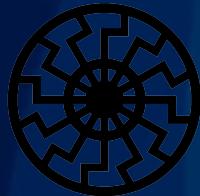


The Copernican Revolution - Separating Science and Superstition

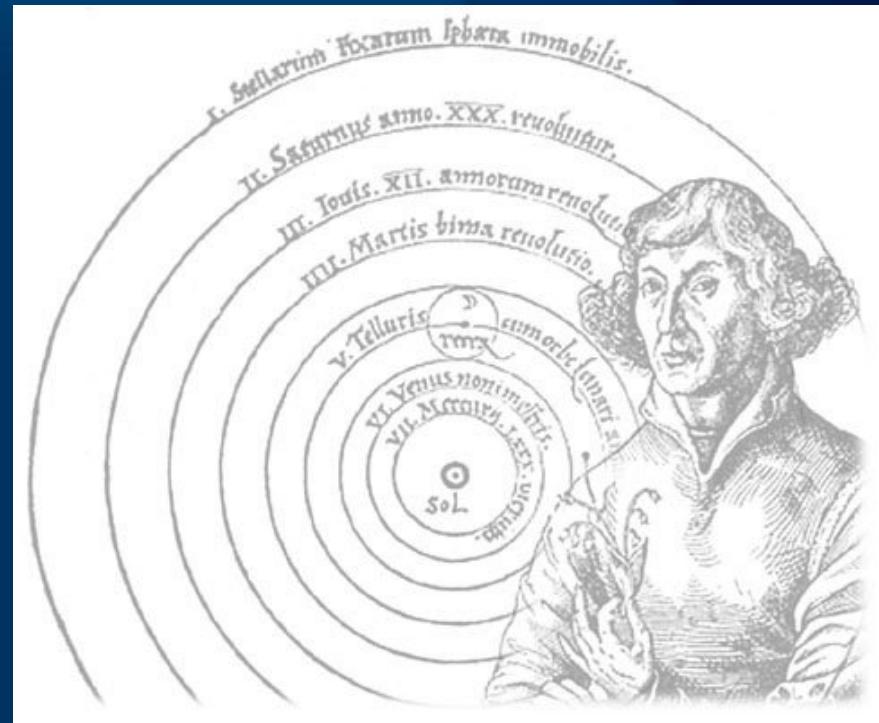


J. Pinkney
ONU 2015



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



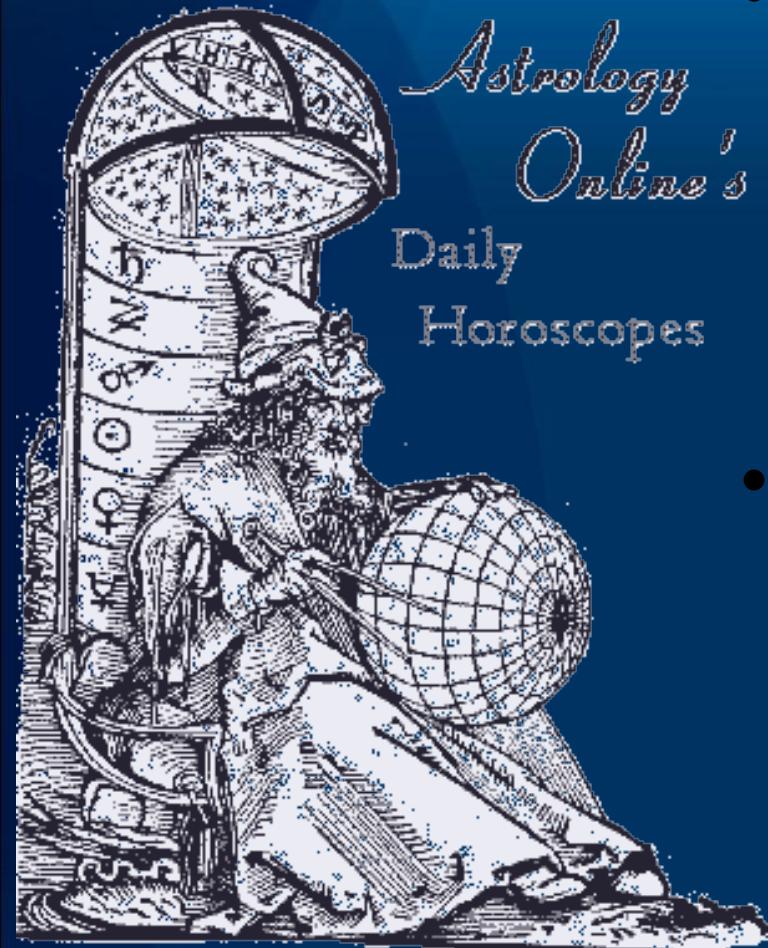
What the Ancients Knew

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

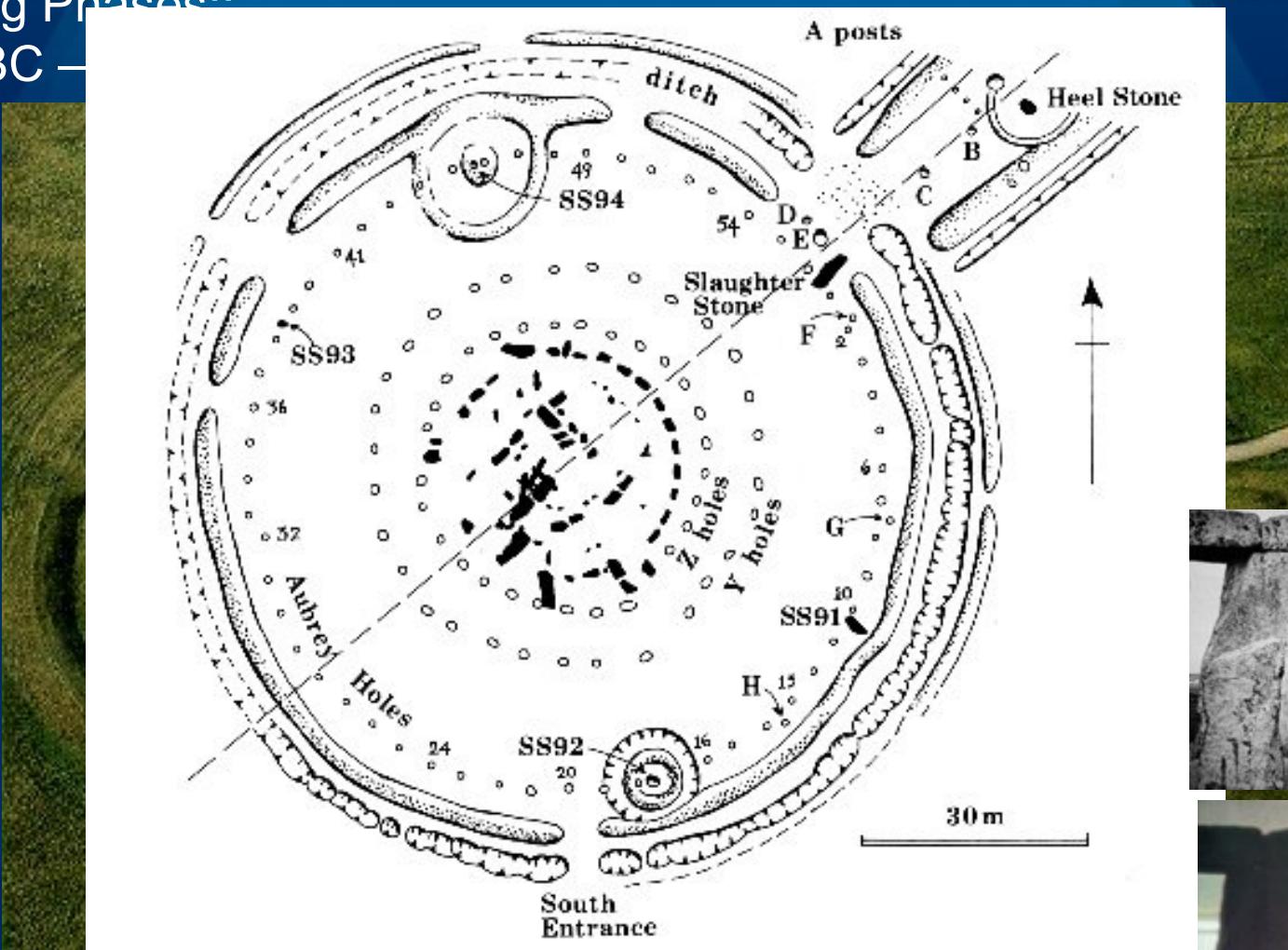


- Mysterious cultures
 - People of stonehenge, Plains Indians, Anasazi, Maya
 - left behind calendar-like constructions.
- Well documented cultures
 - Greek, but also Chinese, Babylonian, Egyptian, Arab
 - left records of lunar cycles, eclipses, comets, novae, star maps, models

Unknown nature → superstition → astrology.

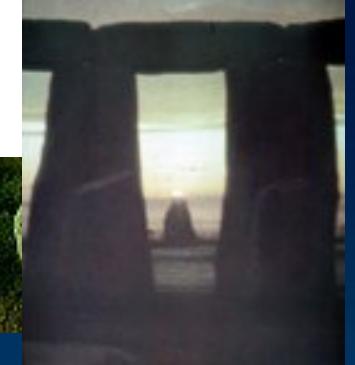
The Ancients: Stonehenge

- Building Phases:
- 2950 BC —



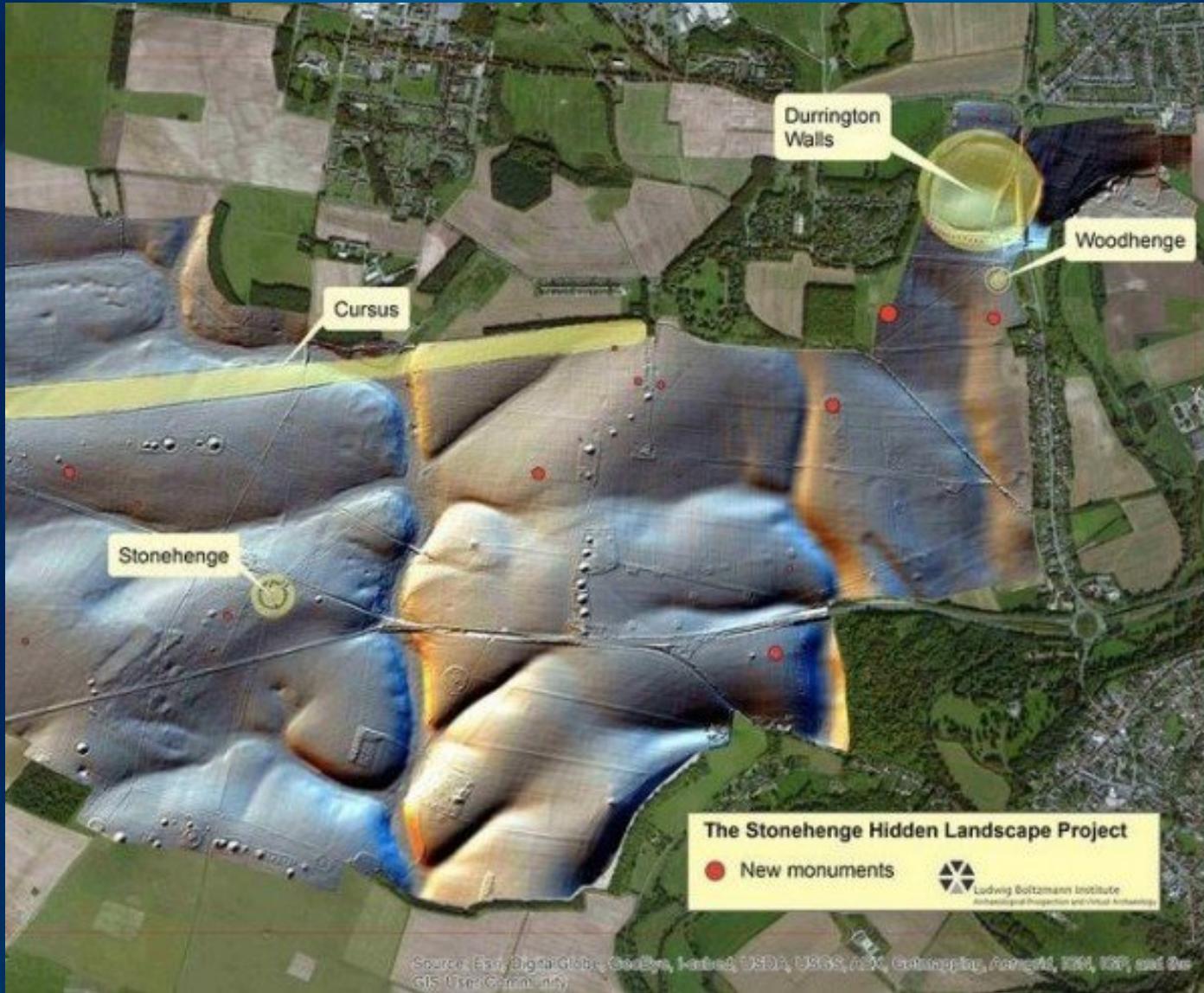
- 30 Y-holes, 28/29 Z-holes, 56 Aubrey holes = 3 Saros cycles*
- Heel stone marks sunrise on Summer Solstice

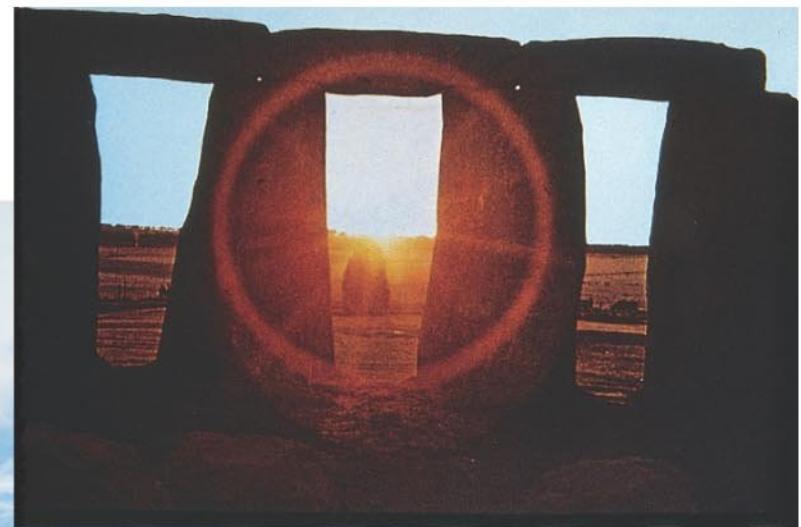
*actually Earth-Moon precession cycles (18.6 yrs)

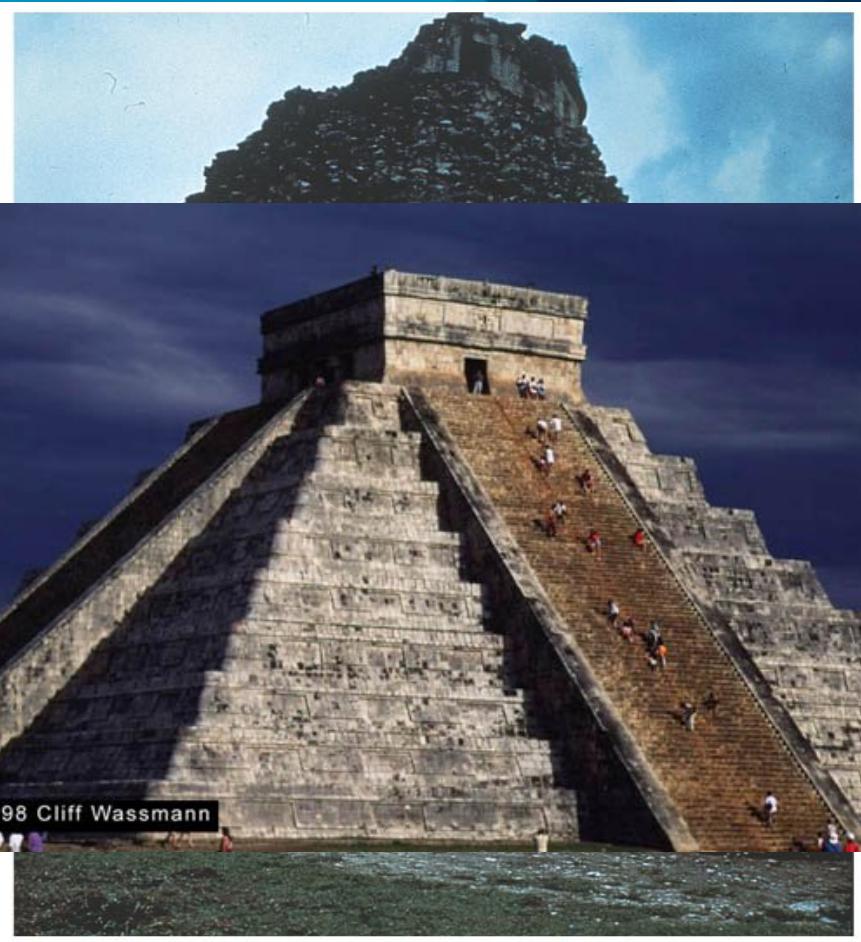


The Ancients: Stonehenge

- Recent discoveries using ground-penetrating radar.







(b)

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

What the Ancients Knew



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.

es

Zodiac, “year of the ___”

alphabet, ziggurats,
planetary rise times,

and Osiris, pyramids, Nile

uring dark ages → algebra,
connection between
1000 AD!

measurements

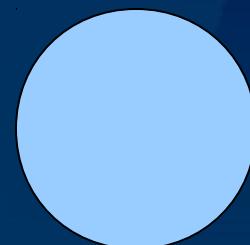
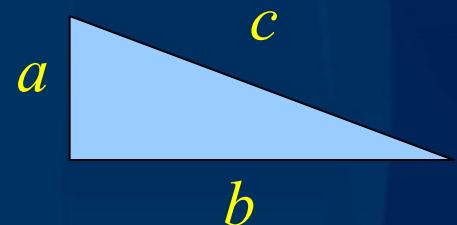
by

Christianity → astrology.

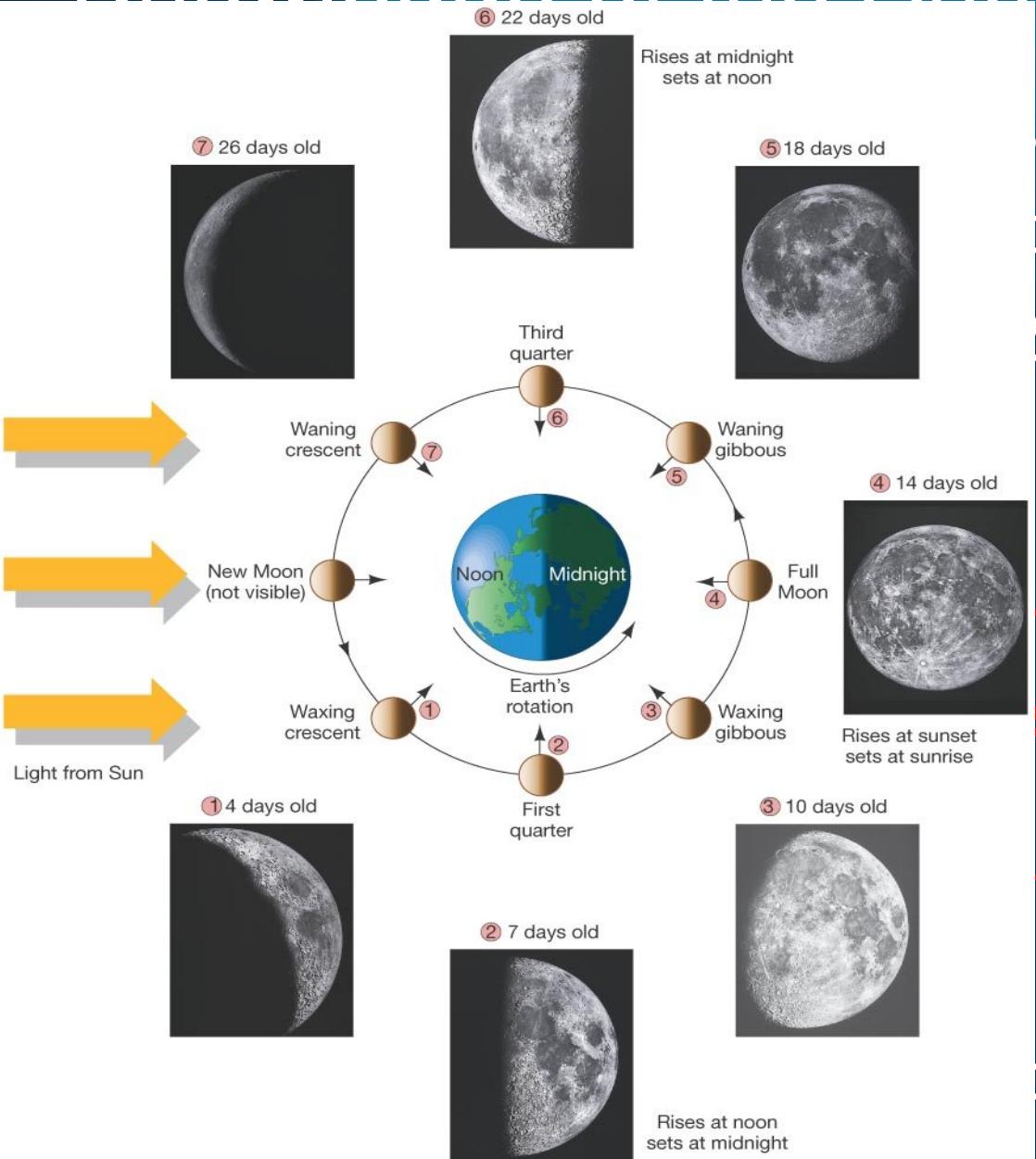


Knowledge of the Ancient Greeks I.

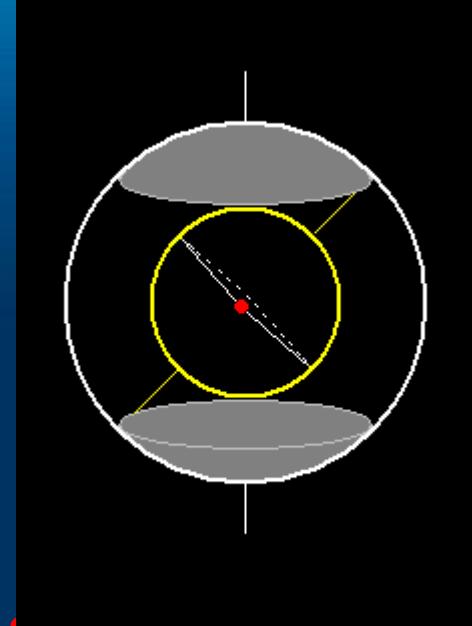
- Ideas and philosophies were rich and varied, some correct and some **incorrect**.
 - Thales of Miletus (624-547 BC):
 - universe is rational
 - predicted eclipse ~585 BC
 - Pythagoras (570-497 BC):
 - math in nature, music of spheres
 - Earth and planets are spherical
 - Plato (428-347 BC):
 - Truth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



Knowledge of the Ancient Greeks II.



c):
model
cycle.



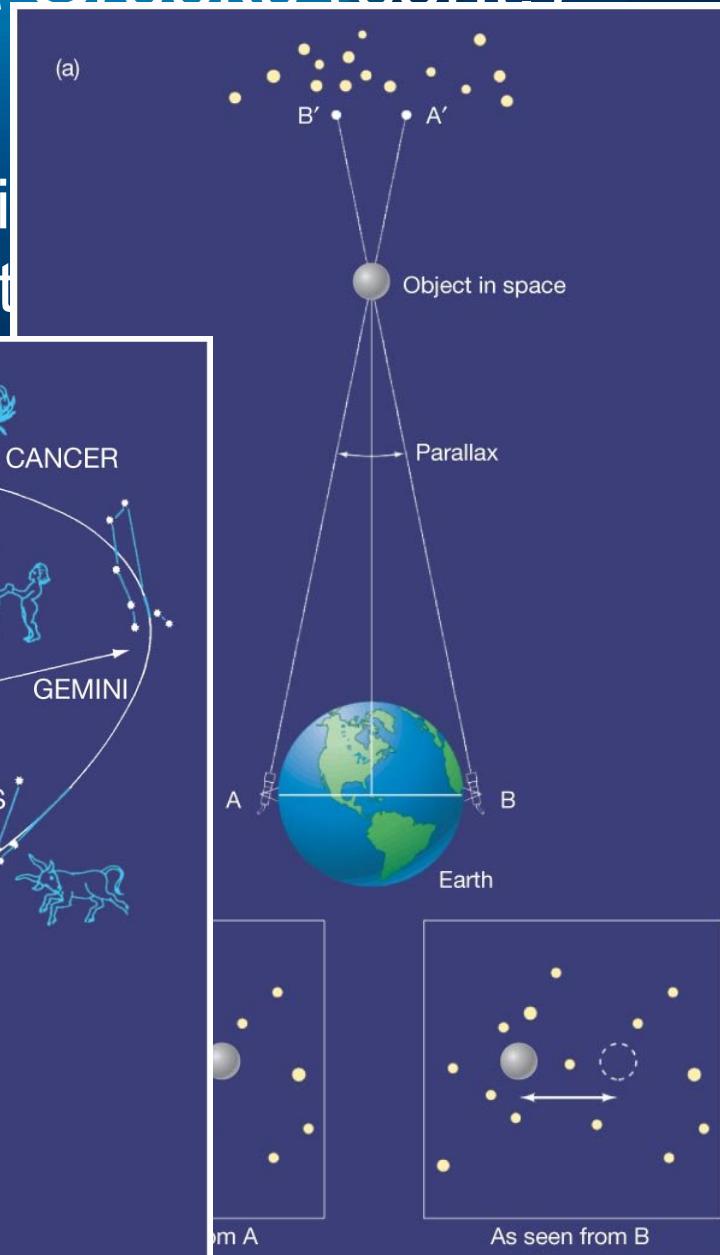
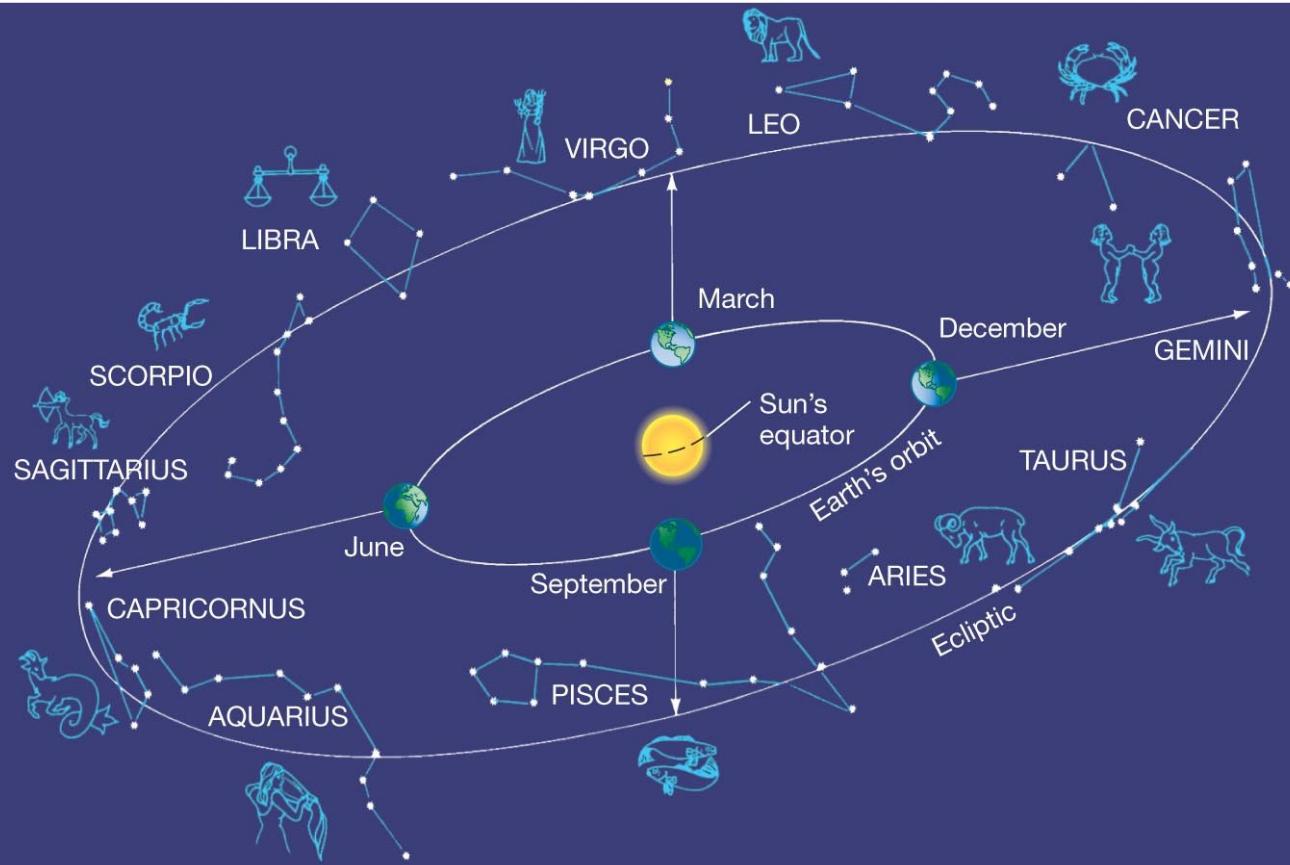
more perfect
elements: earth, water, wind,
fire, air, and

and

should exhibit parallax

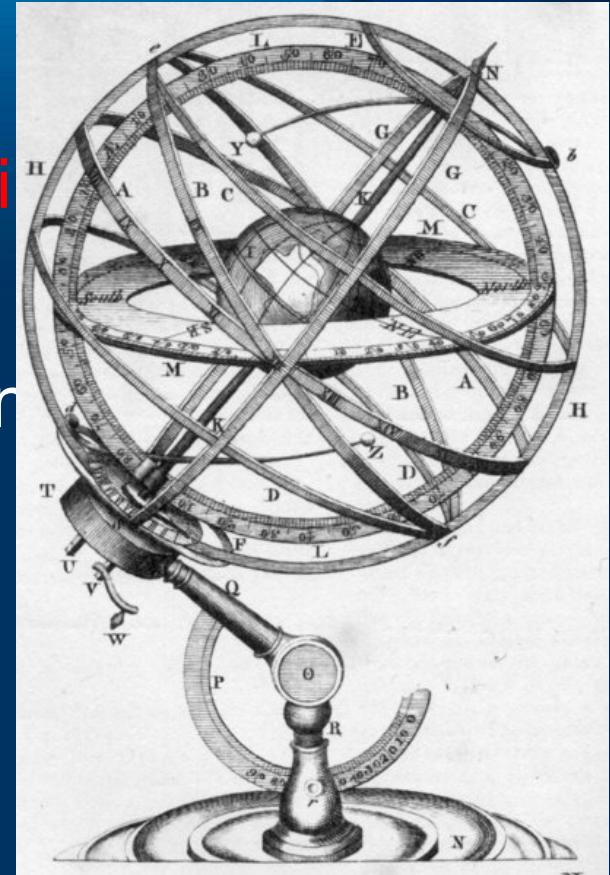
Knowledge of the Ancient Greeks (cont.)

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

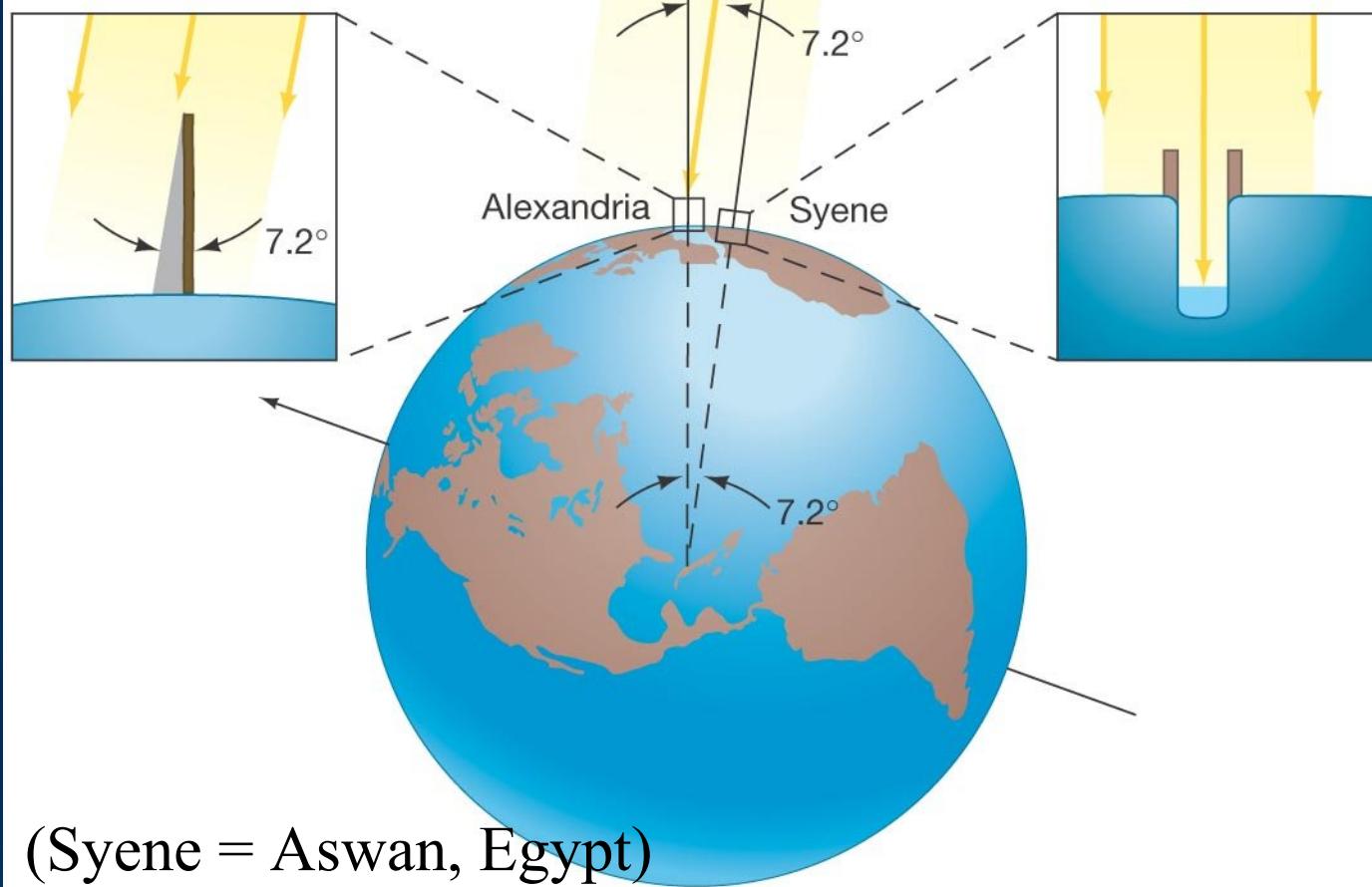


Knowledge of the Ancient Greeks III

- Philolaus (480-385 BC)
 - Earth in motion **around invisible “fire”**
- Aristarchus (310-230 BC)
 - The Earth orbits around the Sun
- 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 eccentricities in modelling motion of Sun and Moon.

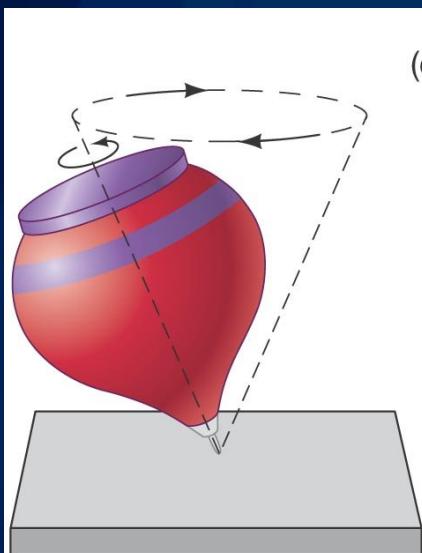


Eratosthenes' method

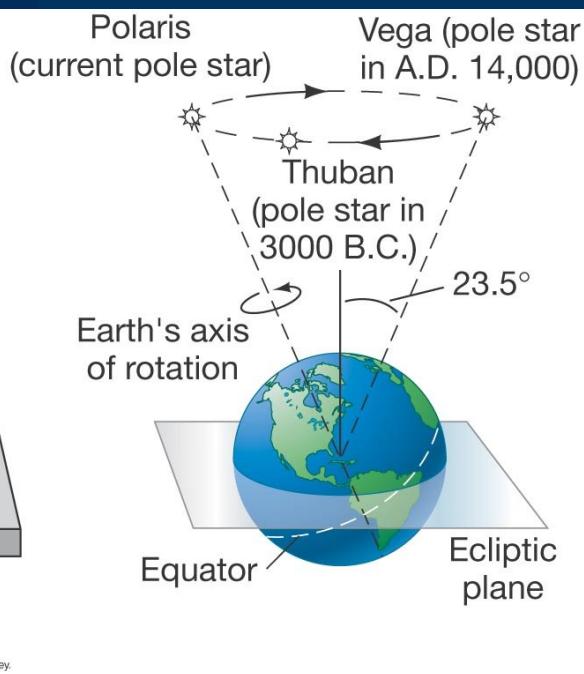


Knowledge of the Ancient Greeks (cont.)

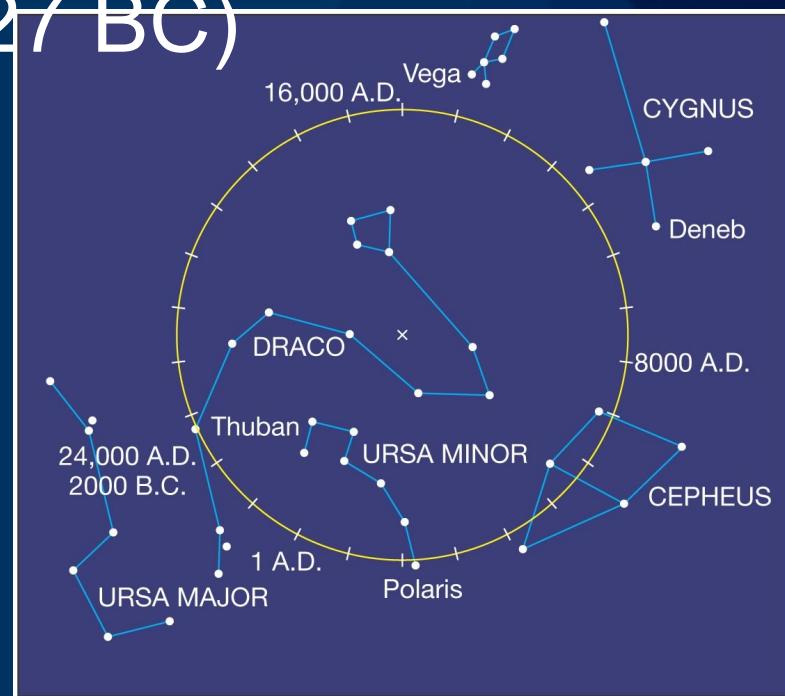
Earth's spin axis precesses with 26,000 yr period (Hipparchus 160-127 BC)



(a)



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.

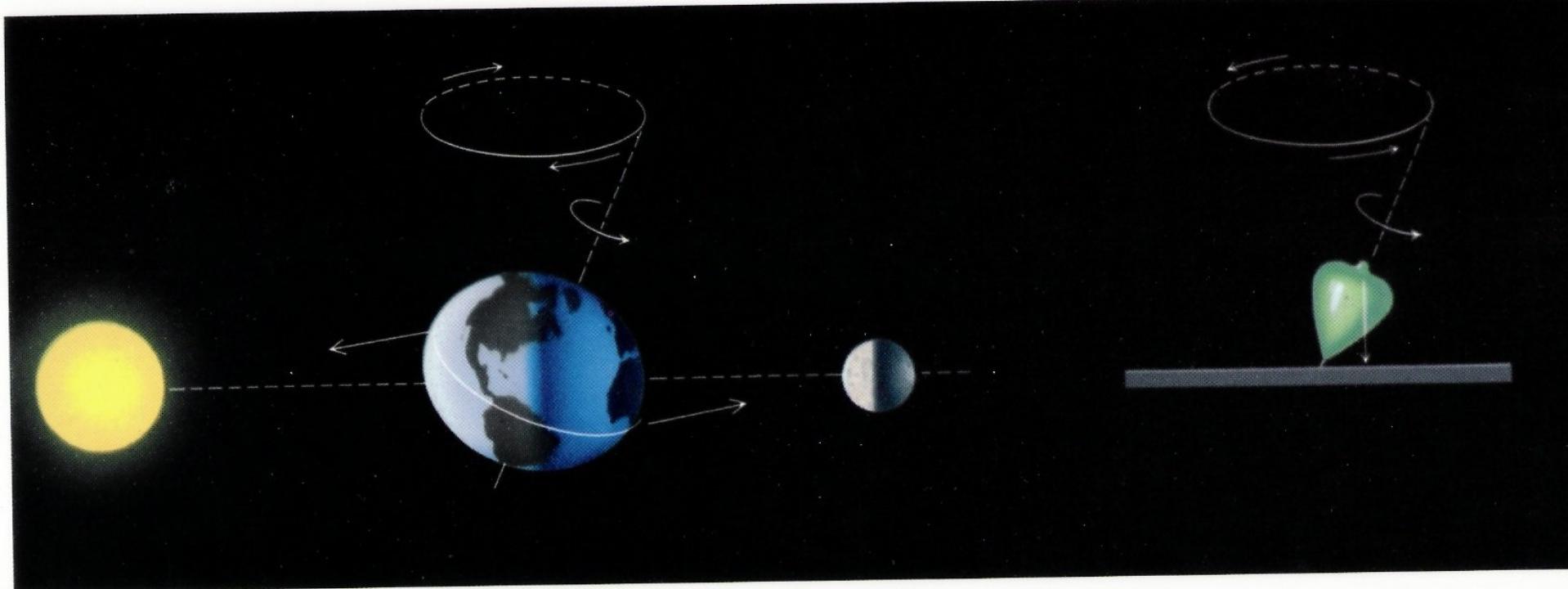


(b)

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.

Knowledge of the Ancient Greeks (cont.)

Cause of precession:



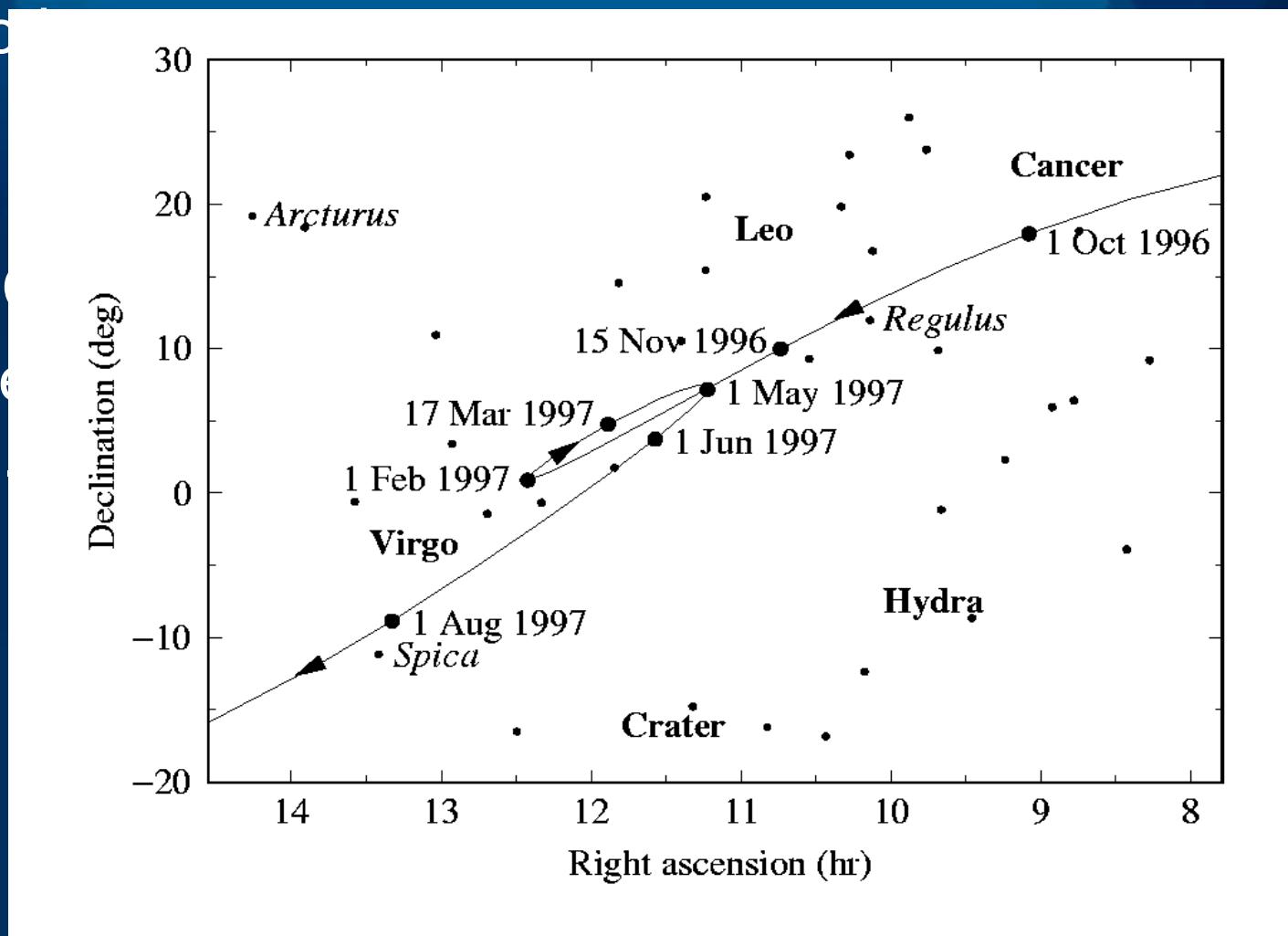
Knowledge of the Ancient Greeks IV

- 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

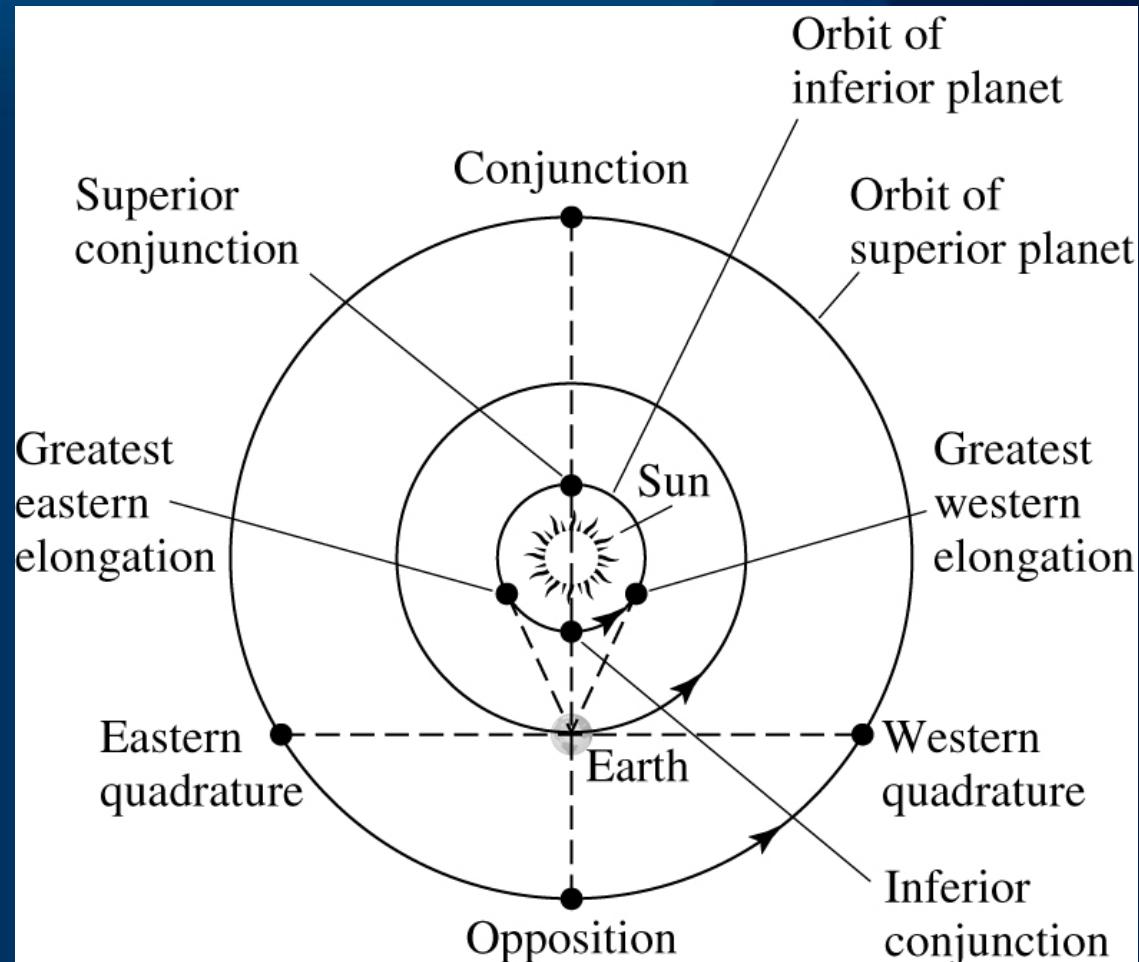
- Daily motion
- Change the sky.
- All orbit the Sun
- Usually called planets
- we call them stars



Retrograde Motion!

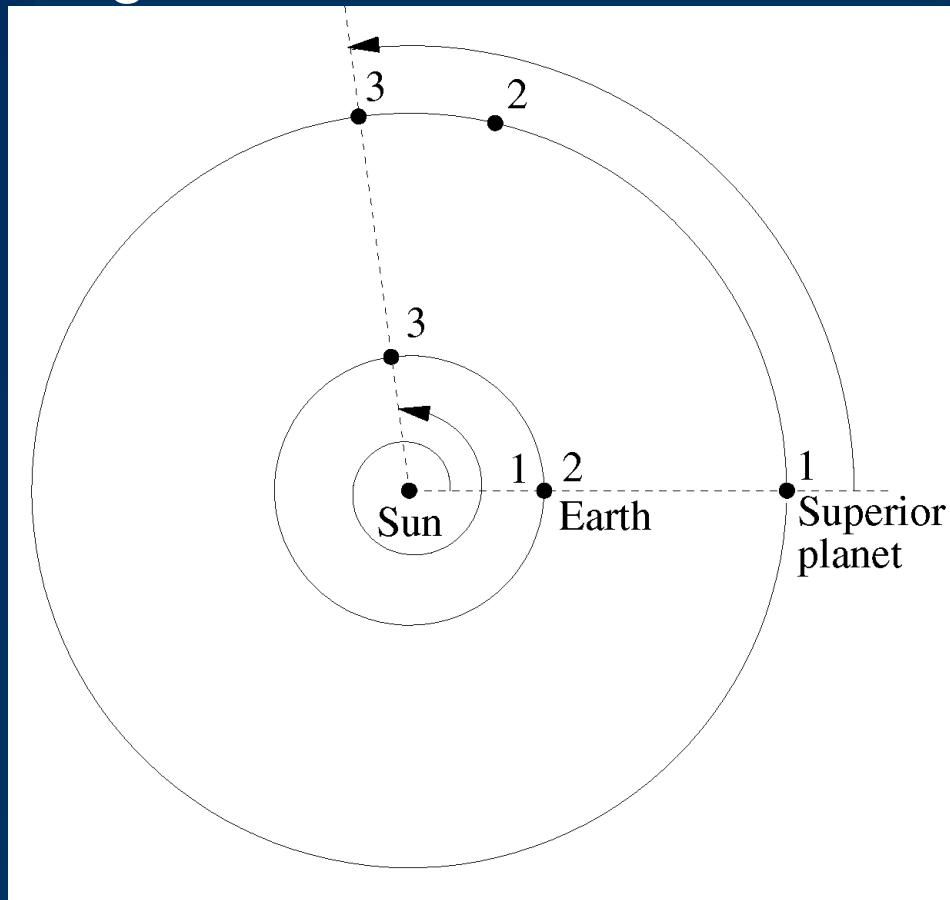
Planetary Configurations

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



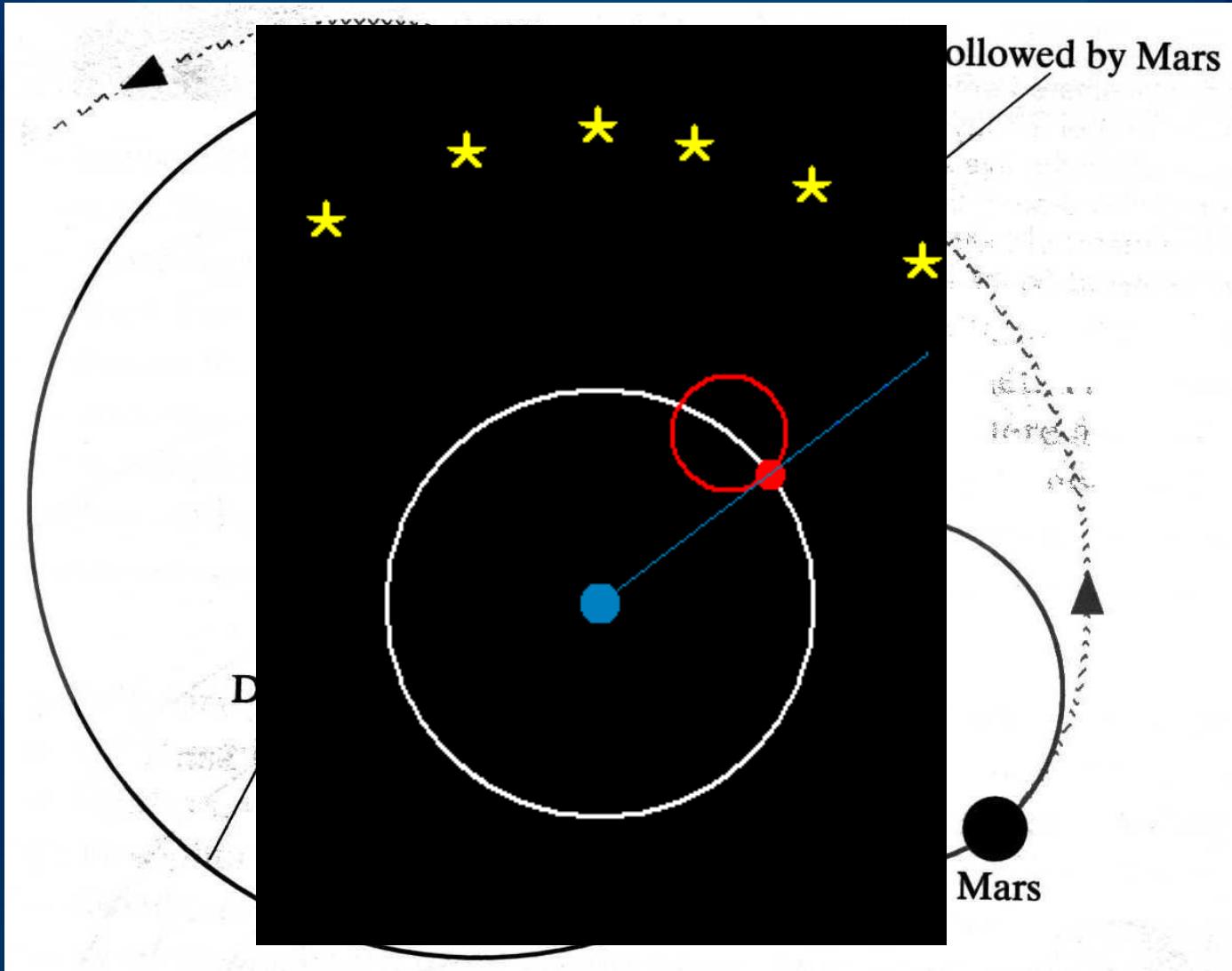
Synodic and Sidereal Periods

- 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



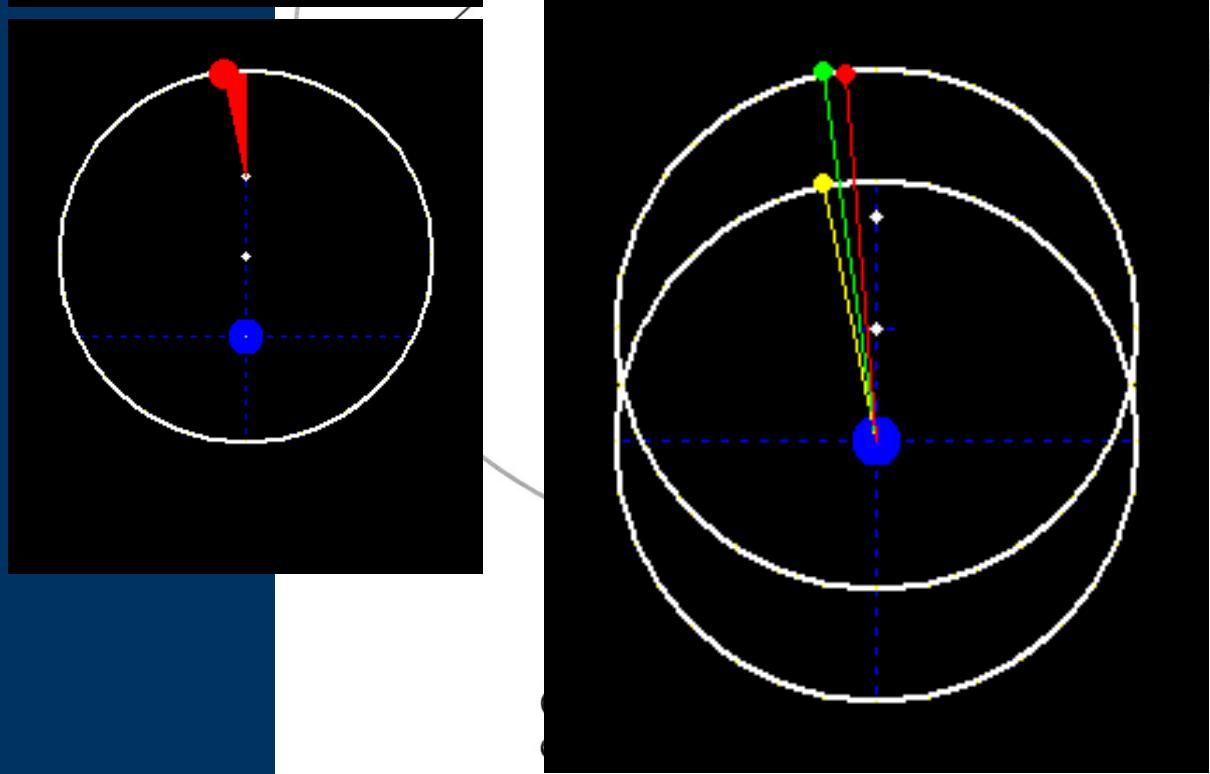
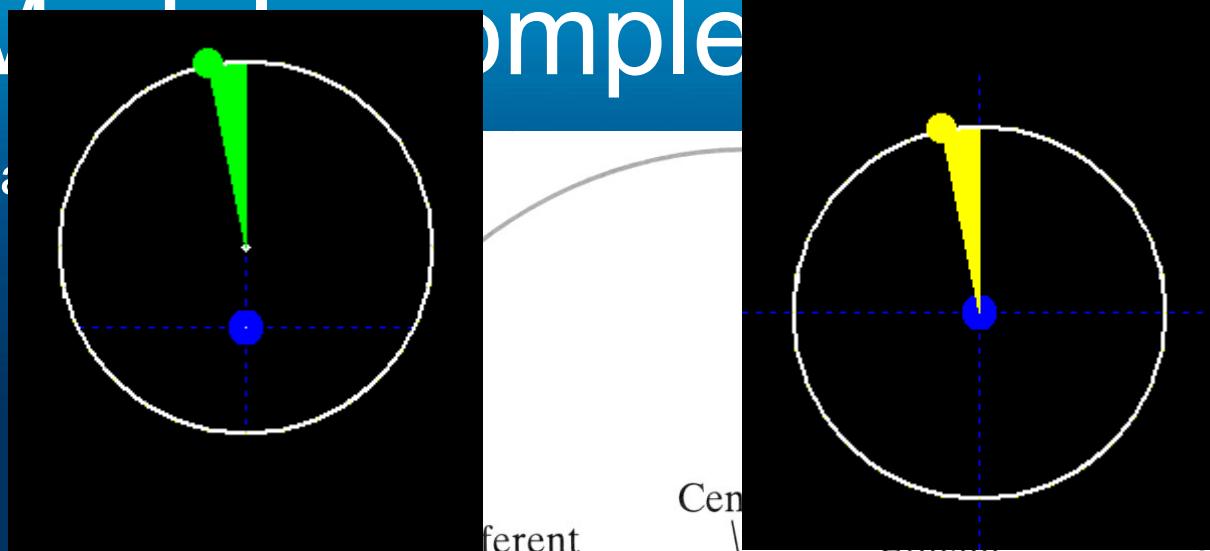
Epicycles on Deferents

- 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



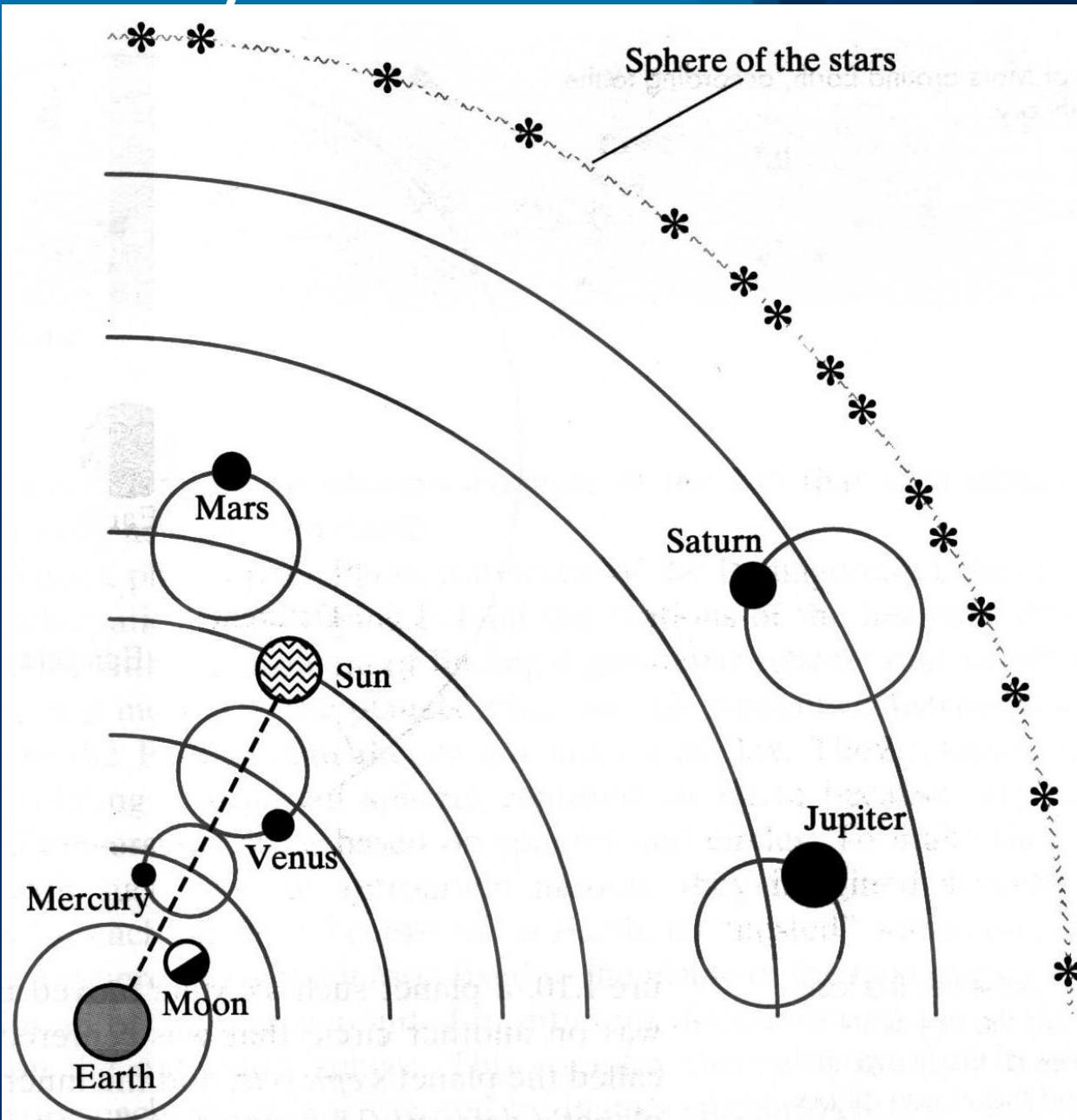
Ptolemy's Model

- 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



· 1632

Dialogue of the Two Chief World Systems

· 1633 Trial at Rome by the Inquisition

· 1642

· 1642

. 1512 1st Comment



. 1543 *De Revolutionibus*

. 1546

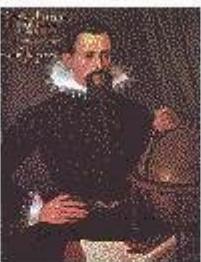
TYCHO BRAHE



. 1601

JOHANNES
KEPLER

. 1571



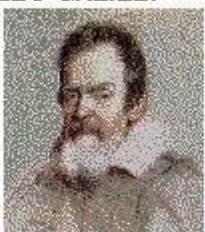
. 1609
New Astronomy

. 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

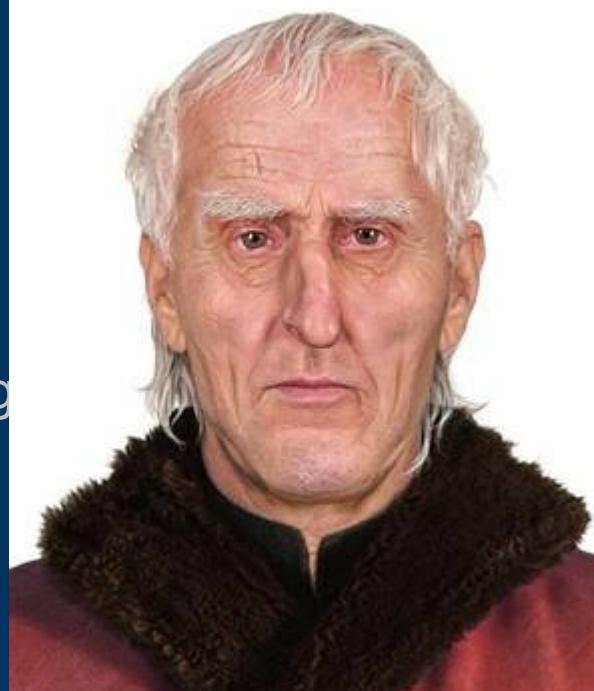
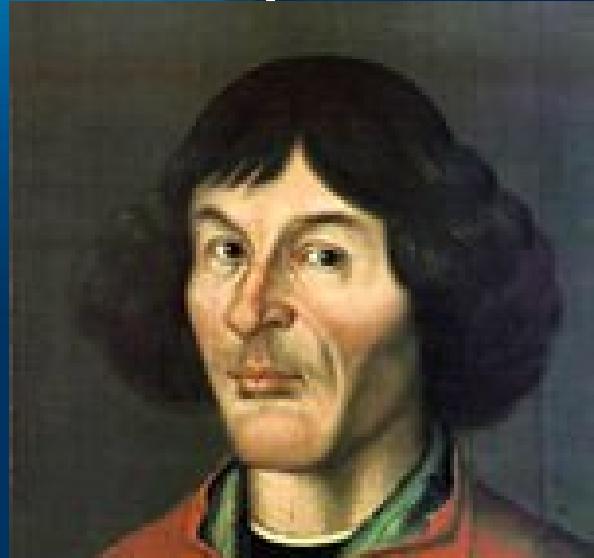


. 1686 *Principia*

. 1727

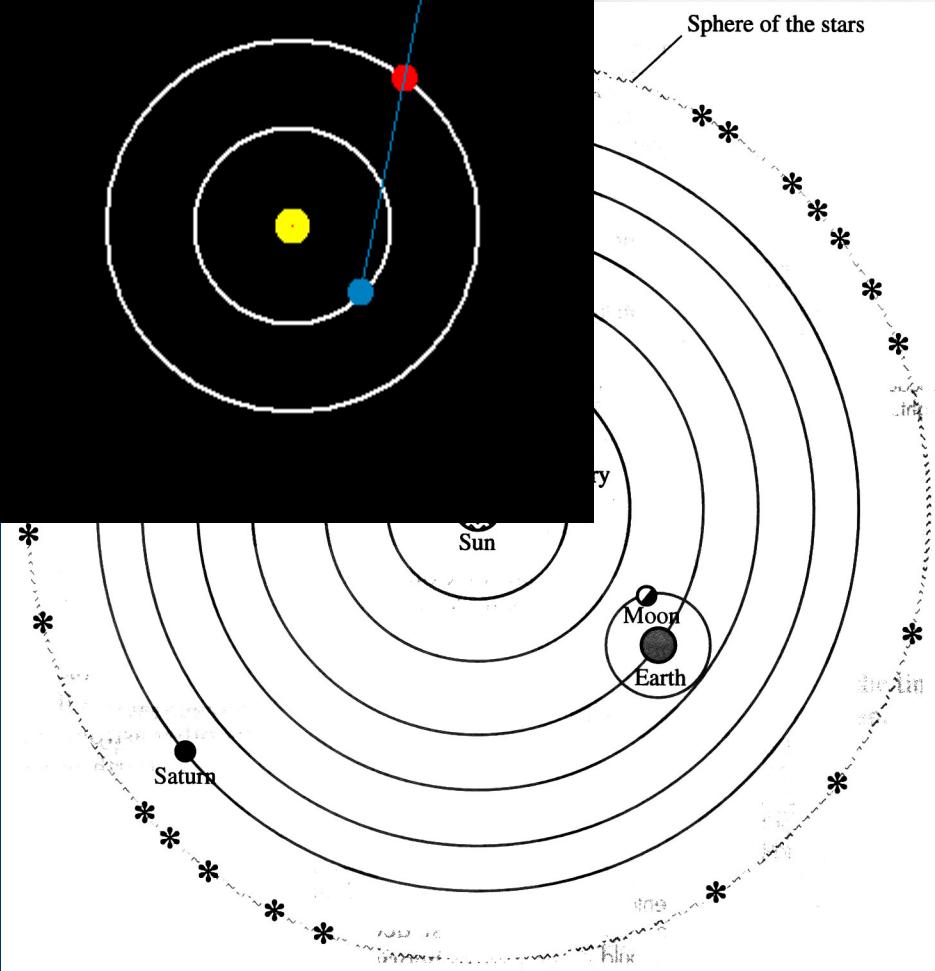
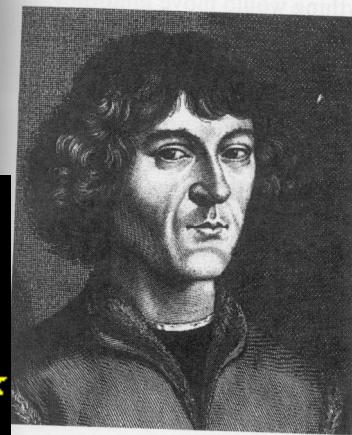
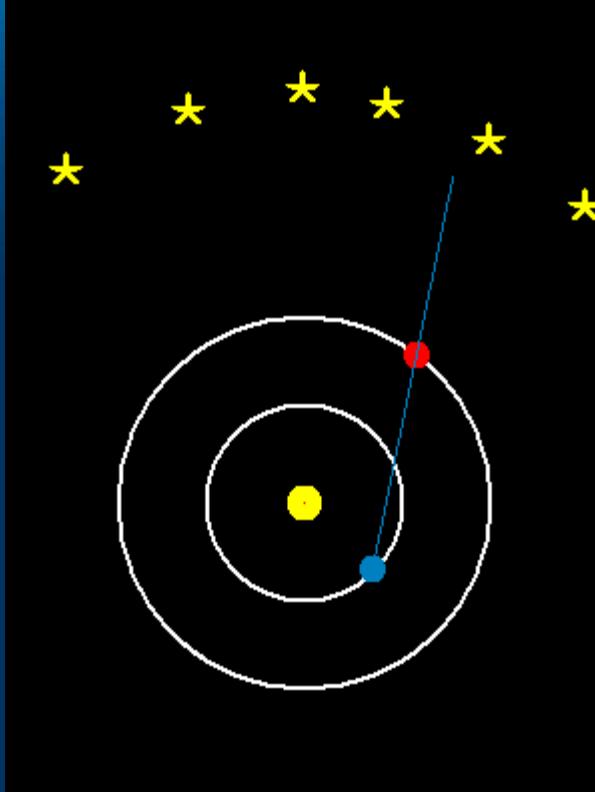
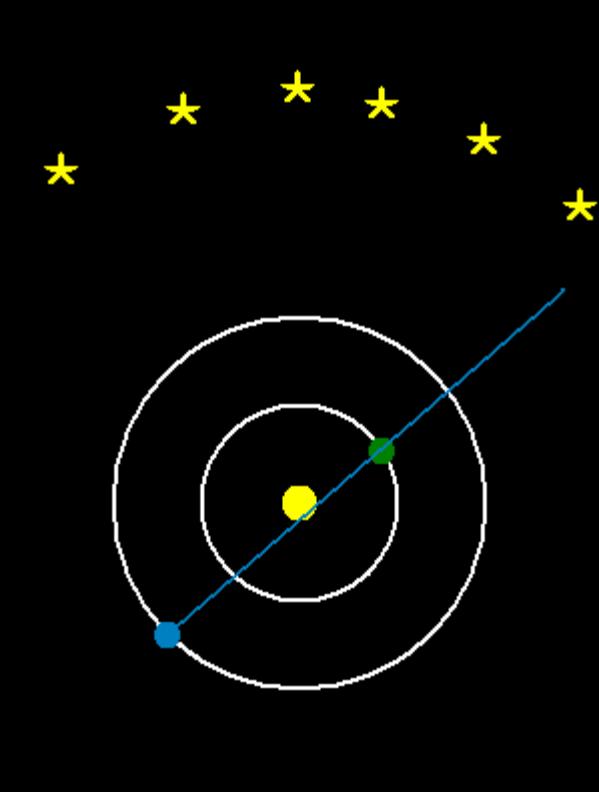
Copernicus (1473-1543)

- Polish Son of 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

- Is there something wrong about the Ptolemaic model?
- Keep some of the Ptolemaic model:
 - spheres
 - uniform motion
- Major Changes:
 - Sun centered
 - Earth moves in a circle
 - Earth is just another planet
- 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

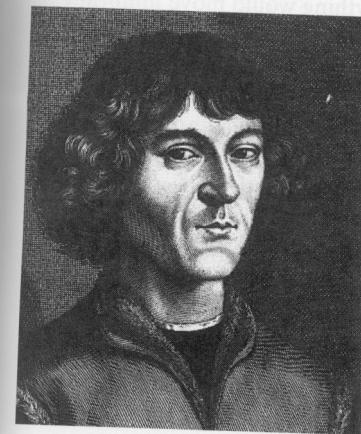
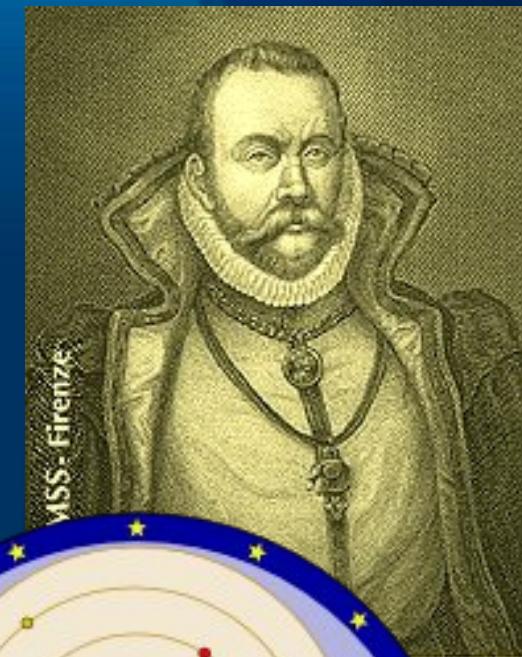


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd 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 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!

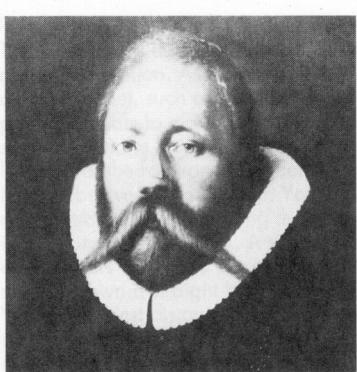


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

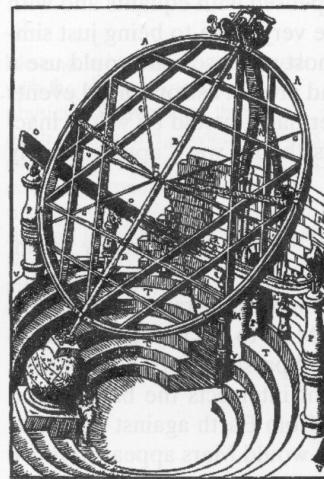


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

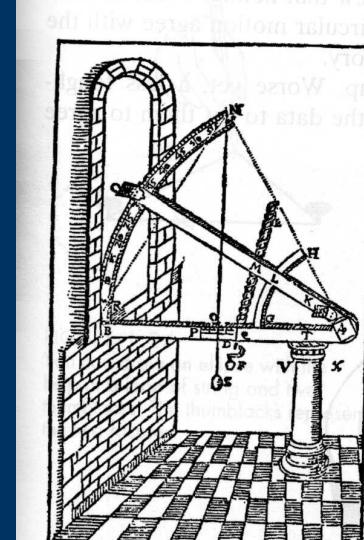


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

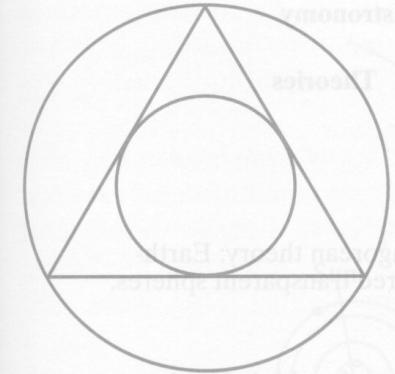
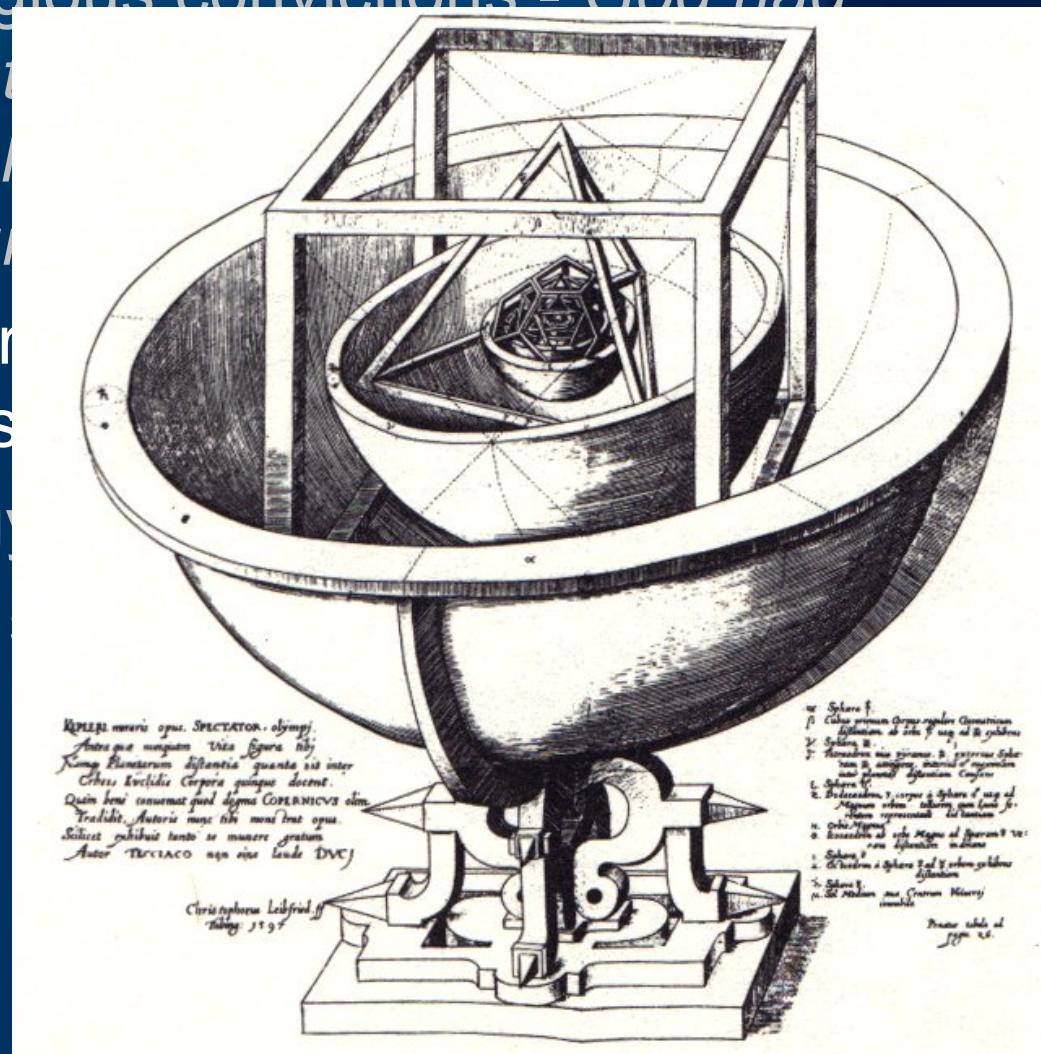


FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

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



Johannes Kepler

- Super
 - Copy
 - Paste
 - Trie
 - AVL
 - Itinerary
 - Range
 - KMP

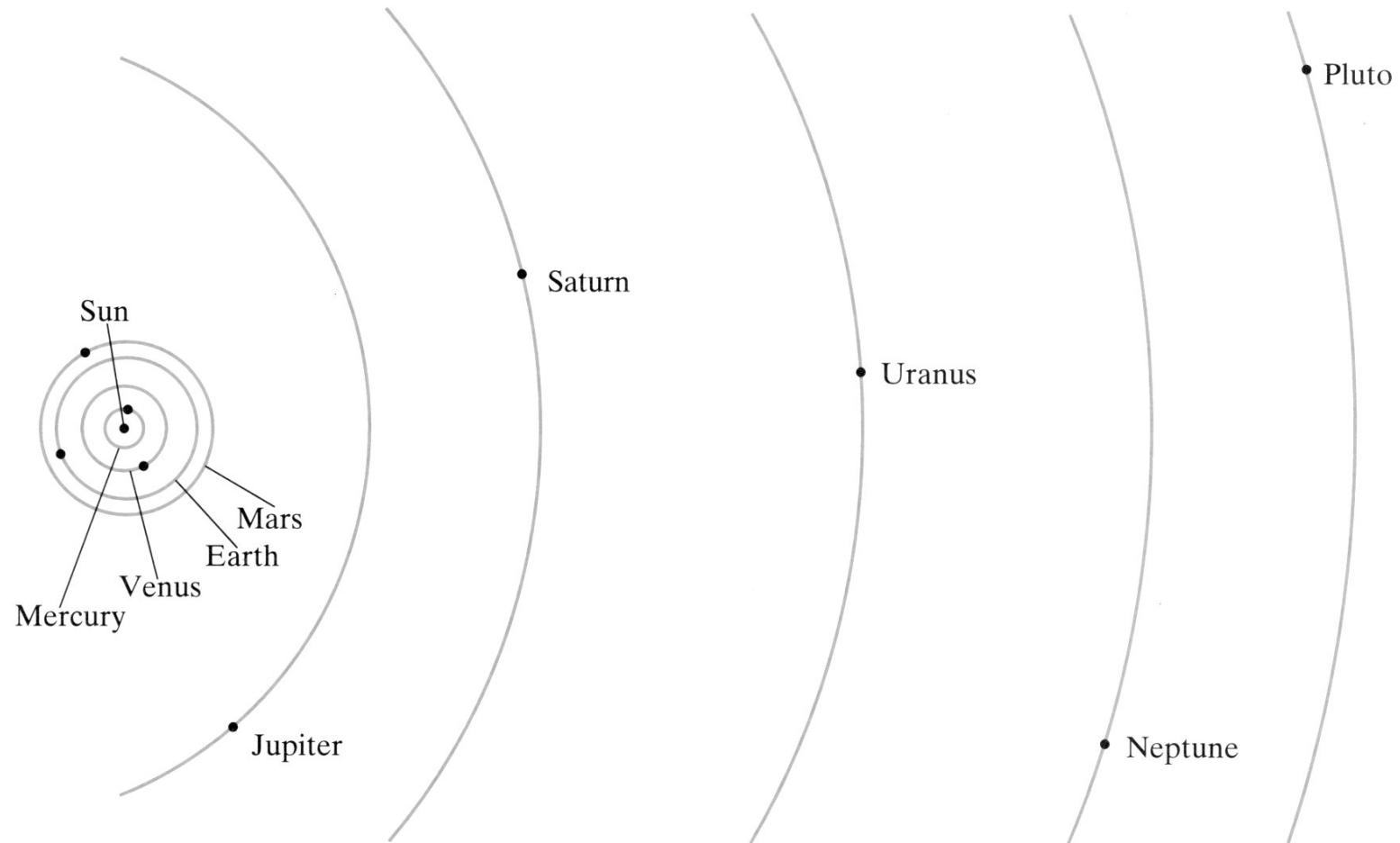
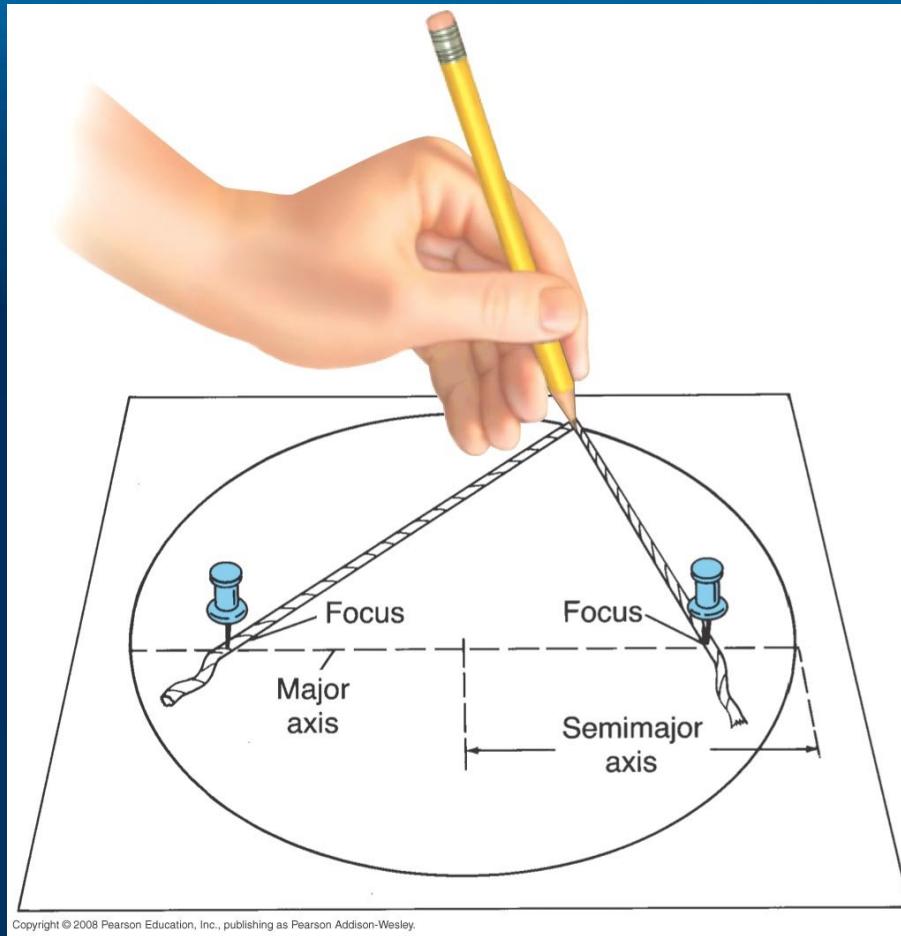


FIGURE 1.26

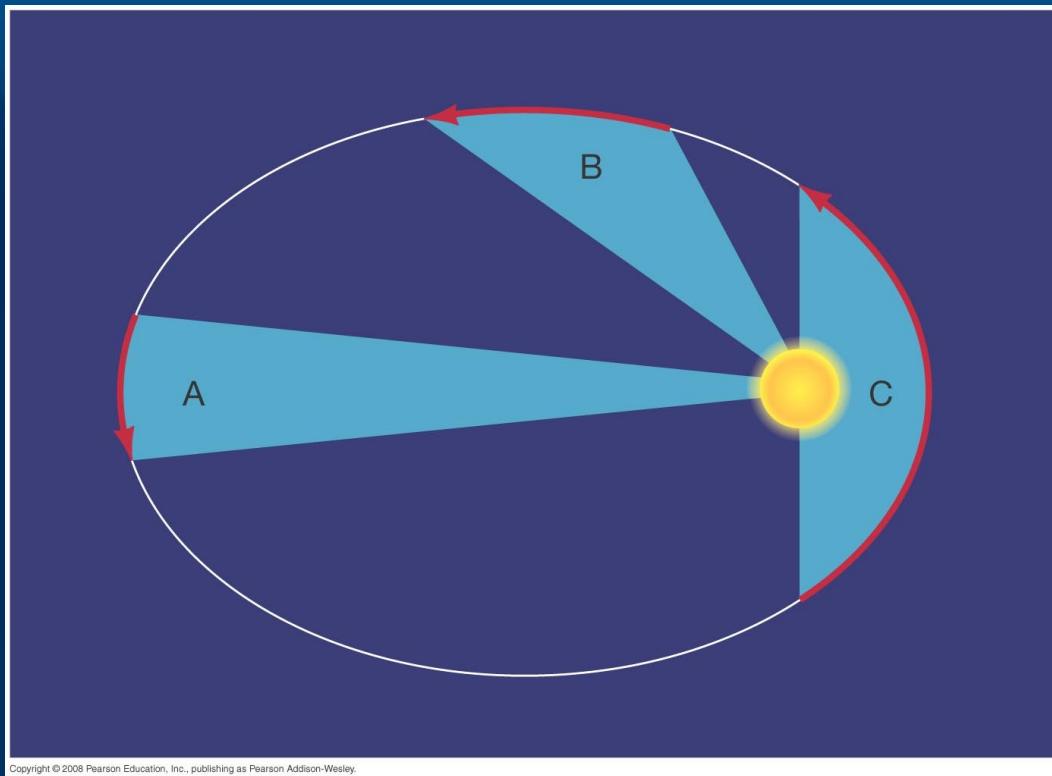
The arrangement of the solar system as it is now known. Uranus, Neptune, and Pluto are visible only with a telescope. The orbits are elliptical, although their ellipticity is too small to be visible in this diagram.

Kepler's 1st law



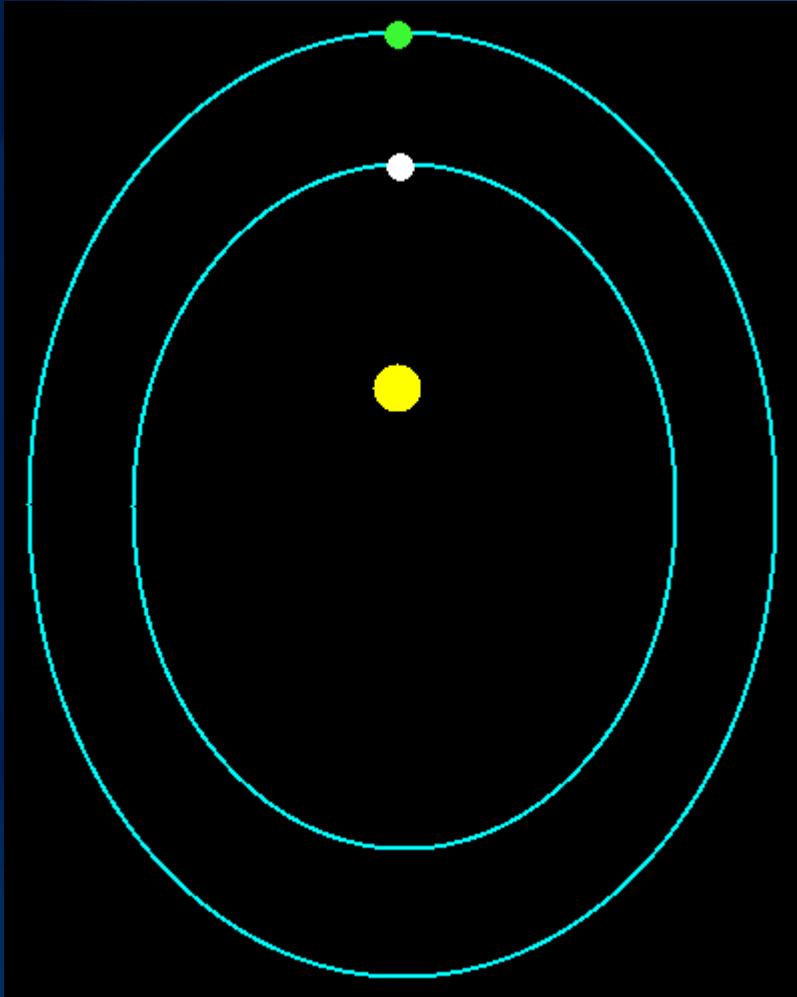
The planets follow elliptical paths with the Sun at one focus.

Kepler's 2nd Law



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

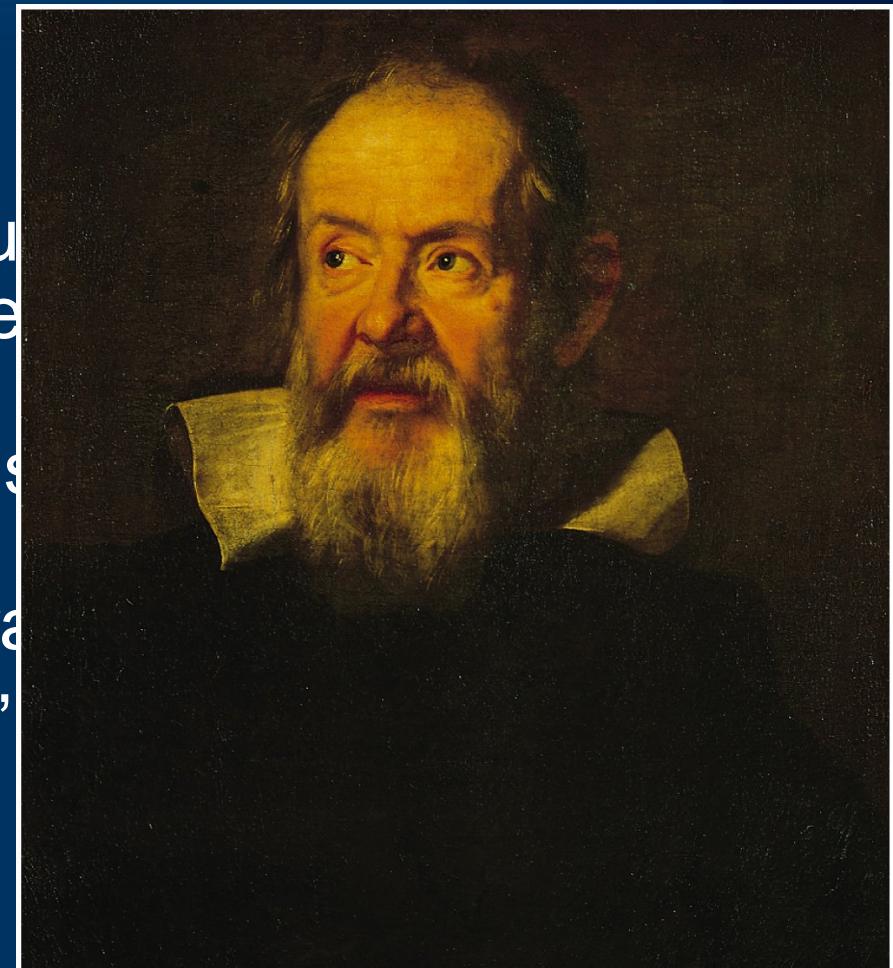


$$P^2 = a^3$$

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 Ju
 - Phases of Venus include
 - Spots on Sun
 - Milky Way resolves into s
 - Saturn has ears?
 - Moon has mountains, cra
- “Father of Modern Physics”



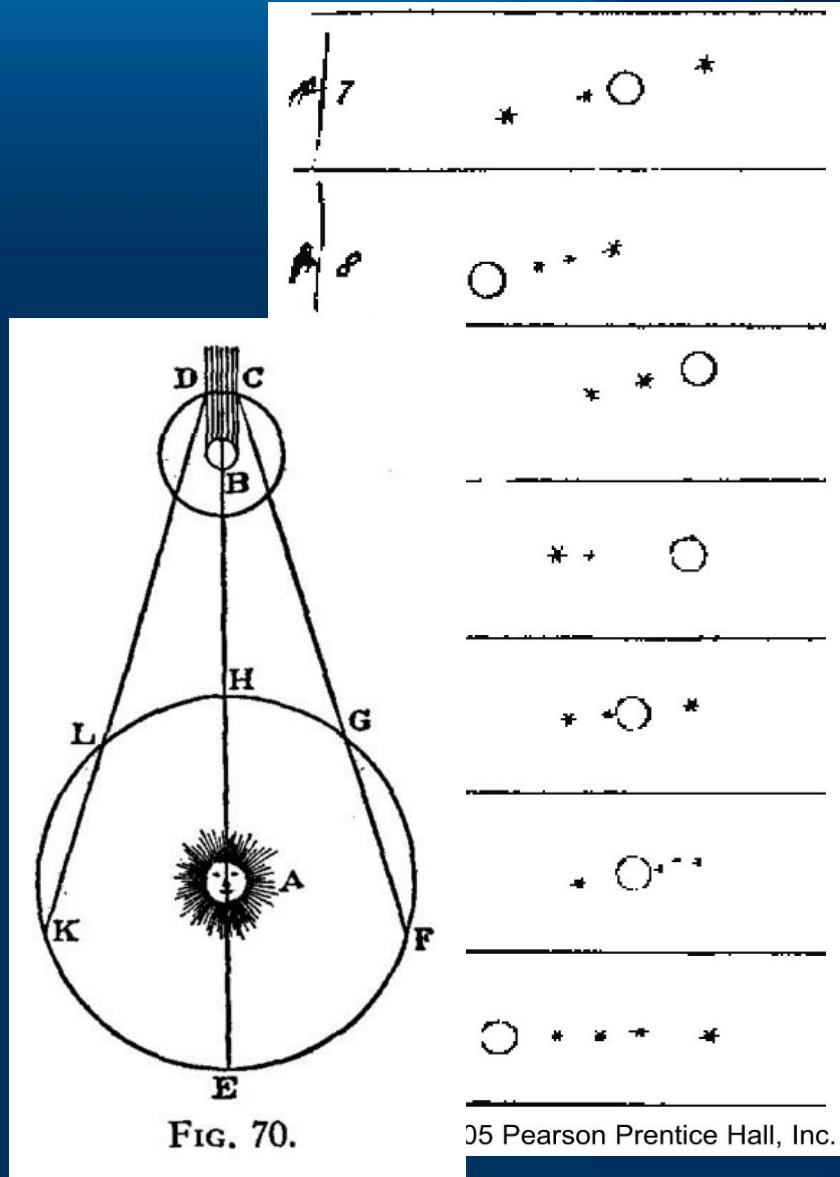
Galileo and Jupiter

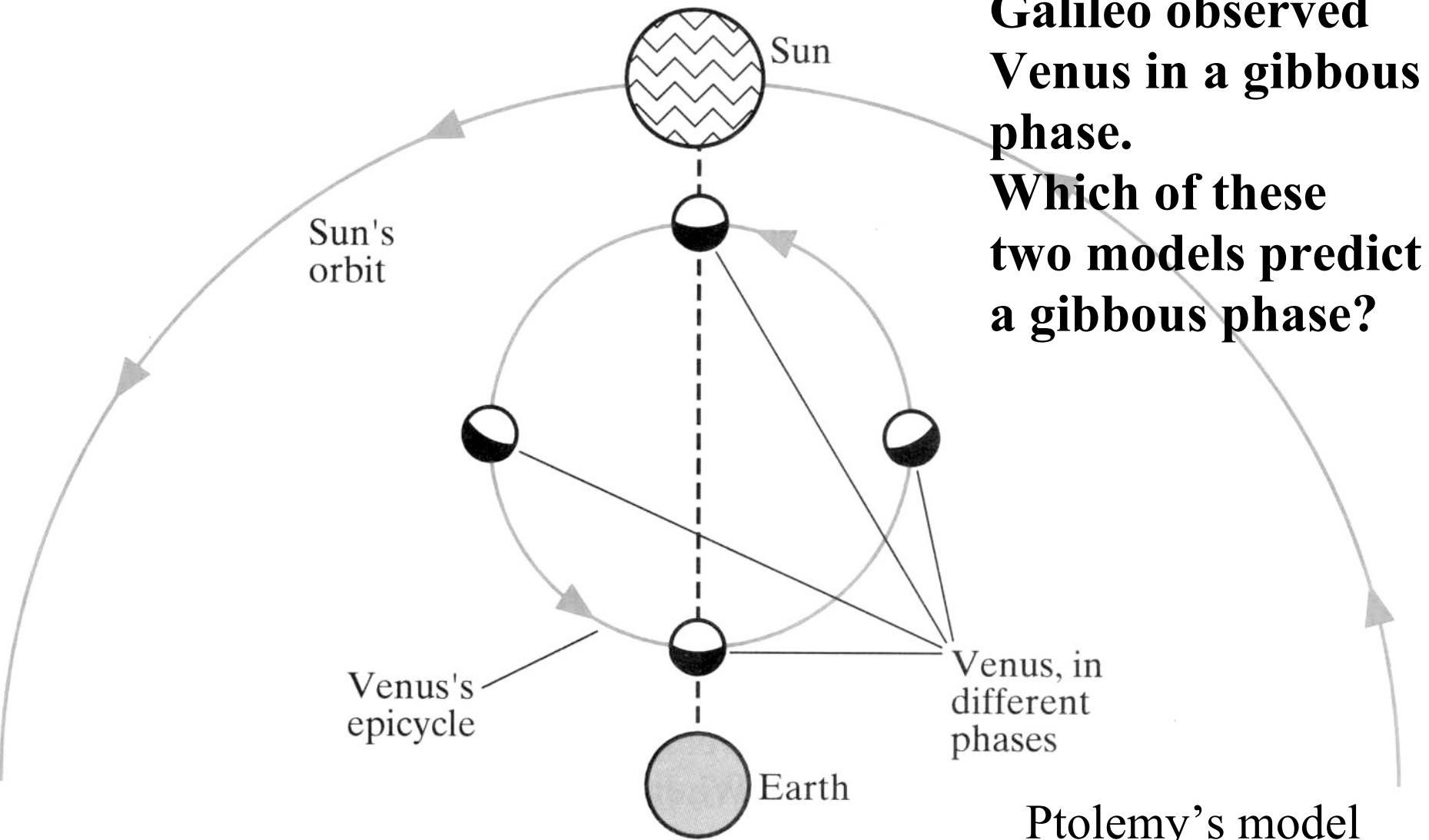
The “Galilean Moons”: Io, Europa, Ganymede, and Callisto.

Not everything orbits the Earth!

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

Ole Roemer 1677





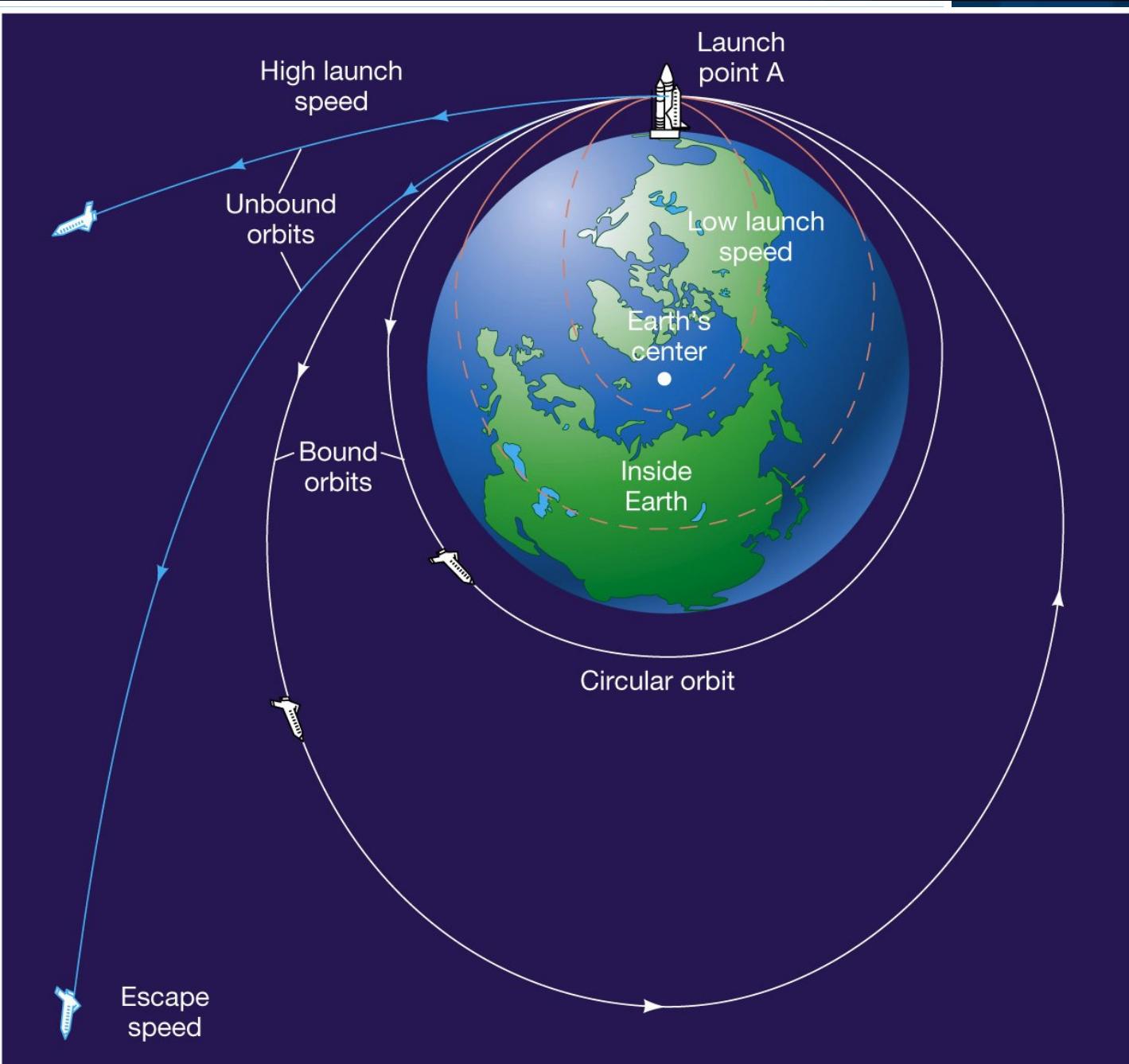
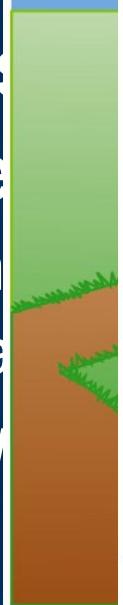
**Galileo observed
Venus in a gibbous
phase.
Which of these
two models predict
a gibbous phase?**

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 Newton to publish his *Philosophy of Nature*
- 3 laws of motion
- Universe
–Canal
–Finance
- “God governs or can’t”



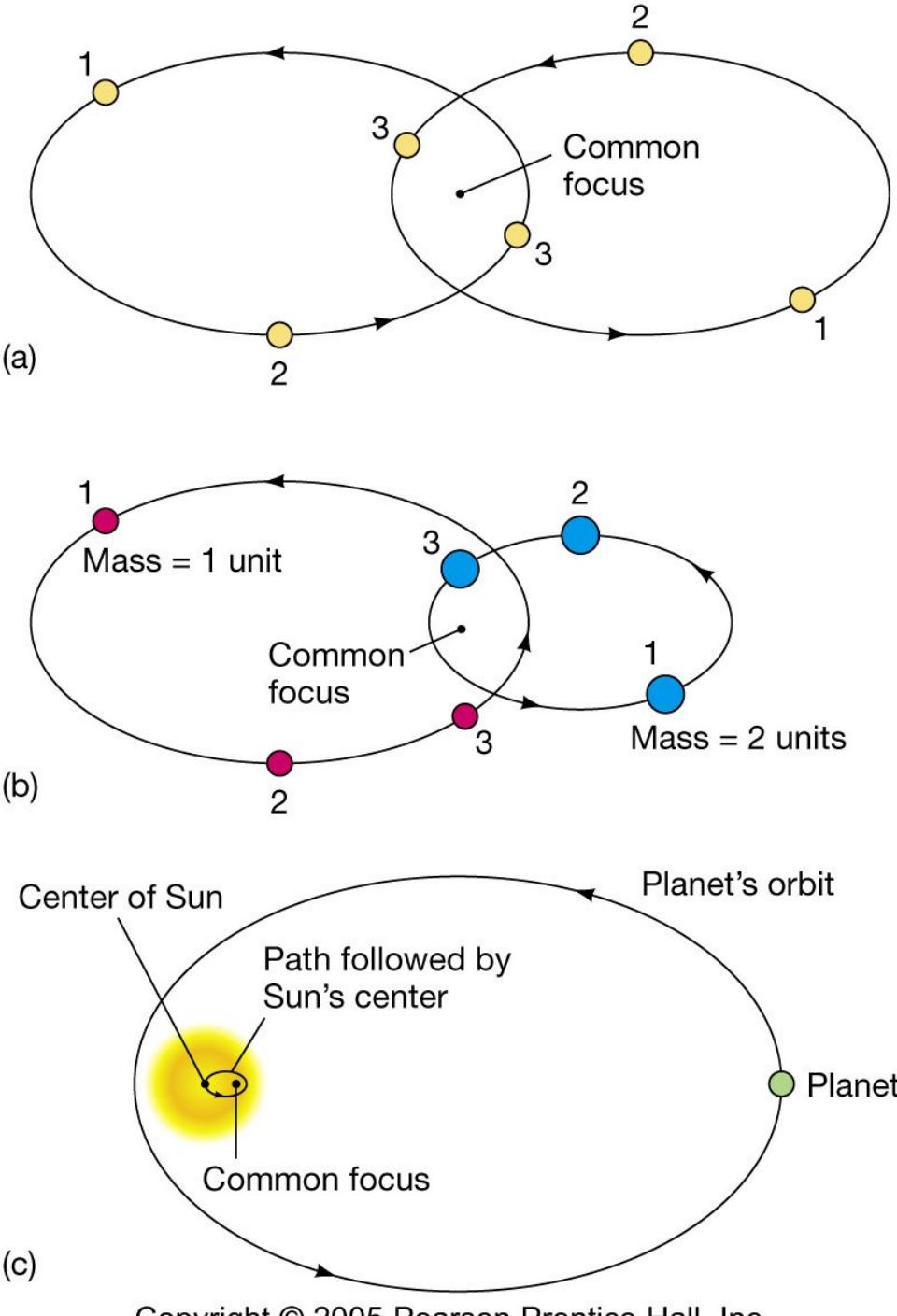
Copyright © 2005 Pearson Prentice Hall, Inc.

Copyright © 2005 Pearson Prentice Hall, Inc.

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.*”

- Kepler I: with the planet of mass of 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

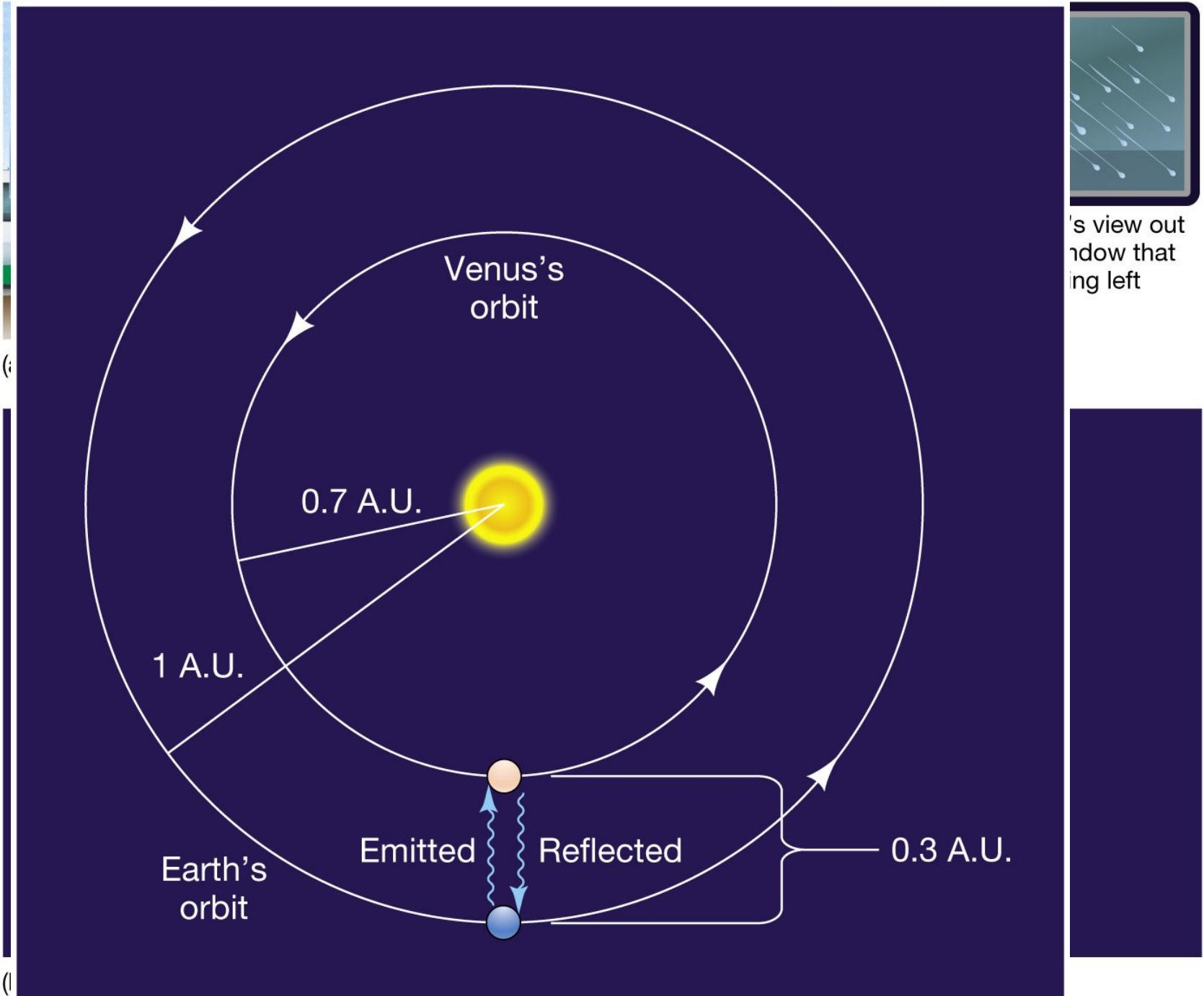
Revived the heliocentric model



F

• V

• W

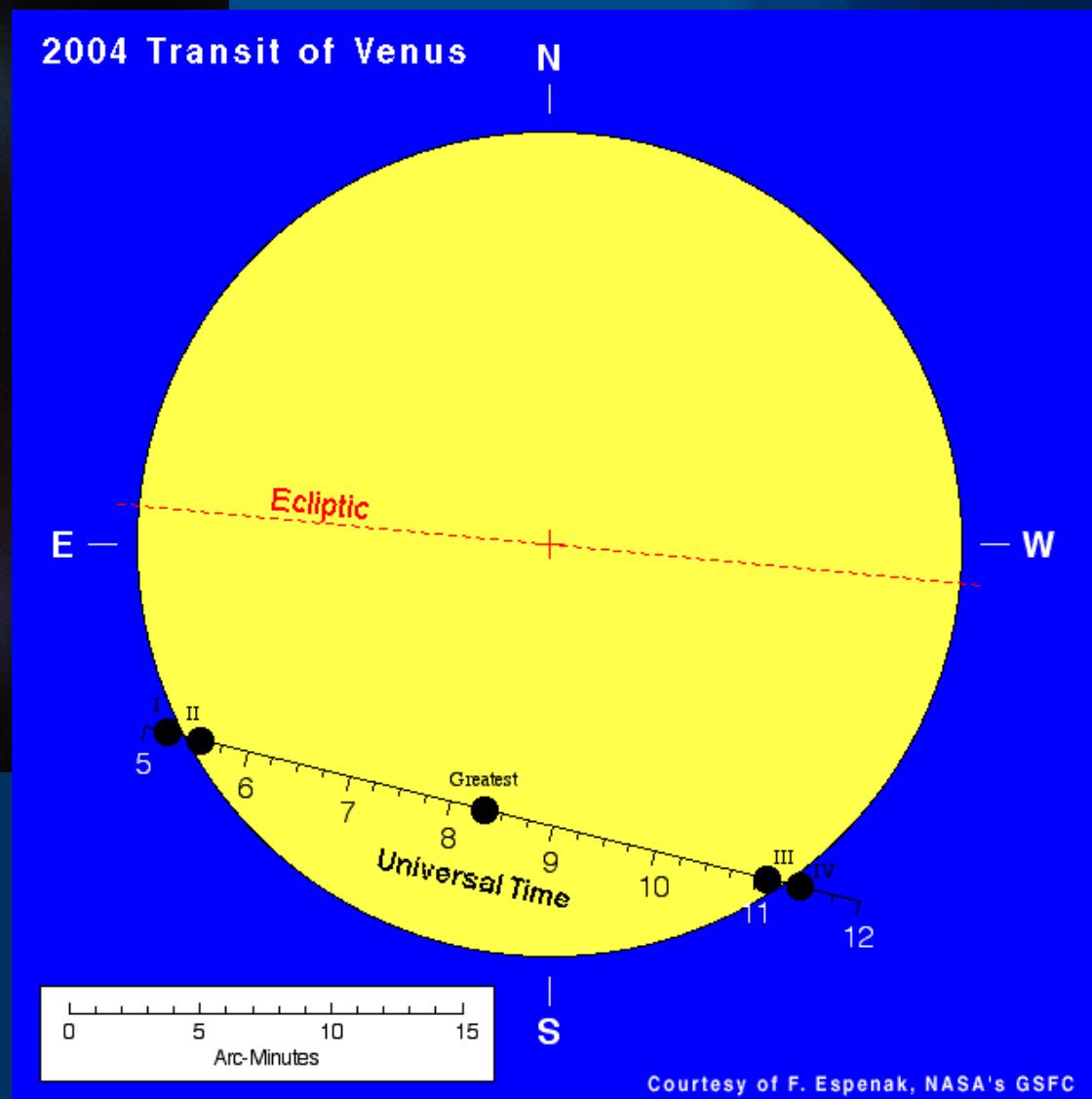


's view out
window that
ing left

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



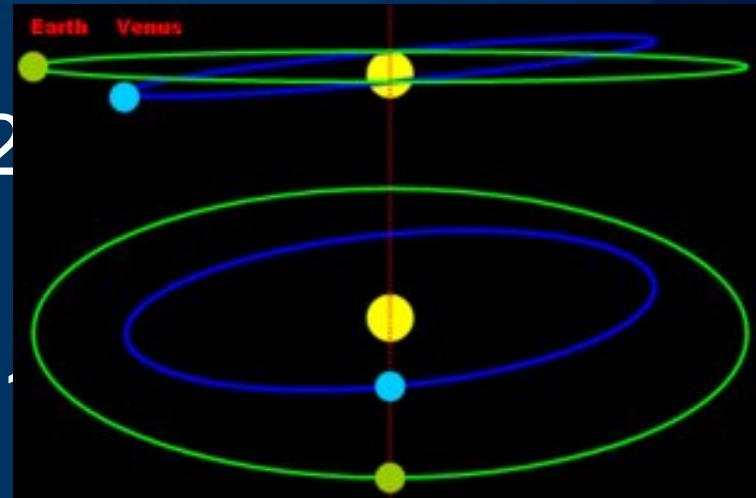
Transits of Venus

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

Last transit: June 6, 2012

Next transits: 2117, 2125

How it works: 3.4° tilt, 8:1
243 yr cycle.



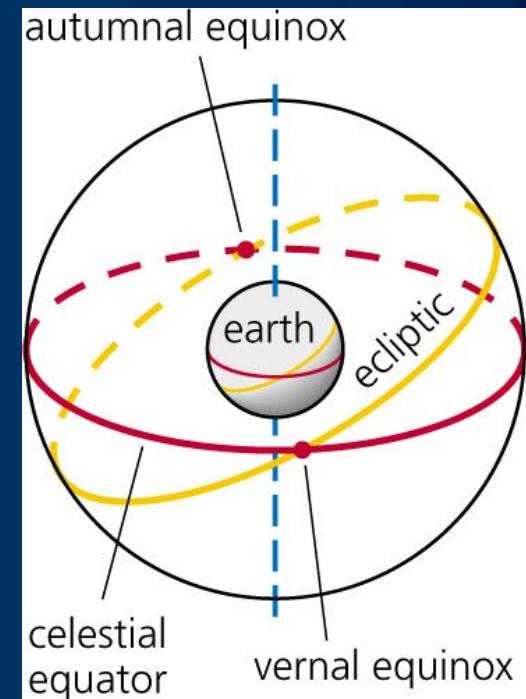
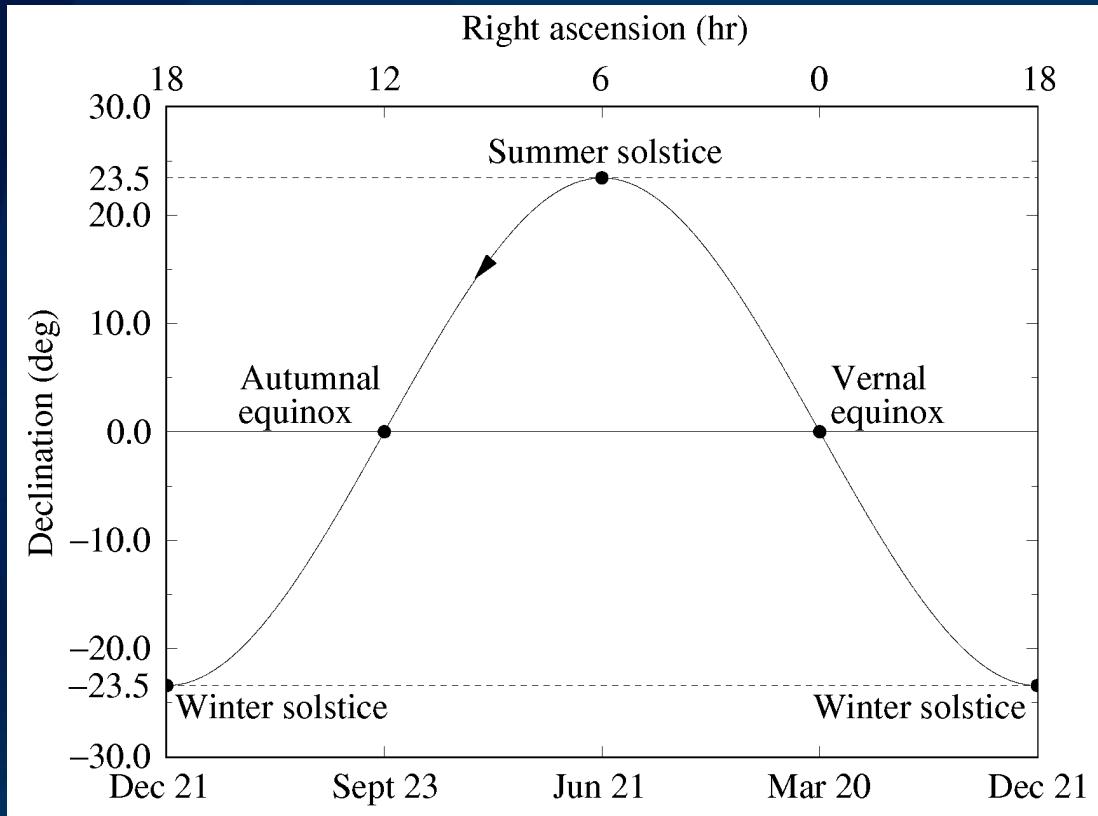
Inferior conjunction while both planets on
line
of nodes.

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

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

