

The Copernican Revolution - Separating Science and Superstition

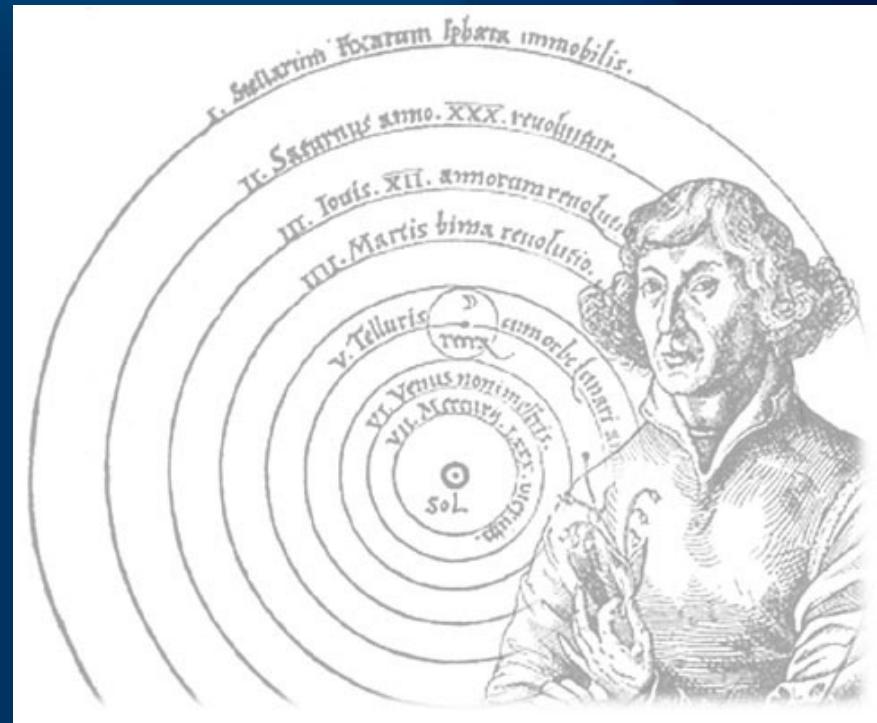


J. Pinkney
ONU 2025



Outline

- Our universe viewed by the ancients
- Greek astronomy
- Copernican Revolution
 - Nicolaus Copernicus
 - Tycho Brahe
 - Johannes Kepler
 - Galileo Galilei
 - Isaac Newton
- Loose ends: first parallax, aberration of starlight
- Science vs Superstition: it never ends



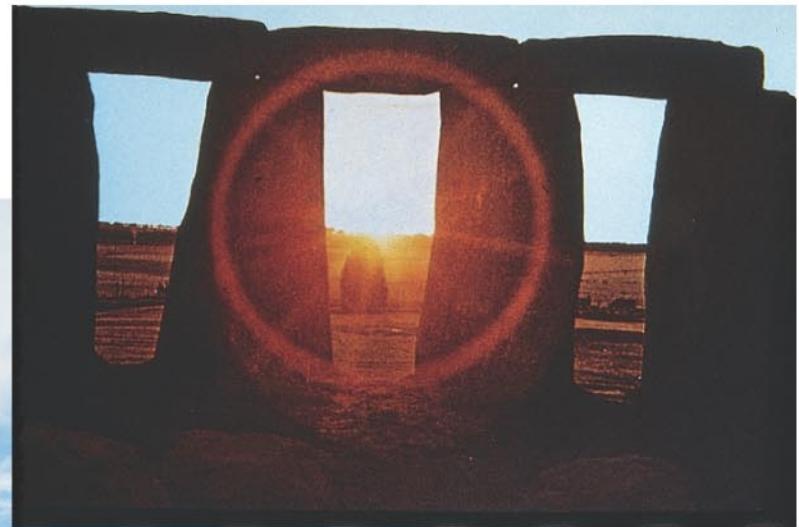
What the Ancients Knew

The Naked-Eye Universe

- The Sun (daily motion and annual motion)
- The Moon (phases, eclipses)
- 5 Planets (not including the Earth)
 - Mercury, Venus, Mars, Jupiter, Saturn
- 6500 Stars
- 3 galaxies
- Occasional novae and supernovae
- Comets
- Aurora, meteors, and other atmospheric phenomena

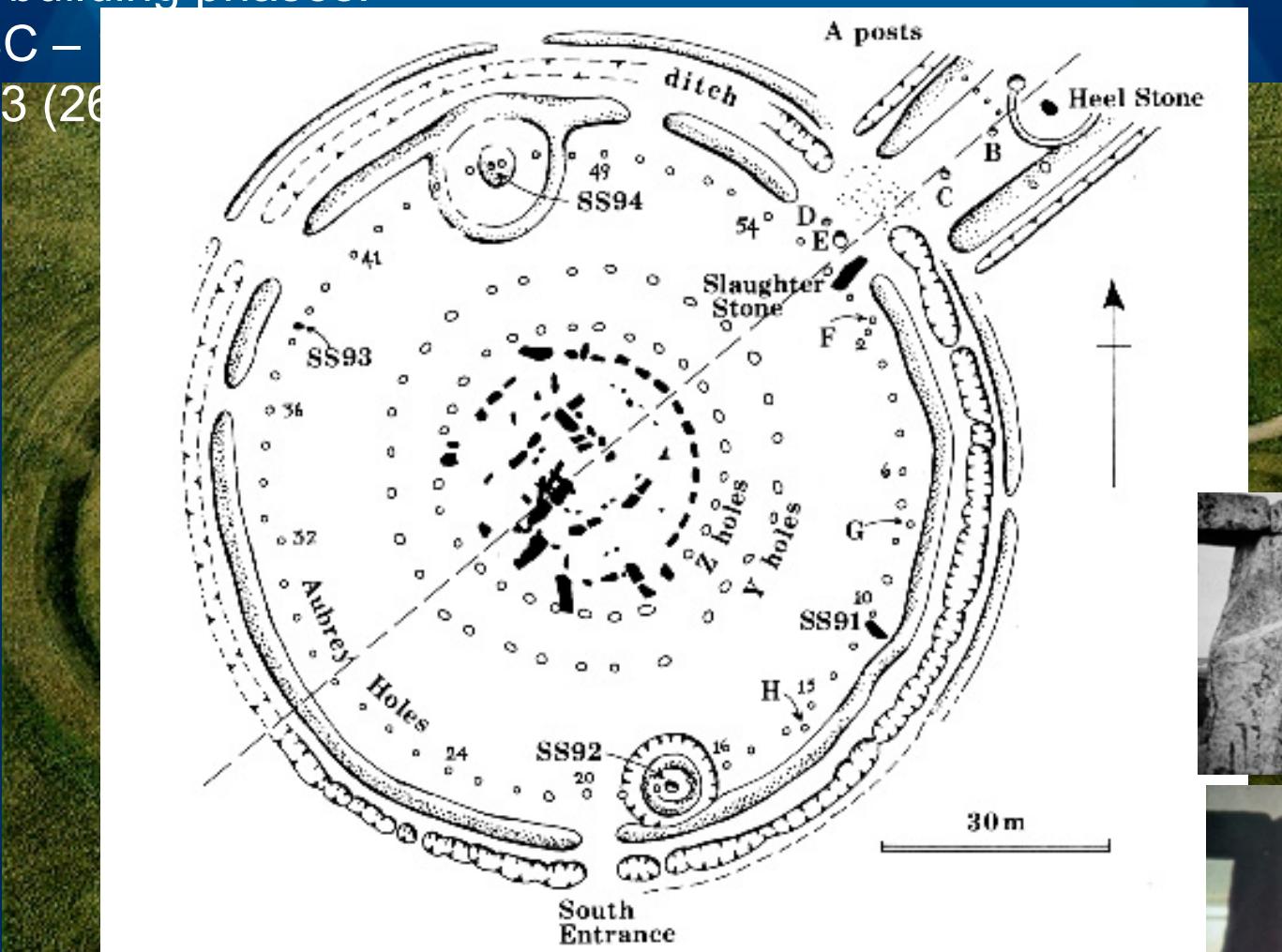


Stonehenge



The Ancients: Stonehenge

- 3 Main building phases:
- 3100 BC –
- Phase 3 (2600 BC)

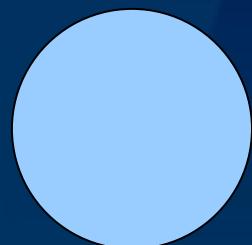
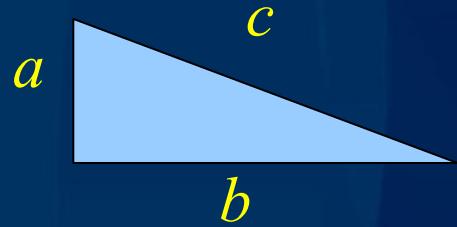


— 30 Y-holes, 28/29 Z-holes, 56 Aubrey holes ~ 3 Saros cycles*
— Heel stone marks sunrise on Summer Solstice

*actually Earth-Moon precession cycles (18.6 yrs)

Knowledge of the Ancient Greeks

- Ideas and philosophies were rich and varied, some correct and some **incorrect**.
 - Thales of Miletus (624-547 BC):
 - Universe is rational
 - Pythagoras (570-497 BC):
 - Math in nature, **music of spheres**
 - Earth and planets are spherical
 - Plato (428-347 BC):
 - Truth through pure thought over observations
 - Circle is most perfect form



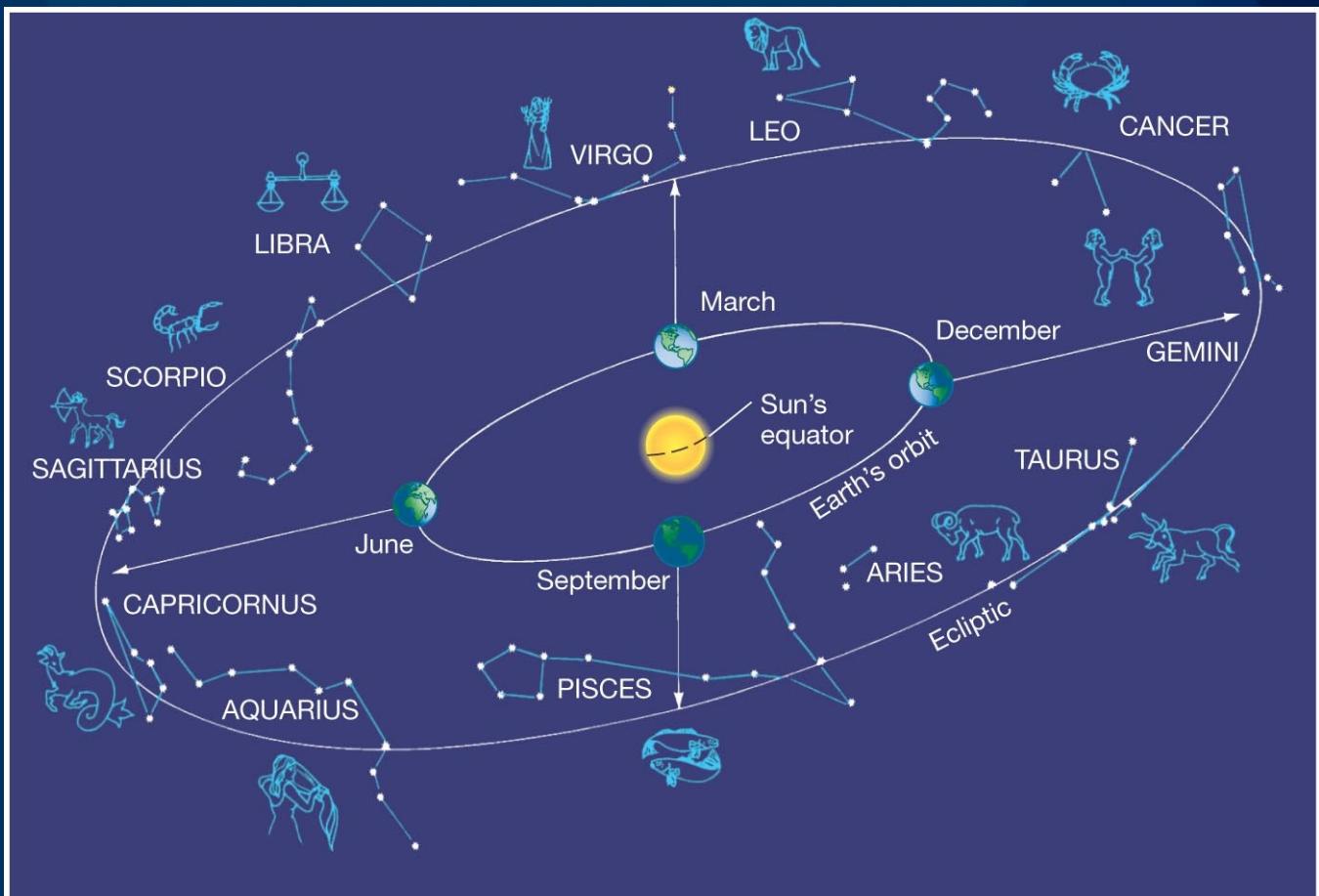
Knowledge of the Ancient Greeks

- Aristotle (384-322 BC):
 - Earth is unmoving, heavens are perfect
 - Everything made of 4 elements: earth, water, wind, fire
 - If Earth rotated, we'd feel a wind
 - Phases of the Moon
 - If Earth revolved, the stars should exhibit parallax

Knowledge of the Ancient Greeks (cont.)

Parallax = the apparent motion or shifting of an object caused by the motion or shifting of the observer.

Biggest stellar parallax is only $\sim 1.0''$, so the Greeks had no hope of detecting it.



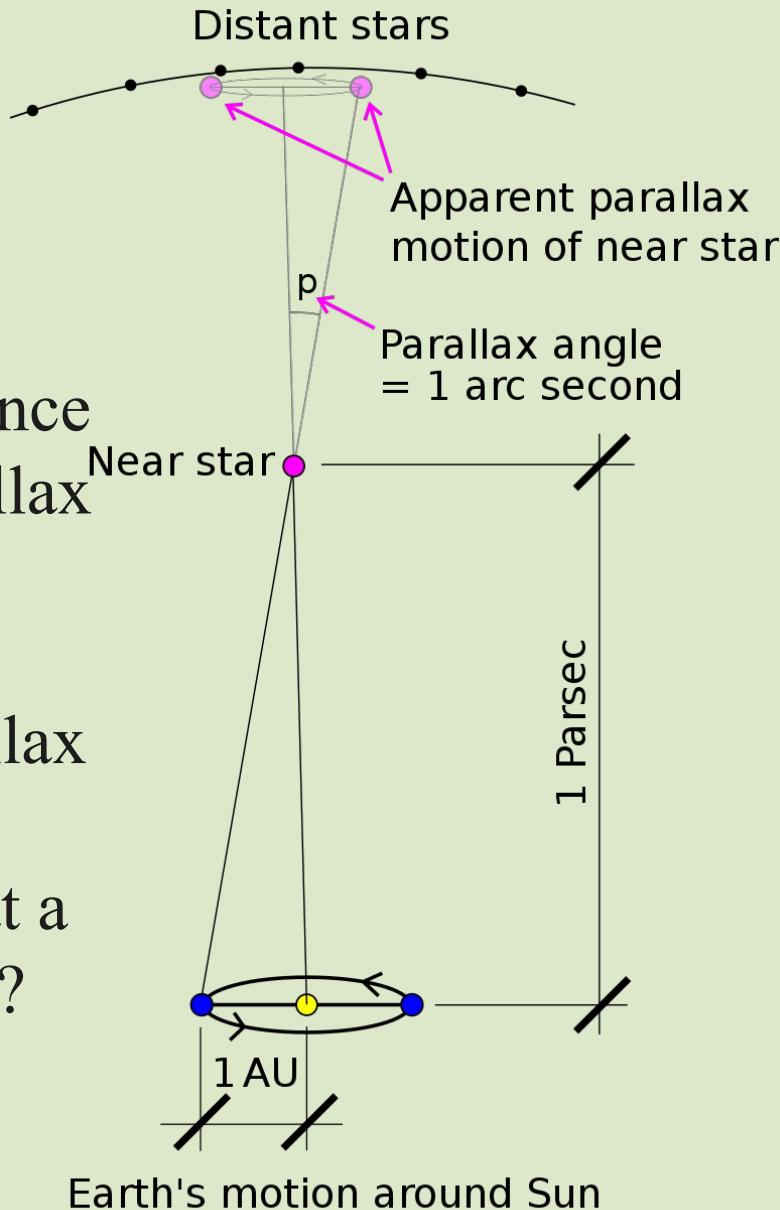
The constellations should expand and contract with a period of 1 year.

Stellar Parallax (for d=1pc)

Key Equation:
 $d(\text{pc}) = 1/p(\text{arcsec})$

Q: What is the distance
to a star with a parallax
of 0.01"?

Q: What is the parallax
of the closest star,
Proxima Centauri, at a
distance of 4.24 LY?



Knowledge of the Ancient Greeks

Aristarchus (310-230 BC)

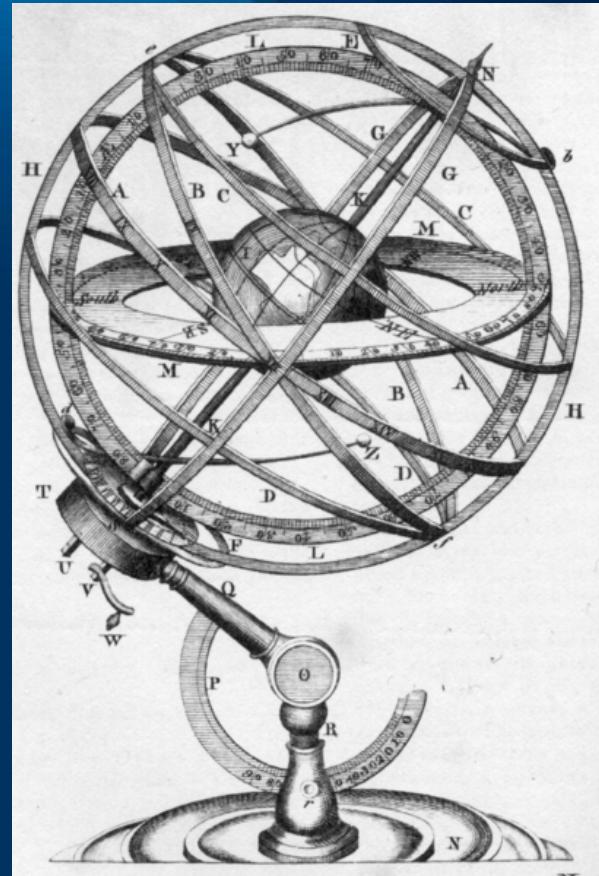
The Earth orbits around the Sun (!)

Eratosthenes (276-195 BC)

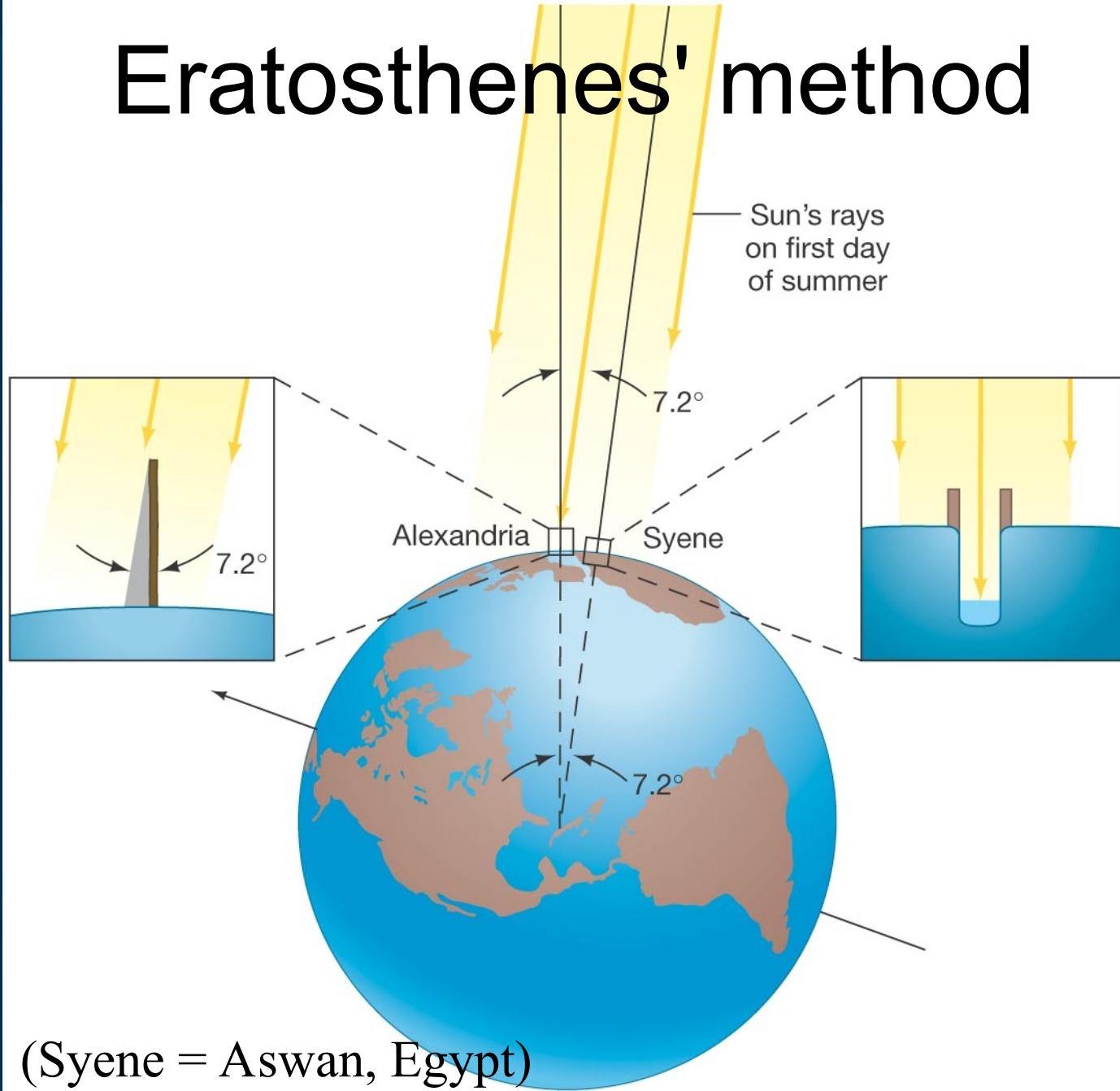
- Measured circumference of the Earth.
- Invents armillary sphere

• Hipparchus (190-120 BC)

- Discovered precession of Earth's spin axis
- Uses epicycles, deferents and eccentrics in modelling motion of Sun and Moon.



Eratosthenes' method



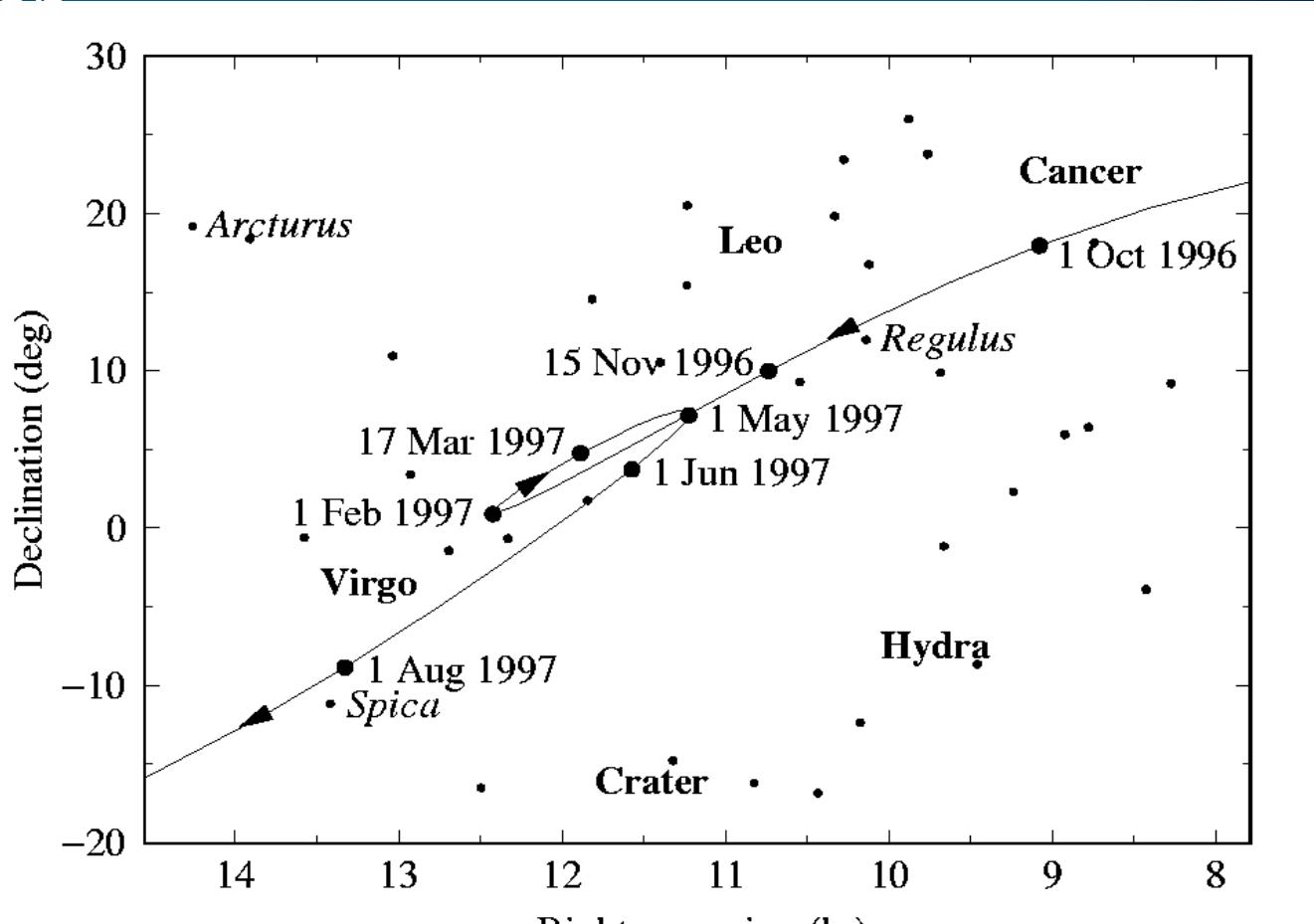
Knowledge of the Ancient Greeks

- Claudius Ptolemy (AD c.90-168)
 - Geocentric universe model
 - Adopts Hipparchus' epicycles to reproduce retrograde motion of planets
 - Added *equants* to better match speeds of planets
 - Insists on circles and uniform speeds



The Appearance of the Planets

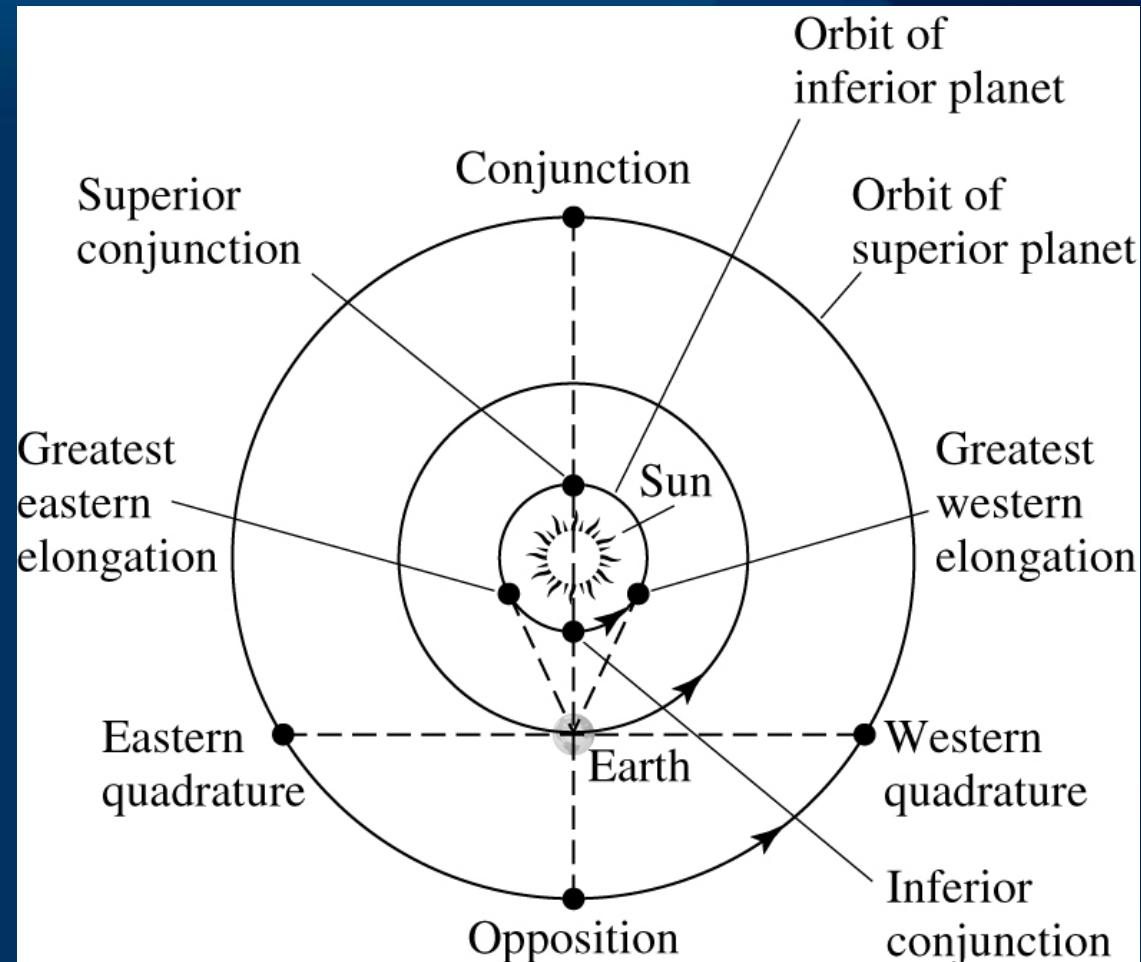
- Daily motion
- Change across sky
- All orbit Sun
- Usually we call



Retrograde Motion!

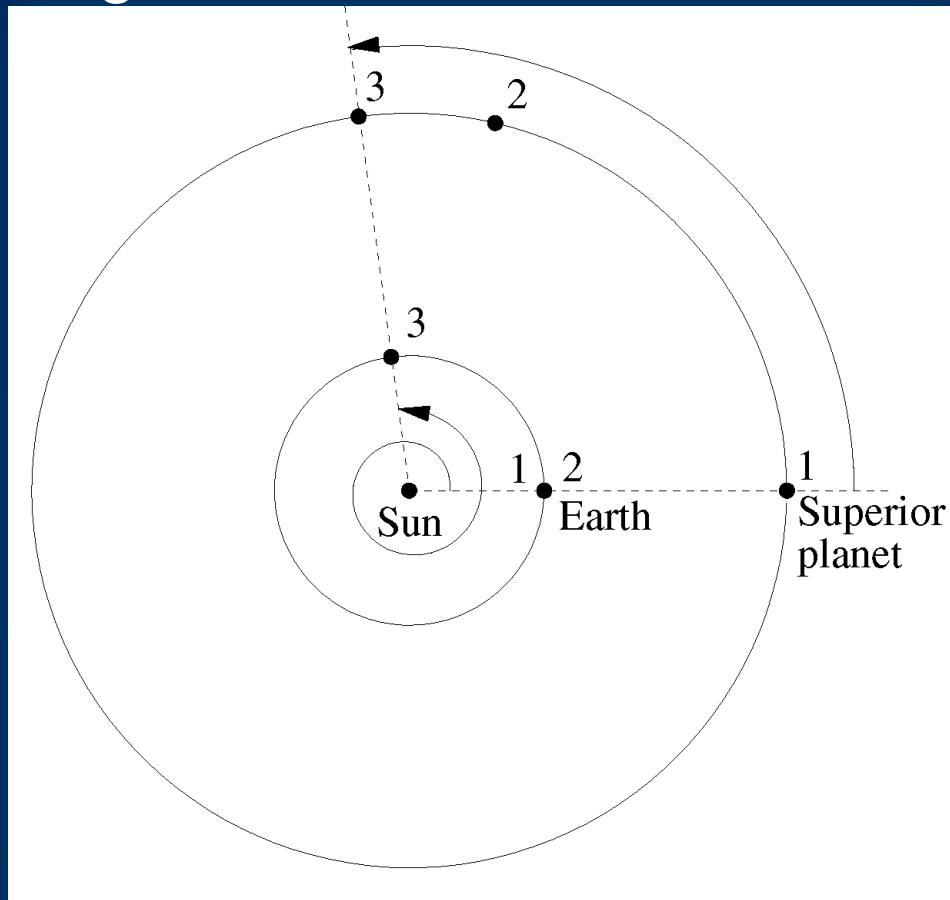
Planetary Configurations

- Inferior planets
 - Two conjunctions
- Superior planets
 - One conjunction
 - Opposition



Synodic and Sidereal Periods

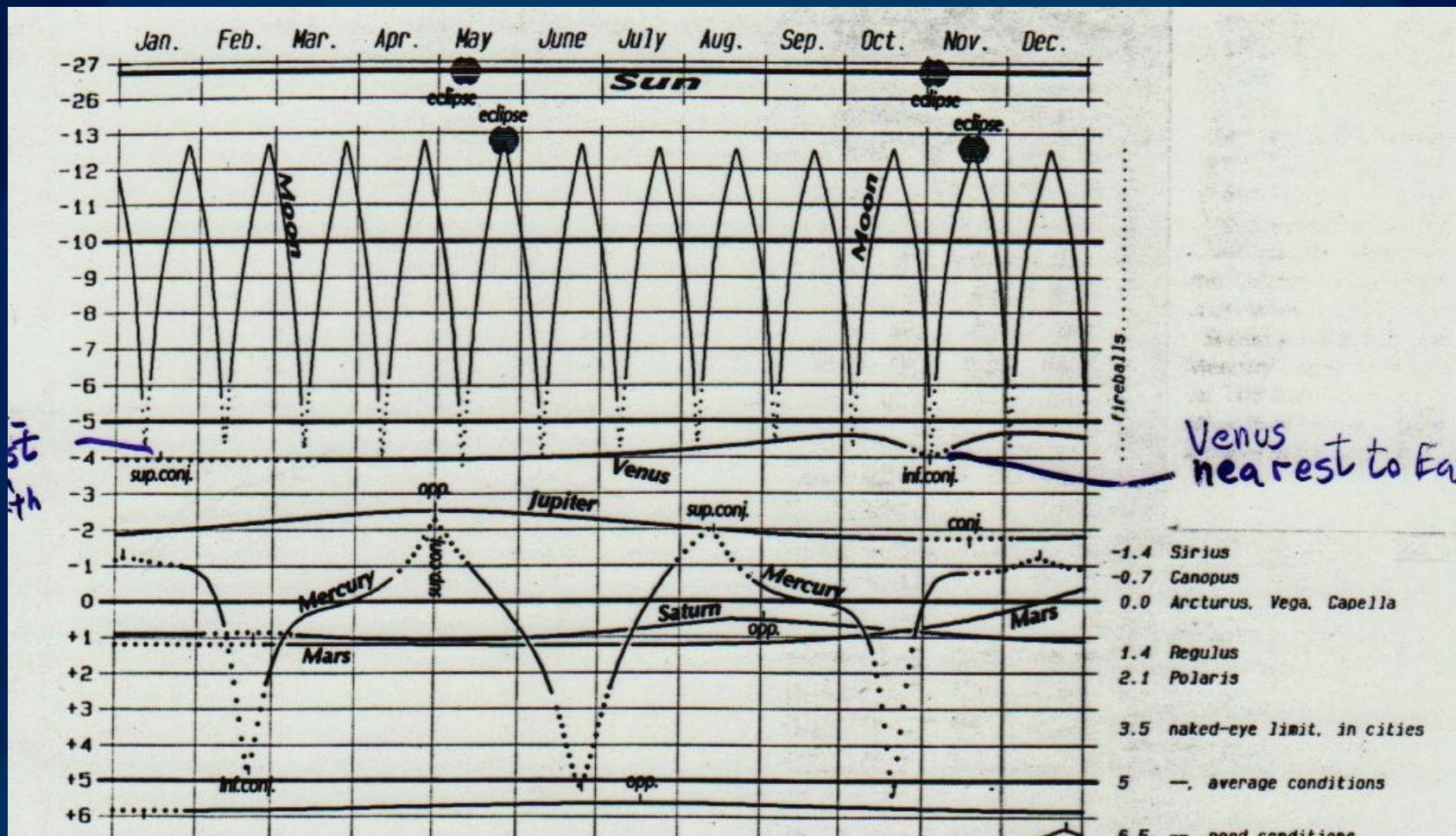
- Synodic period: time interval between successive conjunctions or oppositions, 1 → 3
- Sidereal period: time interval for one complete orbit relative to background stars, 1 → 2



The Appearance of the Planets

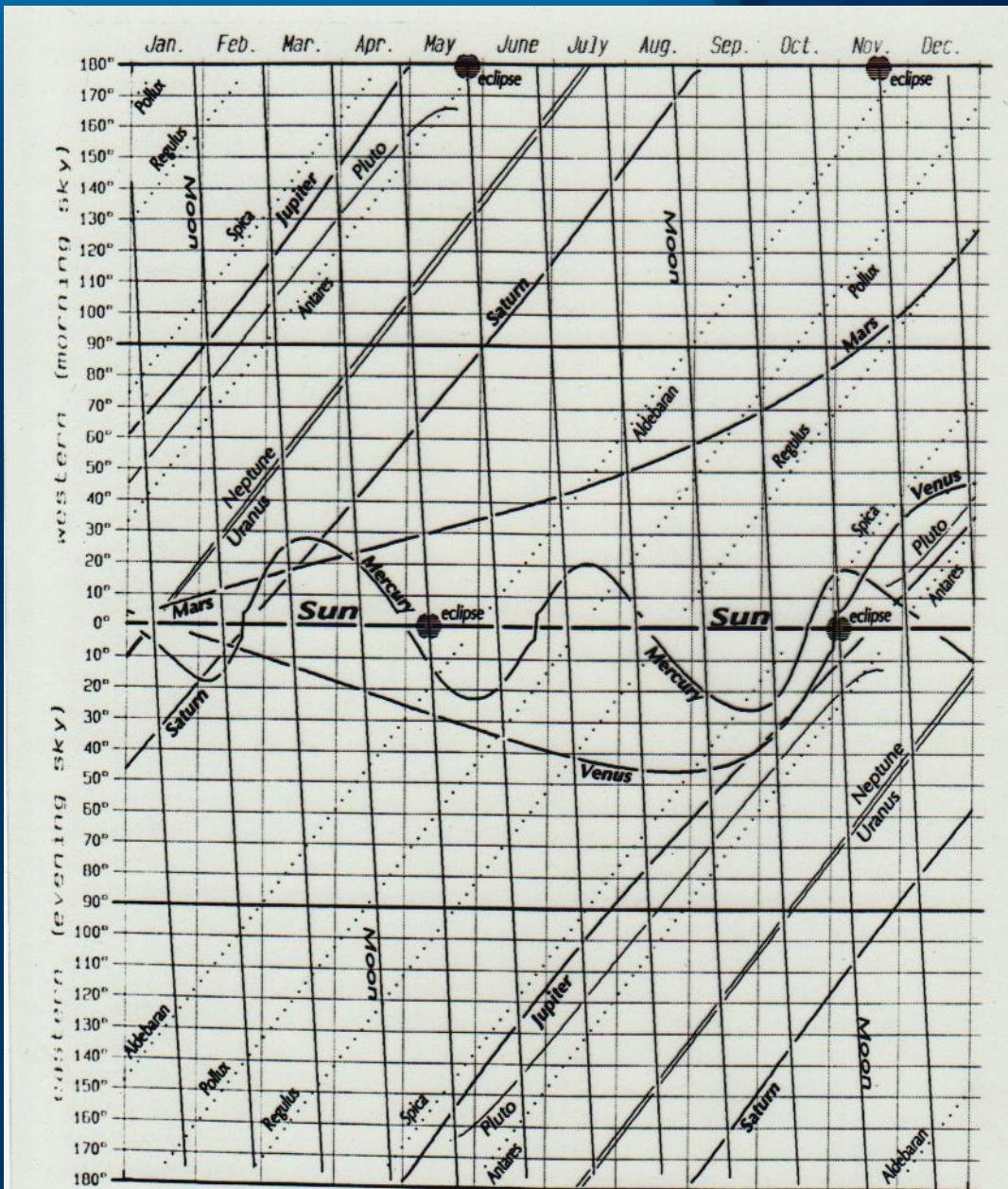
Brightness, measured in magnitudes.

- Smaller magnitude → brighter.



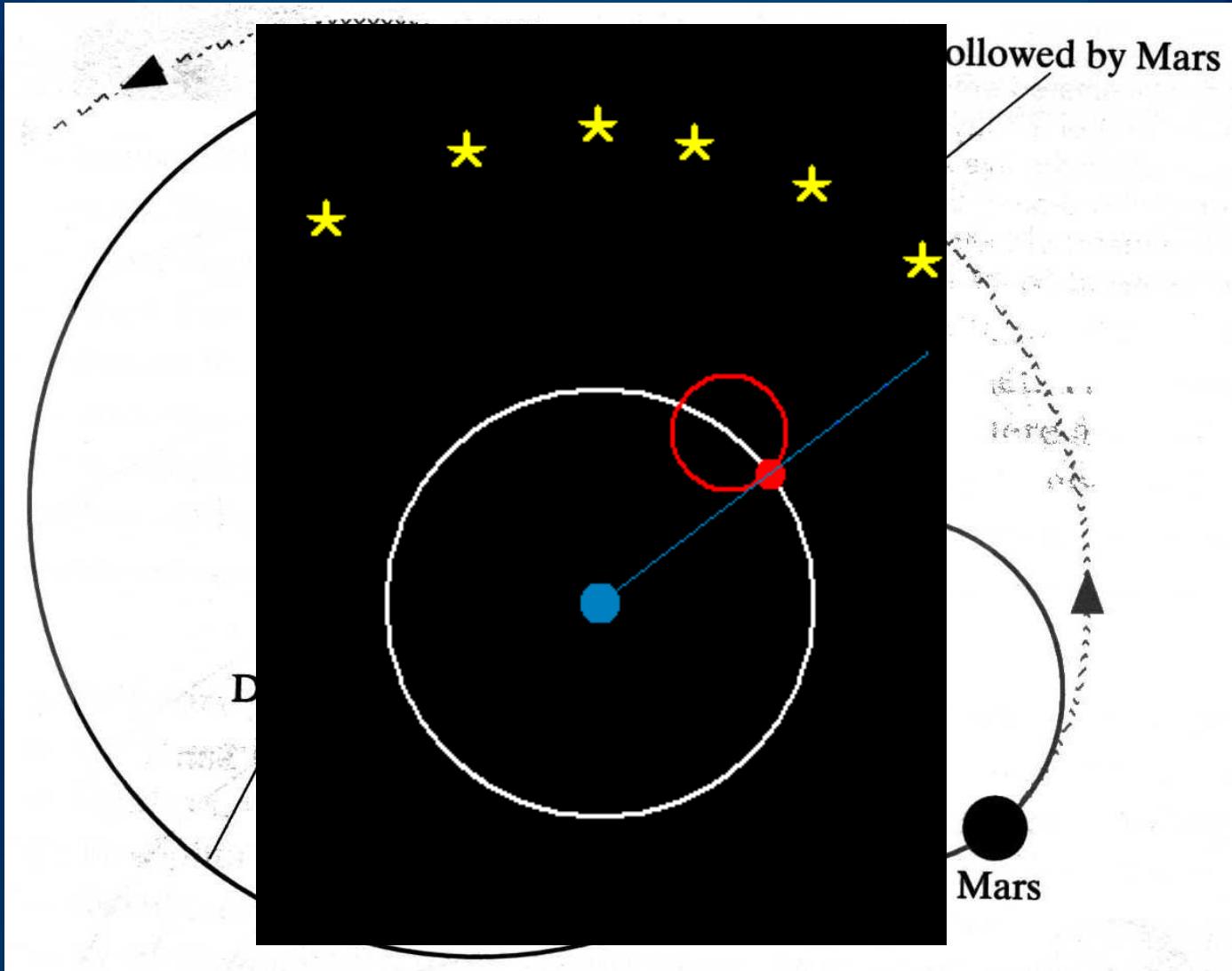
The Appearance of the Planets

- Changing positions
- “Elongation” is measured relative to Sun.



Epicycles on Deferents

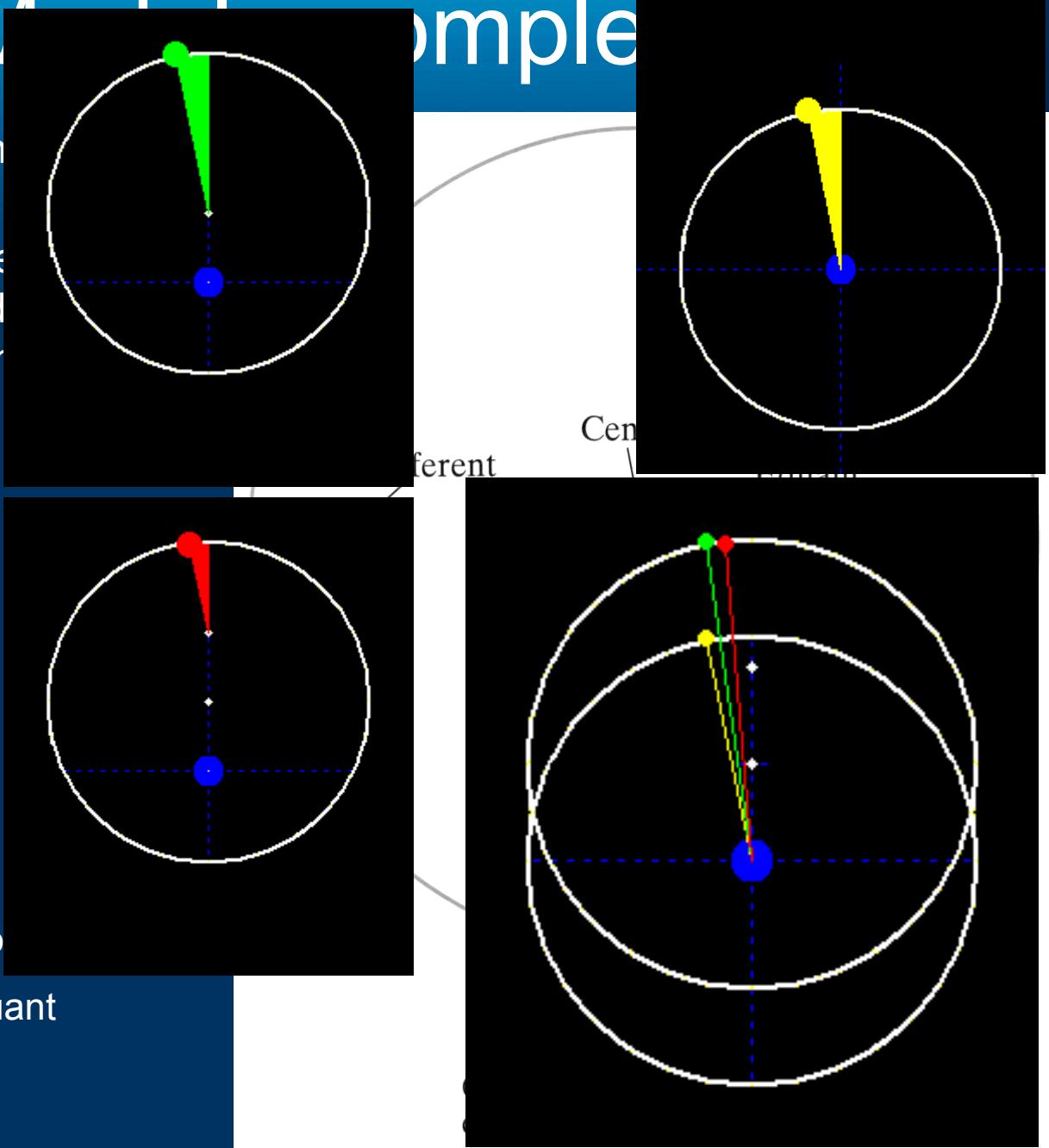
- Ptolemy et al. desired uniform circular motions



Ptolemy's Model of Mars

- Eccentric - displaces Earth from center
- Equant – center of epicycle has uniform angular speed when viewed from this point
- 80+ epicycles
- It works pretty well!
- Occam's Razor (1348)
 - Accept the simplest explanation

See “marsorbit.swf”, which shows the epicycle but not the equant or eccentric.



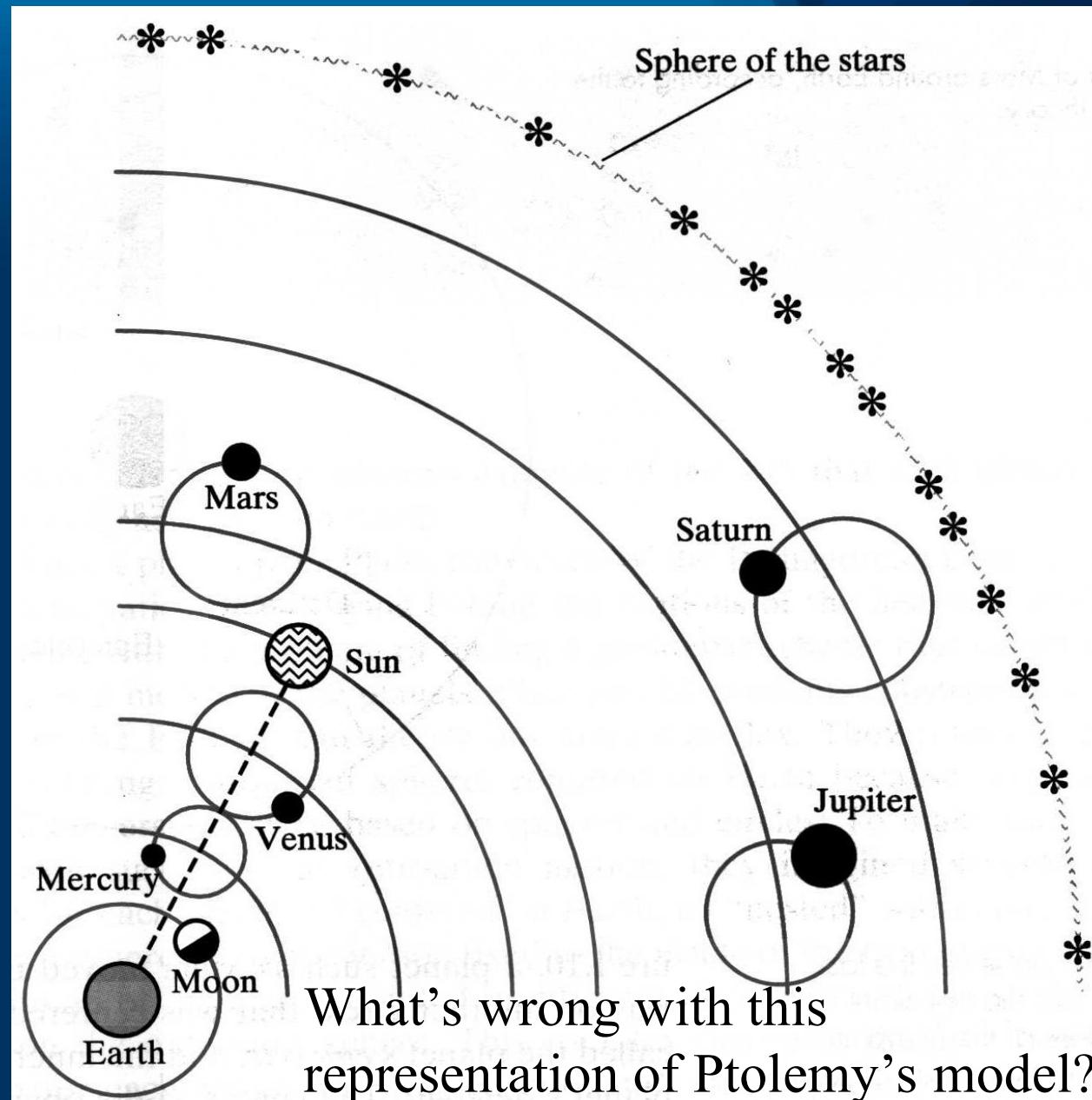
Ptolemy's Model

- Venus and Mercury on invisible “bar”
- Speed is still a problem



FIGURE 1.12

The ancient astronomer Ptolemy, A.D. 85–165. Using epicycles and many other theoretical devices, he perfected the Earth-centered theory of the layout of the universe.



THE COPERNICAN REVOLUTION

· 1473

NICOLAUS COPERNICUS



· 1512 1st Comment

· 1543 *De Revolutionibus*

· 1546

TYCHO BRAHE



· 1601

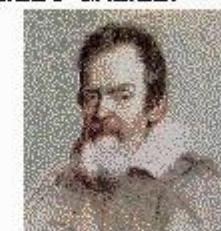
JOHANNES
KEPLER



· 1571

- 1609 *New Astronomy*
- 1619 *The Harmony of the Worlds*
- 1630

· 1564



1609

New Astronomy

· 1619 *The Harmony of the Worlds*

· 1630

· 1642

· 1642

· 1632

Dialogue of the Two Chief World Systems

· 1633 Trial at Rome by the Inquisition

· 1642



. 1543 *De Revolutionibus*

. 1546

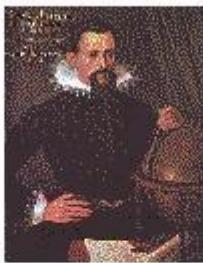
TYCHO BRAHE



. 1601

JOHANNES
KEPLER

. 1571



. 1609
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*The Harmony
of the Worlds*

. 1630

. 1564

GALILEO GALILEI



. 1632

Dialogue of the Two Chief World Systems

. 1633 Trial at Rome by the Inquisition

. 1642

. 1642

SIR ISAAC NEWTON

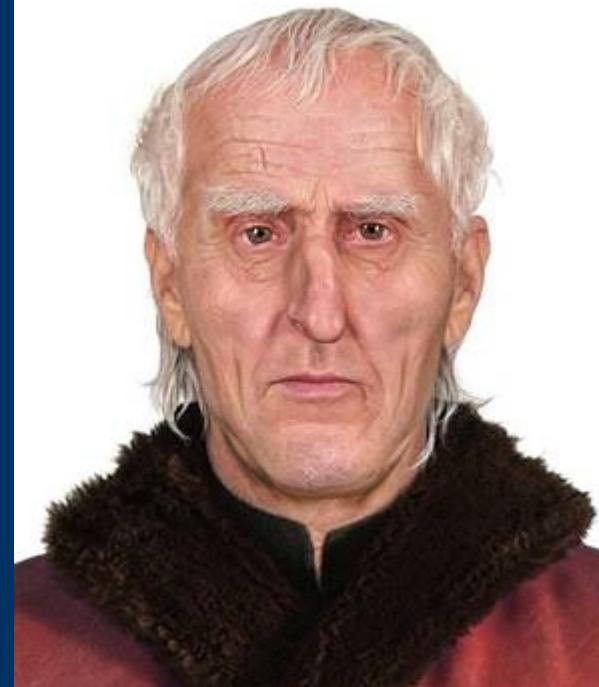
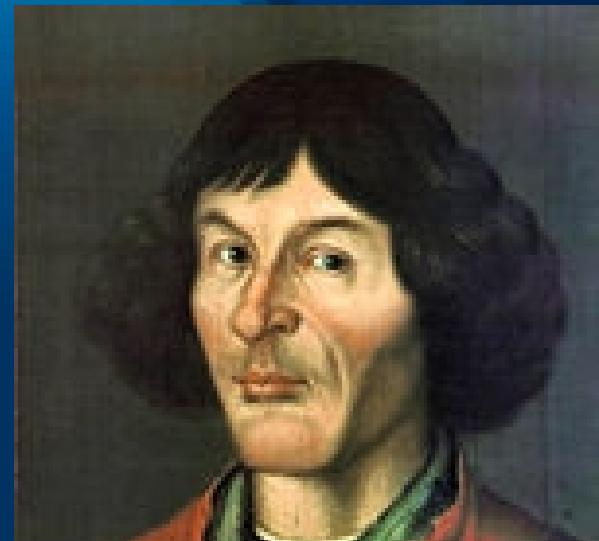


. 1686 *Principia*

. 1727

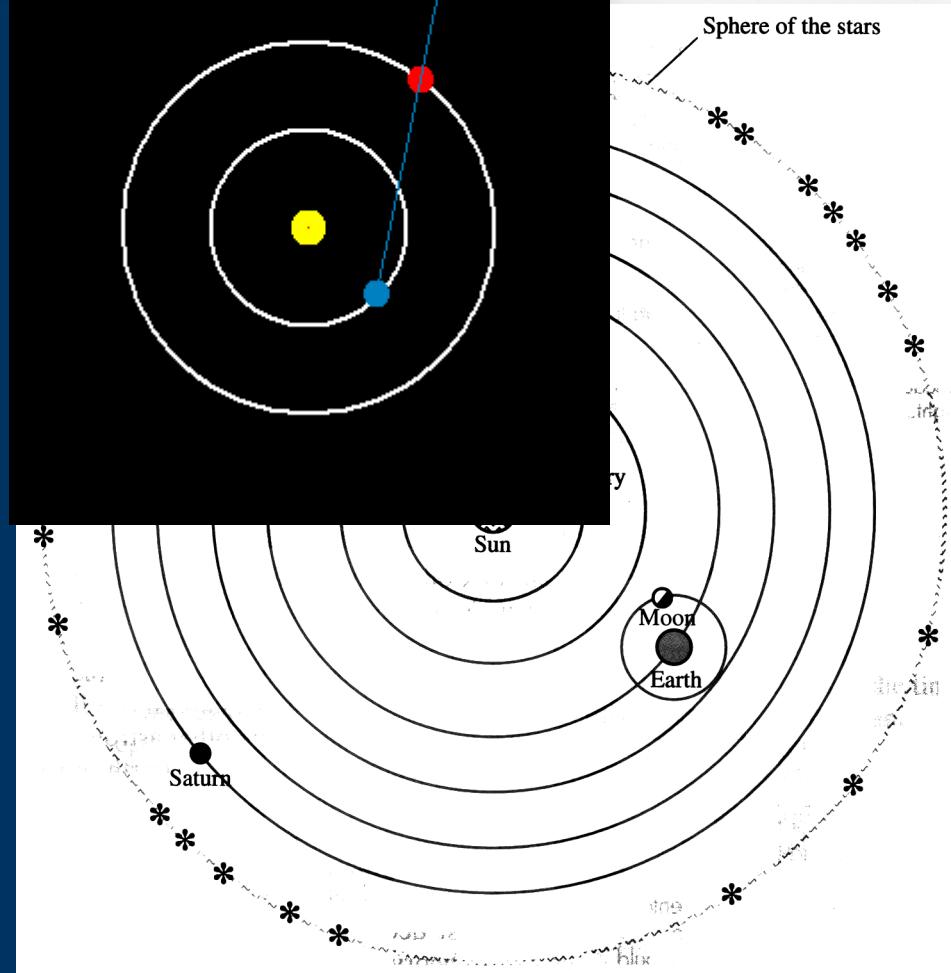
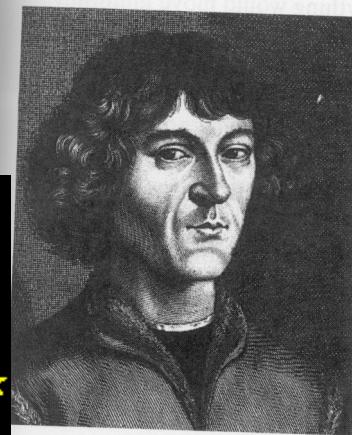
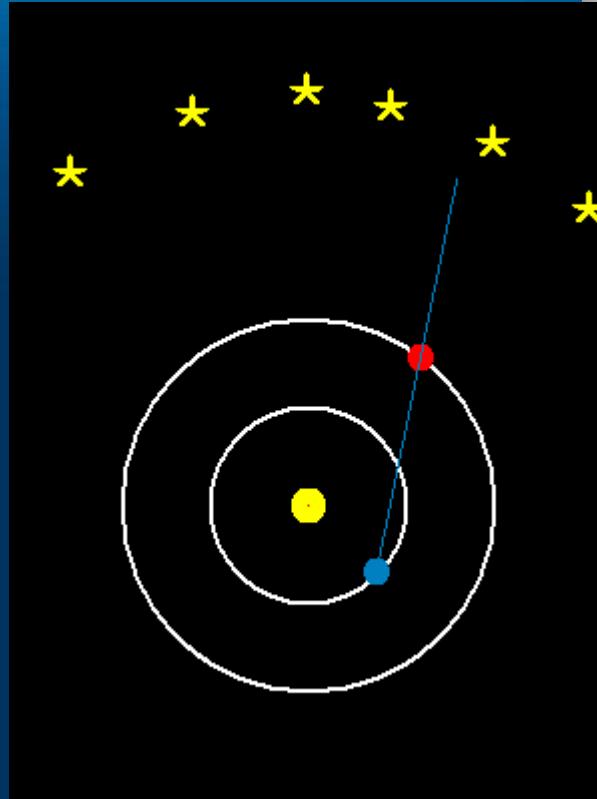
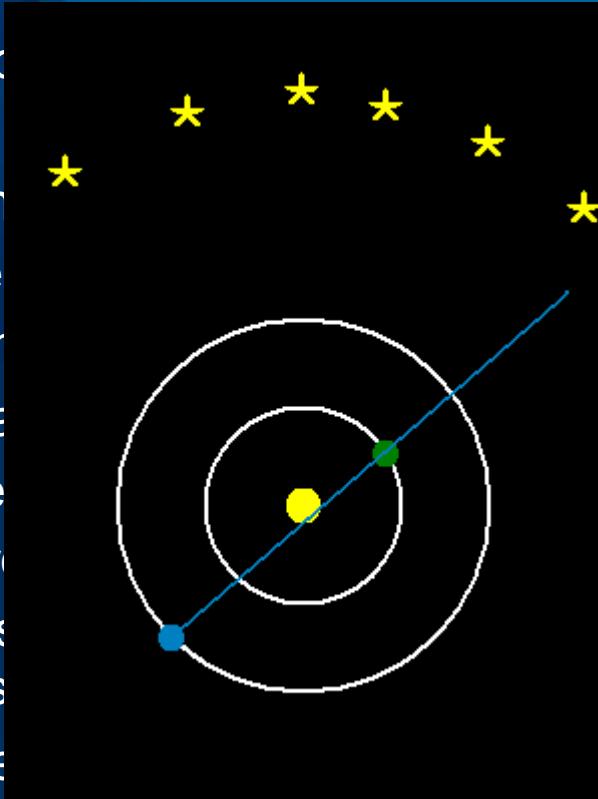
Copernicus (1473-1543)

- Polish Son of merchant
- a mathematician, astronomer, physician, classical scholar, translator, Catholic cleric, jurist, governor, military leader, diplomat and economist
- Astronomy is avocation
- Publications
 - On the Revolutions of the Heavenly Spheres (1543)
 - Little Commentary (1514)
 - Trigonometry, Narratio Prima (Rheticus, 1540)
 - Prutenic tables (1551)
- Reluctant to publish because of fear of criticism, or fear of persecution by church
- In 2005, skull recovered in Cathedral of Frombork



Copernicus

- Is there something wrong about the Ptolemaic model?
- Keep some parts of the Ptolemaic model:
 - sphere
 - uniform motion
- Major Changes:
 - Sun centered
 - Earth rotates
 - Earth is one of the planets
- Established the heliocentric model
- Less complicated explanation for retrograde motion



How Copernicus used epicycles

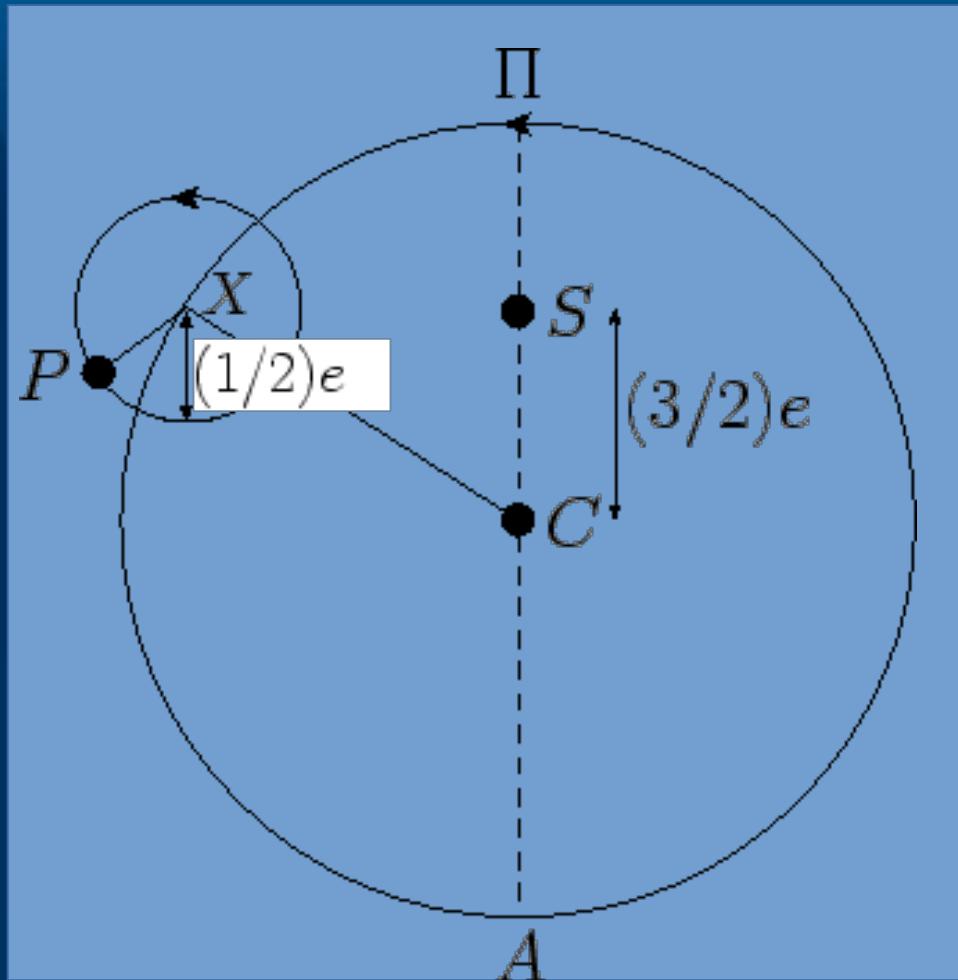


Figure by Richard Fitzpatrick, Utexas.

Copernicus

Main “assumptions” of *Harmony of the Spheres* (see text):

1. There is no one center of all the celestial circles or spheres.
2. The center of the earth is not the center of the universe, but only the center towards which heavy bodies move and the center of the lunar sphere.
3. All the spheres surround the sun as if it were in the middle of them all, and therefore the center of the universe is near the sun.
4. **The ratio of the earth's distance from the sun to the height of the firmament (outermost celestial sphere containing the stars) is so much smaller than the ratio of the earth's radius to its distance from the sun that the distance from the earth to the sun is imperceptible in comparison with the height of the firmament.**
5. Whatever motion appears in the firmament arises not from any motion of the firmament, but from the earth's motion. The earth together with its circumjacent elements performs a complete rotation on its fixed poles in a daily motion, while the firmament and highest heaven abide unchanged.
6. What appear to us as motions of the sun arise not from its motion but from the motion of the earth and our sphere, with which we revolve about the sun like any other planet. The earth has, then, more than one motion.
7. The apparent retrograde and direct motion of the planets arises not from their motion but from the earth's. The motion of the earth alone, therefore, suffices to explain so many apparent inequalities in the heavens.

Copernicus

- Predictions of existing observations are not better than Ptolemy's!!
- Slightly simpler
 - No equants
 - Fewer epicycles (still a lot)
 - If you remove epicycles?
 - Copernicus does okay
 - Ptolemy's is a disaster
- Discriminating experiments not available in his lifetime

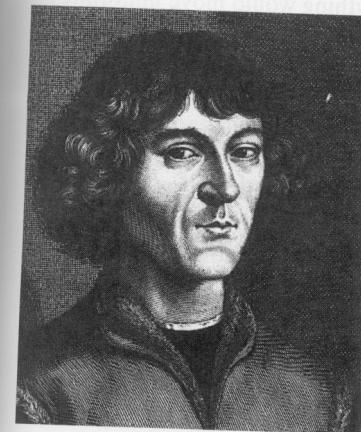
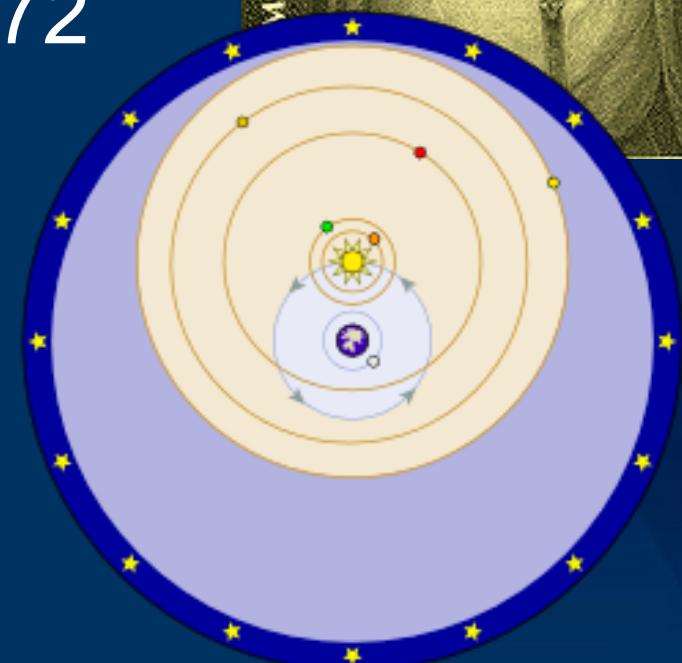


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd idea that Earth moved and was a planet like the other planets met with much resistance because it conflicts with the intuitive notion that Earth is at rest at the center of things and because it conflicted with prevailing philosophies.

Tycho Brahe (1546-1601)

- Danish nobleman
- Wore metal nose
- Death (bladder or mercury?)
- Built “Uraniborg” in Hven
- Meticulous measurements
- Observed supernovae of 1572
- Observed comet of 1577
- Could not detect parallax
- Develops Tychonic System
- Hired Kepler in 1600



Tycho Brahe

- Left Kepler with 20 years of meticulous planet measurements.
- 5x better precision
 - $\pm 2\text{-}4$ arcminutes compared to ± 10 arcminutes
- 20 years of data
- Neither Ptolemy nor Copernicus's models are able to reproduce the observations well.

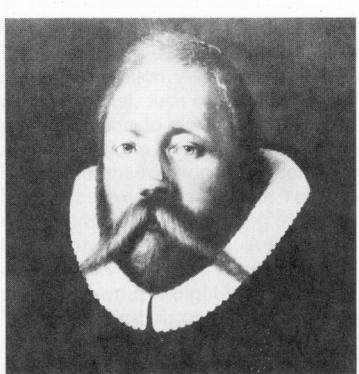


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

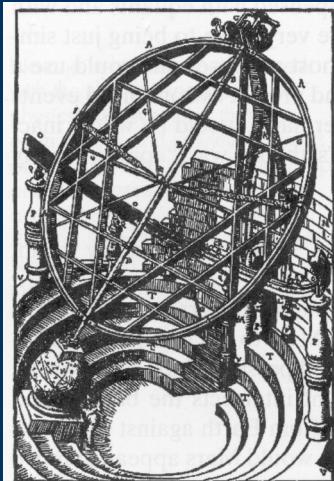


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

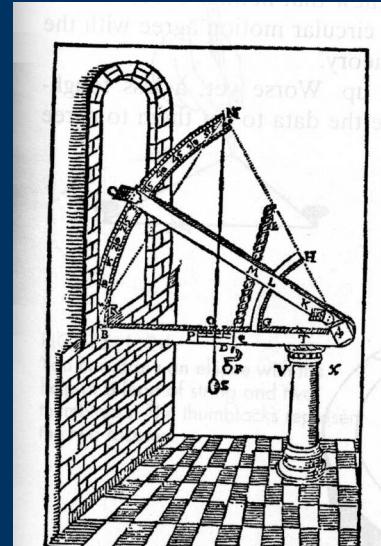


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

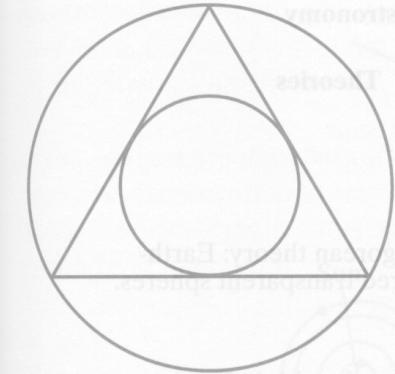
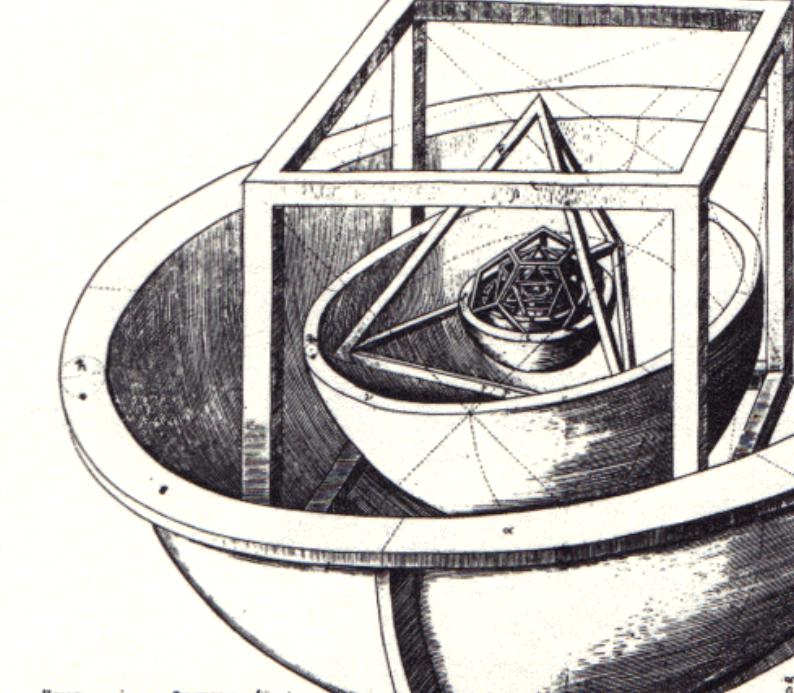
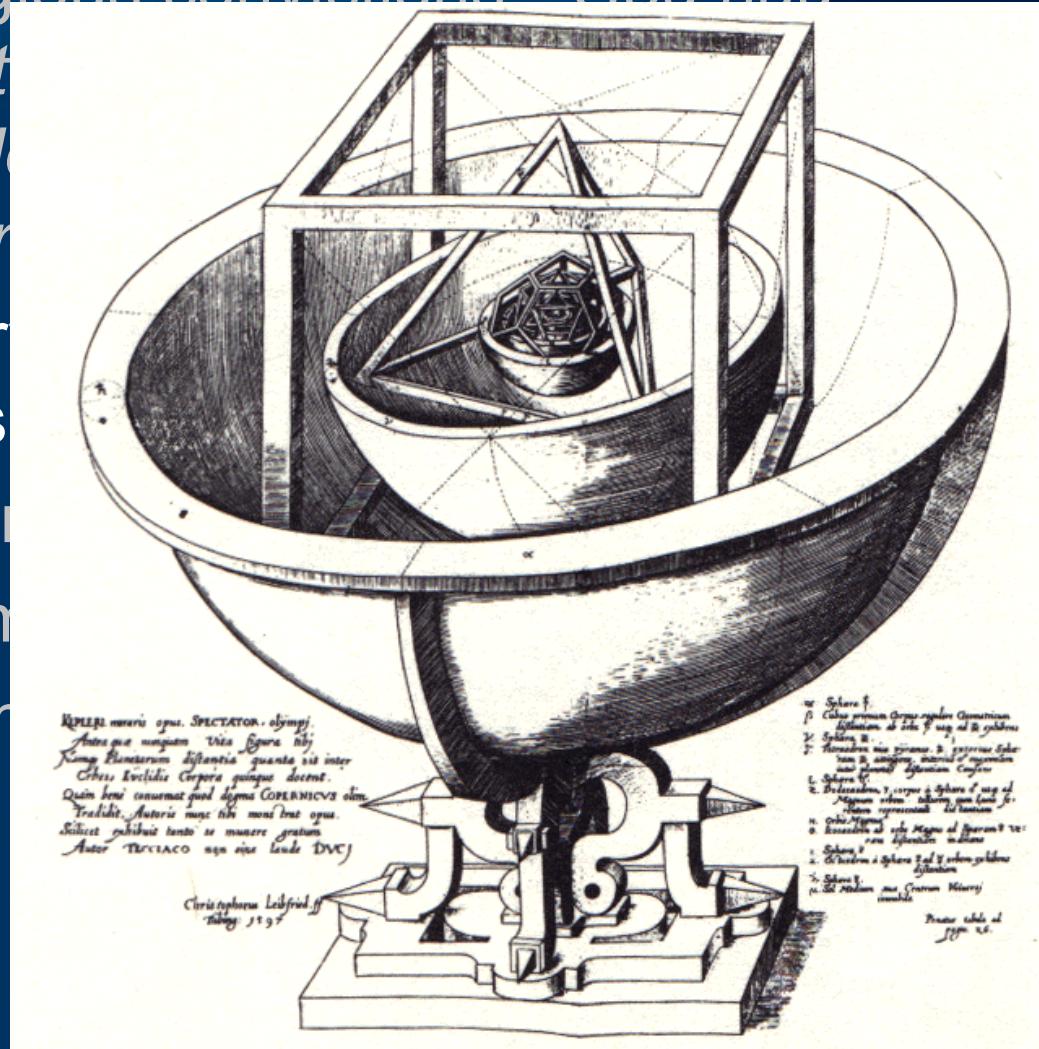


FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

- Mathematician, astronomer, astrologer
 - Had religious convictions - God had created the universe according to the principles of order and intelligibility
 - Geometric model of the universe based on regular solids
 - Mysterium Cosmographicum
 - Astronomia Nova
 - The Harmonies of the World (Harmony Law)

KEPLER novum opus. SPECTATOR. olympi.
Ante me nungam viae figura ubi
Kyma Planorum diffusa figura sibi
Cubes Euclidis Corpus quinque decent.
Quin beni consumat quod deinceps COPERNICVS alio
Tradidit. Asturis magis non mundus opus.
Ergo. Tunc. Tunc.

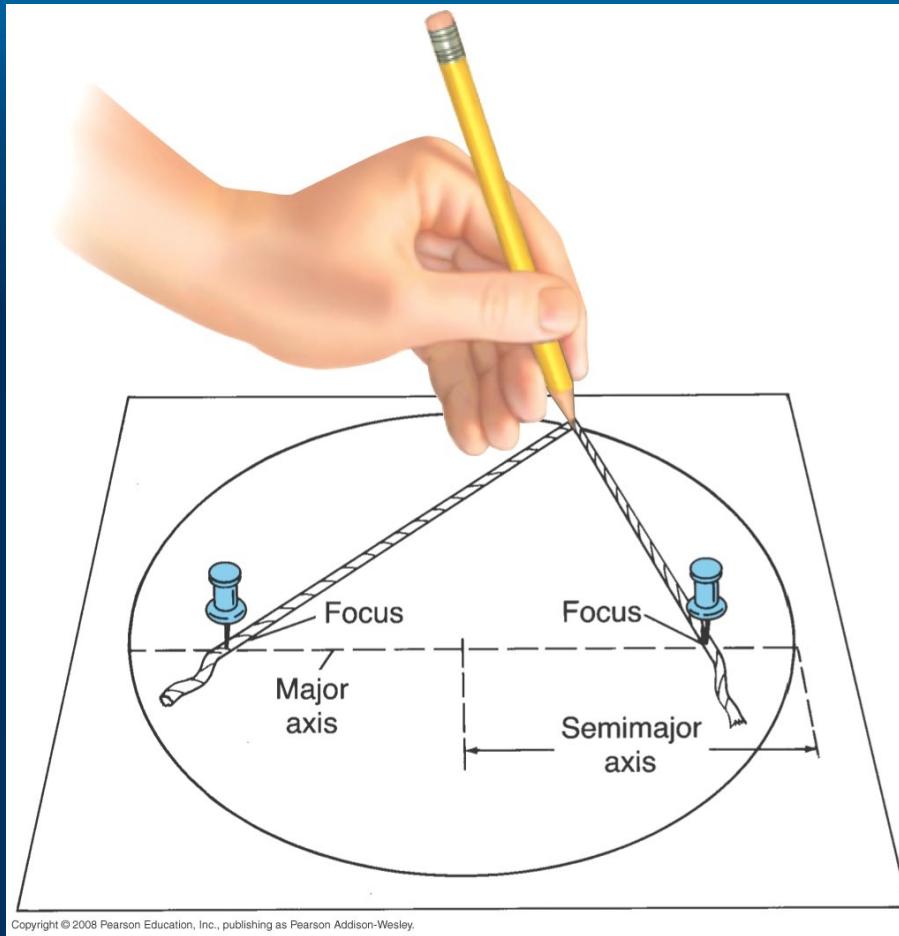
ut Sphere f.
p. Cibus primus. Corpus regis
diffundens ad lata f.
y. Sphere g.
z. Planum non permutans
non etiam permutans
l. Sphaera h.
i. Planum. T. corporis
M. Planum. corporis
n. orbis. M. per
representans



Johannes Kepler

- Supported Copernicus (heliocentric) and Galileo
- Copernicus's Model
 - Struggles to make it work
 - Throws out circles and uniform motion
- Tries Sun-focused ellipse idea
 - A mistake causes him to put it aside
 - It works!!
 - Predicts all existing data including Tycho's
 - Kepler's 3 laws

Kepler's 1st law



The planets follow elliptical paths with the Sun at one focus.

Johannes Kepler

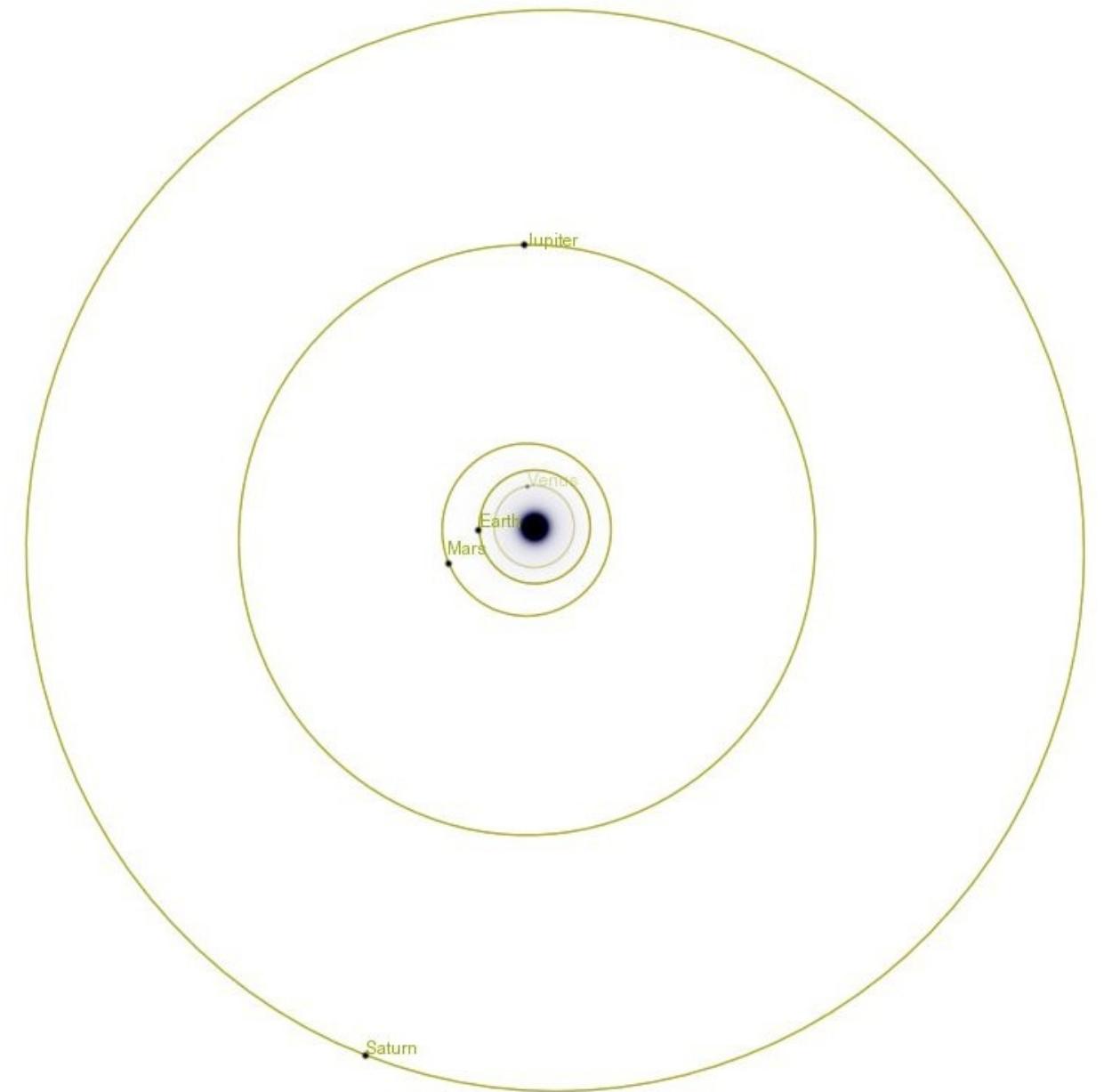
Inner Planet orbits

- Mercury most eccentric (0.206)
- Almost same as off-centered circles, but not.

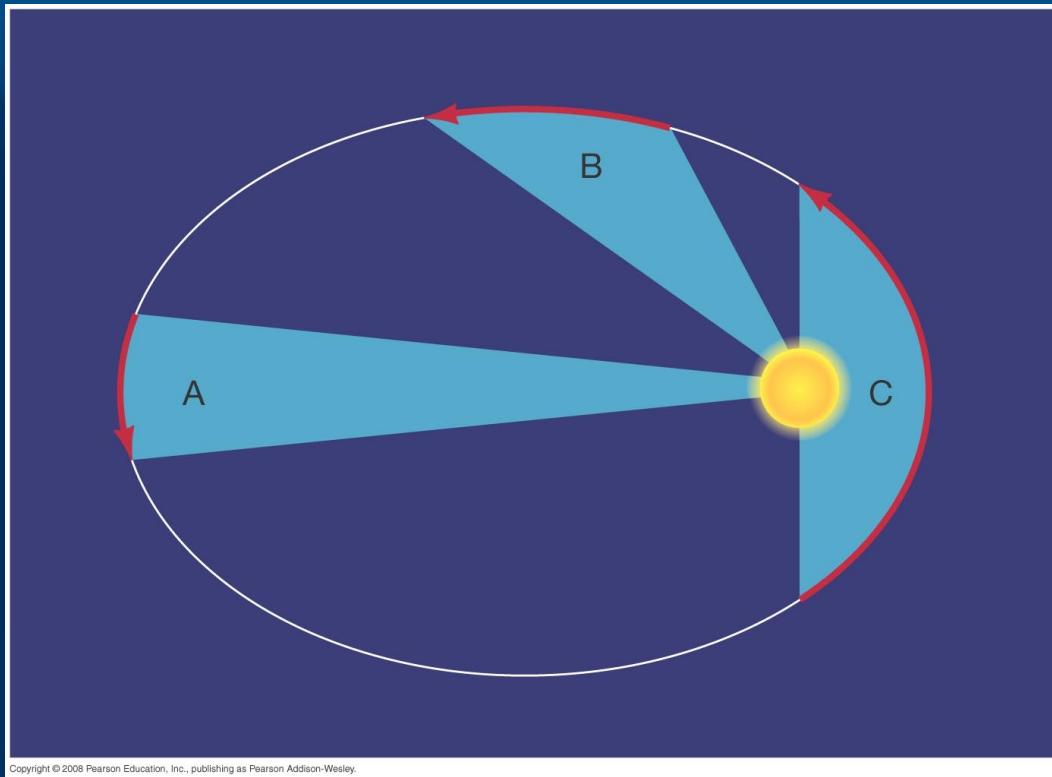
Outer planets

- Mars most eccentric (0.09)

(Date is Jan 31, 2012 for both figures.)



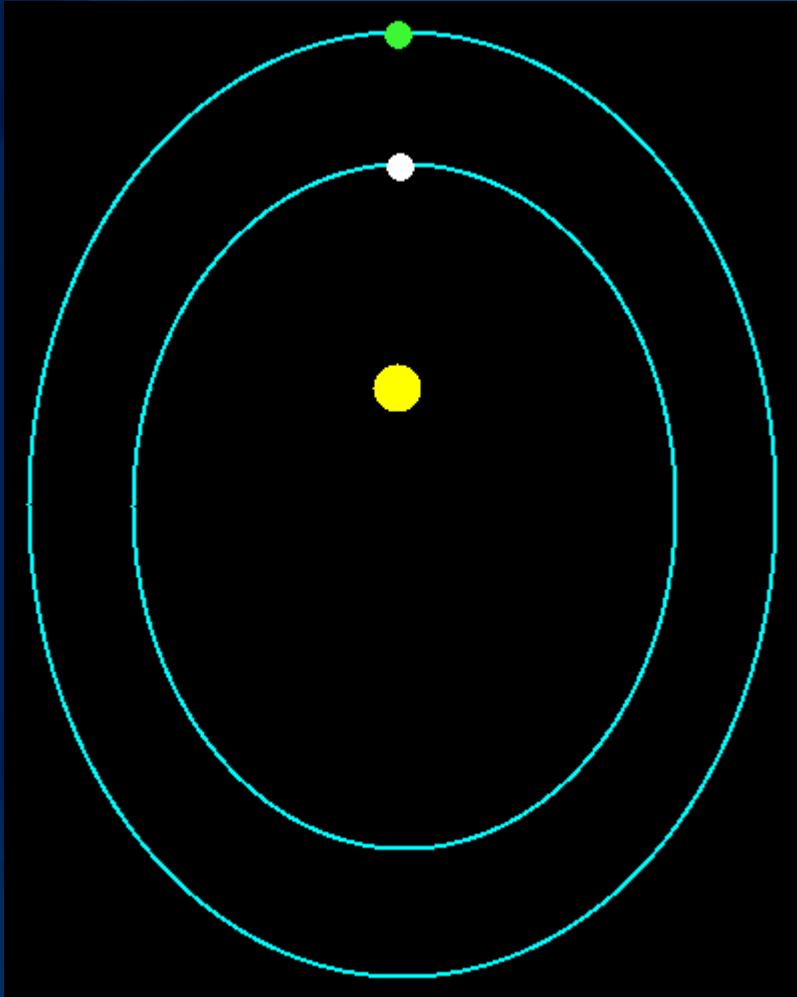
Kepler's 2nd Law



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The planets vary their orbital speed such that they sweep out equal areas in equal time intervals, as seen from the Sun.

Kepler's 3rd law



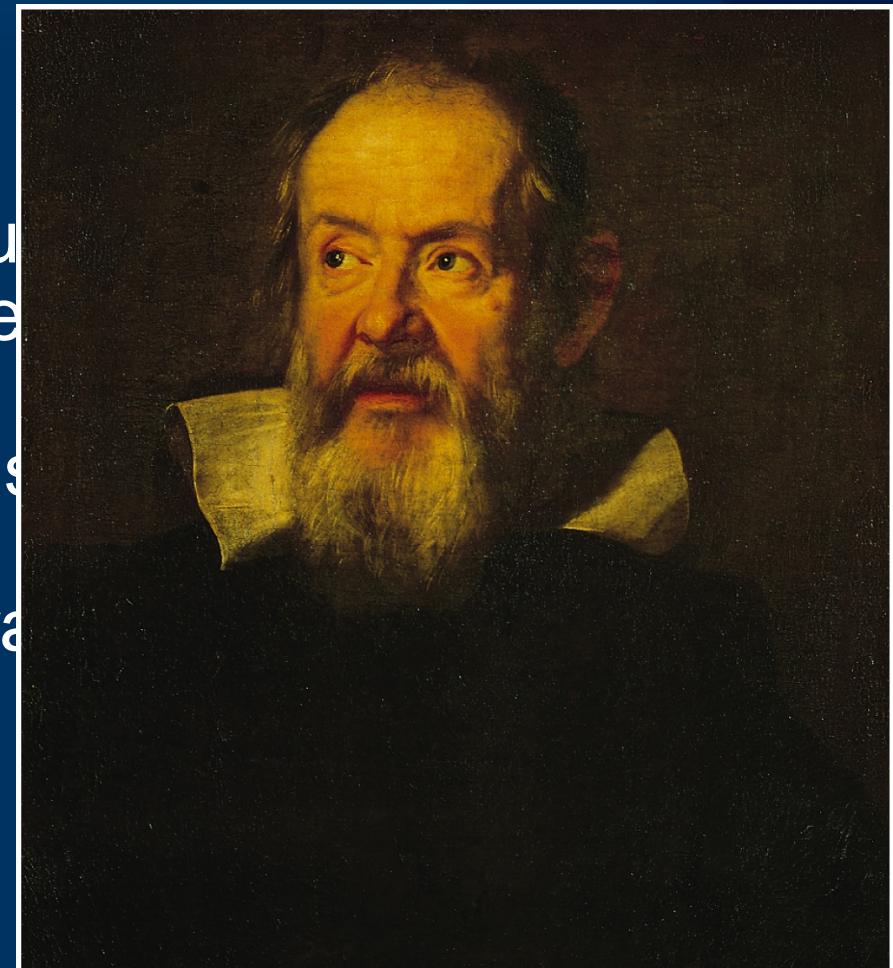
$$P^2 = a^3$$

Period increases
with distance from
the Sun.

P=period, in years
a=semi-major axis, in AU.
See [kepler.swf](#).

Galileo (1564-1642)

- He supports Copernicus, Kepler
- 1609 - uses telescope for astronomical observations
- Experiments & observations refuted Aristotelian physics
 - Free-fall, inclined plane, experiments
 - Moons of Jupiter orbit Jupiter
 - Phases of Venus include
 - Spots on Sun
 - Milky Way resolves into stars
 - Saturn has ears?
 - Moon has mountains, craters
- “Father of Modern Physics”



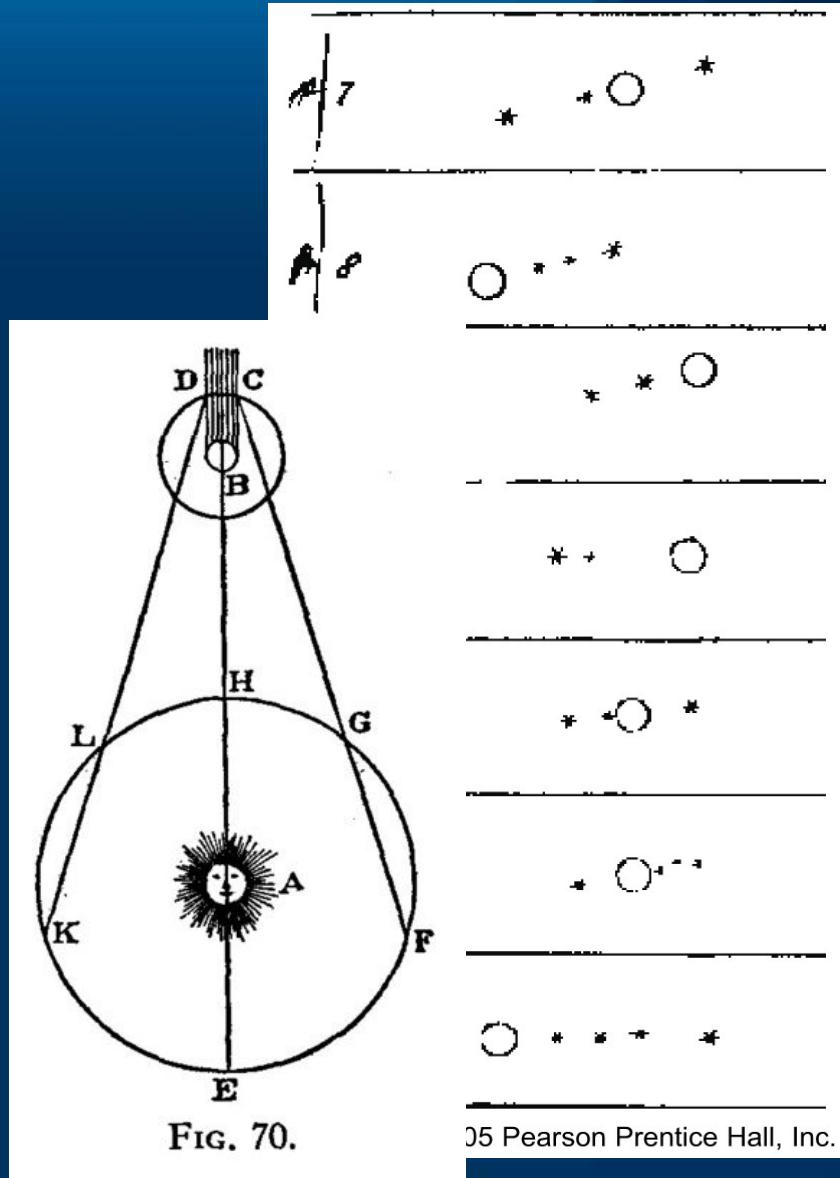
Galileo and Jupiter

The “Galilean Moons”: Io, Europa, Ganymede, and Callisto.

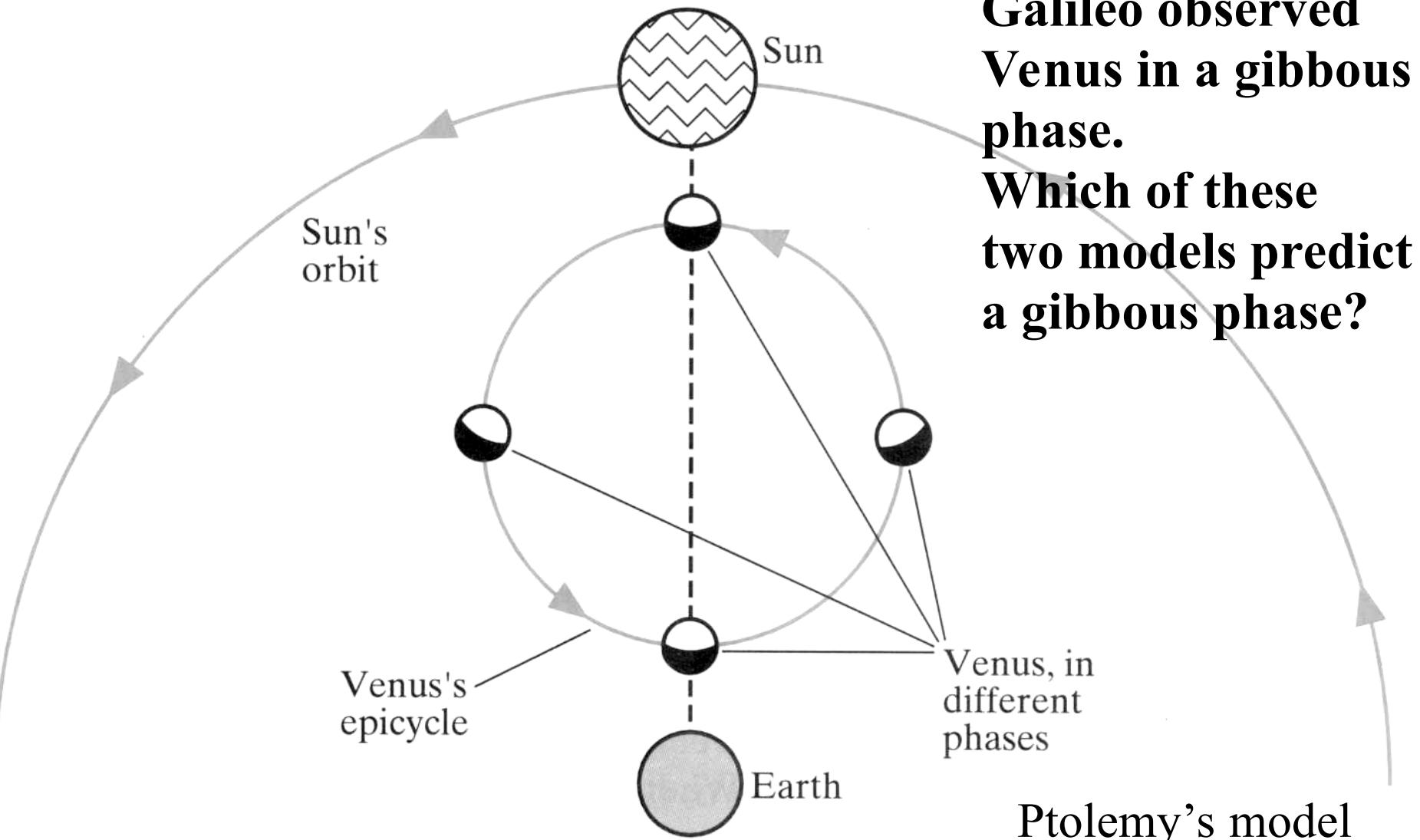
Not everything orbits the Earth!

Note: These moons could be used to measure the speed of light!

Ole Roemer 1677



nus



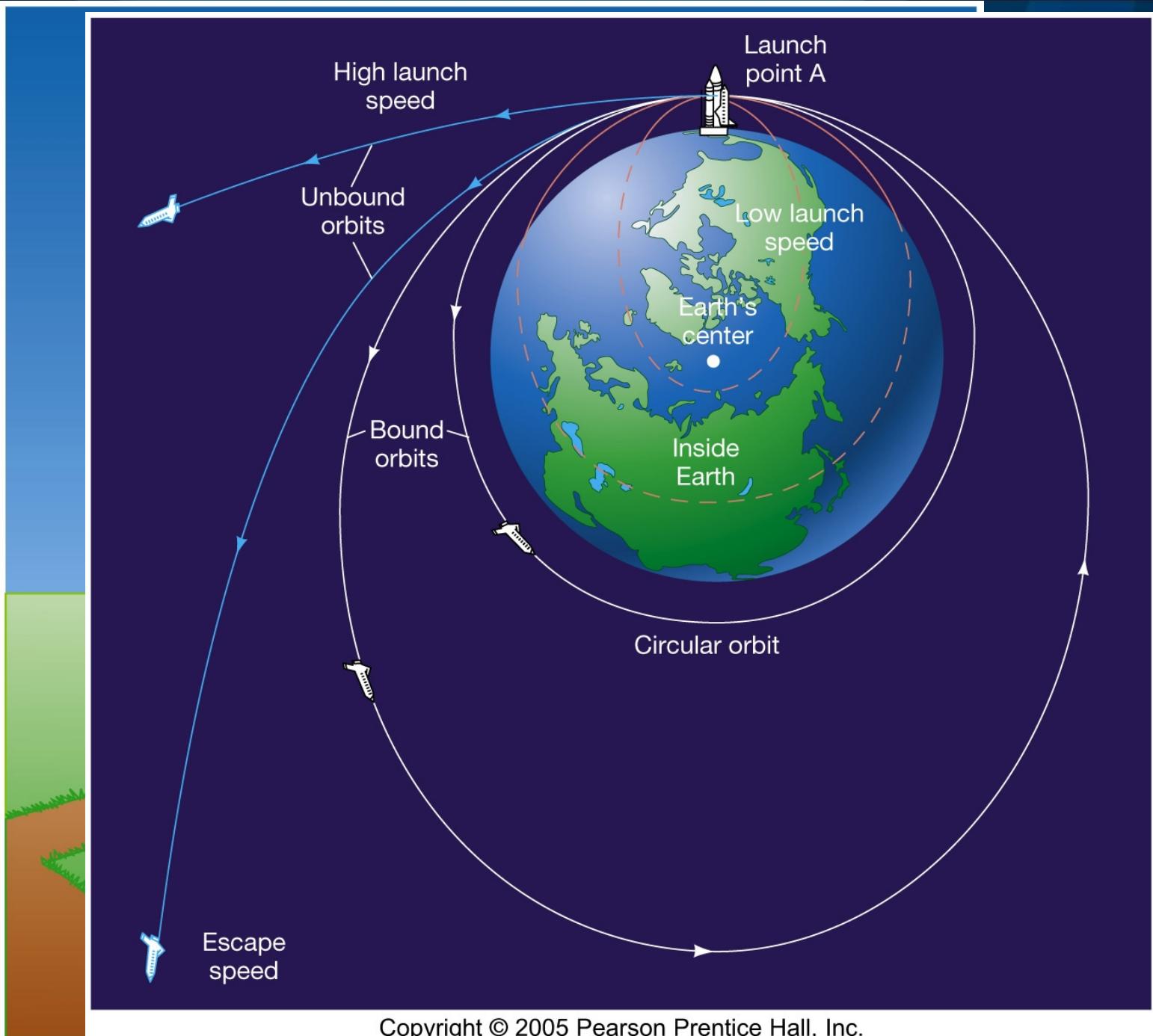
Galileo's troubles

- Galileo was more vociferous and brash than Copernicus and Kepler.
- 1610: Published *Sidereal Nuncius* (Starry Messenger)
- 1616: Galileo (and Copernicus) judged to be heretical
- 1632: Published *Dialogue Concerning the Two Chief World Systems*.
 - Simplicio speaks words of Pope Urban VIII.
 - Published in Italian
- 1633: Sentenced to house arrest.
- 1642: Dies in house arrest.
- 1992: Catholic Church acknowledges their error

- English philosopher
- Inventor
- Urged that the laws of motion apply to the heavens
- *Philosophiæ Naturalis Principia Mathematica*
- 3 laws of motion
- Universal gravitation

 - Can predict planetary motion
 - Finally explained潮汐

- “God governs by the laws he has given, not by caprice or chance.”
- “Nature does not care if you understand her.”

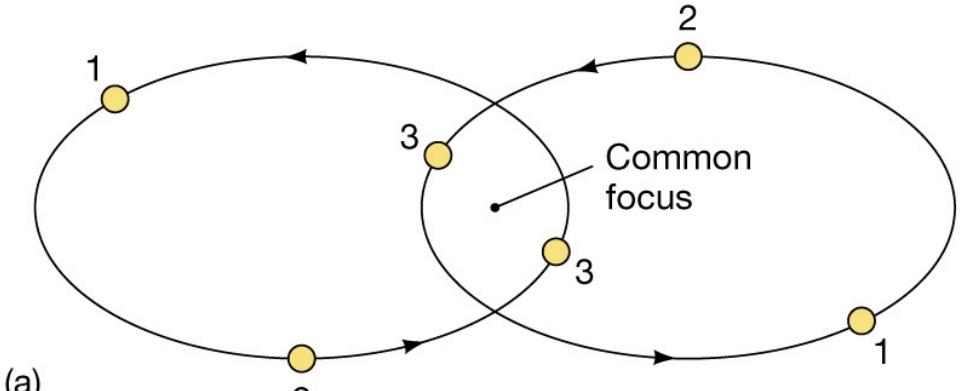


Isaac Newton (1643-1727)

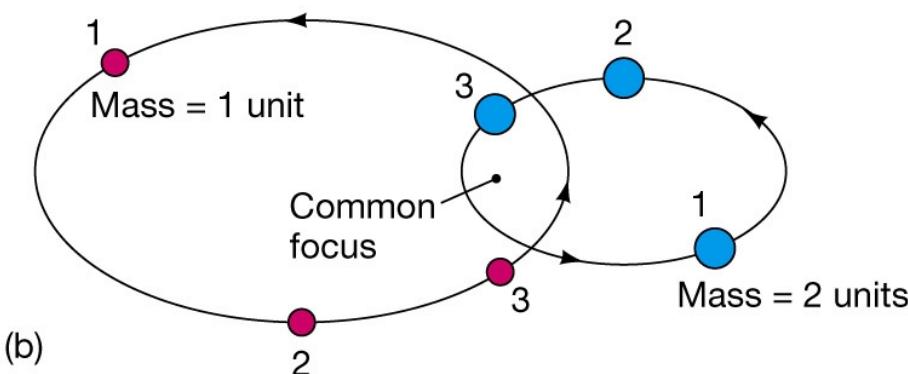
- English physicist, mathematician, theologian, alchemist
 - Invents calculus
 - Urged by Halley to publish “*Principia*”
Philosophiæ Naturalis Principia Mathematica
 - 3 laws of motion
 - Universal law of gravitation
 - Can explain Kepler's laws!
 - Finally, we have a reason for the orbits!
 - “*God governs all things and knows all that is or can be done.*”
- $$F = G \frac{m_1 m_2}{r^2}$$

Is

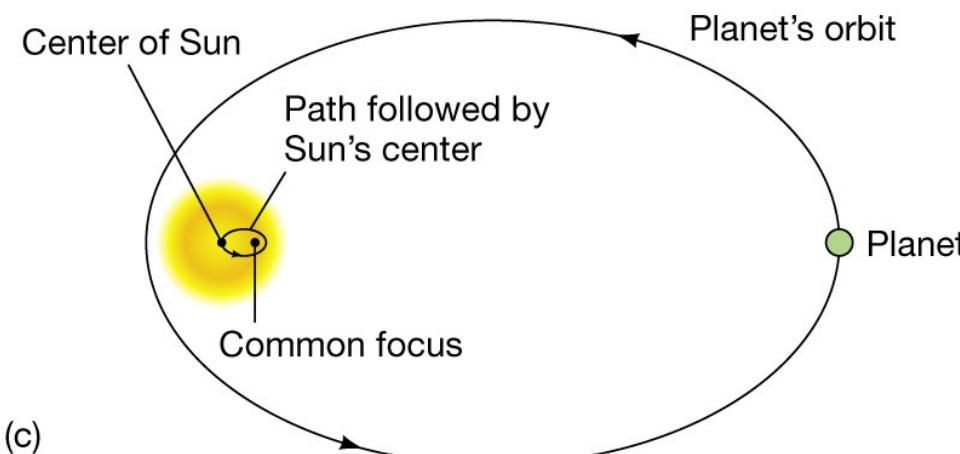
- Kepler I: with the proportionality of mass of Sun)
- Kepler III: system to



(a)



(b)



(c)

S''

S''

$$= \frac{a^3}{M_{tot}}$$

Isaac Newton's “Fixes” to Kepler's Laws

- Kepler I: The planets orbit in ellipses with the principle focus on the center of mass of the solar system, (not the Sun)
- Kepler III: add the total mass of the system to the denominator ...

$$P^2 = \frac{a^3}{M_{tot}}$$

The Copernican Revolution ... *matching!*

Nicolaus
Copernicus

Tycho Brahe

Johannes Kepler

Galileo

Newton



*Observed gibbous phase of
Venus*

*Made precision measurements of
planets*

*Used ellipses to model solar
system*

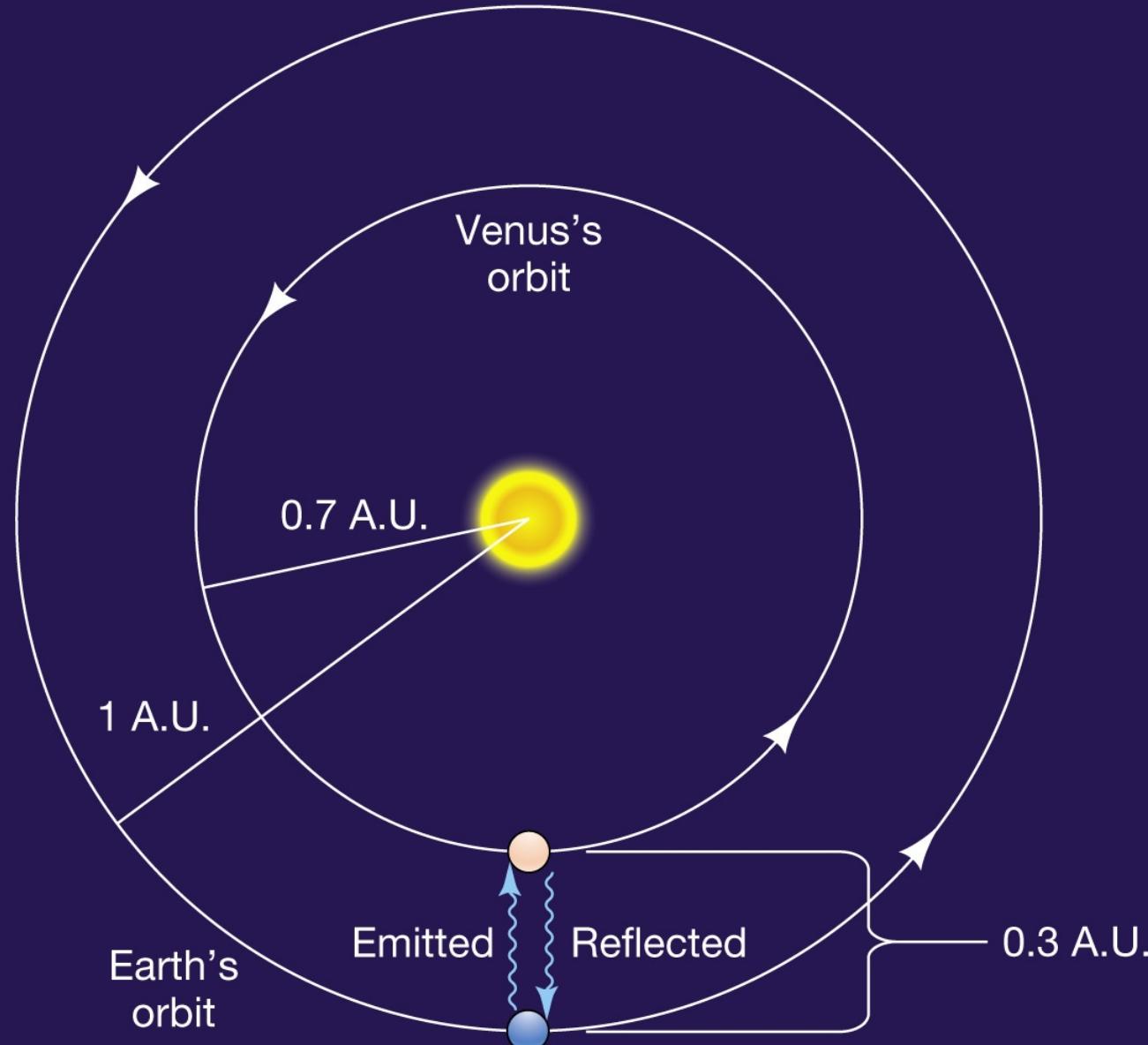
*Said gravity accelerates the
planets*

Revived the heliocentric model

F

• Venus

• Water

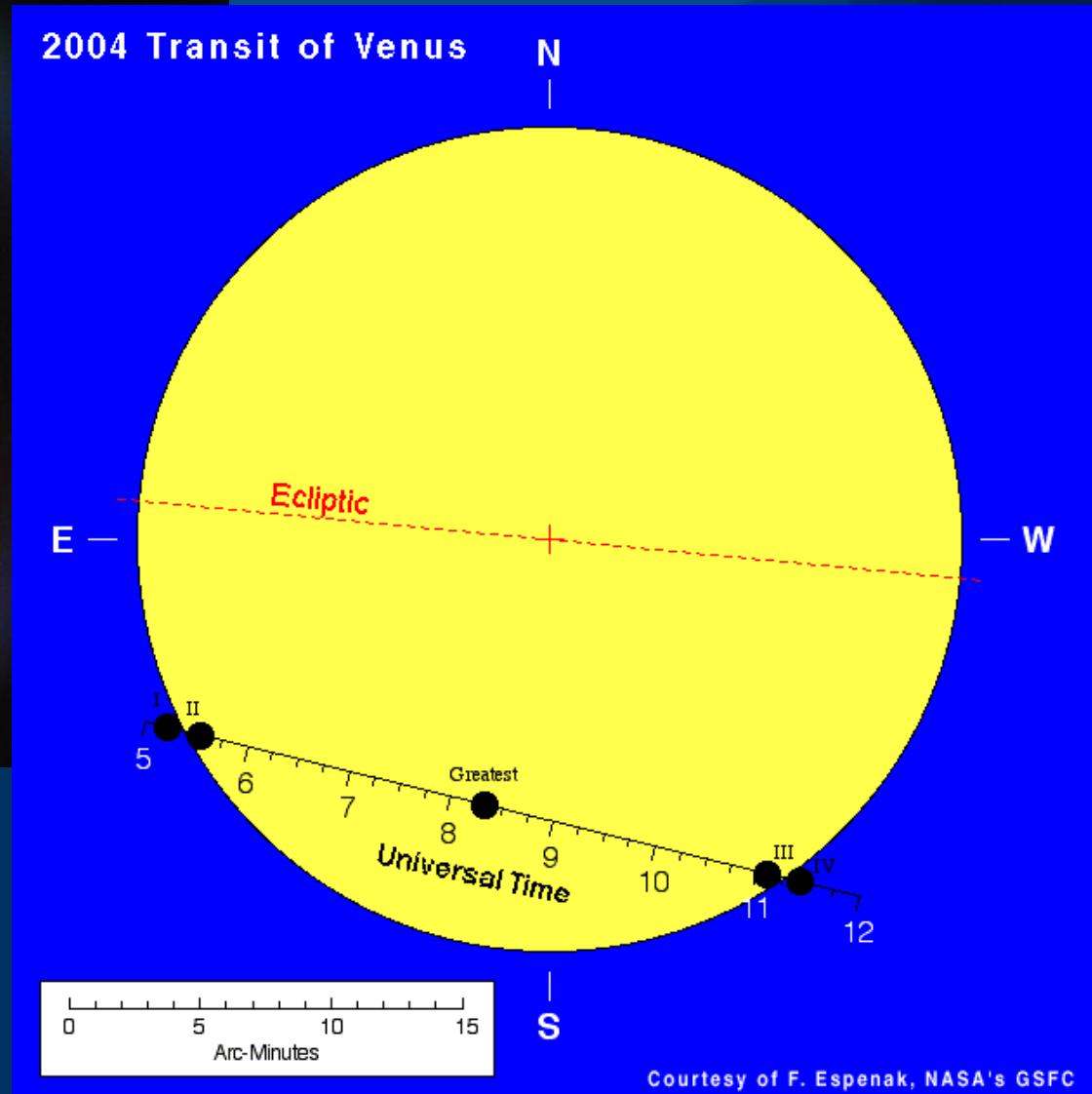


's view out
window that
ing left

Figuring out the remaining loose ends of the Solar System

- Verification that Earth is in motion
 - Ole Roemer's, 1677 - Jupiter Moon delays
 - James Bradley, 1728 – aberration of starlight
 - Frederick Bessel 1838 – first parallax
- What is 1 Astronomical Unit???
 - Use timings of Venus during transits across Sun
 - Bounce radar off of Venus when near inferior conjunction

Transits of Venus



Transits of Venus

Previous transits: 1761, 1769, 1874, 1882,
2004, ...

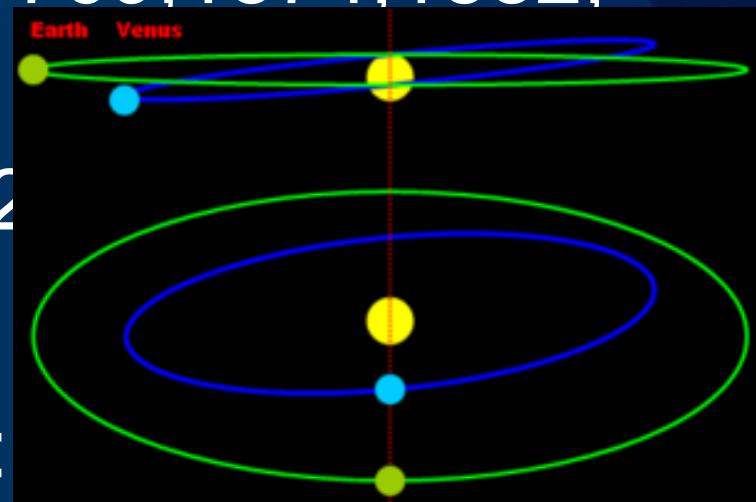
Last transit: June 6, 2012

Next transits: 2117, 2125

How it works: 3.4° tilt, 8:

243 yr cycle.

Inferior conjunction while both planets on
line
of nodes.



Science vs Superstition – it never ends

- The *Copernican Principle*
 - Sun not at center of Galaxy, or of Local Group, or of Local Supercluster, or of expansion of universe. *Are humans the only intel. life?*
- “Crazies” coming out of the woodwork
 - There are people at both extremes; pure skepticism and belief.
- Each of us has to reconcile facts with beliefs.
Follow Kepler's Lead!
- See “The Demon-Haunted World: Science As a Candle in the Dark” - C. Sagan

General philosophy of science

Karl Popper: Logic of falsification

Theories can never be verified by observation.

Theories can be falsified by observation, and so discarded.

The only acceptable theories are those which are falsifiable.

Thomas Kuhn: Paradigms and paradigm shifts

“Normal science” -- investigation within a paradigm

Revolutions -- paradigm shifts driven by anomalous data

Niels Bohr: Correspondence principle

New theories must reduce to good old theories in some limit.

A Summary of the Early History of Astronomy

Observations	Typical Dates	Theories
Stars, sun, moon, and planets are moving overhead.	3000 B.C.	
Each planet moves at a varying rate; retrograde motion.	500	Pythagorean theory: Earth-centered transparent spheres.
	400	Theory of multiple Earth-centered transparent spheres.
Heaven and Earth seem different; Earth seems motionless, apparently contradicting Aristarchus's theory.	300	Aristarchus's theory: sun-centered circles.
	200	
Planets are brighter during retrograde motion.	100	Theory of Earth-centered epicycles.
Detailed quantitative measurements show need for small corrections.	0	Ptolemy's theory: Earth-centered epicycles, equants.
	A.D. 100	
Brahe's accurate measurements disprove Ptolemy's and Copernicus's theories.	1500	Copernicus's theory: sun-centered circles.
Galileo's telescopic observations disprove Earth-centered theories.	1600	Kepler's theory: sun-focused ellipses.