

The Copernican Revolution - Separating Science and Superstition

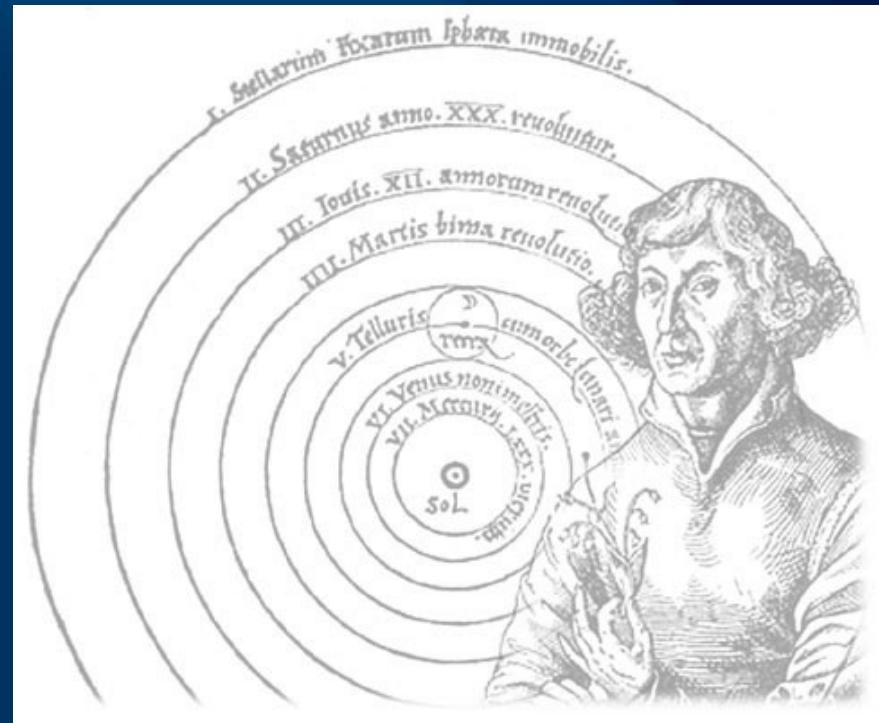


J. Pinkney
ONU 2022



Outline

- Our universe viewed by the ancients
- Greek cosmological models
- Copernican Revolution
 - Nicolaus Copernicus
 - Tycho Brahe
 - Johannes Kepler
 - Galileo Galilei
 - Isaac Newton
- Science vs Superstition: it never ends



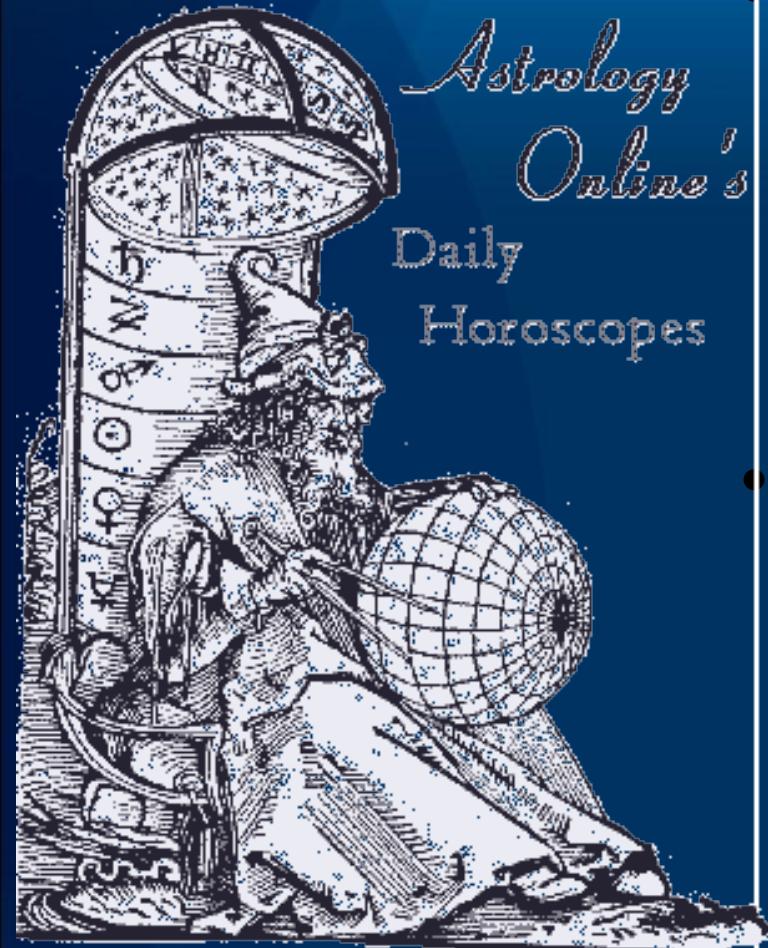
What the Ancients Knew

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



What the Ancients Knew

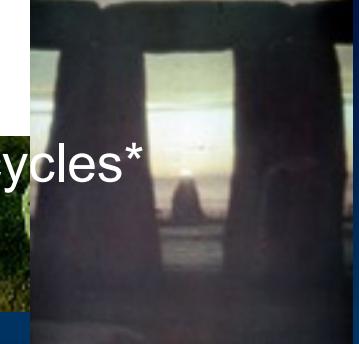
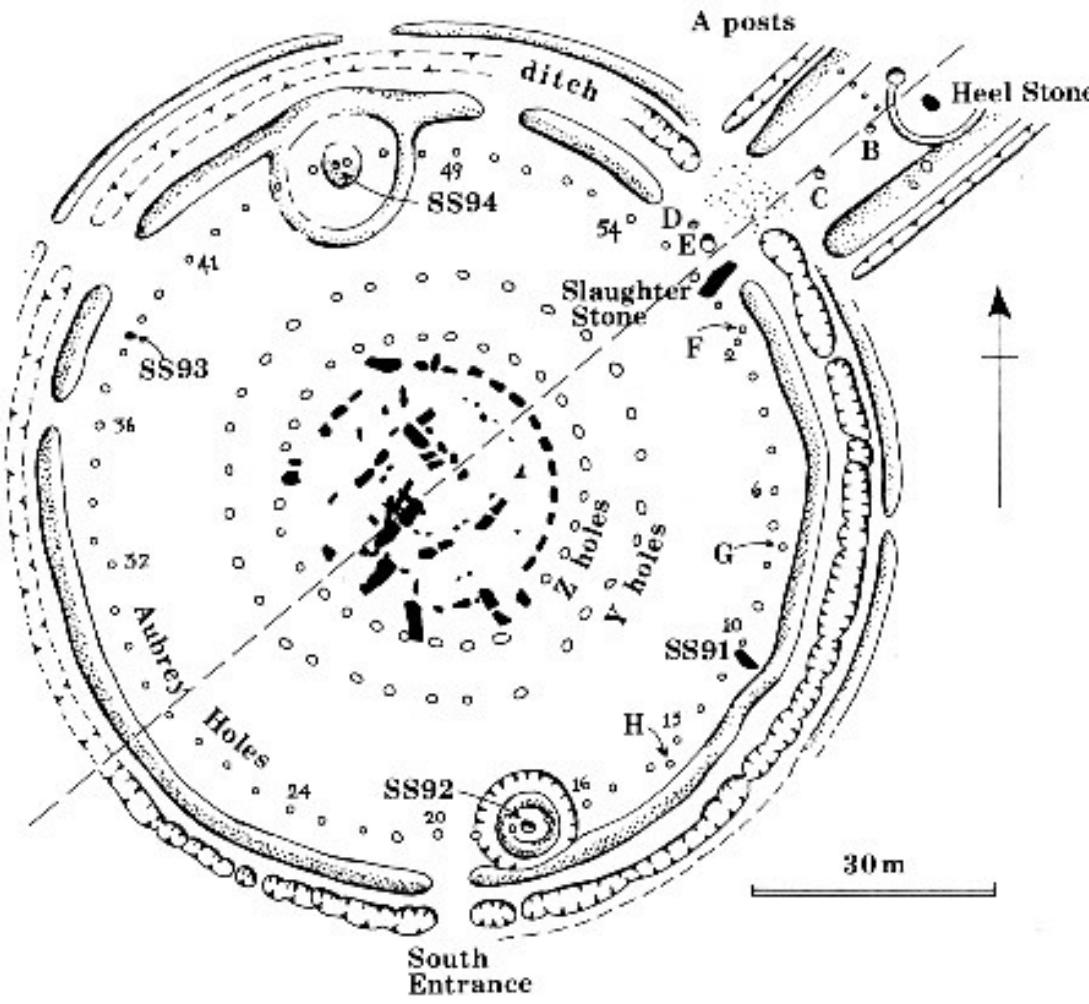


- Mysterious cultures
 - People of stonehenge, Plains Indians, Anasazi, Maya
 - left behind calendar-like constructions.
- Well documented cultures
 - Greek, but also Chinese, Babylonian, Egyptian, Arab
 - left records of lunar cycles, eclipses, comets, novae, star maps, models

Unknown nature → superstition → astrology.

The Ancients: Stonehenge

- Building Phases
- 3100 BC –
- Phase

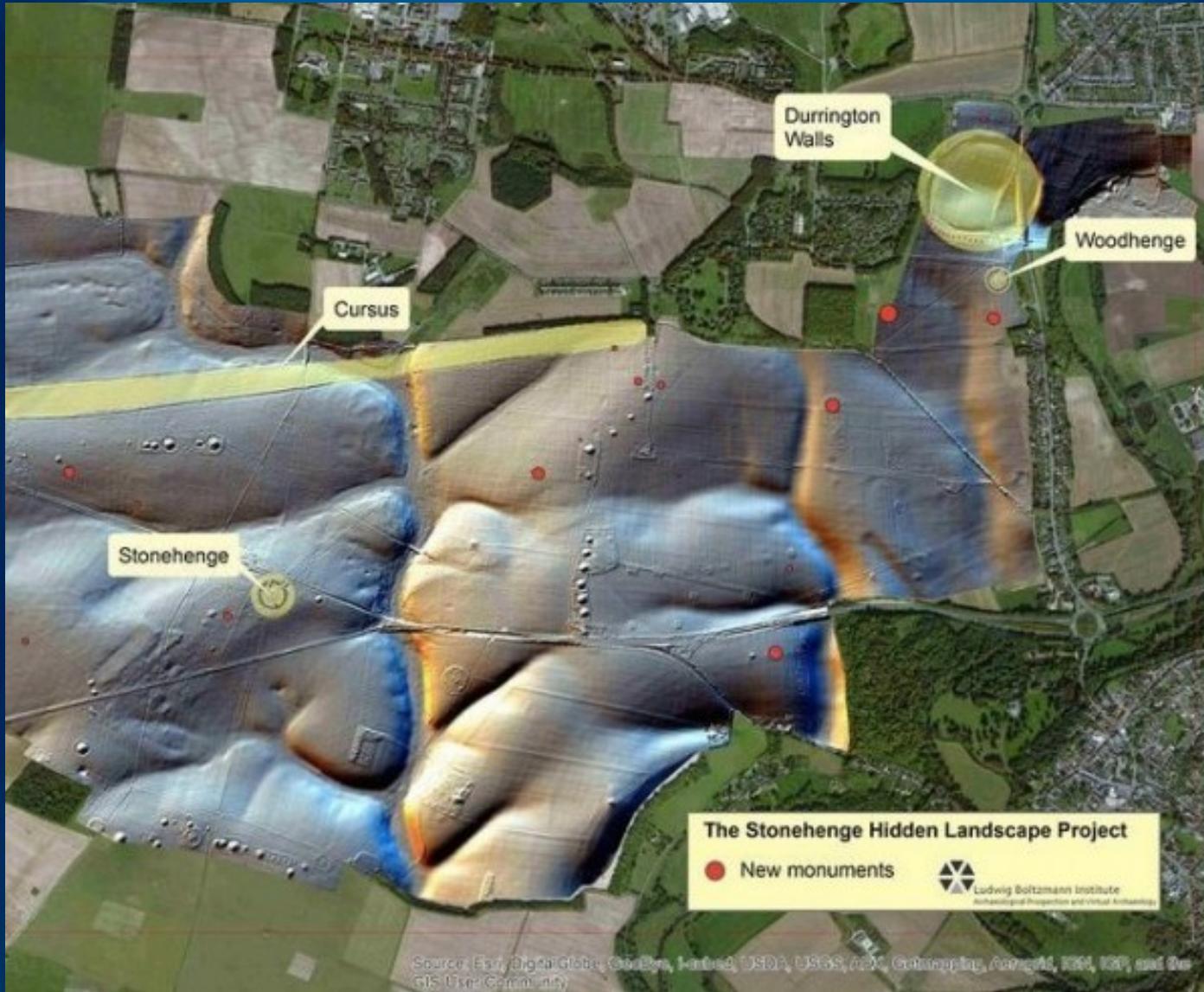


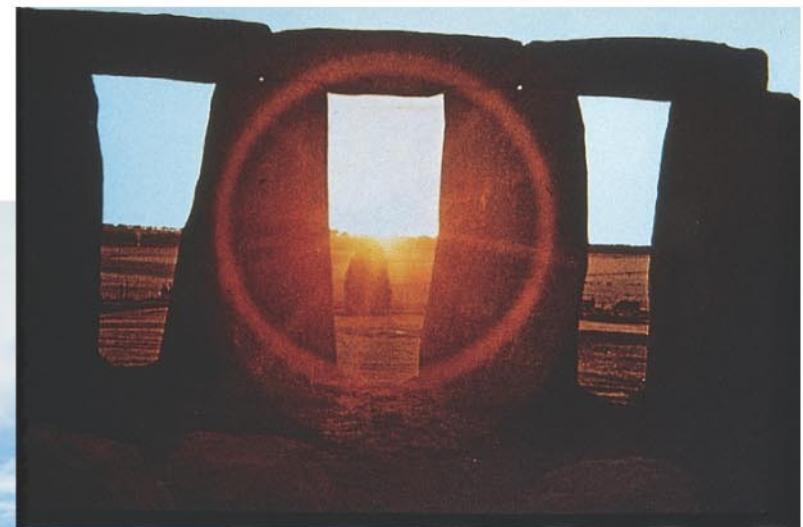
30 Y-holes, 28/29 Z-holes, 56 Aubrey holes = 3 Saros cycles*
Heel stone marks sunrise on Summer Solstice

*actually lunar nodal precession cycle (18.6 yrs)

The Ancients: Stonehenge

- Recent discoveries using ground-penetrating radar and lidar.

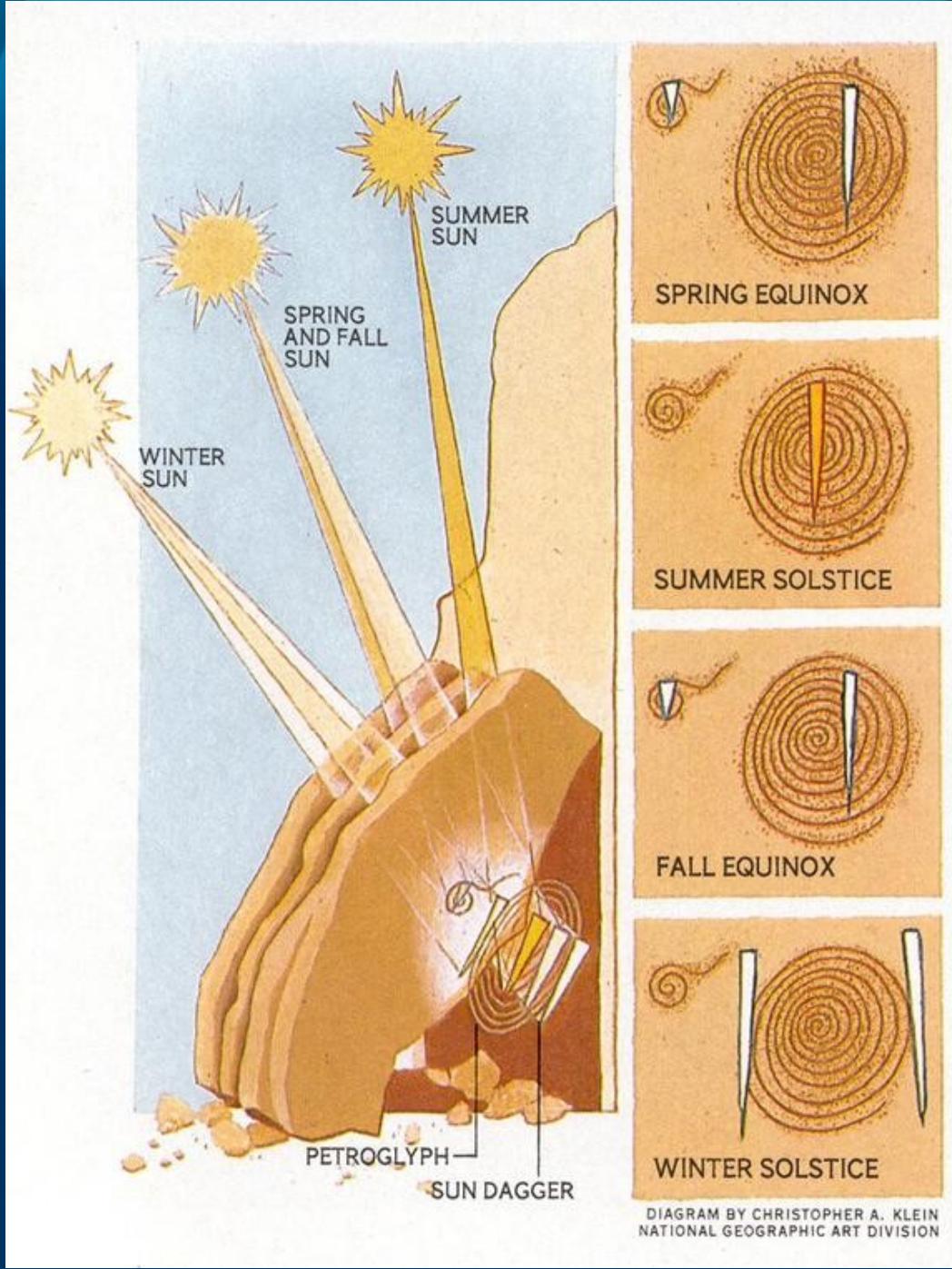






(b)

The Plains Indians – Big Horn
The Maya – Caracol in Chichen
Itza
The Chacoan culture – Fajada Butte
Sun Daggers , Chaco Canyon



What the Ancients Knew



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es

Zodiac, “year of the ____”
- ancient alphabet, ziggurats,
eclipse cycles, math (60

and Osiris, pyramids, Nile

During dark ages - algebra,
function between
1000 AD!

Measurements

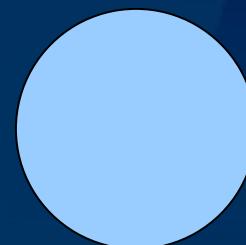
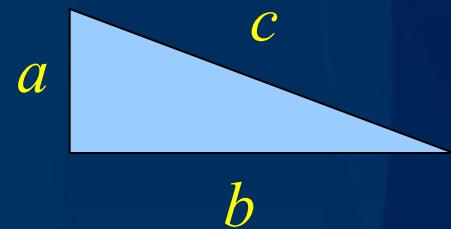
by

superstition → astrology.

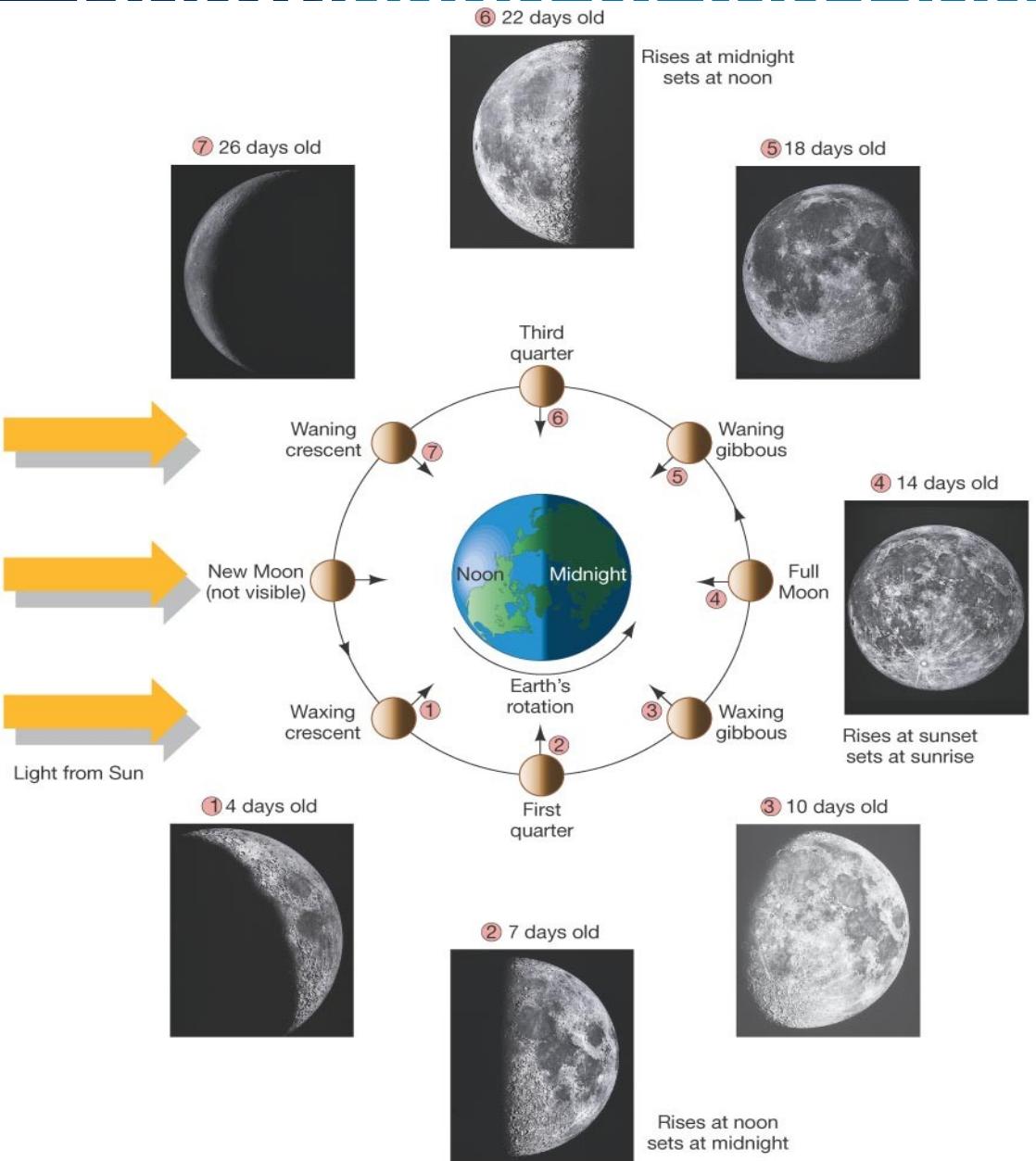


Knowledge of the Ancient Greeks I.

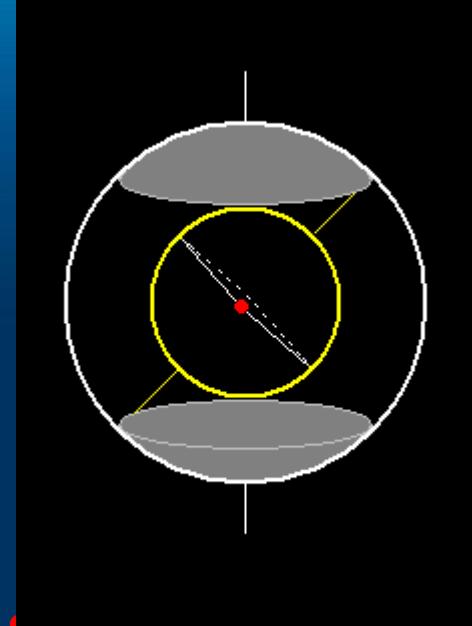
- Ideas and philosophies were rich and varied, some correct and some **incorrect**.
 - Thales of Miletus (624-547 BC):
 - universe is rational
 - predicted eclipse ~585 BC
 - Pythagoras (570-497 BC):
 - math in nature, music of spheres
 - Earth and planets are spherical
 - Plato (428-347 BC):
 - Truth through pure thought over observations
 - Circle is most perfect form



Knowledge of the Ancient Greeks II.



c):
model
cycle.

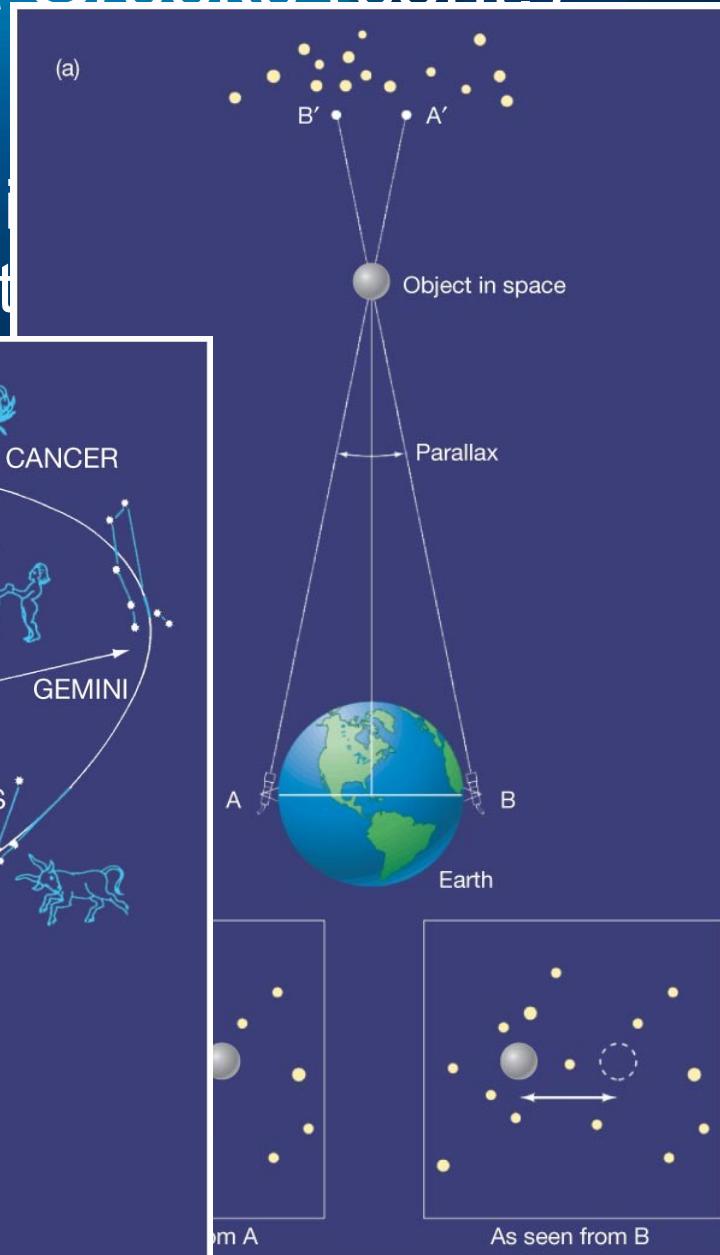
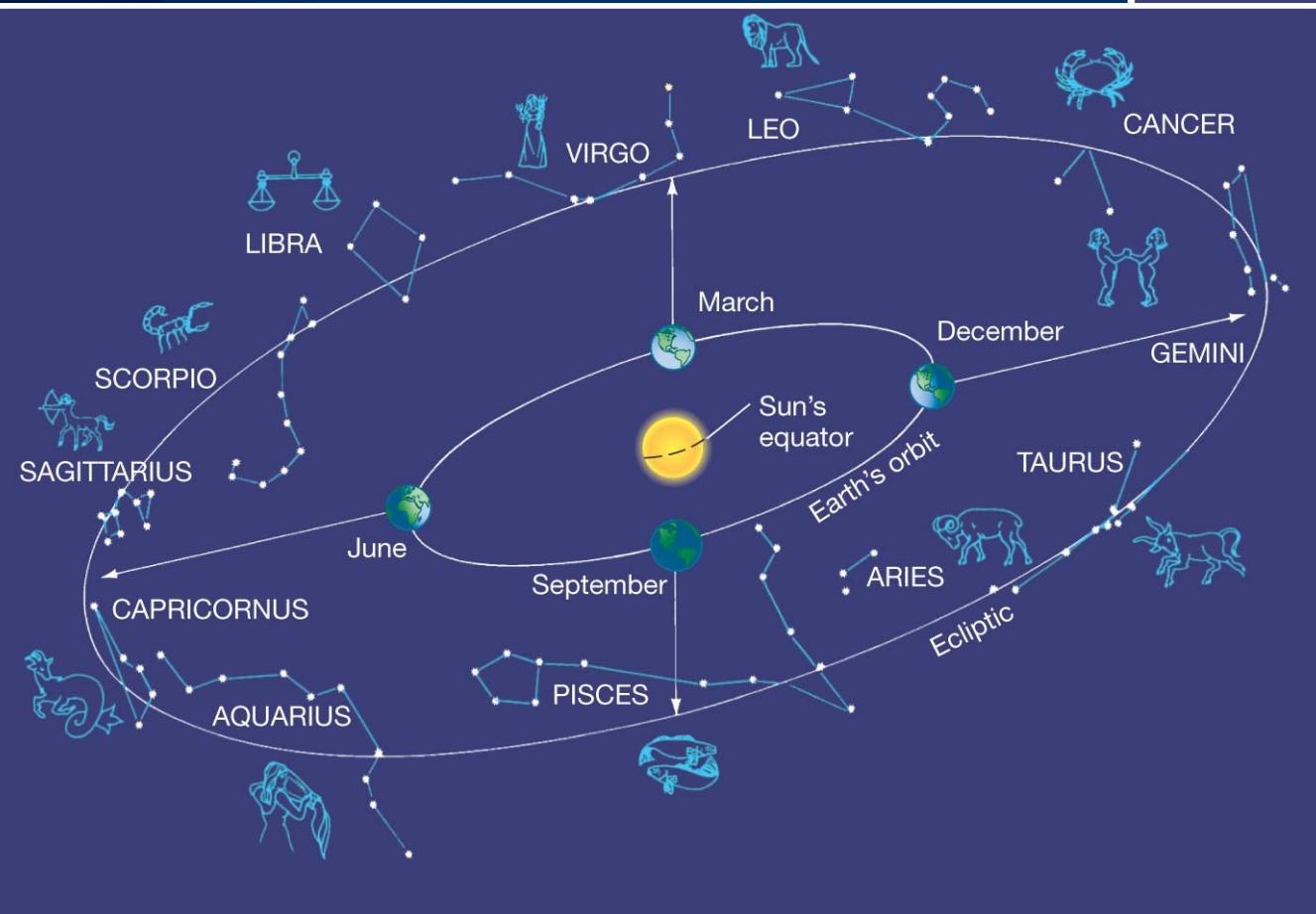


are perfect
elements: earth,
made of aether.
and

should exhibit parallax

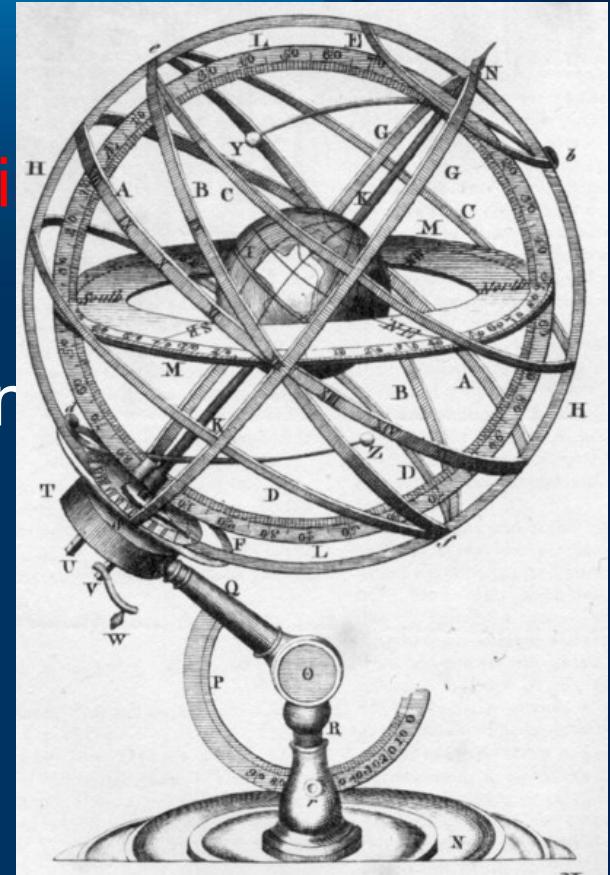
Knowledge of the Ancient Greeks (cont.)

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

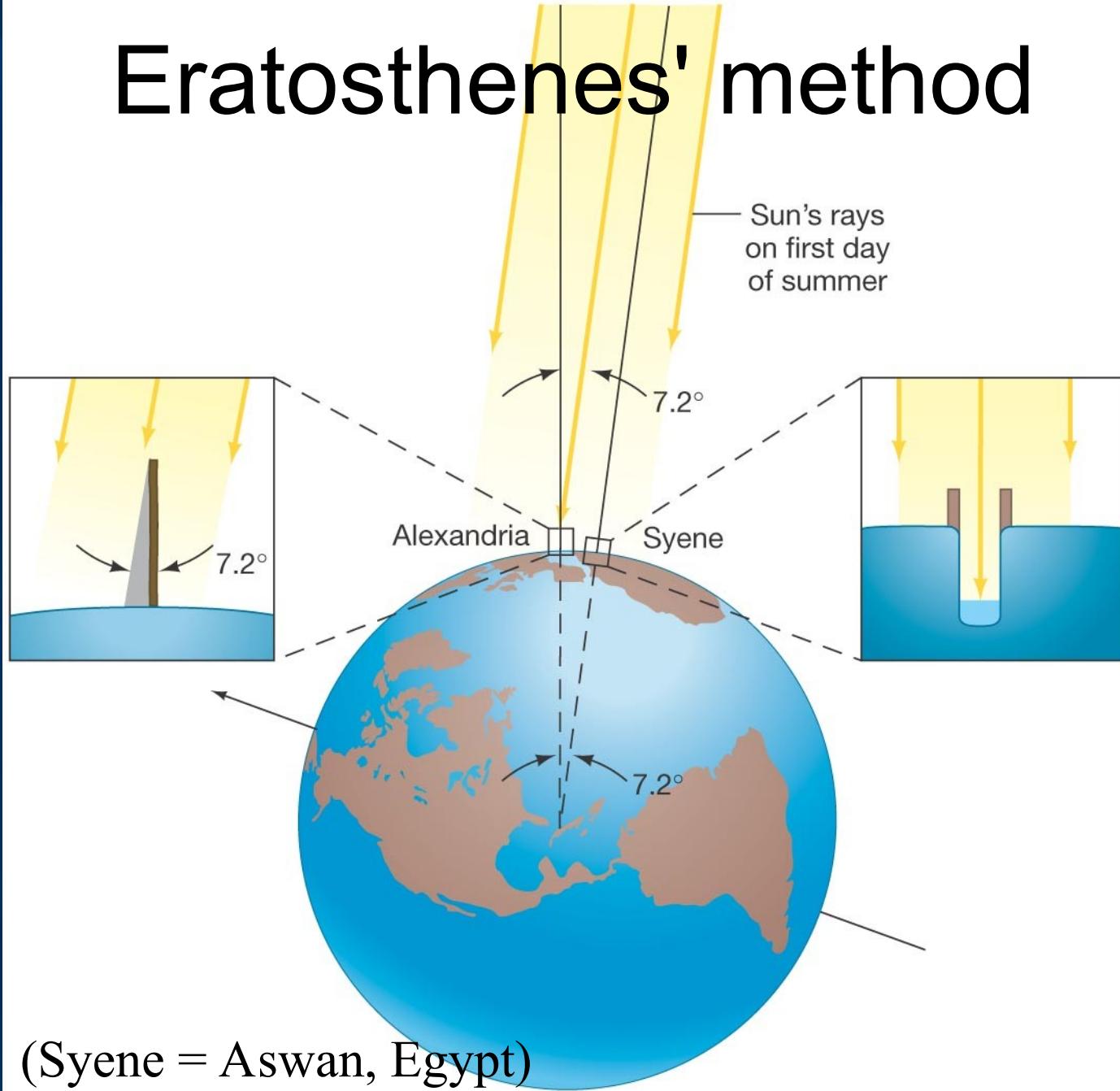


Knowledge of the Ancient Greeks III

- Philolaus (480-385 BC)
 - Earth in motion **around invisible “fire”**
- 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 the equinoxes
 - Uses epicycles, deferents and eccentricities in modelling motion of Sun and Moon.

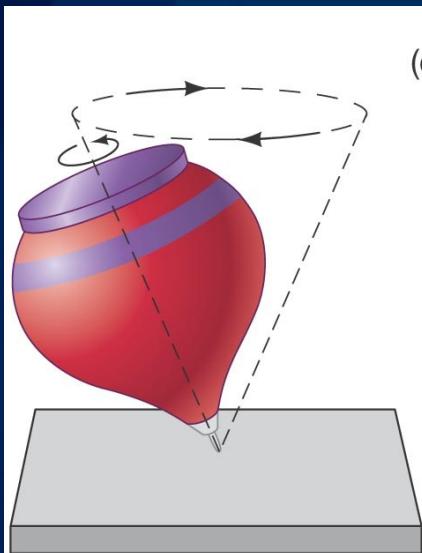


Eratosthenes' method



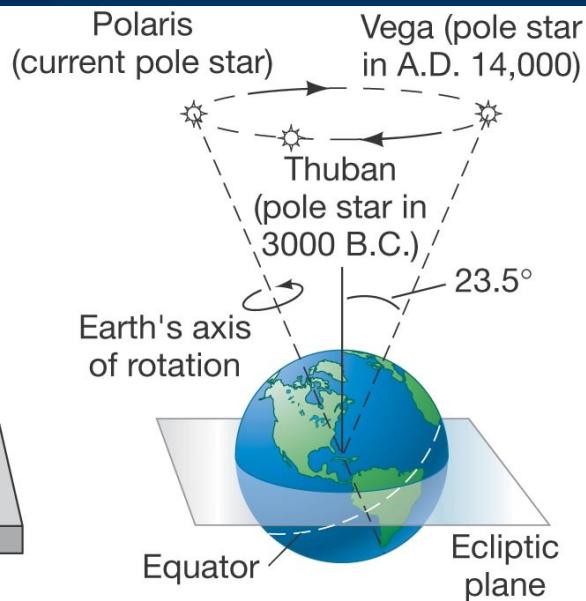
Knowledge of the Ancient Greeks (cont.)

Earth's spin axis precesses with 26,000 yr period (Hipparchus 160-127 BC)



(a)

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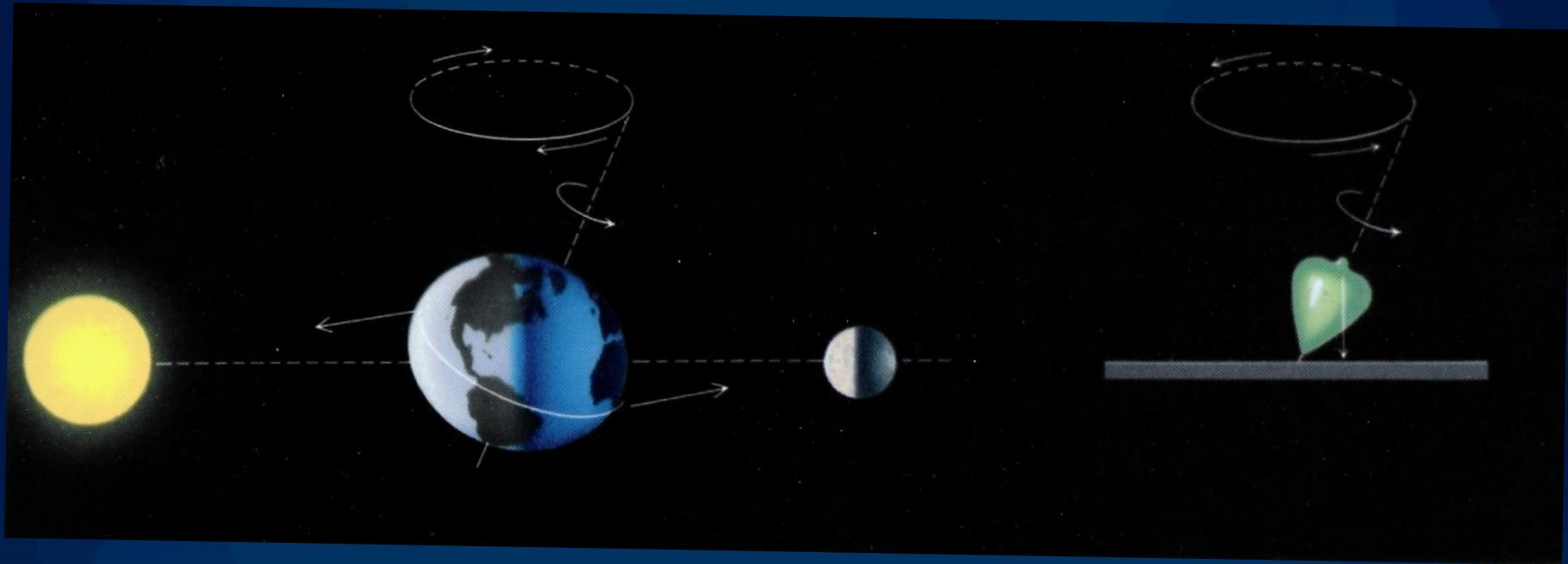


(b)

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Knowledge of the Ancient Greeks (cont.)

Cause of precession:



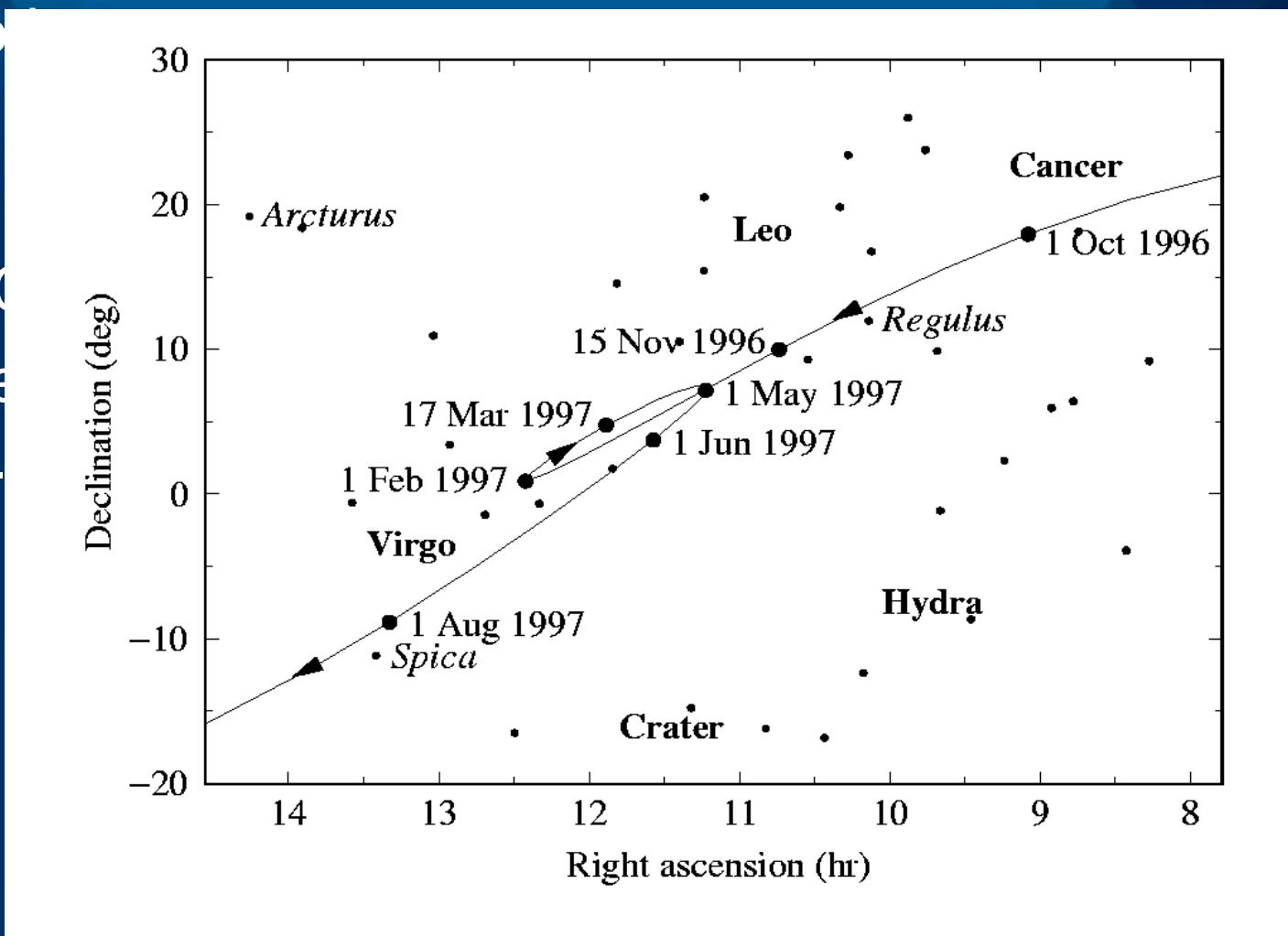
Knowledge of the Ancient Greeks IV

- 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
 - Writings on Optics, Geography, Music
 - Astronomy: “*Mathematike Syntaxis*” = “The Almagest”
 - Astrology: “*Tetrabiblos*” relates horoscopes to Aristotelian philosophy



The Appearance of the Planets

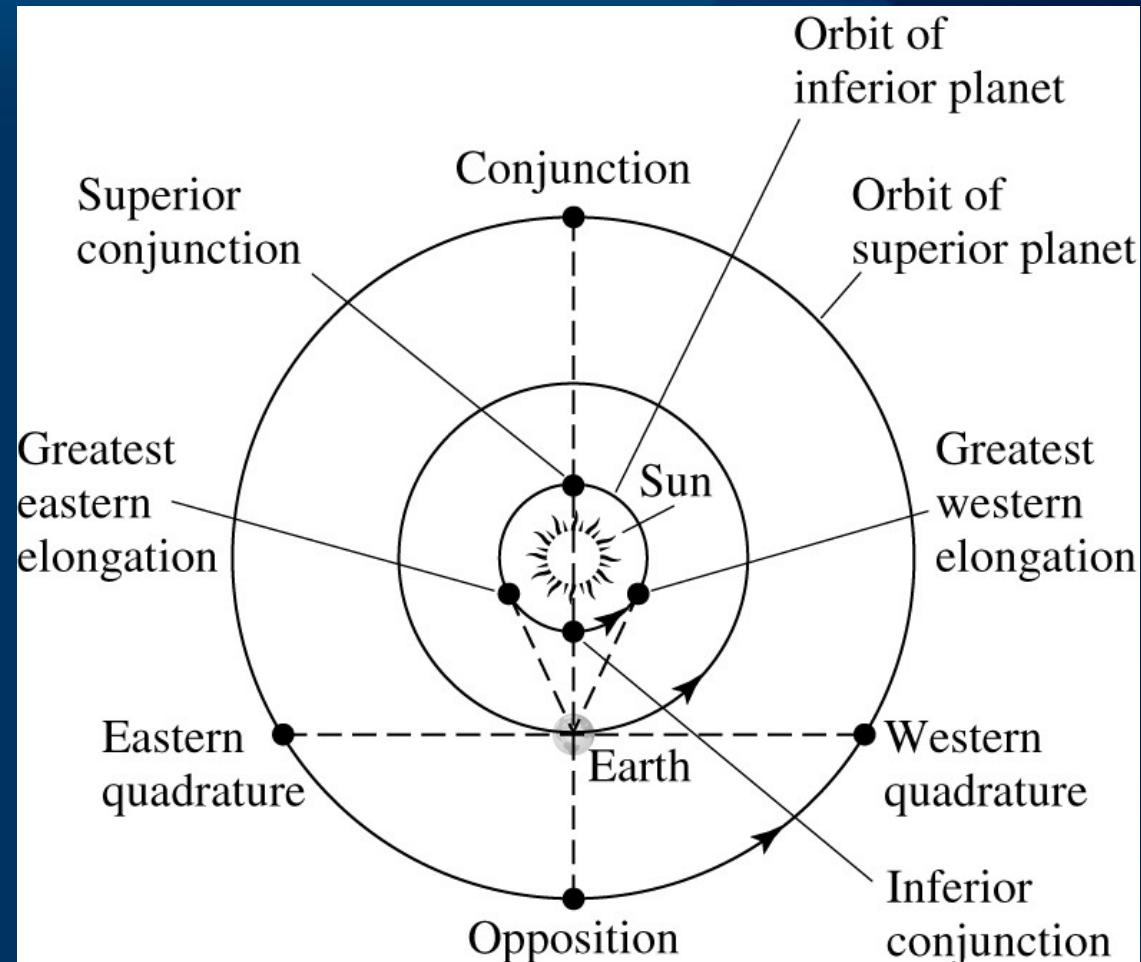
- Daily motion
- Change position in sky.
- All orbit the Sun
- Usually easiest to see we call ...



Retrograde Motion!

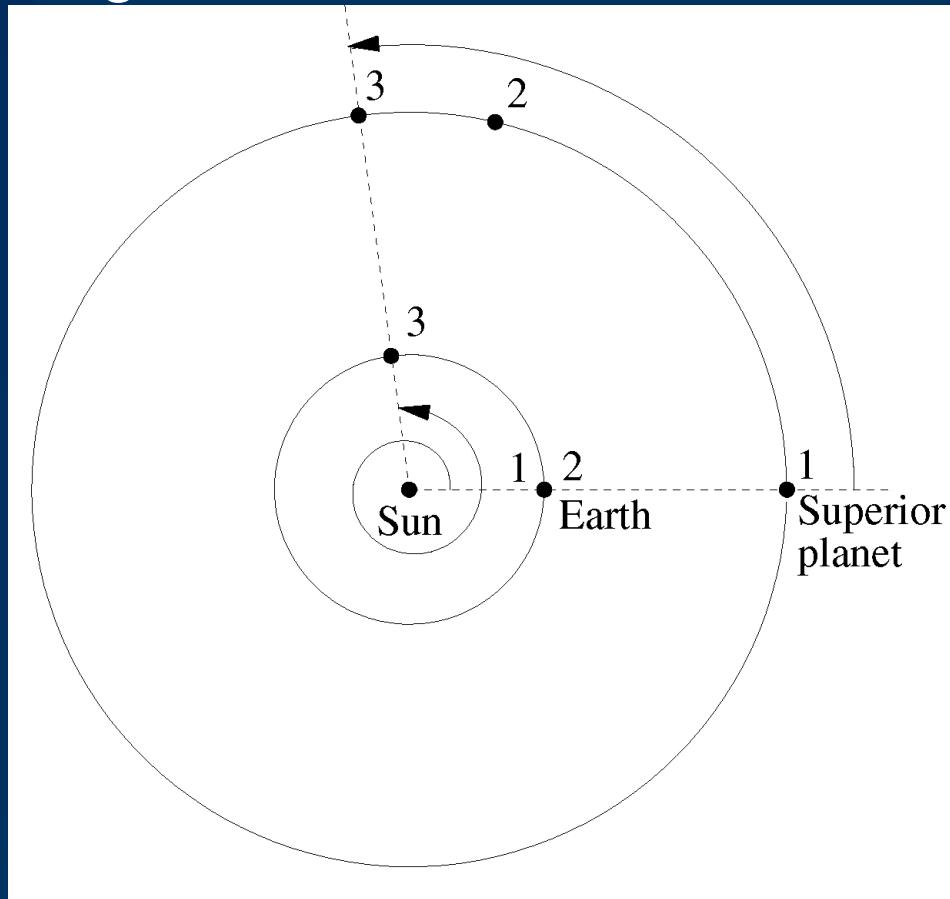
Planetary Configurations

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



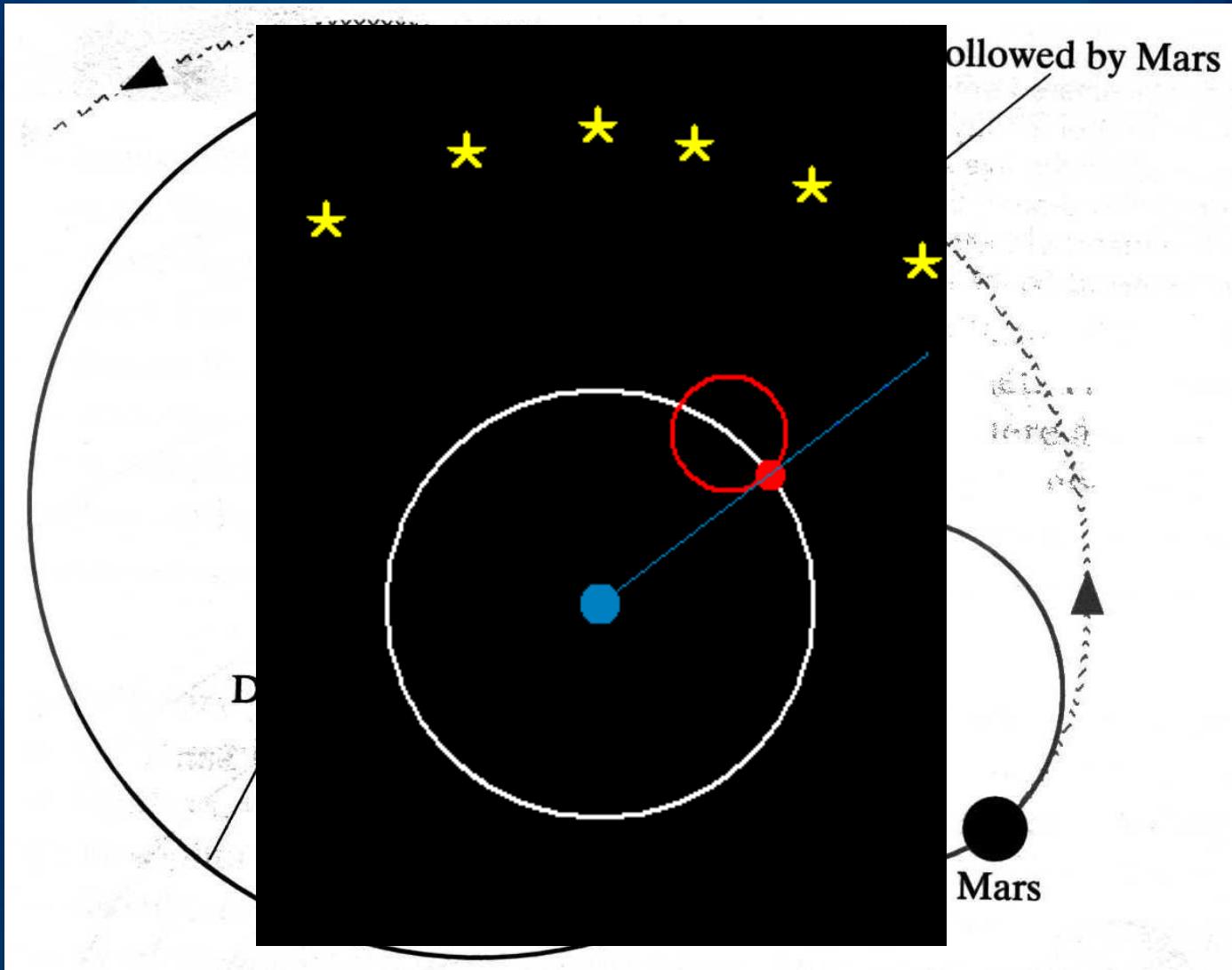
Synodic and Sidereal Periods

- 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



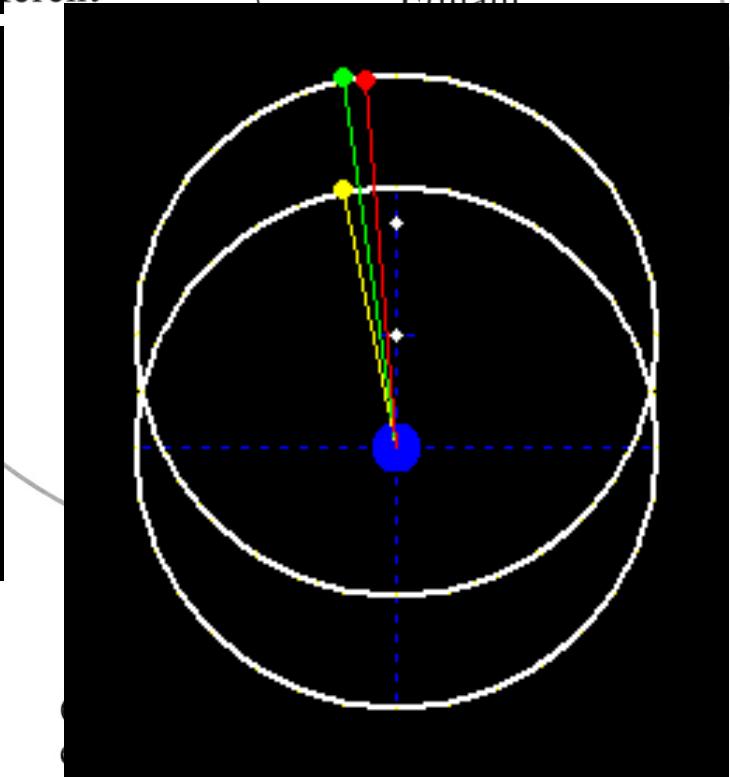
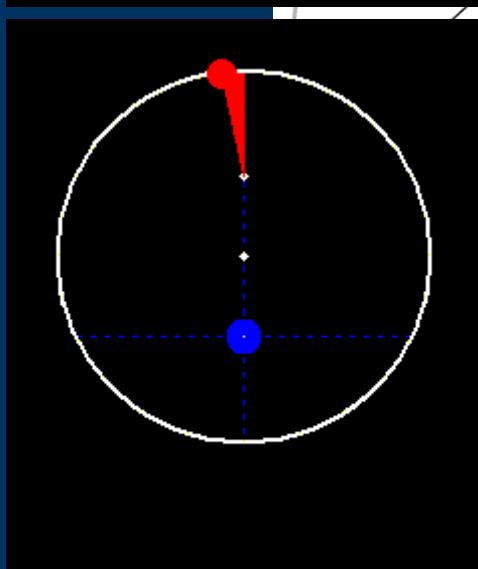
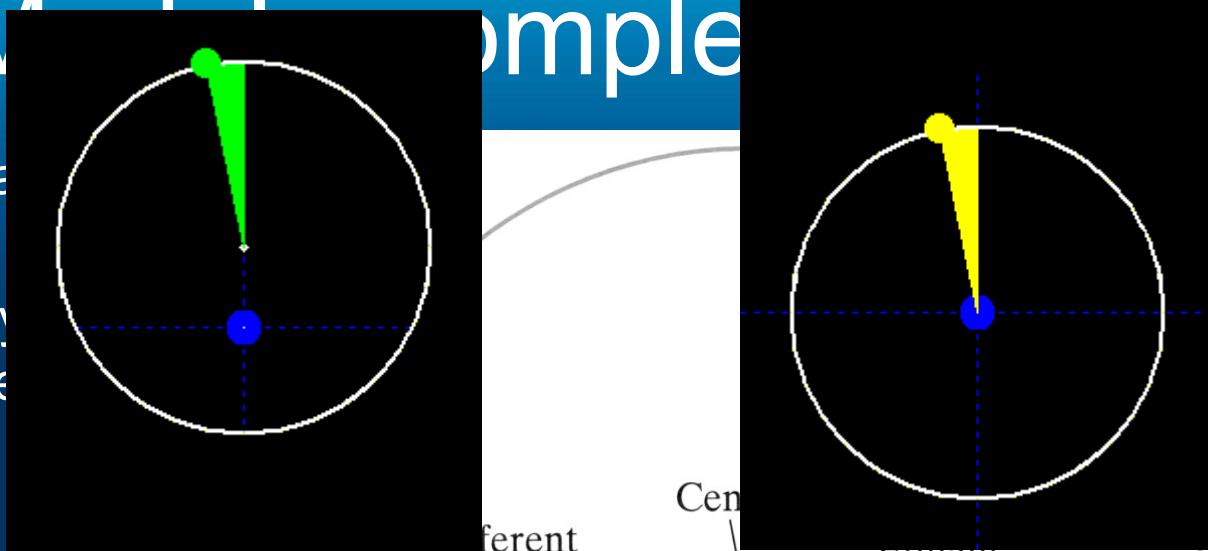
Epicycles on Deferents

- Ptolemy desired uniform circular motions



Ptolemy's Model

- 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



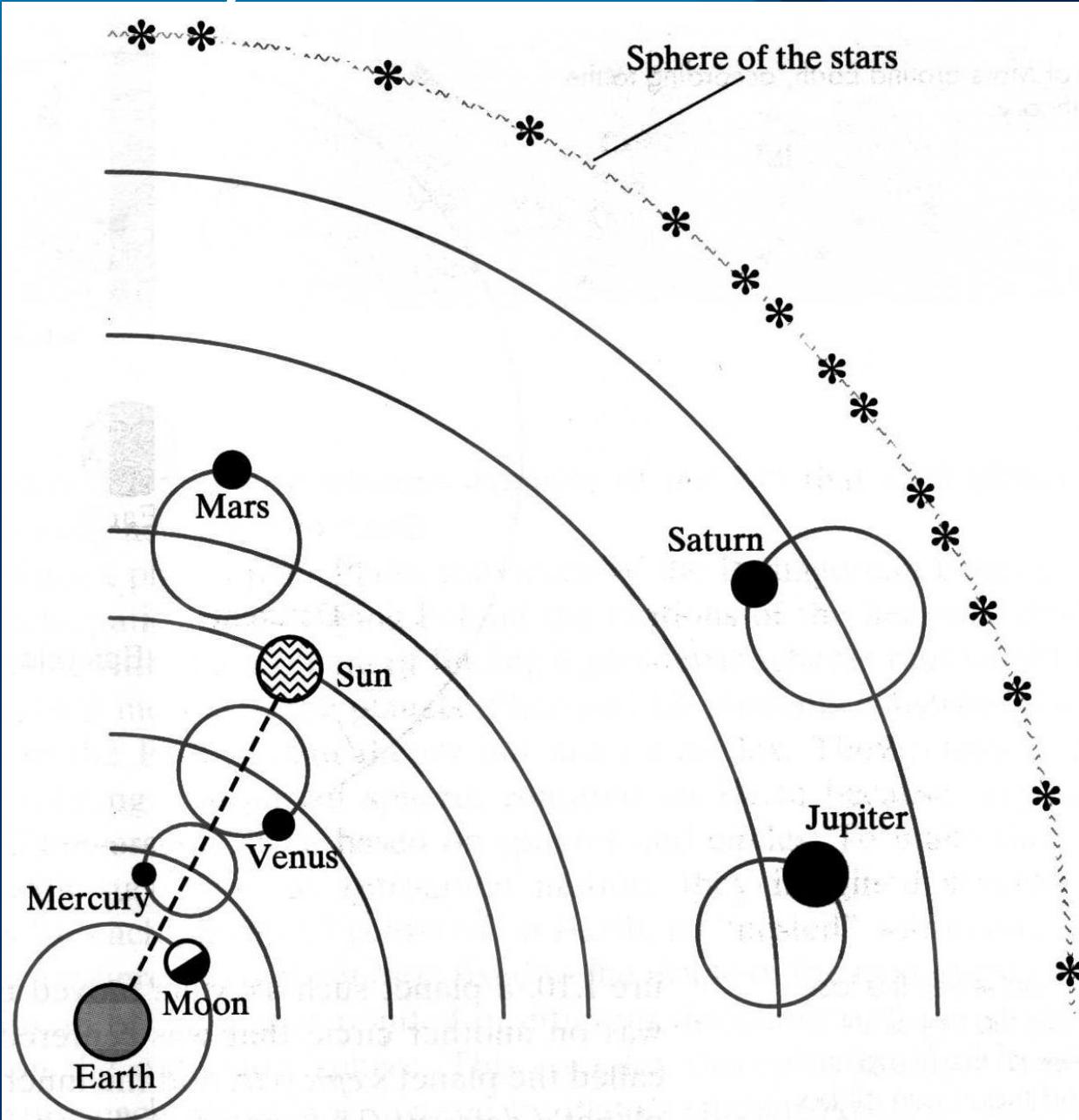
Ptolemy's Model

- 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

GALILEO GALILEI



· 1609

Dialogue of the Two Chief World Systems

· 1633 Trial at Rome by the Inquisition

· 1642

· 1642

. 1512 1st Comment



. 1543 *De Revolutionibus*

. 1546

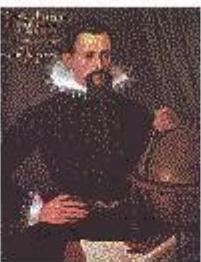
TYCHO BRAHE



. 1601

JOHANNES
KEPLER

. 1571



. 1609
New Astronomy

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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

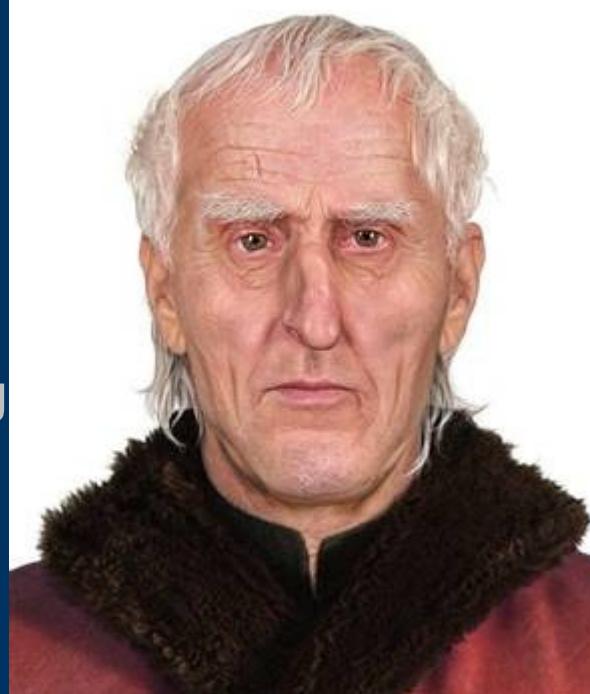
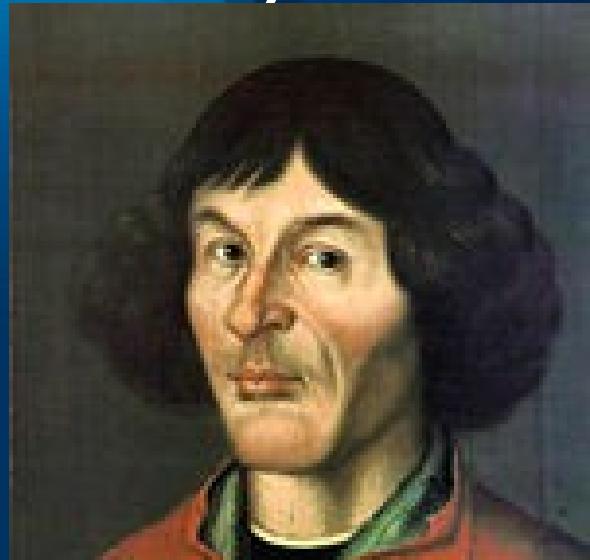


. 1686 *Principia*

. 1727

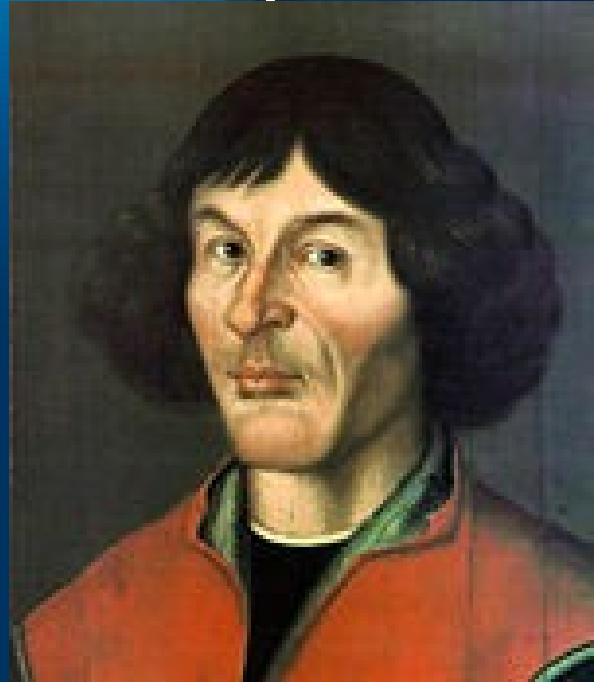
Copernicus (1473-1543)

- 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)
 - Prutenic tables (1551)
- Reluctant to publish because of fear of criticism, or fear of persecution by church
- In 2005, skull recovered in Cathedral of Frauenberg



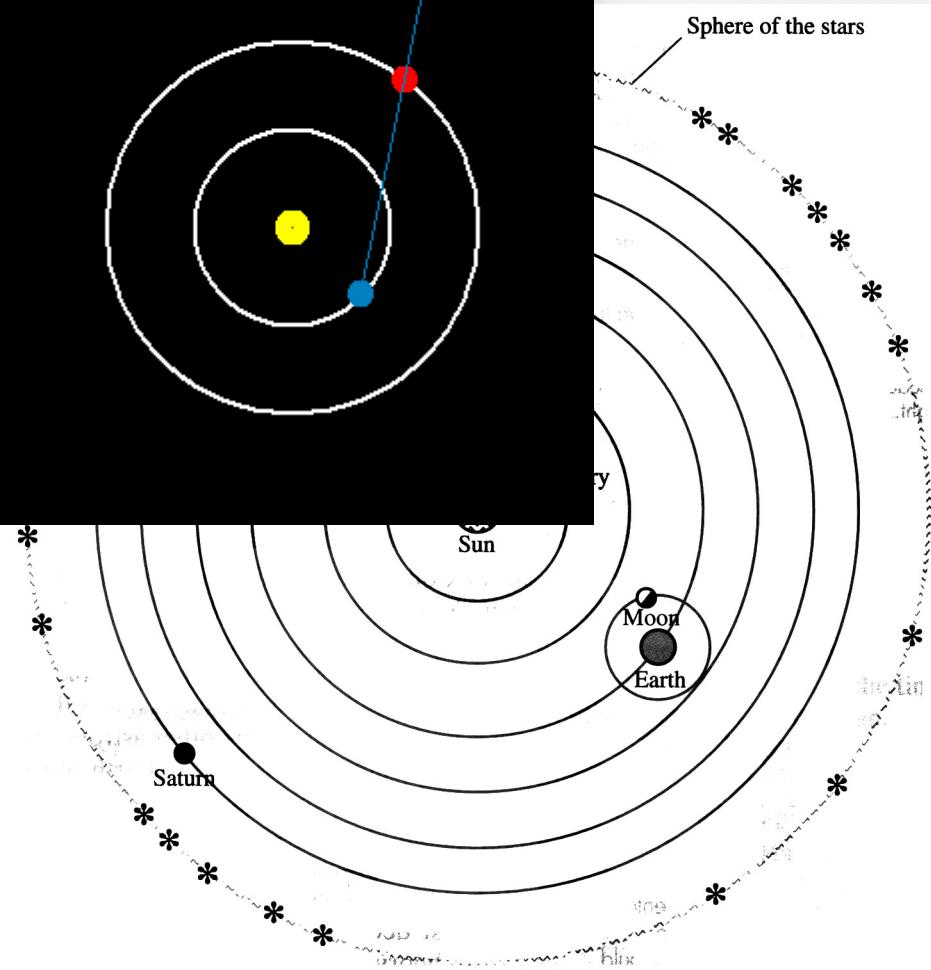
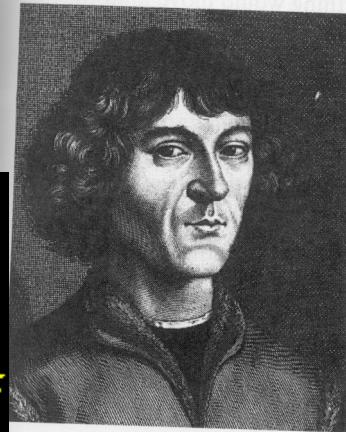
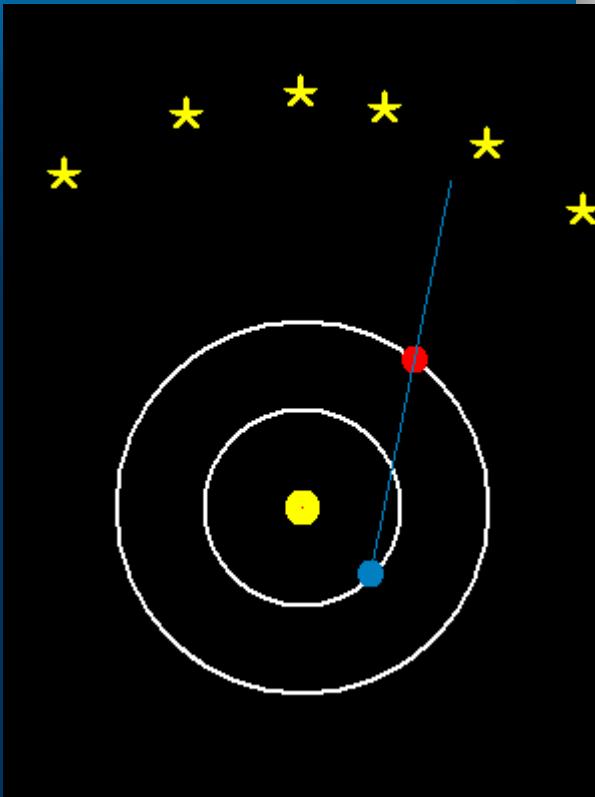
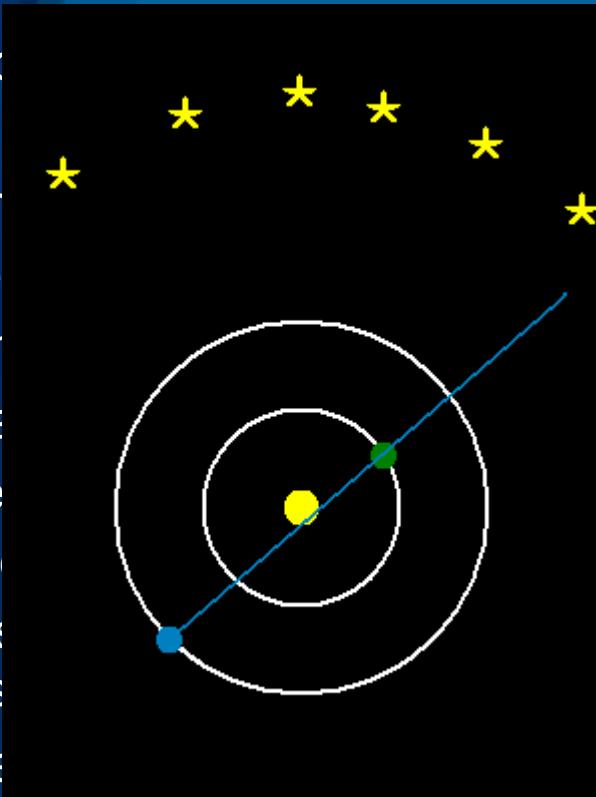
Copernicus (1473-1543)

- **Foundations of the Copernican Revolution**
 - Earth is not at the center of everything
 - Earth is the center of lunar orbit (and its gravity)
 - All planets revolve around the Sun
 - Distance to stars >> distance to Sun
 - Earth rotates causing rising and setting motions
 - Retrograde motion is due to Earth's revolution



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



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

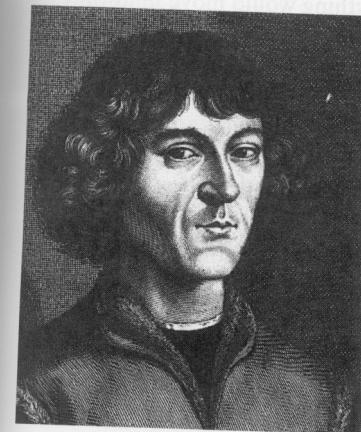
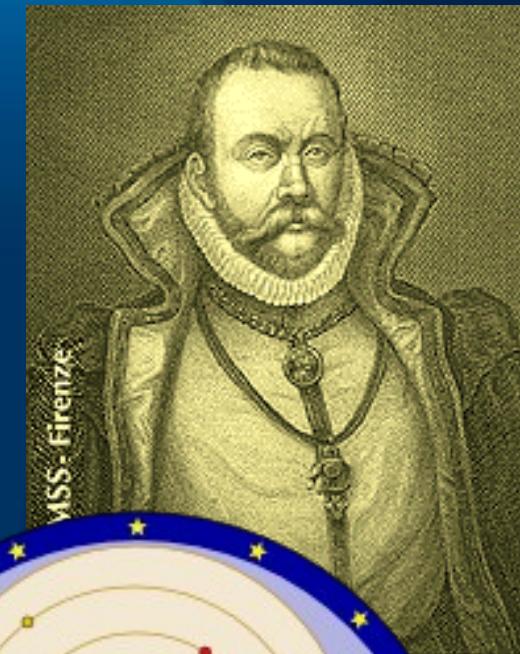


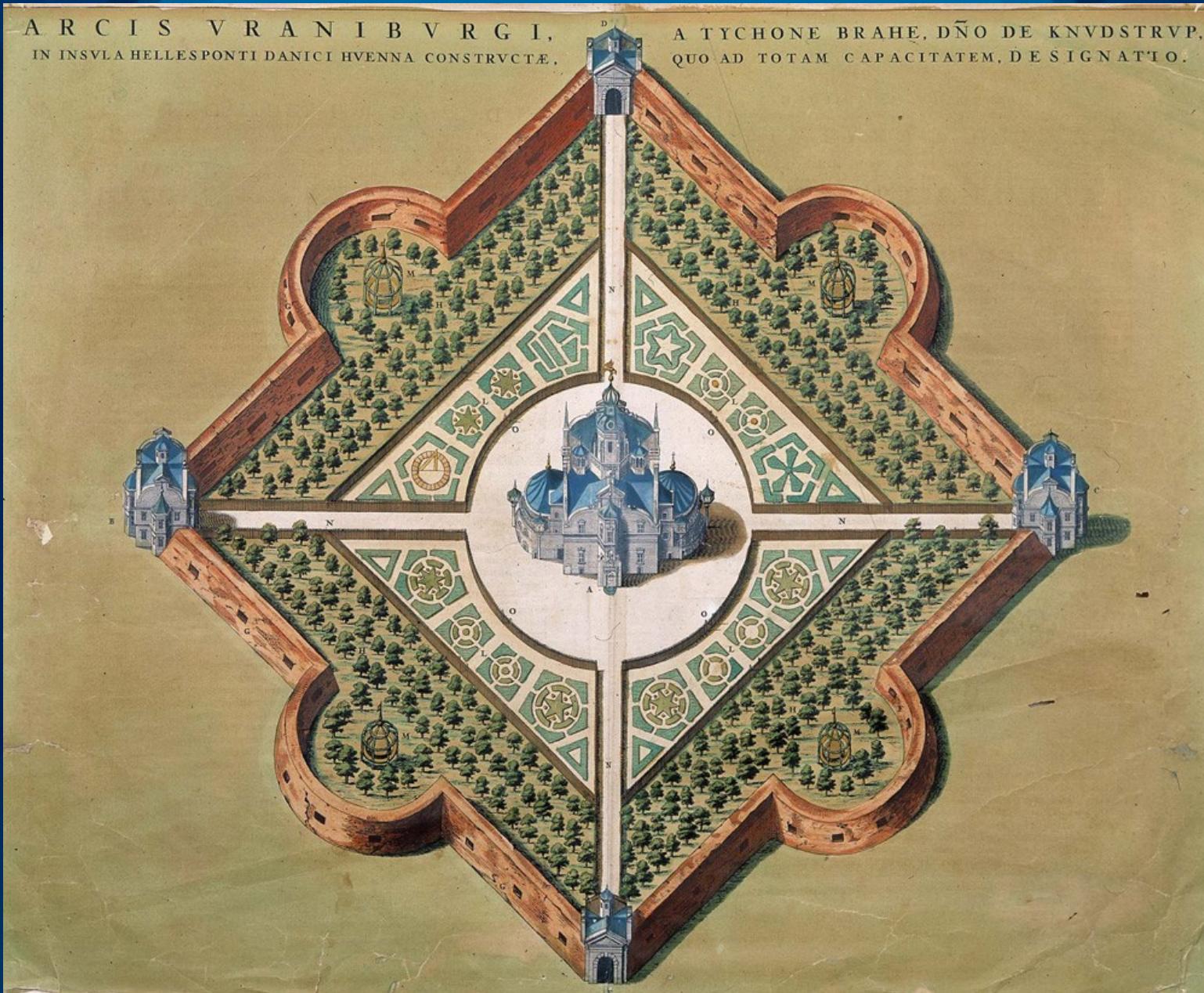
FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd 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 not 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 (1546-1601)



Tycho Brahe

- Left Kepler with 20 years of meticulous planet measurements.
 - 5x better precision
 - 2-4 arc-minutes (1/30 of a degree) compared to 10 arc-minutes (1/6 of a degree)
 - 20 years of data
 - Neither Ptolemy nor Copernicus's models are able to produce the observations!

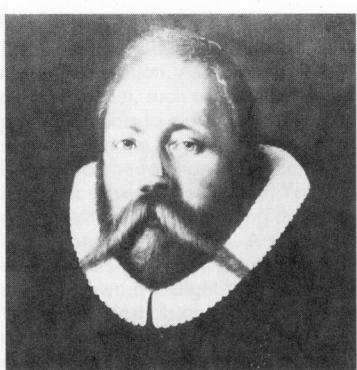


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

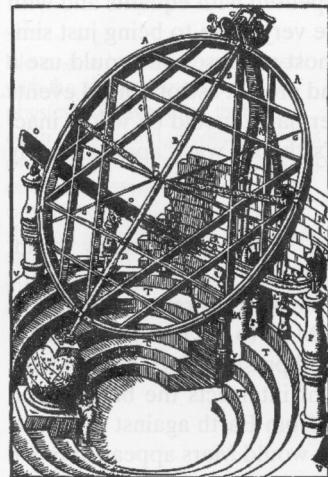


FIGURE 1.19 digigal.org/1213.htm
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

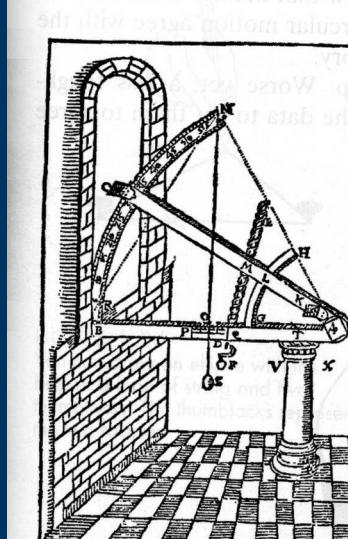


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

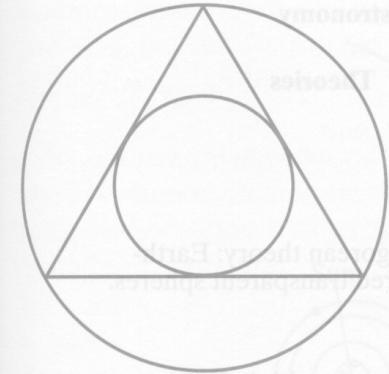
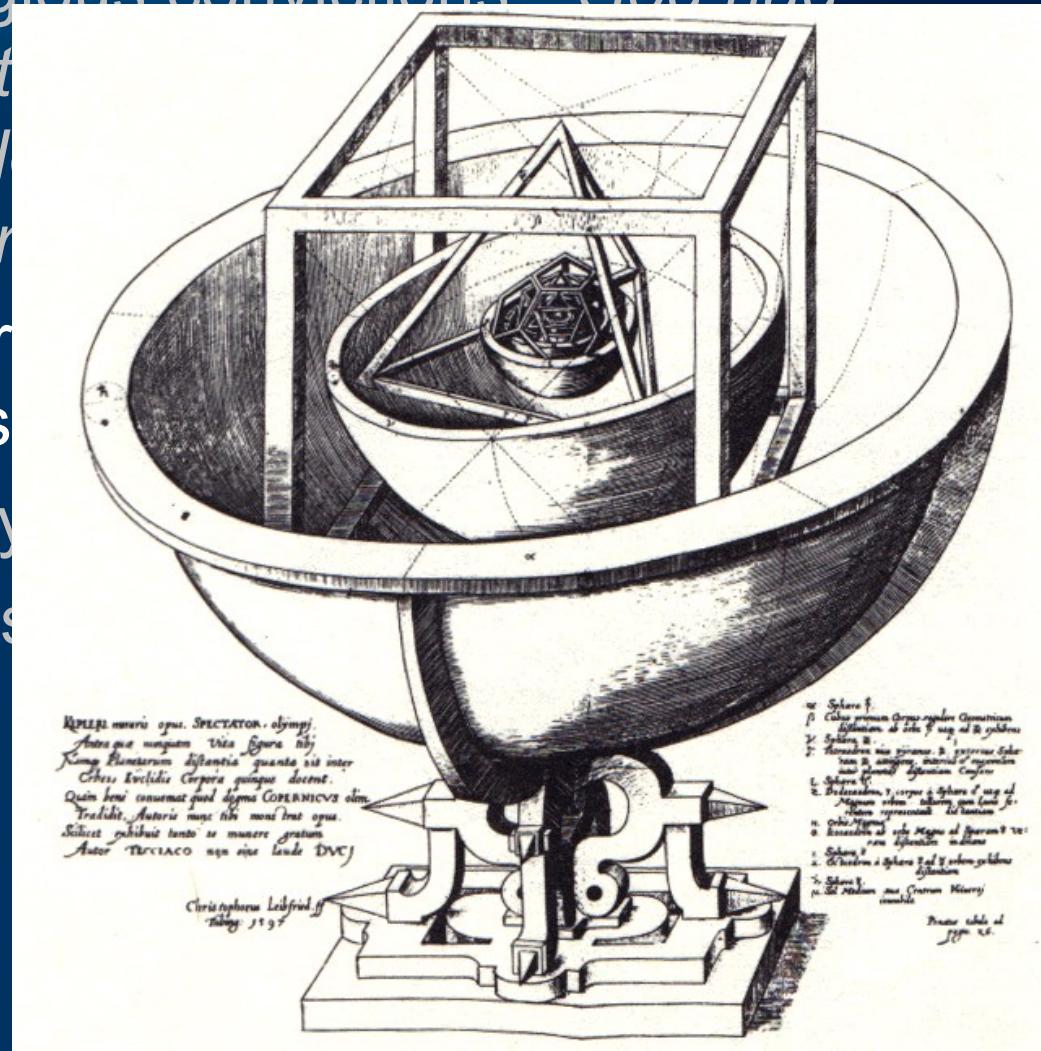


FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

- Mathematician, astronomer, astrologer
- Had religious convictions - *God had created the universe according to a plan that is intelligible to reason*
- Geometric model of the five regular solids
- Astrology
- “mother of all theories”



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
- Publications of Kepler's laws
 - *Astronomica Nova* (1609) contains Kepler's 1st and 2nd laws
 - *Epitome of Copernican Astronomy* (1617) adds Kepler's 3rd
 - *Rudolphine Tables* (1623)

Johannes Kepler

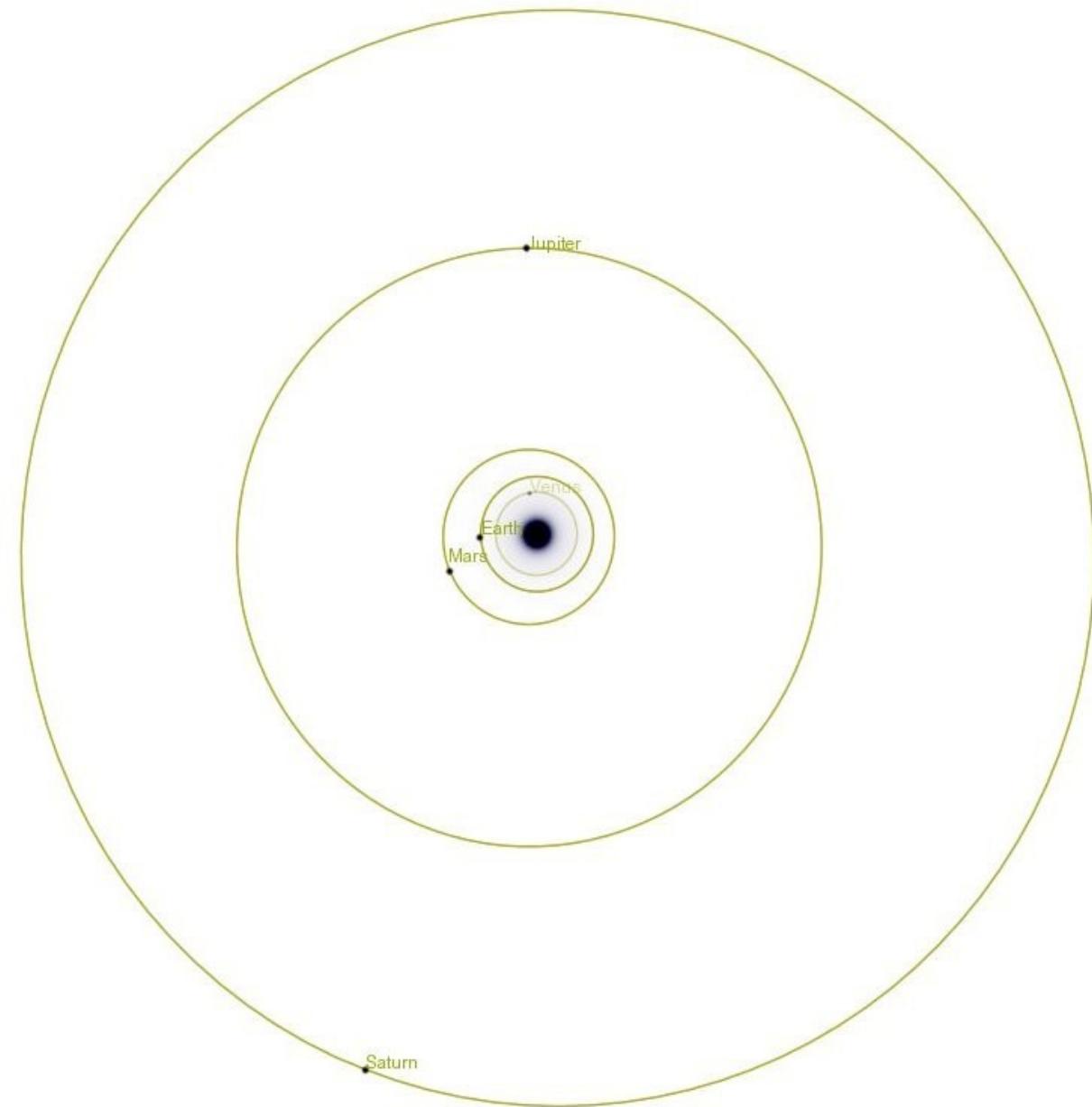
Inner Planet orbits

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

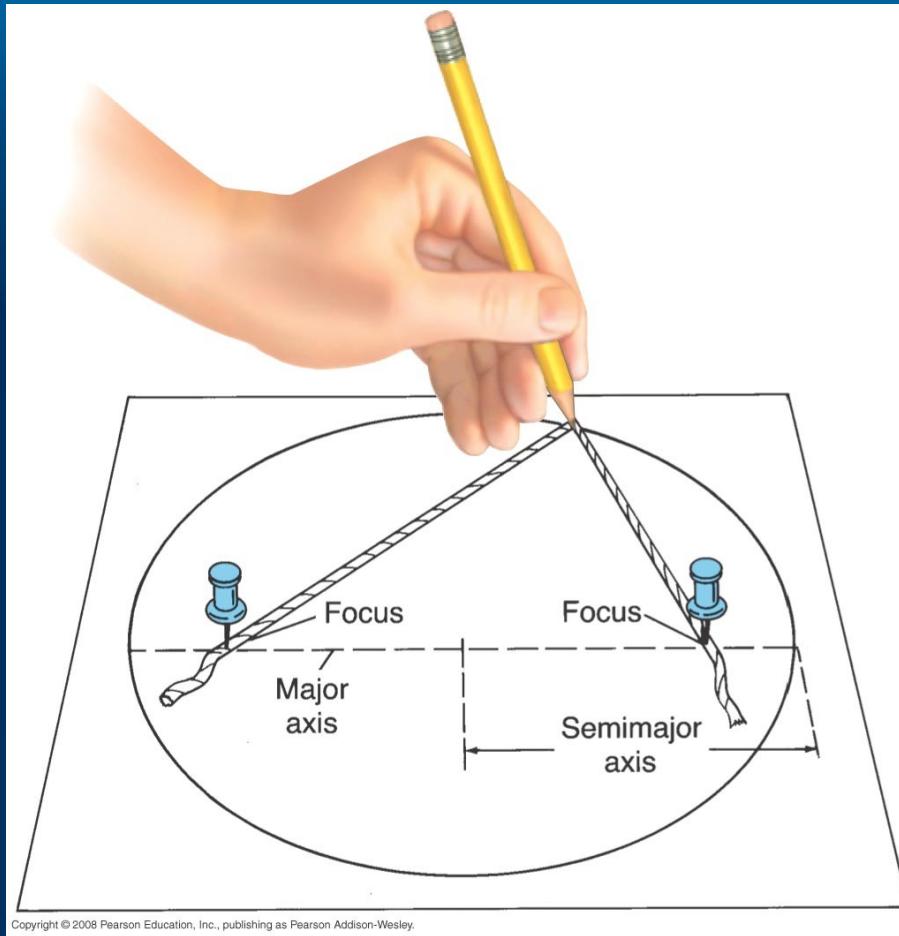
Outer planets

- Mars most eccentric

(Date is Jan 31, 2012 for both.)

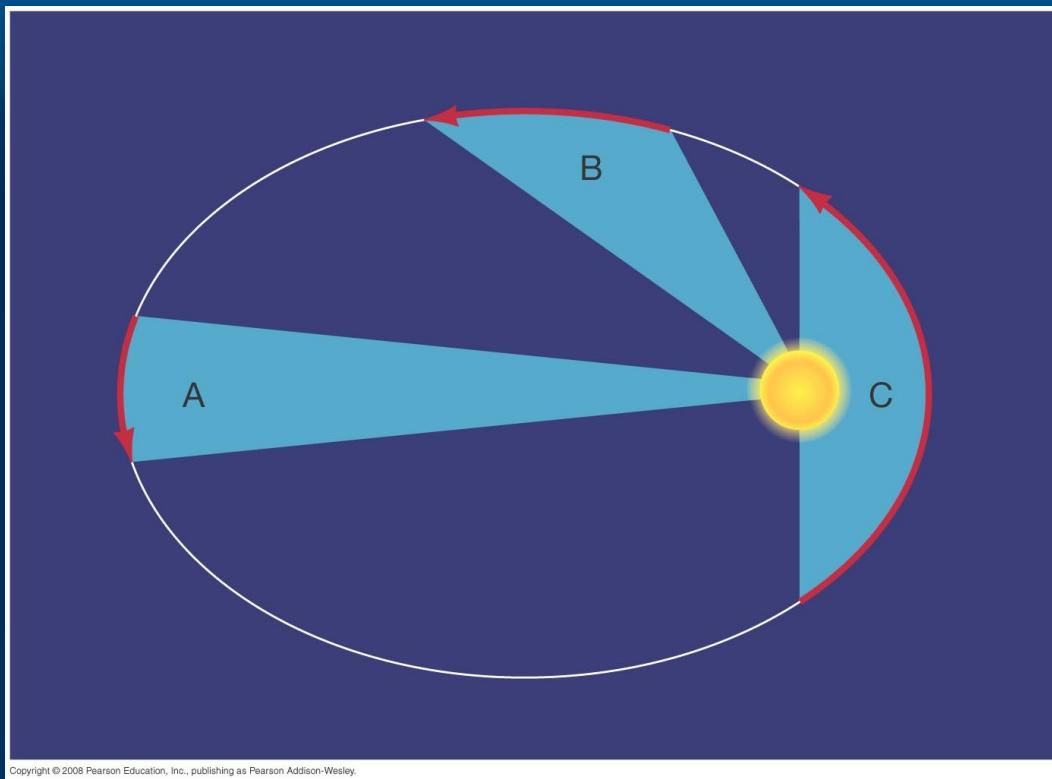


Kepler's 1st law



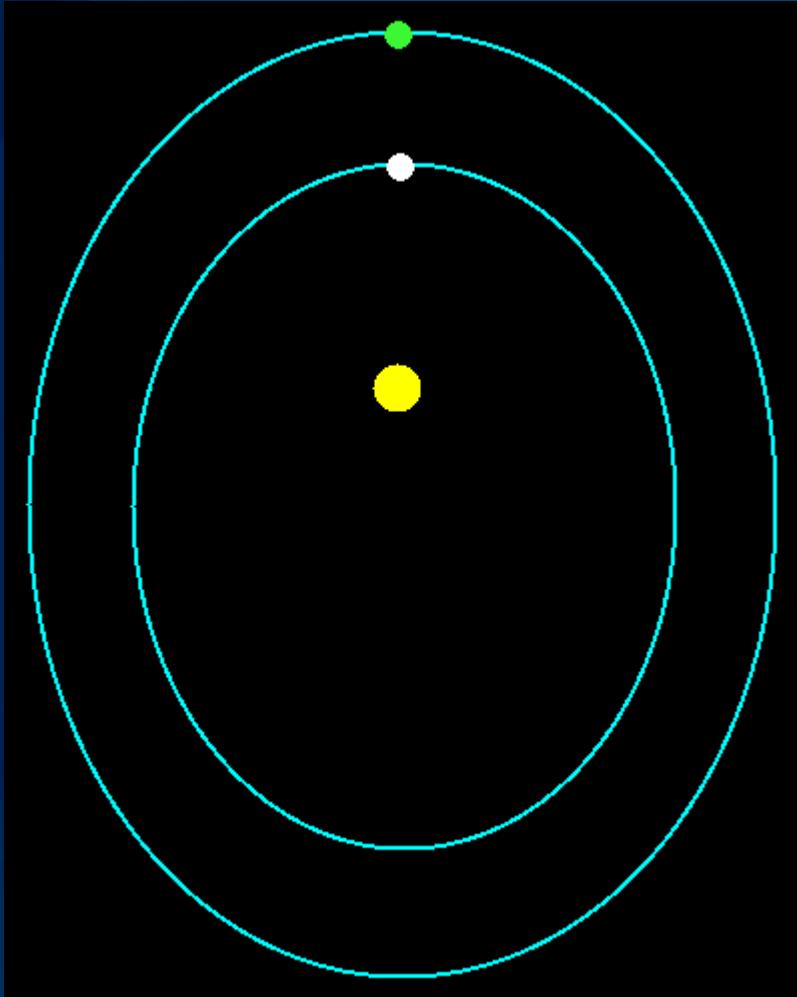
The planets follow elliptical paths with the Sun at one focus.

Kepler's 2nd Law



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

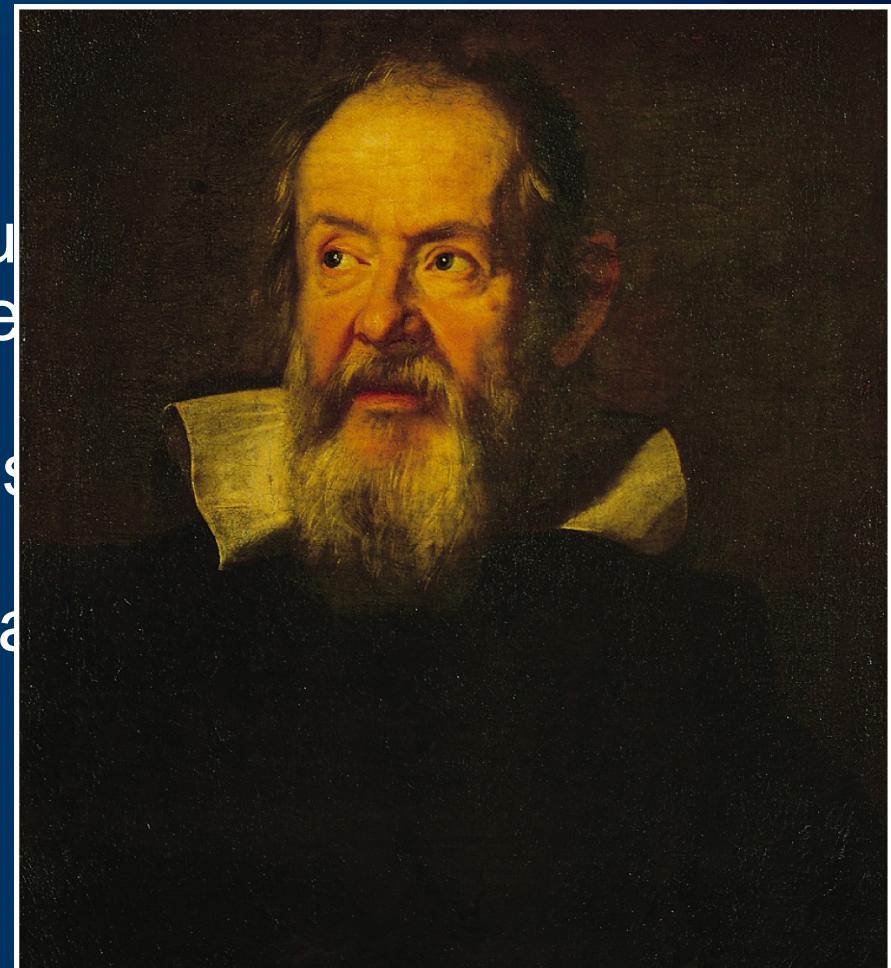


$$P^2 = a^3$$

Period increases
with distance from
the Sun.

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”



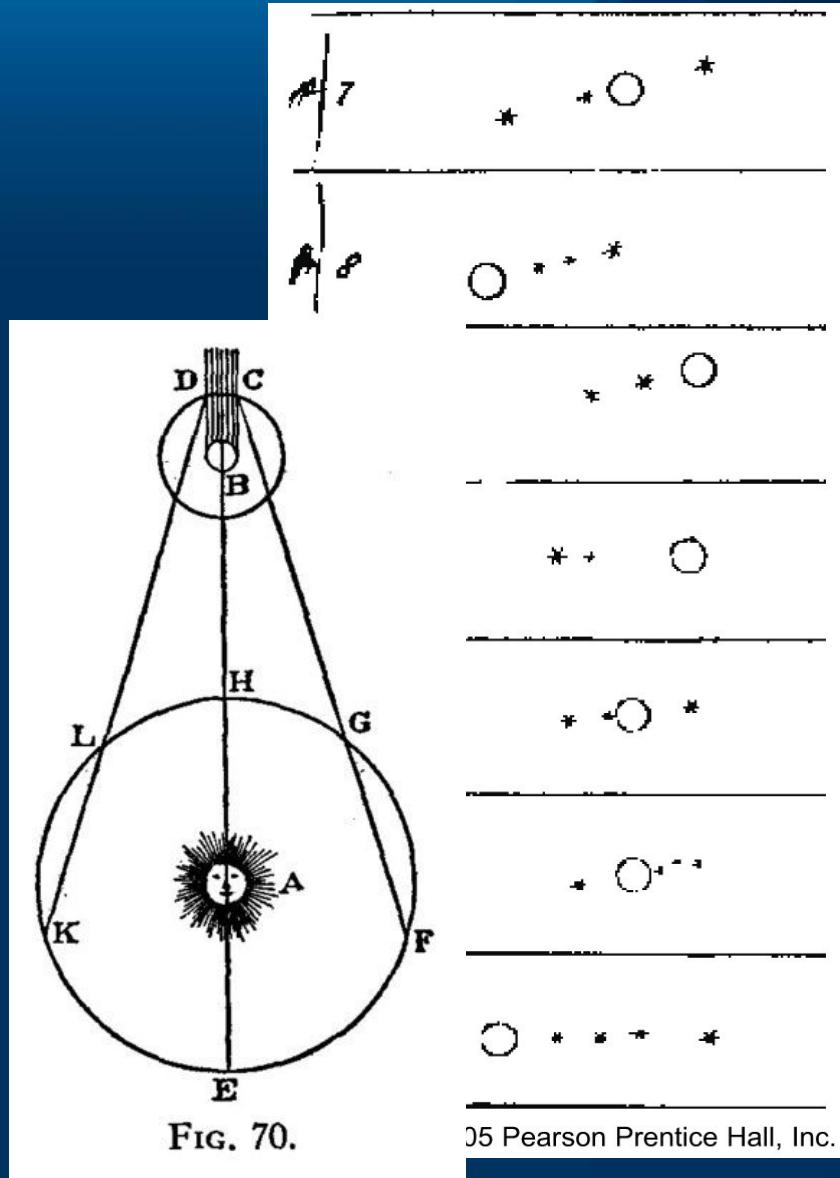
Galileo and Jupiter

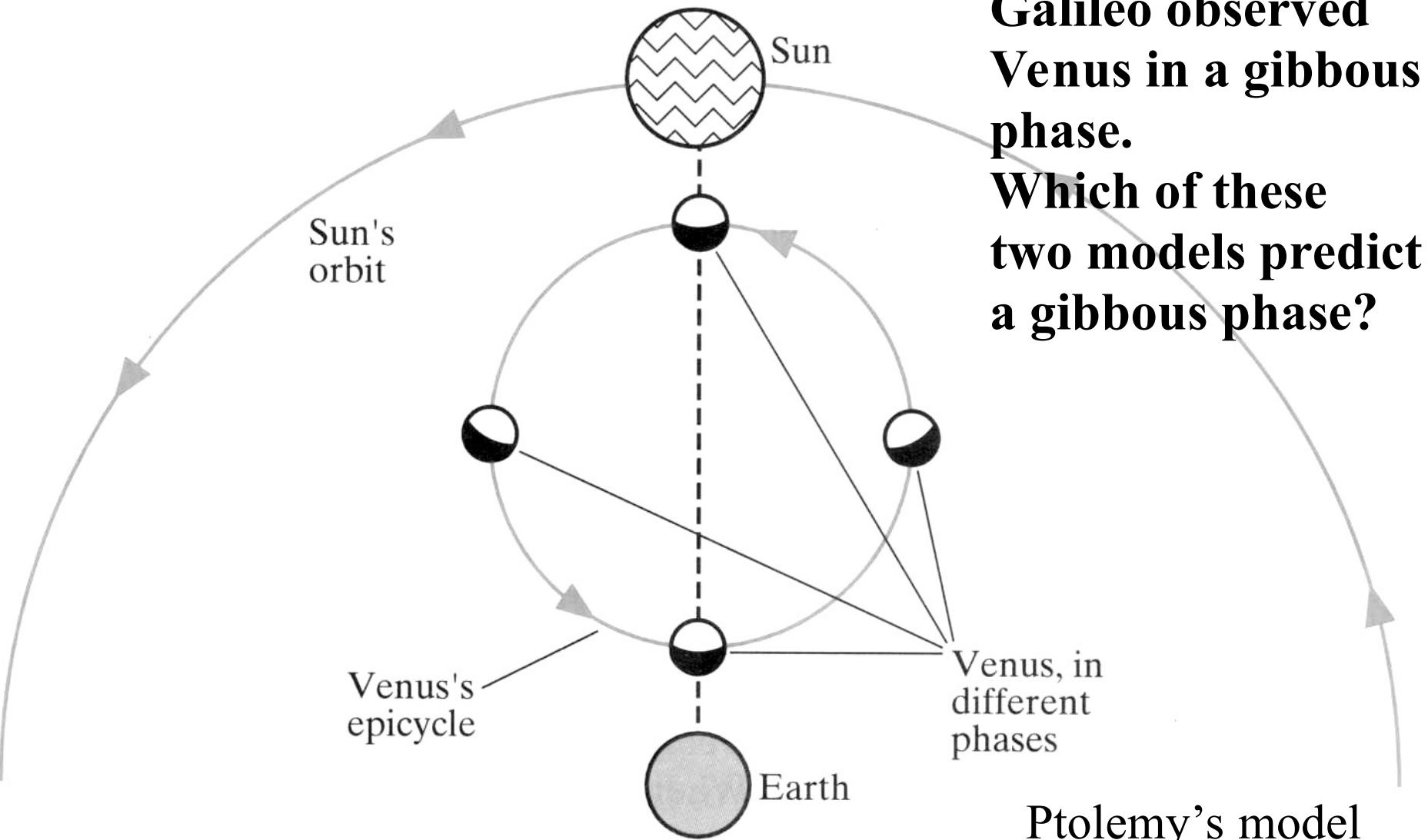
The “Galilean Moons”: Io, Europa, Ganymede, and Callisto.

Not everything orbits the Earth!

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

Ole Roemer 1677

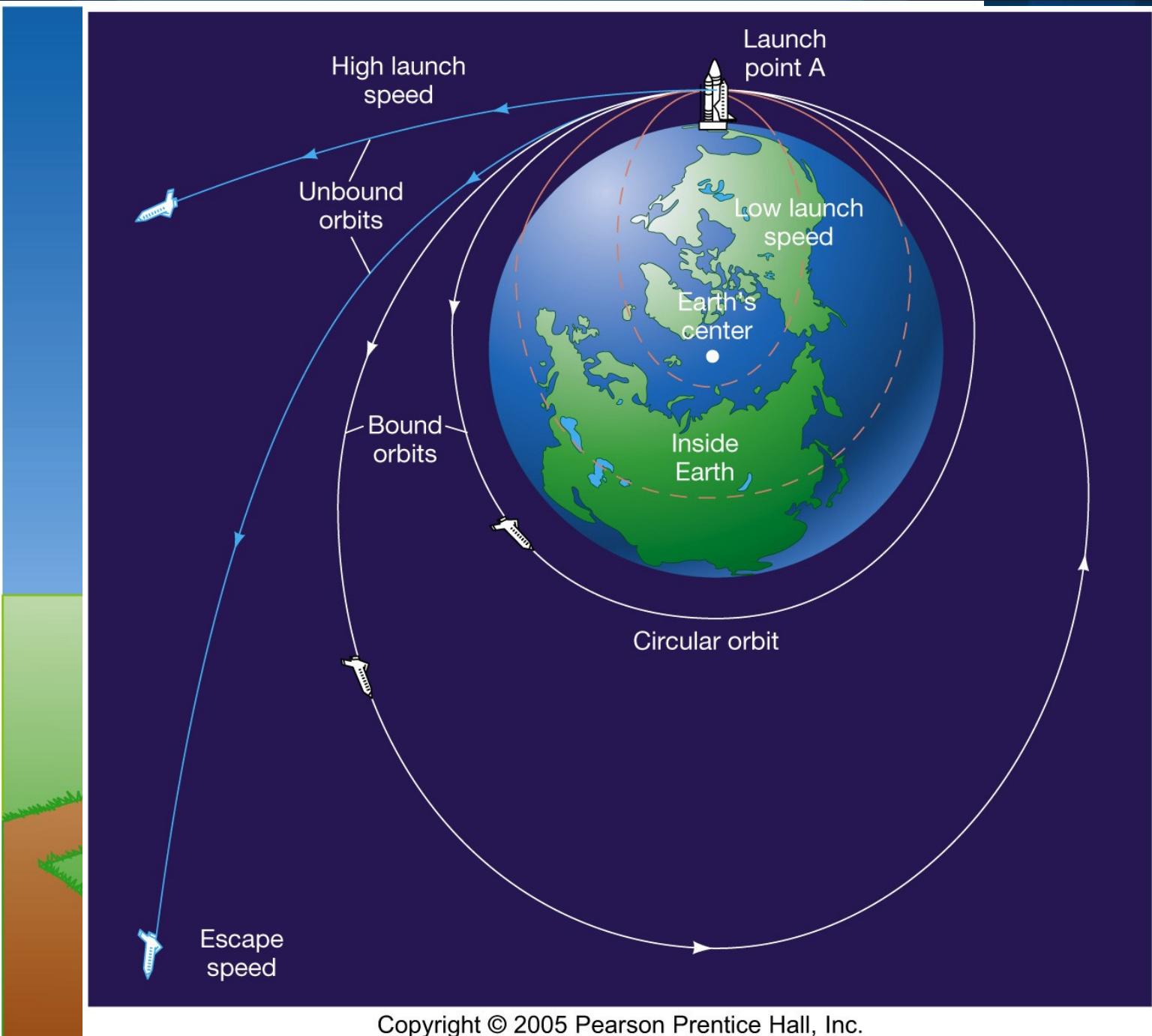




Galileo's troubles

- 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 the old Philosopher
- 3 laws of motion
- Universe
–Can be measured
–Final cause
- “God governs in accordance with the law”



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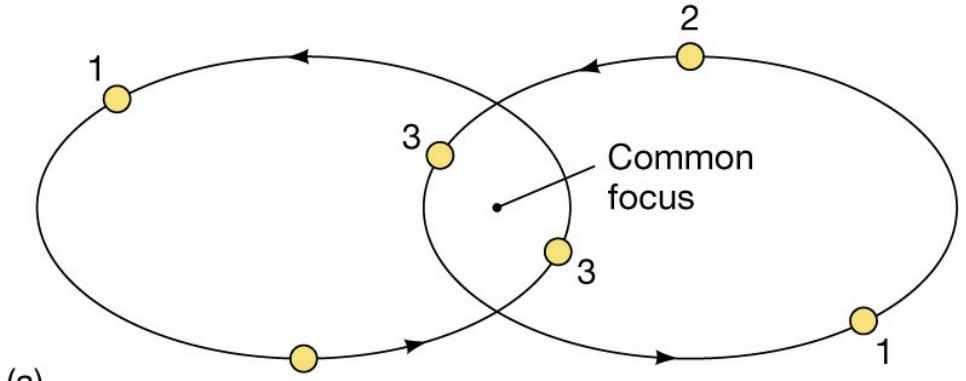
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Isaac Newton (1643-1727)

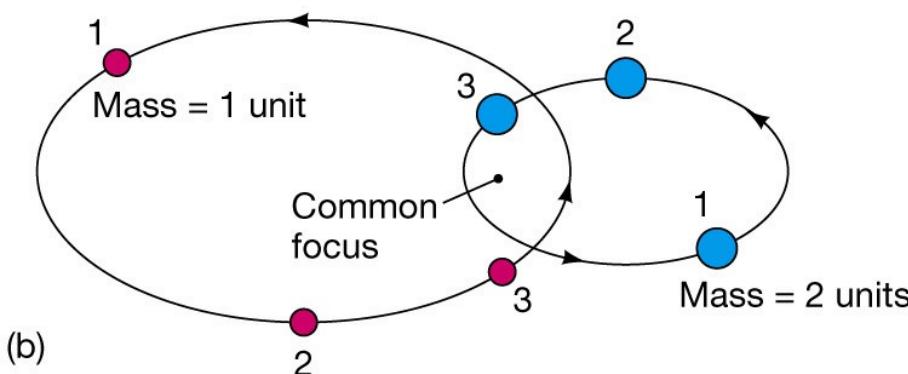
- English physicist, mathematician, theologian, alchemist
- Invents calculus
- Urged by Halley to publish “*Principia*”
Philosophiæ Naturalis Principia Mathematica
- 3 laws of motion
- Universal law of gravitation $F = G \frac{m_1 m_2}{r^2}$
 - Can explain Kepler's laws!
 - Finally, we have a reason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

Is

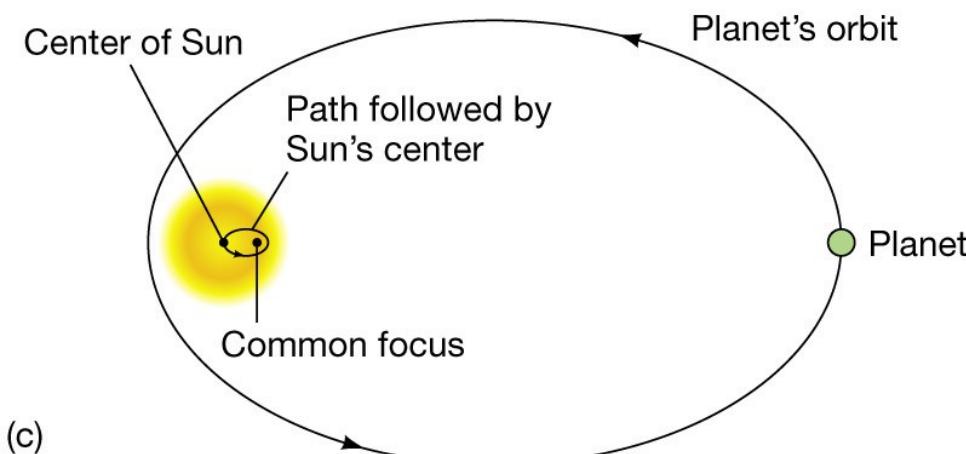
- Kepler I: with the proportionality of mass of Sun)
- Kepler III: system to



(a)



(b)



(c)

S''

S
r
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y

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

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*

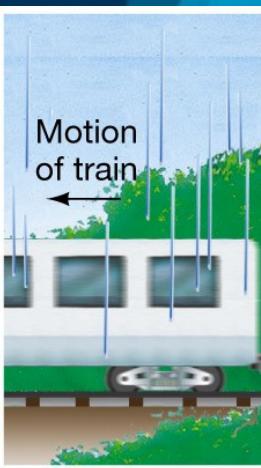
*Used ellipses to model solar
system*

*Said gravity accelerates the
planets*

Revived the heliocentric model

Figure

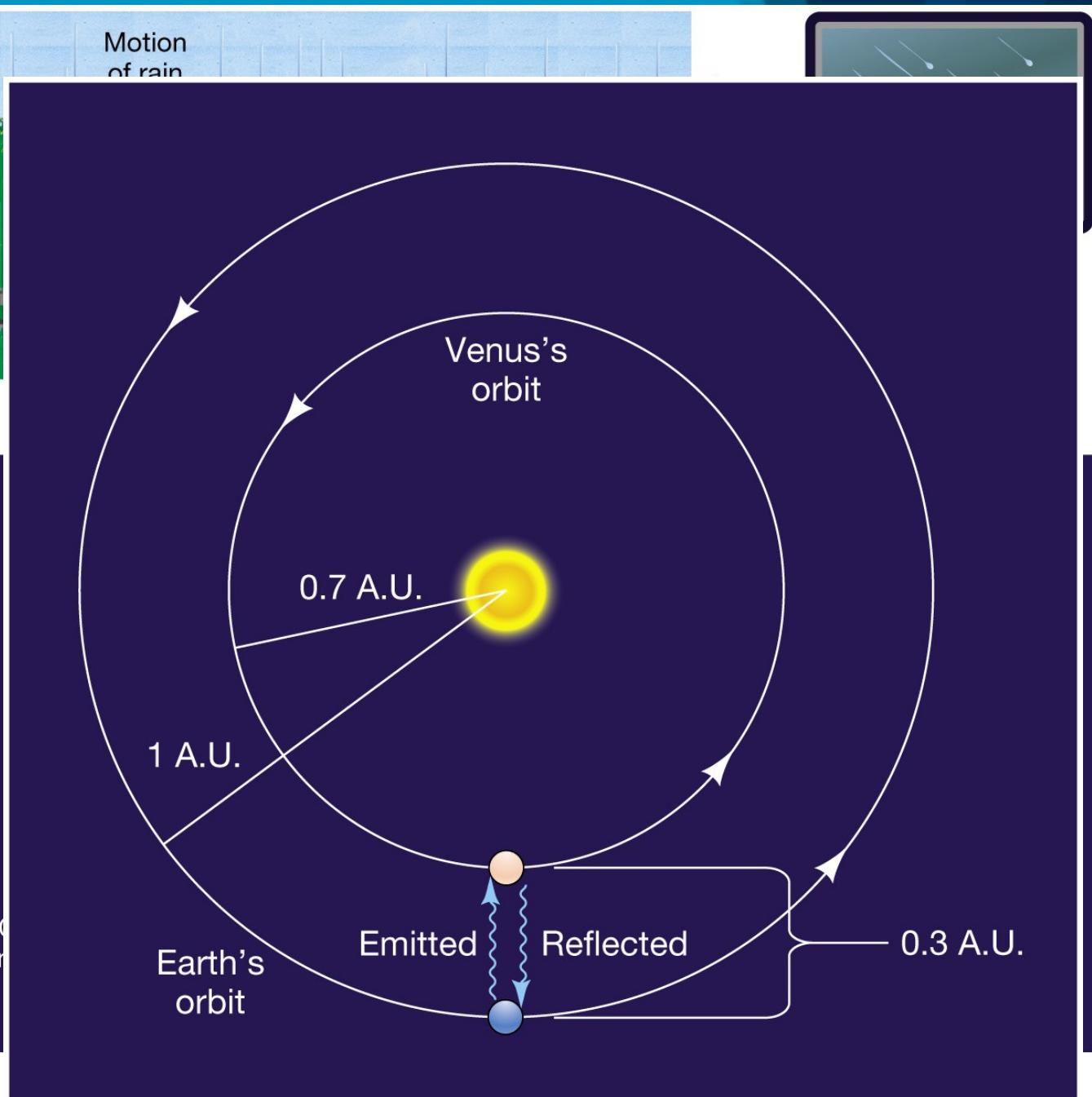
- Venus is closer to the Sun than Earth.
- Venus has a longer day than Earth.
- Venus has a shorter year than Earth.
- Venus has a very thick atmosphere.
- Venus has no magnetic field.
- Venus has no moon.



(a)



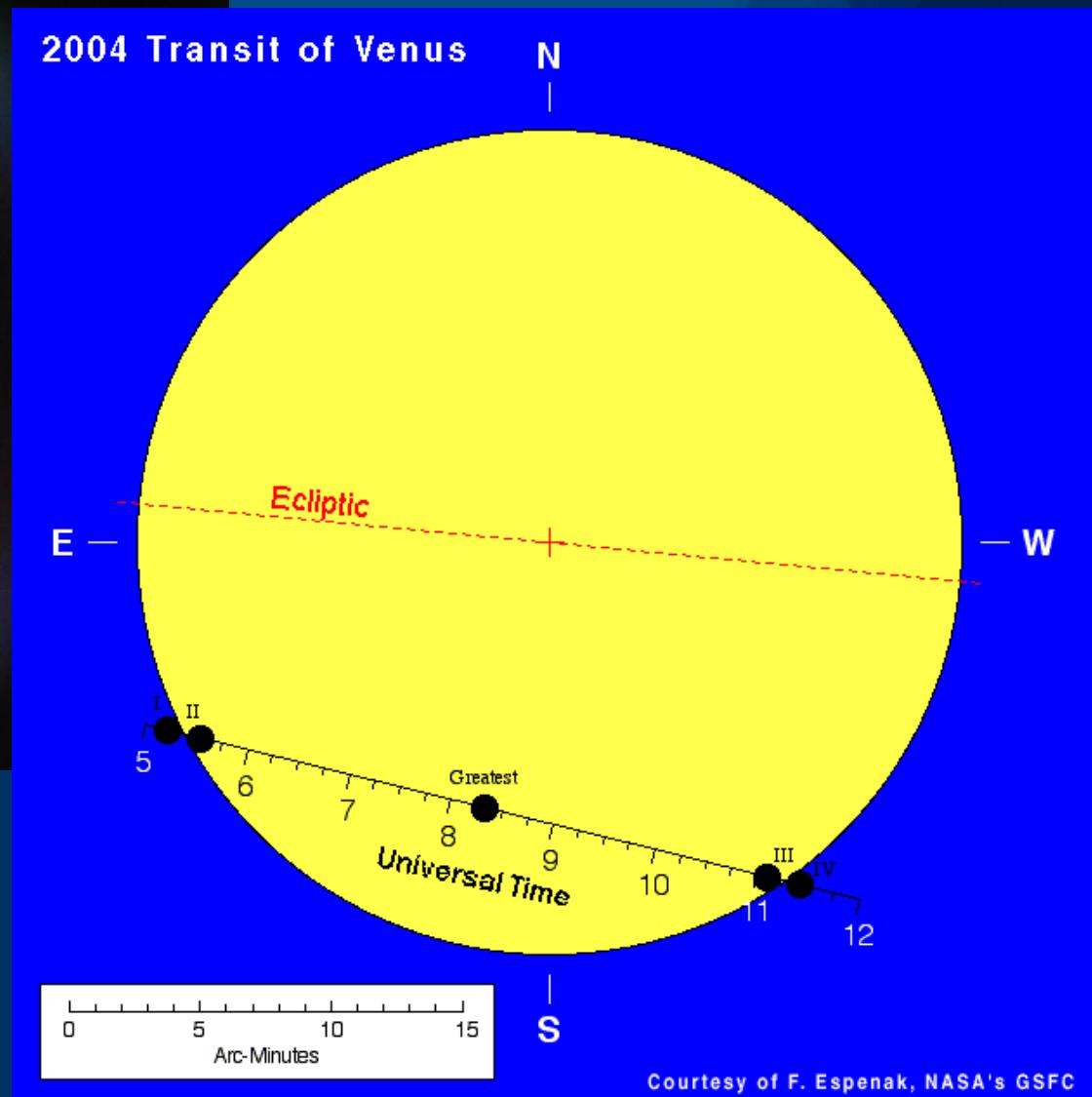
(b)



Figuring out the remaining loose ends of the Solar System

- Verification that Earth is in motion
 - Ole Roemer, 1677 - Jupiter Moon delays
 - James Bradley, 1728 – aberration of starlight
 - Frederick Bessel 1838 – first parallax
 - Foucault pendulum 1851
- 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: 1639, 1761, 1769, 1874,
1882, 2004, ...

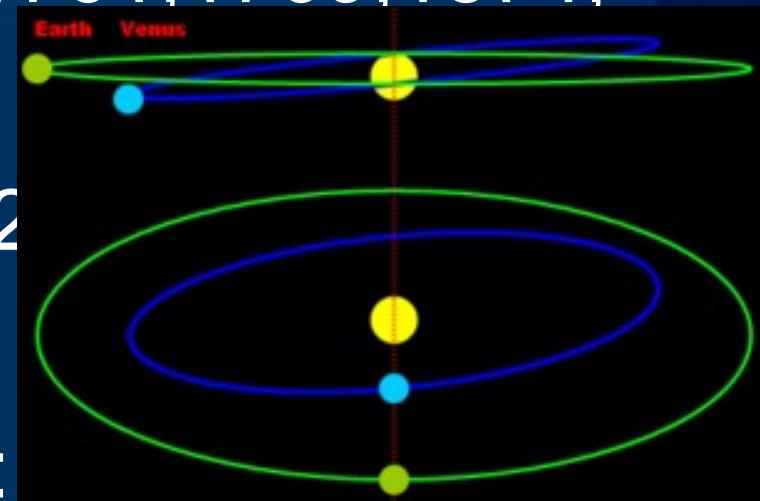
Last transit: June 6, 2012

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*
 - We are 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.