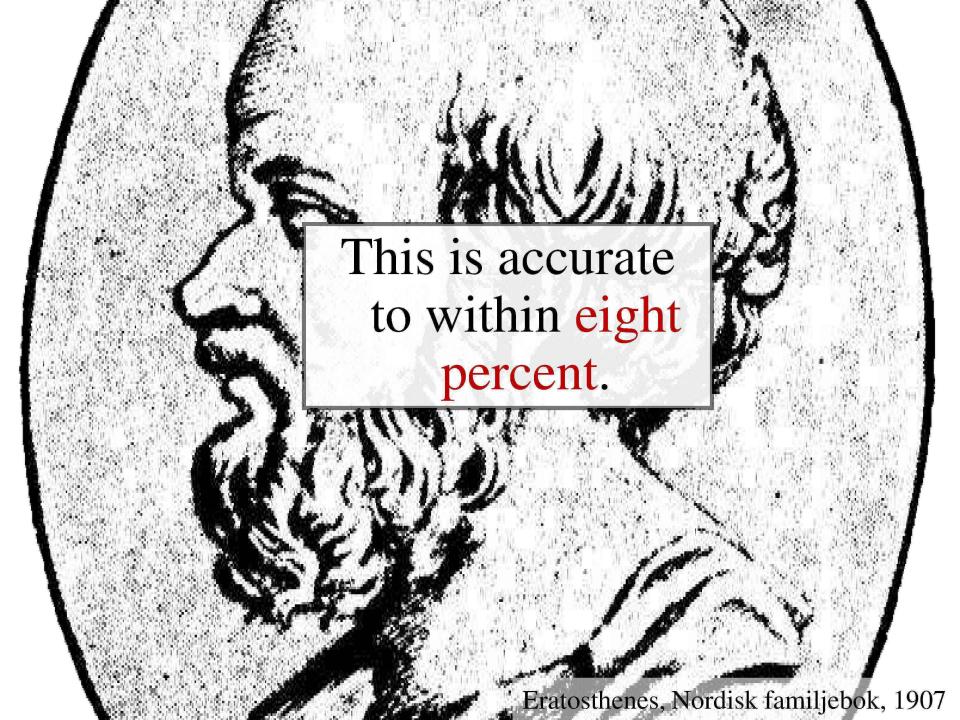


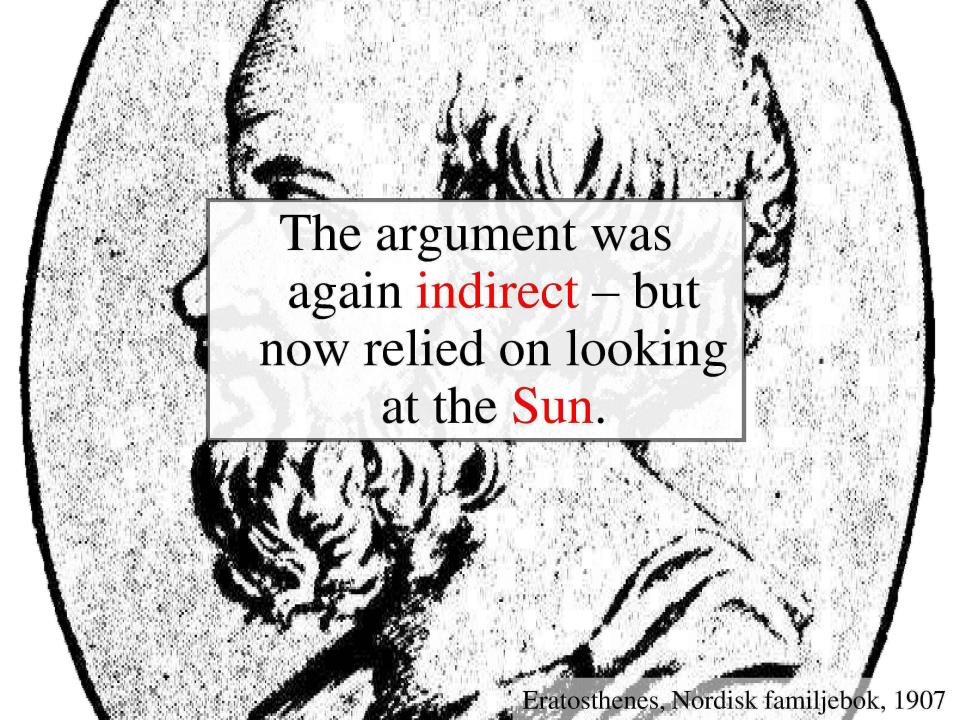


He reasoned that this was due to the curvature of the Earth, so that its radius was finite.









Eratosthenes read of a well in Syene, Egypt which at noon on the summer solstice (June 21) would reflect the overhead sun.



Tropic of Cancer: Swinburne University, COSMOS Encyclopedia of Astronomy





Eratosthenes tried the same experiment in his home city of Alexandria.



But on the solstice, the sun was at an angle and did not reflect from the bottom of the well.



Tropic of Cancer: Swinburne University, COSMOS Encyclopedia of Astronomy

Using a gnomon (measuring stick), Eratosthenes measured the deviation of the sun from the vertical as 7°.



From trade caravans and other sources, Eratosthenes knew Syene to be 5,000 stadia (740 km) south of Alexandria.

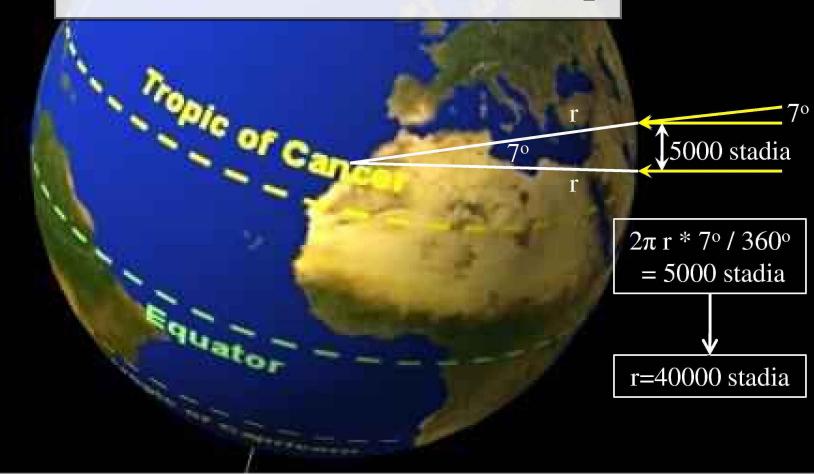


This is enough information to compute the radius of the Earth.



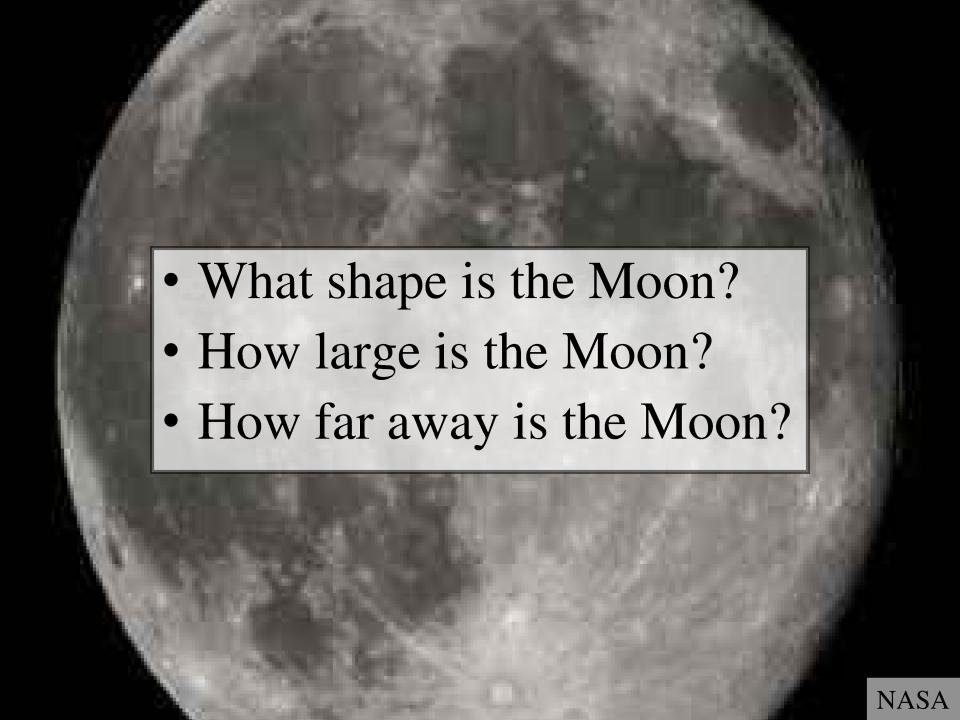
Tropic of Cancer: Swinburne University, COSMOS Encyclopedia of Astronomy

[This assumes that the Sun is quite far away, but more on this later.]

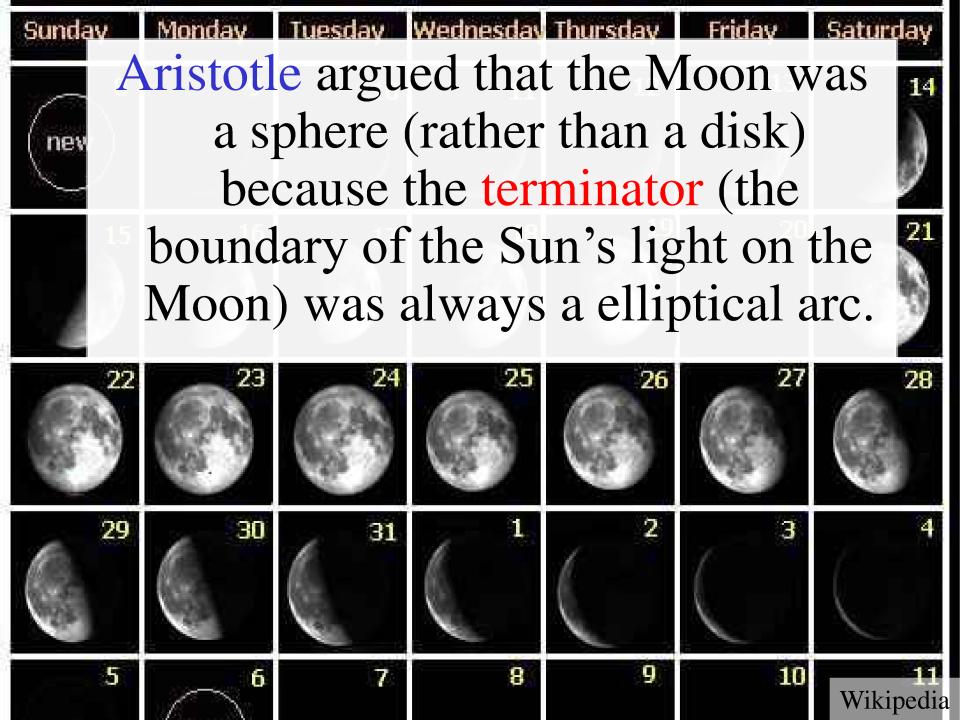


Tropic of Cancer: Swinburne University, COSMOS Encyclopedia of Astronomy









Aristarchus (310-230 BCE) computed the distance of the Earth to the Moon as about 60 Earth radii.

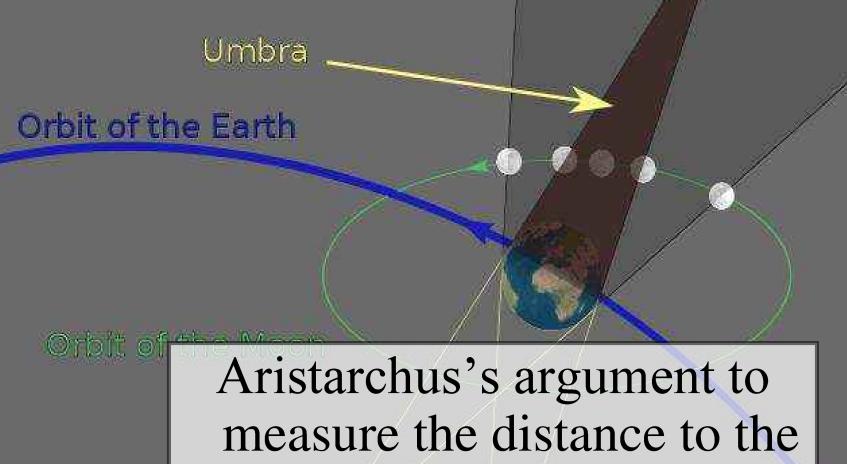
[In truth, it varies from 57 to 63 Earth radii.]

Aristarchus also computed the radius of the Moon as 1/3 the radius of the Earth.

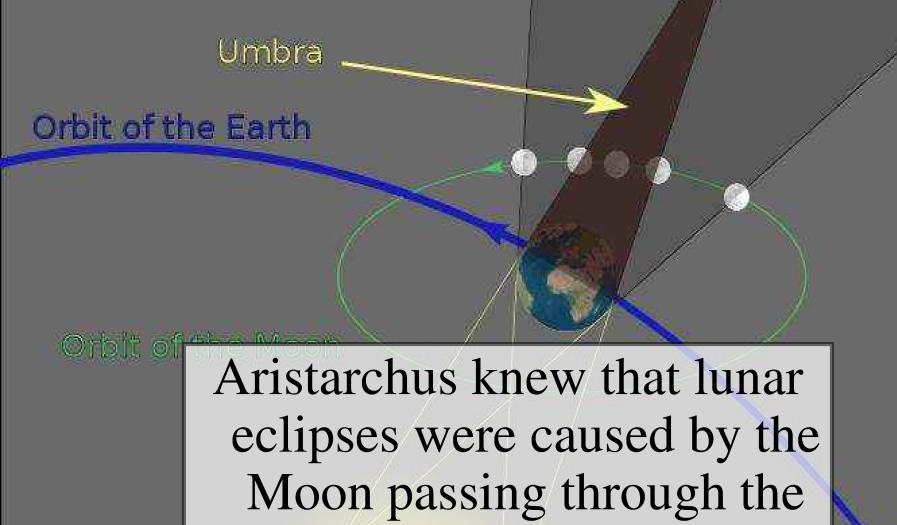
[In truth, it is 0.273 Earth radii.]

The radius of the Earth was computed in the previous rung of the ladder, so we now know the size and location of the Moon.

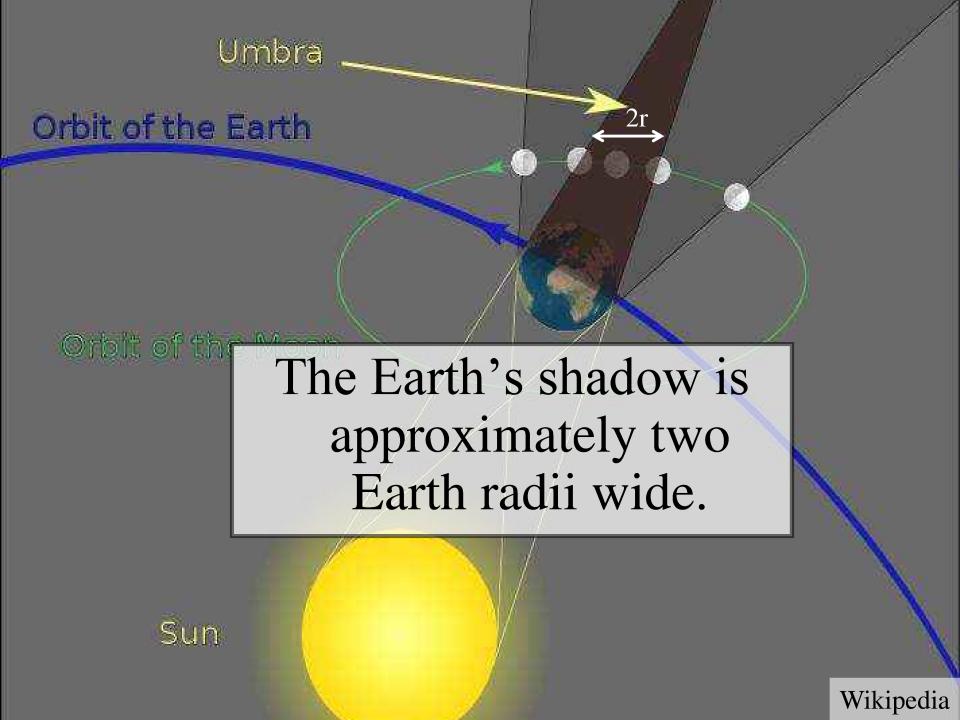
Radius of moon = 0.273 radius of Earth = 1,700 km = 1,100 mi Distance to moon = 60 Earth radii = 384,000 km = 239,000 mi



Moon was indirect, and relied on the Sun.



Earth's shadow.



Umbra

Orbit of the Earth

v = 2r / 3 hours

Orbit of the M

The maximum length of a lunar eclipse is three hours.



v = 2r / 3 hours= $2\pi D / 1 \text{ month}$

Orbit of the

It takes one month for the Moon to go around the Earth.



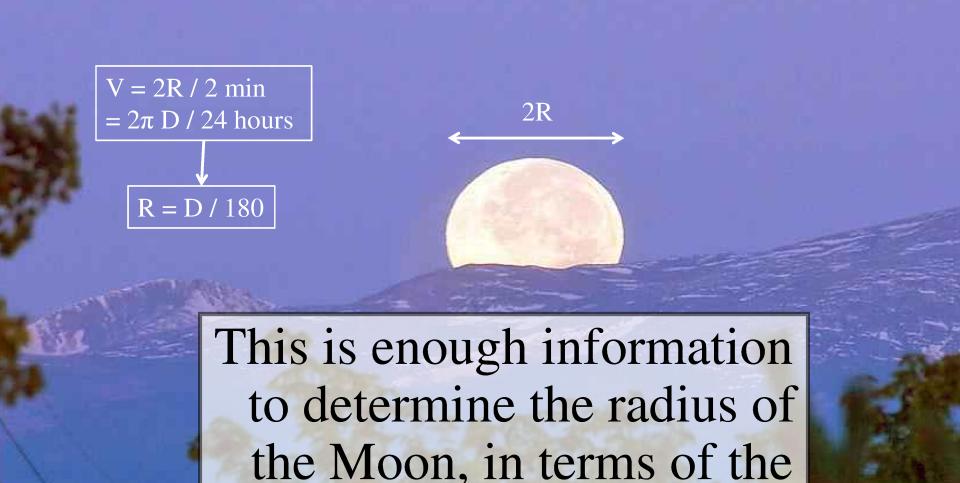
This is enough information to work out the distance to the Moon in Earth radii.

Sun

D = 60 r

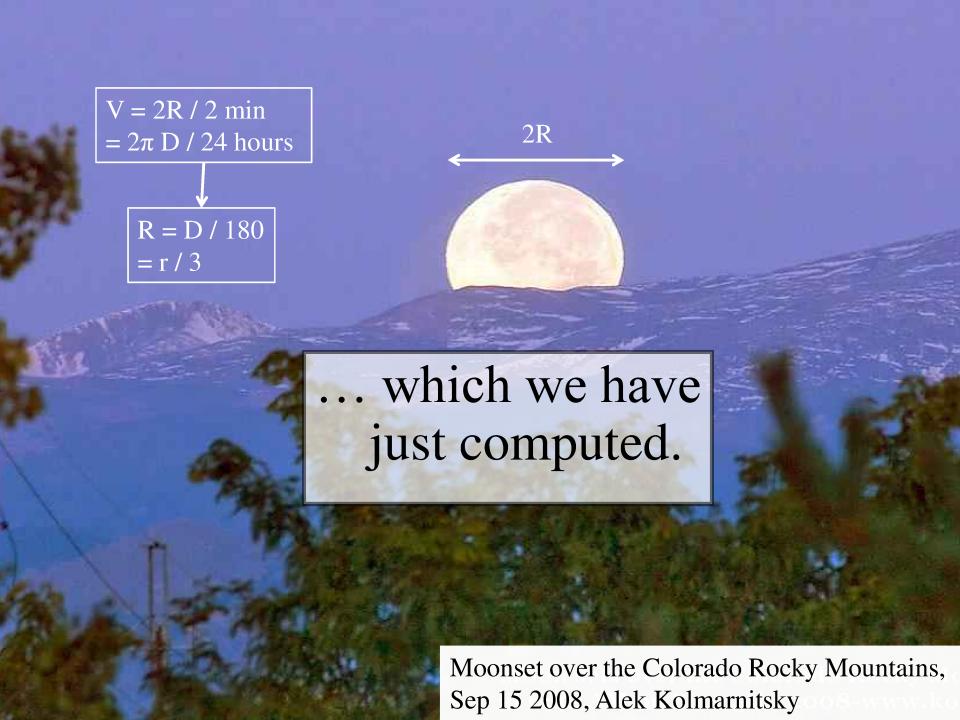


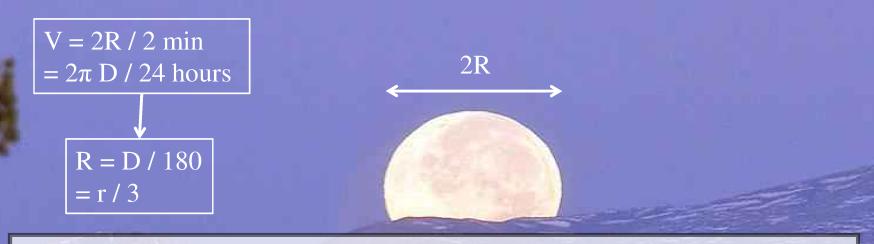




distance to the Moon...

Moonset over the Colorado Rocky Mountains, Sep 15 2008, Alek Kolmarnitsky





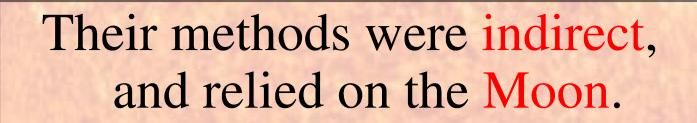
[Aristarchus, by the way, was handicapped by not having an accurate value of π, which had to wait until Archimedes (287-212BCE) some decades later!]

Moonset over the Colorado Rocky Mountains, Sep 15 2008, Alek Kolmarnitsky



- How large is the Sun?
- How far away is the Sun?

Once again, the ancient Greeks could answer these questions (but with imperfect accuracy).



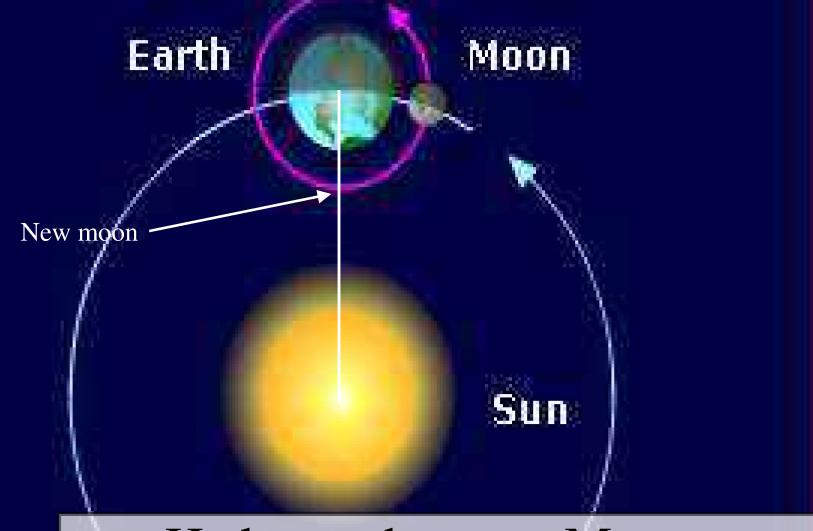
Aristarchus already computed that the radius of the Moon was 1/180 of the distance to the Moon.

He also knew that during a solar eclipse, the Moon covered the Sun almost perfectly.

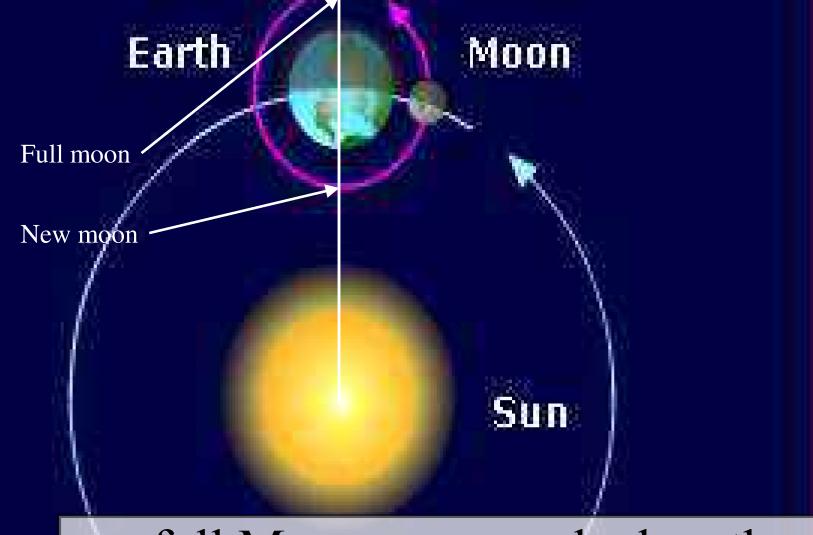
Using similar triangles, he concluded that the radius of the Sun was also 1/180 of the distance to the Sun.



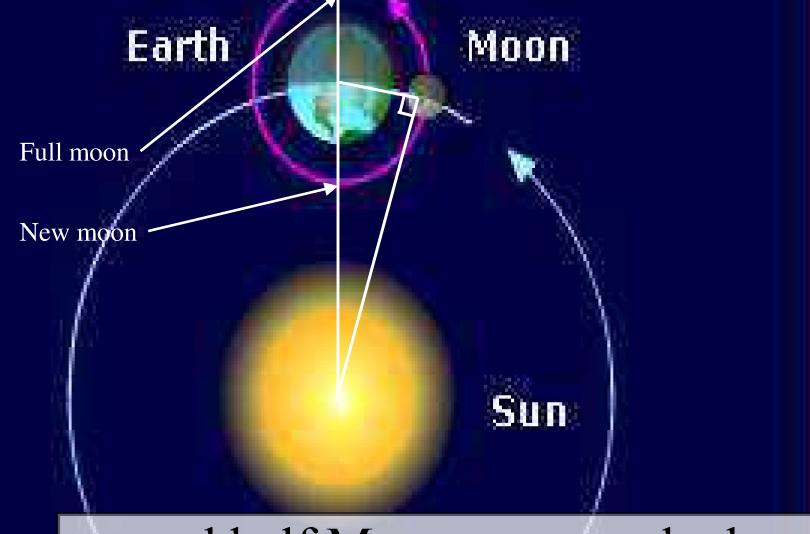




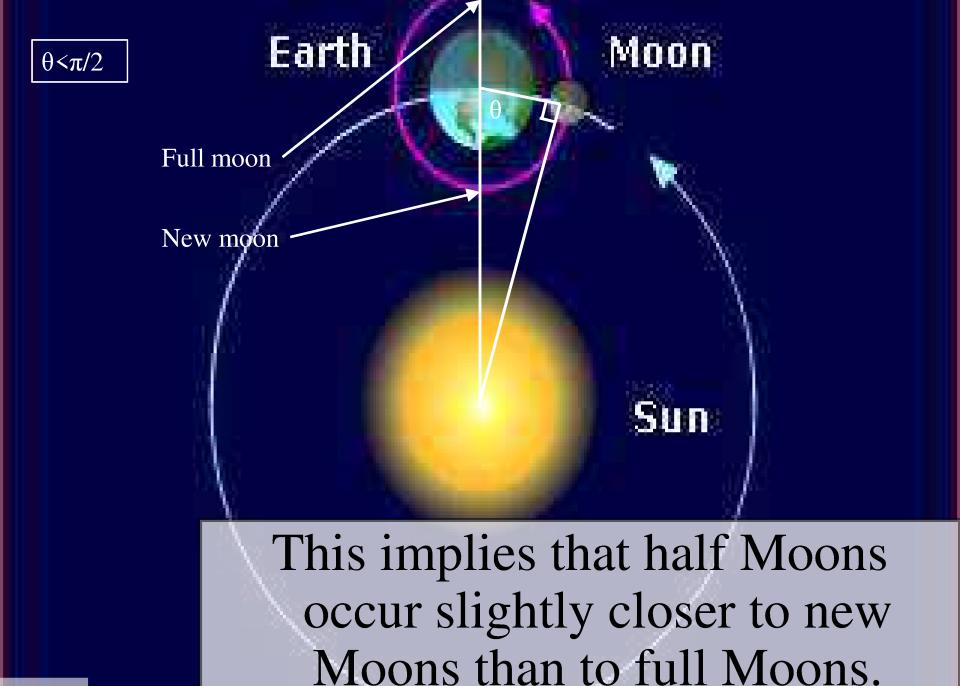
He knew that new Moons occurred when the Moon was between the Earth and Sun...

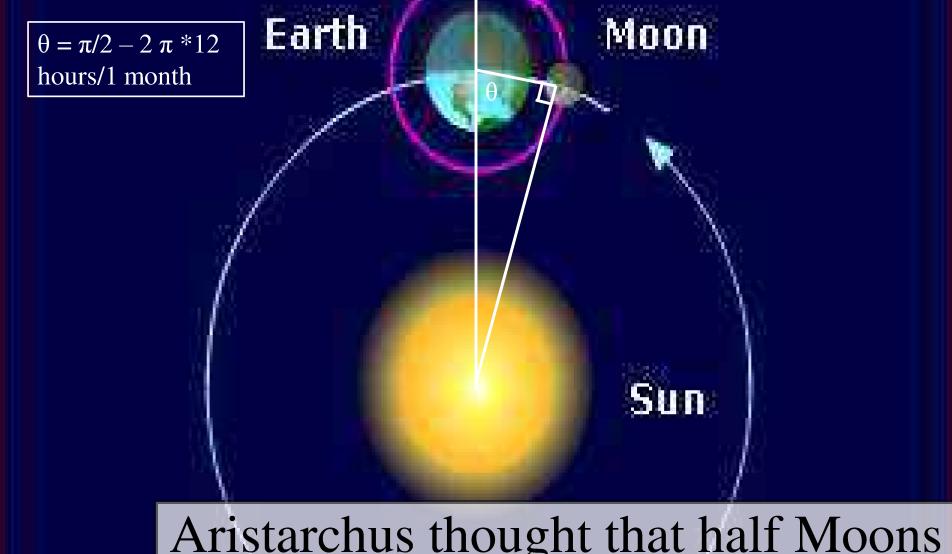


... full Moons occurred when the Moon was directly opposite the Sun...

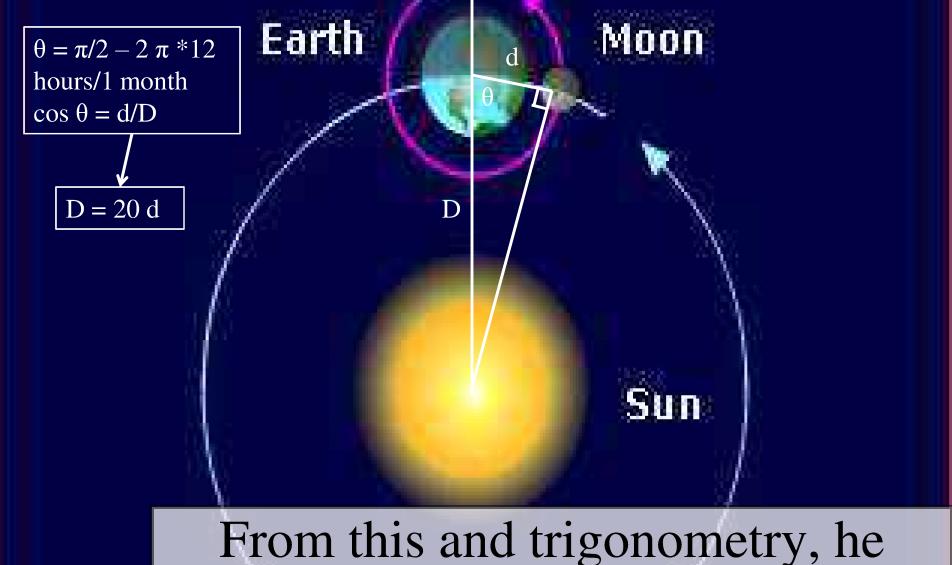


... and half Moons occurred when the Moon made a right angle between Earth and Sun.

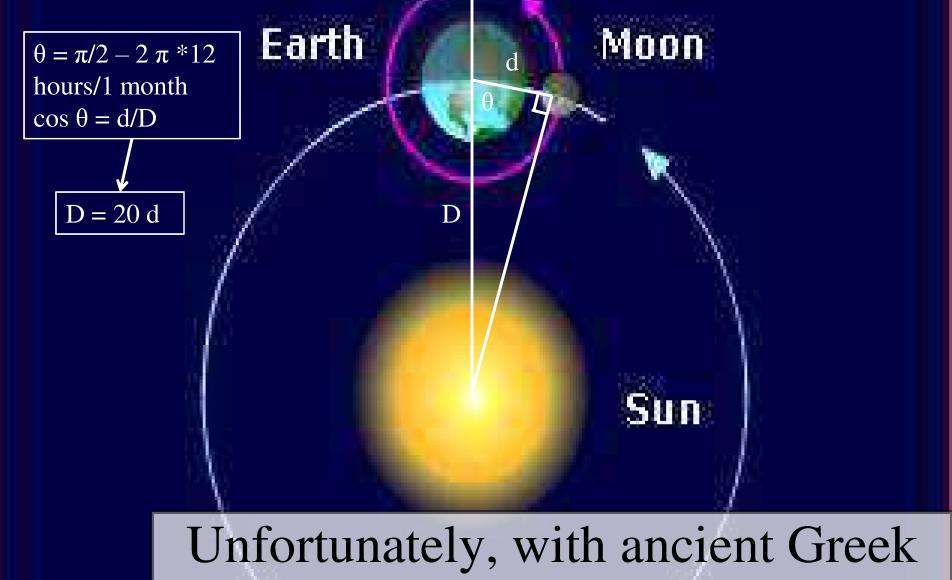




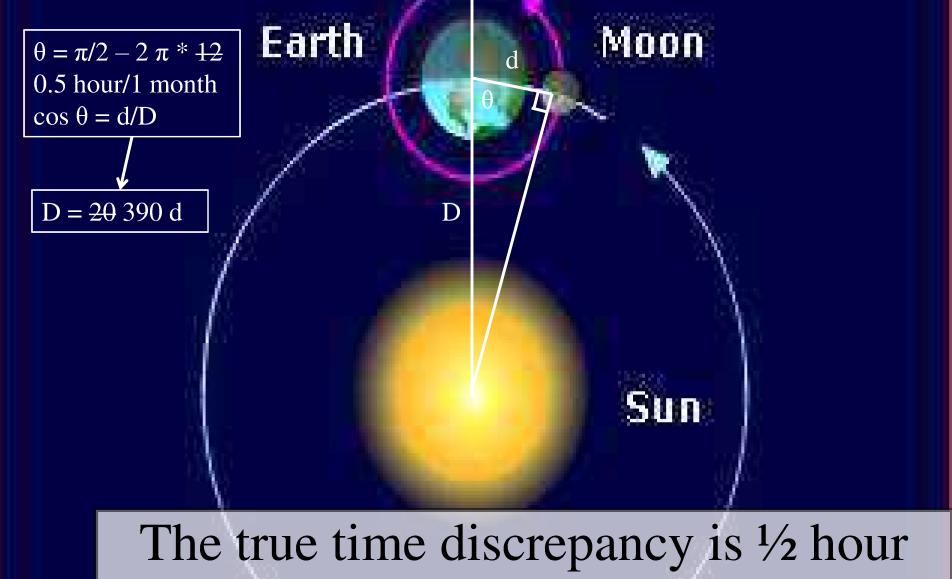
Aristarchus thought that half Moons occurred 12 hours before the midpoint of a new and full Moon.



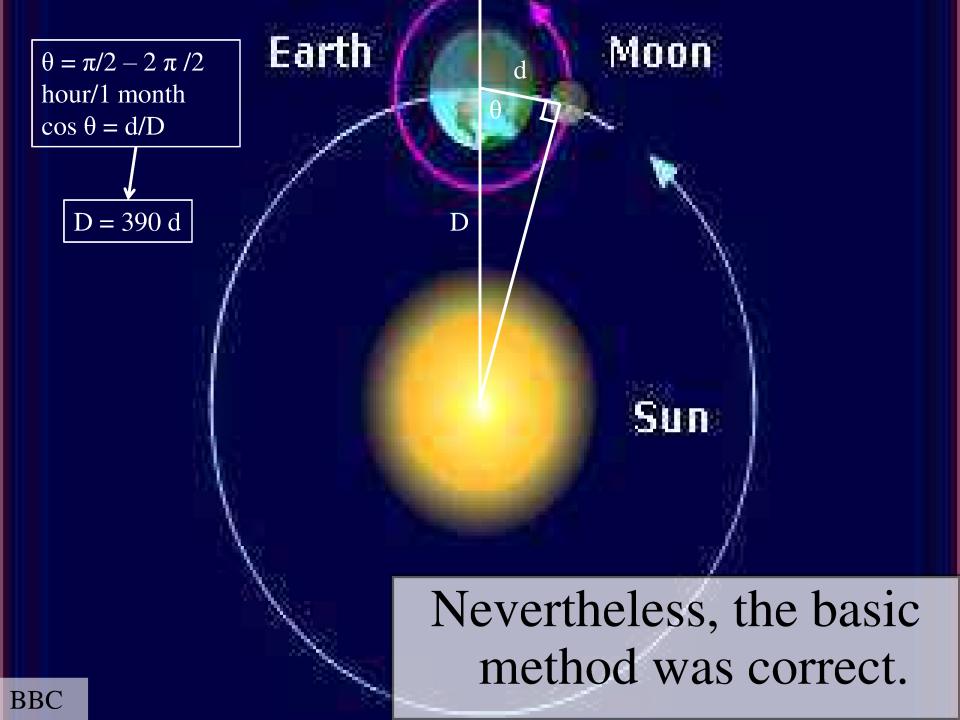
From this and trigonometry, he concluded that the Sun was 20 times further away than the Moon.

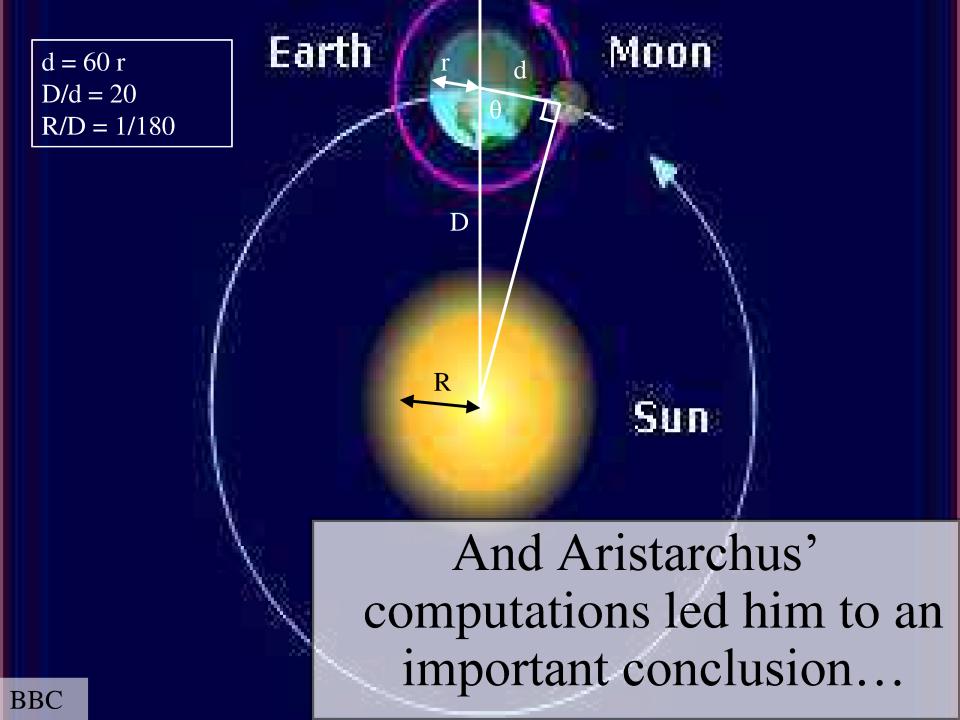


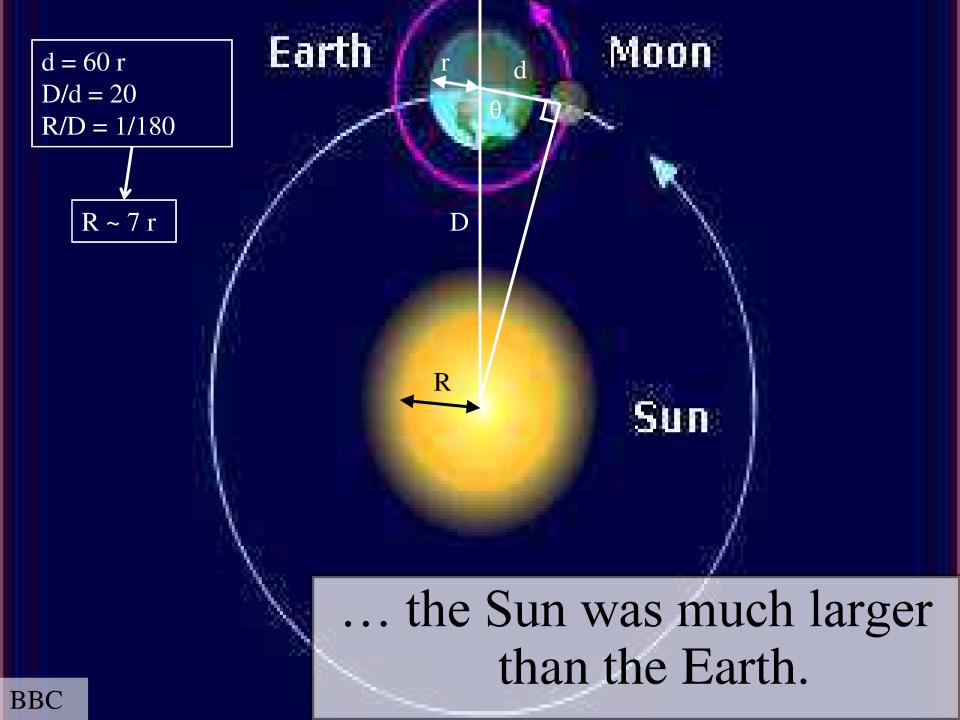
Unfortunately, with ancient Greek technology it was hard to time a new Moon perfectly.

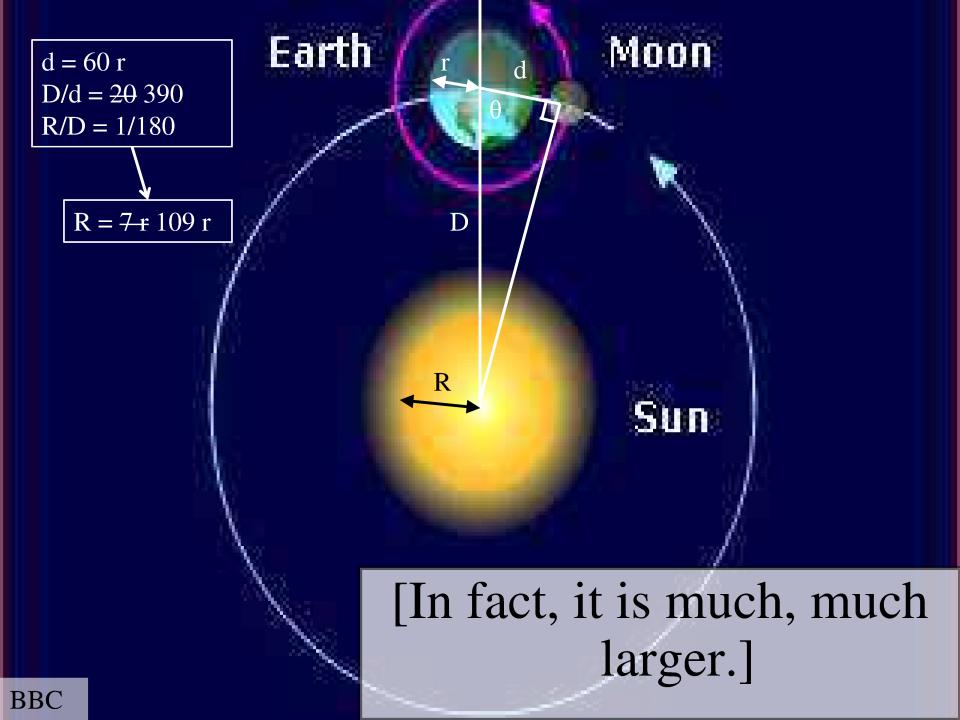


The true time discrepancy is ½ hour (not 12 hours), and the Sun is 390 times further away (not 20 times).









He then concluded it was absurd to think the Sun went around the Earth...

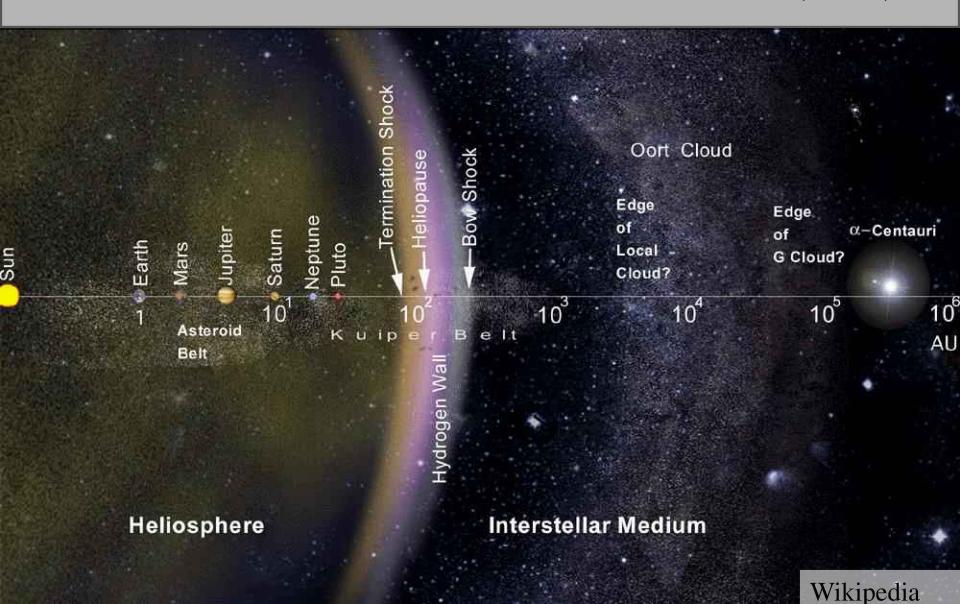
... and was the first to propose the heliocentric model that the Earth went around the Sun.

> [1700 years later, Copernicus would credit Aristarchus for this idea.]

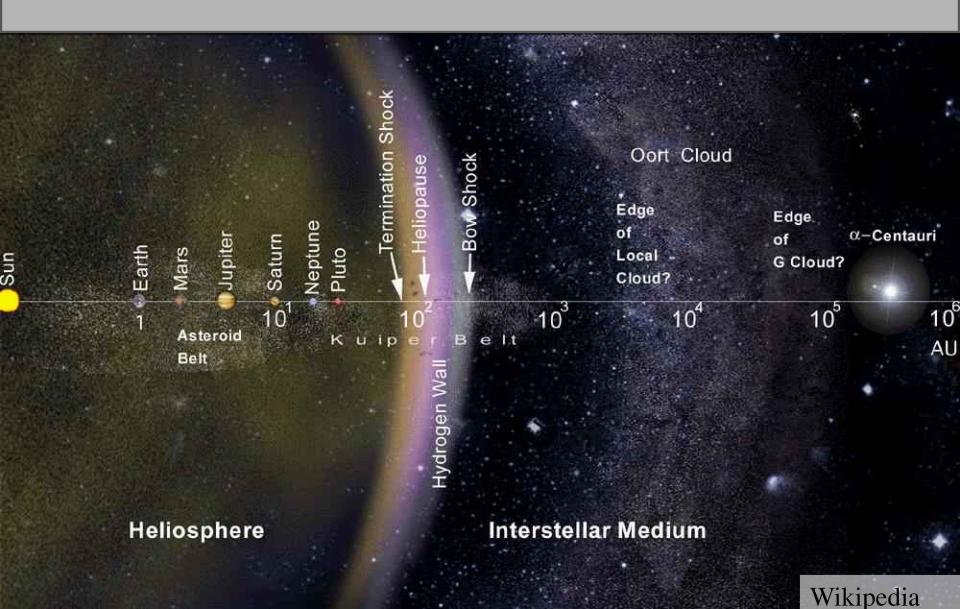
Ironically, Aristarchus' theory was not accepted by the other ancient Greeks...

... but we'll explain why later.

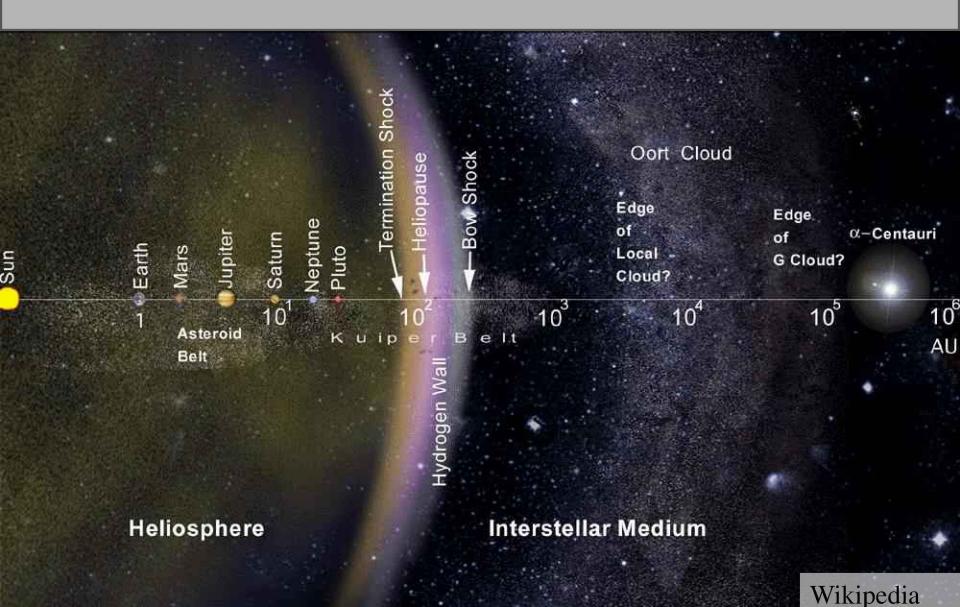
The distance from the Earth to the Sun is known as the Astronomical Unit (AU).



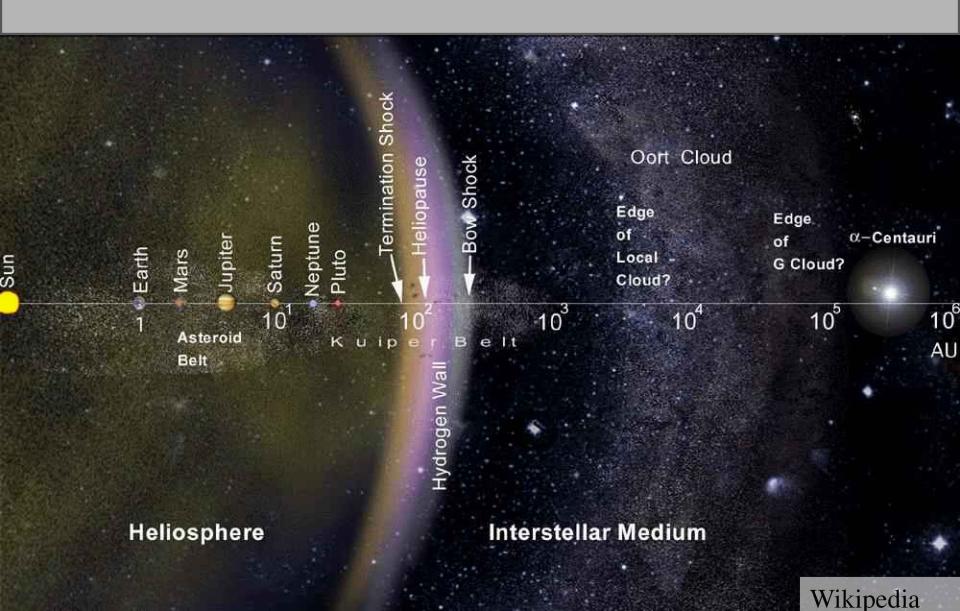
It is an extremely important rung in the cosmic distance ladder.

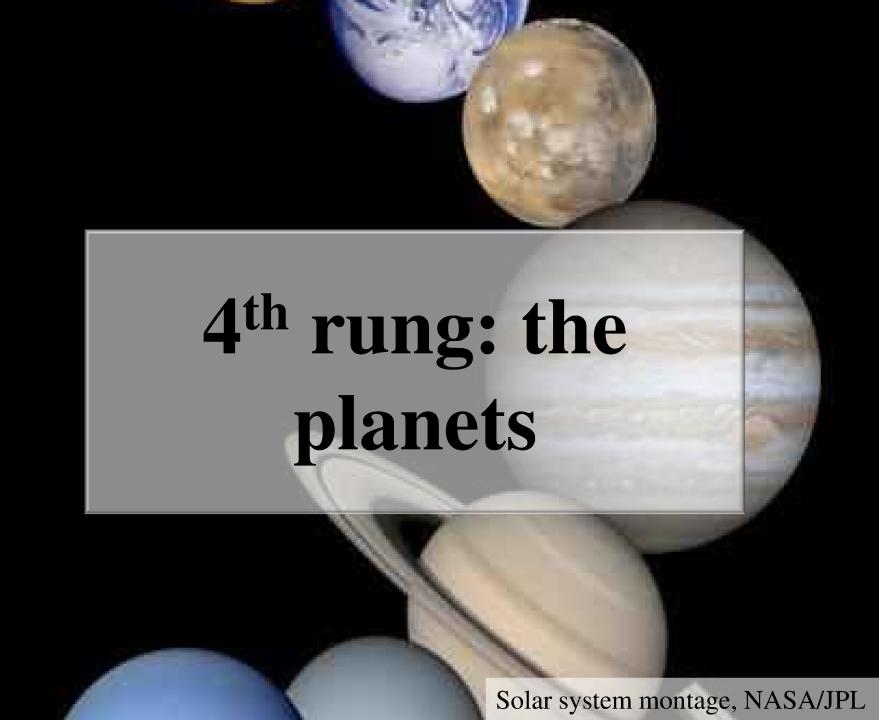


Aristarchus' original estimate of the AU was inaccurate...



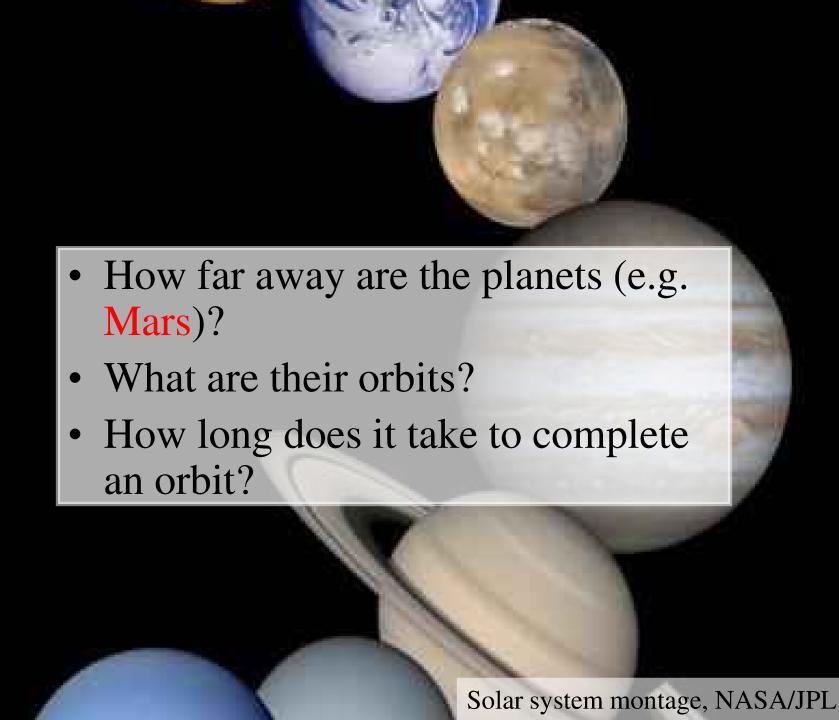
... but we'll see much more accurate ways to measure the AU later on.







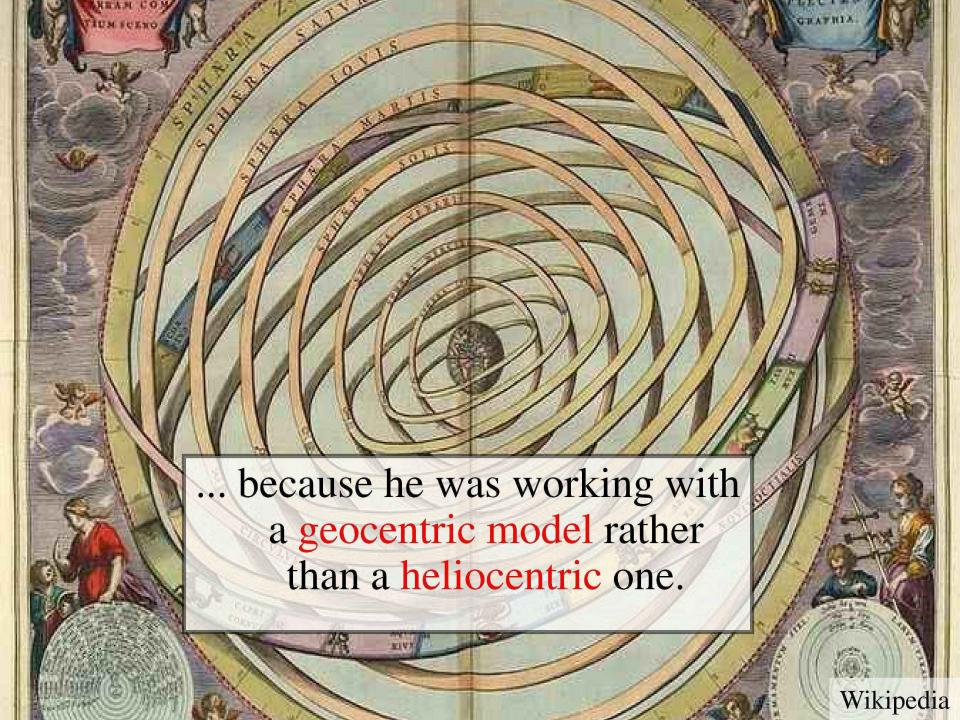


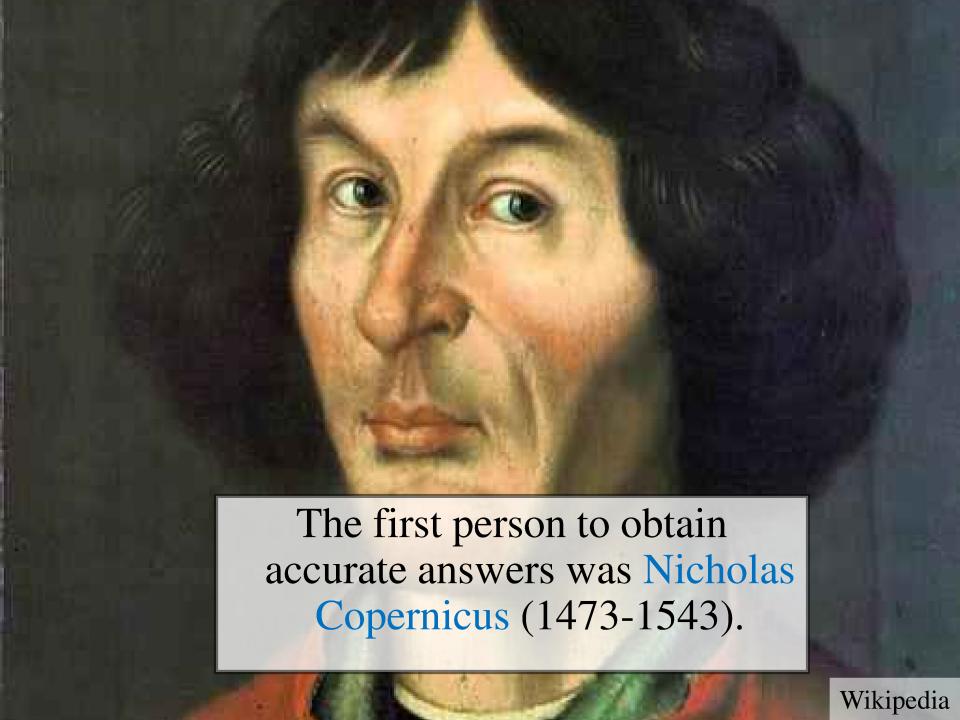


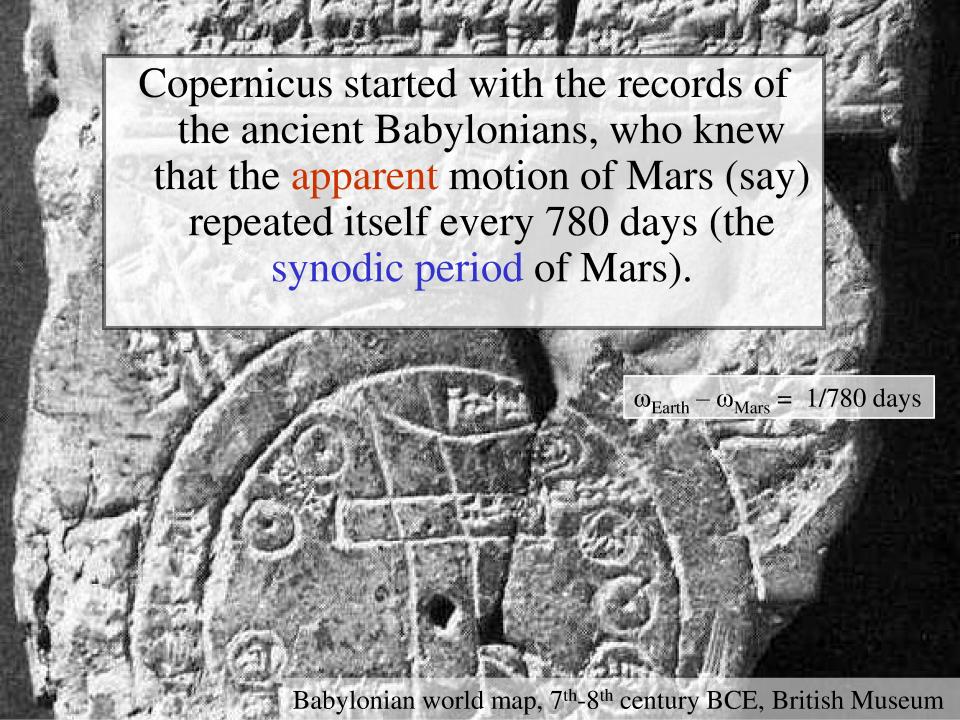


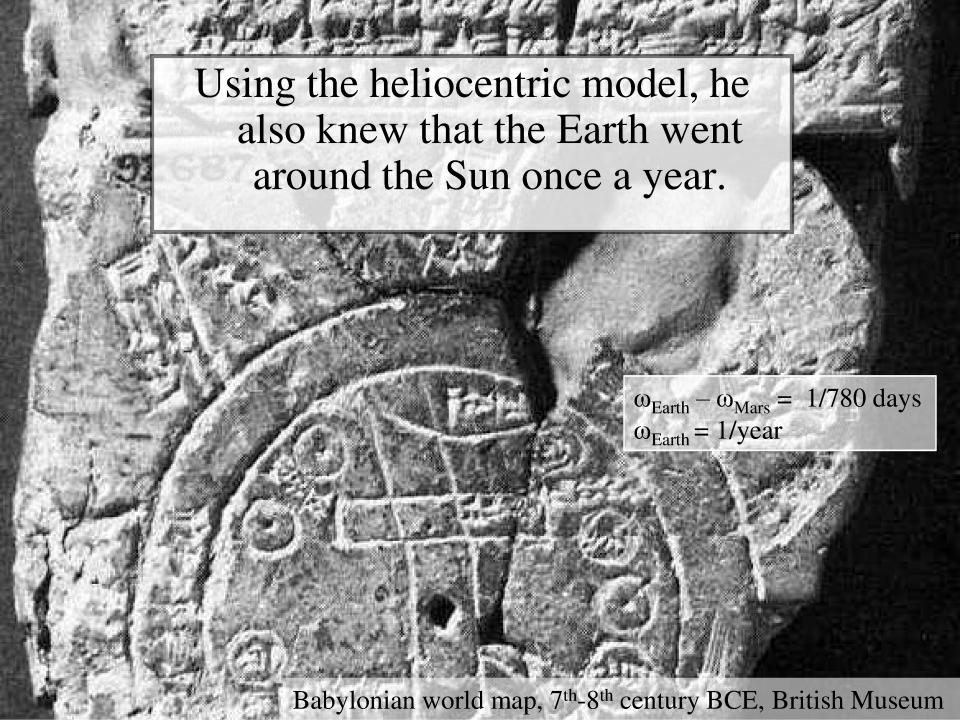
Ptolemy (90-168 CE) attempted to answer these questions, but obtained highly inaccurate answers...

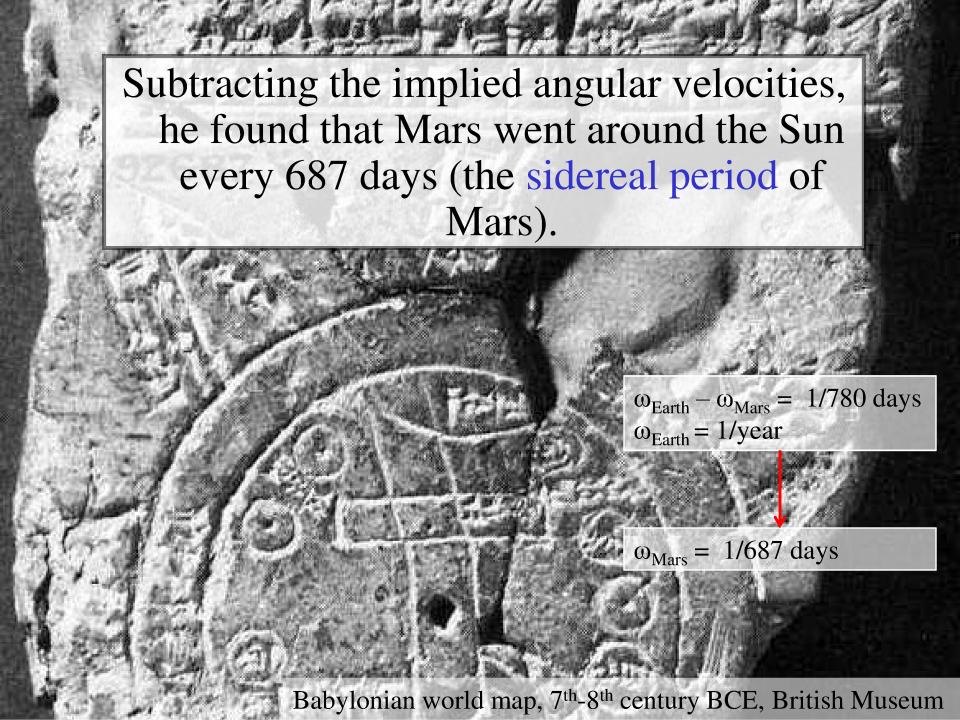


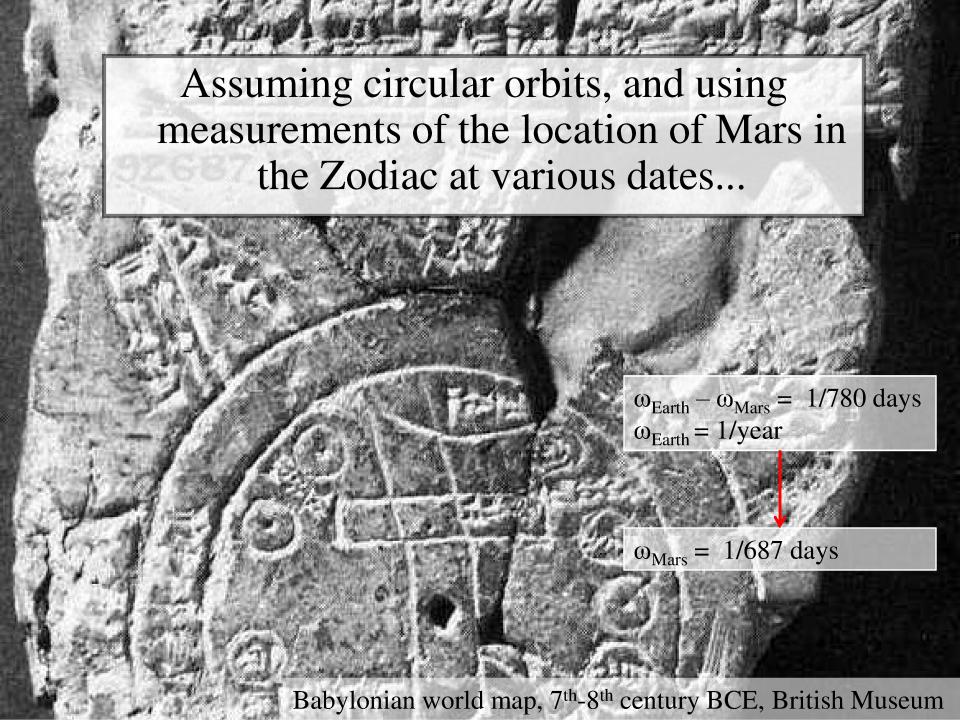


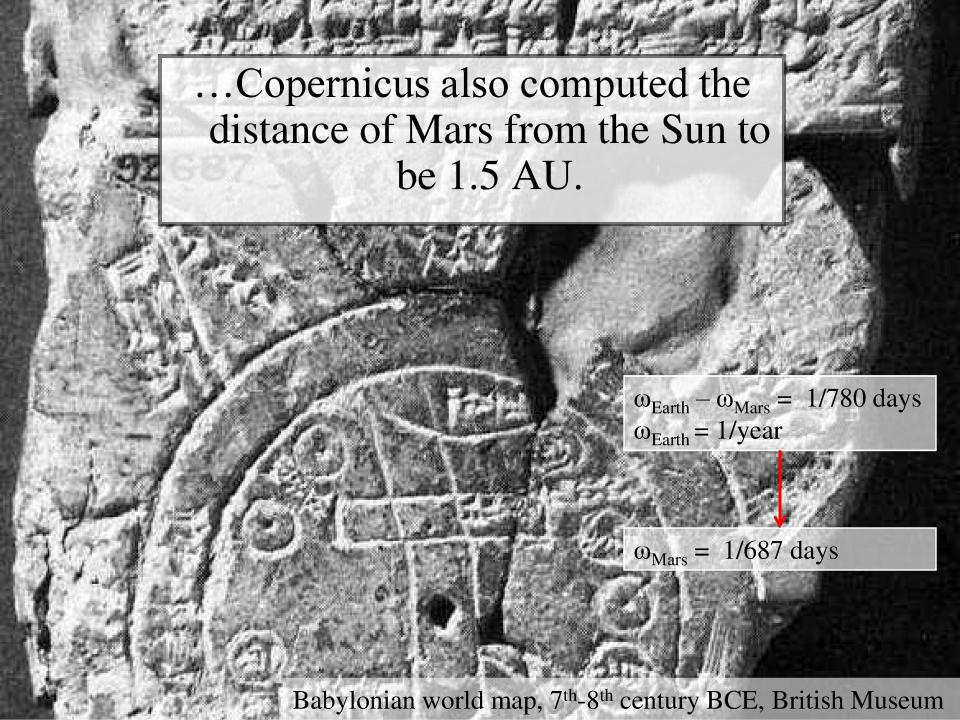


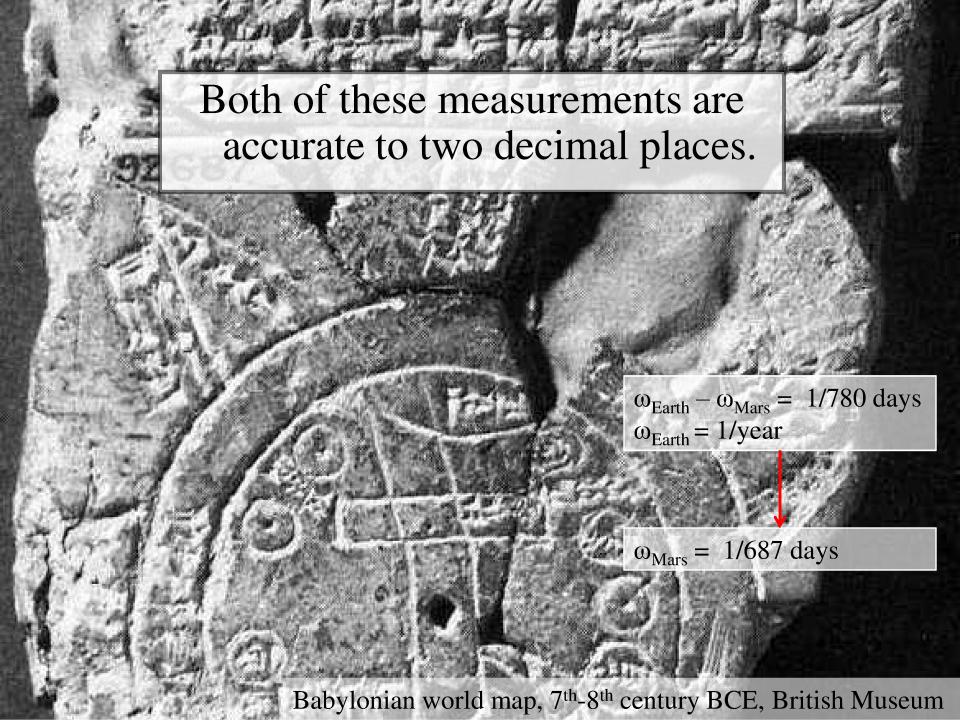


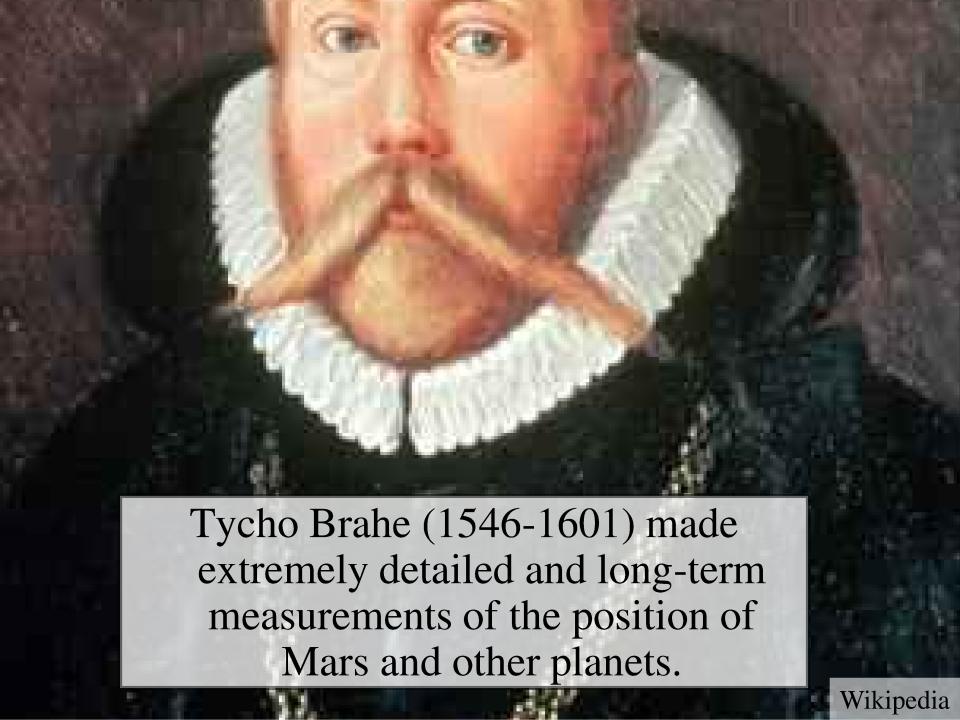






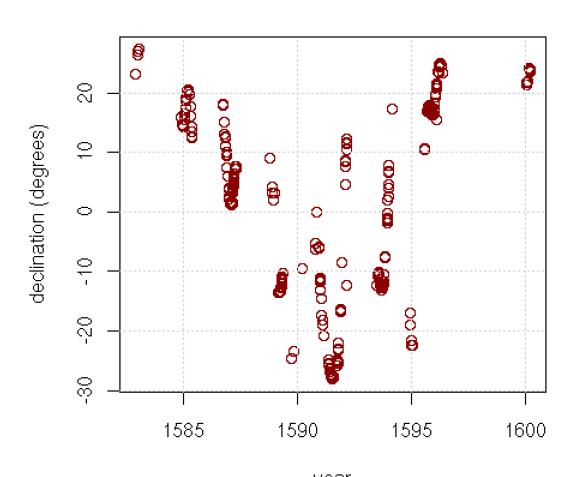






Unfortunately, his data deviated slightly from the predictions of the Copernican model.

Tycho Brahe's Mars Observations

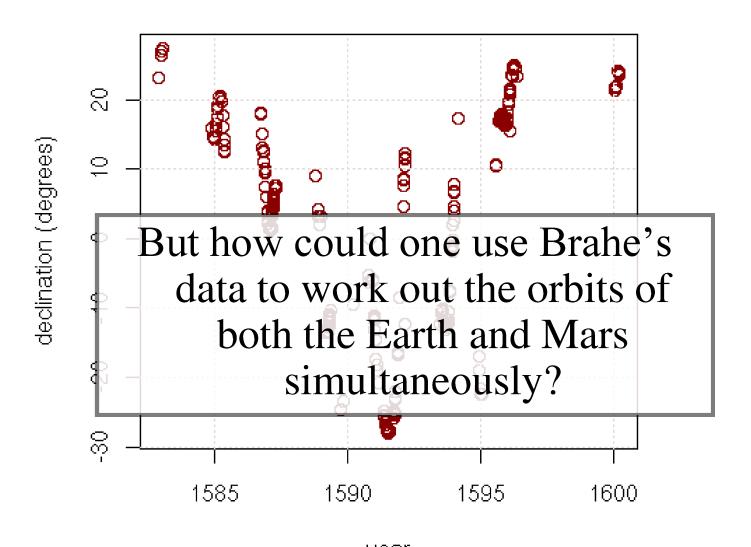


year source: Tychonis Brahe Dani Opera Omnia

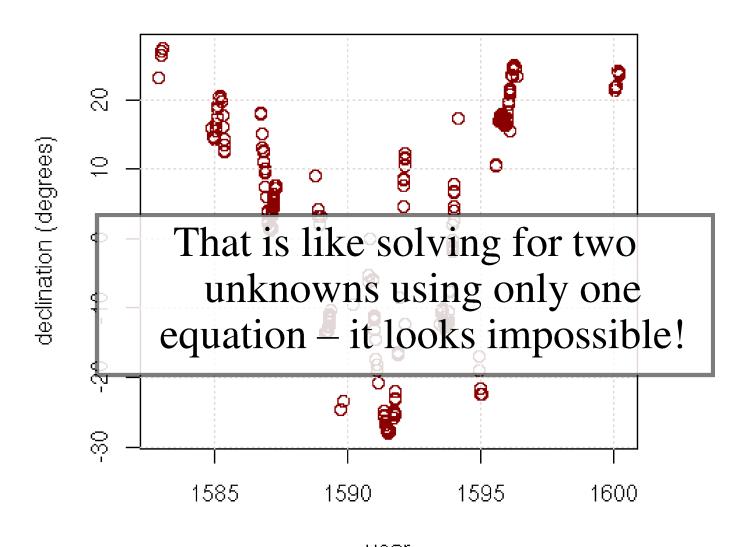


Johannes Kepler (1571-1630) reasoned that this was because the orbits of the Earth and Mars were not quite circular.

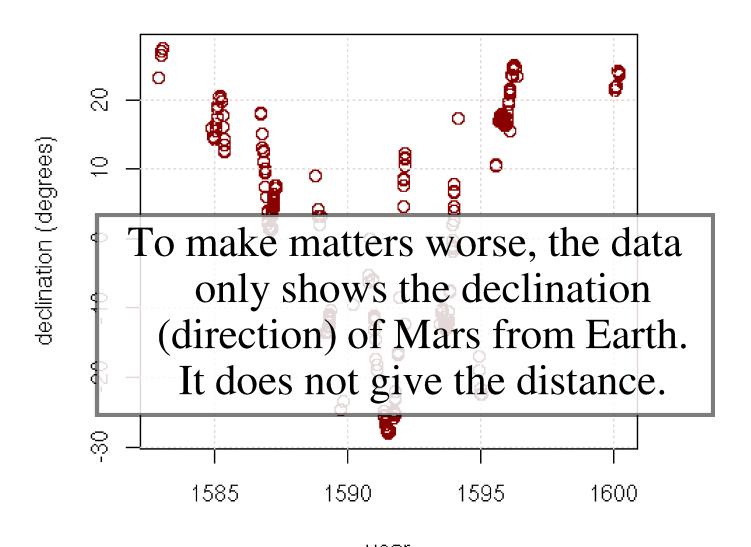




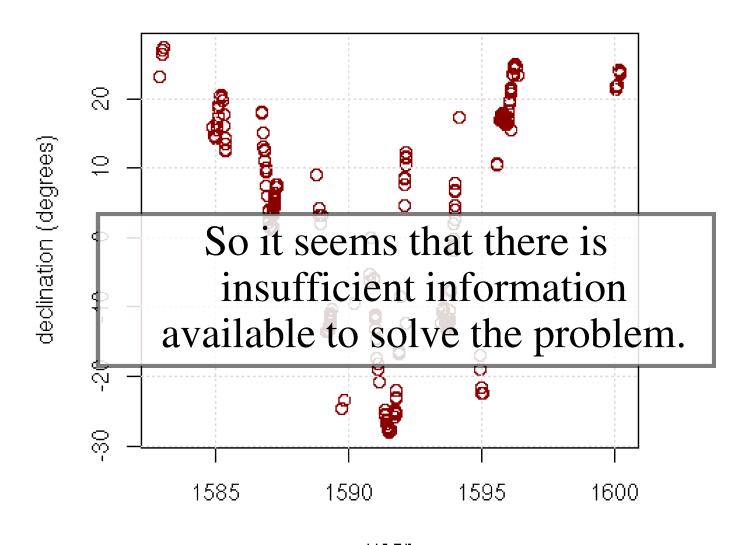
year source: Tychonis Brahe Dani Opera Omnia



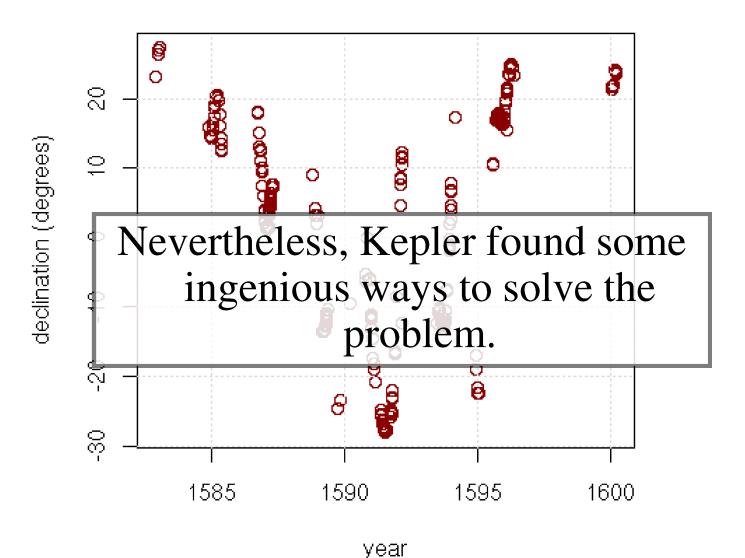
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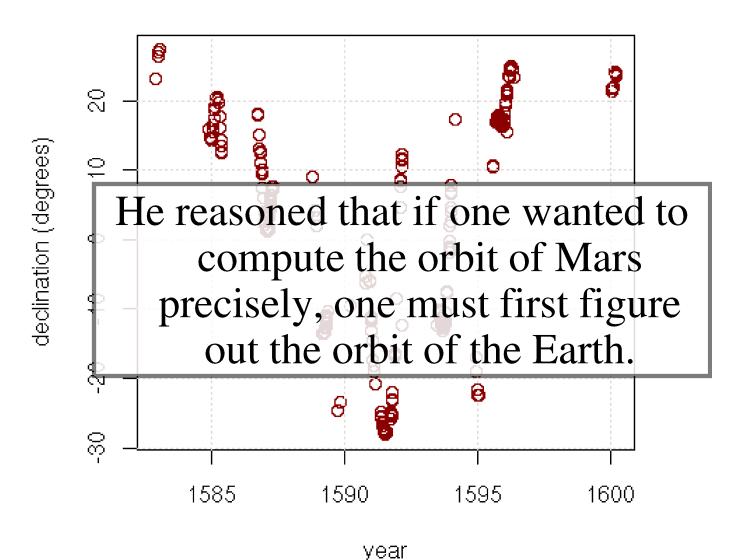
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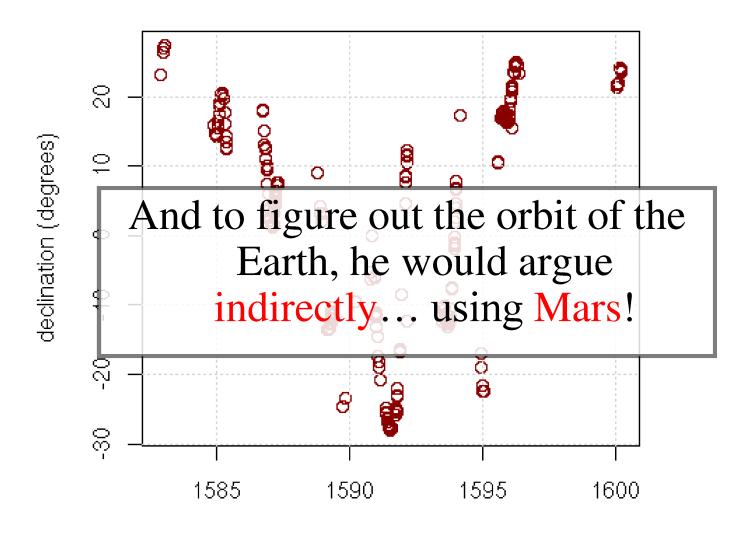
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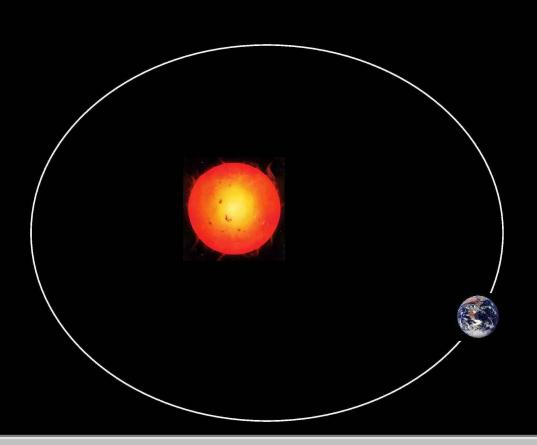
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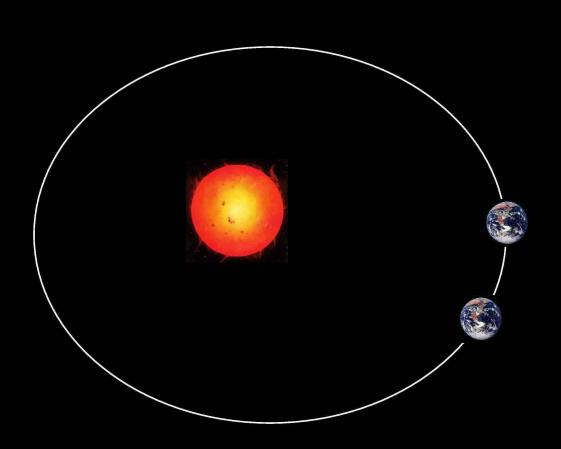
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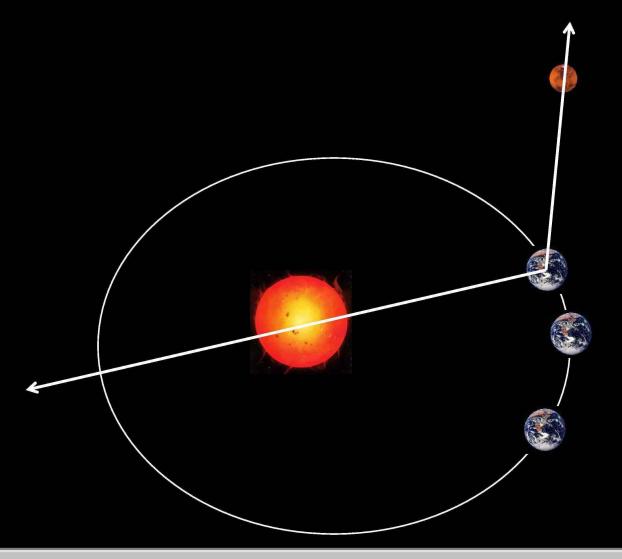
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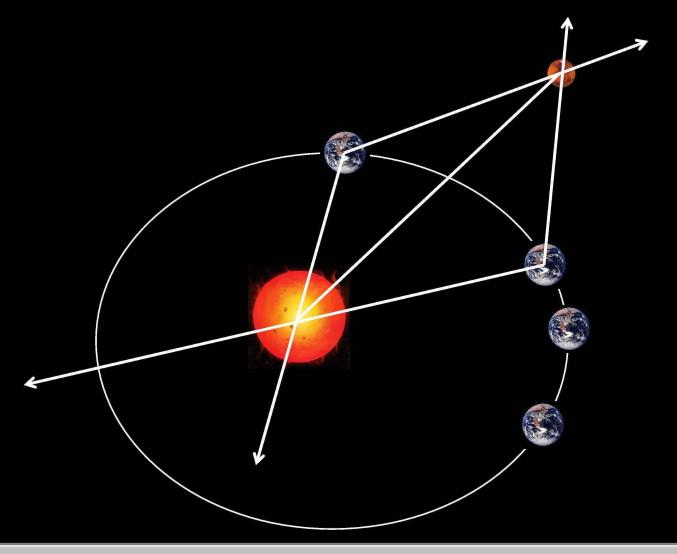
To explain how this works, let's first suppose that Mars is fixed, rather than orbiting the Sun.



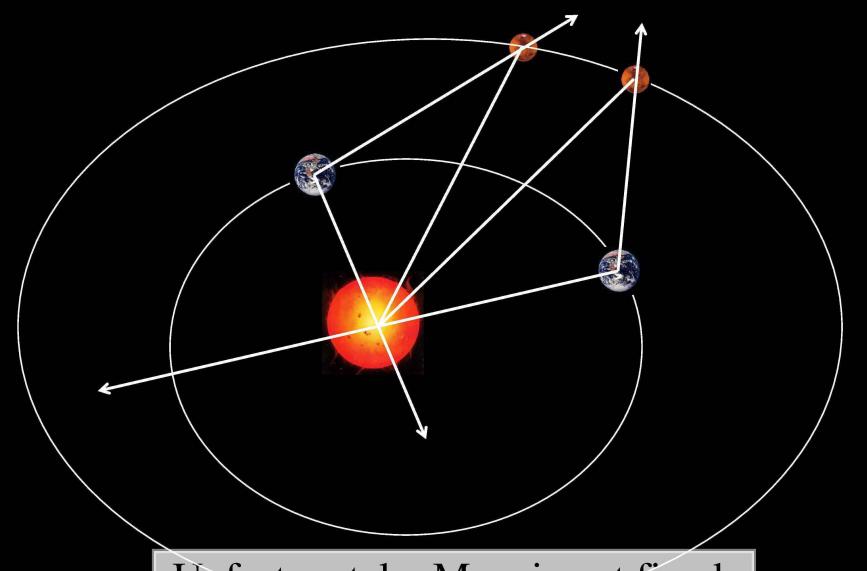
But the Earth is moving in an unknown orbit.



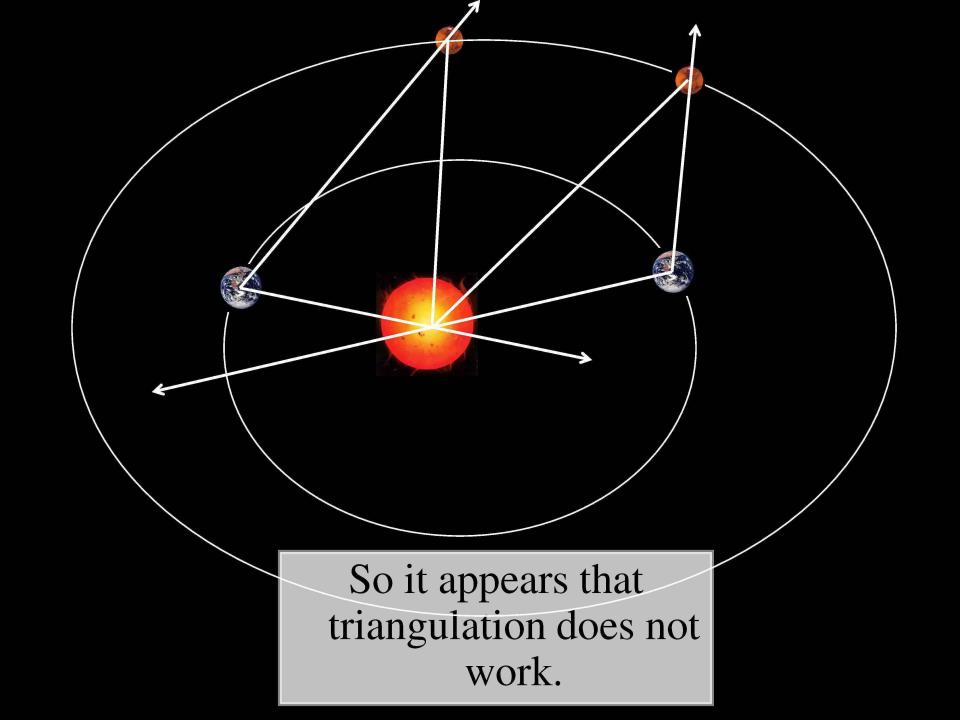
At any given time, one can measure the position of the Sun and Mars from Earth, with respect to the fixed stars (the Zodiac).

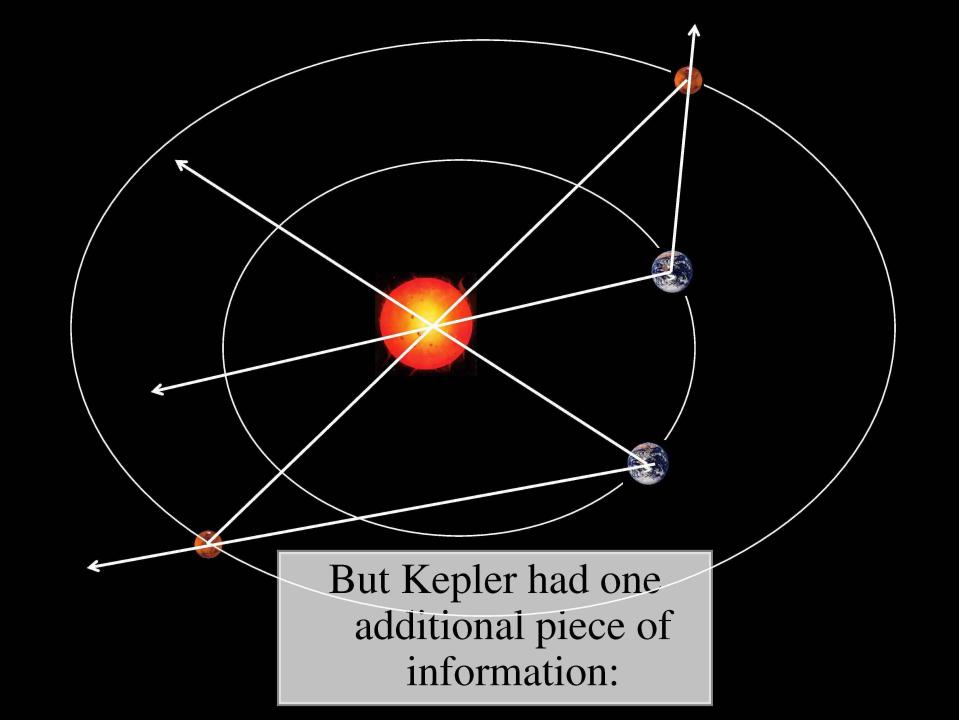


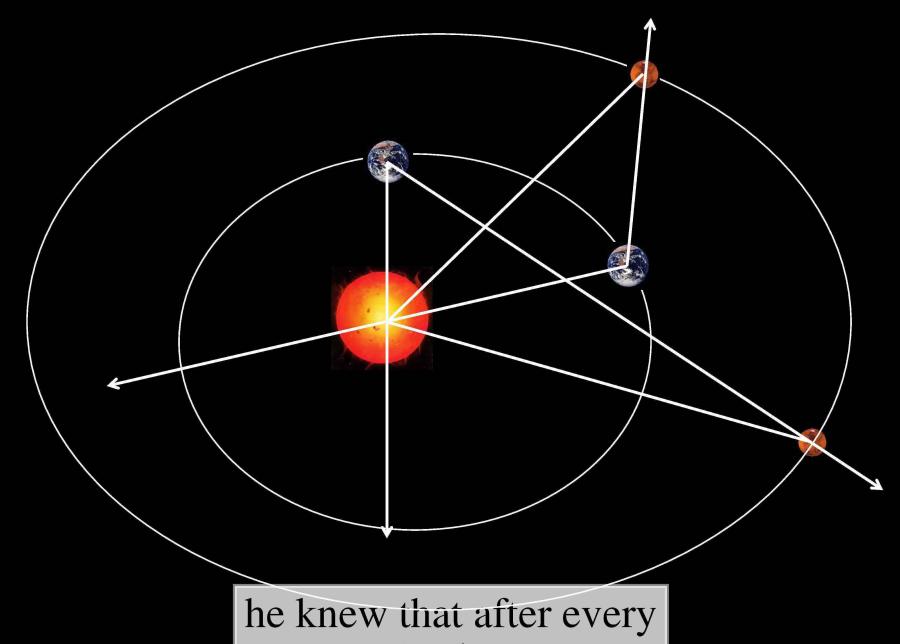
Assuming that the Sun and Mars are fixed, one can then triangulate to determine the position of the Earth relative to the Sun and Mars.



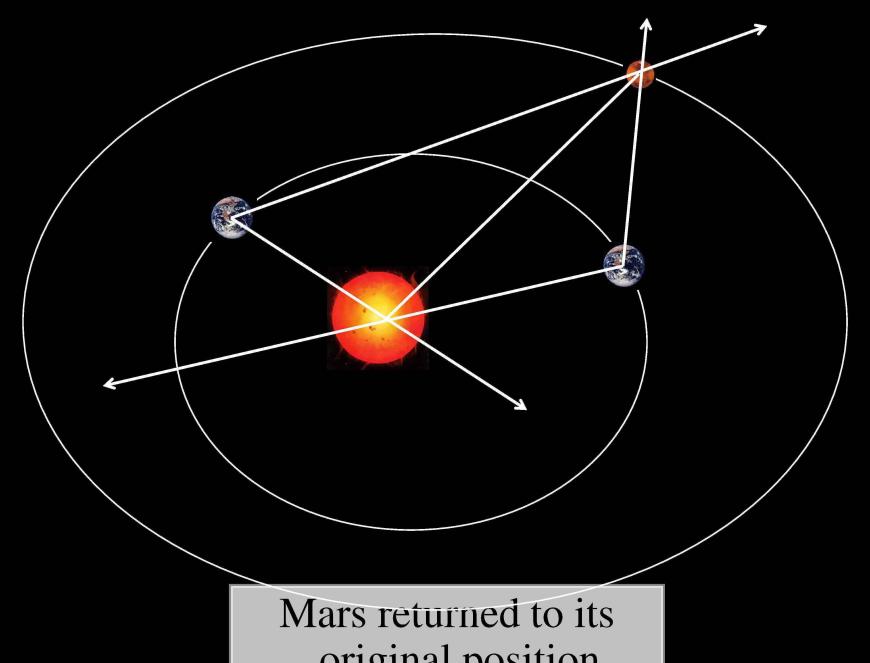
Unfortunately, Mars is not fixed; it also moves, and along an unknown orbit.



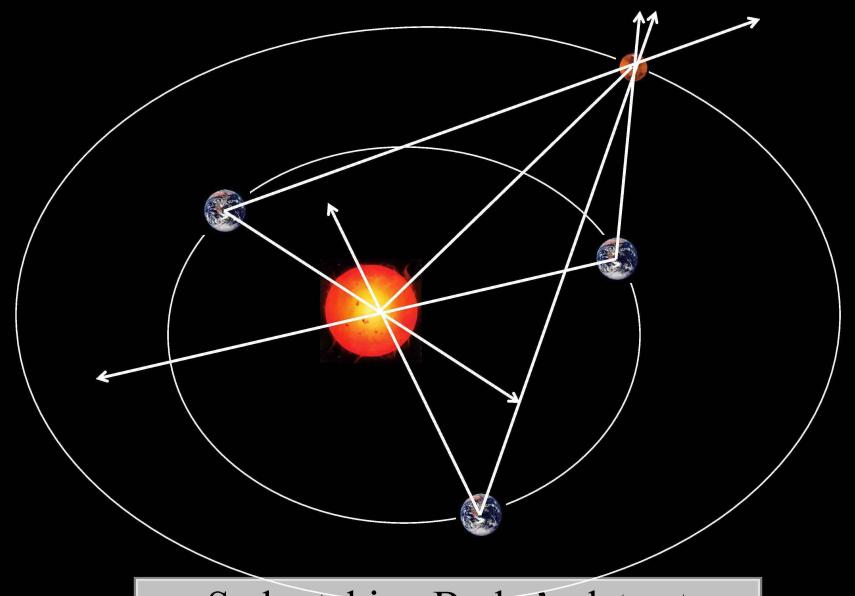




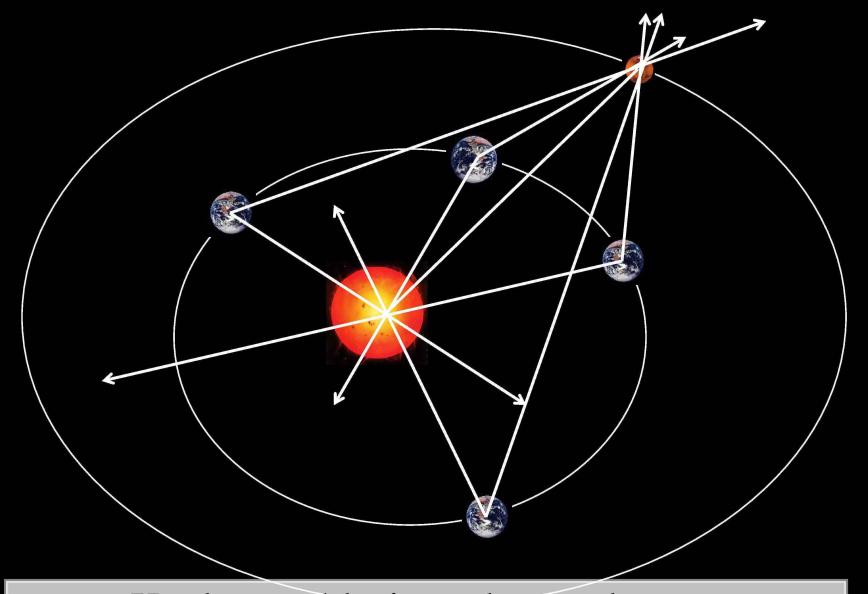
687 days...



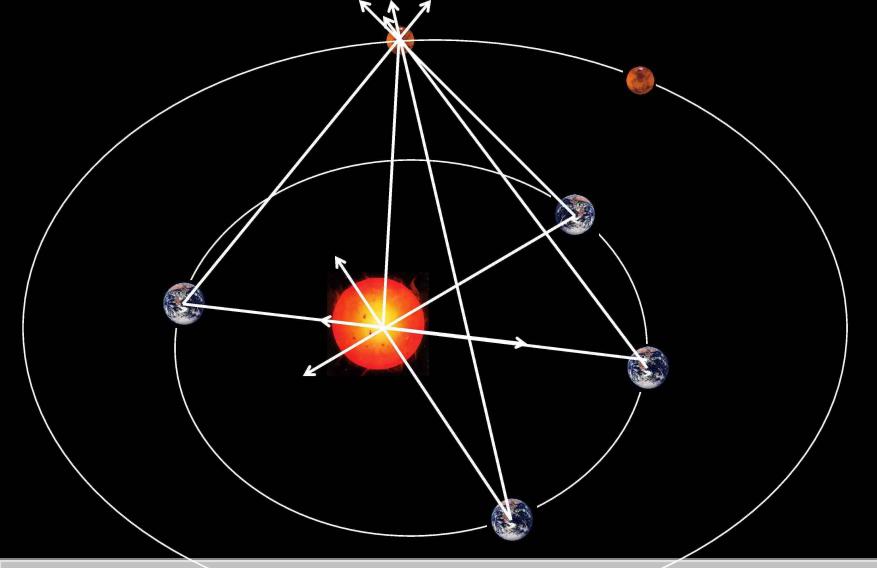
original position.



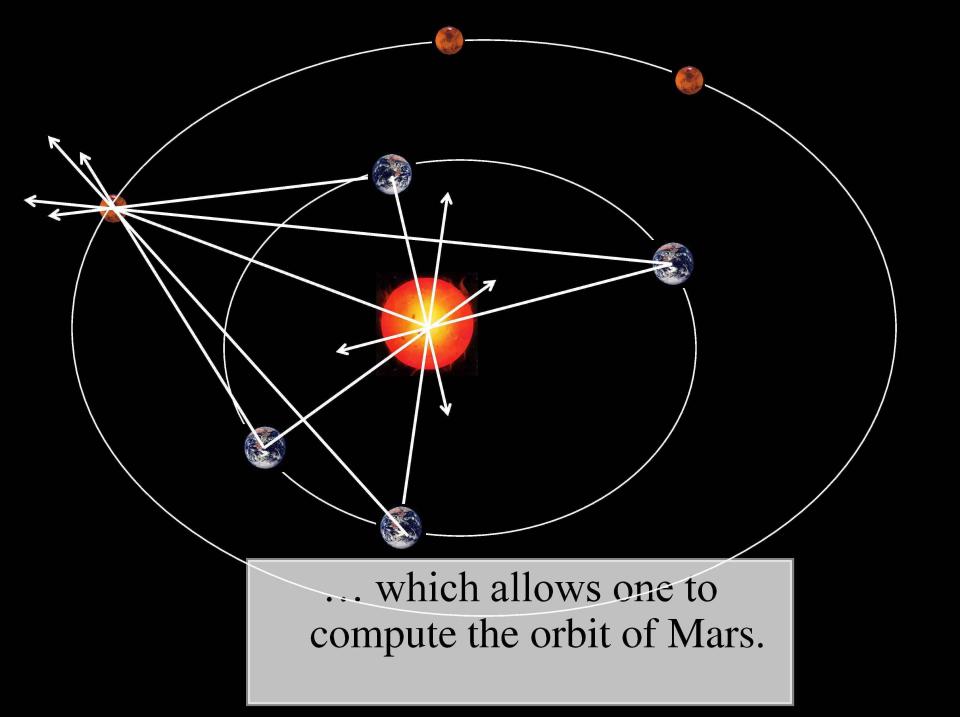
So by taking Brahe's data at intervals of 687 days...



... Kepler could triangulate and compute Earth's orbit relative to any position of Mars.



Once Earth's orbit was known, it could be used to compute more positions of Mars by taking other sequences of data separated by 687 days...



Using the data for Mars and other planets, Kepler formulated his three laws of planetary motion.

Kepler's laws of planetary motion

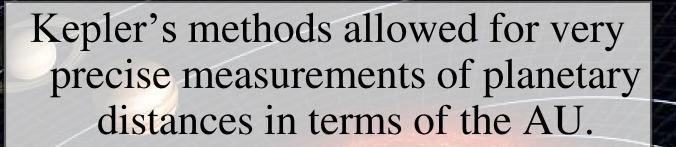
- 1. Planets orbit in ellipses, with the Sun as one of the foci.
- 2. A planet sweeps out equal areas in equal times.
- 3. The square of the period of an orbit is proportional to the cube of its semi-major axis.

This led Isaac Newton (1643-1727) to formulate his law of gravity.

Newton's law of universal gravitation

Any pair of masses attract by a force proportional to the masses, and inversely proportional to the square of the distance.

$$|F| = G m_1 m_2 / r^2$$



Mercury: 0.307-0.466 AU

Venus: 0.718-0.728 AU

Earth: 0.98-1.1 AU

Mars: 1.36-1.66 AU

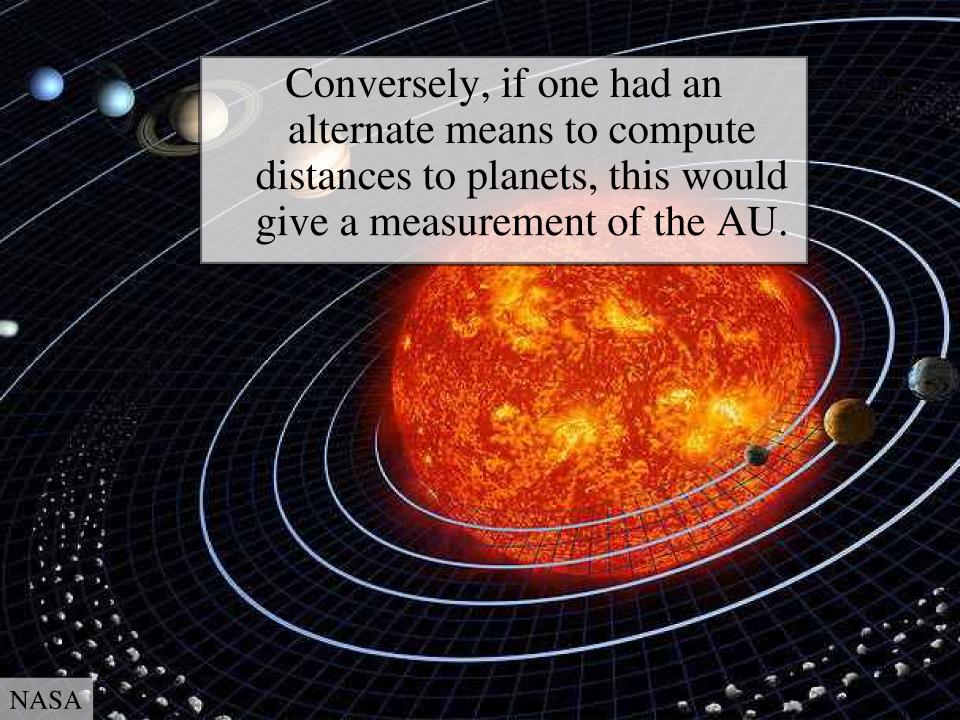
Jupiter: 4.95-5.46 AU

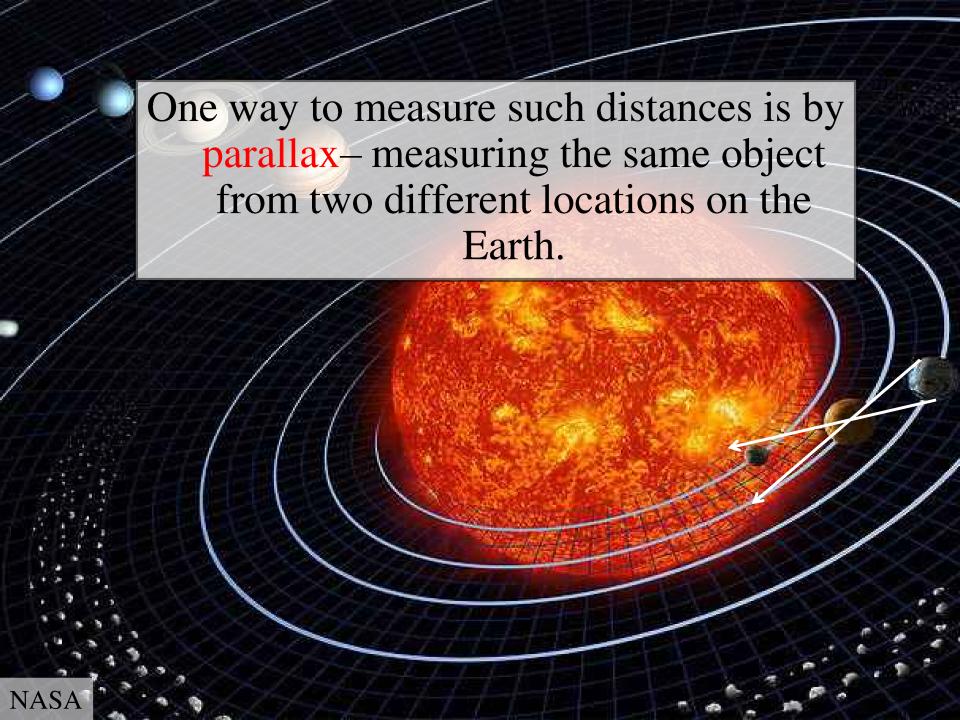
Saturn: 9.05-10.12 AU

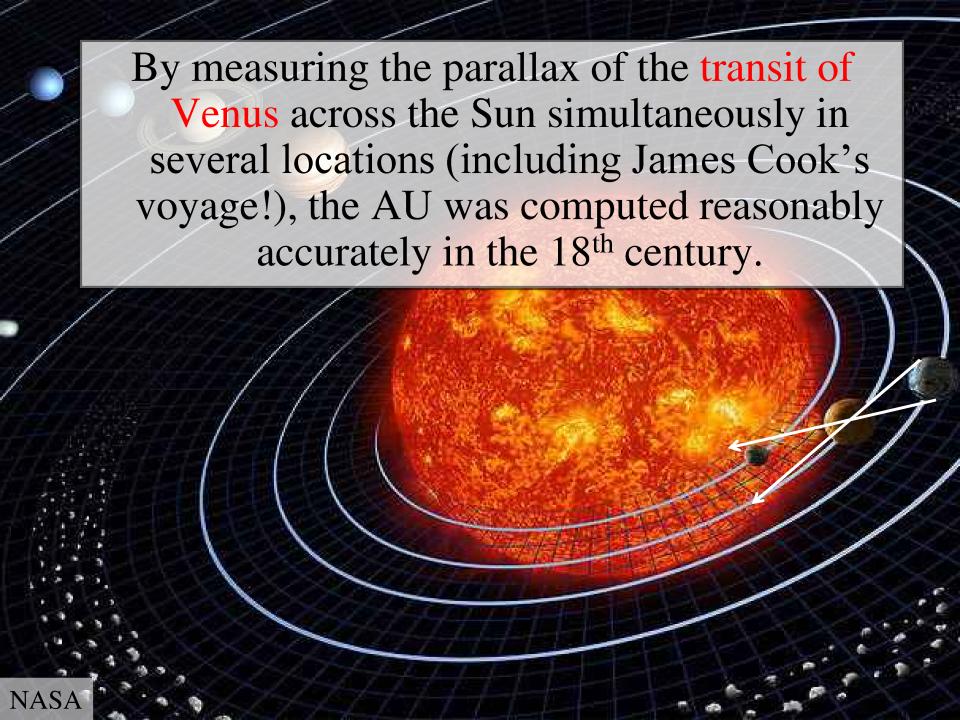
Uranus: 18.4-20.1 AU

Neptune: 29.8-30.4 AU

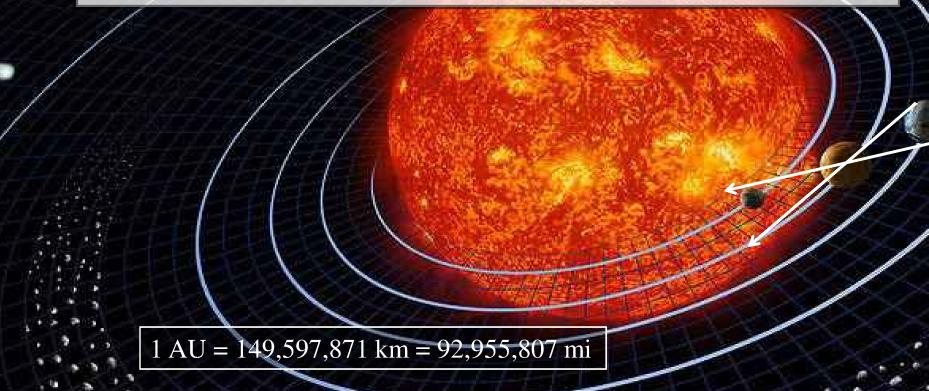


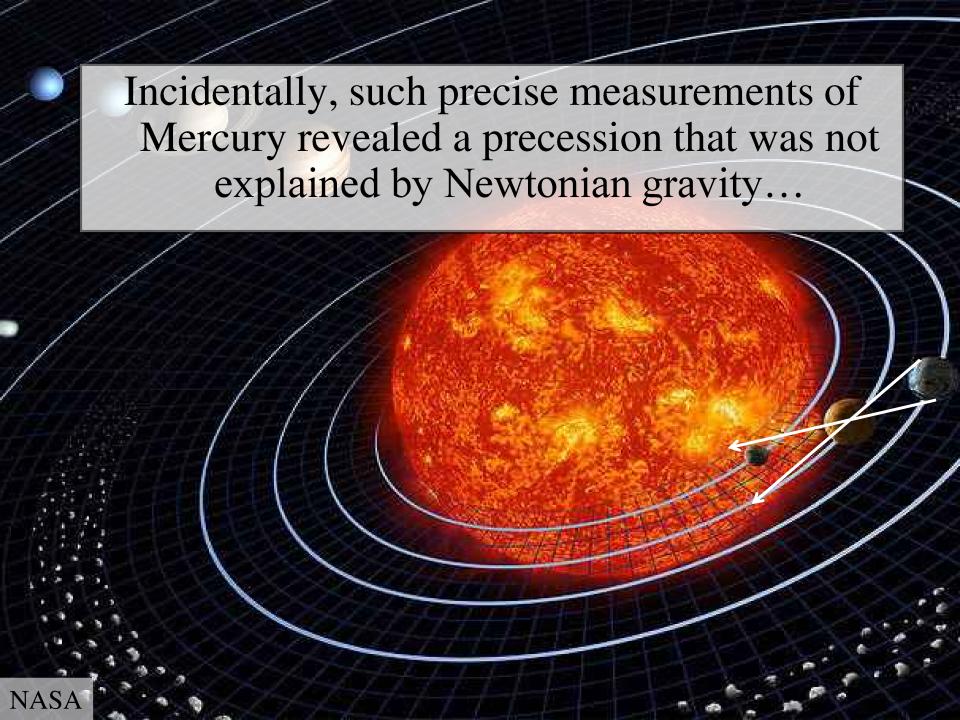


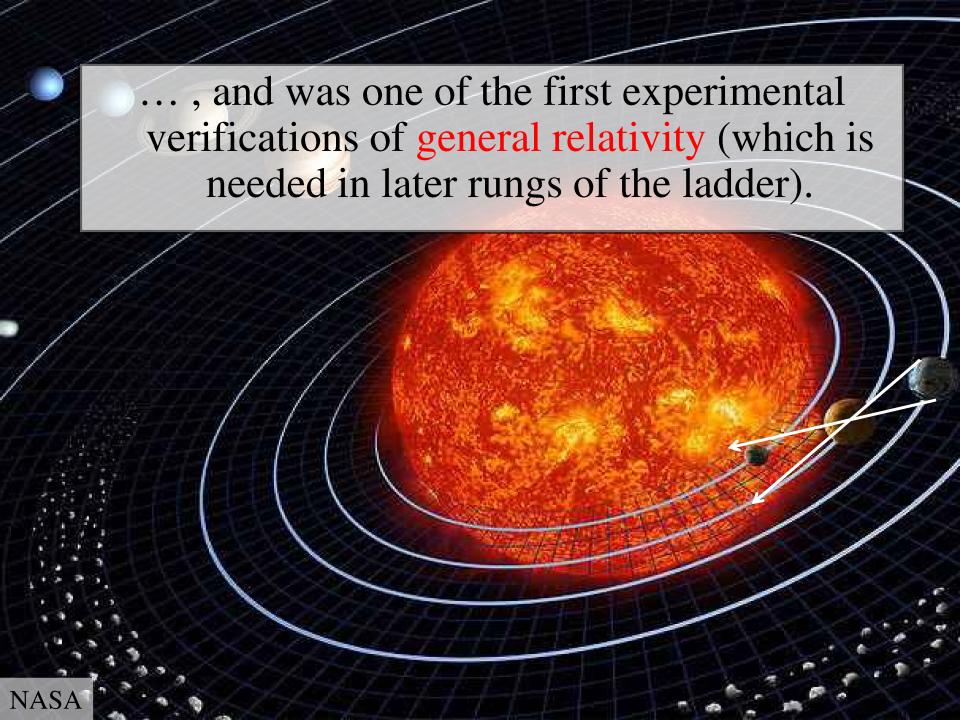




With modern technology such as radar and interplanetary satellites, the AU and the planetary orbits have now been computed to extremely high precision.

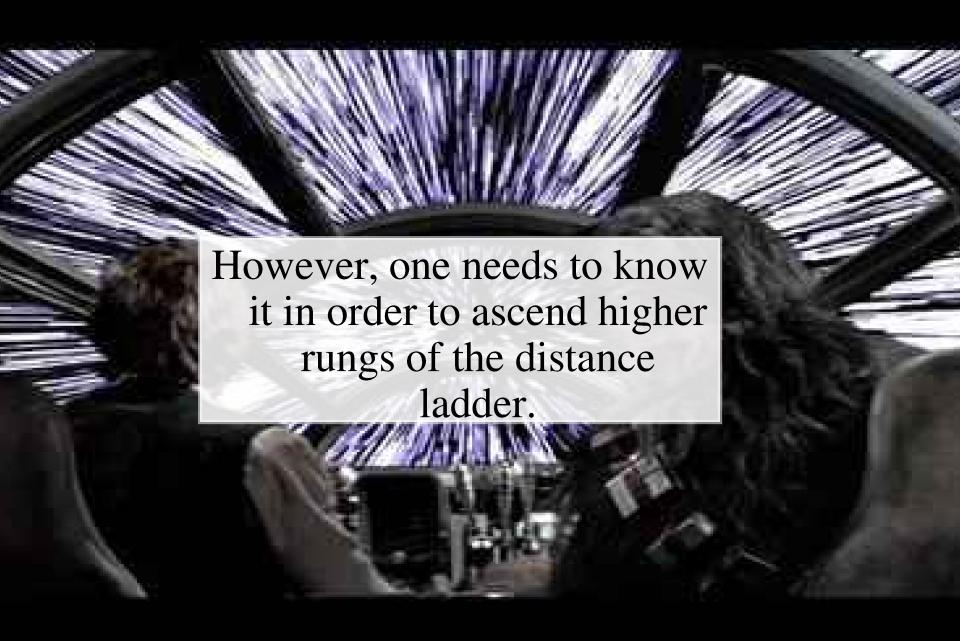






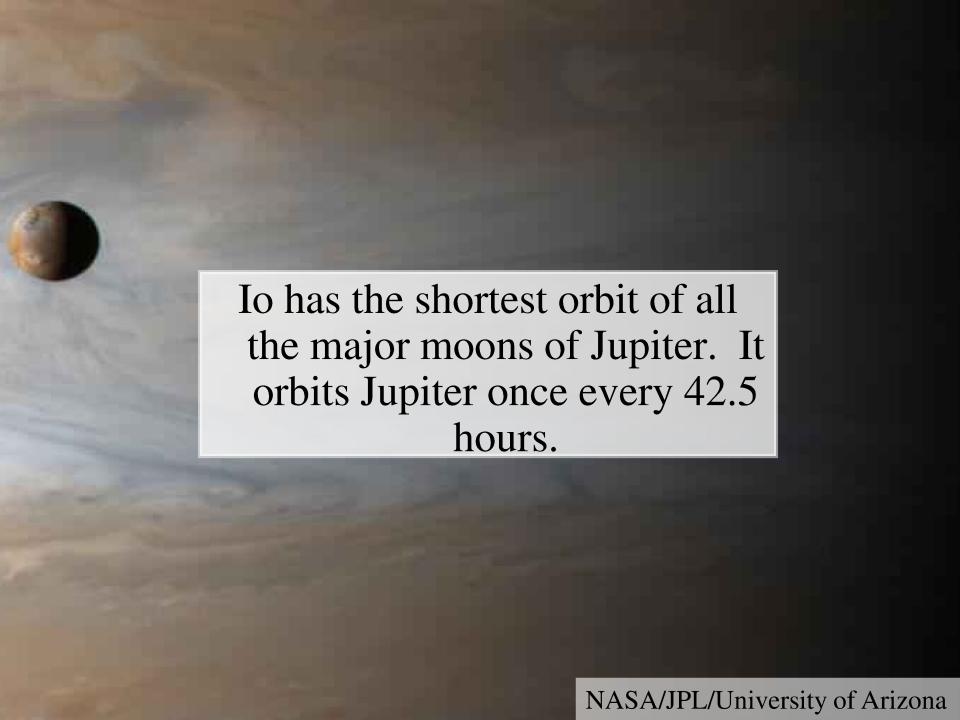


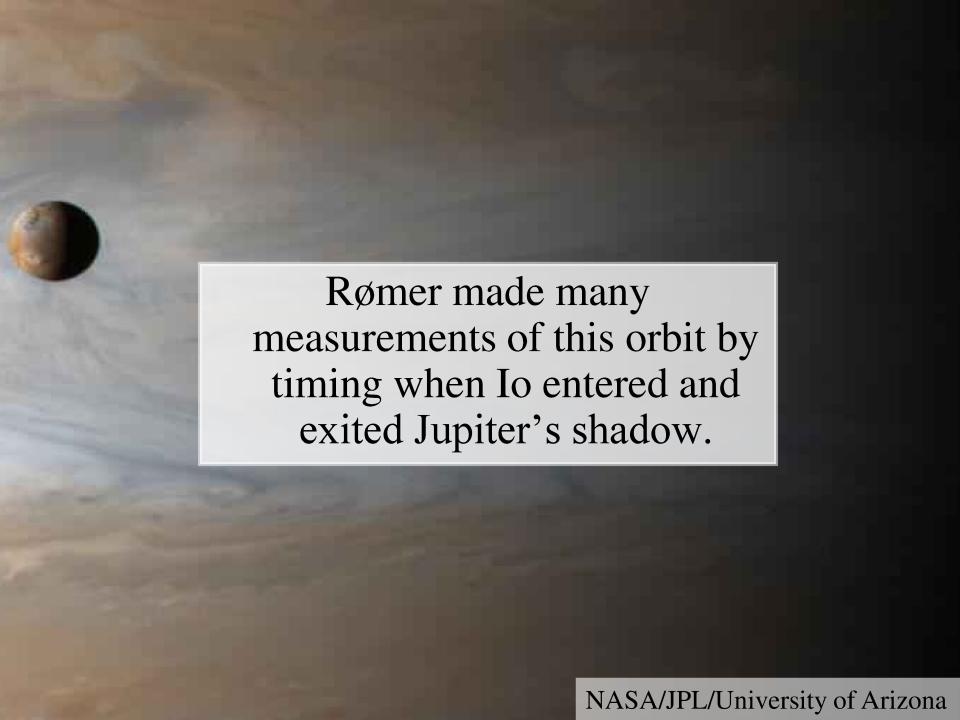


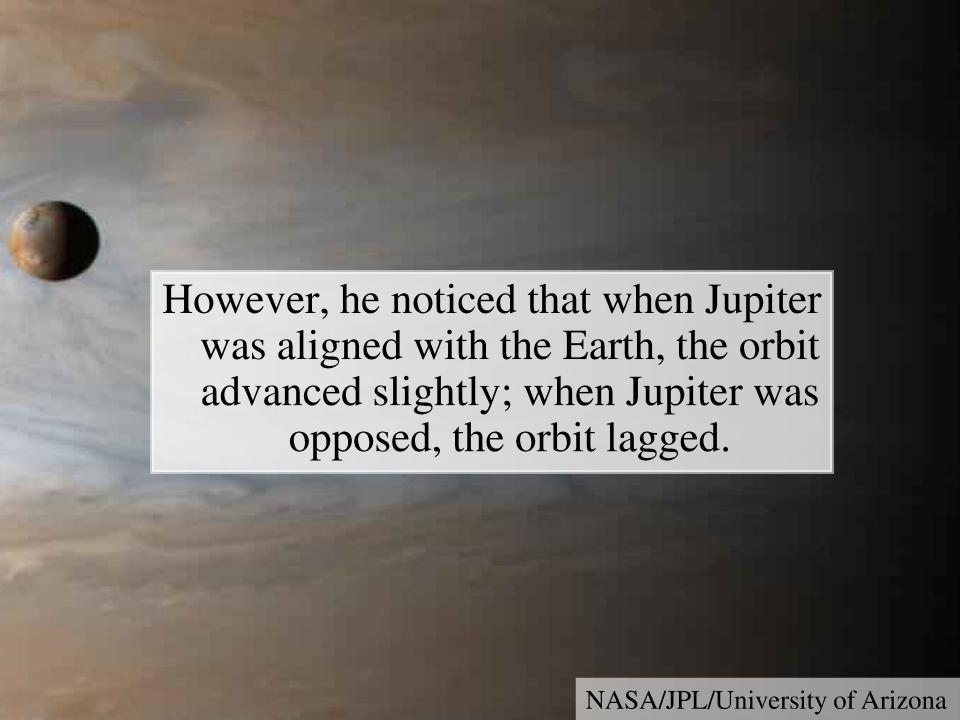


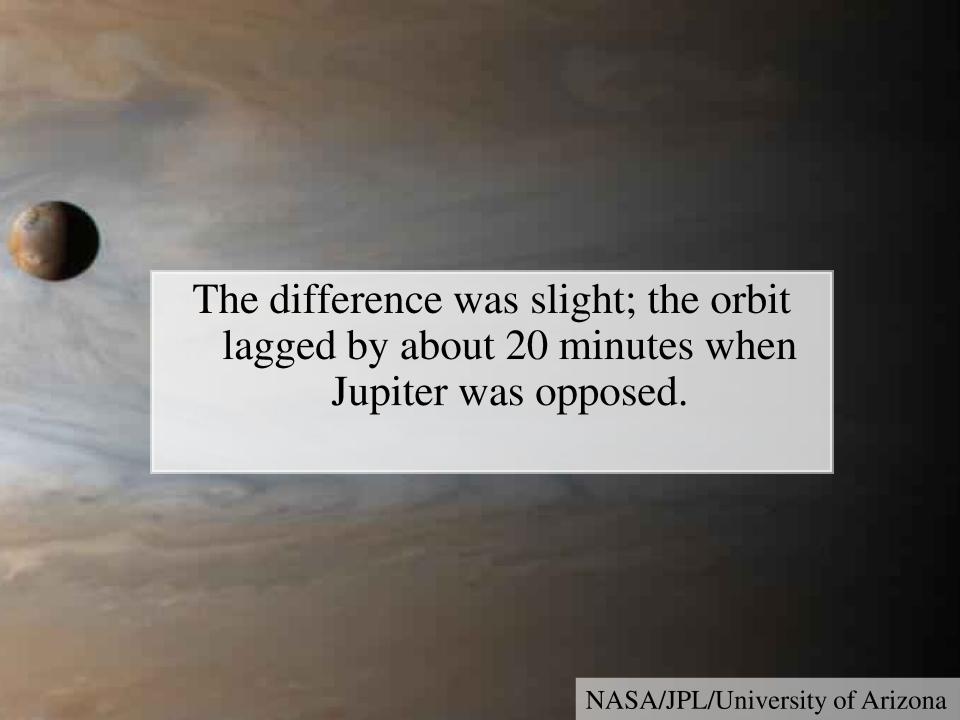


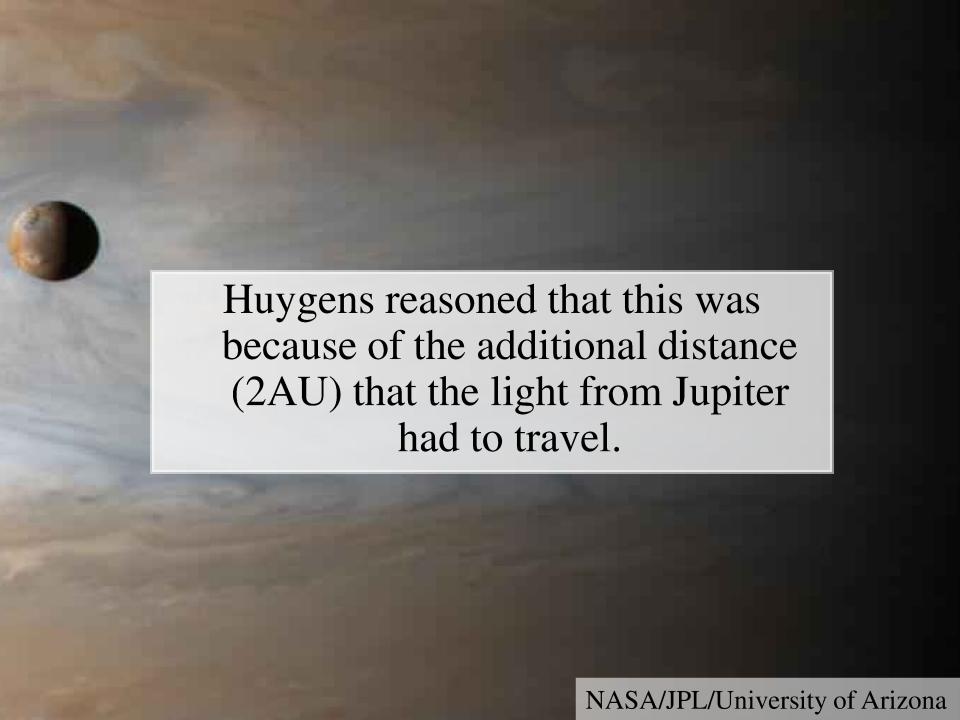


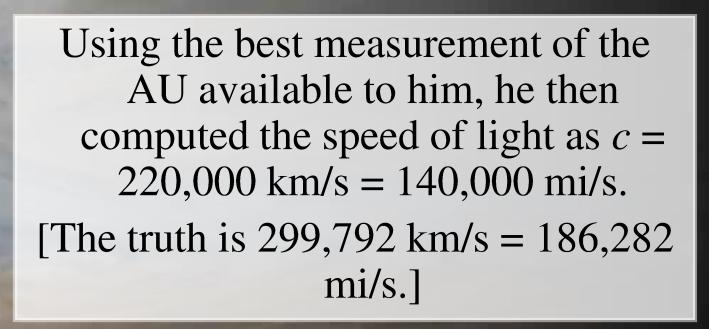


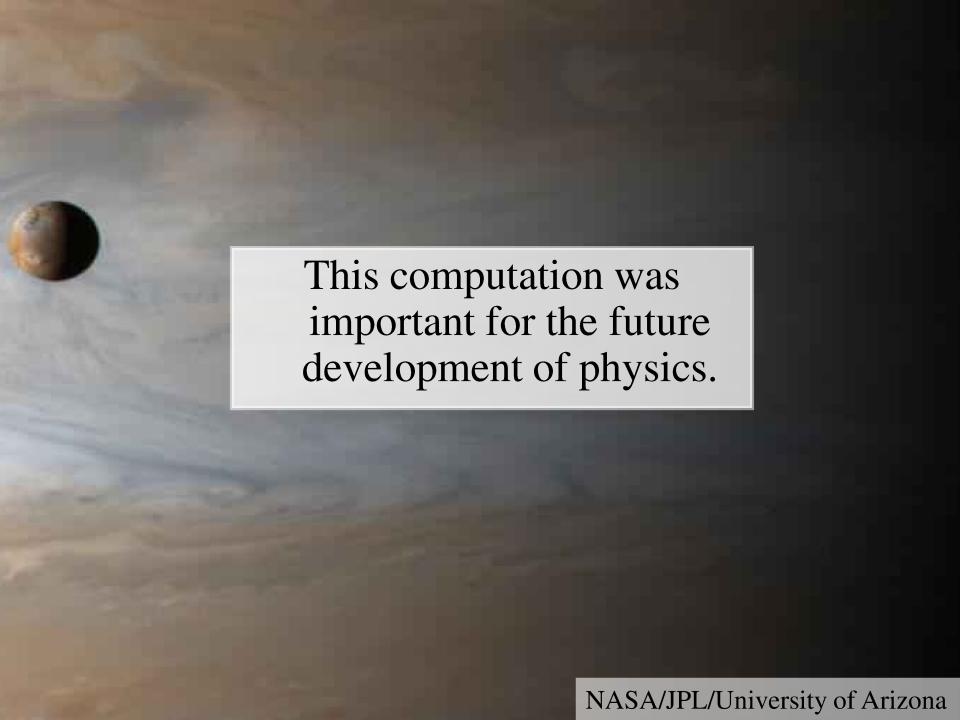








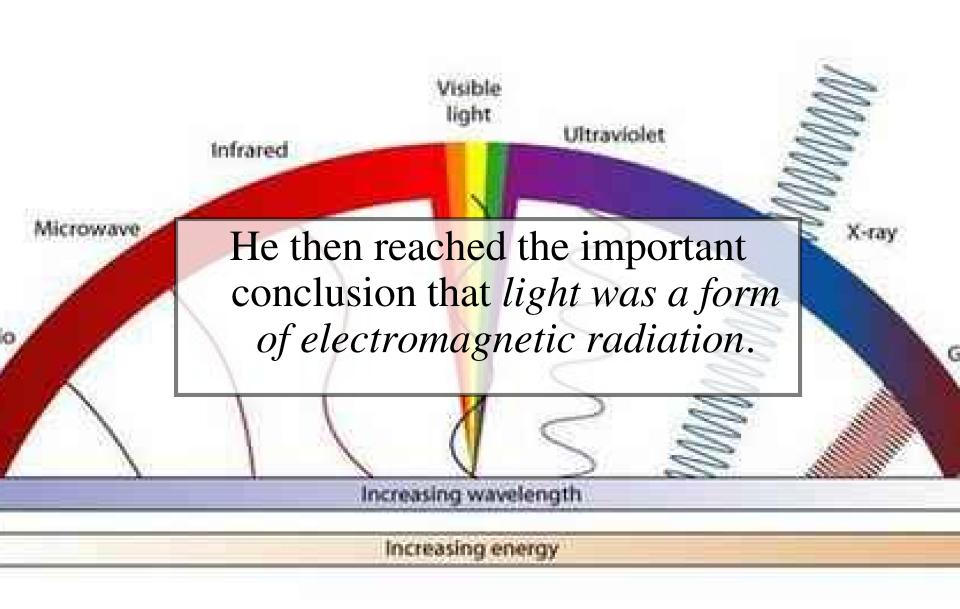


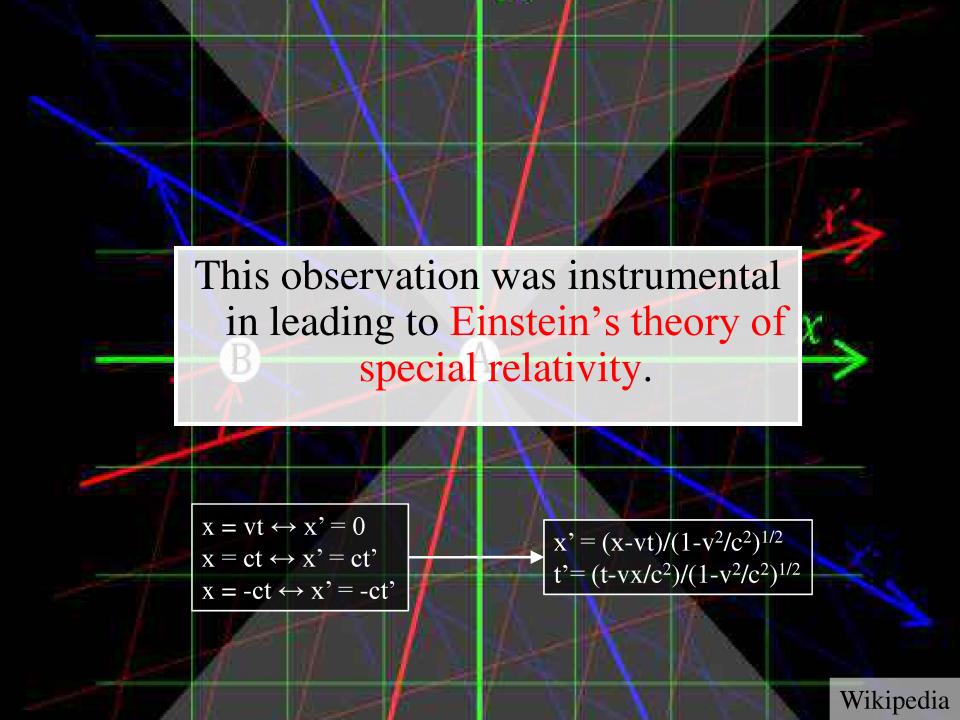


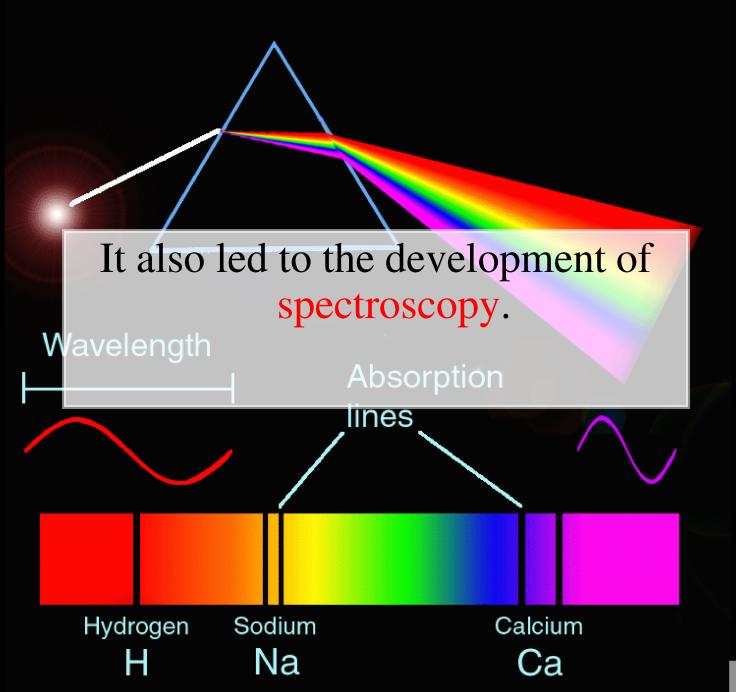


James Clerk Maxwell (1831-1879)
observed that the speed of light
almost matched the speed his
theory predicted for
electromagnetic radiation.

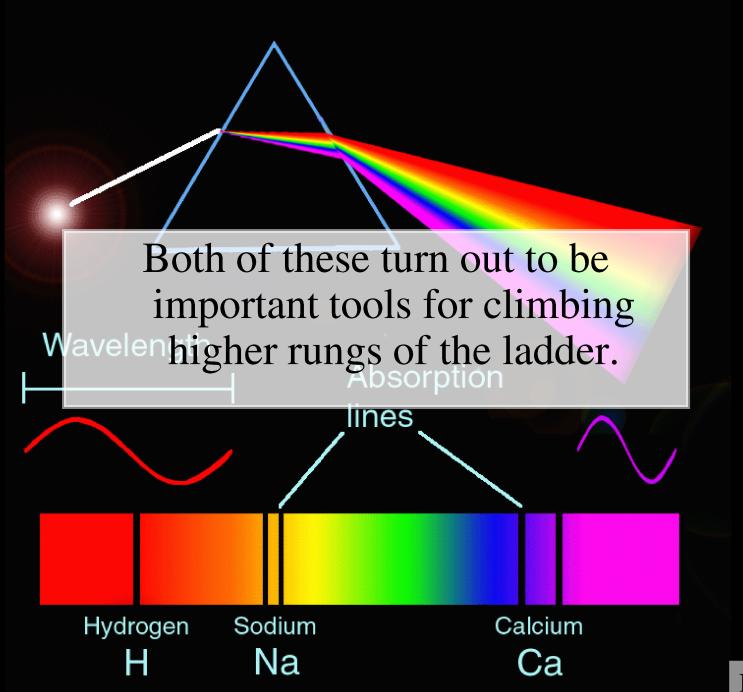
 $c \sim 3.0 \text{ x } 10^{10} \text{ m/s}$ $\epsilon_0 \sim 8.9 \text{ x } 10^{-12} \text{ F/m}$ $\mu_0 \sim 1.3 \text{ x } 10^{-6} \text{ H/m}$ $(\epsilon_0 \mu_0)^{1/2} \sim 3.0 \text{ x } 10^{10} \text{ m/s}$

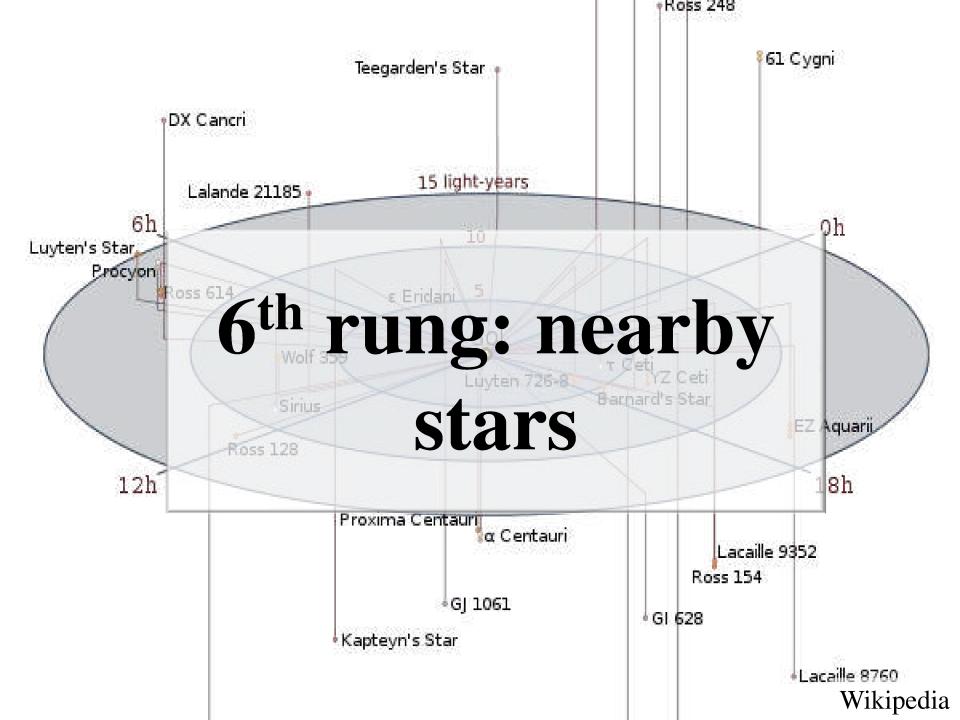


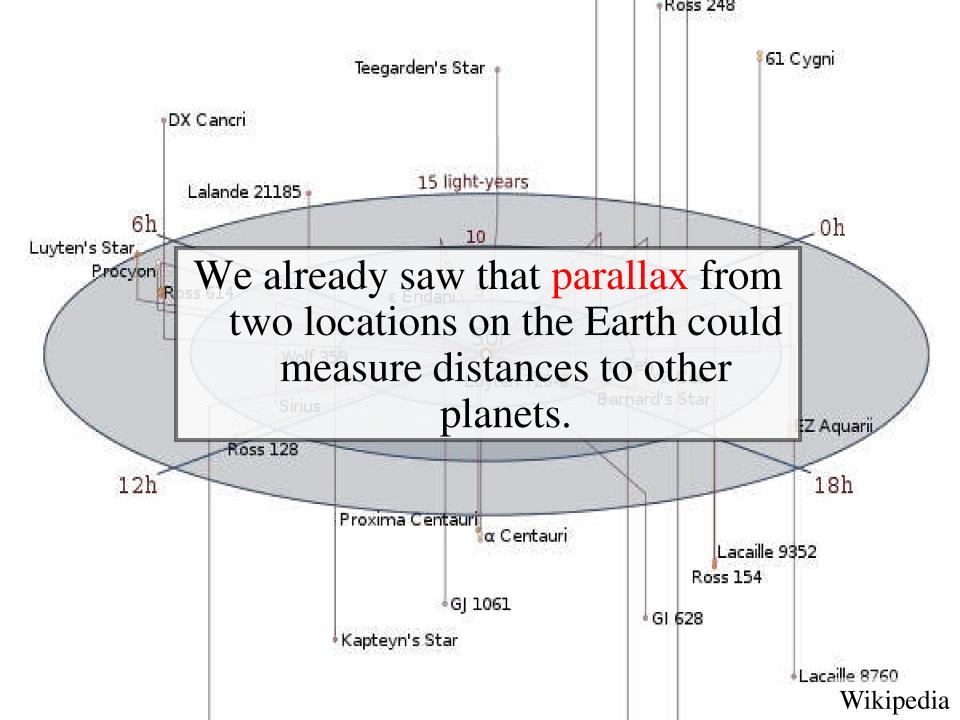


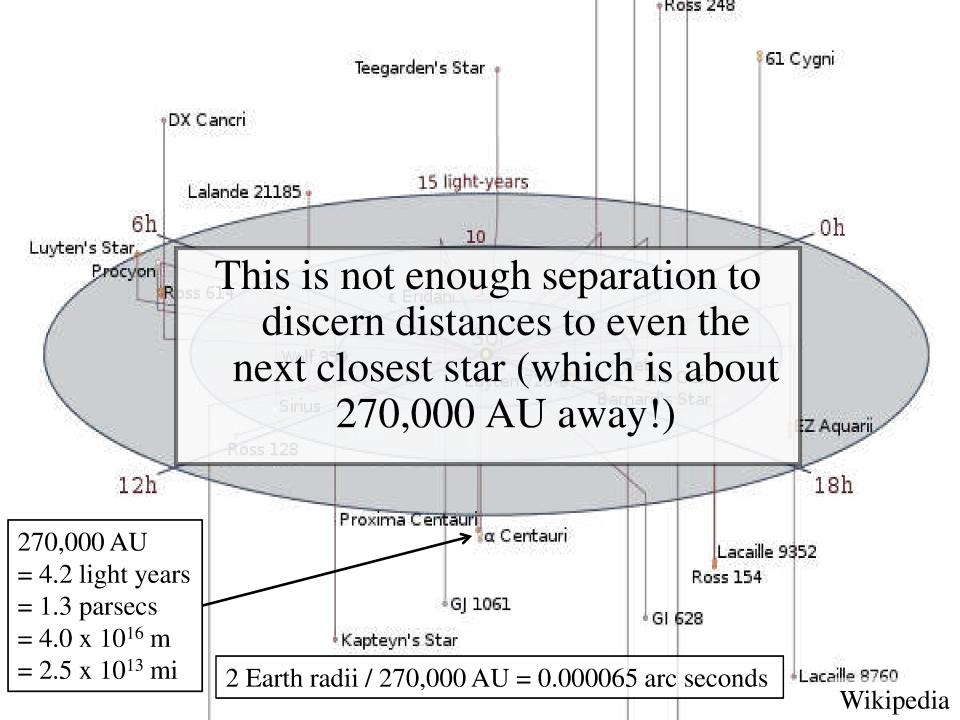


Ian Short





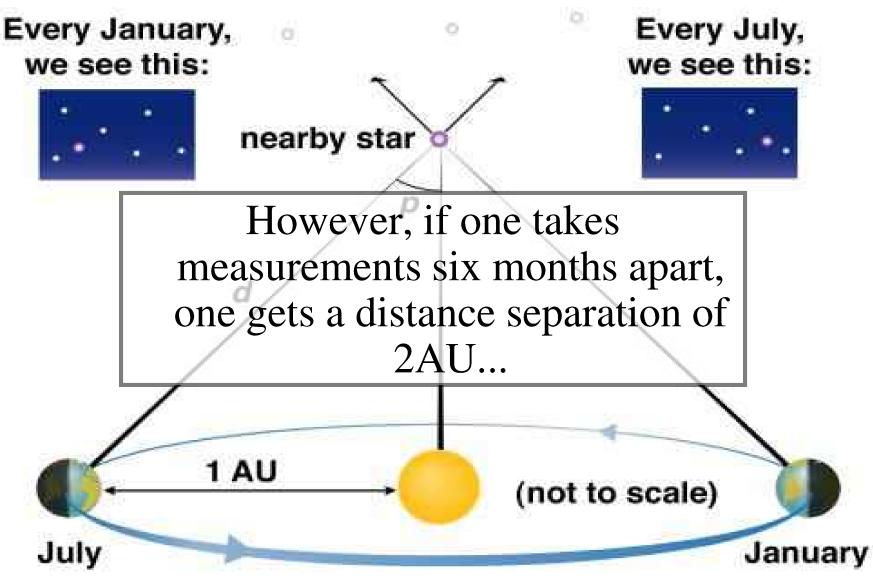




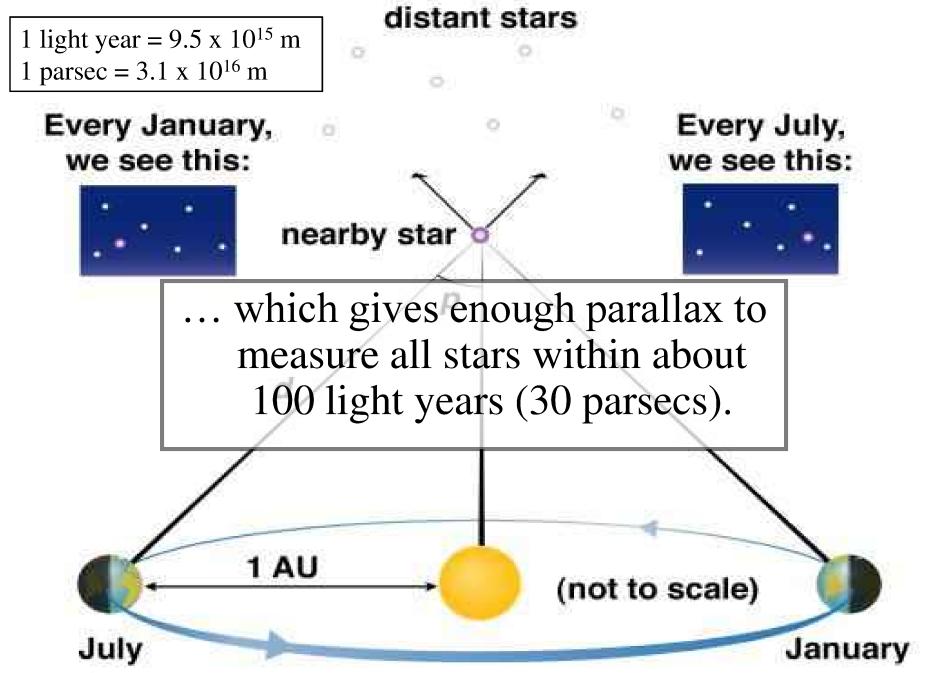
distant stars

2 Earth radii = 12,700 km

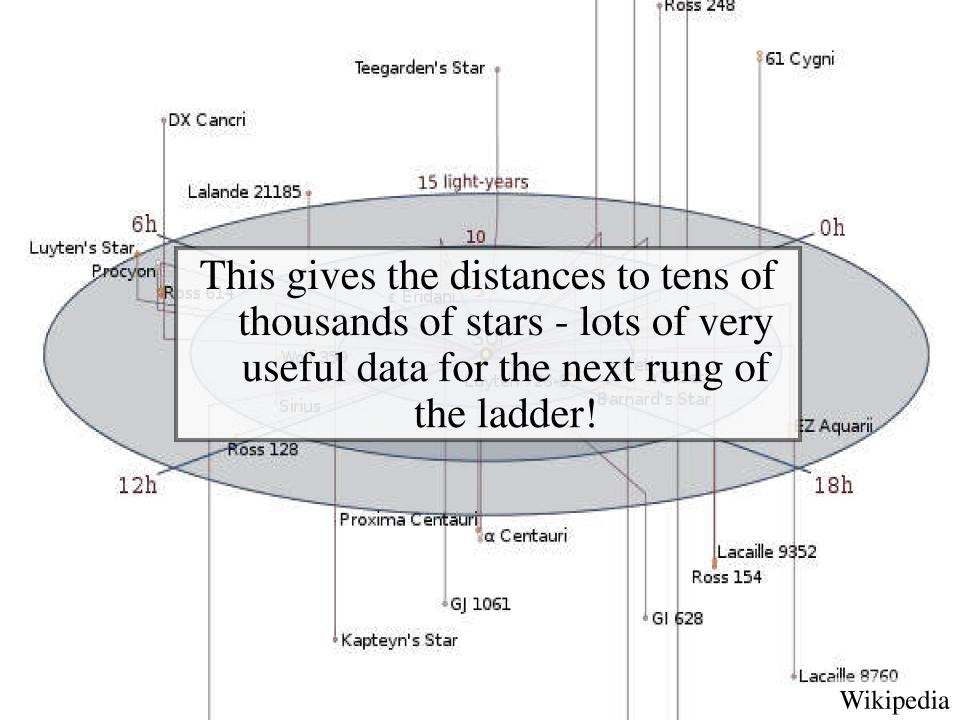
2 AU = 300,000,000 km



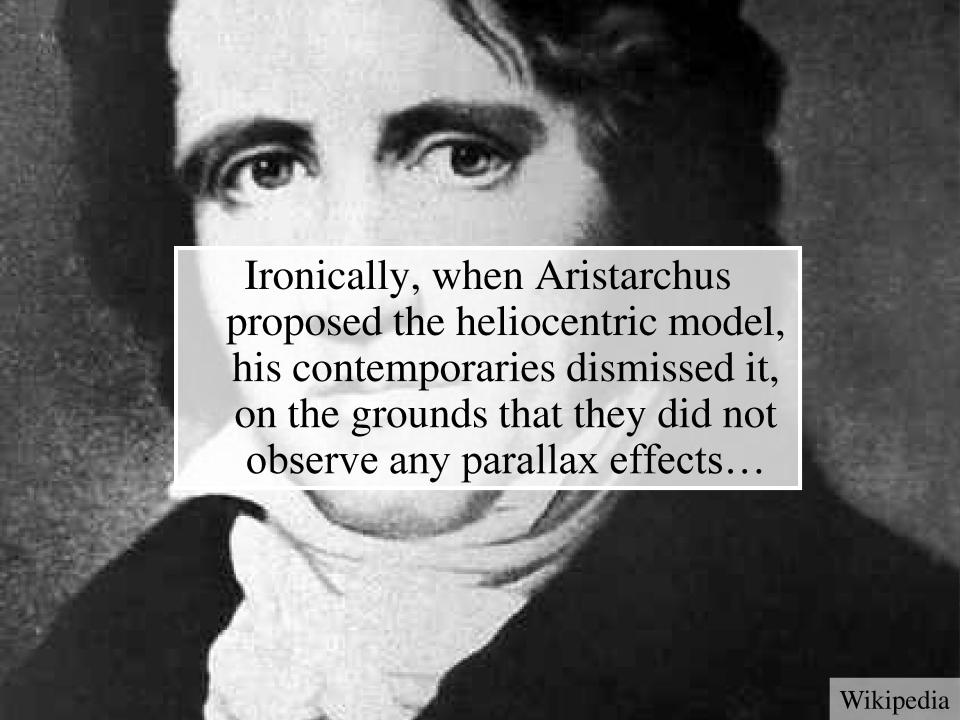
From "The Essential Cosmic Perspective", Bennett et al.

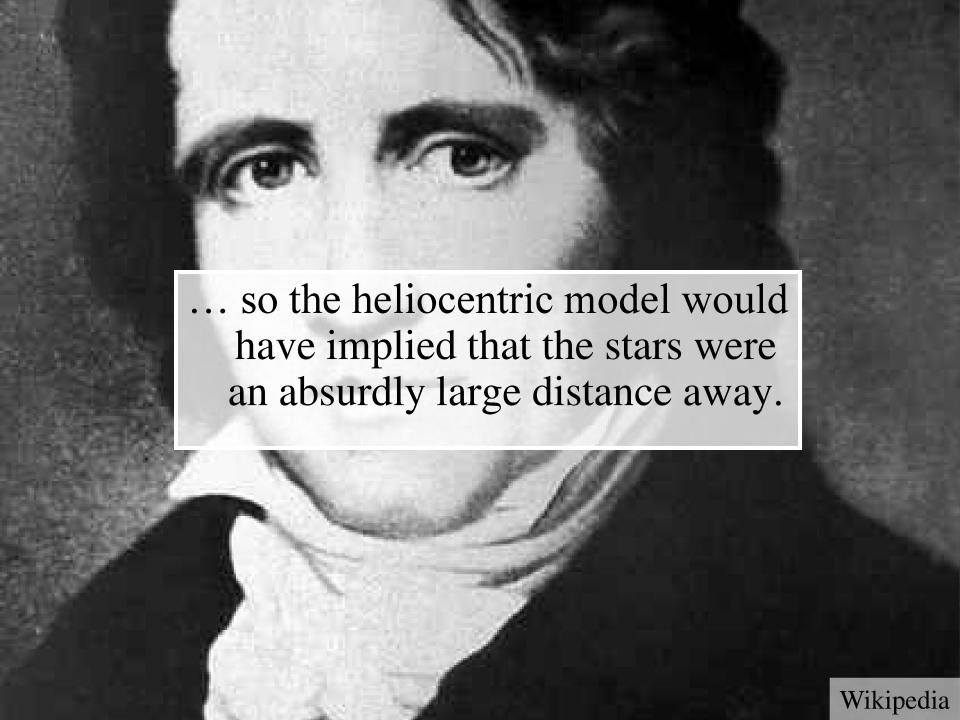


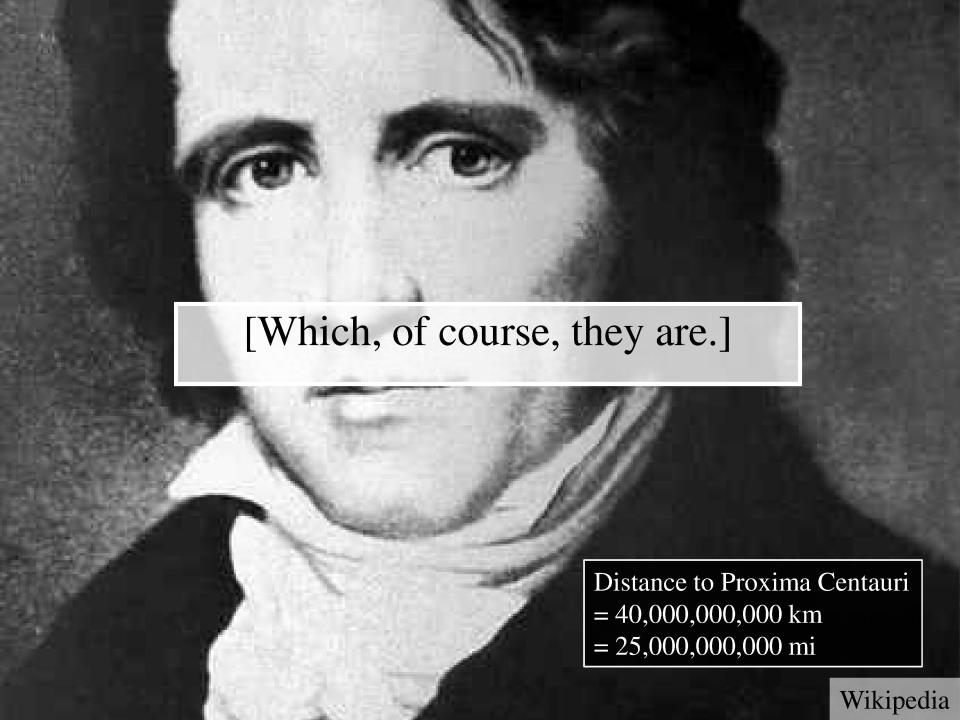
From "The Essential Cosmic Perspective", Bennett et al.



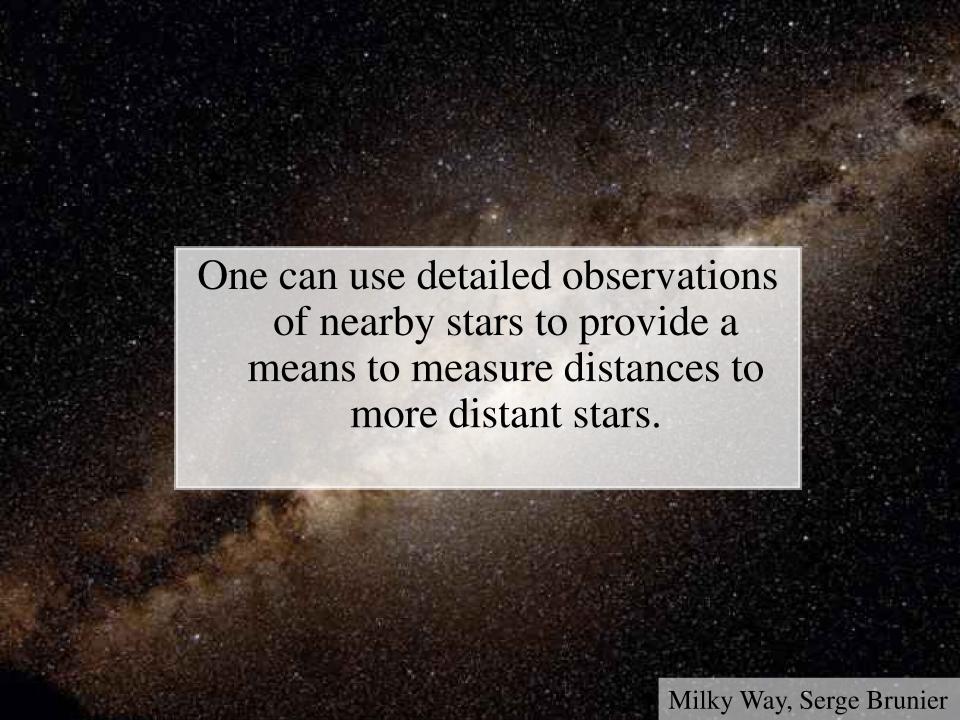


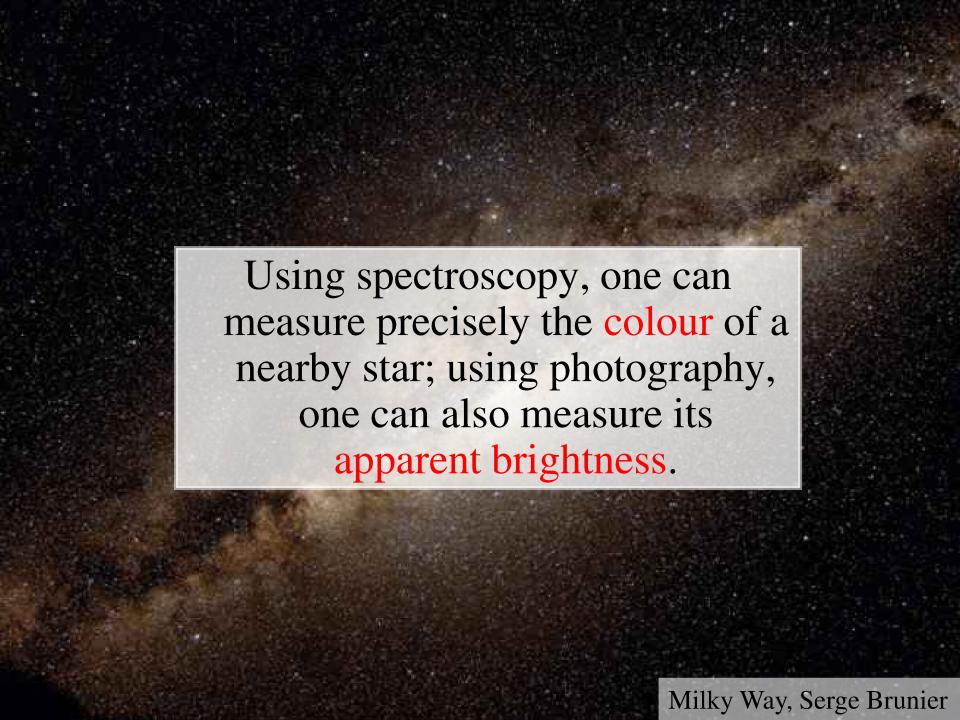






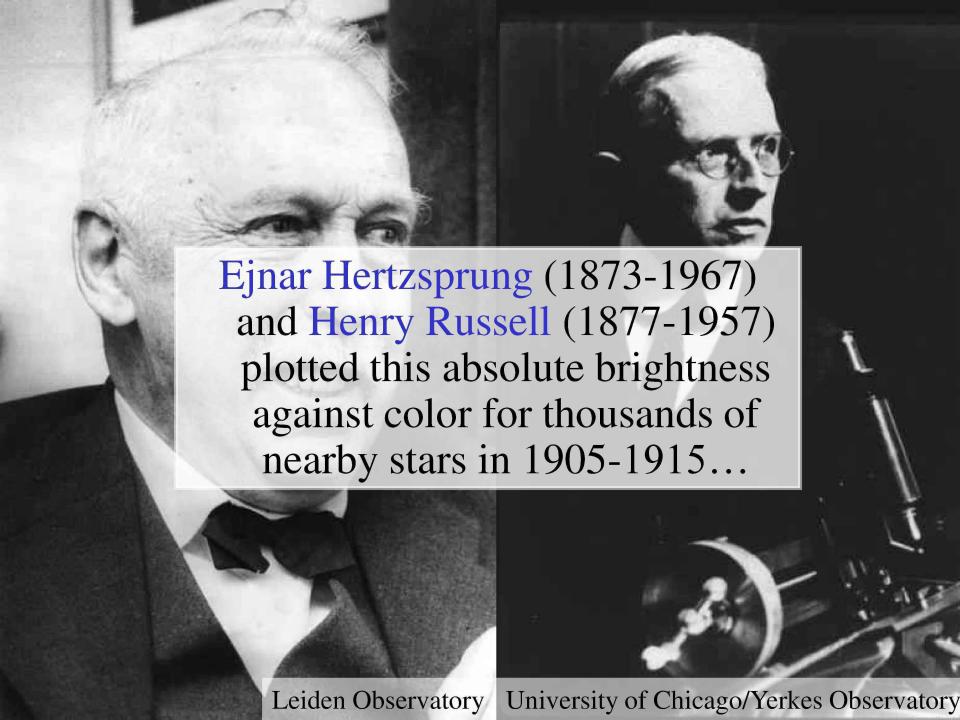


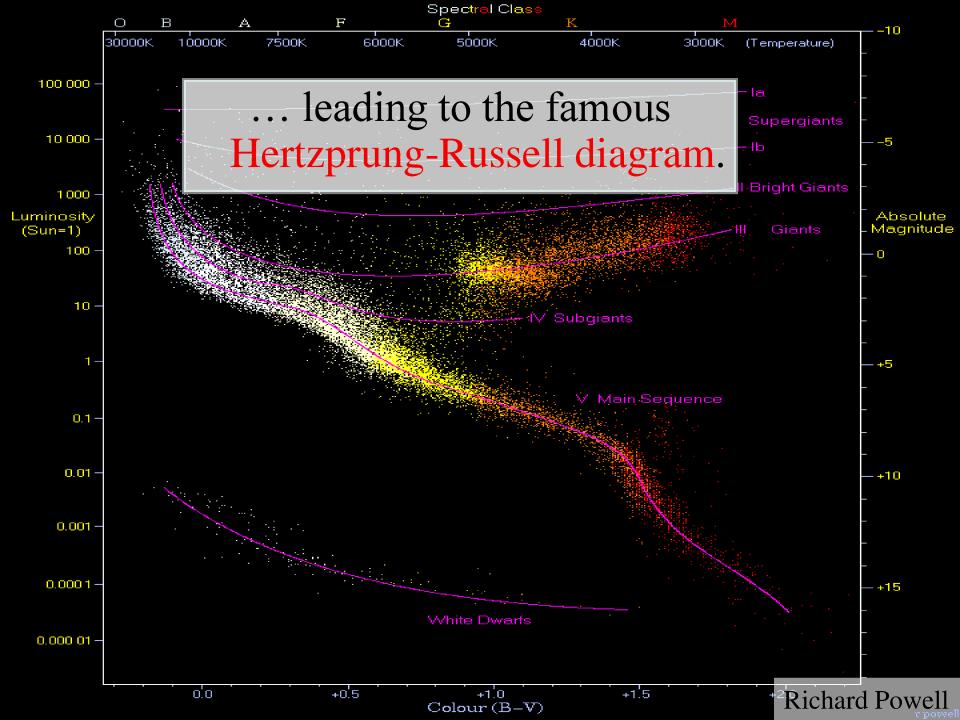


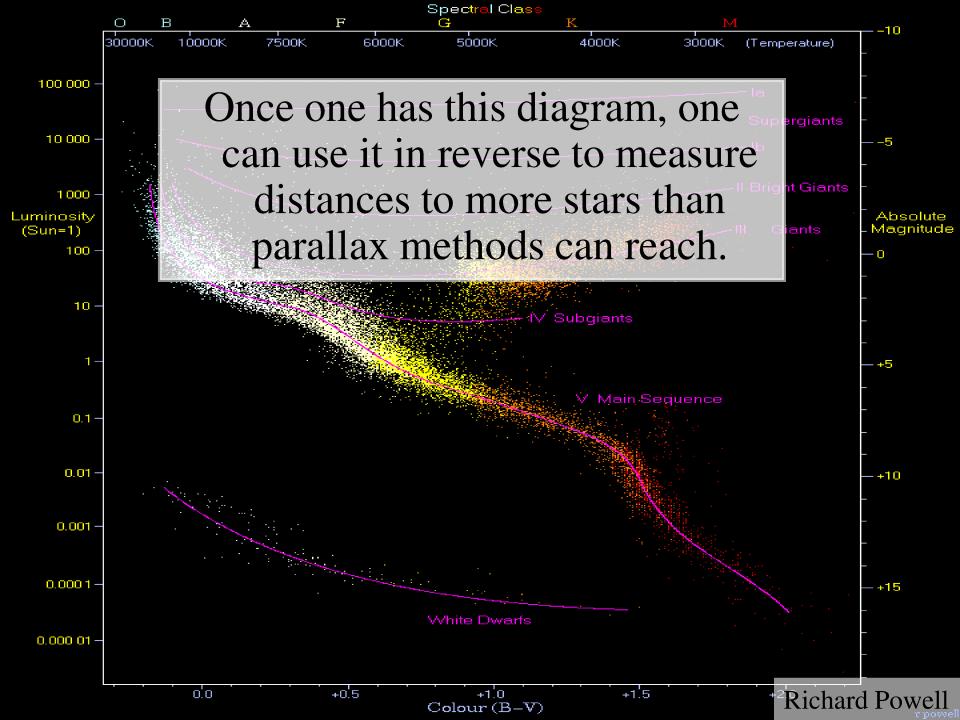


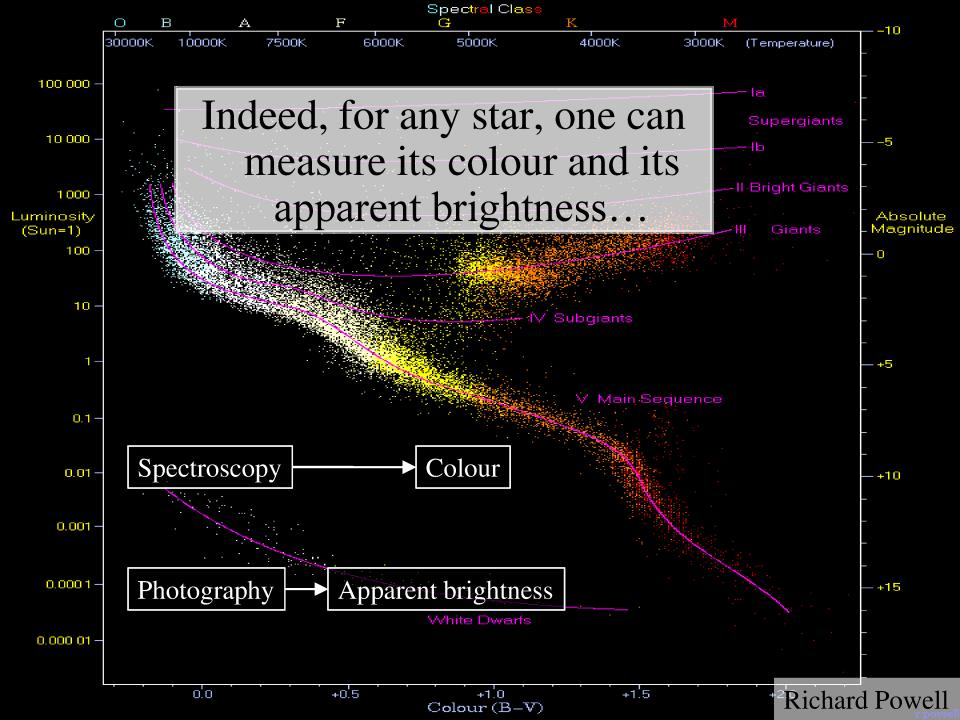
Using the apparent brightness, the distance, and inverse square law, one can compute the absolute brightness of these stars.

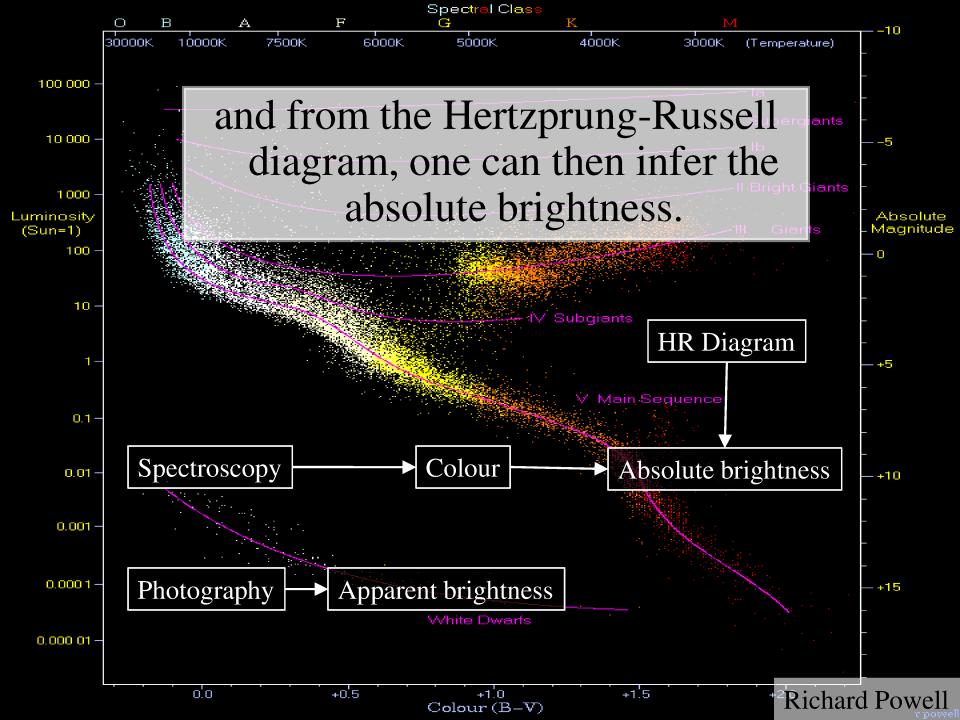
 $M = m - 5(\log_{10} D_L - 1)$

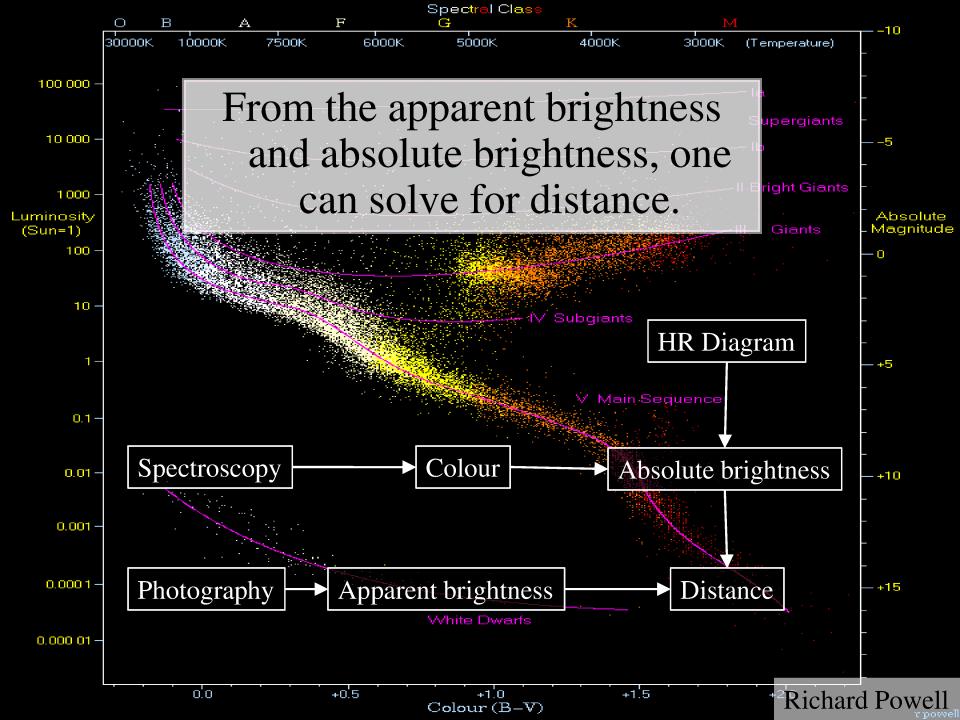






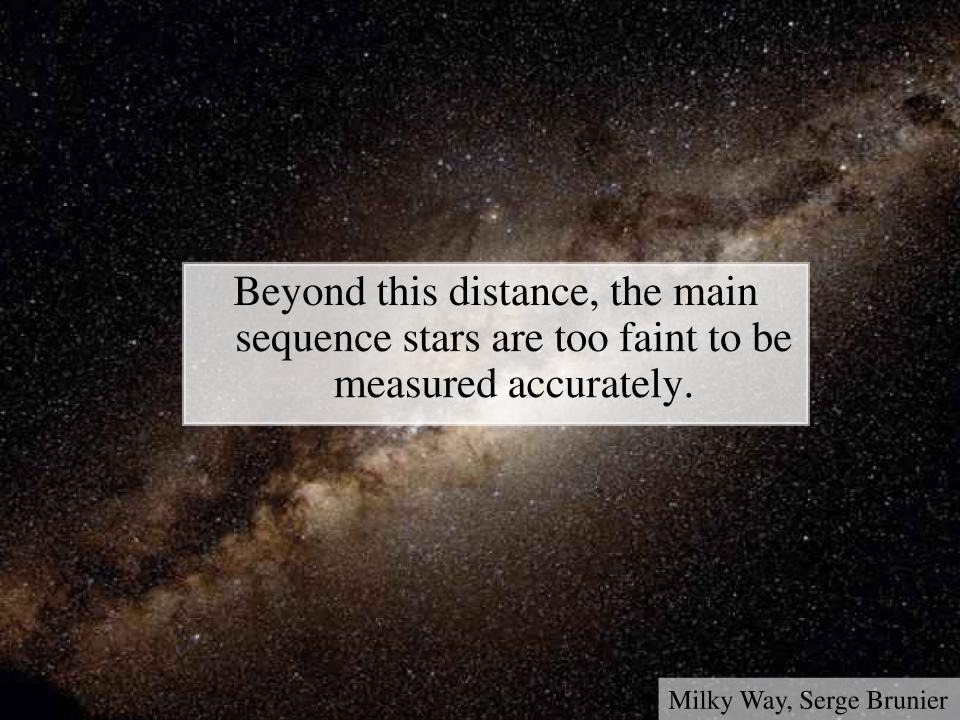






This technique (main sequence fitting) works out to about 300,000 light years (covering the entire galaxy!)

 $300,000 \text{ light years} = 2.8 \times 10^{21} \text{ m} = 1.8 \times 10^{18} \text{ mi}$ Diameter of Milky Way = 100,000 light years



8th rung: Other galaxies



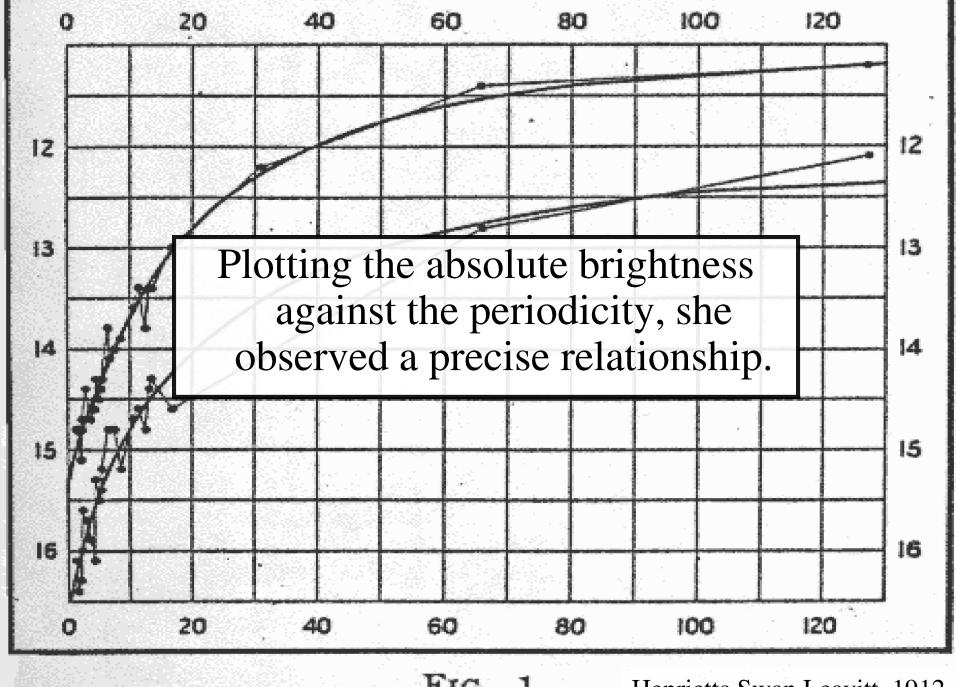


Fig. 1. Henrietta Swan Leavitt, 1912

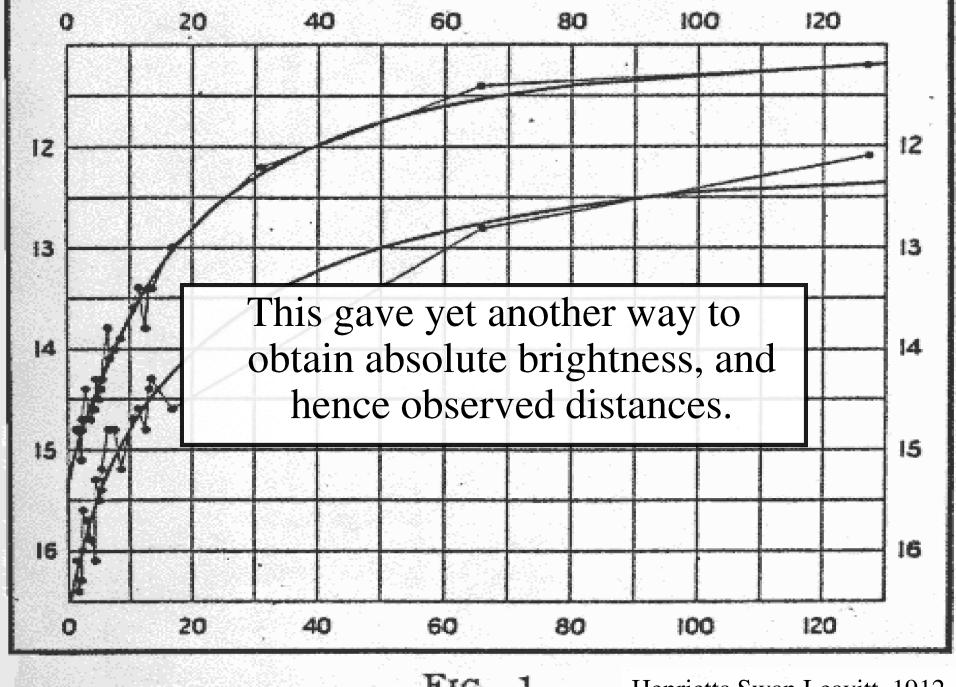
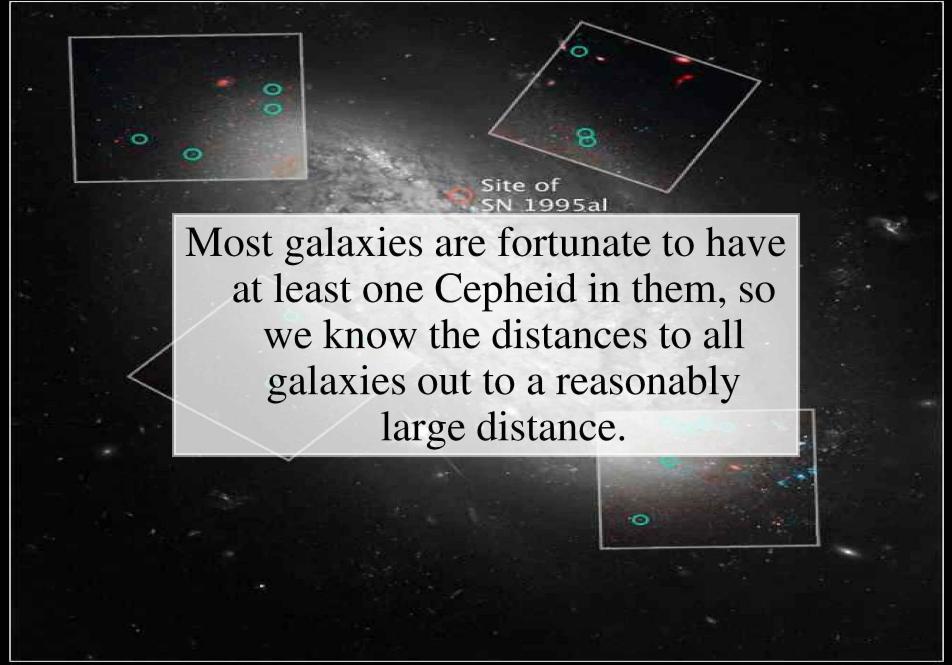


Fig. 1. Henrietta Swan Leavitt, 1912

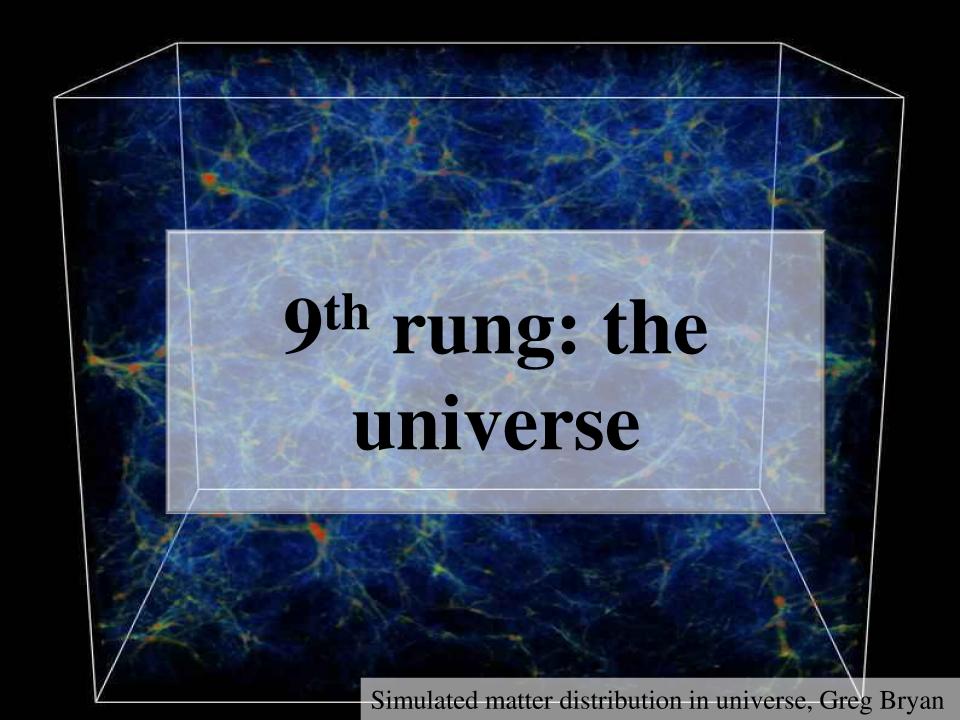


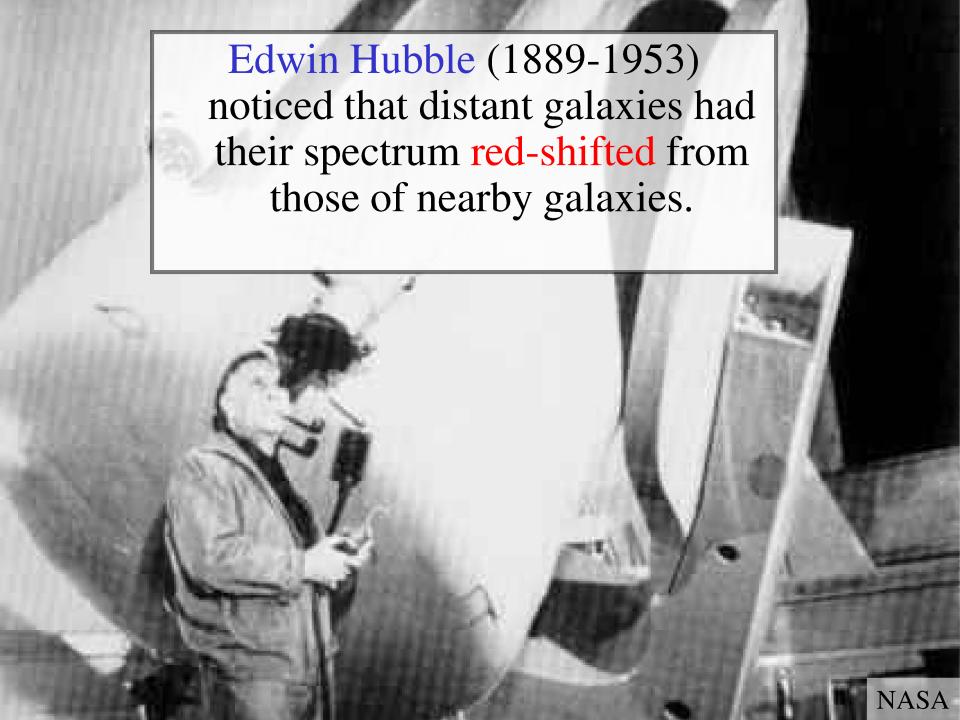
Diameter of Milky Way = 100,000 light years Most distant Cepheid detected (Hubble Space Telescope) = 108,000,000 light years Diameter of universe > 76,000,000,000 light years

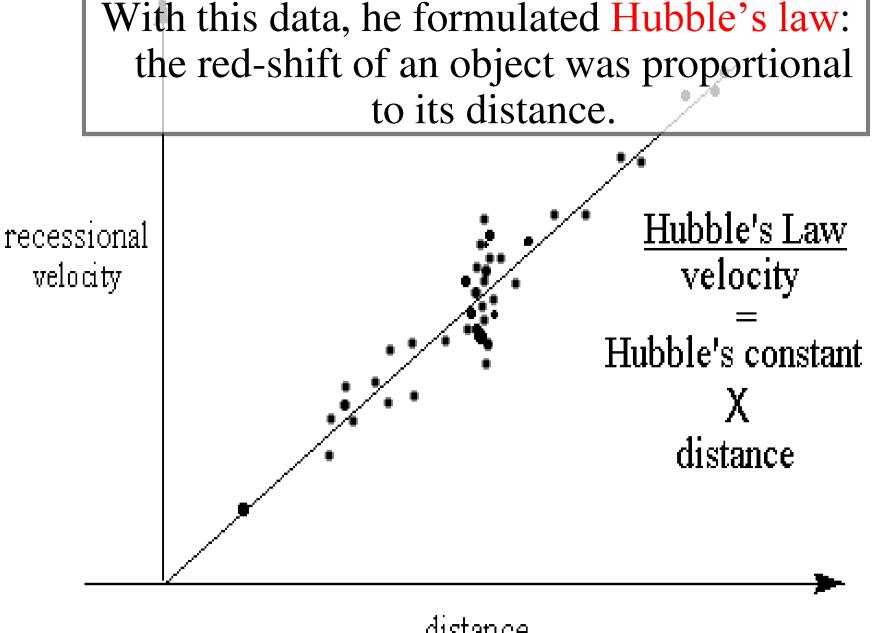


Diameter of Milky Way = 100,000 light years Most distant Cepheid detected (Hubble Space Telescope) = 108,000,000 light years Most distant Type 1a supernova detected (1997ff) = 11,000,000,000 light years Diameter of universe > 76,000,000,000 light years

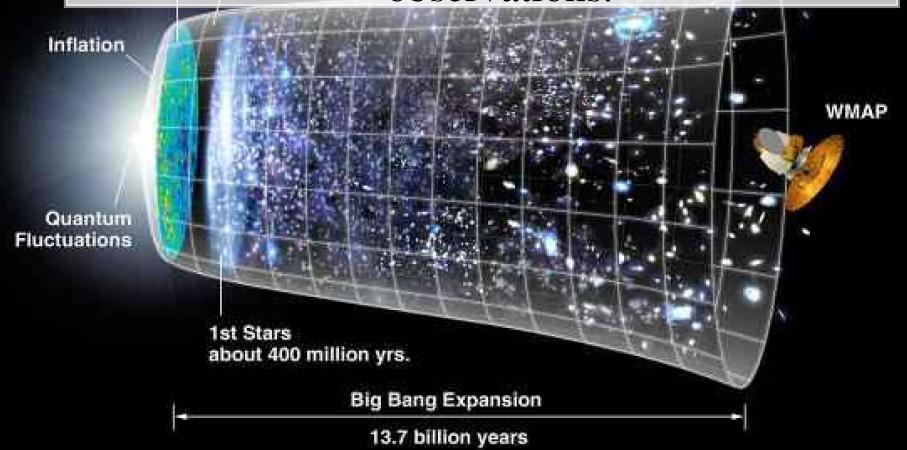
Similar methods, using supernovae instead of Cepheids, can sometimes work to even larger scales than these, and can also be used to independently confirm the Cepheid-based distance measurements.

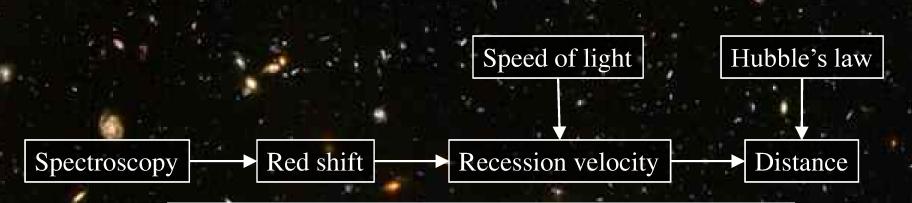




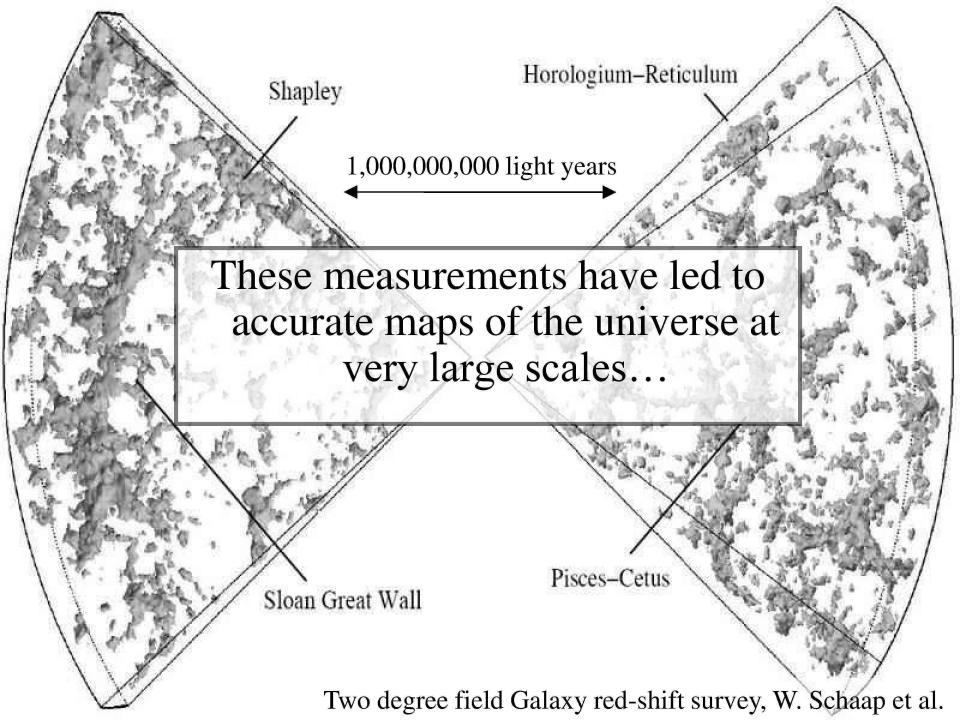


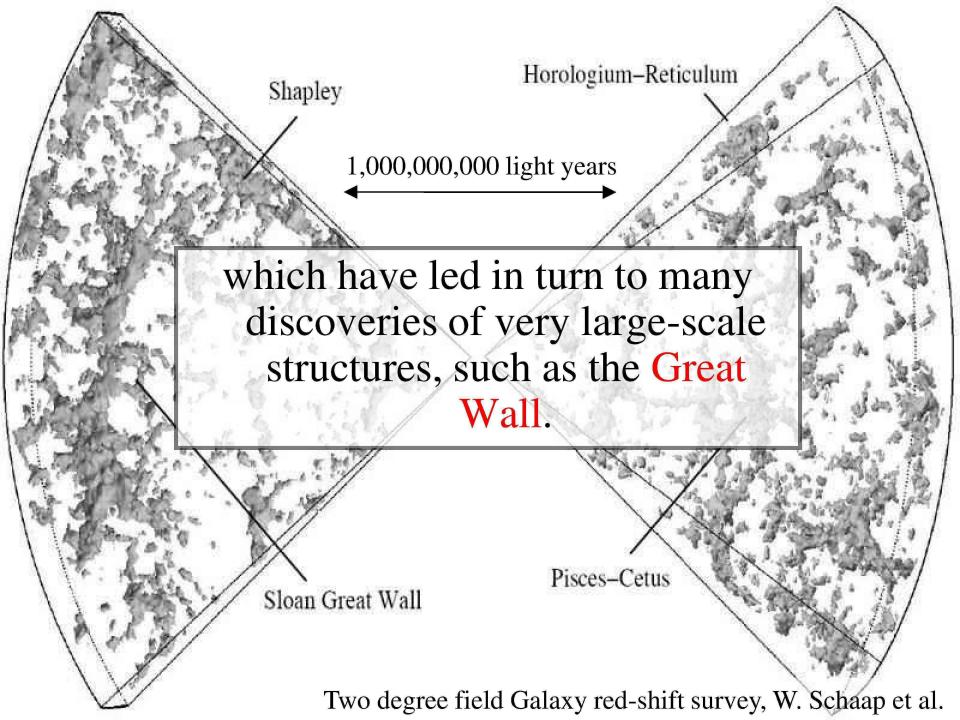
This led to the famous Big Bang model of the expanding universe, which has now been confirmed by many other cosmological observations.

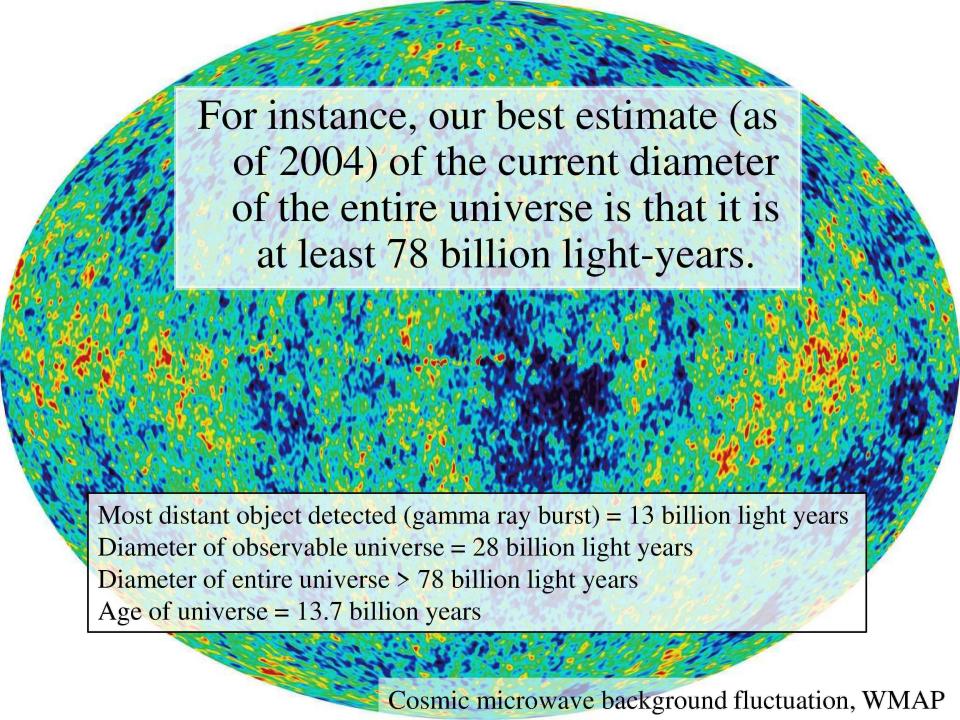


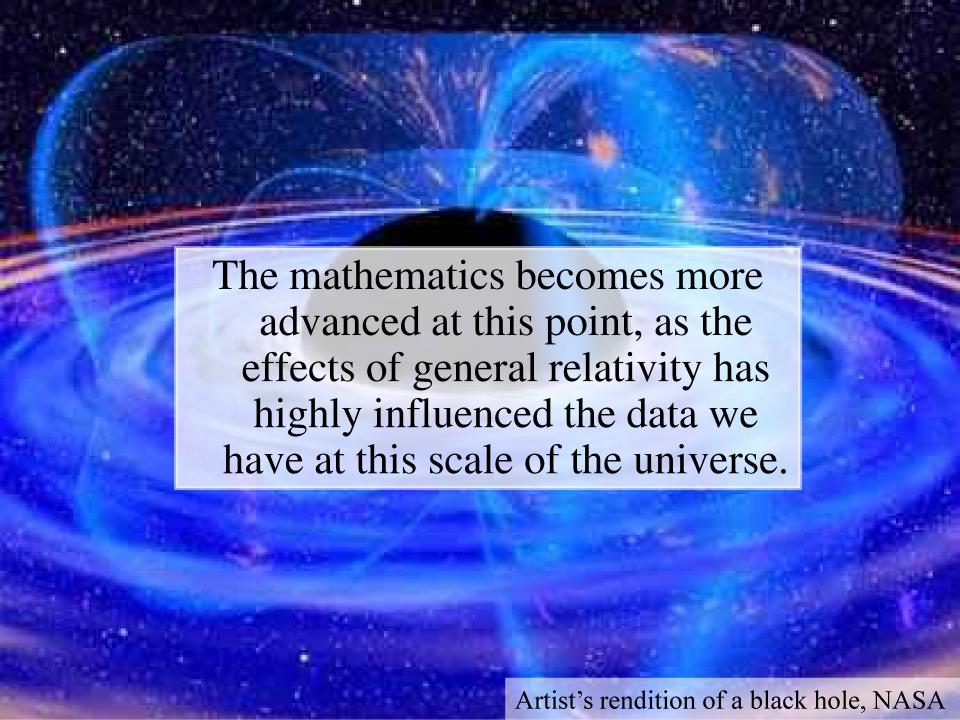


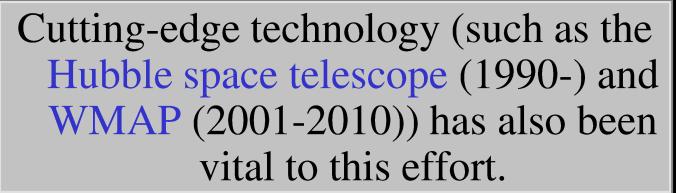
But it also gave a way to measure distances even at extremely large scales... by first measuring the red-shift and then applying Hubble's law.





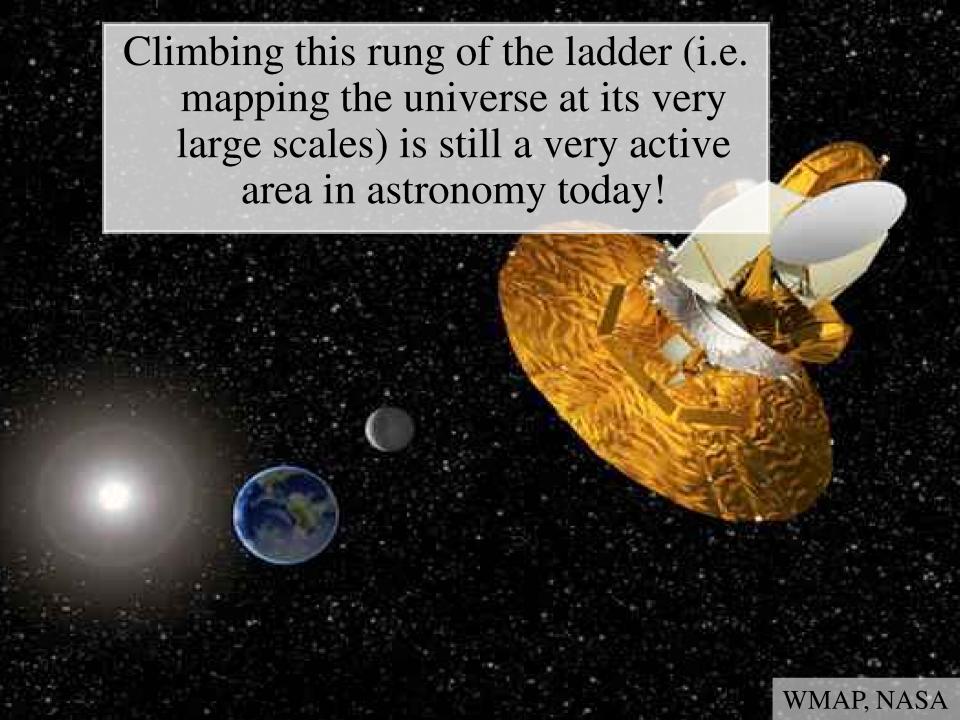


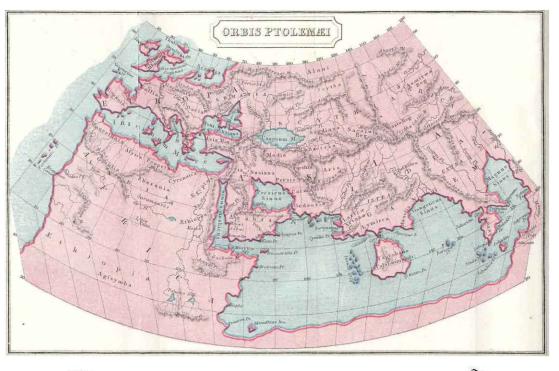




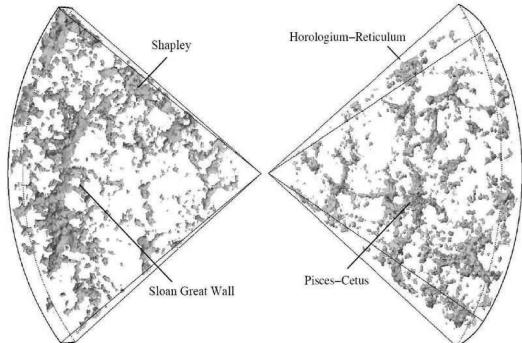


Hubble telescope, NASA









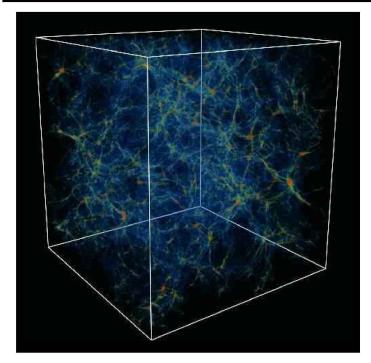


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