Scientific Thinking and the Scientific Method

“Science is not a heartless pursuit of objective information; it is a creative human activity.”

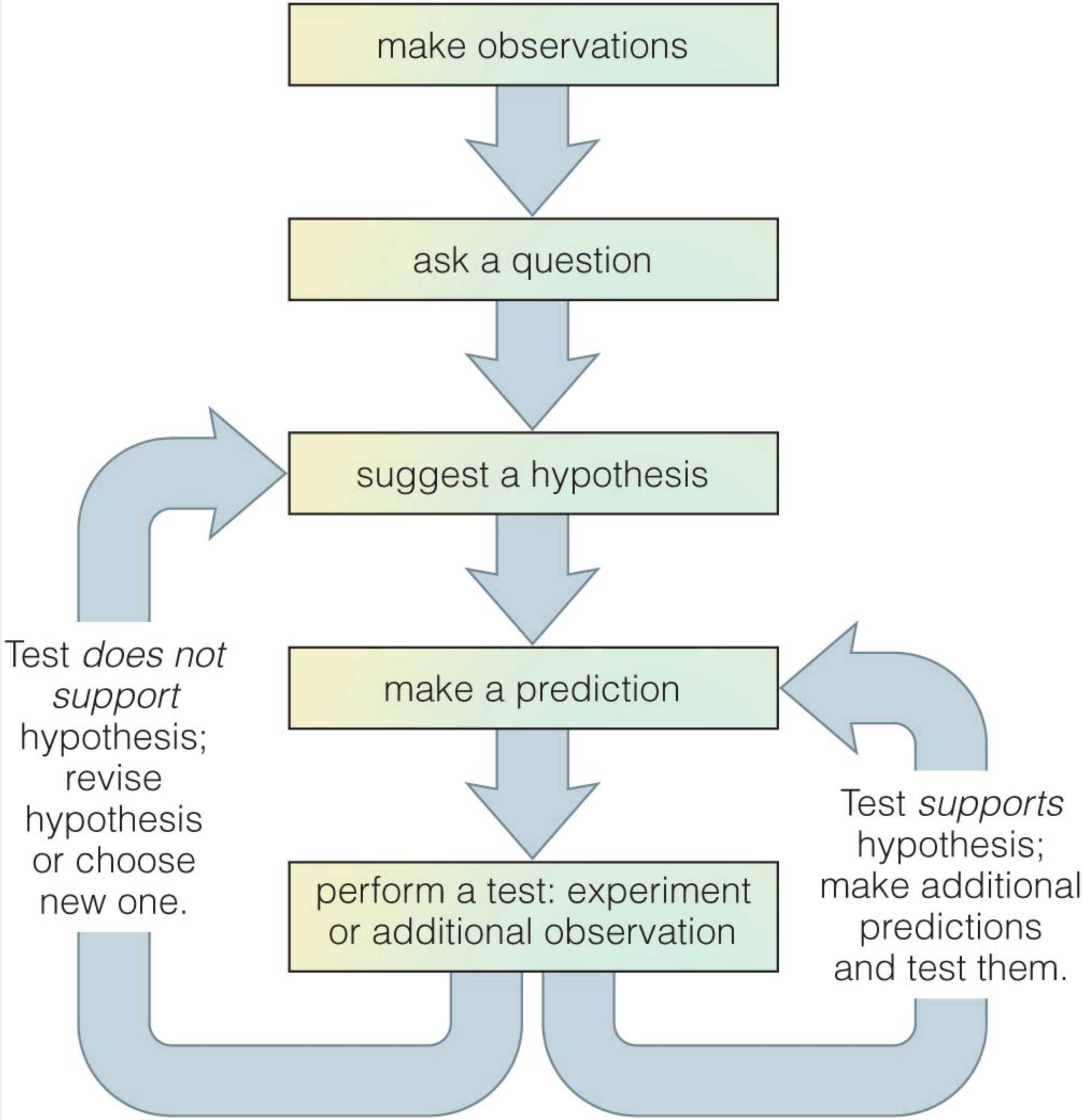
- Stephen Jay Gould (1941-2002)

What did the ancient Greeks mean by the “immutability of the heavens”?

a. the positions and brightnesses of each star remained constant over time
b. the distances of the stars remained constant
c. the stars will live forever

According to our textbook, scientific thinking is based on everyday ideas of observation and trial-and-error experiments.

Using simple equipment and simple geometry we can determine many fundamentals about the Earth (tilt with respect to the plane of its orbit, dates of summer and winter solstices, dates of spring and autumn equinoxes), positions of stars and changing positions of Moon and planets.



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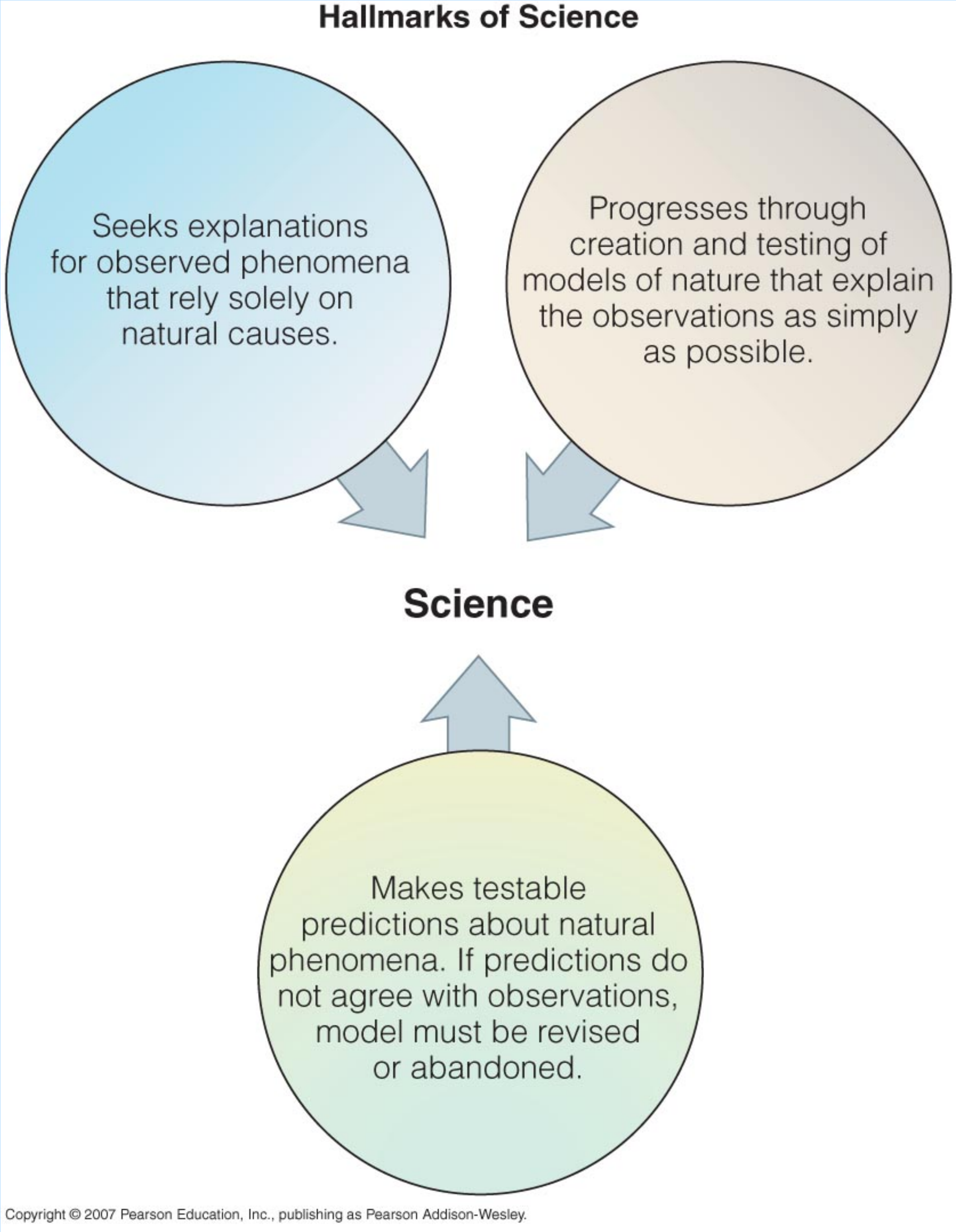
The most important thing about a scientific hypothesis is:

a) that it involves complex mathematics
b) that it involves complex verbiage
c) that it is advocated by a famous scientist
d) that it is testable



William of Occam (1285-1349) suggested that the simplest idea that explains an observed phenomenon is mostly likely the correct explanation. This perspective is known as Occam's razor.

A curious example of scrambled scientific reasoning can be seen at

http://ccinsider.comedycentral.com/2009/05/01/john-oliver-visits-the-large-hadron-collider/

A high school teacher from Hawaii insists that the Large Hadron Collider will either create a black hole, or it won't. So the probability of that happening is 50%.

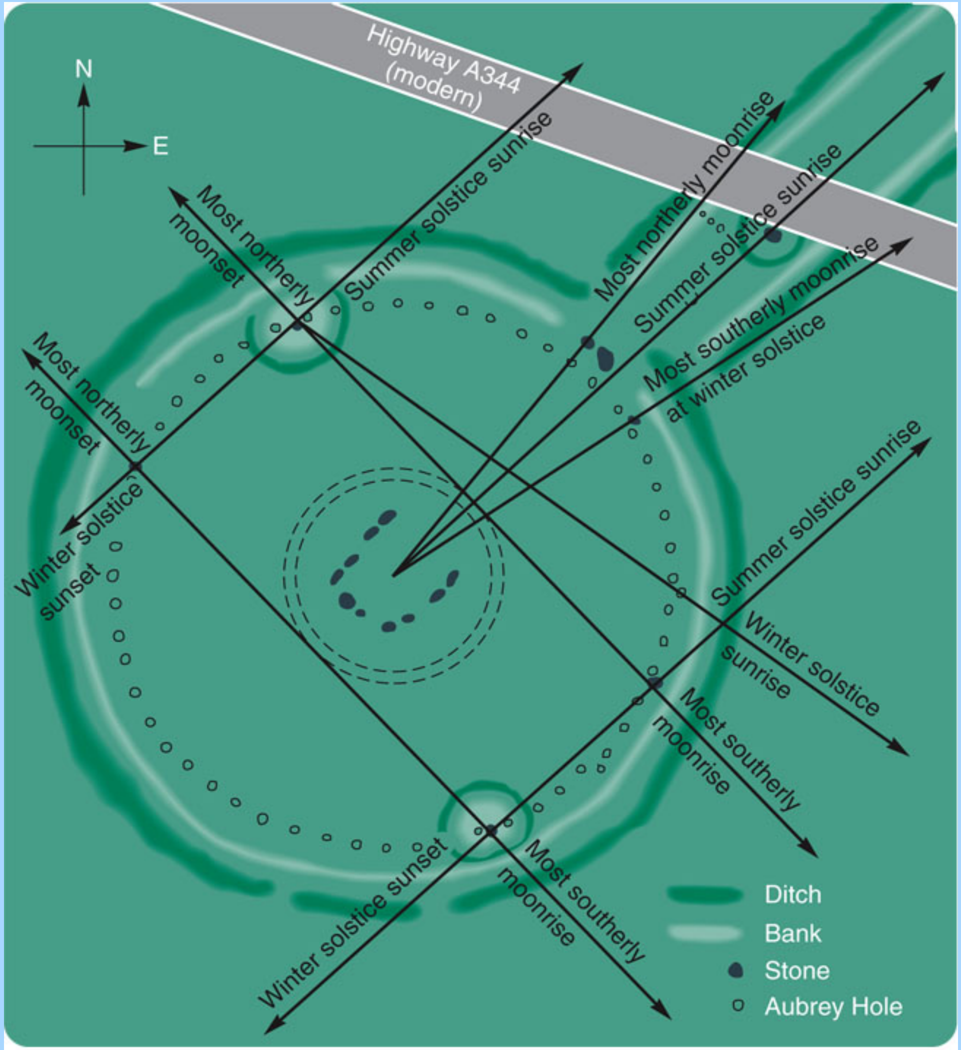
The most frequently encountered pseudoscience is *astrology*, which at best is a remote branch of psychology.

These are some of the common characteristics of *pseudoscience*:

A. It explains things people care about that may not have other explanations.
B. It explains things after the fact. (It does not make accurate predictions.)
C. If it fails, there is always an excuse – the theory is *not* discarded (e.g. astrology is only a *tendency*; it isn't supposed to always work).
D. It uses scientific-sounding jargon incorrectly

Astronomy of the ancients

Many ancient cultures took note of celestial objects and celestial phenomena. They noted certain patterns in the heavens and were able to construct calendars. The Chinese, Egyptians, Britons, Mayans, and others have left us evidence of their interest in astronomy.



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Stonehenge can be used as an astronomical calculator to some extent.
its prime purpose had to do with burial rituals.

In the history of astronomy discoveries and developments are regarded as “important” depending on a chain of influence. This could be considered cultural prejudice. Some of what we know has depended on good luck or bad luck. The Arabs preserved the astronomy of the ancient Greeks. The Spanish *conquistadores* destroyed almost all the manuscripts of the Mayans. The Chinese were more interested in astrology (or at least good luck and bad luck days) than astronomy.

For better or for worse, the highlights of ancient astronomy were almost all accomplishments of the Greeks.

Some highlights of ancient Greek astronomy

Thales (ca. 624-546 BC) – famous for his "prediction" of the eclipse of 585 BC; taught that the universe was rational and therefore could be understood

Pythagorus (ca. 582-507 BC) and his followers were fascinated by mathematical relations. Originated the notion of the "harmony of the spheres".

Philolaus (ca. 470-385 BC) – first to advocate that the Earth was in motion around a "central fire"

The Pythagoreans were fascinated with geometrical shapes and asserted that the sphere was the “most perfect”. They concluded on the basis of this theoretical idea that the Earth must be a sphere.

Aristotle (384-322 BC), the tutor of Alexander the Great, concluded that the Earth must be a sphere because only a sphere could always cast a shadow that was circular. (Recall the recent discussion about lunar eclipses.)

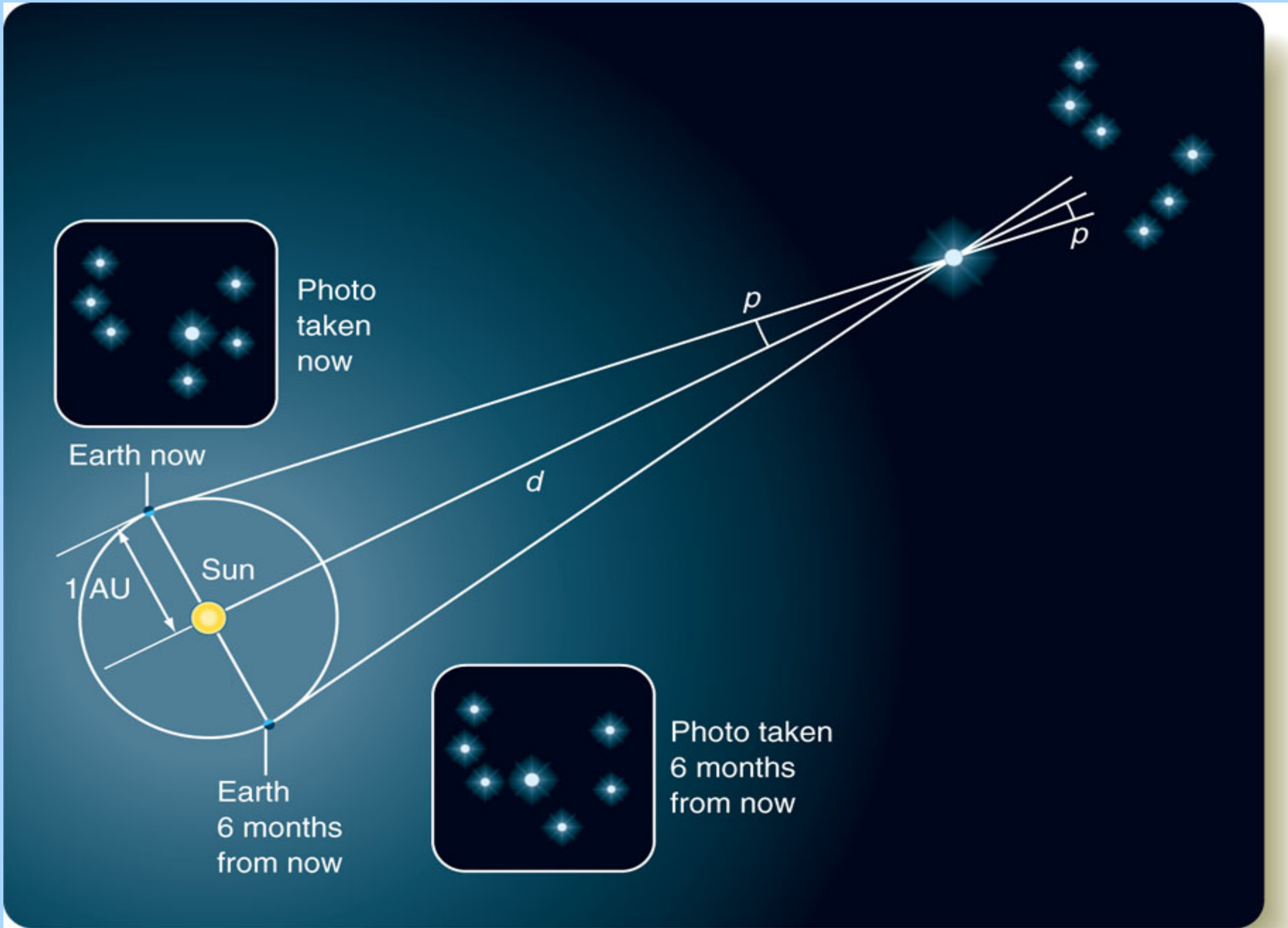
Heraclides (387-312 BC) asserted that the Sun orbited the Earth, but that Venus and Mercury orbited the Sun.

Aristarchus of Samos (ca. 310-230 BC) described a method of determining the distance to the Moon using the geometry of a lunar eclipse. He found that the Moon is 60 to 70 Earth radii distant.

He also described a method to determine the distance to the Sun in terms of the distance to the Moon. His method was correct but it is very difficult to use in practice. His value for the distance to the Sun was 19 times the distance to the Moon. The correct value is close to 400. His value for the Sun's distance was used until ~1600 AD.

Let's consider for a few minutes that the Earth revolves around the Sun and that the stars are distributed at different distances from our solar system.

How can we determine the distances to the stars in terms of the size of the Earth's orbit?



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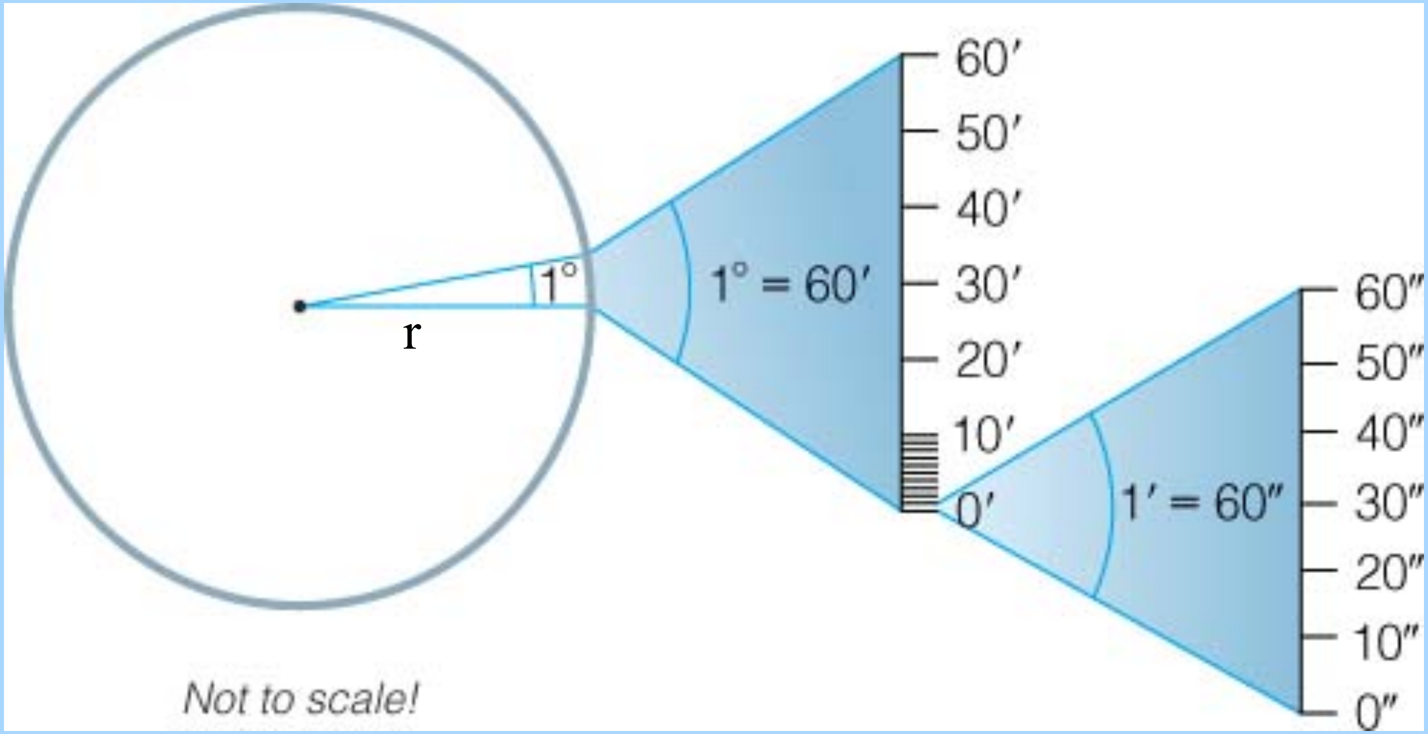


The circumference of a circle is 2π times the radius in length. If we let the radius of the circle equal 1 unit, then an arc of 1 degree will have length $2\pi/360 \sim 1/57.3$ units of length.

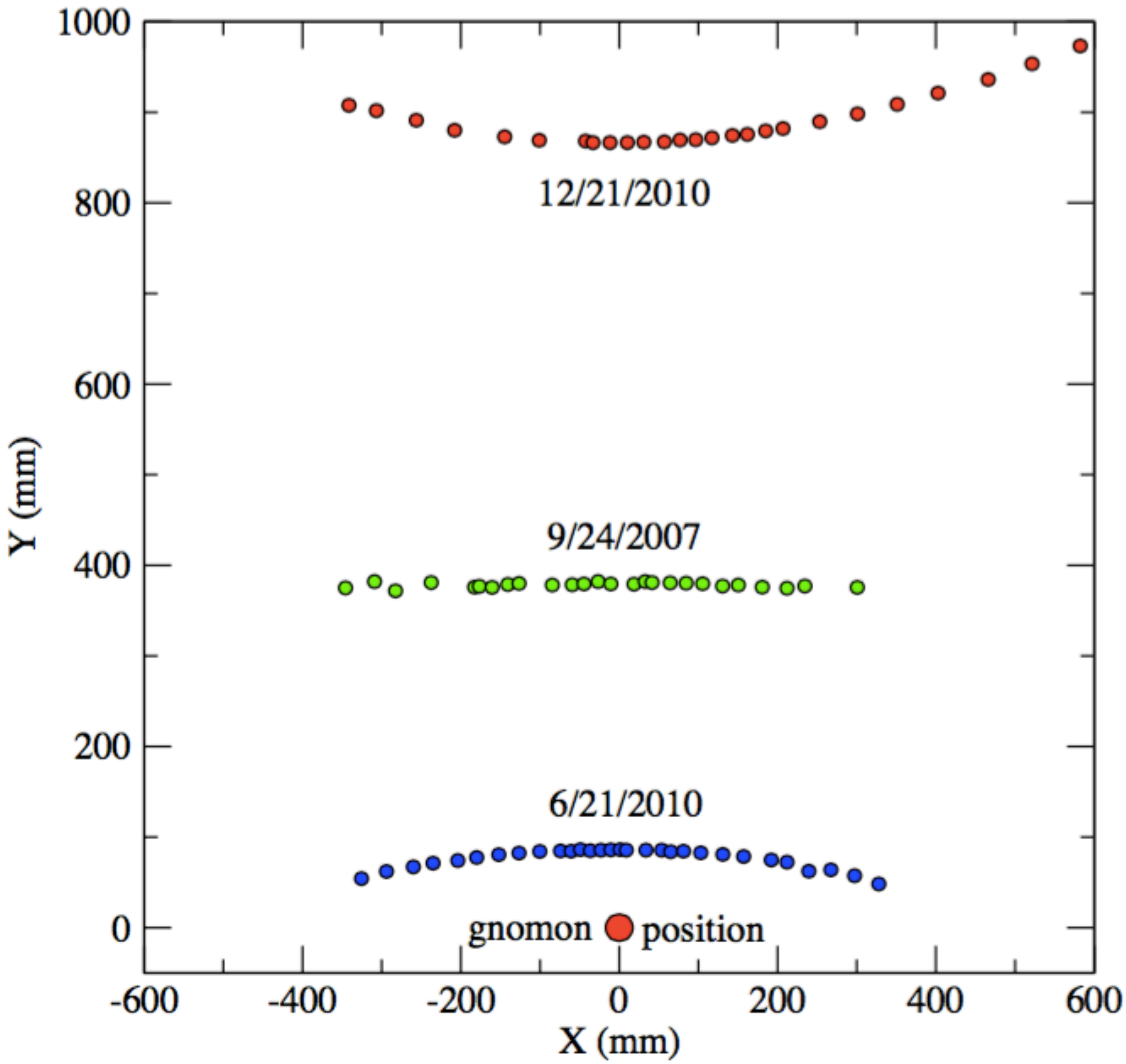
If the closest stars were as close as a couple hundred Astronomical Units, the ancient Greeks would have been able to measure the parallaxes of the nearest stars. Their equipment allowed positional measures to +/- 0.25 degree. By 1600 the best stellar positions were good to +/- 1 or 2 arcminutes. *If* the nearest stars were as close as a couple thousand AU's, parallaxes could have been measured. But no parallaxes were measured by the ancient Greeks or by Renaissance astronomers.

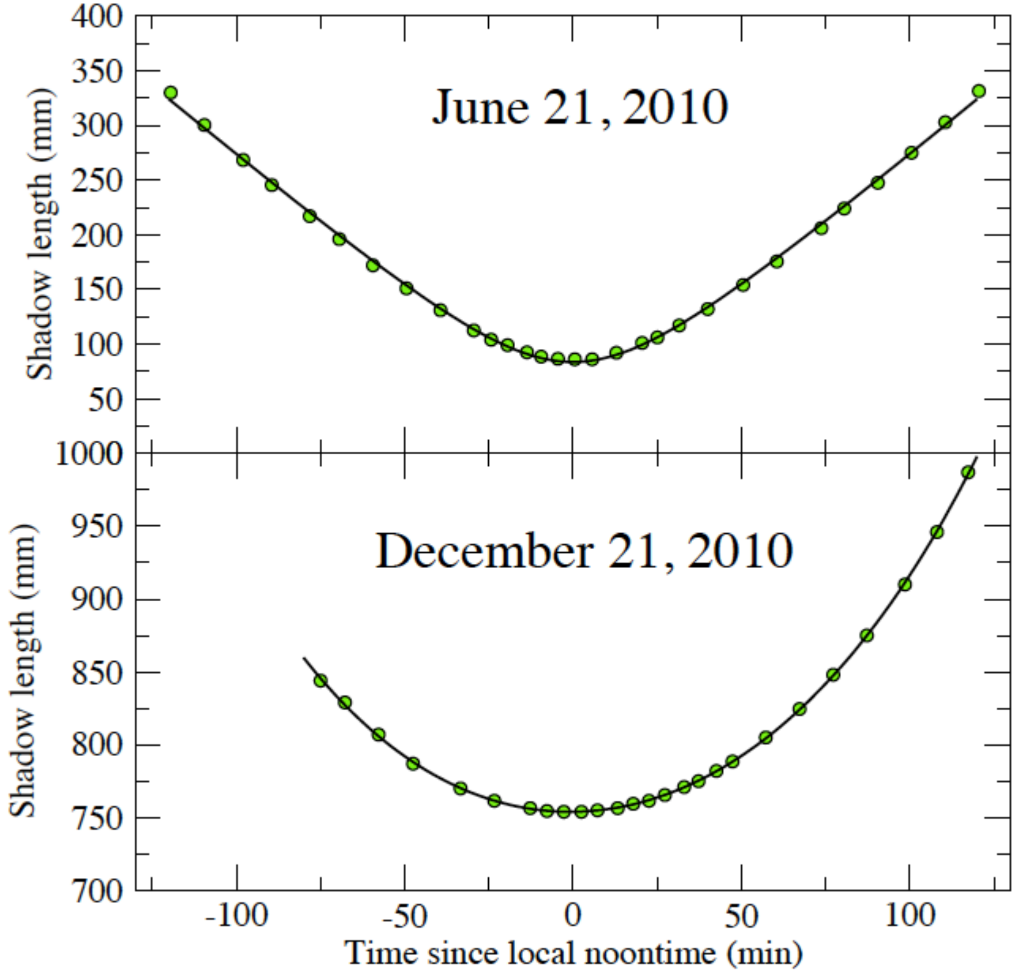
If the nearest stars had distances of 206265 AU, then they would shift back and forth on an annual basis only 1 arc second against the distant background. We call this distance one **parsec**, meaning "parallax of one second of arc". One parsec = 3.26 light-years, or 3.086 X 10^{13} km.

Even the nearest stars have parallaxes less than one arc second! It was not until the 1830's that astronomers developed telescopes and micrometers able to measure the positions of stars to a small fraction of an arc second. The *proof* that the Earth revolved around the Sun was not obtained until 300 years after Copernicus lived.

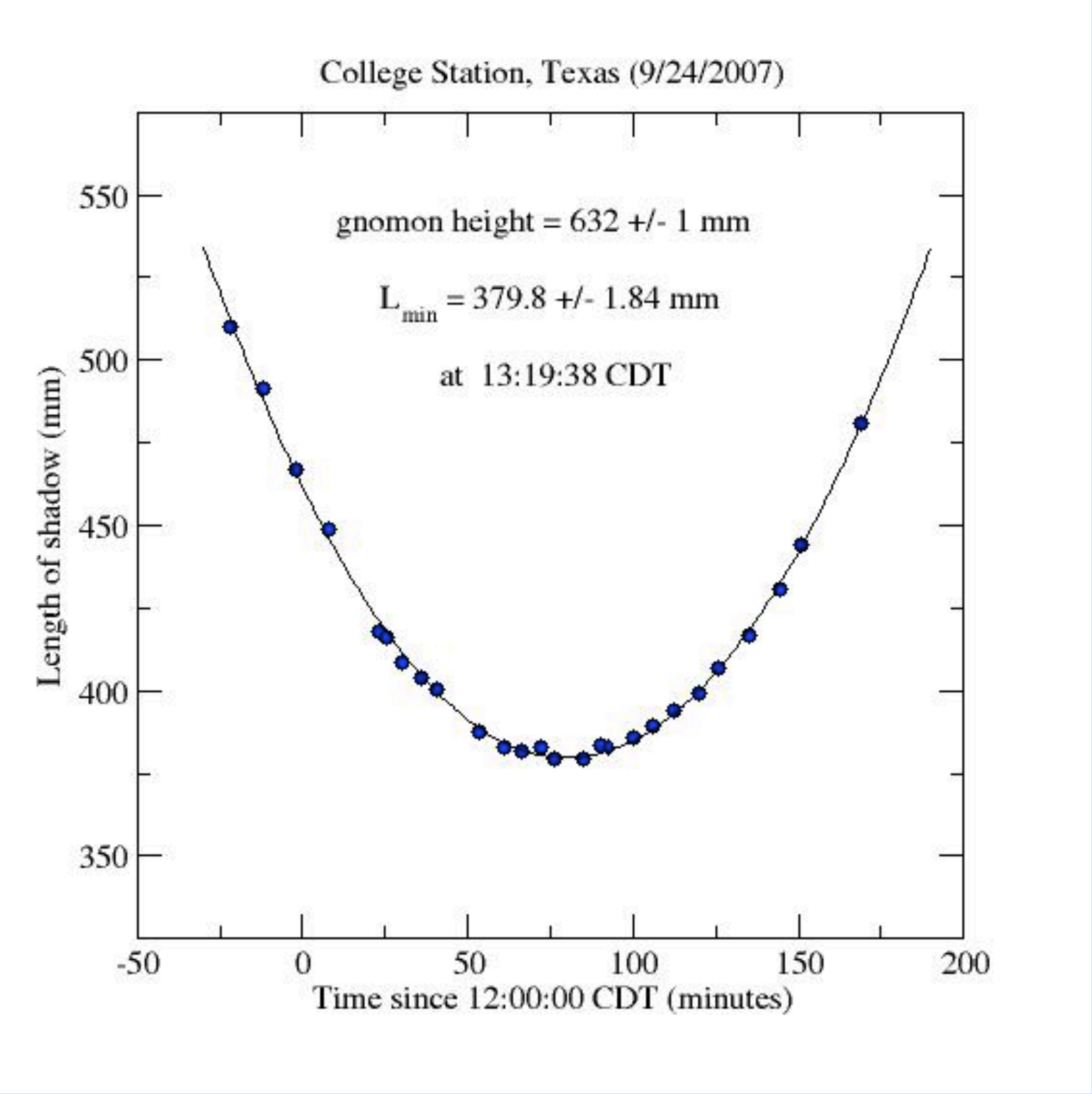
One of the simplest astronomical instruments is called a *gnomon*.

The shadow of the vertical stick can be used to determine the maximum elevation of the Sun above the horizon on a given day.

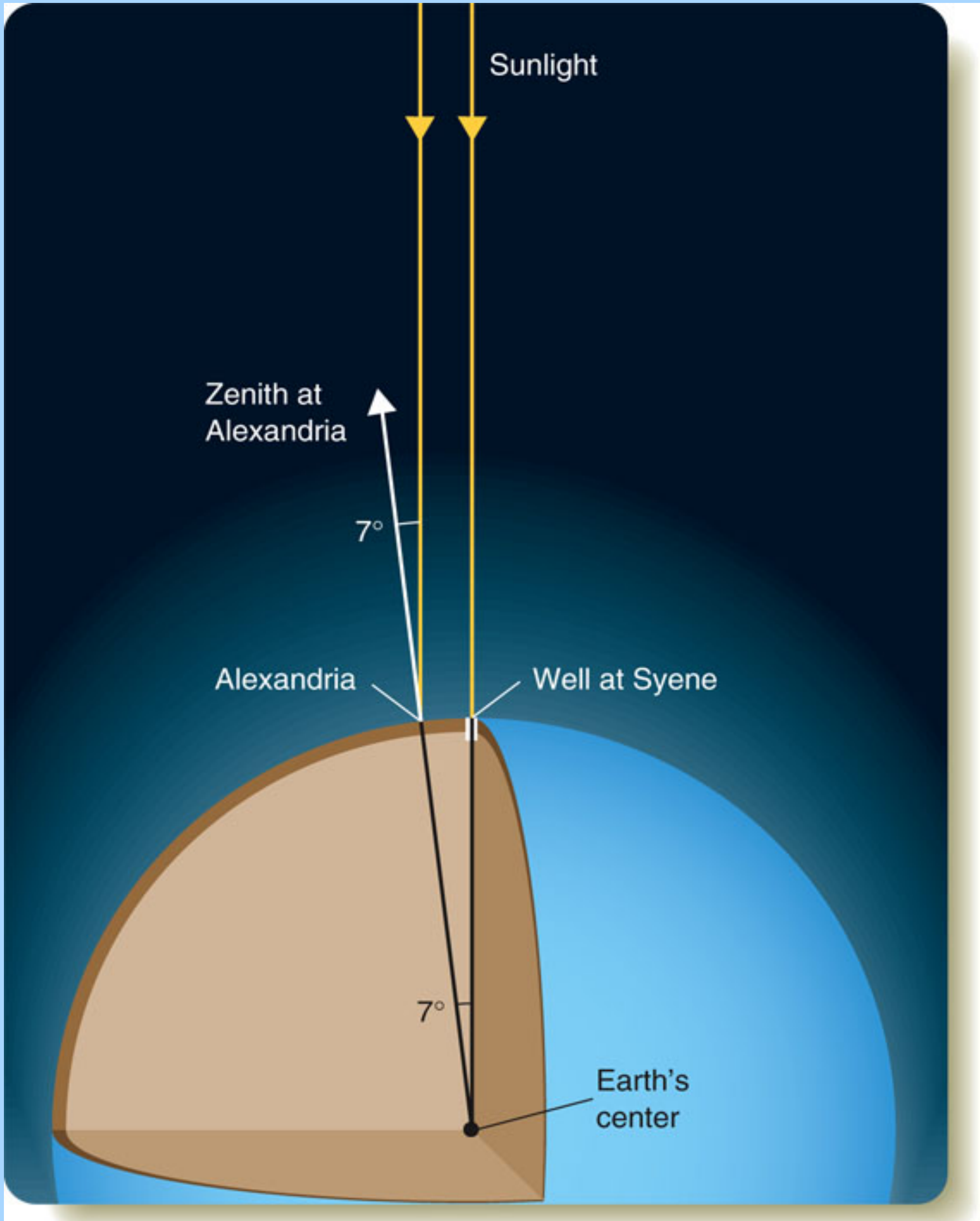

1000
800
600
400
200
0
Y (mm)
-600
-400
-200
0
200
400
600
X (mm)
12/21/2010
9/24/2007
6/21/2010
gnomon position



Krisciunas *et al.* Fig. 4


College Station, Texas (9/24/2007)
gnomon height = 632 +/- 1 mm
L min = 379.8 +/- 1.84 mm
at 13:19:38 CDT
Length of shadow (mm)
550
500
450
400
350
-50
0
50
100
150
200
Time since 12:00:00 CDT (minutes)

Eratosthenes (276-194 BC) figured out a way to measure the circumference of the Earth. Where he worked in Alexandria, he noted that on the summer solstice the elevation angle of the Sun reached 83 degrees (just like College Station). But he heard that in Syene, to the south, the sunlight went straight down wells and reflected off of the water in the bottom on that day, so he knew that Sun reached the zenith at Syene. Therefore, the two locations were 7 degrees apart in latitude. Given the linear distance between the two sites, he obtained an estimate of the size of the Earth.



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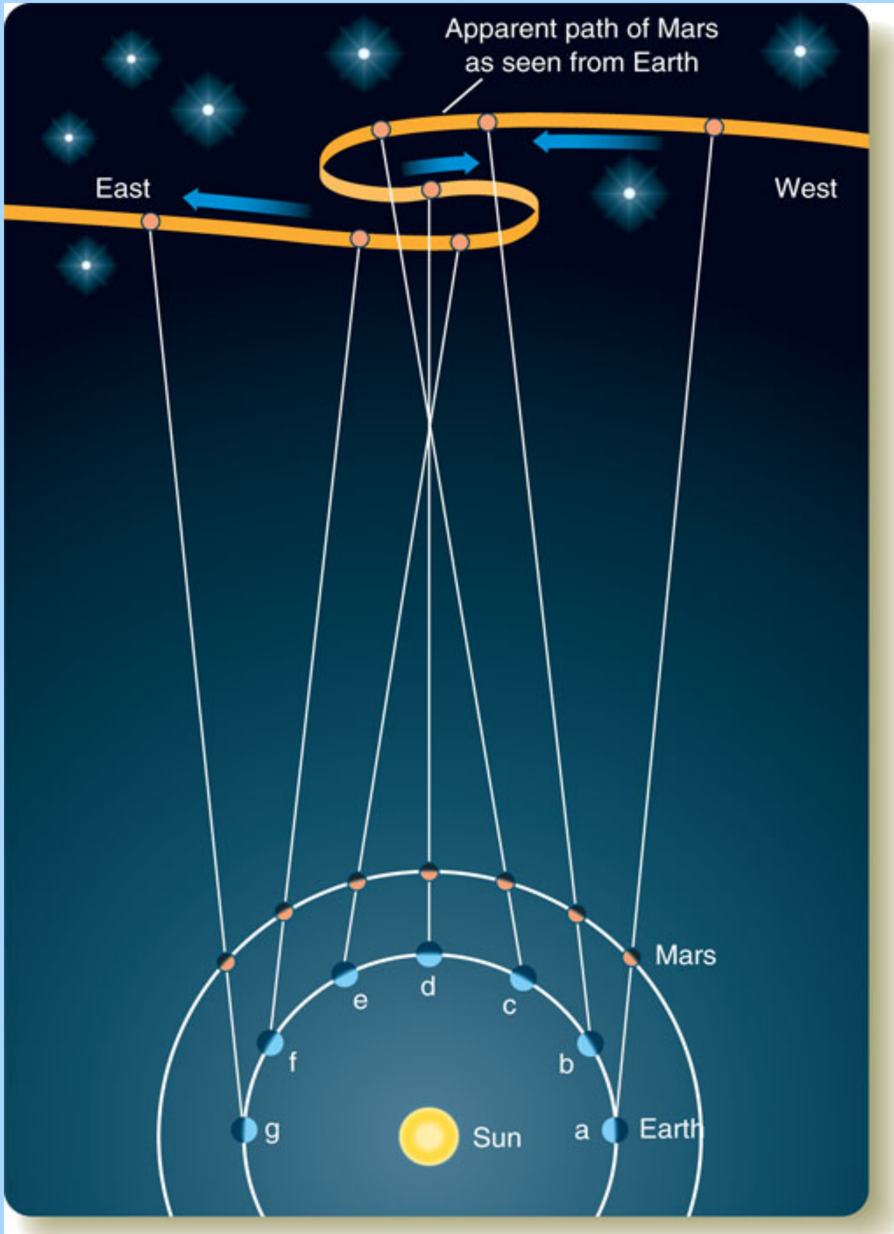
IF THE EARTH WAS FLAT
CATS WOULD HAVE PUSHED EVERYTHING OFF IT BY NOW

The word **planet** comes from the Greek, meaning "wandering star". The planets move through the constellations of the zodiac, primarily from west to east. This is called **direct motion**. Every so often a planet moves from east to west against the background of stars. This is called **retrograde motion**.

The amount of time between occurrences of retrograde motion for any given planet is called the **synodic period**.



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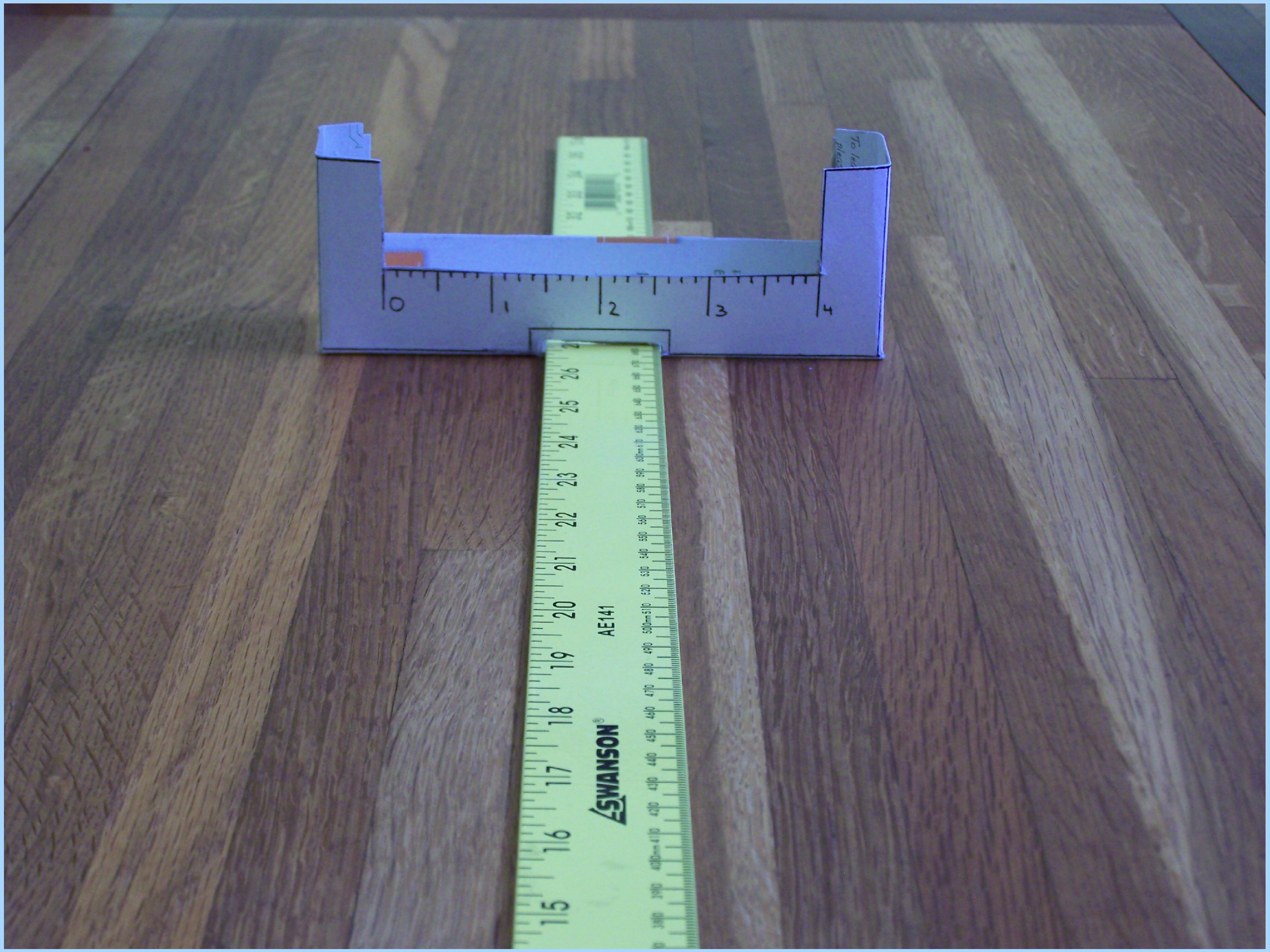
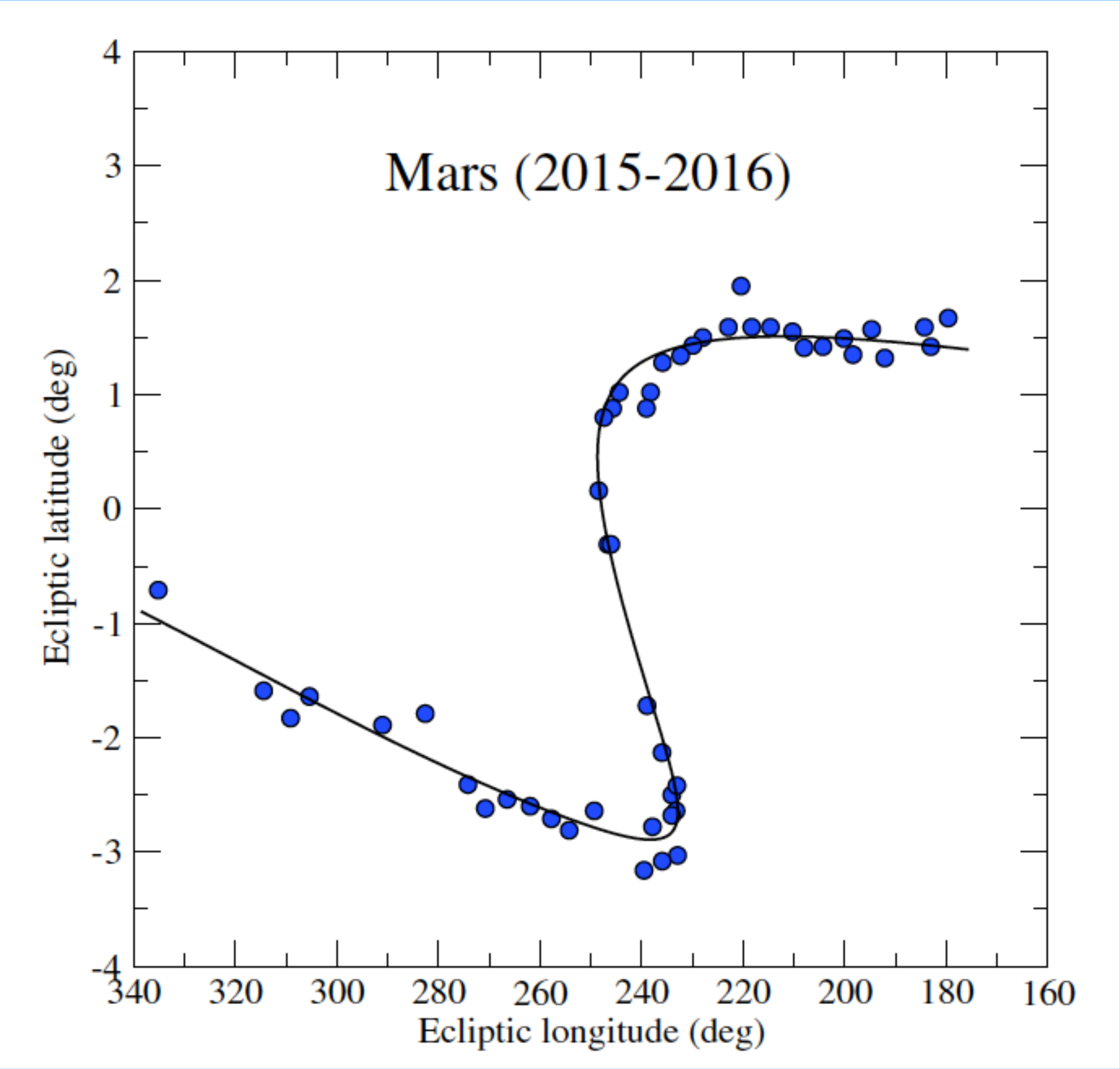
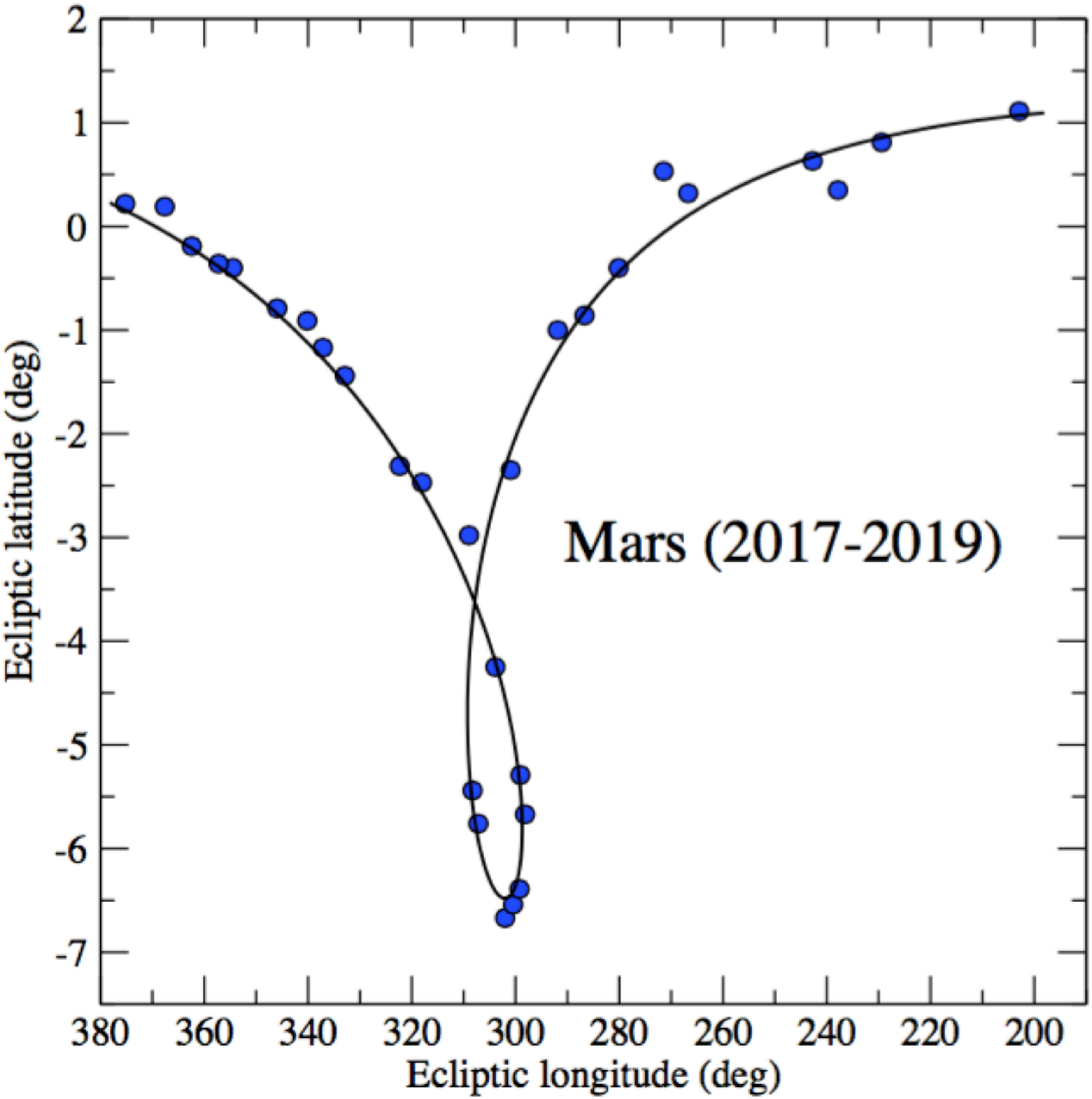
So let’s do an experiment using a simple cross staff:

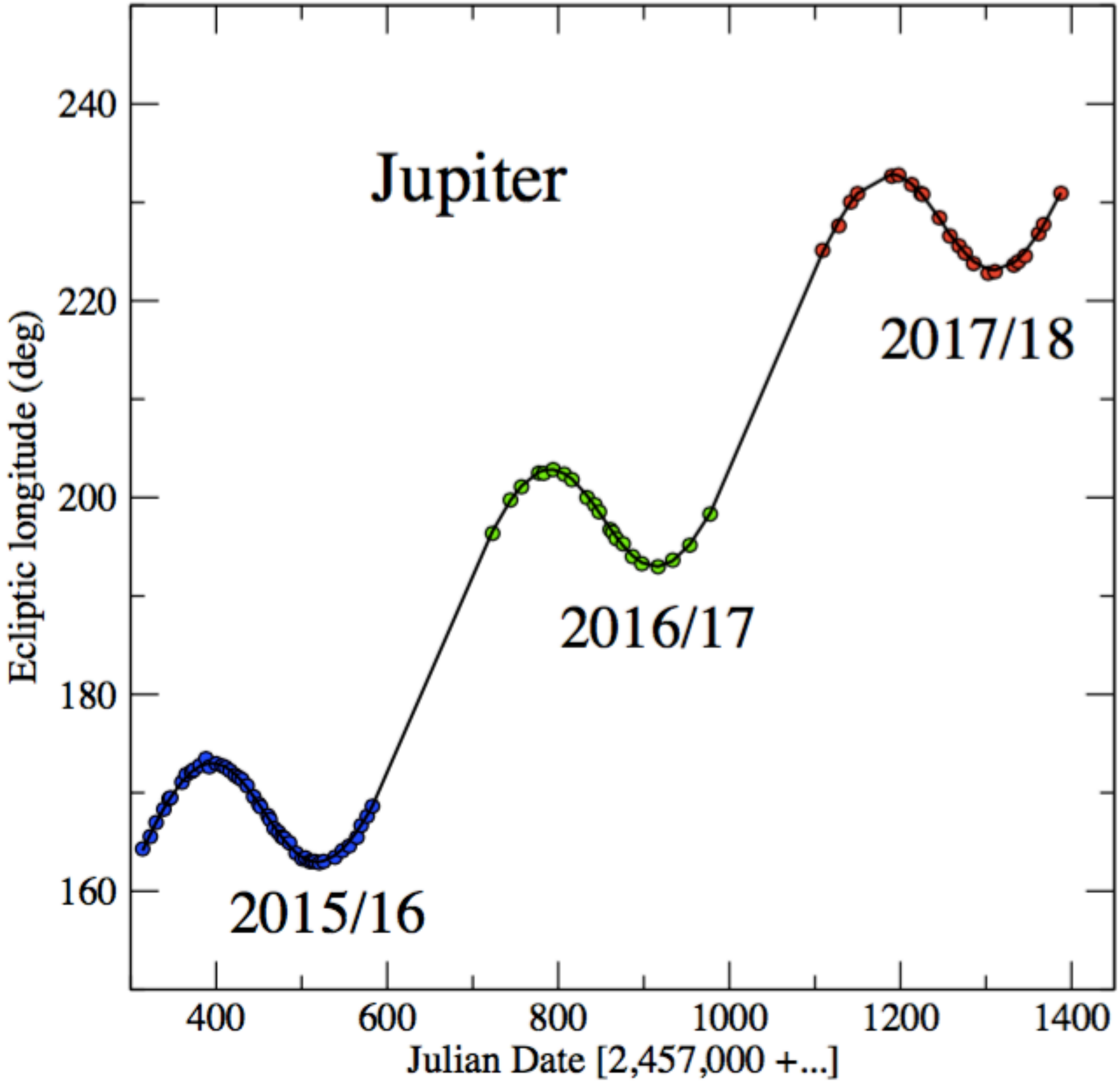




Actual positions of Mars, measured with a simple cross staff and reference stars of known position.

As we can see, the primary motion of Mars is to increasing ecliptic longitude (east). But for 75 days it was moving west (retrograde).


Mars (2017-2019)
Ecliptic latitude (deg)
Ecliptic longitude (deg)
2
1
0
-1
-2
-3
-4
-5
-6
-7
380
360
340
320
300
280
260
240
220
200

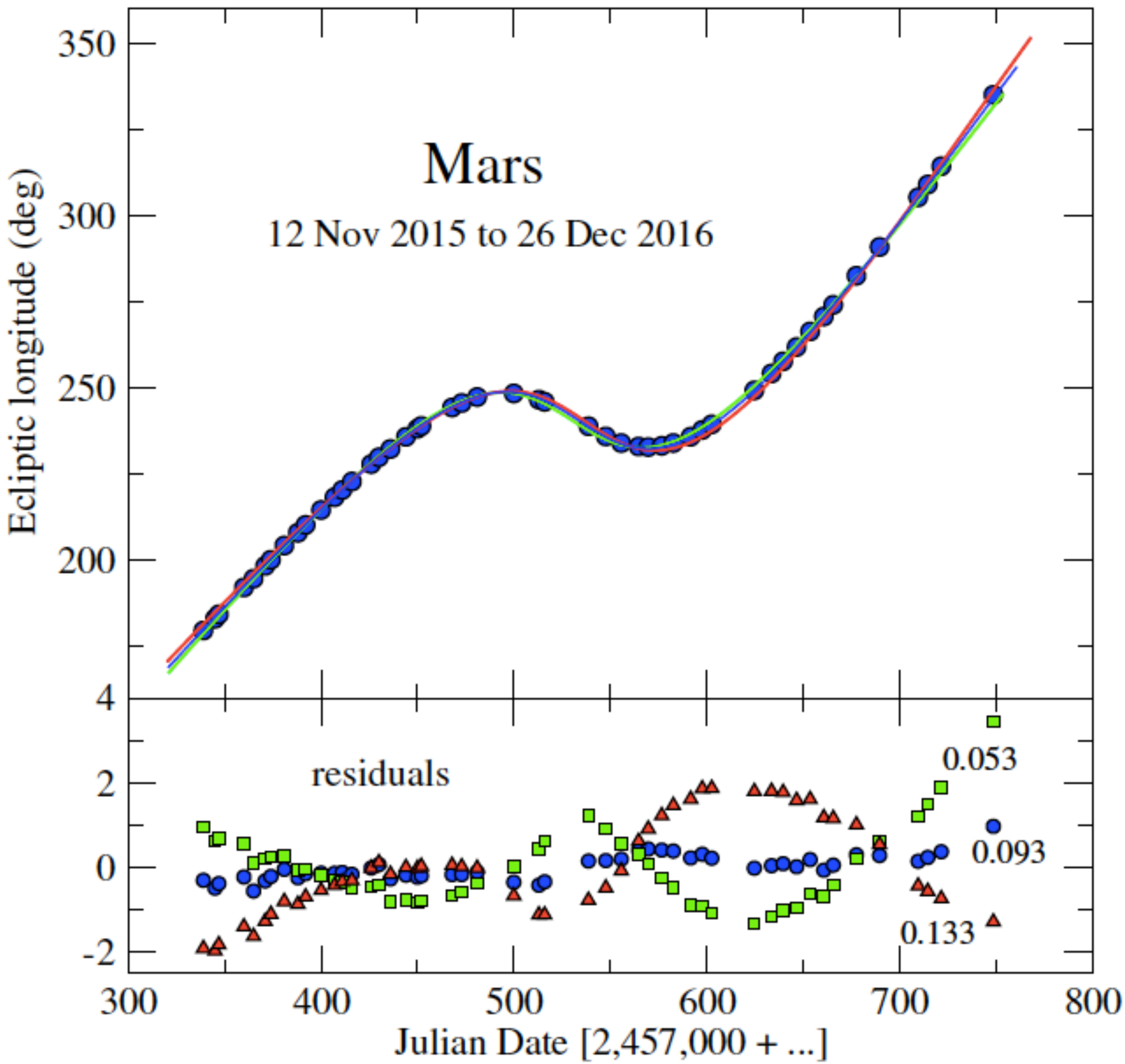


Jupiter
2015/16
2016/17
2017/18
240
220
200
180
160
400
600
800
1000
1200
1400
Ecliptic longitude (deg)
Julian Date [2,457,000 +...]

Measured duration and angular size of retrograde loop

Planet	Δt (days)	$\Delta\lambda$ (degrees)	
Mars	73.3	16.4	(2016)
	61.9	10.7	(2018)
Jupiter	123.9	10.0	(2015/16)
	121.1	9.3	(2016/17)
Saturn	143.5	6.7	(2015/16)
	134.7	6.4	(2016/17)

As we proceed outward in the solar system, the retrograde loops get smaller and smaller.


Mars
12 Nov 2015 to 26 Dec 2016
Ecliptic longitude (deg)
350
300
250
200
4
2
0
-2
residuals
0.053
0.093
0.133
300
400
500
600
700
800
Julian Date [2,457,000 + ...]

Planet	sidereal period (years)	synodic period (days)
Mercury	0.24	116
Venus	0.62	584
Mars	1.88	780
Jupiter	11.86	399
Saturn	29.4	378

If you are located on one planet (A) orbiting the Sun with period P_A and you observed another planet (B), whose orbital period about the Sun is P_B, the synodic period is given by this formula:

$$1/P_{syn} = 1/P_A - 1/P_B \quad .$$

The Earth‘s orbital period is 365.2422 days, while that of Mars is 686.9 days. The synodic period is 780 days (2.14 years).

A useful model of the motion of the planets accounts for:

1. existence of the ecliptic
2. retrograde and direct motion
3. the synodic periods
4. changes of brightness of the planets
5. changes in the angular velocities of the planets

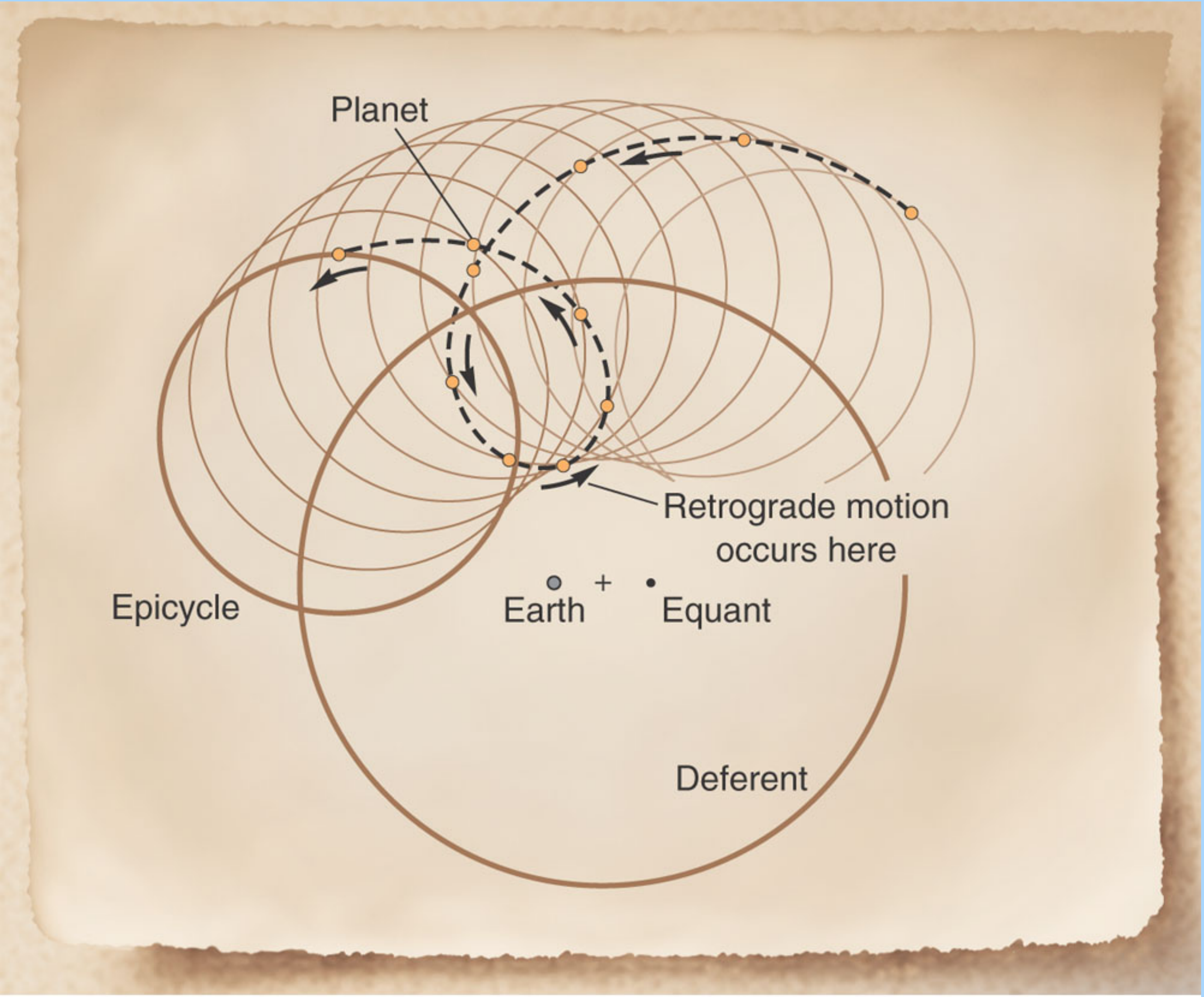
Hipparchus (ca. 190-120 BC) accomplished much:

1. catalogue of 1000 stars
2. classified stars by brightness
3. discovered precession of the equinoxes
4. determined: obliquity of the ecliptic
5. synodic periods of planets
6. inclination of Moon's orbit
7. place of Sun's "apogee"
8. eccentricity of the "Sun's orbit"
9. estimate of the Moon's parallax, using the diameter of the Earth as a baseline

He put astronomy on a geometrical basis.

The Greeks had a notion that because the planets were located in the heavens, their motions must be "perfect". Uniform, circular motion was regarded as perfect. So - the planets must move through space uniformly on circles.

But – the planets do not move uniformly to the east against the stars. Therefore, to "save the phenomenon" of uniform motion, the Greeks postulated that each planet could move on one circle, whose center uniformly moved on another circles. This was the system of **deferents** and **epicycles**.



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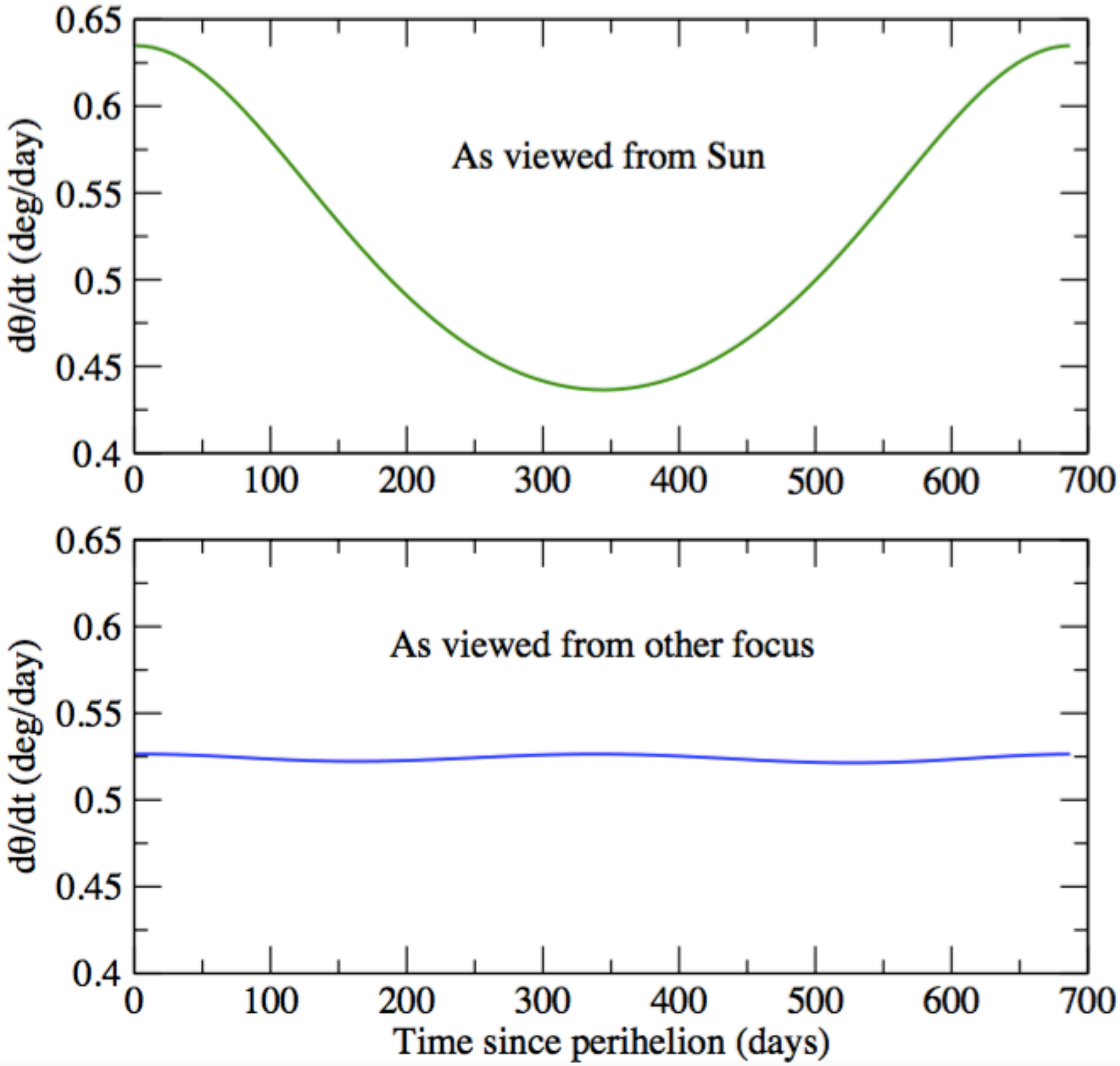
In order to account for the varying brightness of the planets, the Greeks also invented the **equant** point. The center of an epicycle appeared to move at a constant rate as seen from the equant.

Because of the *requirement* that the motion of each planet must be described by uniform, circular motion, the geometry of the Greek model of the solar system became very complex. Each planet had many epicycles.

Angular motion of Mars



Another great astronomer of ancient times was Claudius Ptolemy (ca. 100-170 AD), who worked at the Alexandrian Museum. He summarized Greek astronomy in the *Almagest*, a work which has been preserved.

As mathematician David Hilbert said, "The importance of a scientific work can be measured by the number of previous publications it makes superfluous to read."

For over a thousand years, Ptolemy had no successor, just commentators.

Epigram from Ptolemy: “I know that I am mortal and the creature of a day; but when I search out the massed wheeling circles of the stars, my feet no longer touch the earth, but, side by side with Zeus himself, I take my fill of ambrosia, the food of the gods.”

Translated by Thomas Heath in *Greek Astronomy* (1932, 1991 reprint).

The muses

Calliope (epic poetry), Euterpe (lyric song), Clio (history), Erato (erotic poetry), Melpomene (tragedy), Polyhymnia (sacred song), Terpsichore (dance), Thalia (comedy and bucolic poetry), and Urania (astronomy).

Where do the muses reside? In a **museum**, of course!

In a way, Ptolemy can be considered a plagiarist. He probably did not reobserve the 1000 brightest stars visible from Alexandra. He simply took the star catalogue of Hipparchus and precessed the coordinates for precession by adding the same angular value to the celestial longitudes of those stars. How do we know this? Hipparchus's value for precession was 1degree per century, and the correct value is 1 degree per 72 years. If Ptolemy had observed all the stars again, shouldn't some of the positions of the stars be ahead, and some behind, those of Hipparchus, adjusted for precession?

During medieval times the astronomy of the Greeks was preserved by the Moslems. Centers of astronomical scholarship included Baghdad (9th century), Cairo (10th century), Cordova (10th century), and Toledo (11th century).

The Mongolian-Turkish prince Ulugh Beg (1394-1449), who lived in Samarkand (in modern-day Uzbekistan), hired a number of astronomers to work with him. They reobserved the 1000 brightest naked eye stars – the first time this had been done perhaps since the time of Hipparchus. This required the construction of observing instruments, such as a meridian sextant with a radius of 40 meters!


Почта СССР 1987
5 к
1394-1449
Узбекский астроном и математик УЛУГБЕК
1437
„Новые астрономические таблицы“ –
главный труд обсерватории
Улугбека,
излагающий теоретические основы
астрономии и сведения
о наблюдении
звезд.
Обсерватория Улугбека в Самарканде
(схема разреза по меридиану)

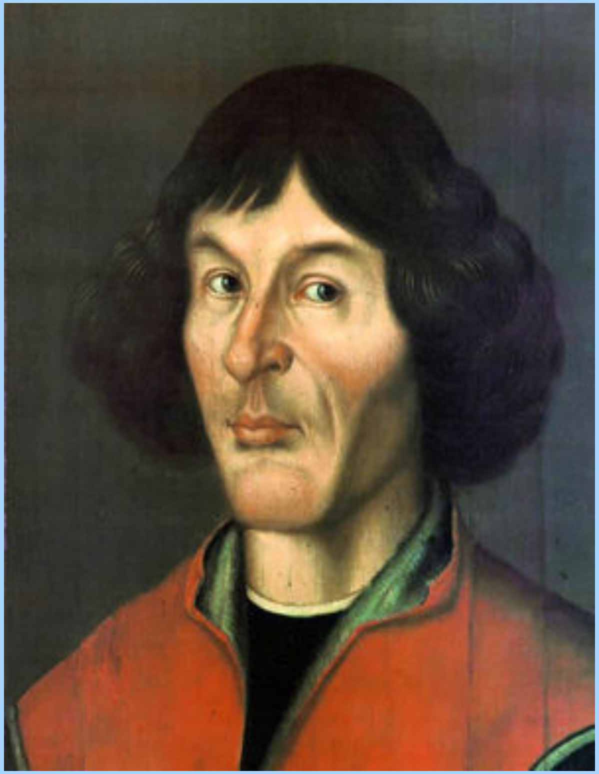
Meanwhile, back in Europe.......

In the 12^{th} and 13^{th} centuries universities were founded: Bologna, Paris, Oxford, the Sorbonne, Cambridge...

King Alfonso X of Castile ("el Sabio") was patron of a group of astronomers who revised Ptolemy's tables of the motion of the Sun, Moon, and planets. He is reputed to have said, "If I had been present at the creation of the world, I would have proposed some improvements." They published the Alfonsine tables, the last great revision of Ptolemaic astronomy.

1543 – the *annus mirabilis* (miracle year)

Andreas Vesalius (1514-1564), *De humani corporis fabrica* (on the workings of the human body)

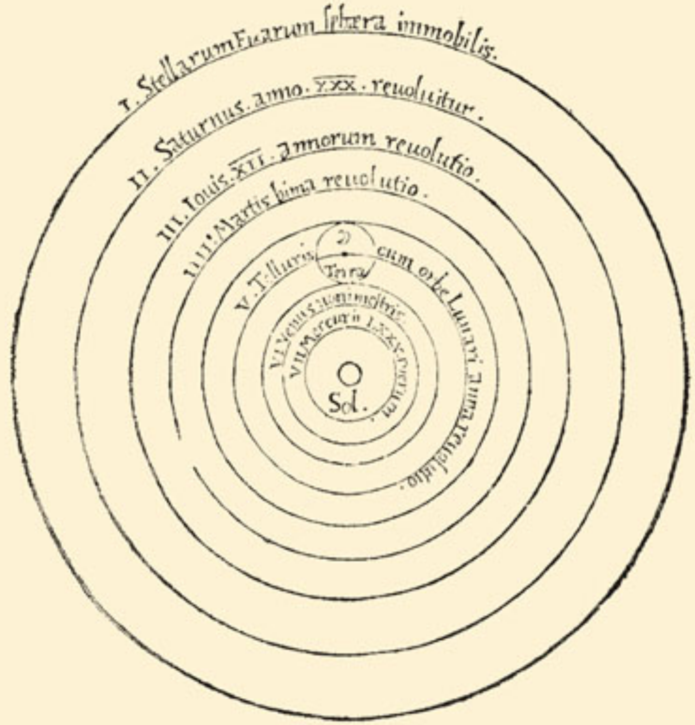


Nicholas Copernicus (1473-1543), *De revolutionibus orbium coelestium* (on the revolutions of the heavenly spheres). Copernicus's great book was published shortly after his death.

When did we prove that Copernicus was right, that the Earth really does orbit the Sun?

A. 1543, when his book was published
B. 1610, when Galileo first observed with a telescope
C. 1687, when Newton published the Law of Gravity
D. 1830's, when astronomers measured the first trigonometric parallaxes

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono menſe reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum ſpacio circū currens. In medio uero omnium reſidet Sol. Quis enim in hoc



pulcherrimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum ſimul poſsit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegiſtus uiſibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in ſolio regali Sol reſidens circum agentem gubernat Aſtrorum familiam. Tellus quoque minime fraudatur lunari miniſterio, ſed ut Ariſtoteles de animalibus ait, maximam Luna cum terra cognationē habet. Cōcipit interea à Sole terra, & impregnatur annno partu. Inuenimus igitur ſub

hac

a

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On this famous page, Copernicus wrote: "In the very center of all the Sun resides. For who would place this lamp in another or better place within this most beautiful temple, than where it can illuminate the whole at once? Even so, not inaptly, some have called it the light, mind, or ruler of the universe. Thus indeed, as though seated on a throne, the Sun governs the circumgyrating family of planets."

Clearly, Copernicus is not just describing a mathematical model of the solar system, put together solely to calculate the positions of the planets. He is appealing to our sense of aesthetics.

Copernicus would have been dismayed to learn that an anonymous preface was added to his book, which claimed that the Sun-centered *(heliocentric)* model of the universe was just a model and had nothing to do with reality.

Why did this happen? The political realities of the time made it dangerous to assert that the Earth was not the center of the world. Joshua (10:12) commanded the Sun to stand still, not the Earth. Psalm 93 states that "the world also is established, that it cannot be moved." Psalm 104, verse 5, says something quite similar.


SOMEDAY, MR. NICKY COPERNICUS, SOMEDAY YOU'LL LEARN THAT THE WORLD DOESN'T REVOLVE AROUND YOU!
CARTOONSTOCK .com
Search ID: bven594

The word **paradigm** means a fundamental idea which has many implications. In a way it is an assumption, but one that results in specific predictions, which we can test and confirm or refute. It has become a commonly used word as a result of the success of Thomas Kuhn's 1962 book *The Structure of Scientific Revolutions*. Examples of scientific paradigms are: 1) the Earth is just one of a number of planets, and it orbits the Sun; 2) natural selection causes the extinction of species and the creation of new species; 3) the continents are attached to plates, which slowly move over time.

Copernicus's *hypothesis* was correct. The Earth does orbit the Sun. This correctly explains retrograde motion, the changing brightness of the planets, and it makes certain predictions, such as the phases of the planets, and stellar parallax.

However, Copernicus's *model* of the solar system was not correct. He retained the idea of circular motion, so even he needed epicycles!

What was the fundamental **paradigm** of ancient Greek astronomy?

a. Mercury and Venus orbit the Sun, but the Sun and outer planets orbit the Earth
b. the Sun is at the center of the solar system
c. the Earth is at the center of the solar system
d. the apparent motion of the Sun traces out the ecliptic