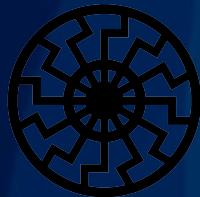


The Copernican Revolution - Separating Science and Superstition

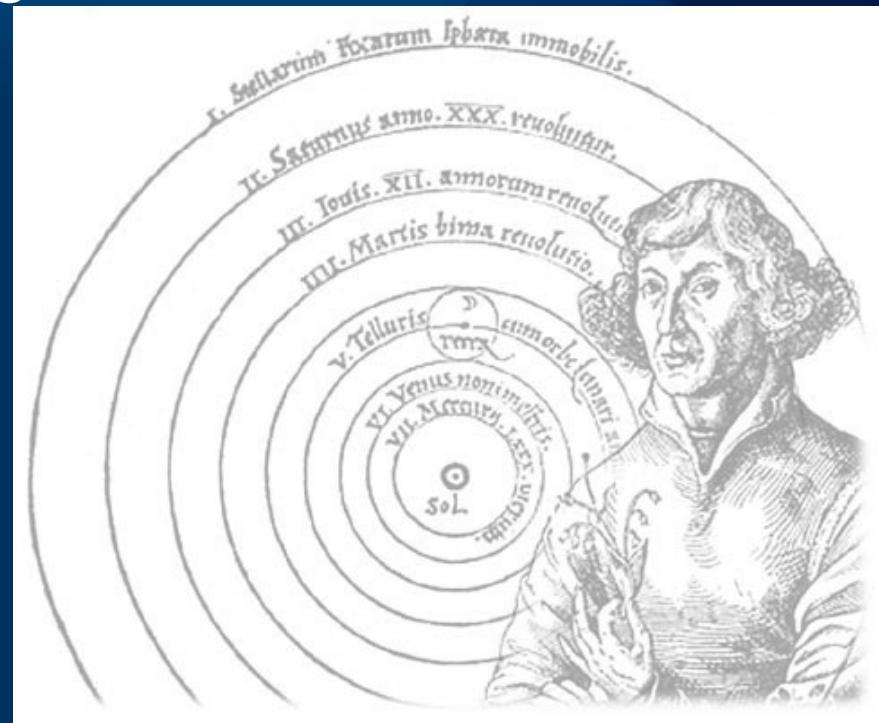


J. Pinkney
ONU 2013



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

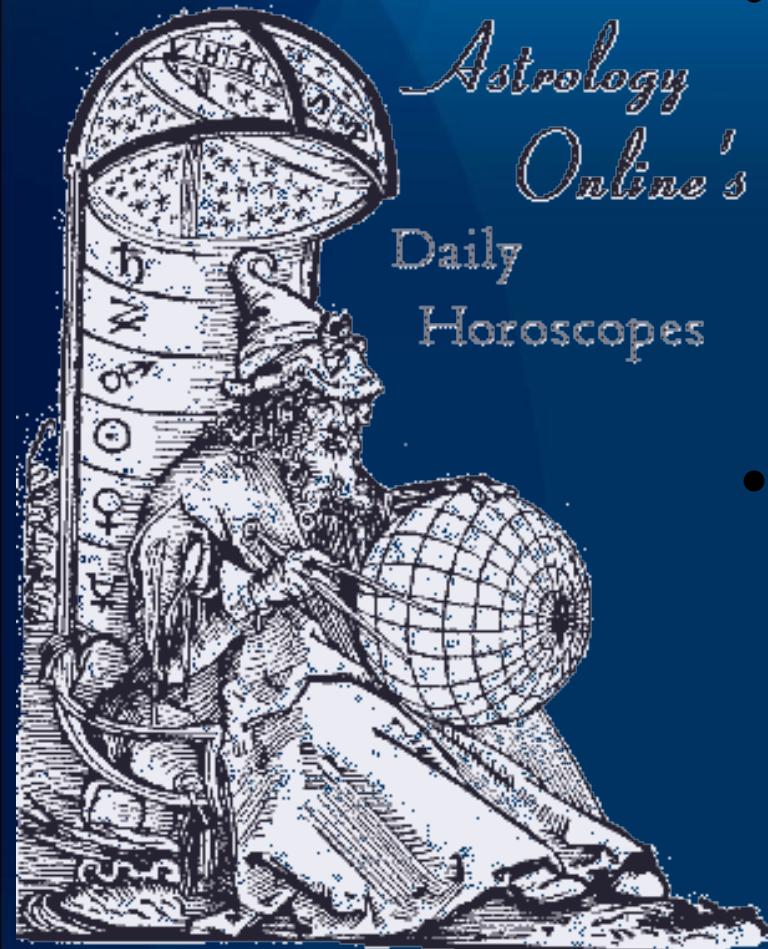
The Naked-Eye Universe

- The Sun (daily motion and annual motion)
- The Moon (phases, eclipses)
- 5 Planets (not including the Earth)
 - Mercury, Venus, Mars, Jupiter, Saturn
- 6500 Stars (contained within 88 constellations)
- 3 galaxies
- Occasional novae and supernovae
- Comets
- Aurora, meteors, and other atmospheric phenomena



What the Ancients Knew

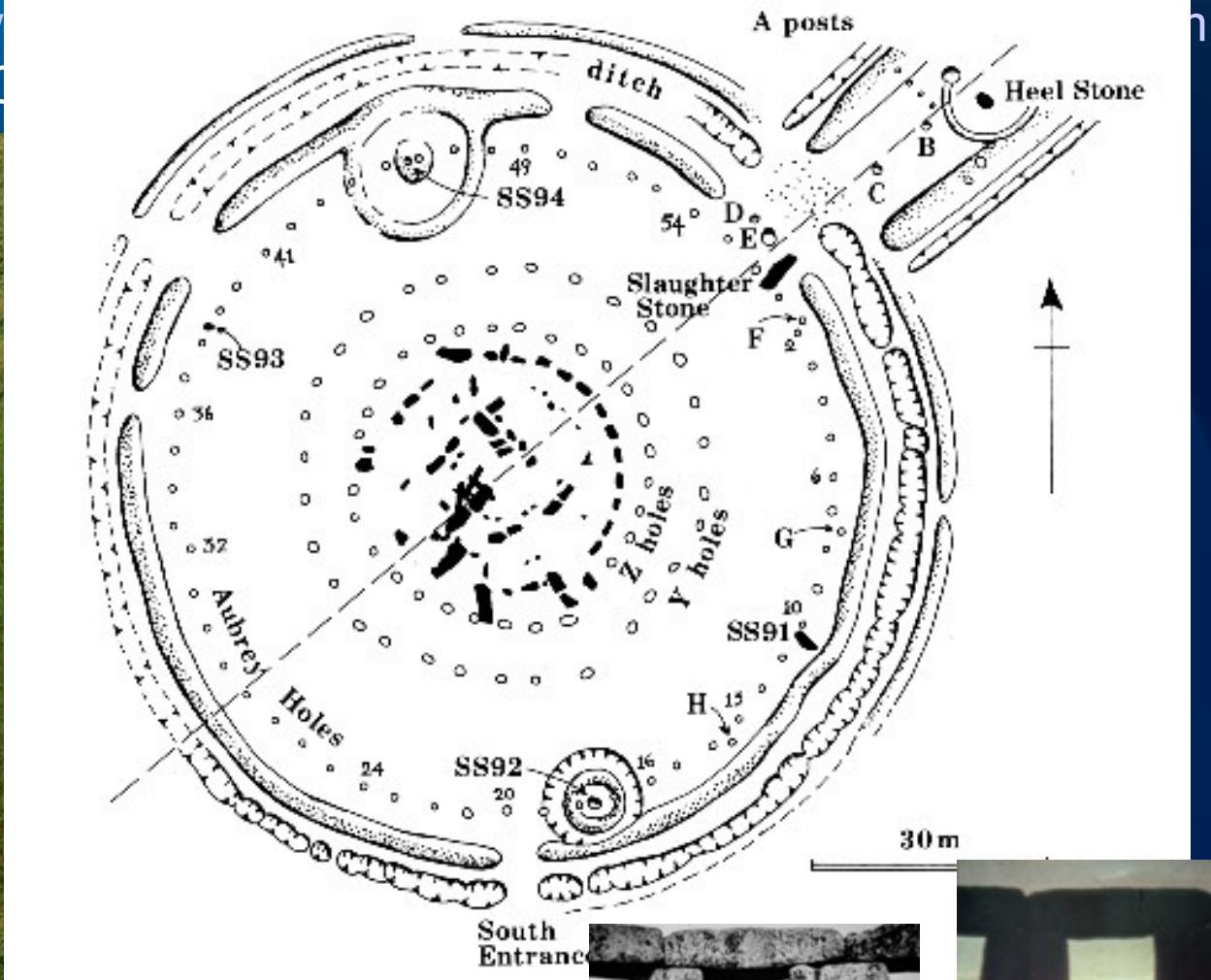
- Mysterious cultures
 - People of stonehenge, Plains Indians, Anasazi, Mayans
 - left behind calendar-like constructions.
- Well documented cultures
 - Greek, but also Chinese, Babylonian, Egyptian, Arab
 - left records of lunar cycles, eclipses, comets, novae, star maps, models



Unknown nature → superstition → astrology.

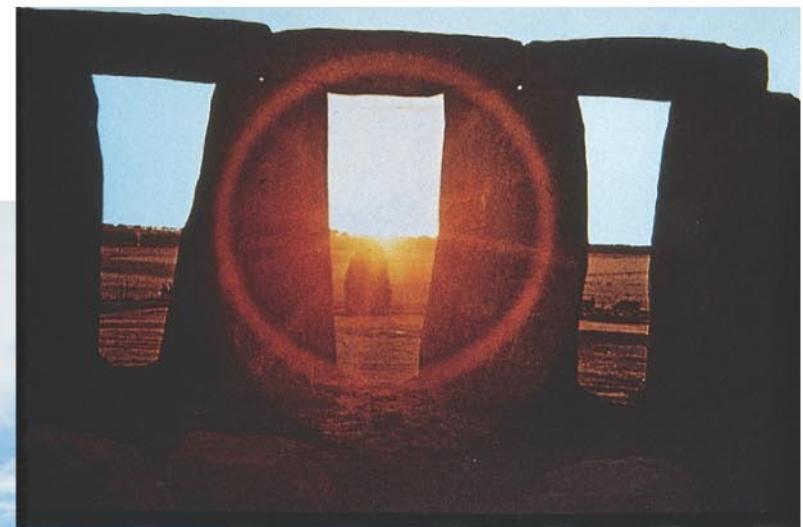
The Ancients: Stonehenge

- Check out: <http://www.stonehenge.com>
- 2950 BC – 1600 BC



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







What the Ancients Knew



es

Zodiac, “year of the ____”
alphabet, ziggurats,
planetary rise times,

and Osiris, pyramids, Nile

during dark ages → algebra,
invention between
1000 AD!

measurements

by

Christianity → astrology.



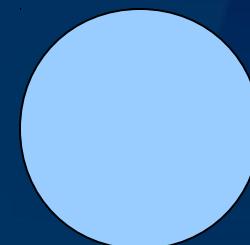
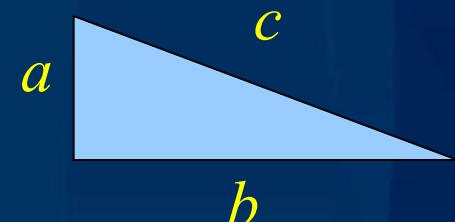
What the Ancients Knew

- Well documented cultures
 - Chinese: comet records, zodiac, “year of the _____”
 - Sumerians/Babylonians: 1st alphabet, ziggurats, origin of western astrology, planetary rise times, math
 - Egyptians: gods like Ra and Osiris, pyramids, Nile flooding
 - Arabs: upheld astronomy during dark ages, algebra, star names. Semantic distinction between astronomy and astrology – 1000 AD!
 - ► All made astronomical measurements
 - ► All had forms of astrology

Unknown nature → superstition → astrology.

Knowledge of the Ancient Greeks I.

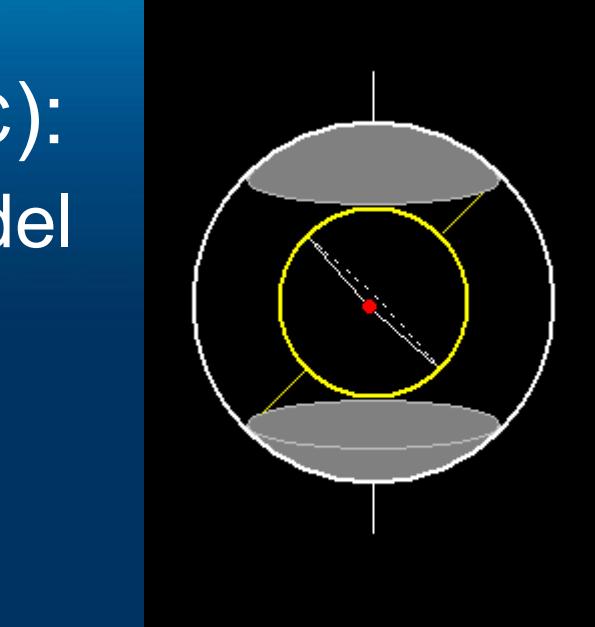
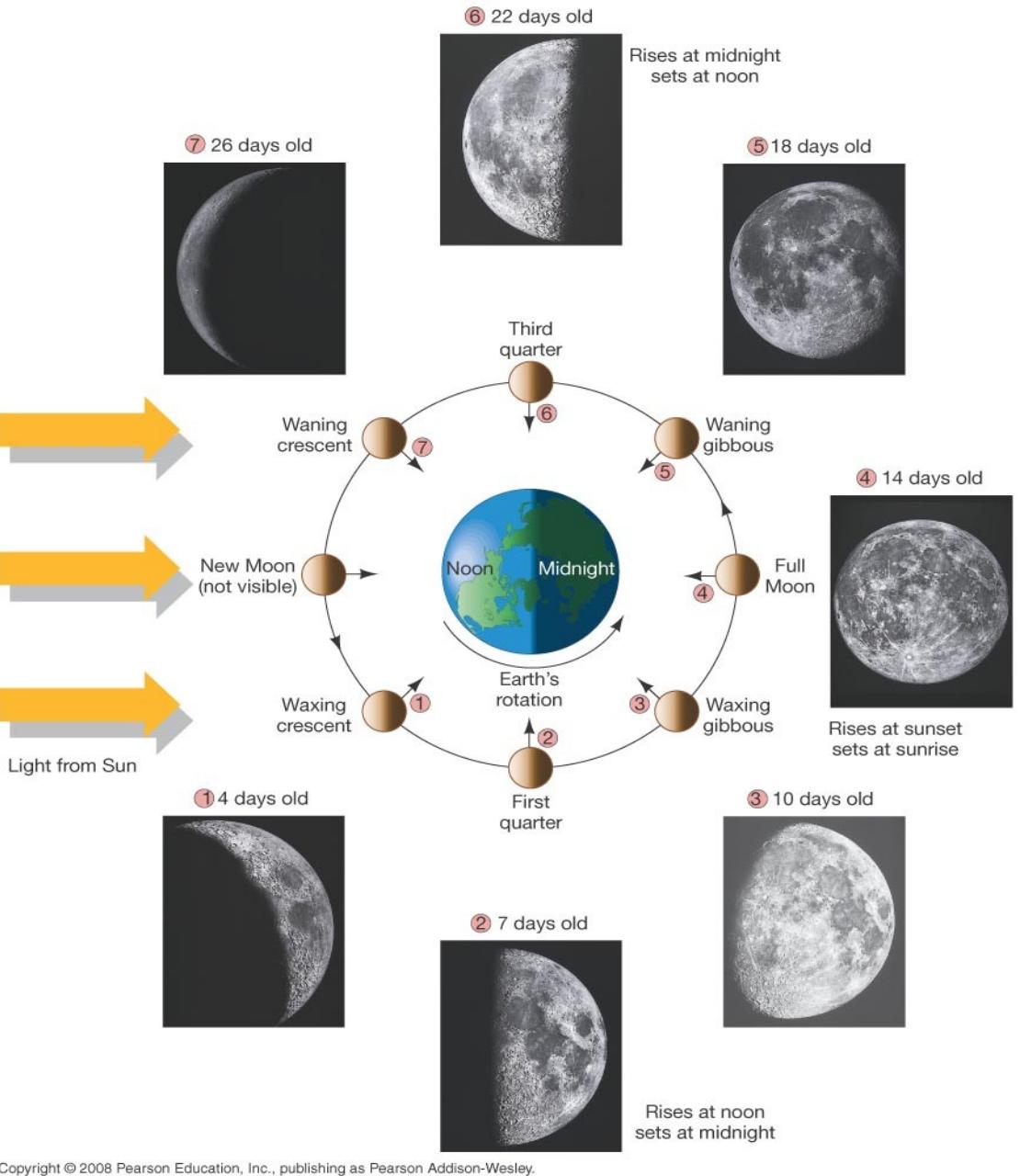
- Ideas and philosophies were rich and varied, some correct and some **incorrect**.
 - Thales of Miletus (624-547 BC):
 - universe is rational
 - predicted eclipse ~585 BC
 - Pythagoras (570-497 BC):
 - math in nature, music of spheres
 - Earth and planets are spherical
 - Plato (428-347 BC):
 - Truth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



Knowledge of the Ancient Greeks II.

- Eudoxes of Cnidus (390-337 BC):
 - Nested (crystalline) sphere model
- 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 II.



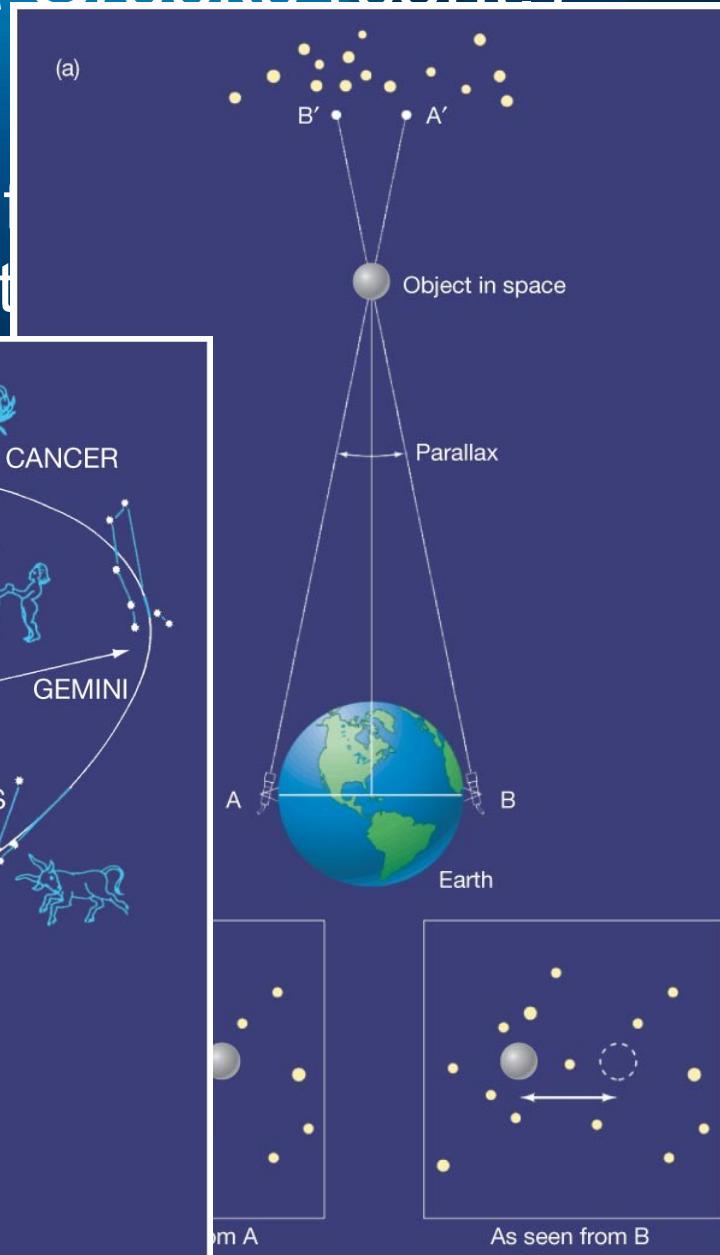
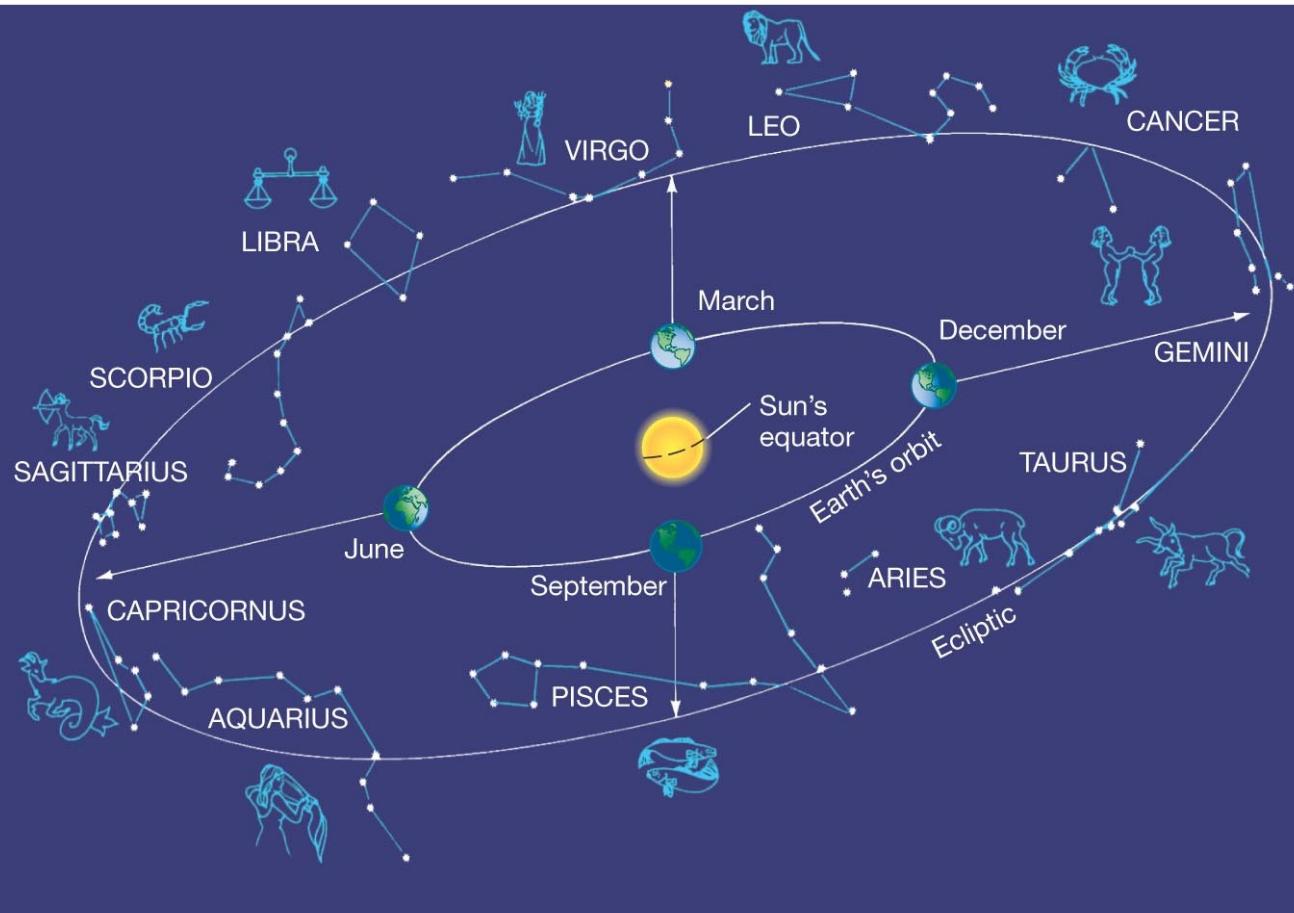
perfect
earth, water, wind,

d

ould exhibit parallax

Knowledge of the Ancient Greeks (cont.)

Parallax = the apparent motion or shift 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”**

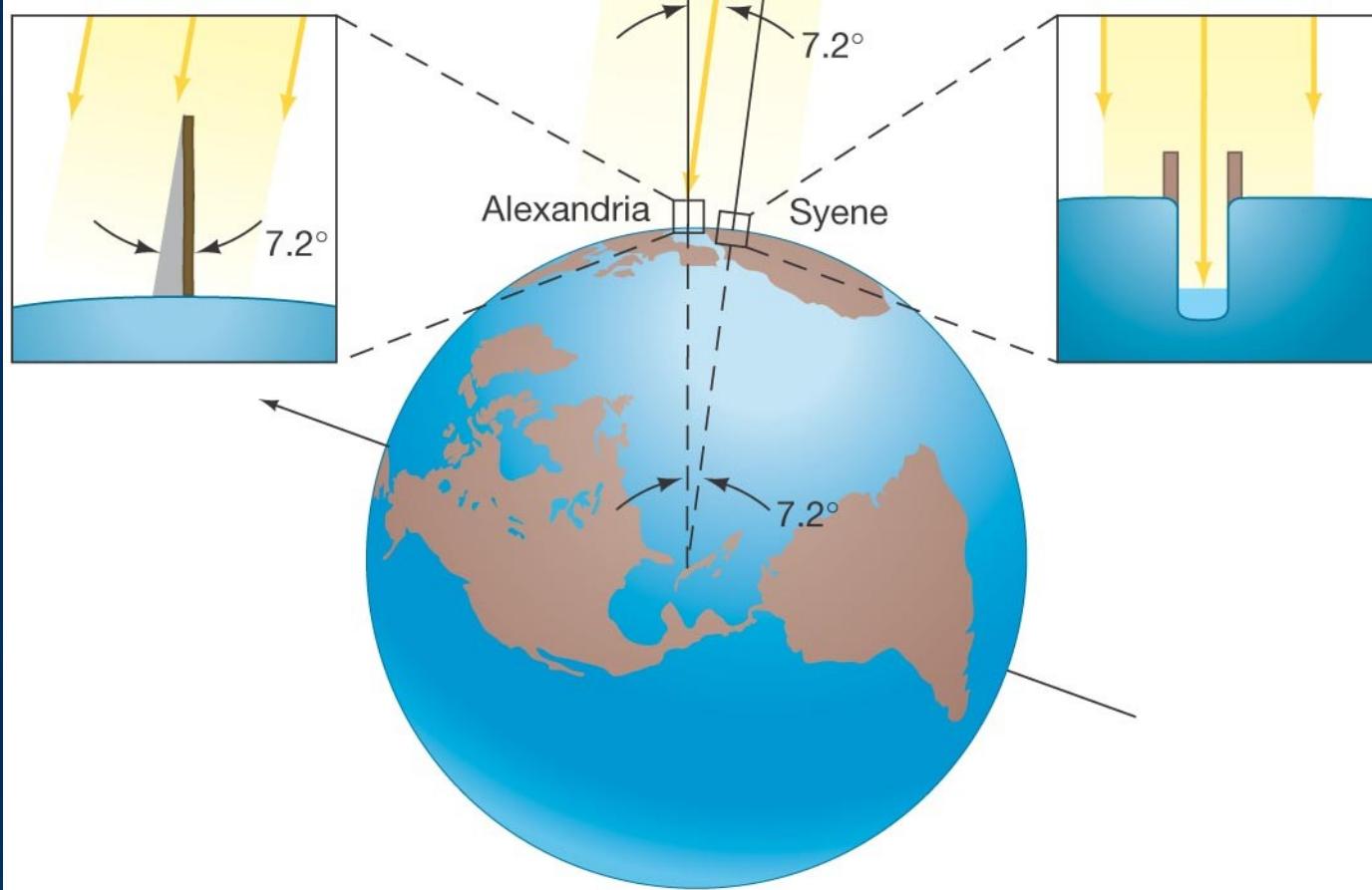
–Aristarchus (310-230 BC)

- The Earth orbits around the Sun (!)
- Size and distance to Moon
- Size and distance to Sun

–Eratosthenes (276-195 BC)

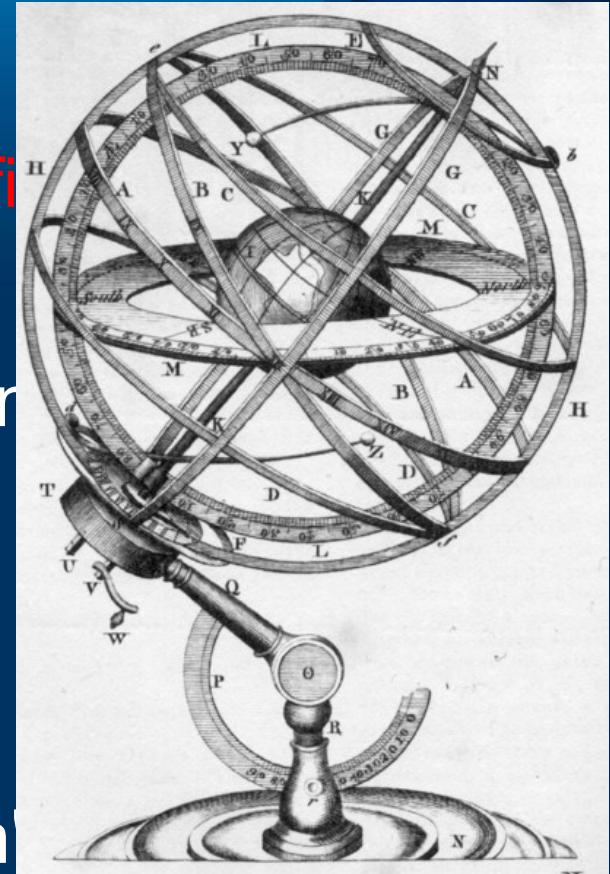
- Measured circumference of the Earth.

Eratosthenes' method



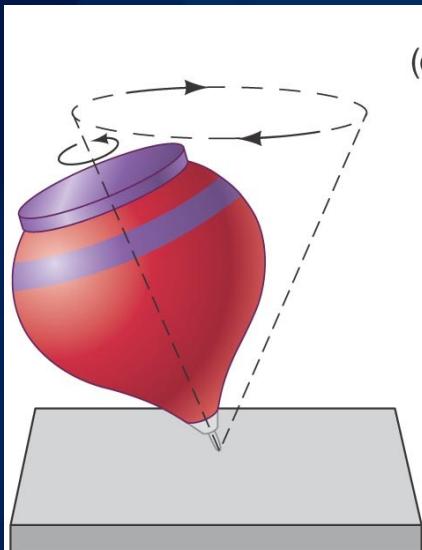
Knowledge of the Ancient Greeks III

- 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
- Hipparchus (190-120 BC)
 - Discovered precession of Earth's axis
 - Uses epicycles, deferents and eccentrics in modelling motion of Sun and Moon.
 - Invents armillary sphere



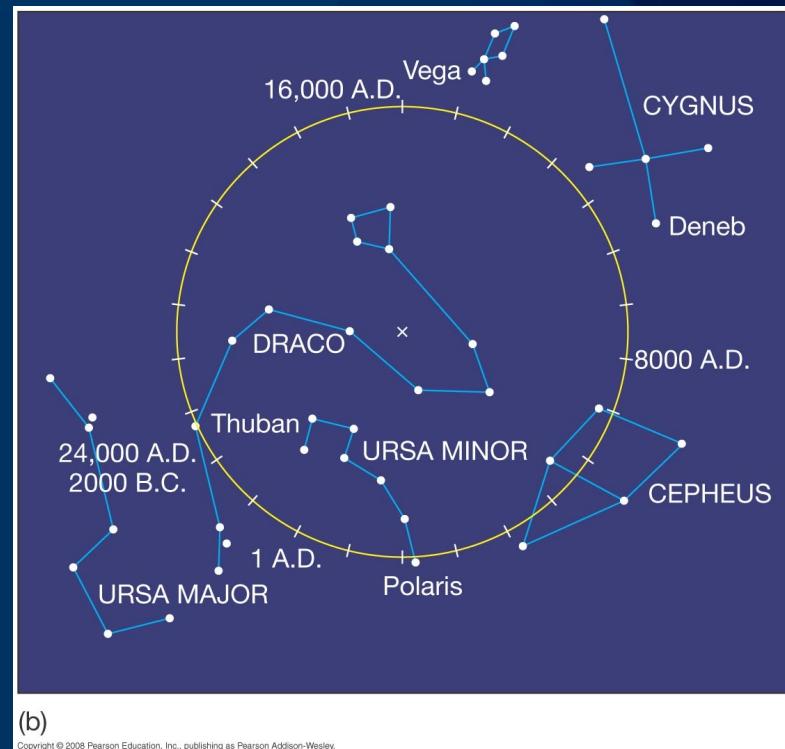
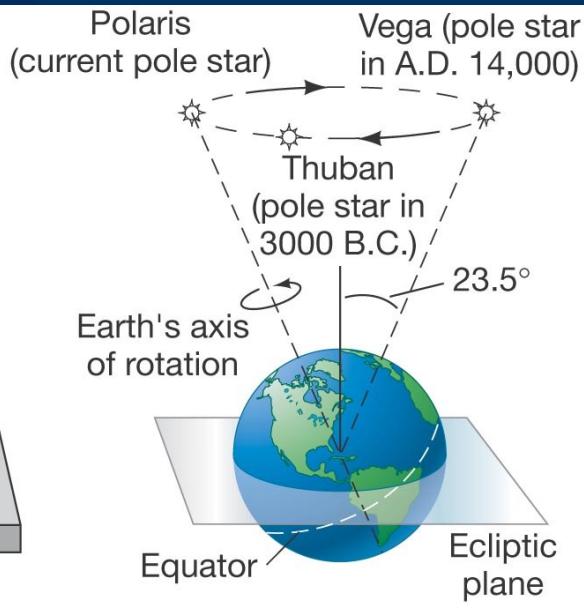
Knowledge of the Ancient Greeks (cont.)

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



(a)

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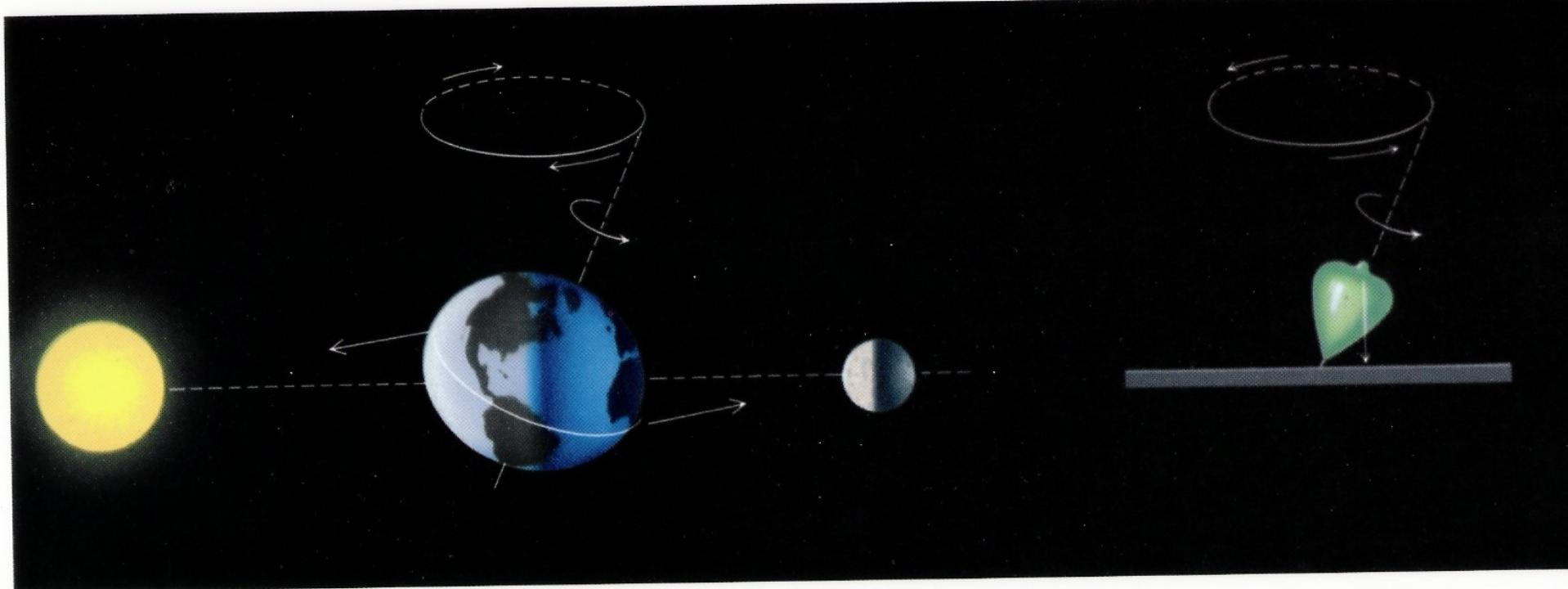
(b)

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Retrograde motion of planets can be modelled with epicycles and deferents (Hipparchus)

Knowledge of the Ancient Greeks (cont.)

Cause of precession:



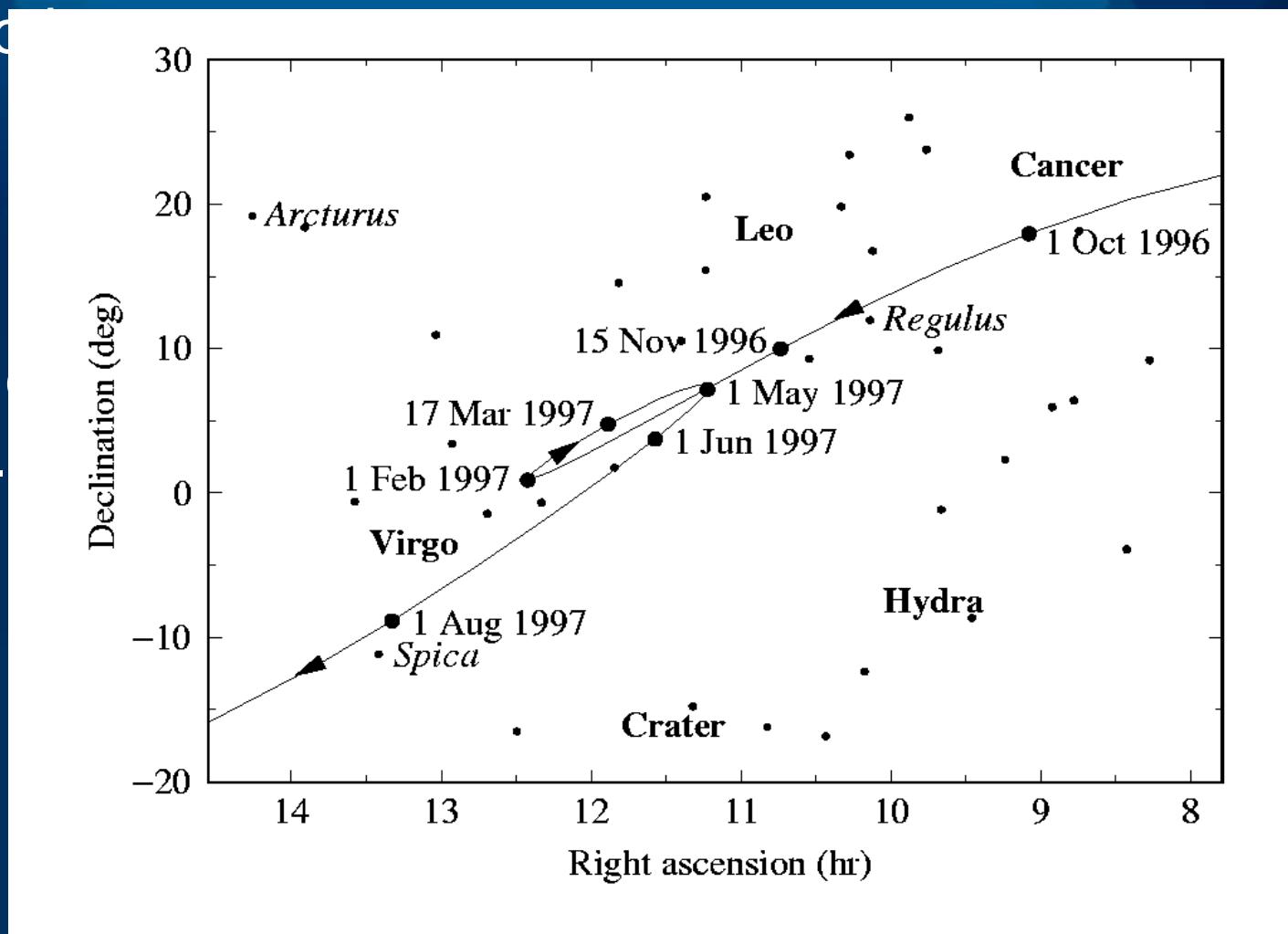
Knowledge of the Ancient Greeks IV

- Claudio 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

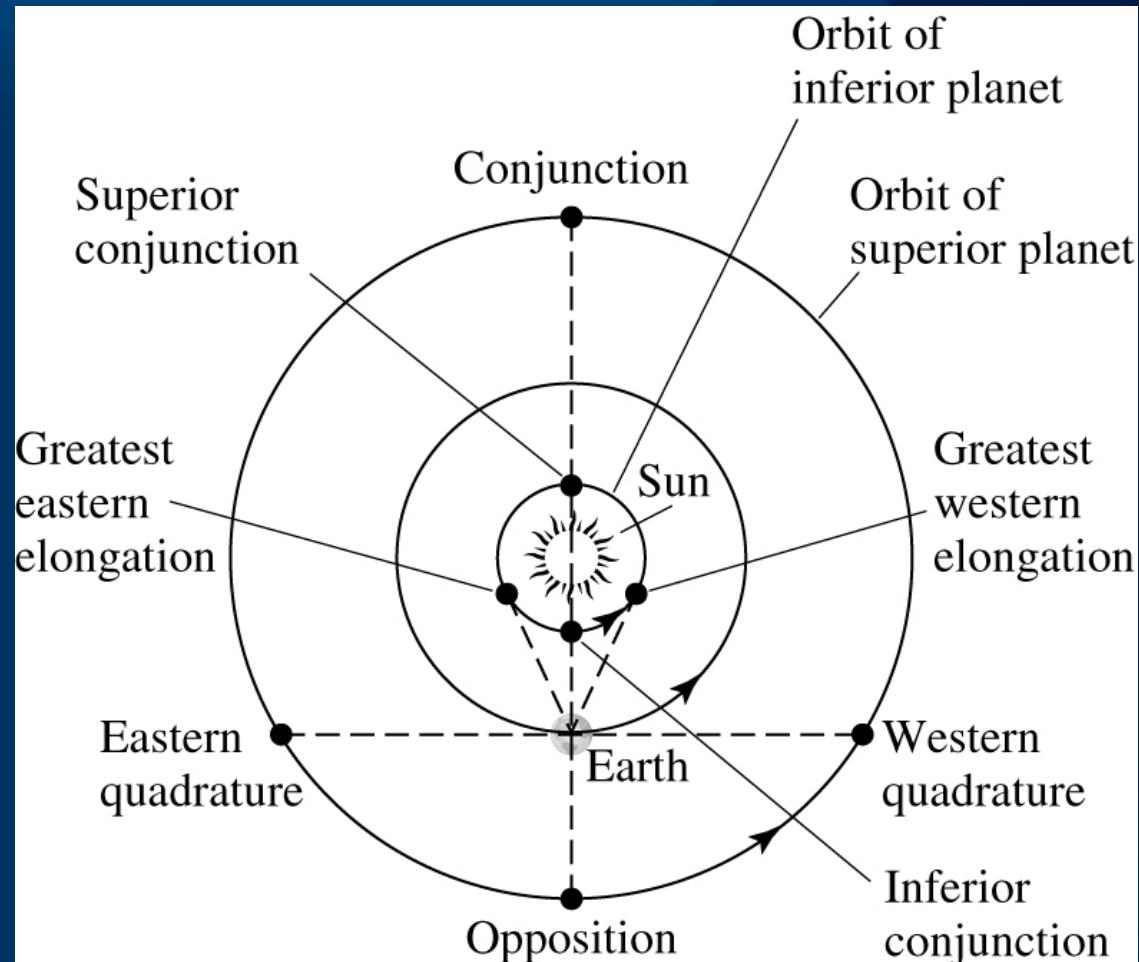
- Daily motion
- Change our sky.
- All orbit the Sun
- Usually we call them planets



Retrograde Motion!

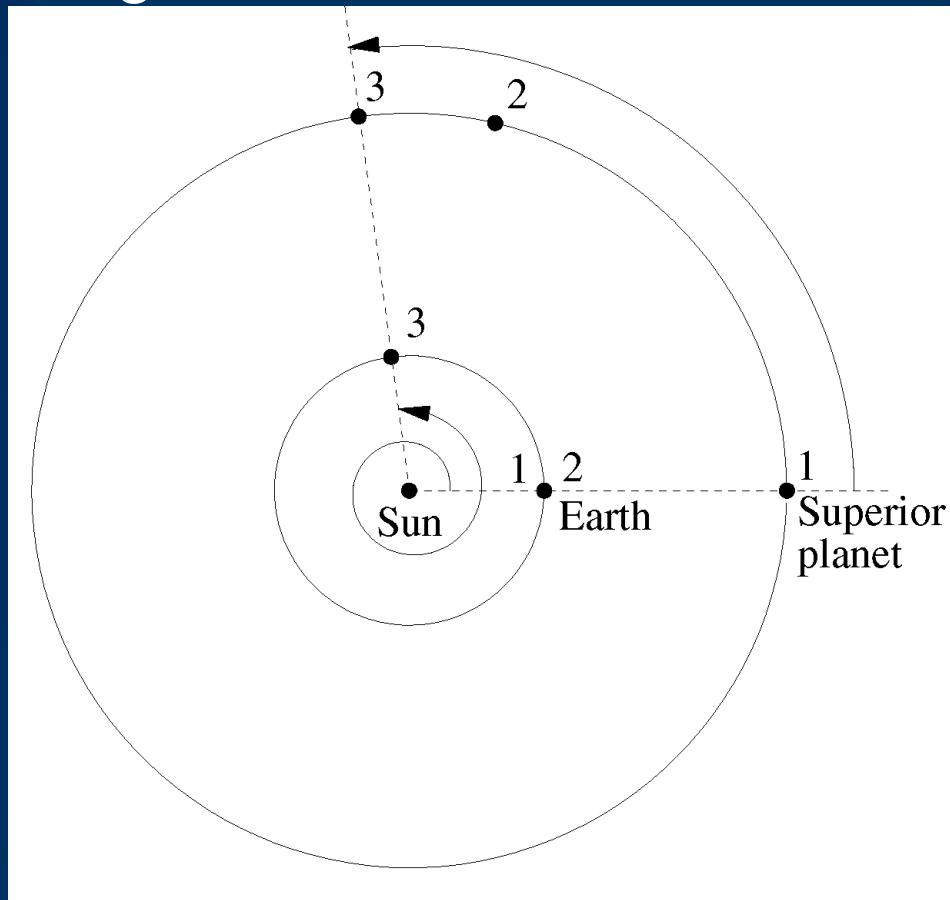
Planetary Configurations

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



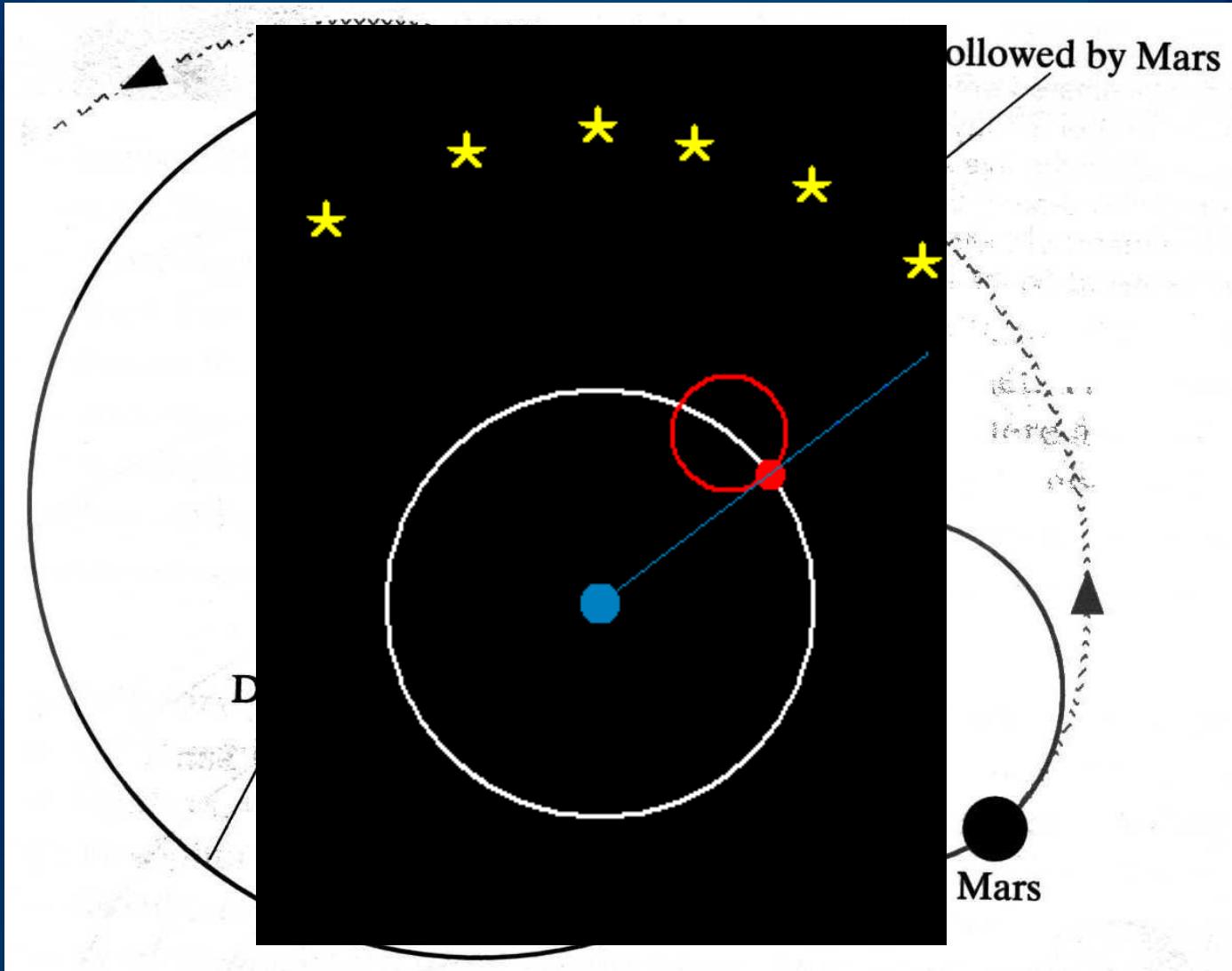
Synodic and Sidereal Periods

- 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



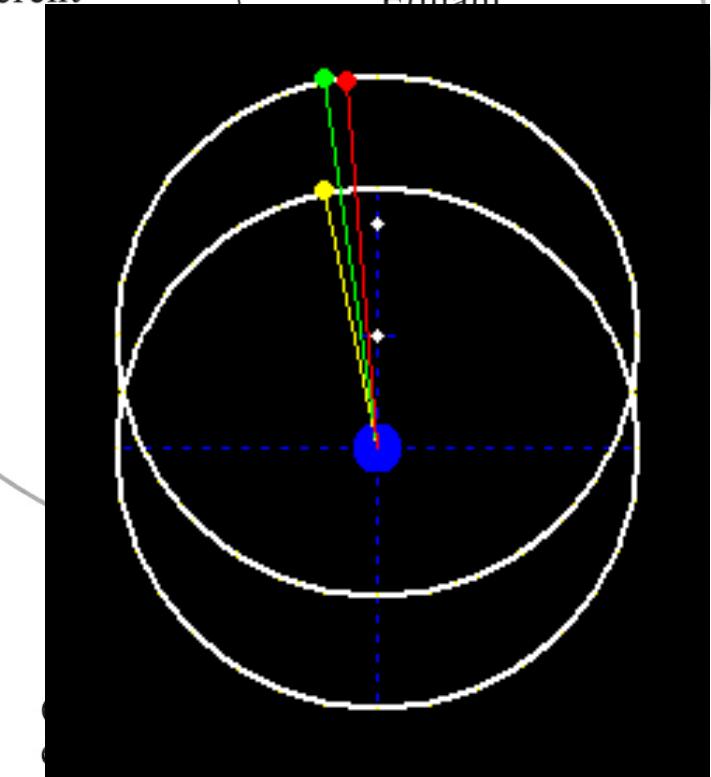
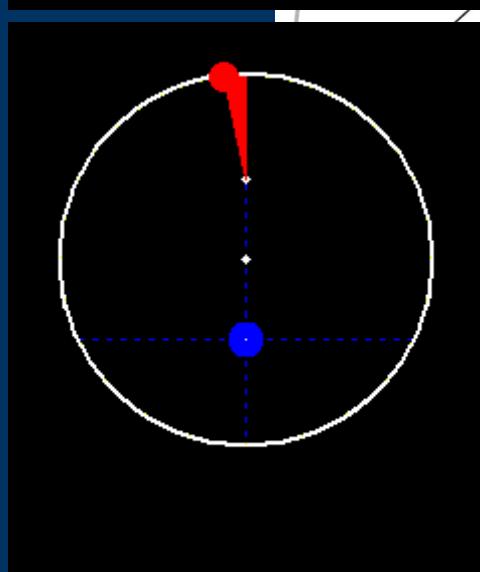
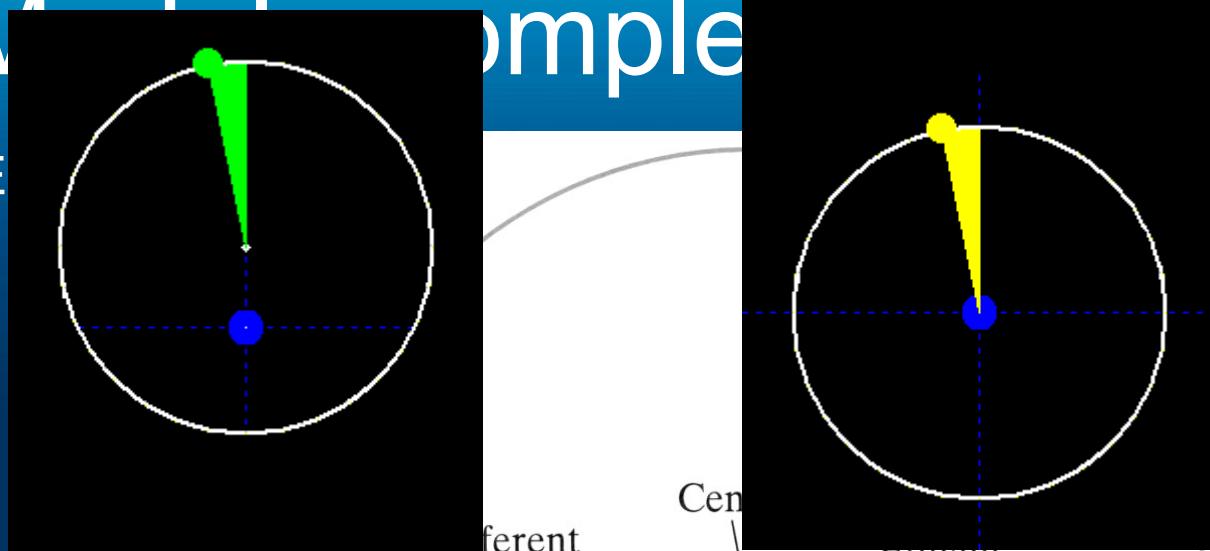
Epicycles on Deferents

- Ptolemy et al. 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



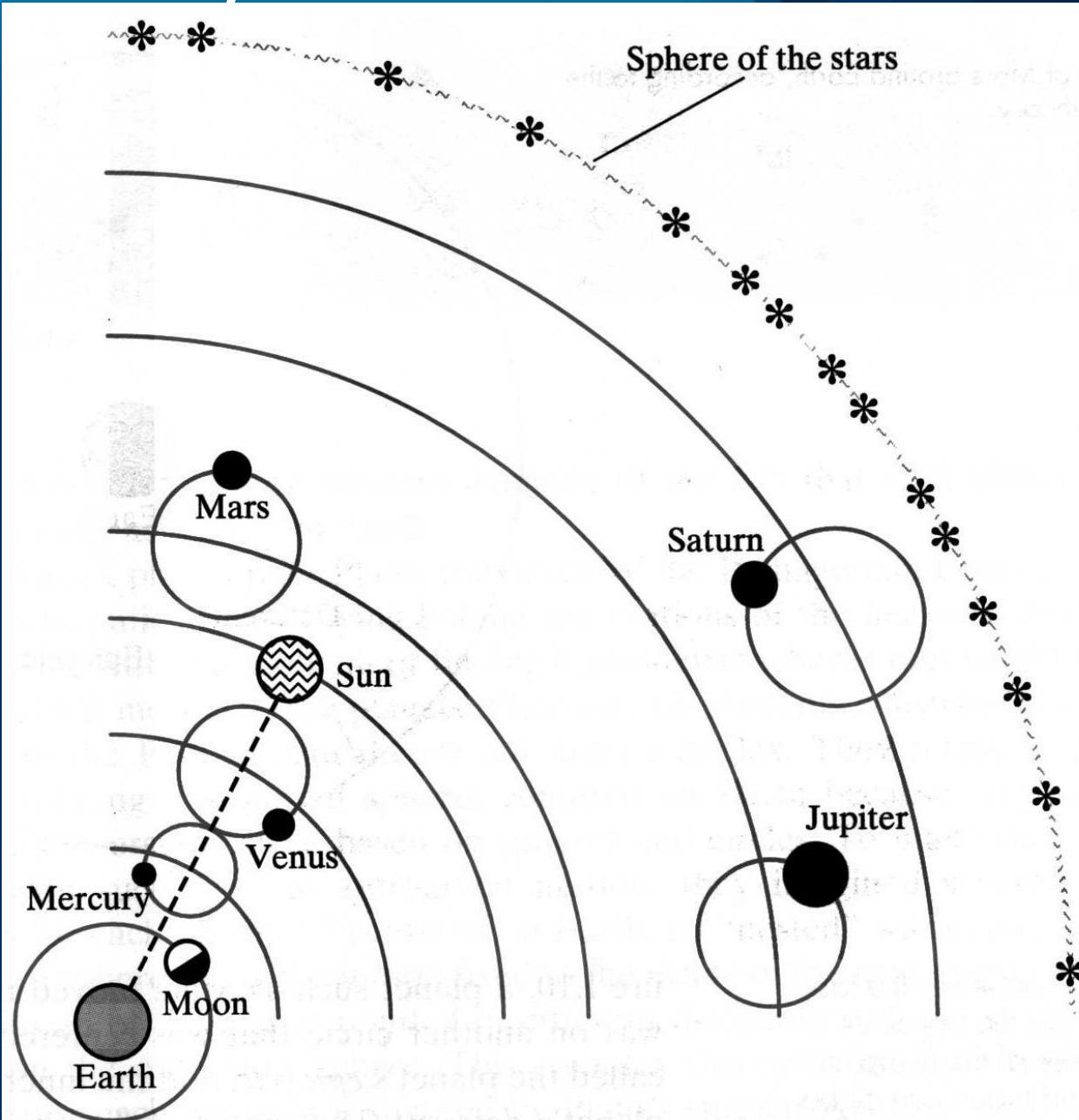
Ptolemy's Model

- 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

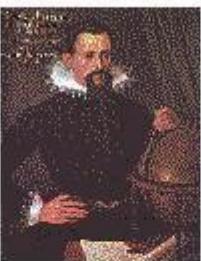
TYCHO BRAHE



. 1601

JOHANNES
KEPLER

. 1571



- . 1609 *New Astronomy*
- . 1619 *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

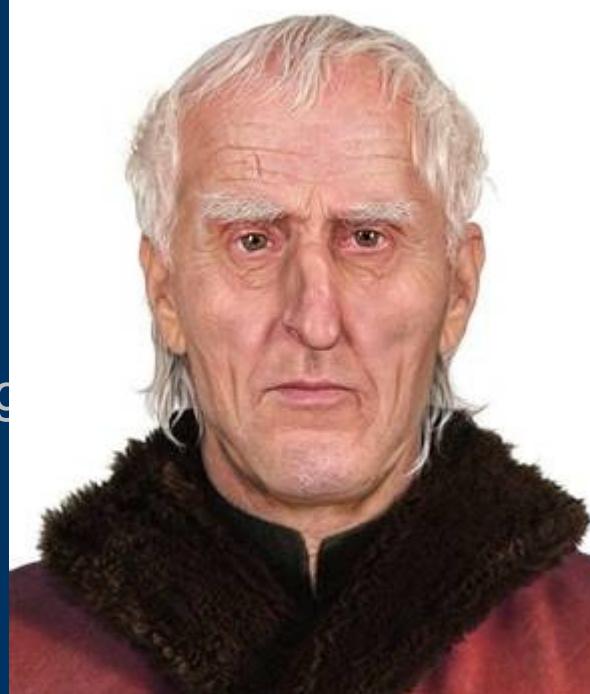
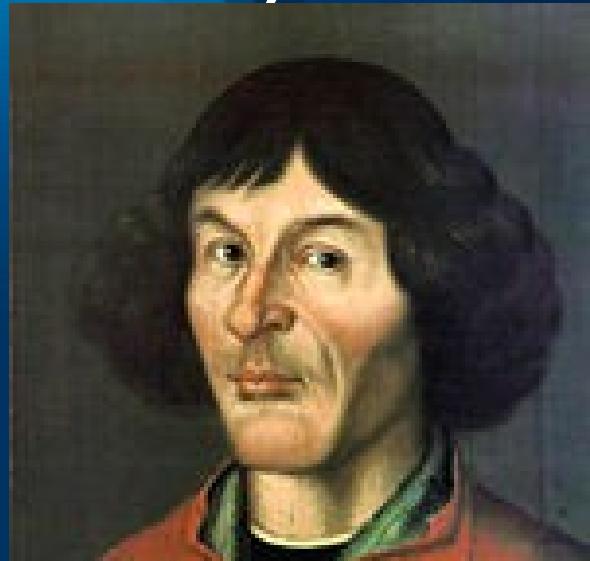


. 1686 *Principia*

. 1727

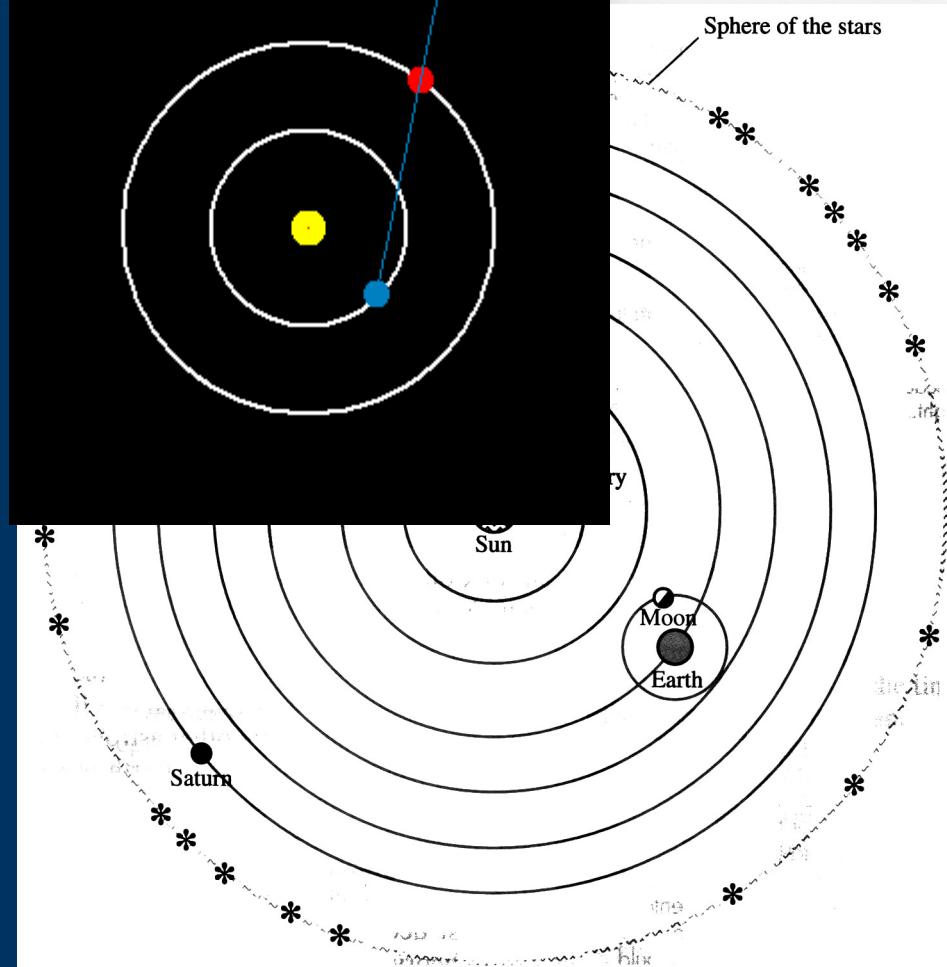
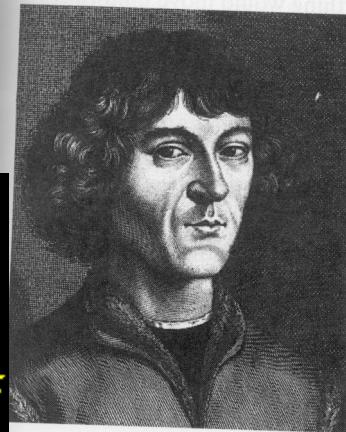
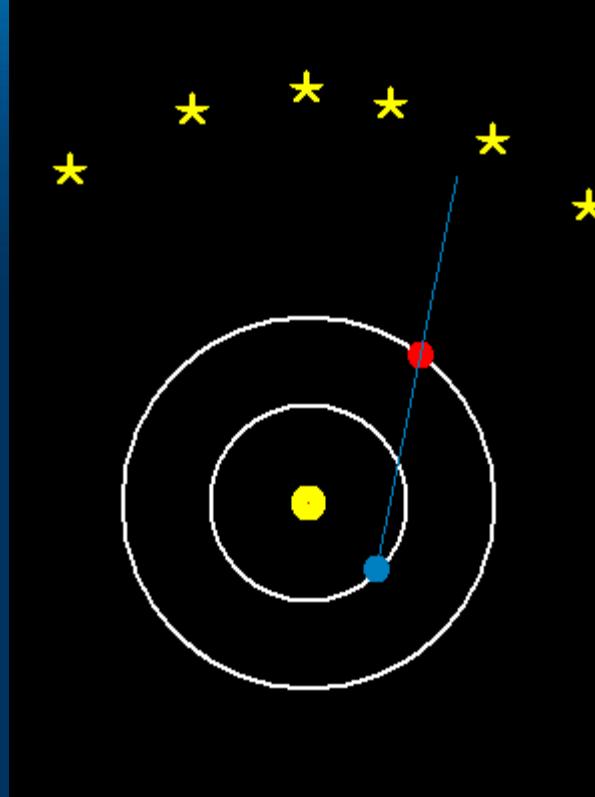
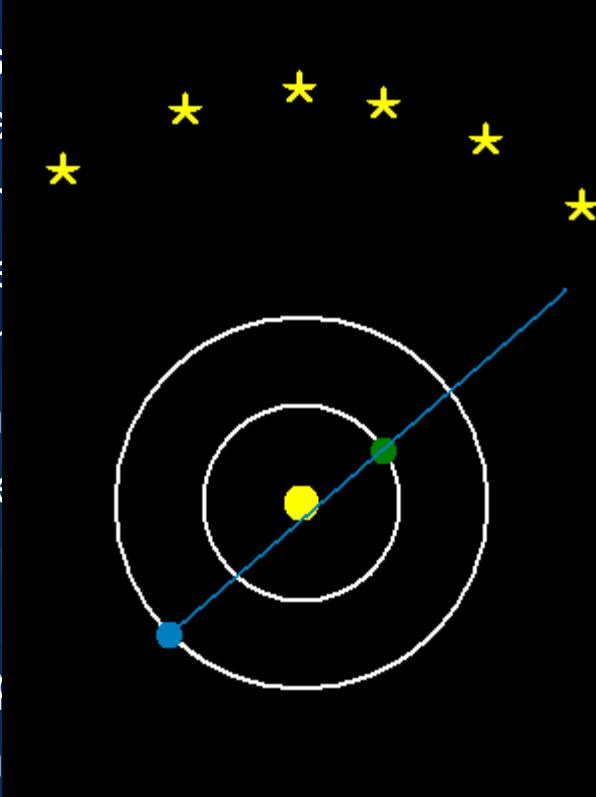
Copernicus (1473-1543)

- Polish Son of copperworker
- 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

- Is there something wrong about the Ptolemaic model?
- Keep some of the Ptolemaic model:
 - spheres
 - uniform motion
- Major Changes:
 - Sun centered
 - Earth orbits Sun
 - Earth moves uniformly
 - other planets move uniformly
- Establishes 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

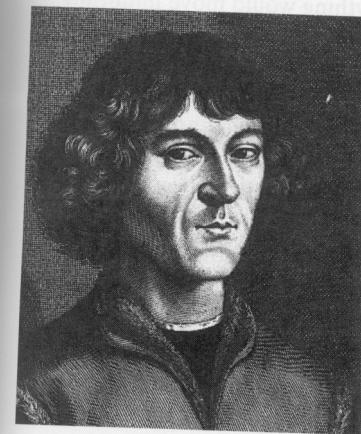


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd 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 or mercury)
- Built “Uraniborg” in Hven
- Meticulous measurements
- Observed supernovae of 1572
- 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
 - 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!

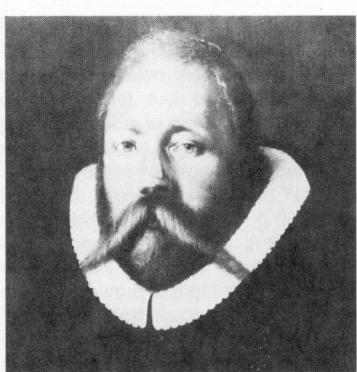


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

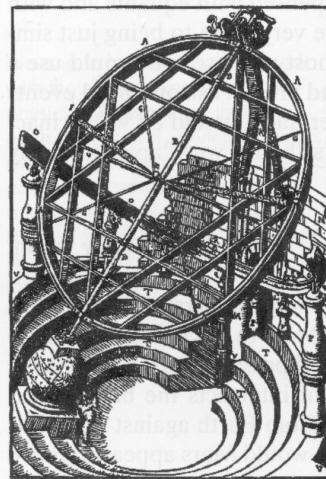


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

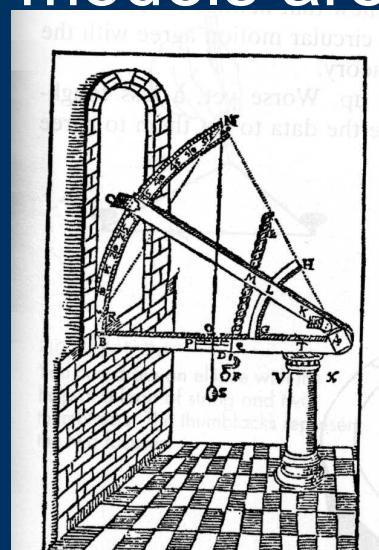


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

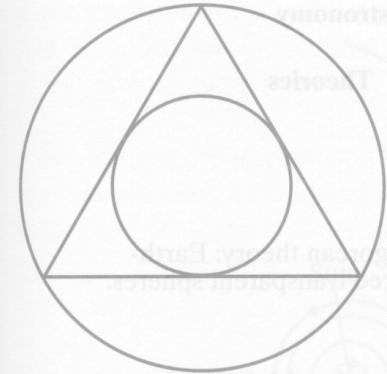
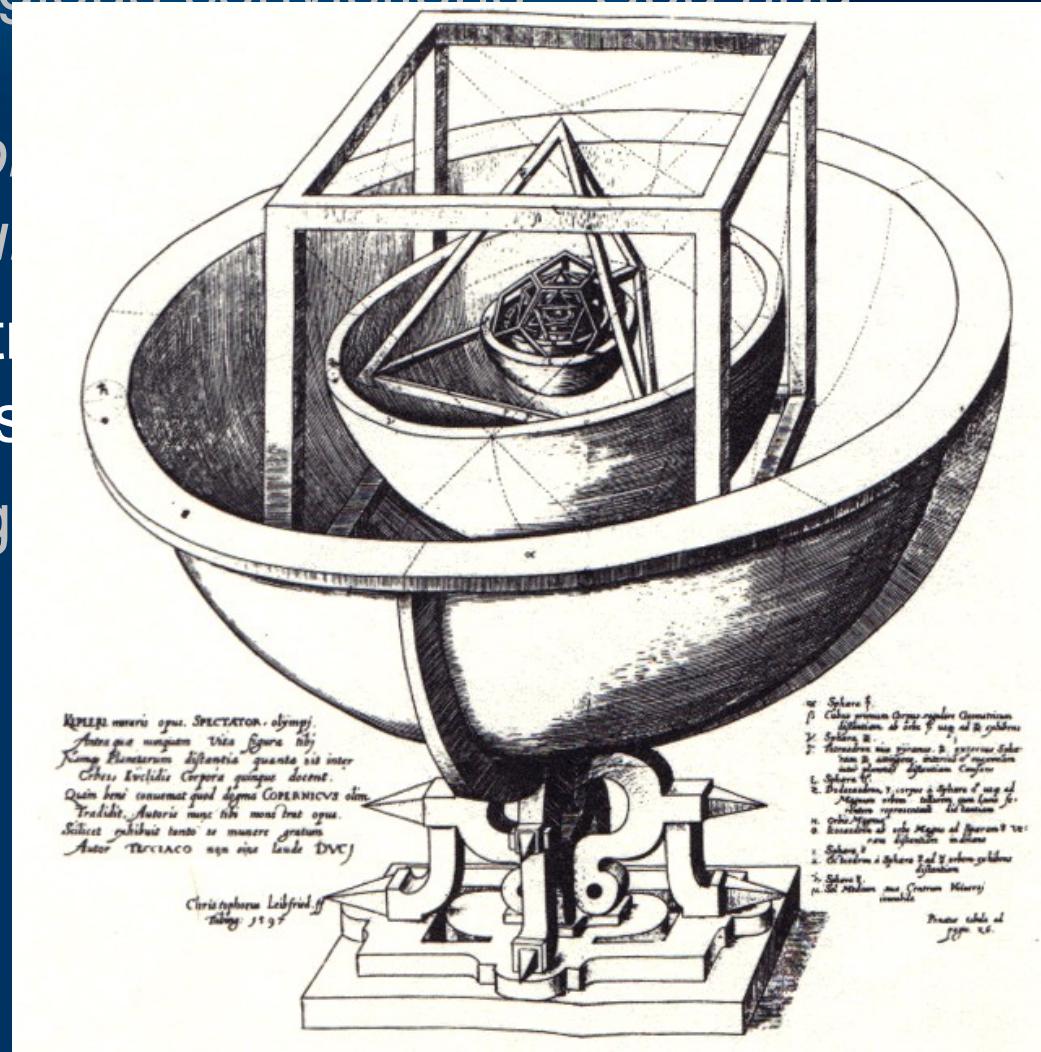


FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

- Mathematician, astronomer, astrologer
- Had religious convictions - *God had created intelligible forms in the nature of things*
- Geometric model of the solar system using regular solids
- Astrologer
- “mother of science”



Johannes Kepler

- Super
 - Co
 - S
 - T
 - Try

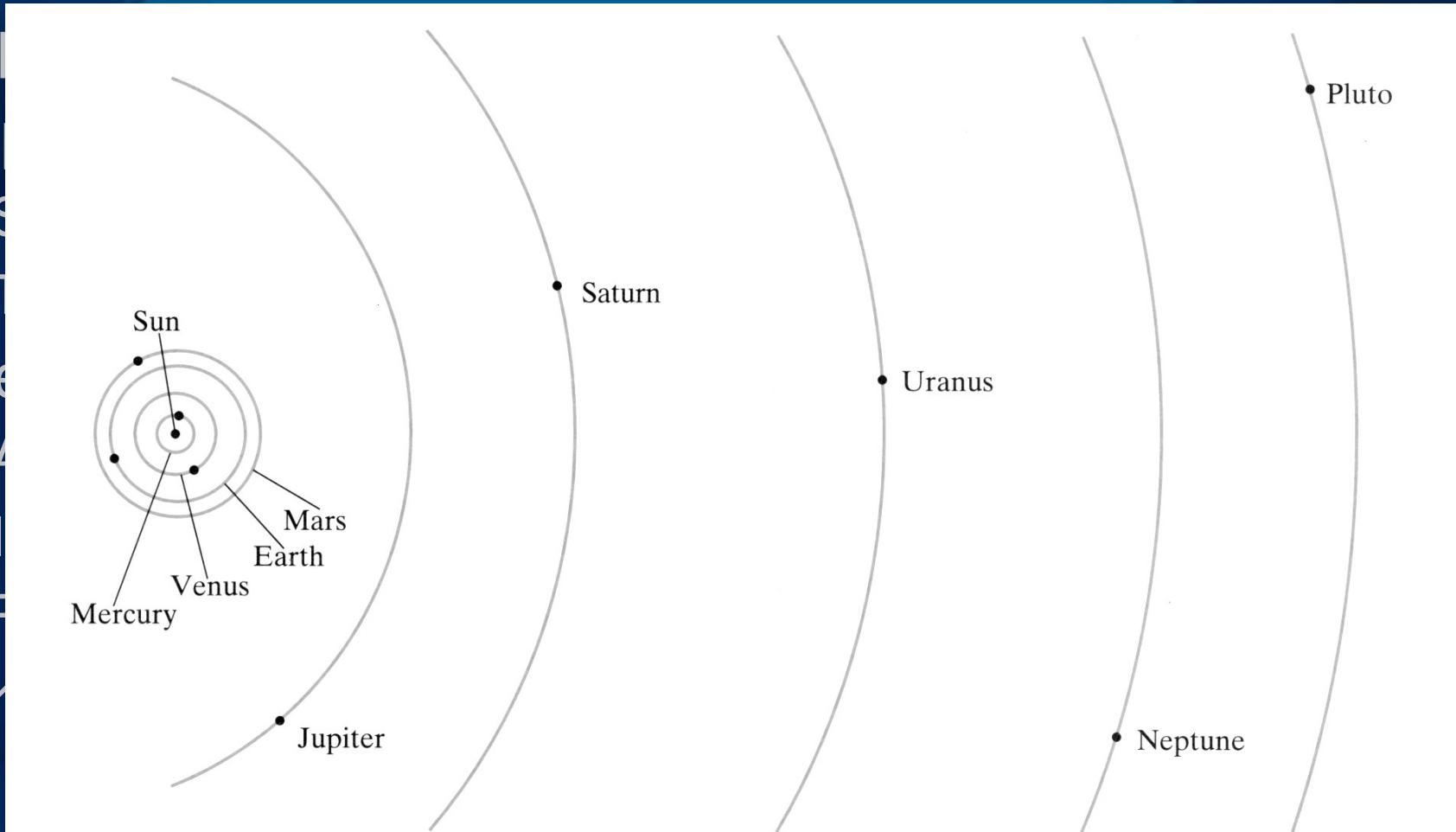
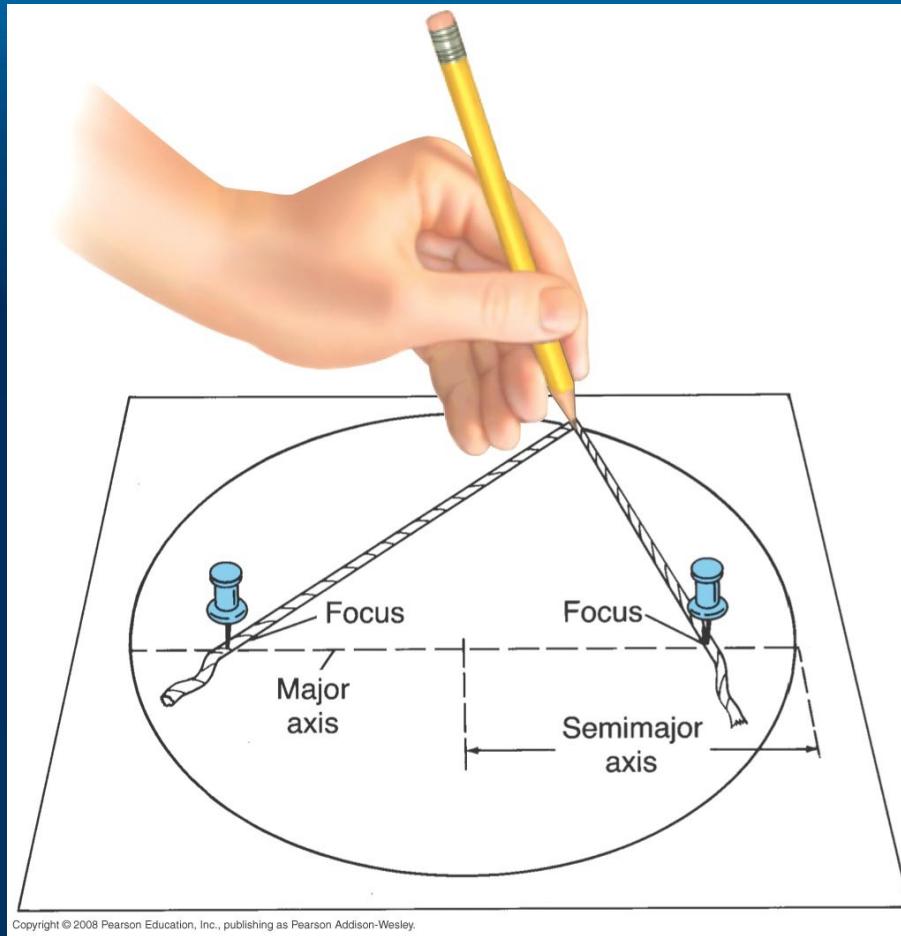


FIGURE 1.26

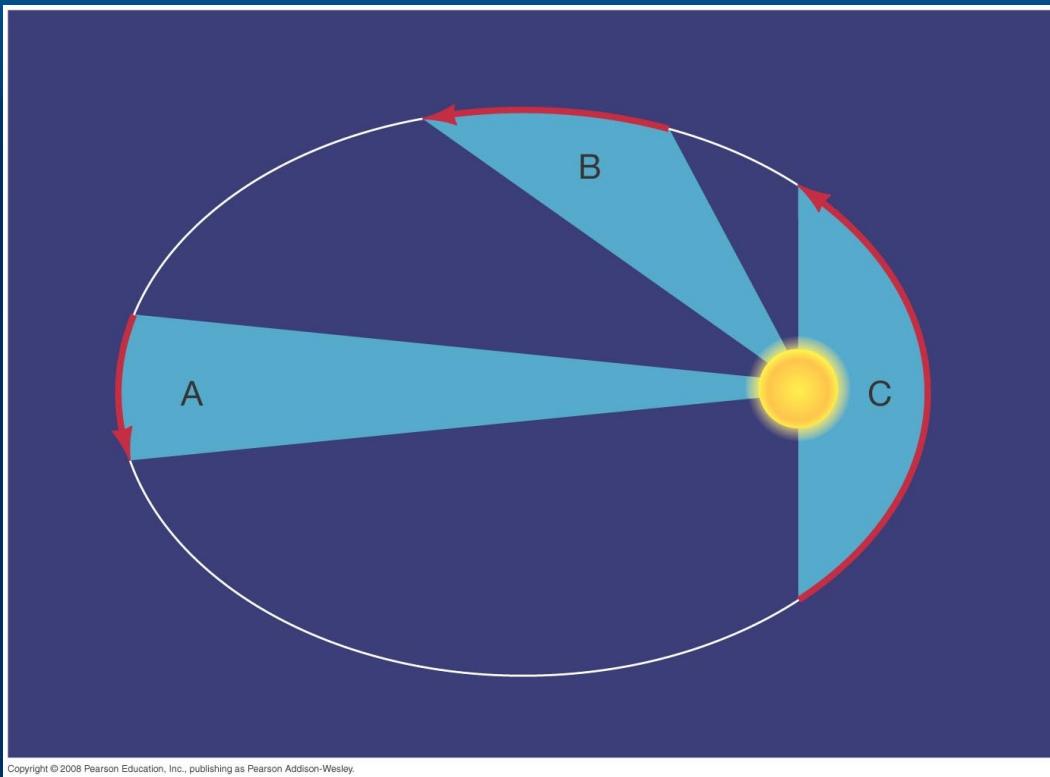
The arrangement of the solar system as it is now known. Uranus, Neptune, and Pluto are visible only with a telescope. The orbits are elliptical, although their ellipticity is too small to be visible in this diagram.

Kepler's 1st law



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

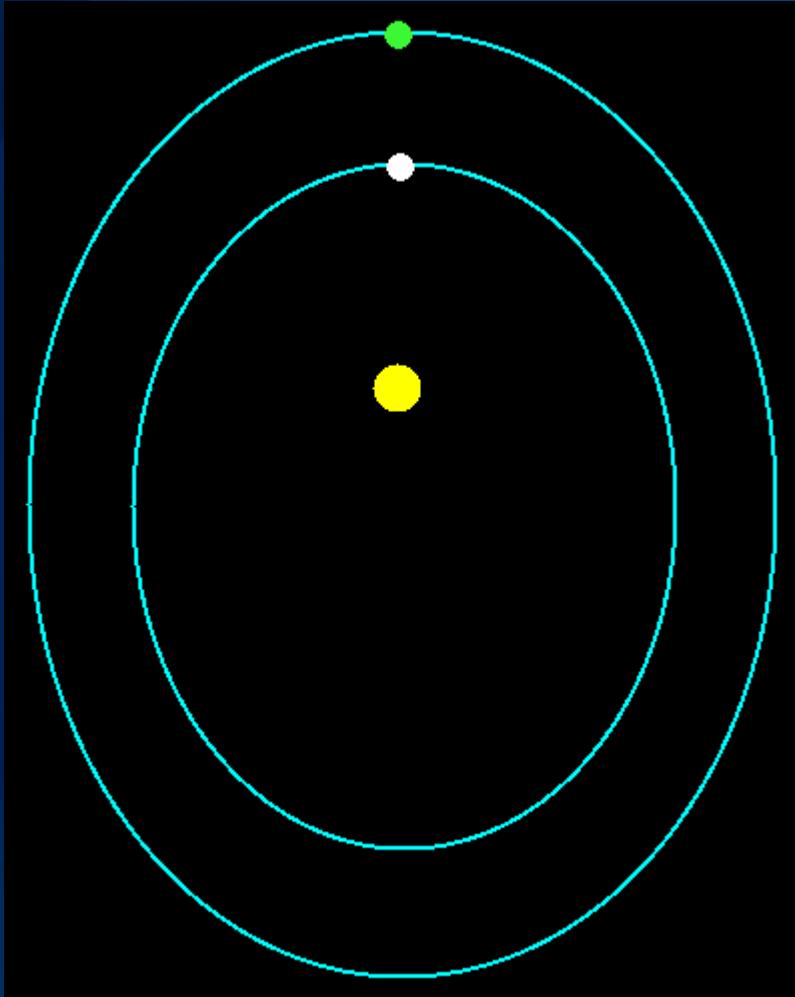
Kepler's 2nd Law



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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

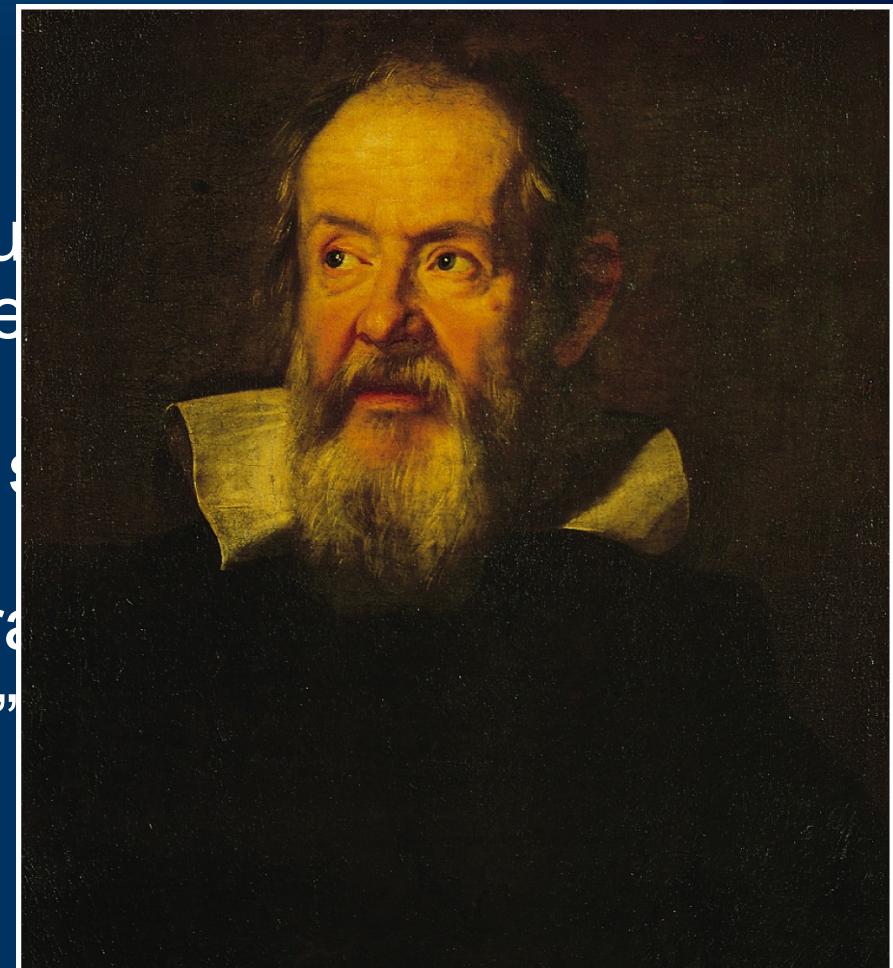


$$P^2 = a^3$$

Period increases
with distance from
the Sun.

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”



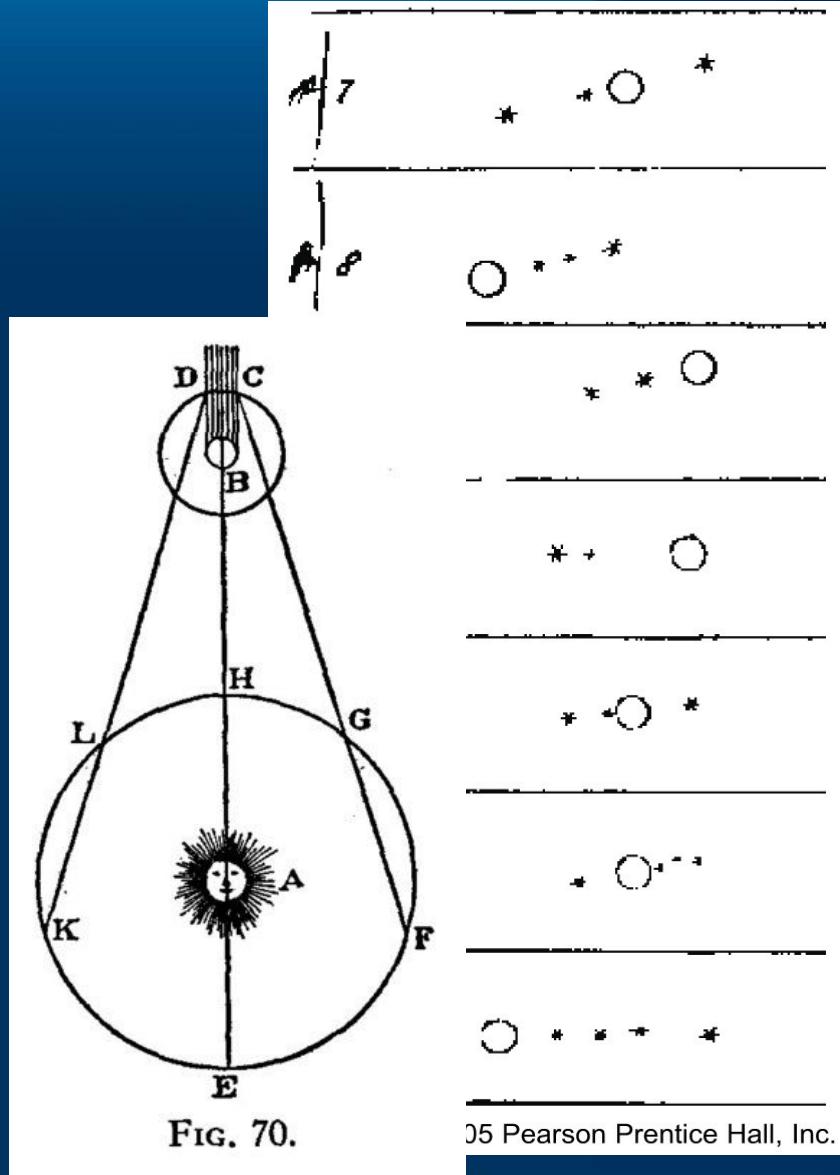
Galileo and Jupiter

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

Not everything orbits the Earth!

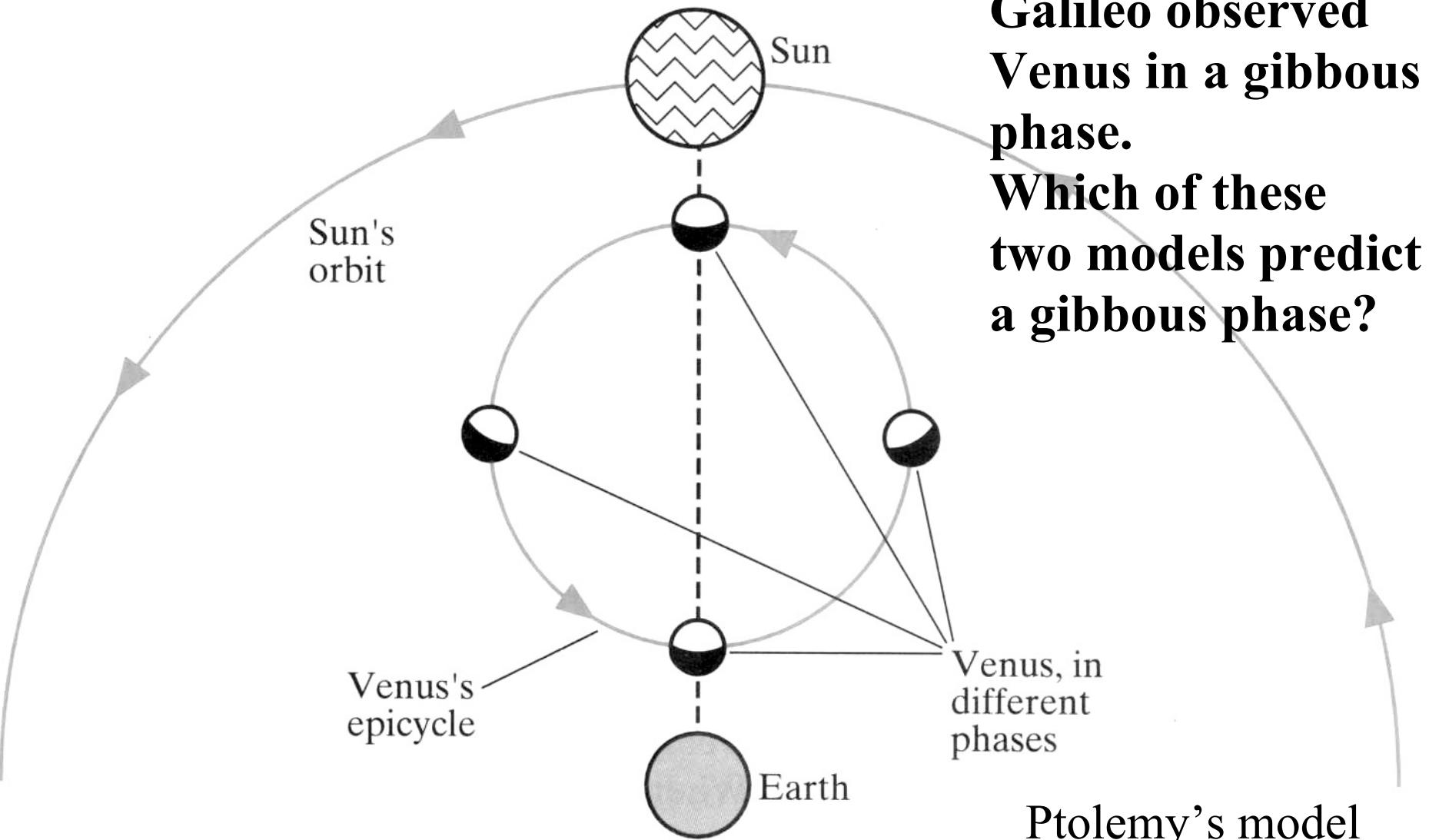
Note: These moons could be used to measure the speed of light!

Ole Roemer 1677



Galileo and Venus

**Galileo observed
Venus in a gibbous
phase.
Which of these
two models predict
a gibbous phase?**



**Galileo observed
Venus in a gibbous
phase.
Which of these
two models predict
a gibbous phase?**

Ptolemy's model

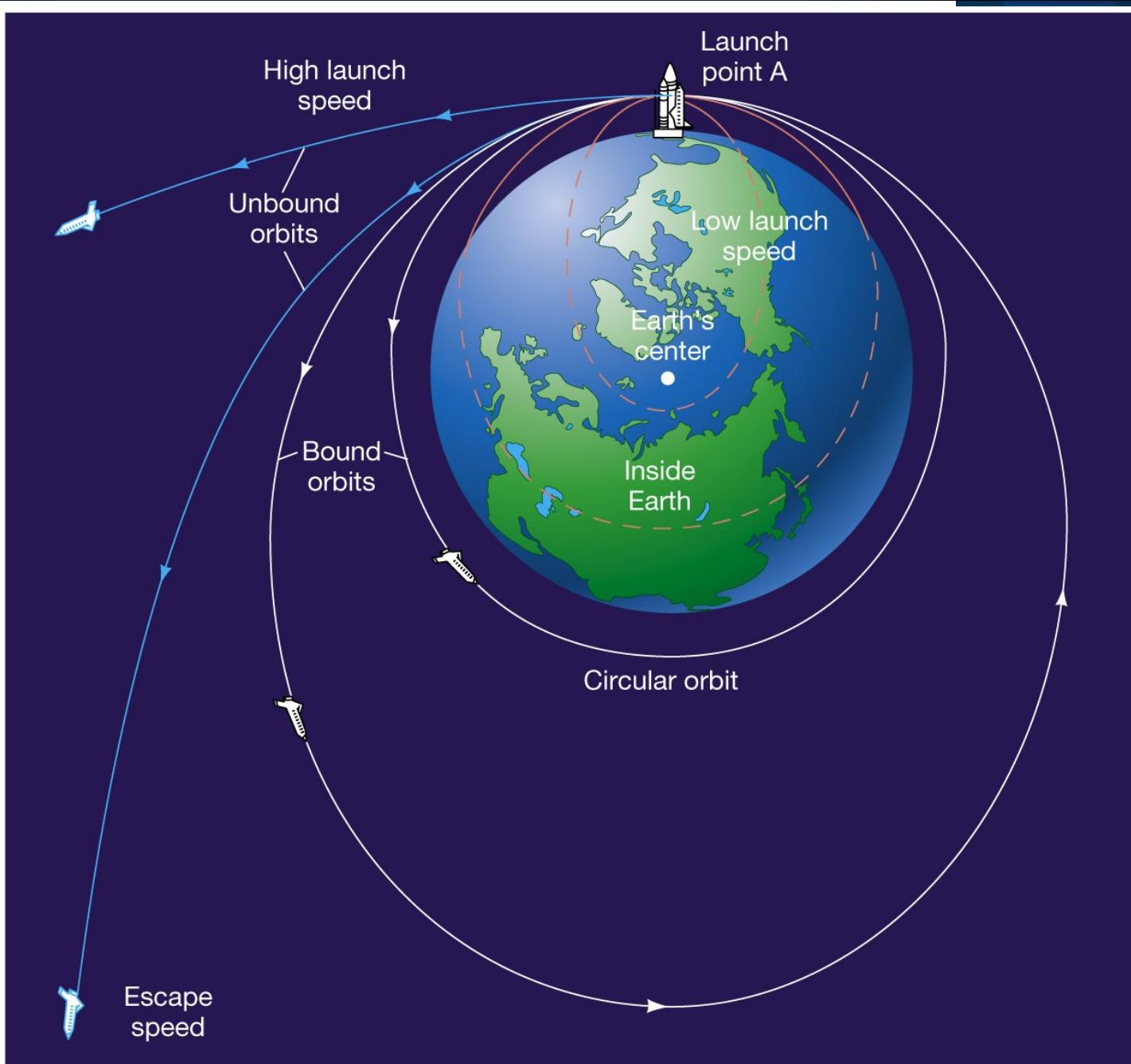
Galileo's troubles

- 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.

- English theologian
- Inventor
- Urged King James to fund translation of the Bible
- *Philosophiæ Naturalis Principia Mathematica*
- 3 laws of motion
- Universe is finite

 - Cannot be infinite
 - Finite

- “God governs in accordance with the law, or can do otherwise”



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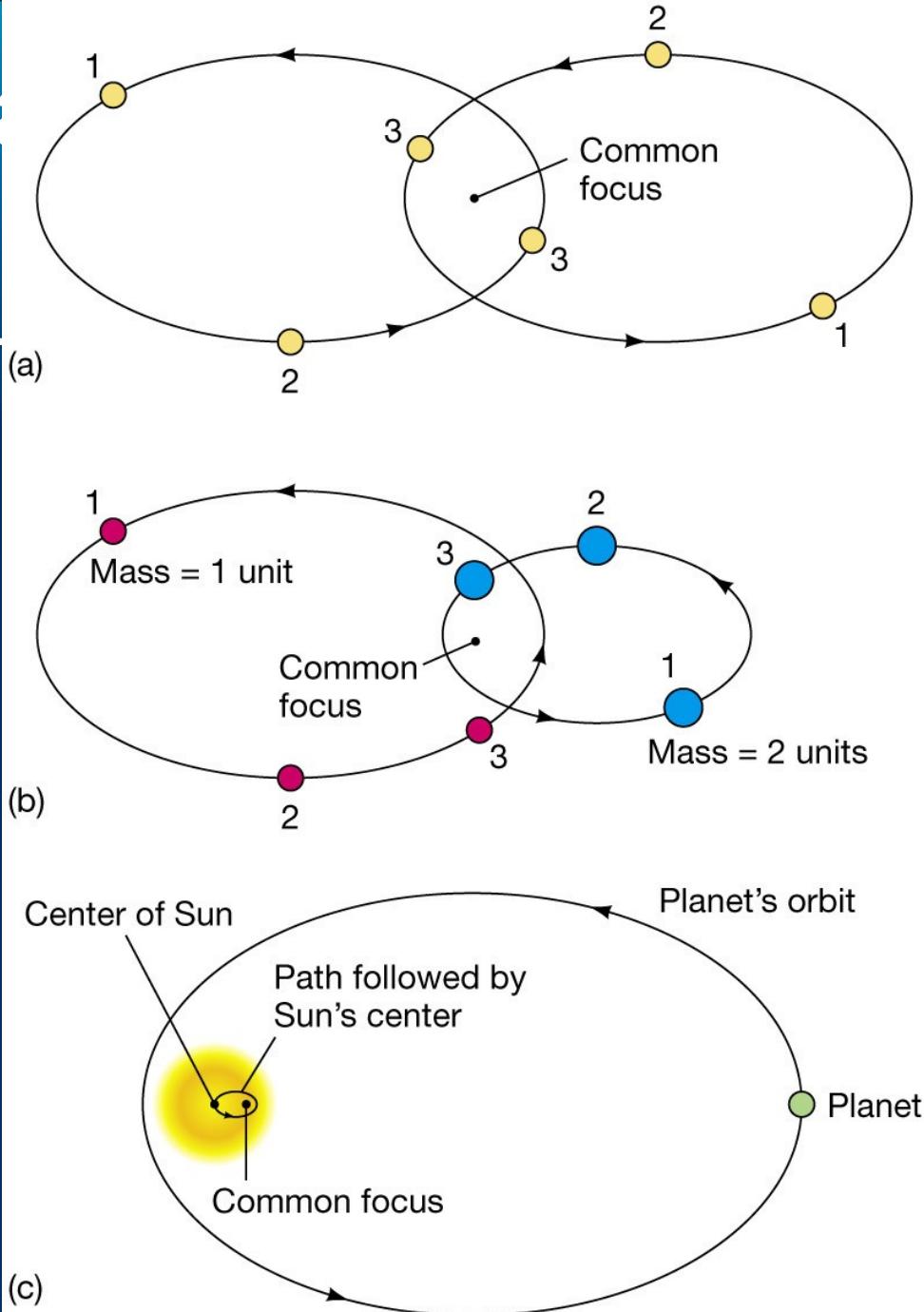
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Isaac Newton (1643-1727)

- 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
 - 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.*”

$$F = G \frac{m_1 m_2}{r^2}$$

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



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

Observed gibbous phase of Venus

Tycho Brahe

Made precision measurements of planets

Johannes Kepler

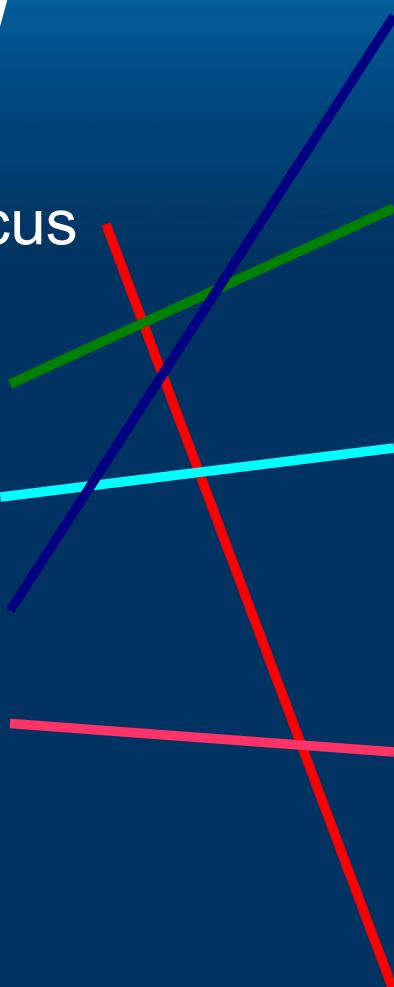
Used ellipses to model solar system

Galileo

Said gravity accelerates the planets

Newton

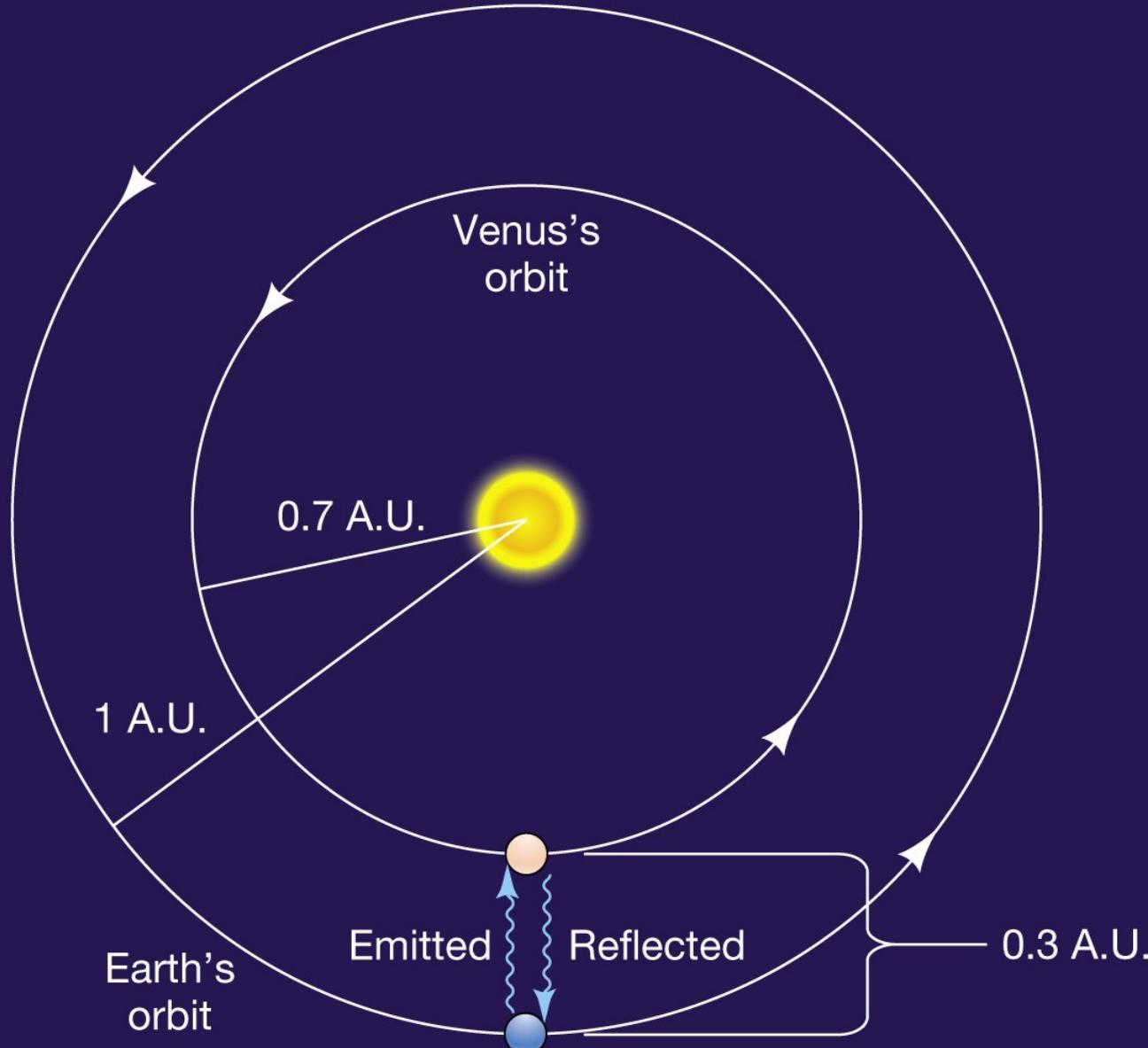
Revived the heliocentric model



F

• V

• W



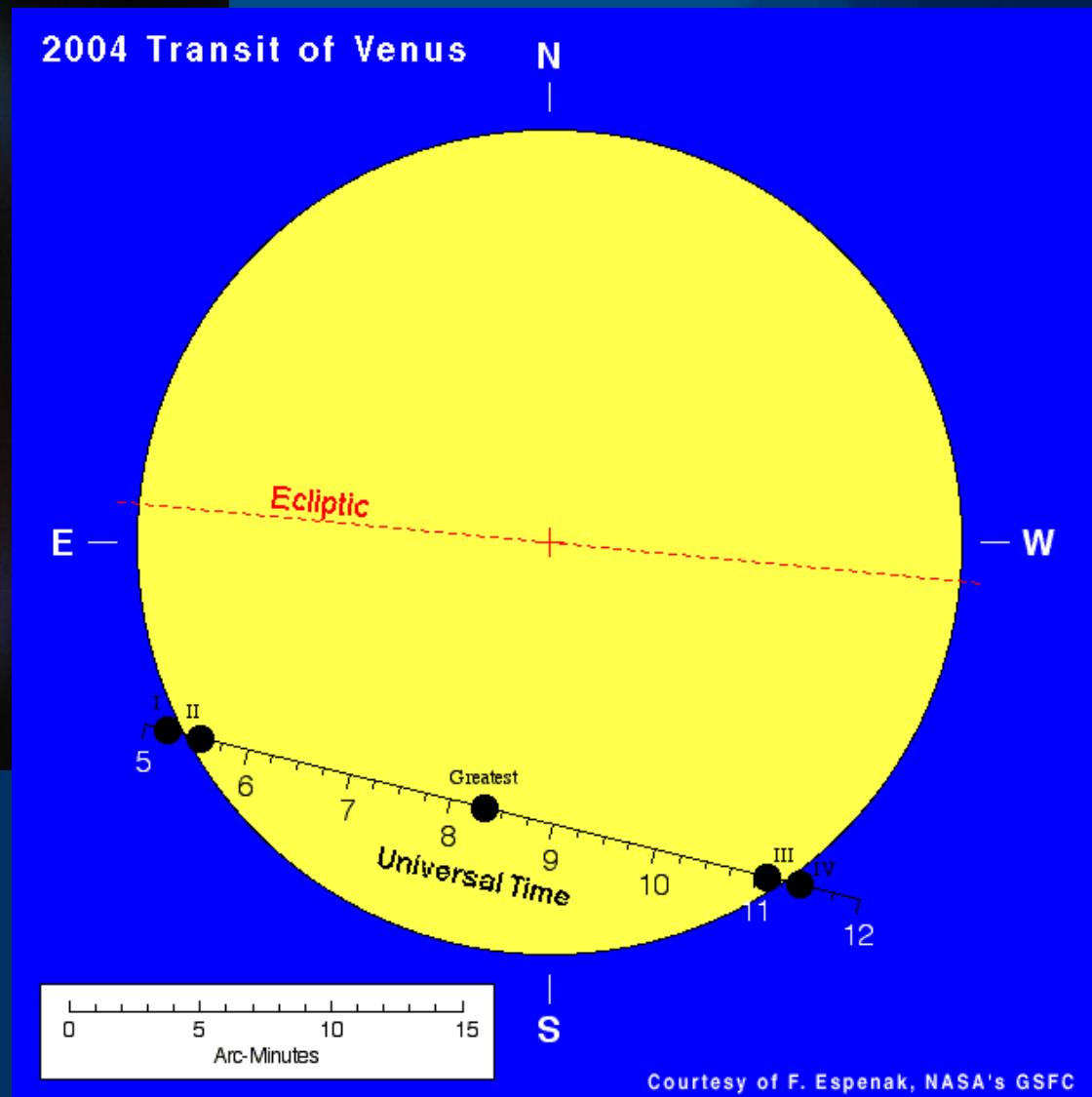
's view out
window that
ing left



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



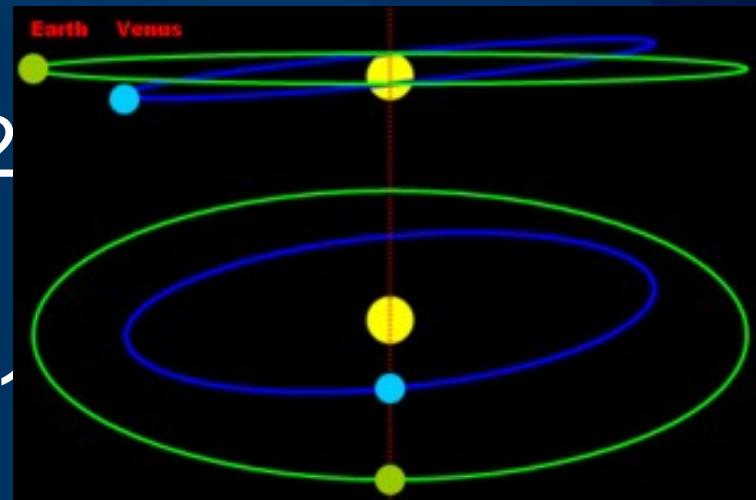
Transits of Venus

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.

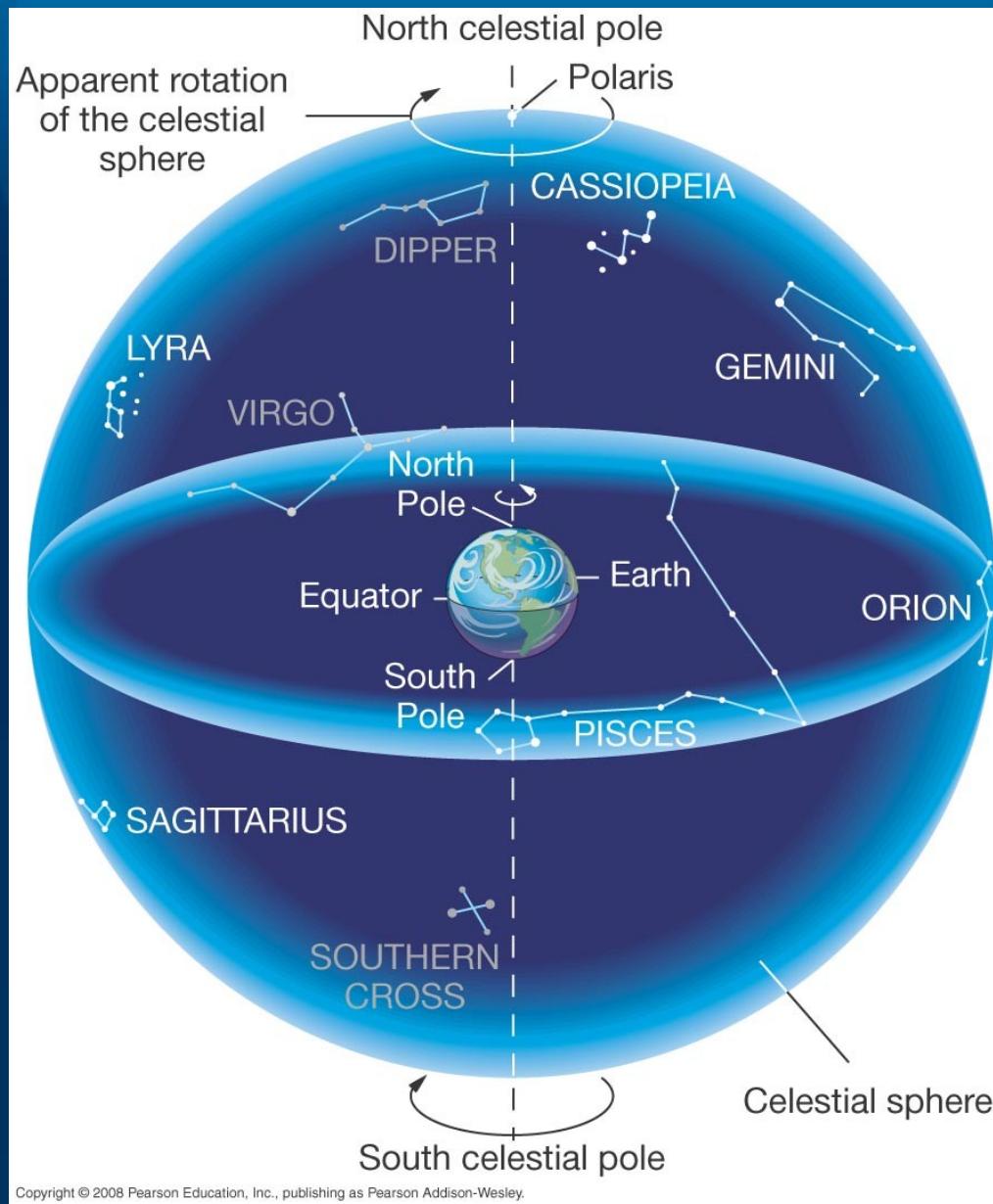


Inferior conjunction while both planets on line
of nodes.

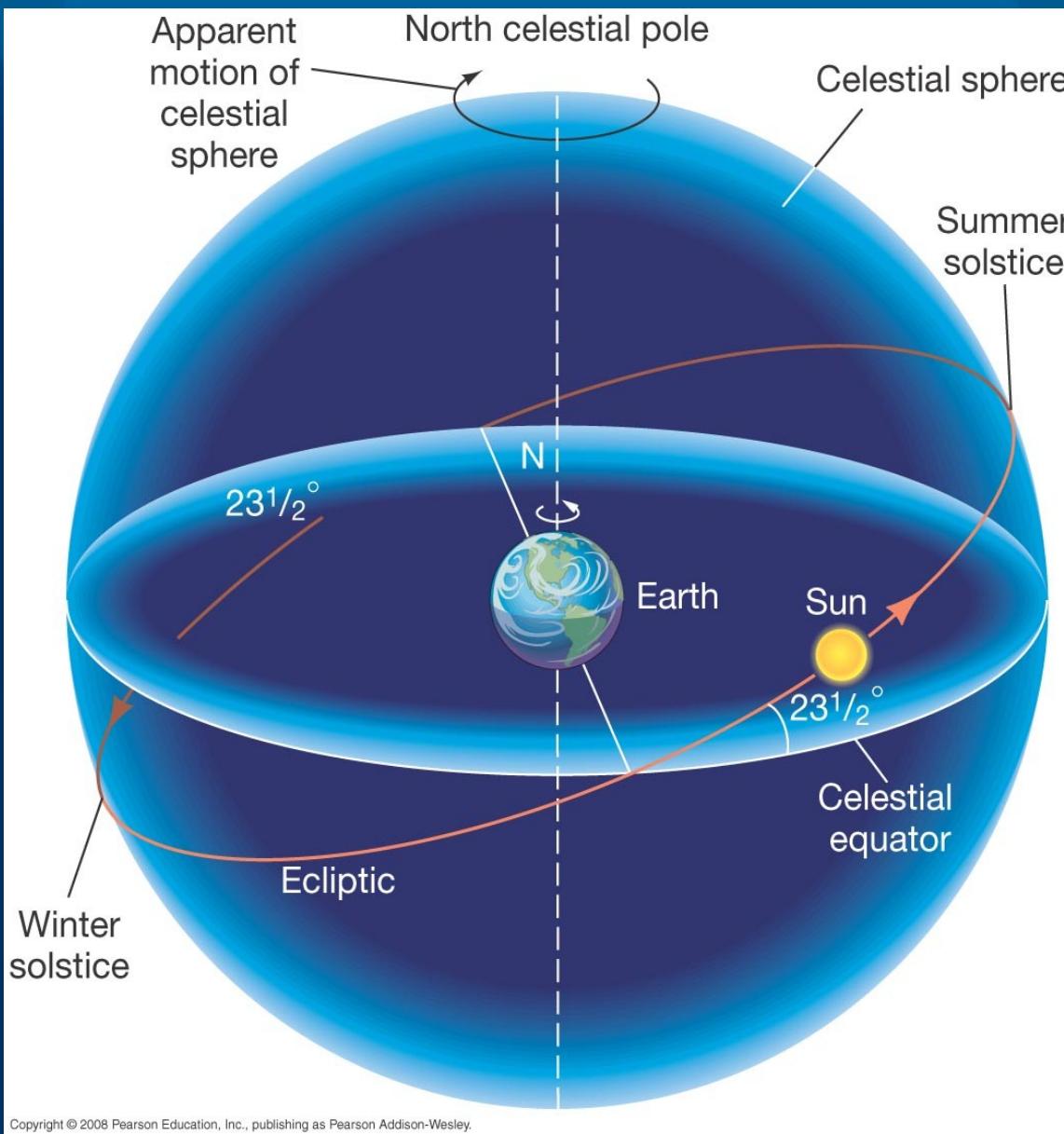
Science vs Superstition – it never ends

- 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

The Celestial Sphere

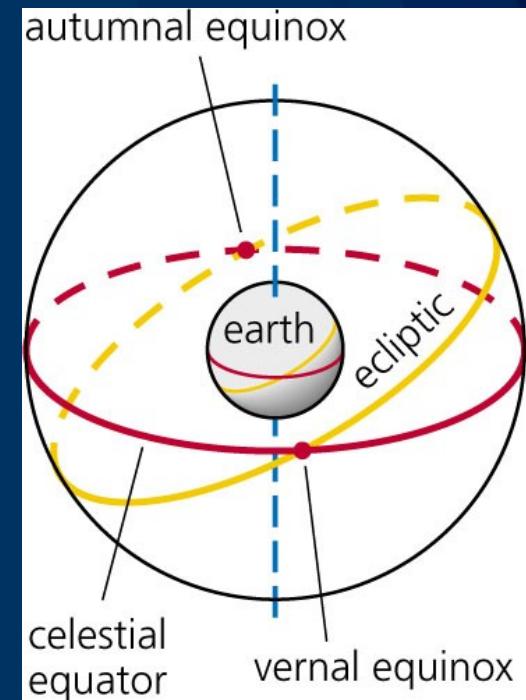
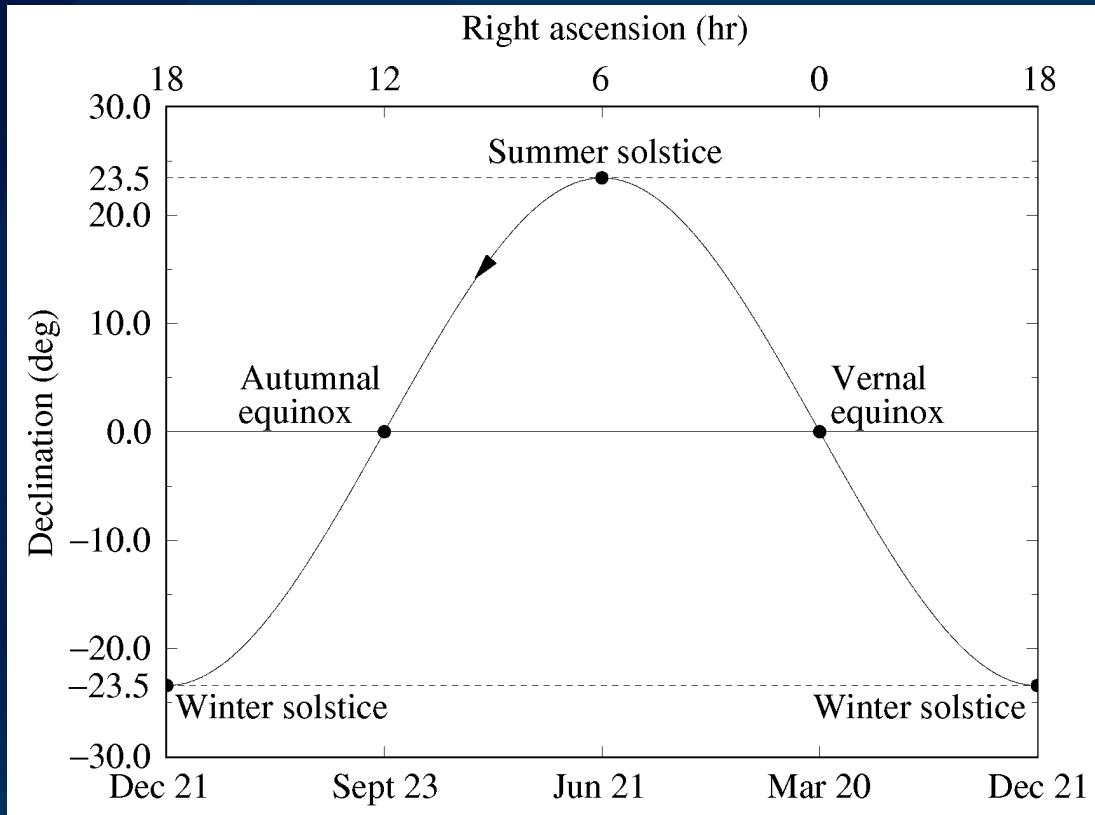


Celestial Sphere and the ecliptic



Ecliptic

- Seasonal variations due to orbital motion and the 23.5° tilt of Earth's rotational axis



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

