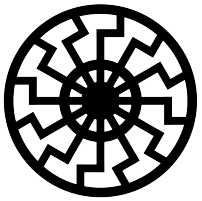
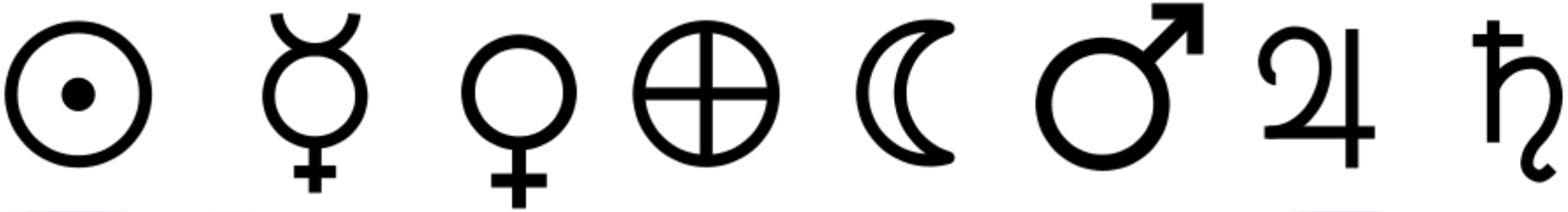
The Copernican Revolution - Separating Science and Superstition



J. Pinkney

ONU 2014



Outline

- Our universe viewed by the ancients
- Greek cosmological models
- Copernican Revolution
  - Nicolaus Copernicus
  - Tycho Brahe
  - Johannes Kepler
  - Galileo Galilei
  - Isaac Newton
-

What the Ancients Knew

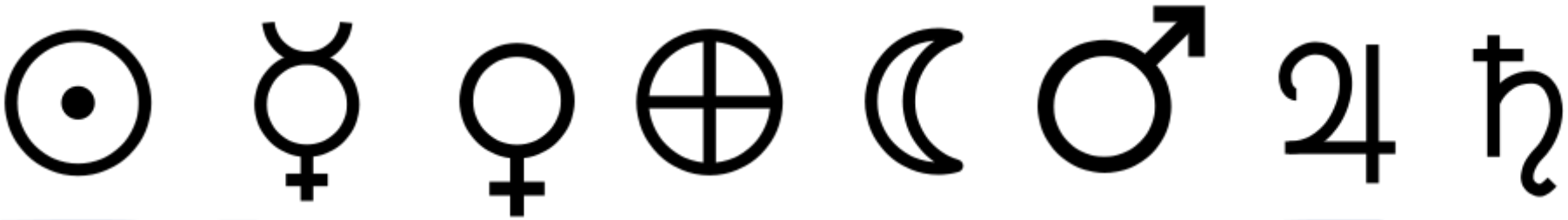
The Naked-Eye Universe

- 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



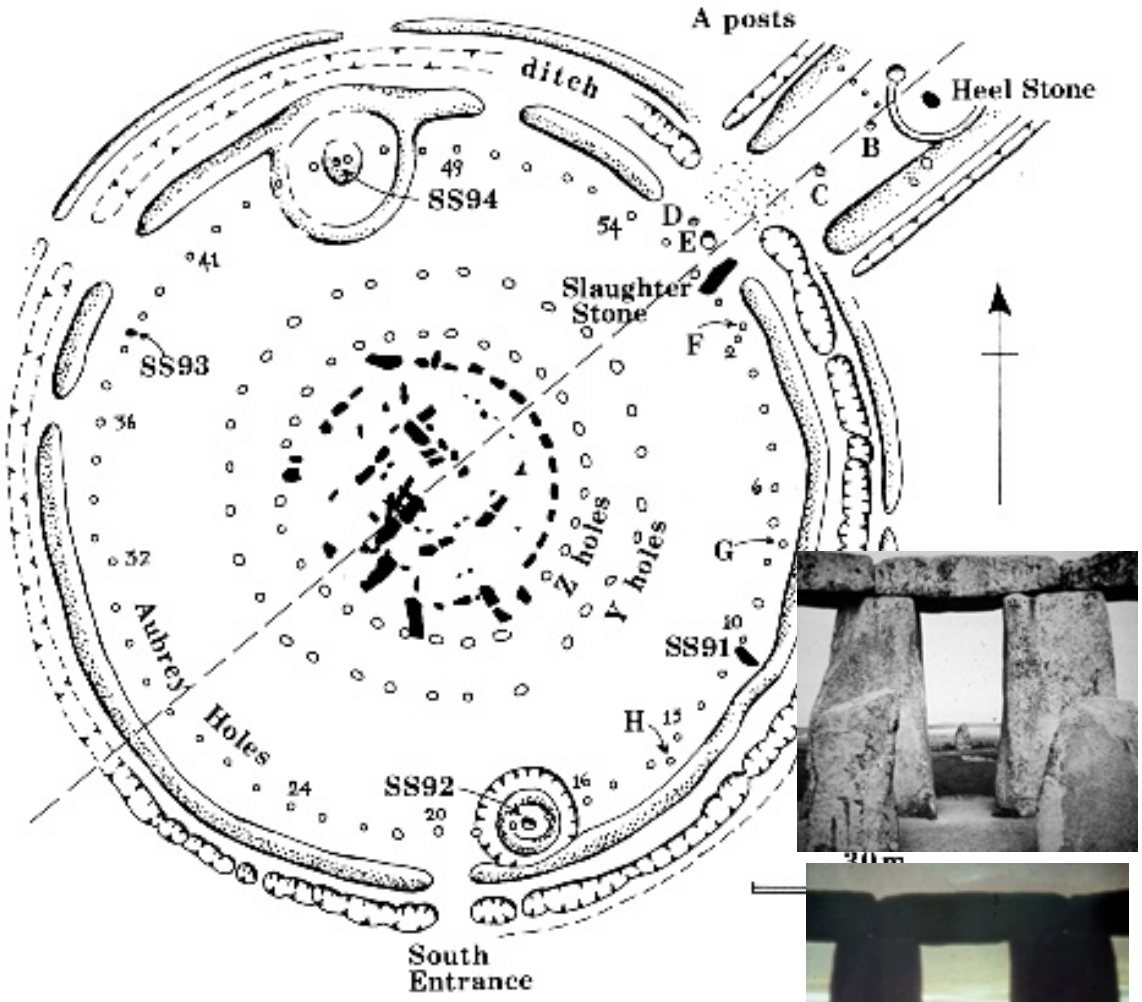
What the Ancients Knew

- Mysterious cultures
  - –People of stonehenge, Plains Indians, Anasazi, 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

- Building Phases::
- 2950 BC – 1600 BC (3 I



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

(a)

(b)

(c)

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

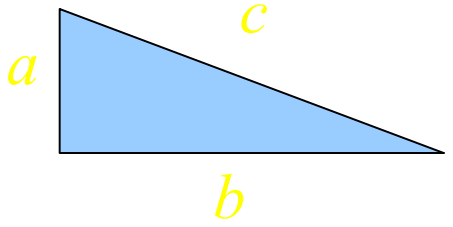
What the Ancients Knew

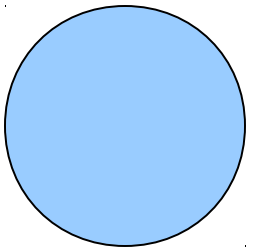
- Well documented cultures
  - Chinese: comet records, zodiac, "year of the ____"
  - Sumerians/Babylonians: 1st alphabet, ziggurats, origin of western astrology, planetary rise times, math (60 subdivisions)
  - Egyptians: gods like Ra and Osiris, pyramids, Nile flooding
  - Arabs: upheld astronomy during dark ages, algebra, star names. Semantic distinction betwe astronomy and astrology – 1000 AD!
  - ► All made astronomical measurements
  - ► All had forms of astrology

Unknown nature → superstition → a rology.

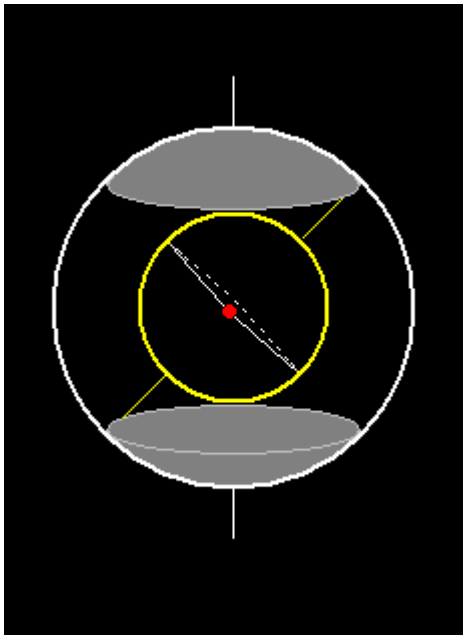
Knowledge of the Ancient Greeks I.

- 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.



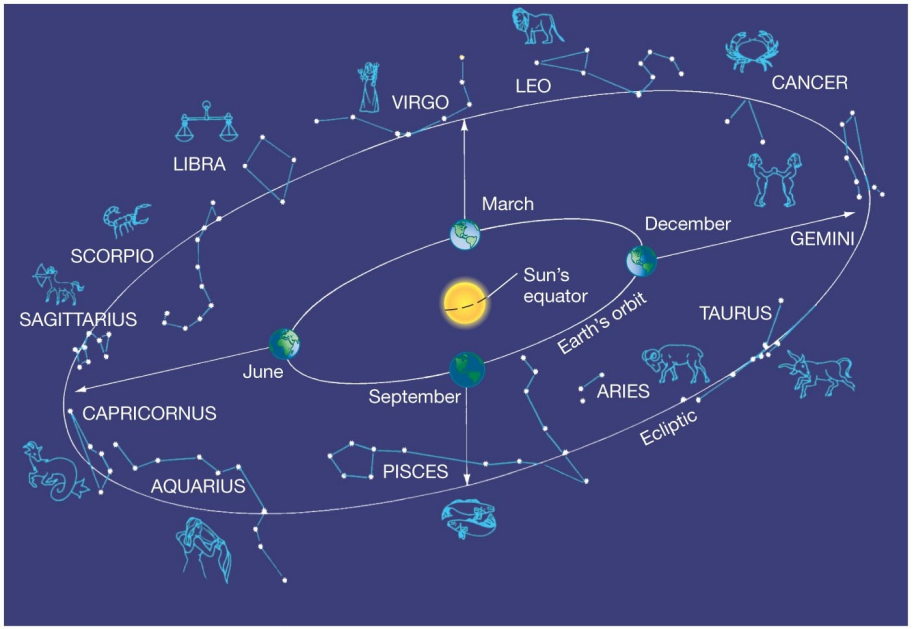
- Eudoxus of Cnidus (390-337 BC):
  - Nested (crystalline) sphere model
  - 27 spheres total, lunar node cycle.

- 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.

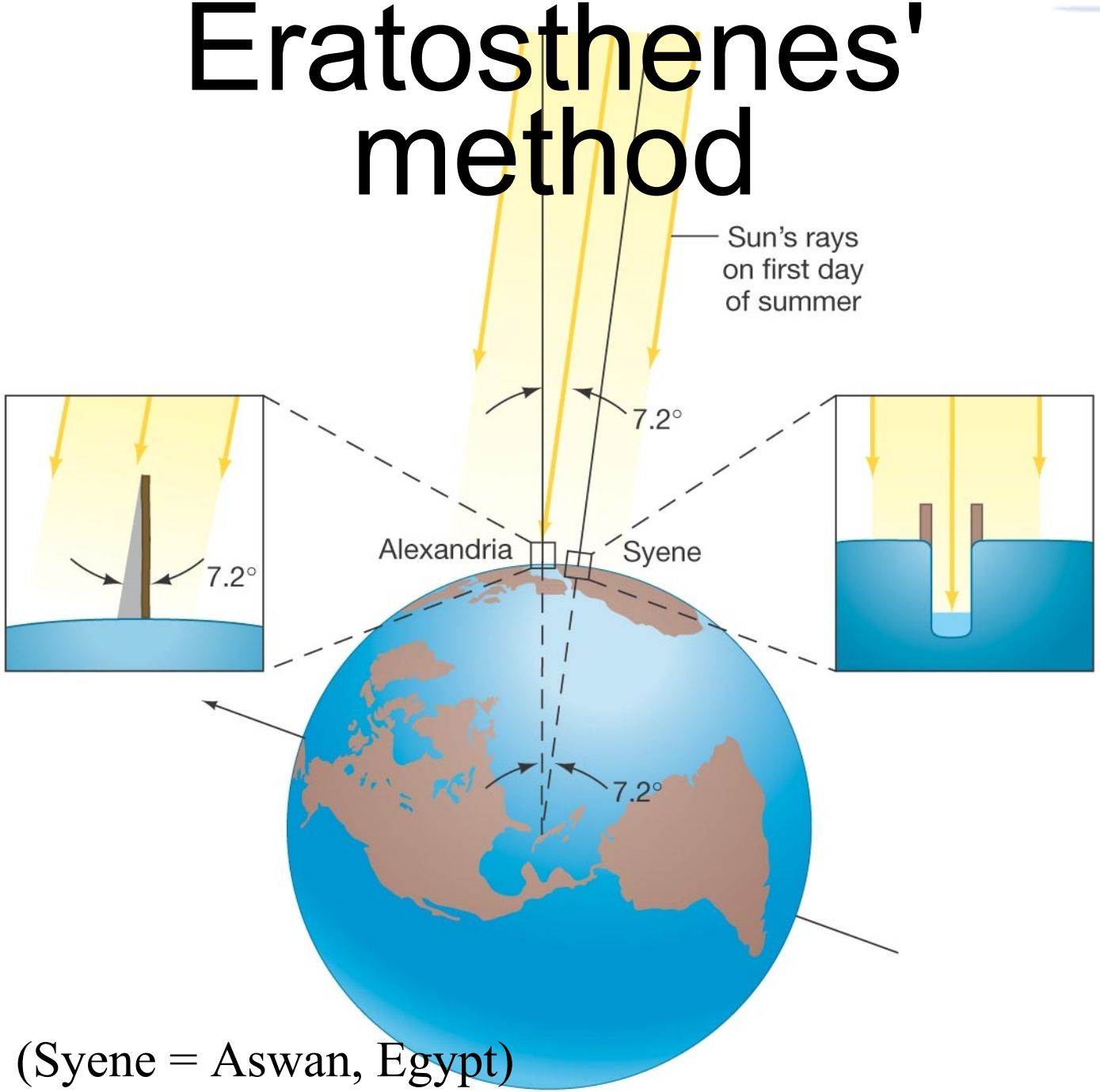
Stellar parallax – apparent motion of foreground stars due to Earth's orbital motion. (Typically <~ 0.1", biggest ~1.0" Proxima Cen.)



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 eccentrics in modelling motion of Sun and Moon.

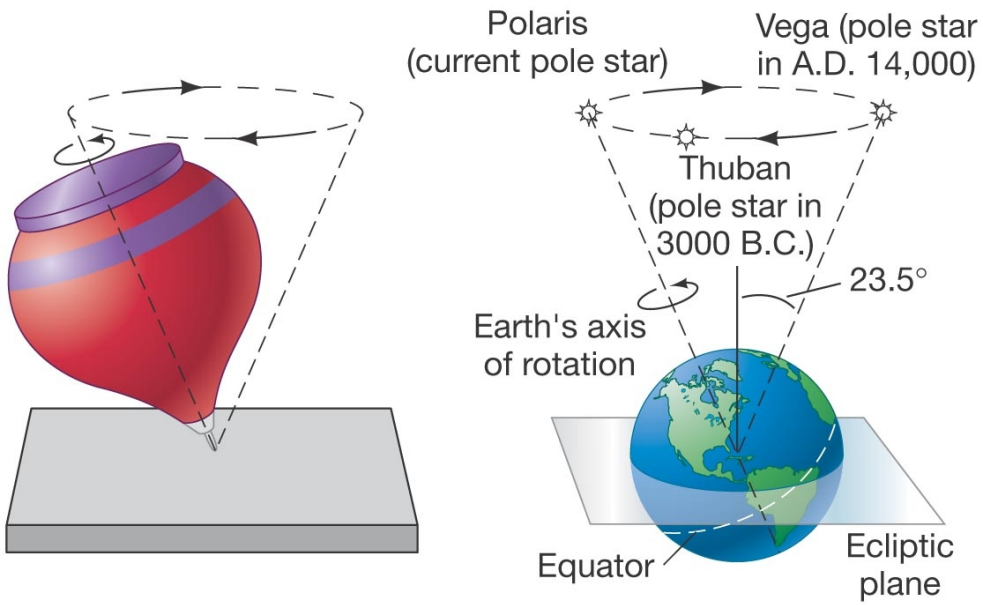
Eratosthenes' method



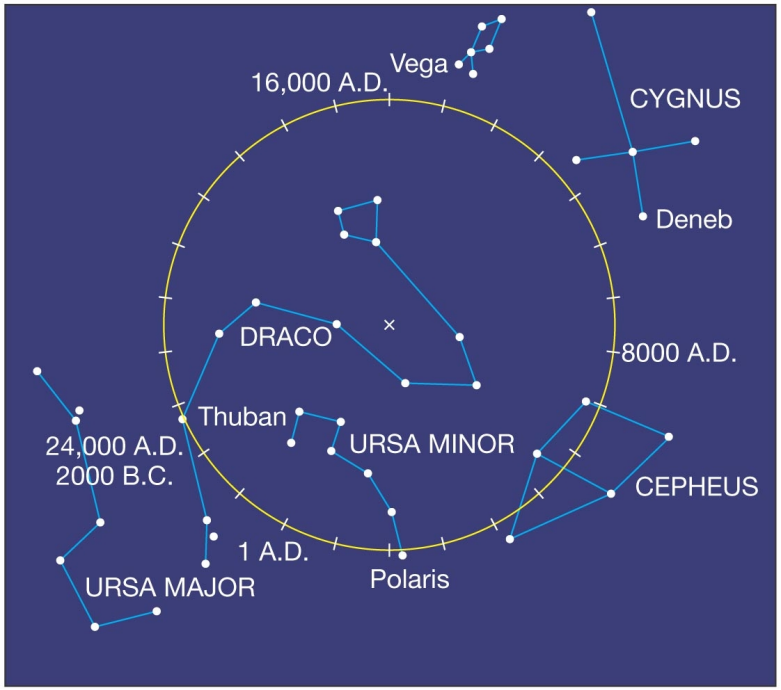
(Syene = Aswan, Egypt)

Knowledge of the Ancient Greeks (cont.)

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



(a)

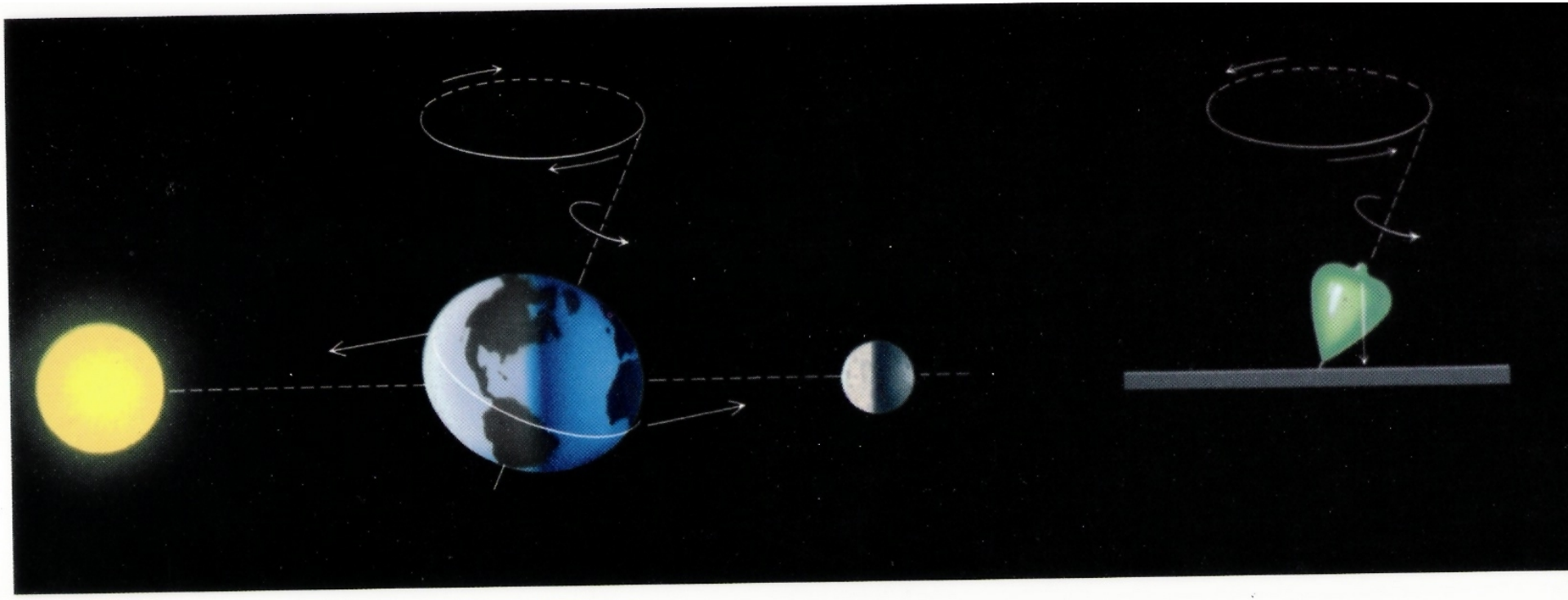


(b)

Retrograde motion of planets can be modelled with

Knowledge of the Ancient Greeks (cont.)

Cause of precession:

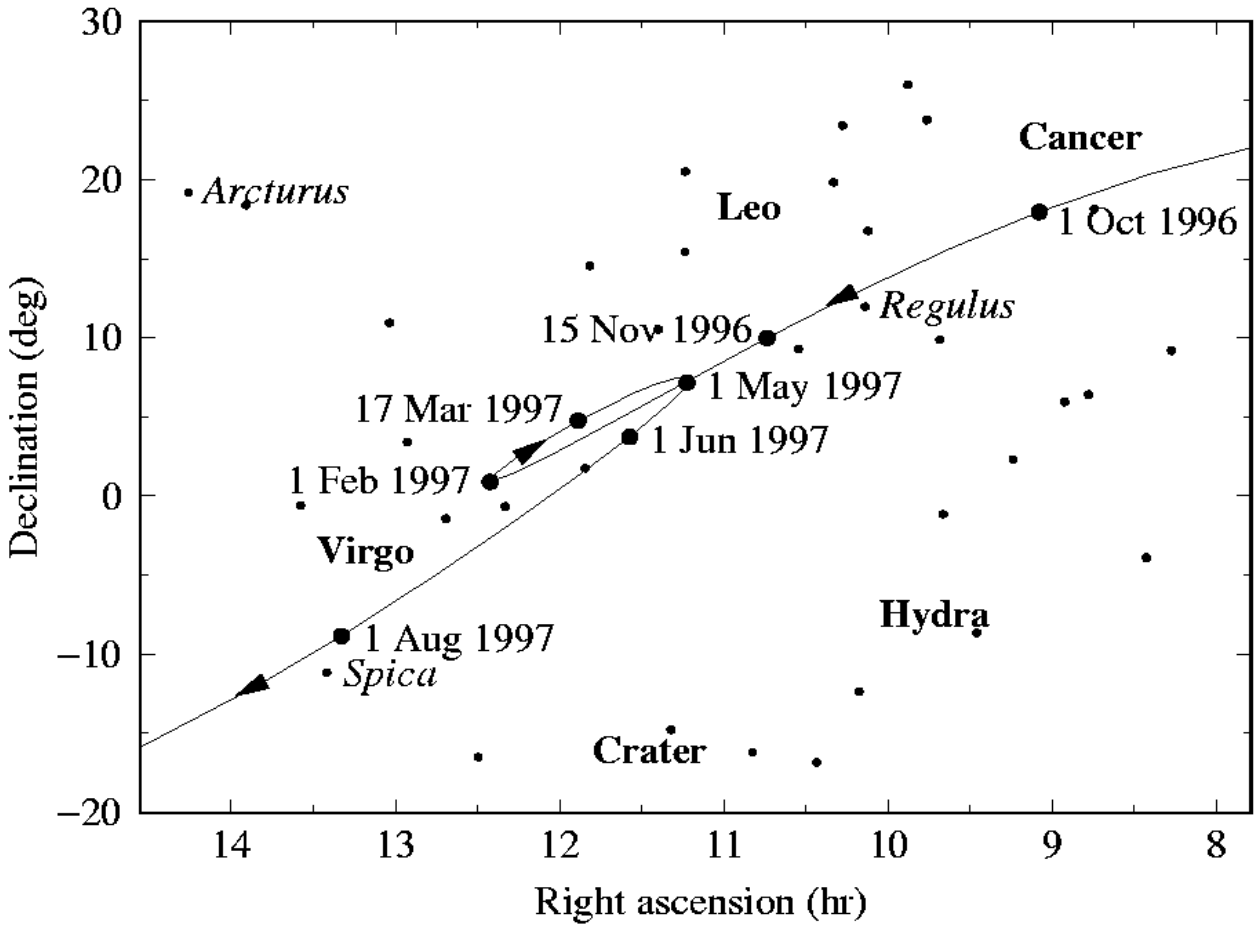


Knowledge of the Ancient Greeks IV

- 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

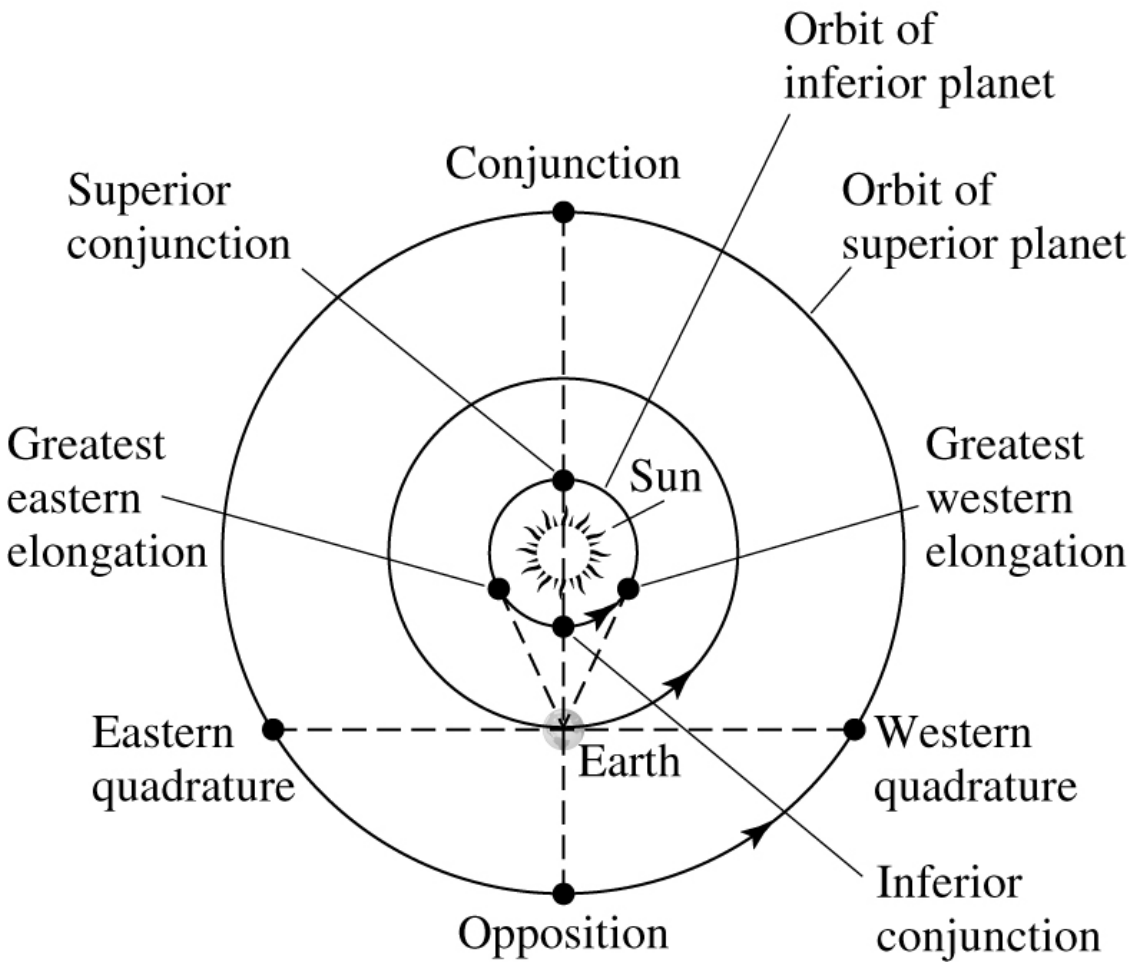
The Appearance of the Planets

- Daily mo
- Change
  sky.
- All orbit
- Usually
  we call .



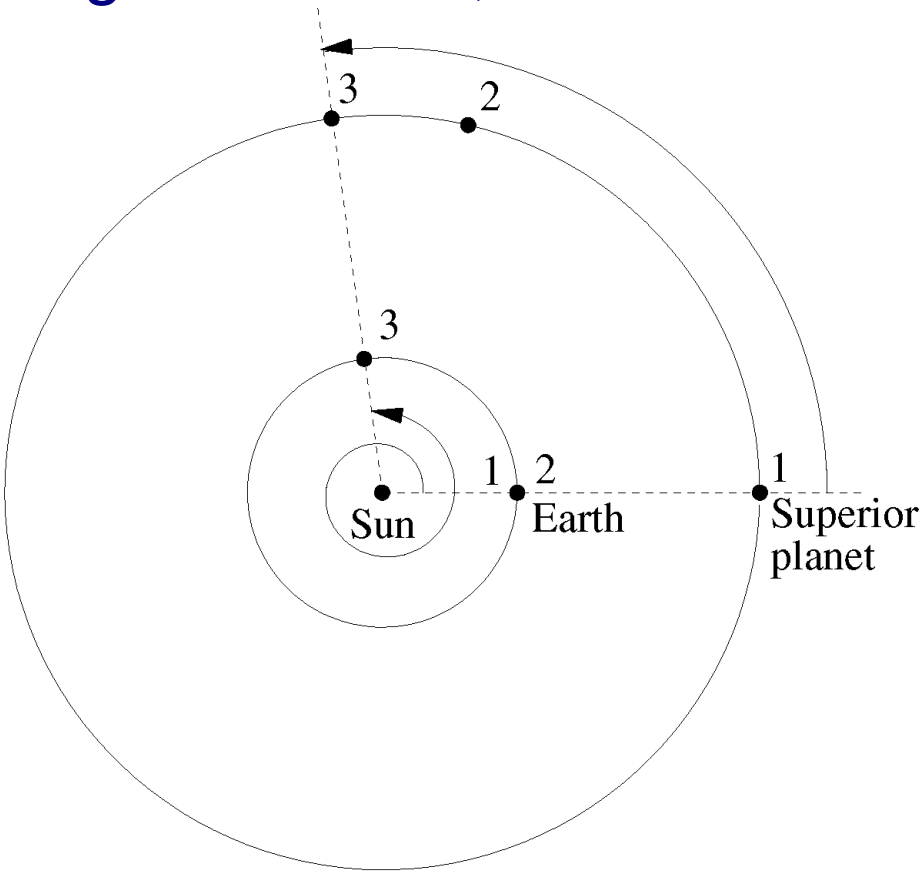
Planetary Configurations

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



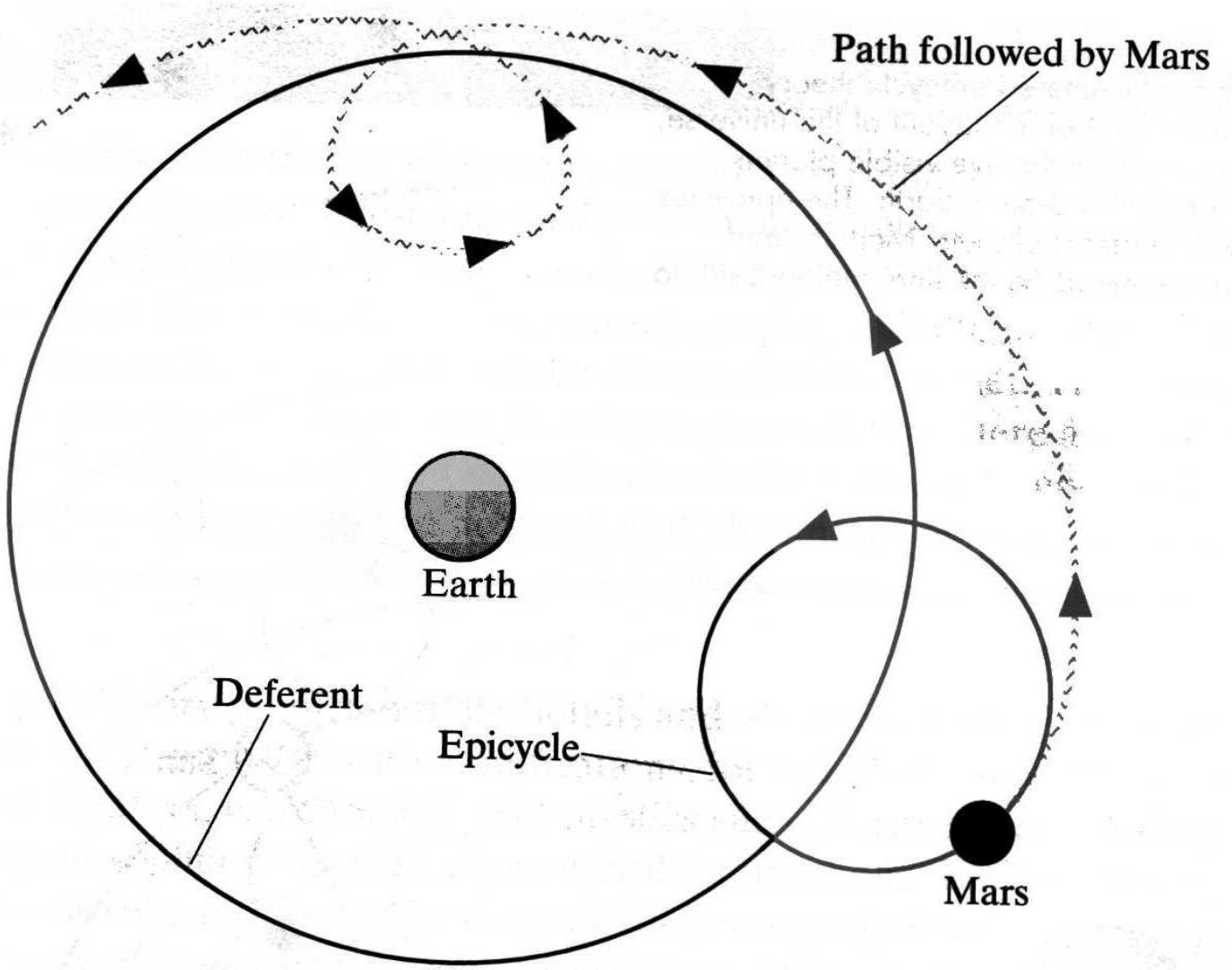
Synodic and Sidereal Periods

- 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

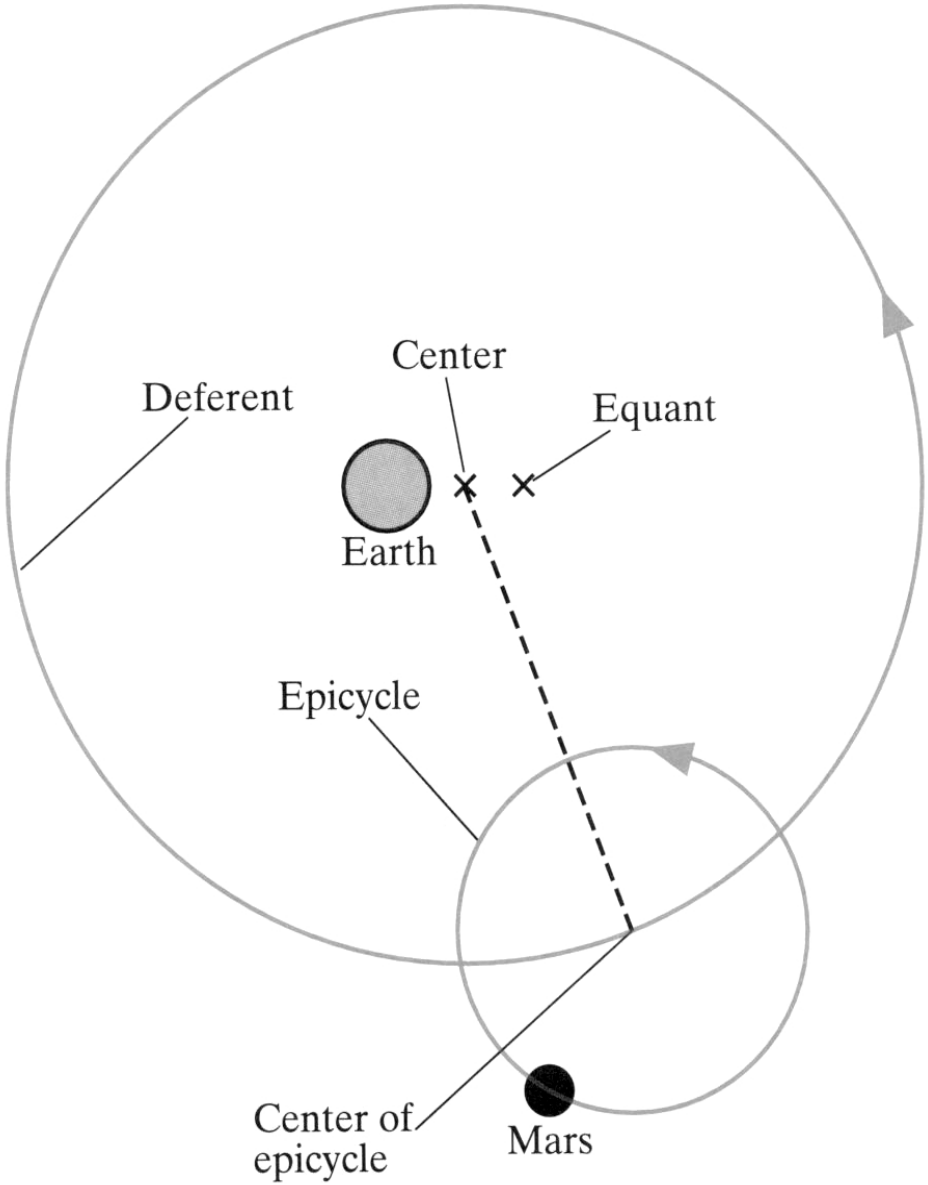


Ptolemy's Model - complex!

- Eccentric - displaces Earth from center
- Equant – center of epicycle has uniform angular speed when viewed from this point

- 80+ epicycles
- It works pretty well!

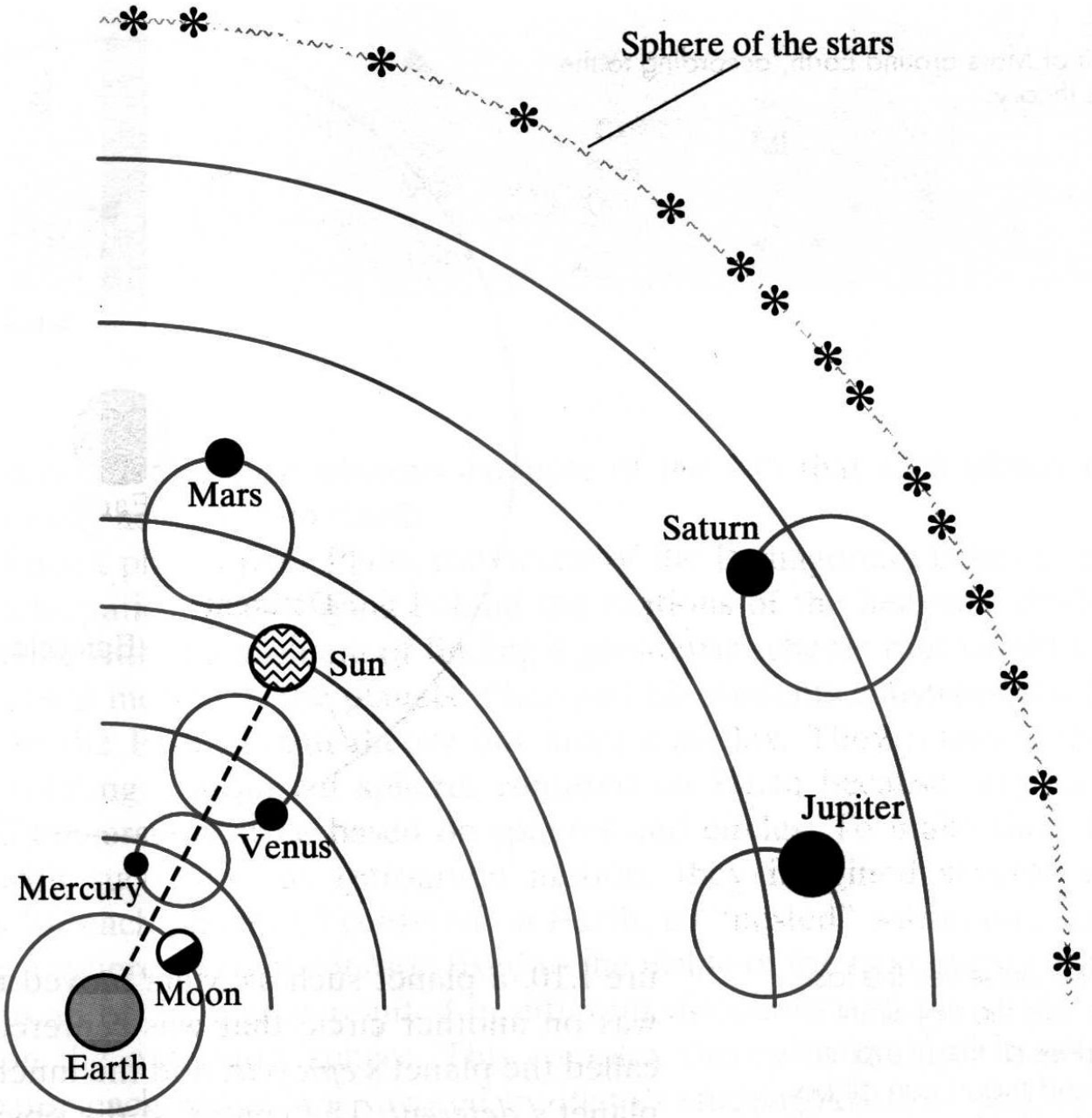
- Occam's Razor (1348)
  - Accept the simplest explanation



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 prefected the Earth-centered theory of the layout of the universe.



THE COPERNICAN REVOLUTION

. 1473

NICOLAUS COPERNICUS

. 1512 1st Comment

. 1543 De Revolutionibus

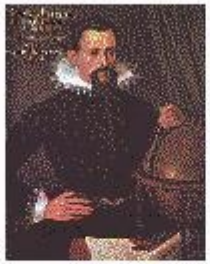
. 1546

TYCHO BRAHE

. 1601

JOHANNES KEPLER

. 1571



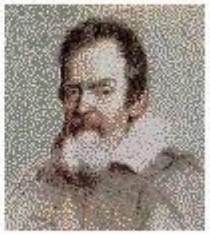
. 1609 New Astronomy

· 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

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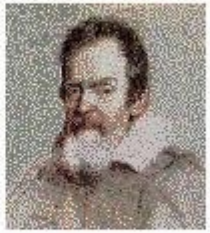
GALILEO GALILEI



1632 Dialogue of the Two Chief World Systems

1633 Trial at Rome by the Inquisition

. 1642

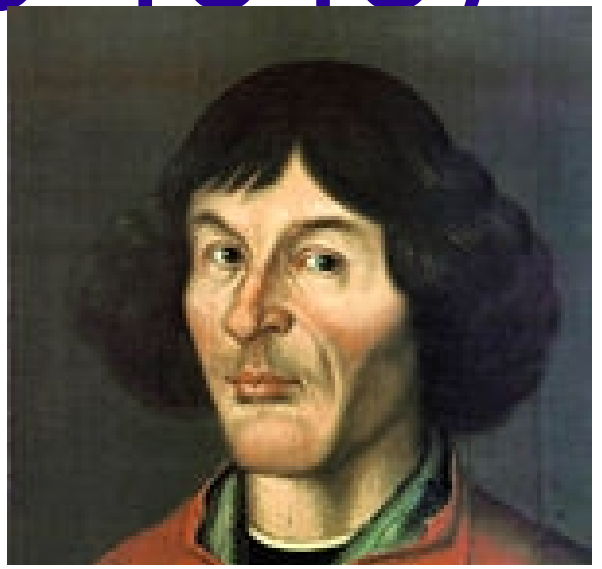
· 1642

SIR ISAAC NEWTON

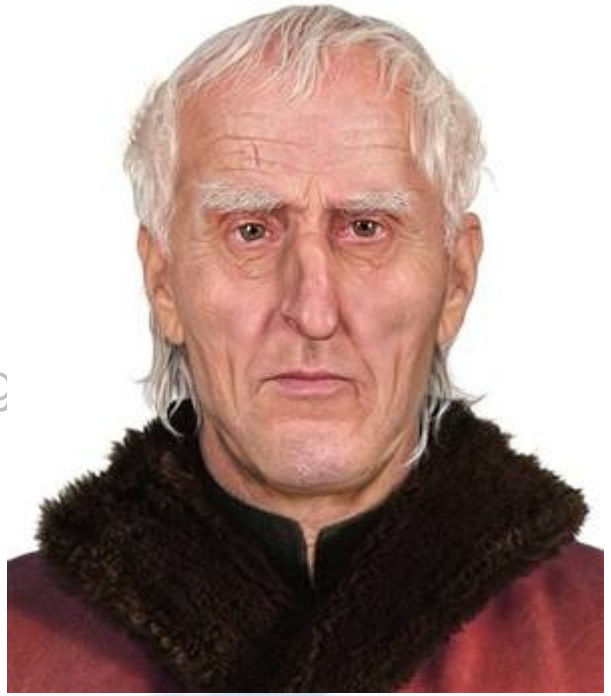
. 1686 Principia

. 1727

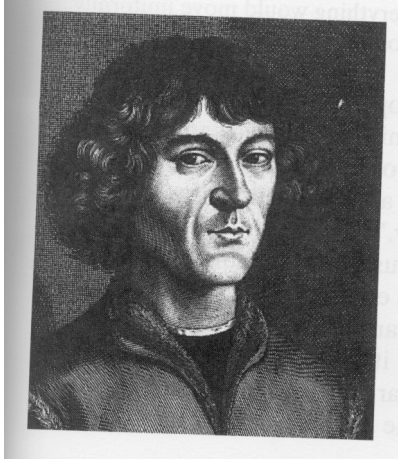
Copernicus (1473-1543)



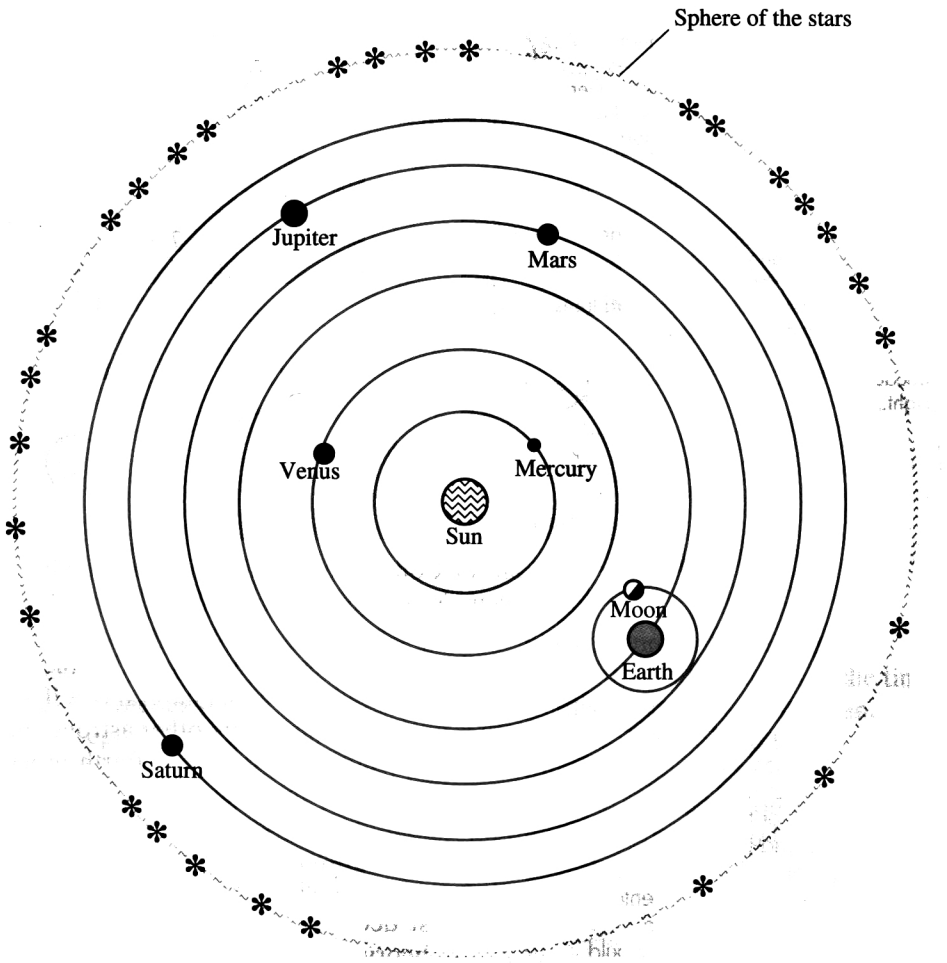
- Polish Son of merchant
- a mathematician, astronomer, physician, classical scholar, translator, Catholic cleric, jurist, governor, military leader, diplomat and economist
- Astronomy is avocation
- Publications
  - On the Revolutions of the Heavenly Spheres (1543)
  - Little Commentary (1514)
  - Trigonometry, 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 simpler? How about the Sun in the Center!!!?
- Keep some Aristotelian ideas
  - spheres (circles)
  - uniform motion
- Major Changes
  - Sun centered (heliocentric)
  - Earth rotates
  - Earth is no different from the other planets and stars!
- Established order of the planets
- 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

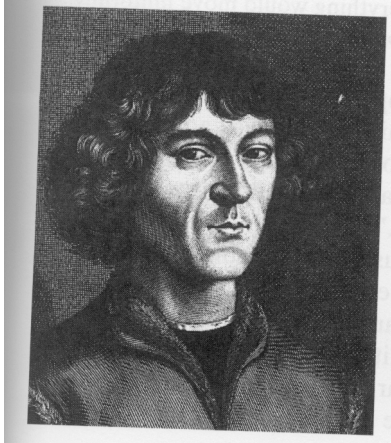
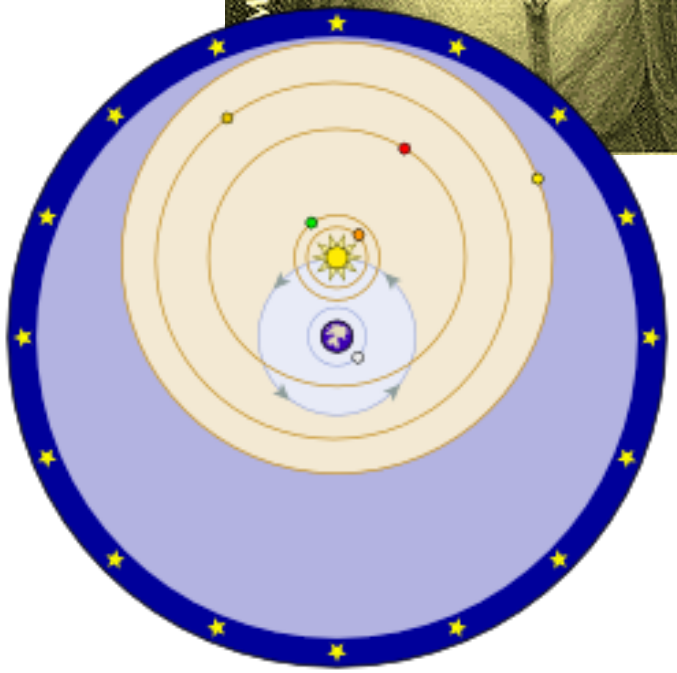


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd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

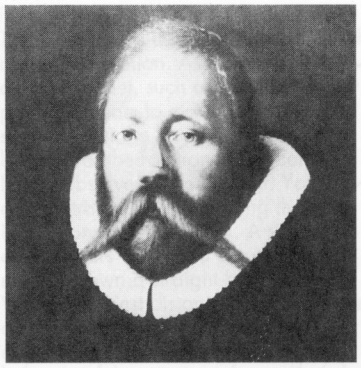


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

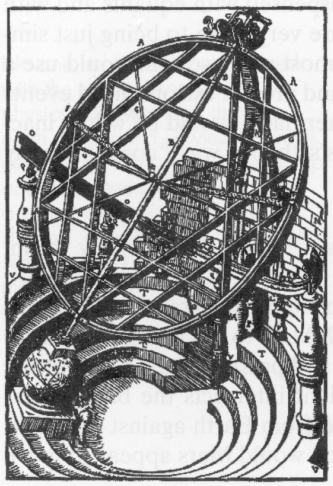


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

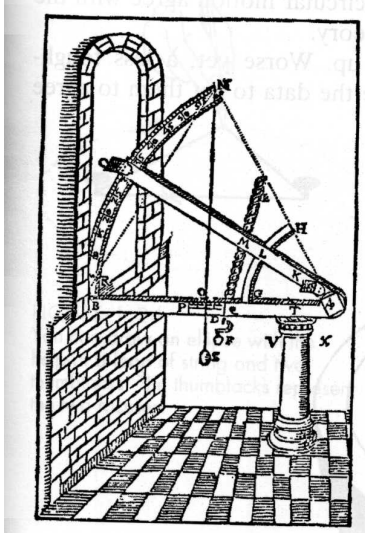


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

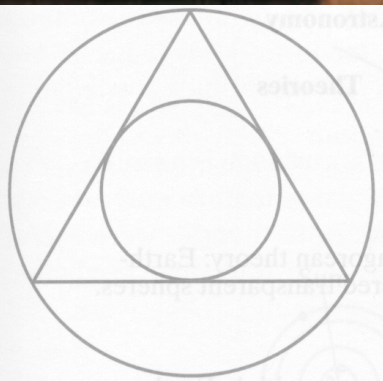


FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

- Mathematician, astronomer, astrologer
- Had religious convictions - *God had created the world according to an intelligible plan that is accessible through the natural light of reason*.
- Geometry in nature – tries concentric regular solids for 4 years.
- Astrology, numerology
- “mother sold drugs”

Johannes Kepler

- Sup
- Cop
  - S
    T
- Trie
  - A
  - I
  - F
  - K

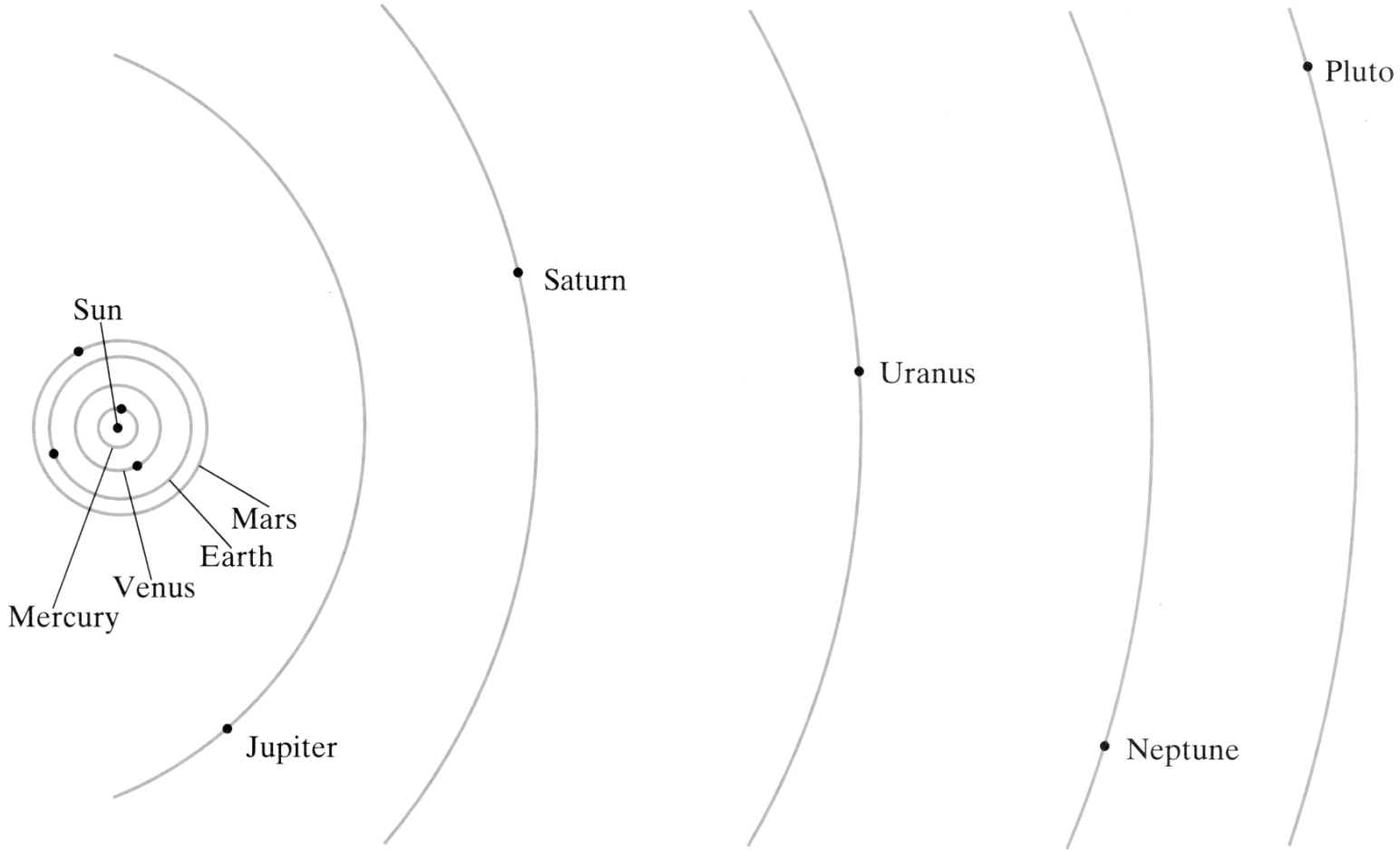
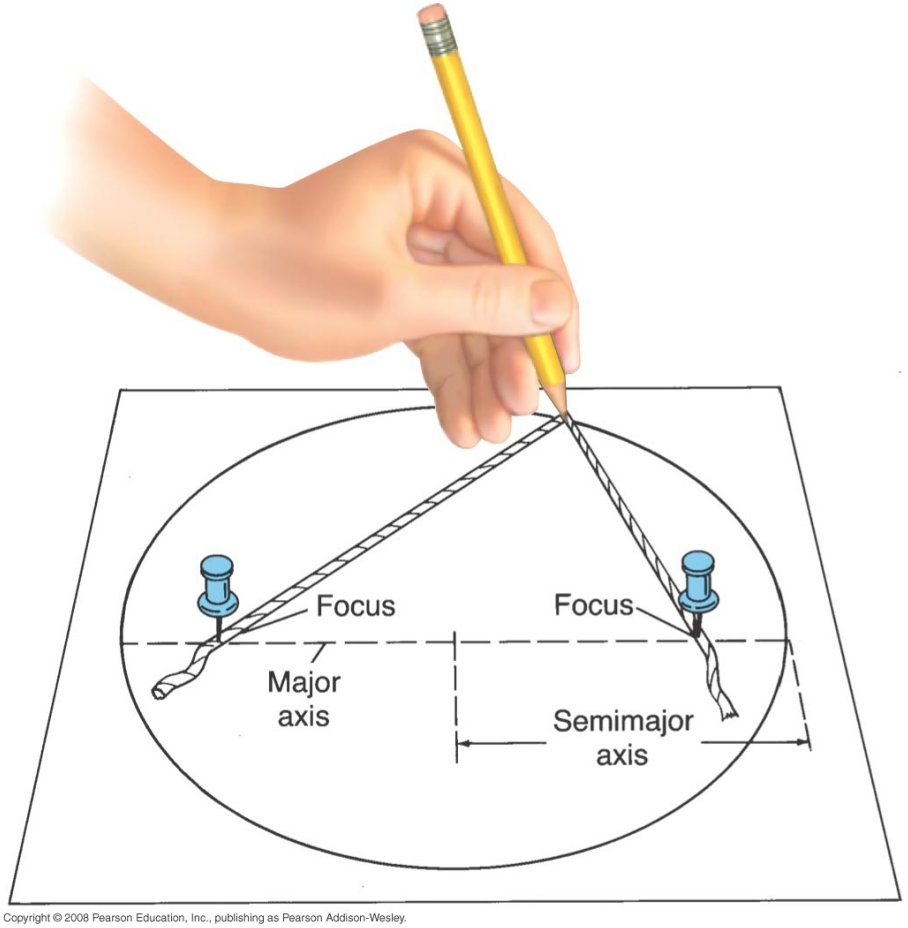


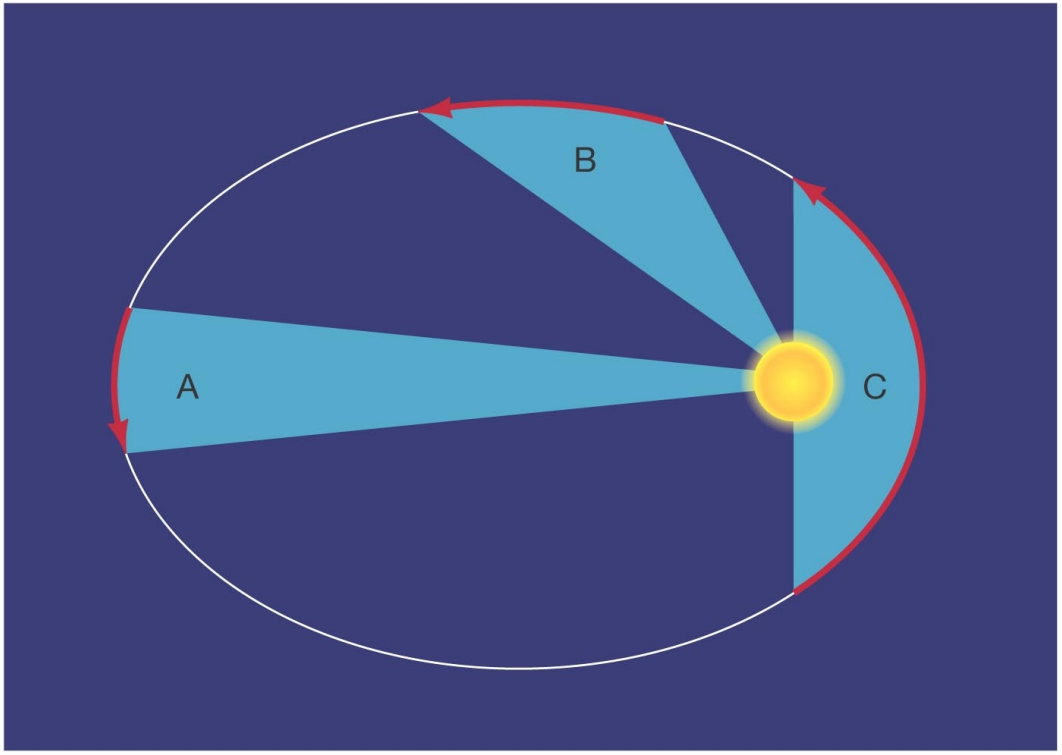
FIGURE 1.26
The arrangement of the solar system as it is now known. Uranus, Neptune, and Pluto are visible only with a telescope. The orbits are elliptical, although their ellipticity is too small to be visible in this diagram.

Kepler's 1st law



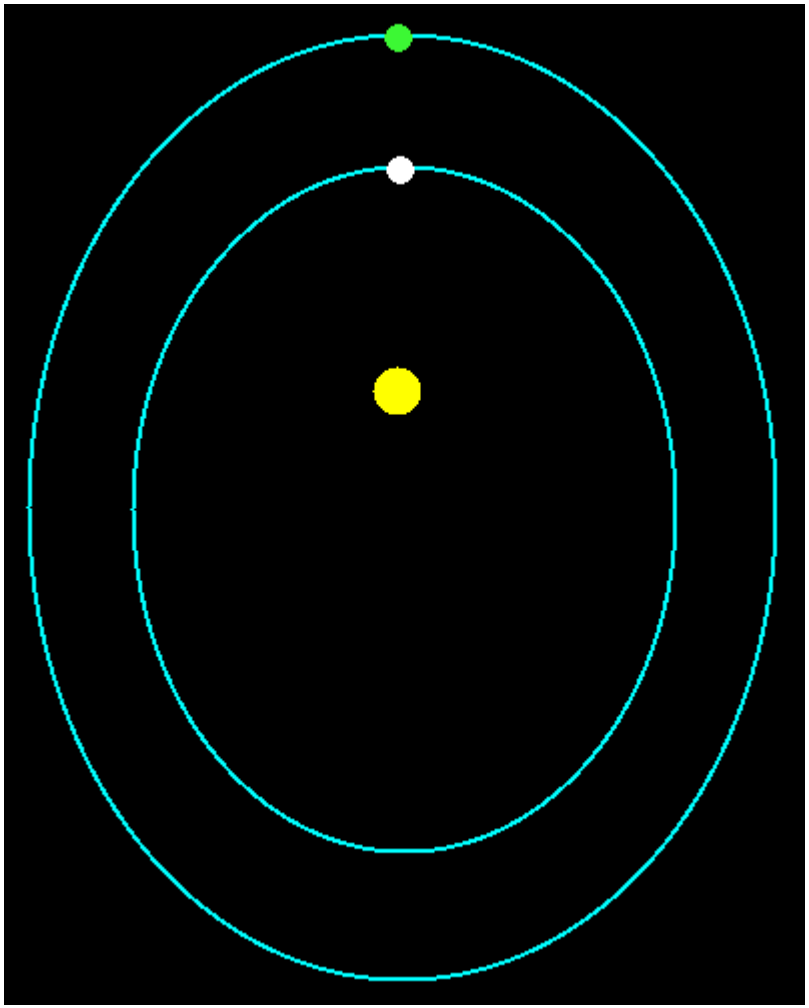
The planets follow elliptical paths with the Sun at one focus.

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, speed of light experiments
  - Moons of Jupiter orbit Jupiter!
  - Phases of Venus include the gibbous phase!
  - 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

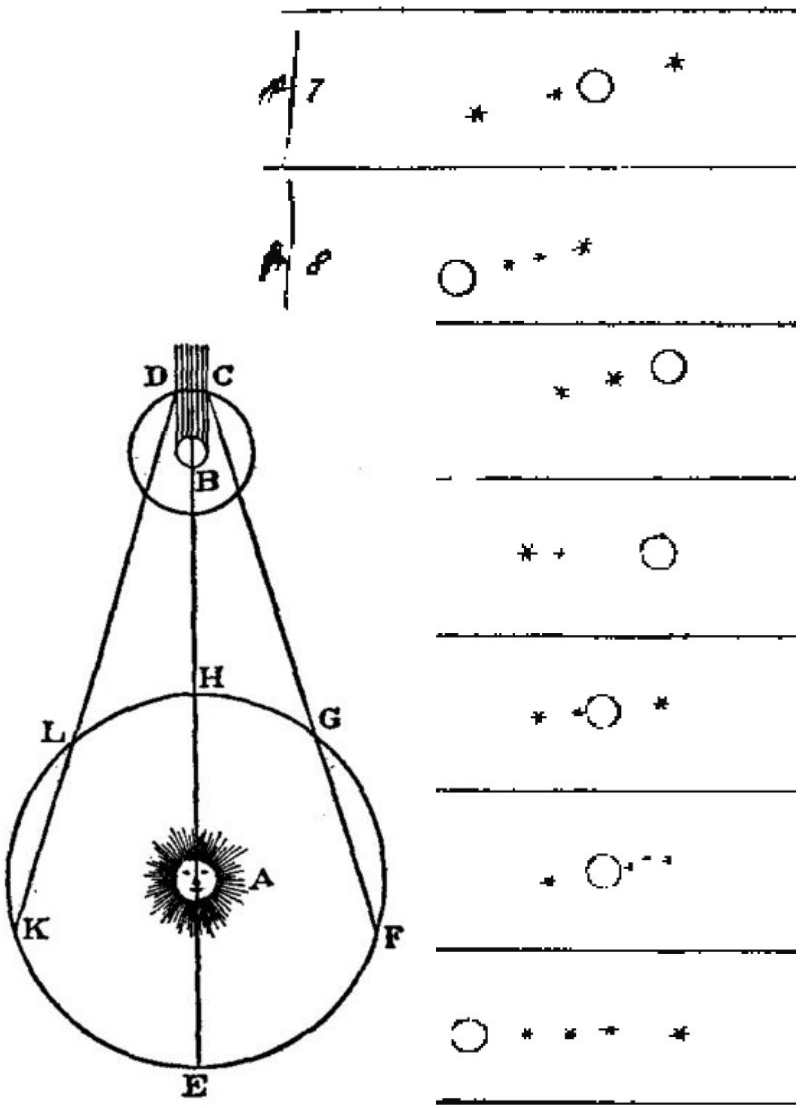
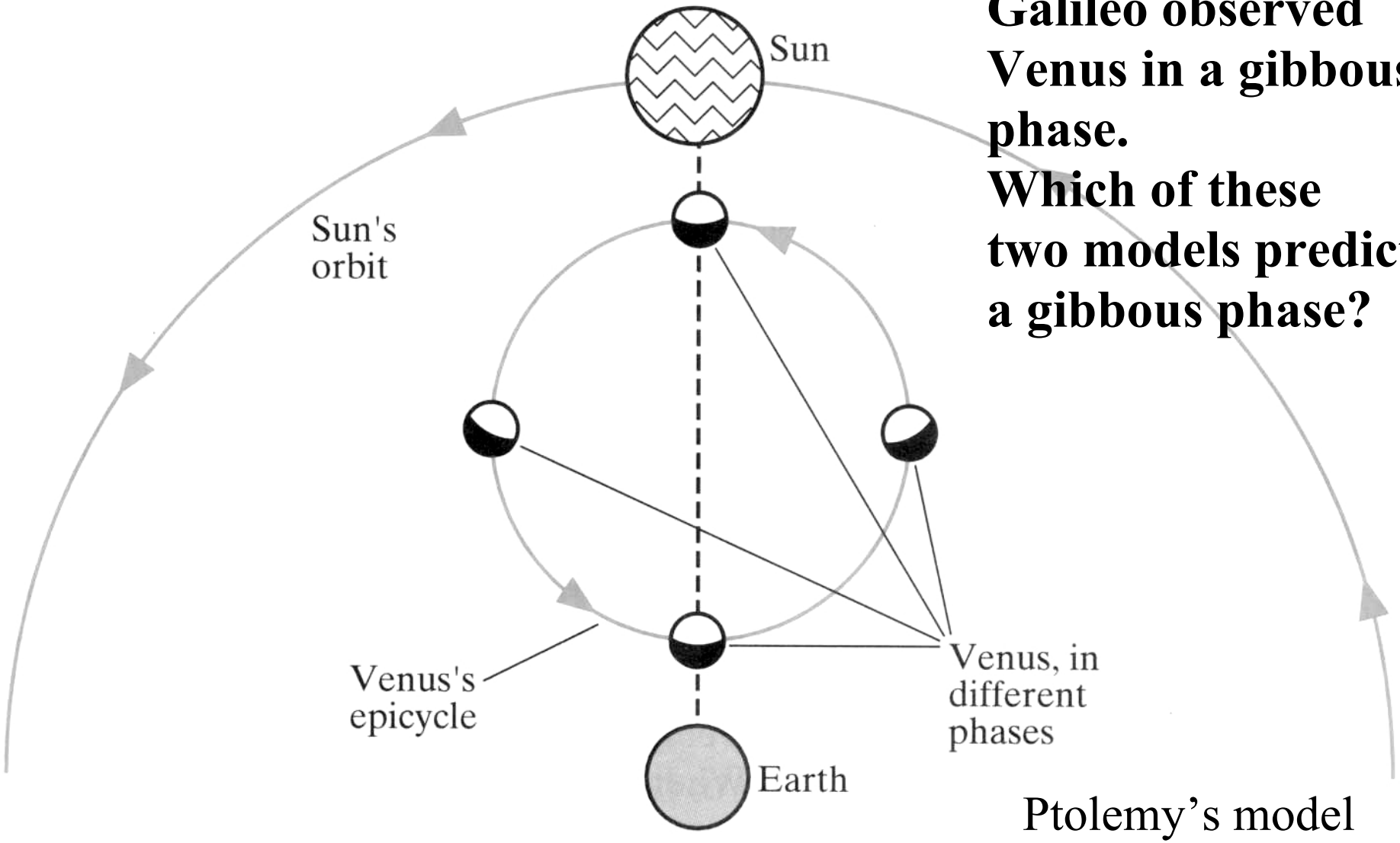


FIG. 70.

Galileo and Venus



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.

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."

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."

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 ...

$$P^2 = \frac{a^3}{Mtot}$$

The Copernican Revolution ...

matching!

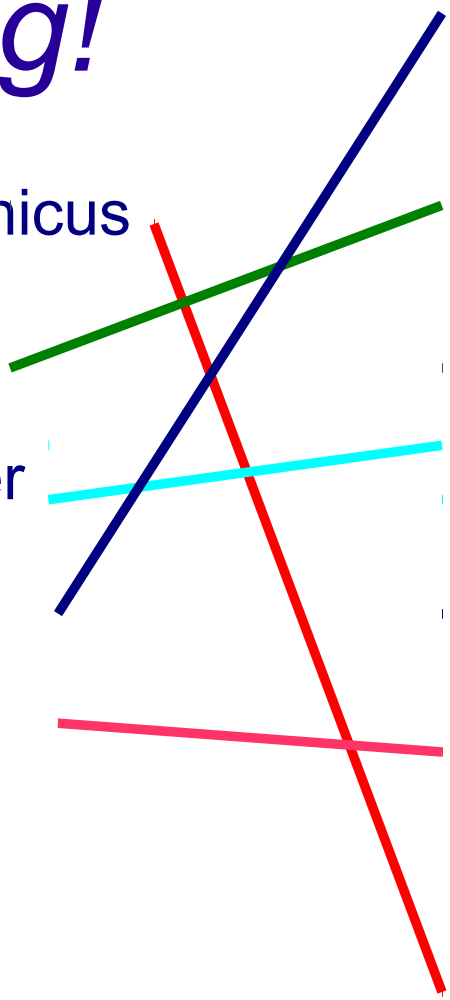
Nicolaus Copernicus

Tycho Brahe

Johannes Kepler

Galileo

Newton



Observed gibbous phase of Venus

Made precision measurements of planets

Used ellipses to model solar system

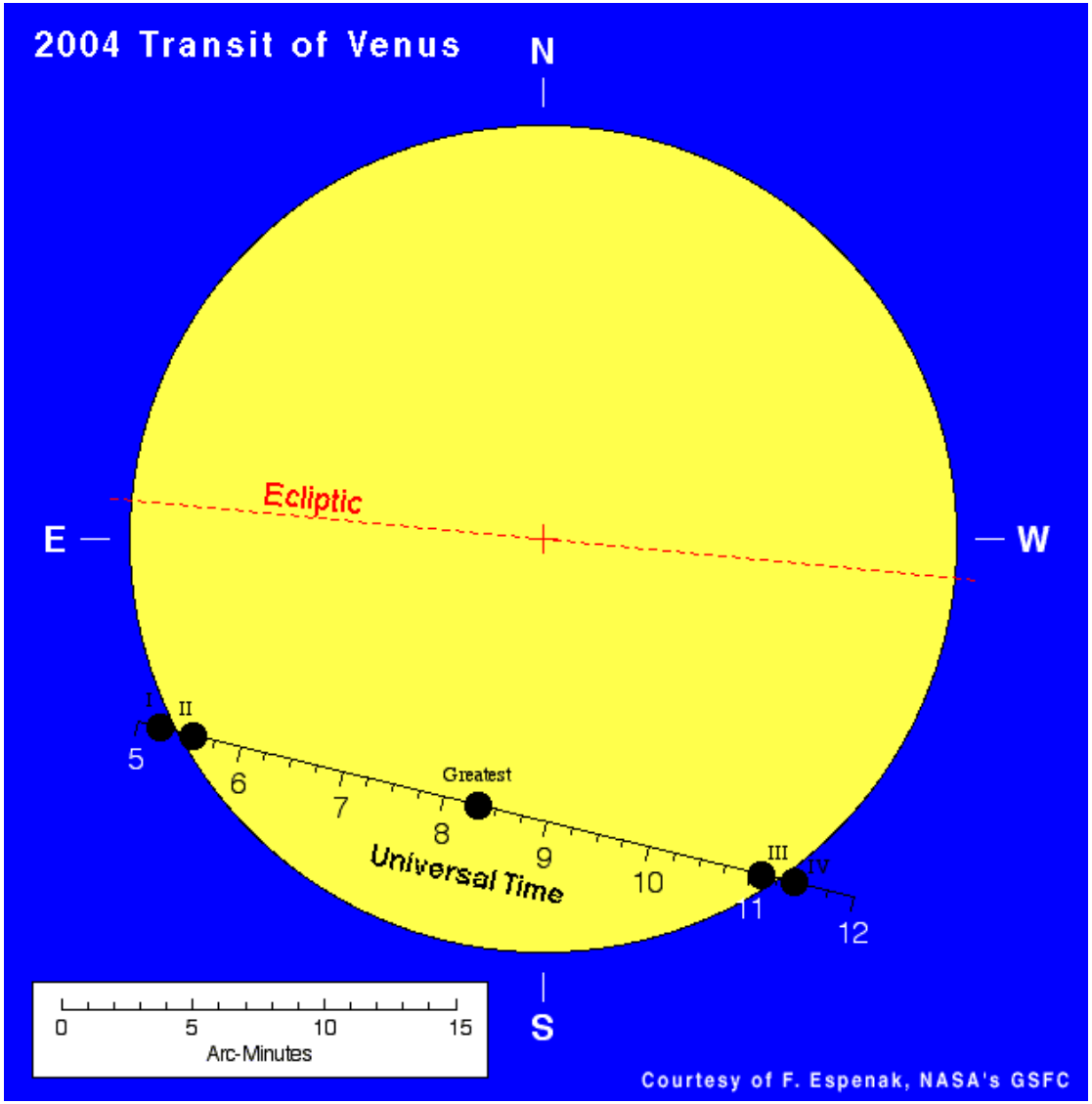
Said gravity accelerates the planets

Revived the heliocentric model

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

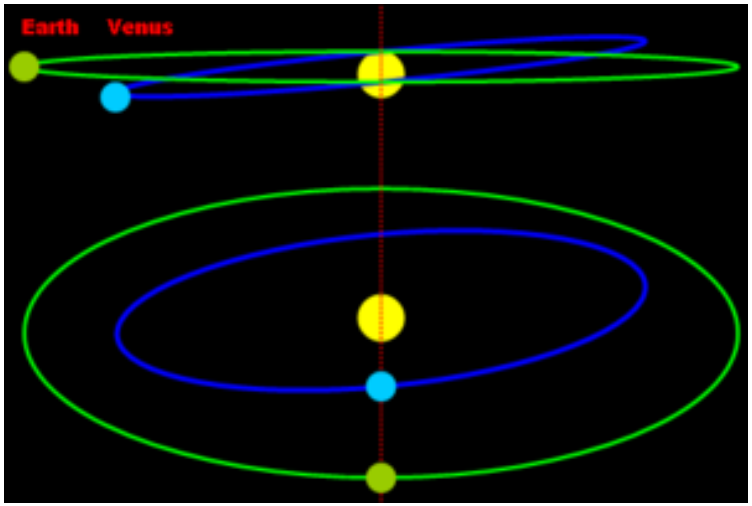
Transits of Venus



Transits of Venus

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

…



Last transit: June 6, 2012

Next transits: 2117, 2125

How it works: 3.4º tilt, 8:13

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

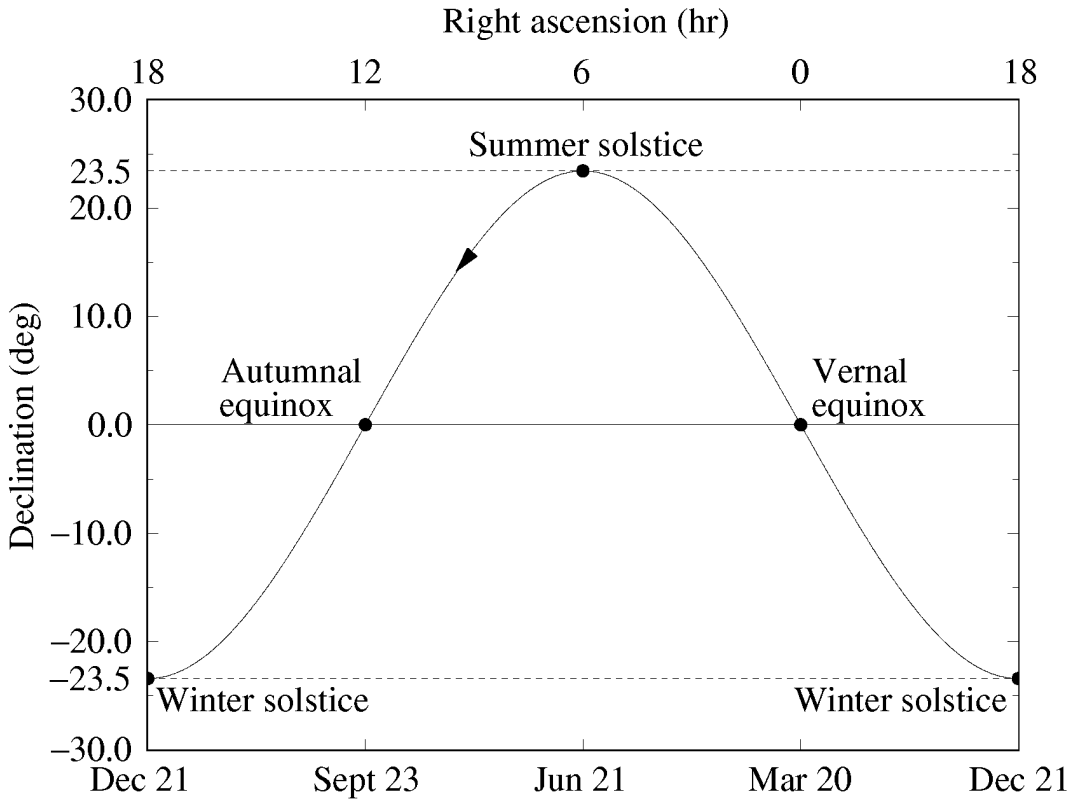
- There are people at both extremes; pure skepticism and belief.

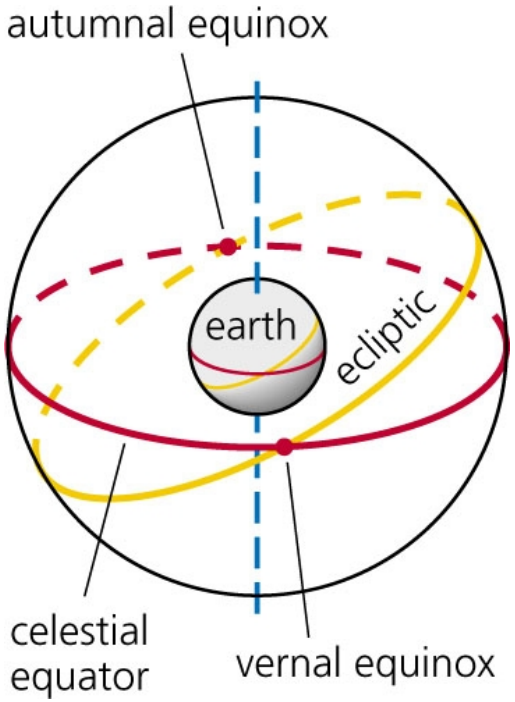
Each of us has to reconcile facts with beliefs. Follow Kepler's Lead!

See "The Demon-Haunted World: Science As a Candle in the Dark" - C. Sagan

Ecliptic

- Seasonal variations due to orbital motion and the 23.5^0 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

Observations	Typical Dates	Theories
Stars, sun, moon, and planets are moving overhead.	3000 B.C.	
	500	Pythagorean theory: Earth-centered transparent spheres.
Each planet moves at a varying rate; retrograde motion.	400	Theory of multiple Earth-centered transparent spheres.
	300	Aristarchus's theory: sun-centered circles.
Heaven and Earth seem different; Earth seems motionless, apparently contradicting Aristarchus's theory.	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	
	1500	Copernicus's theory: sun-centered circles.
Brahe's accurate measurements disprove Ptolemy's and Copernicus's theories.	1600	Kepler's theory: sun-focused ellipses.
Galileo's telescopic observations disprove Earth-centered theories.		