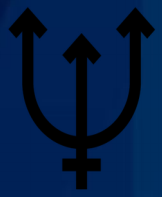
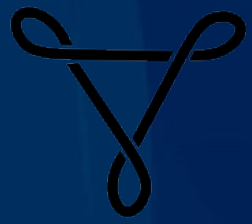
The Copernican Revolution - Separating Science and Superstition



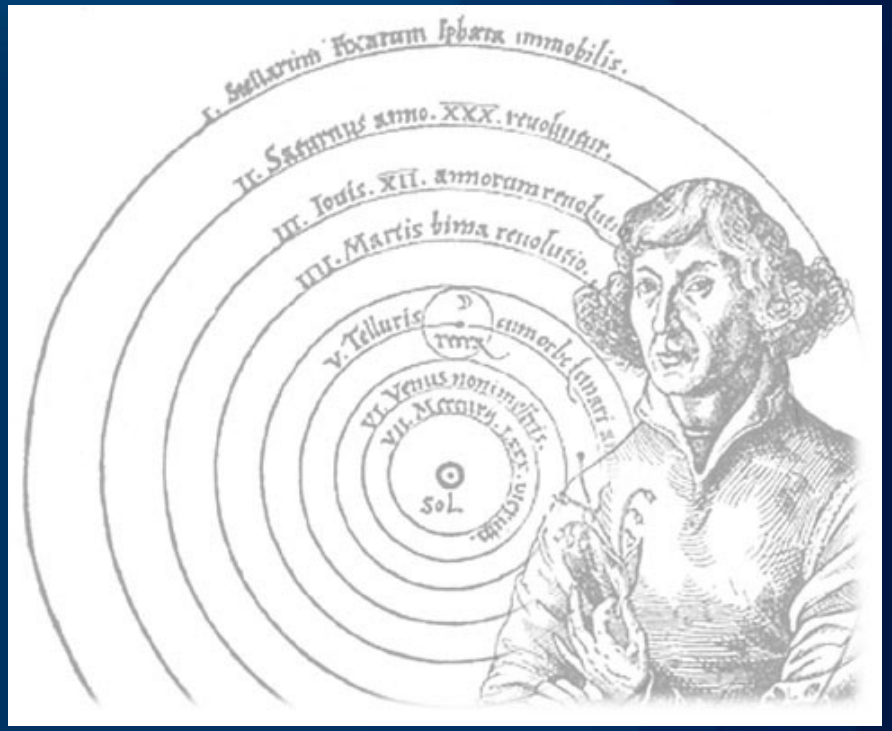


J. Pinkney

ONU 2021

Outline

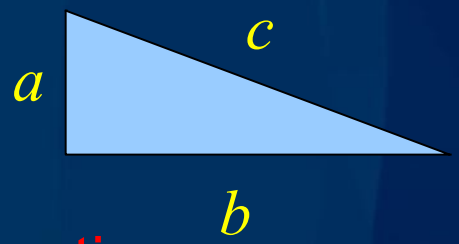
- Our universe viewed by the ancients
- Greek astronomy
- Copernican Revolution
  - Nicolaus Copernicus
  - Tycho Brahe
  - Johannes Kepler
  - Galileo Galilei
  - Isaac Newton

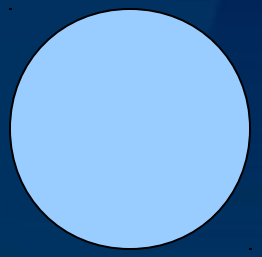


- Loose ends: first parallax, abberation of starlight
- Science vs Superstition: it never ends

Knowledge of the Ancient Greeks

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





Knowledge of the Ancient Greeks

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

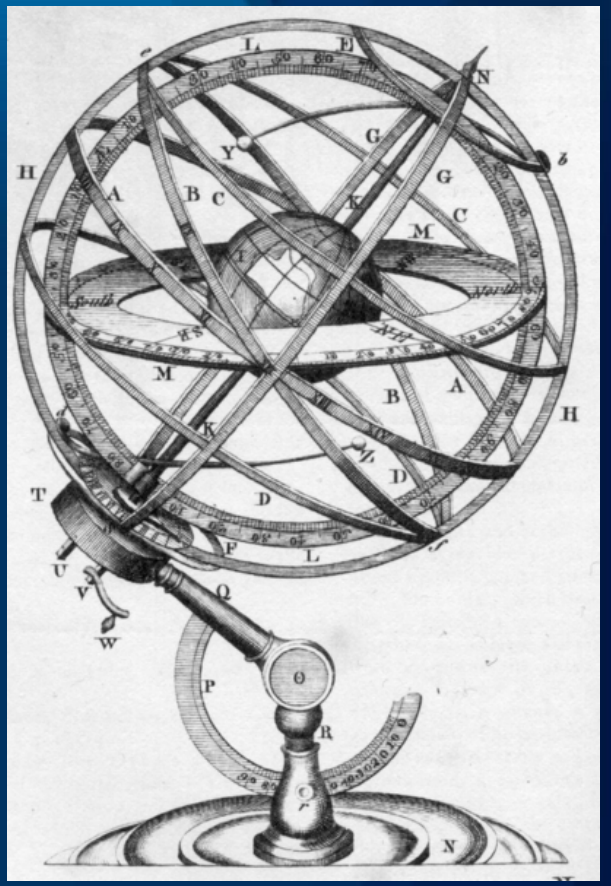
Knowledge of the Ancient Greeks (cont.)

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

Biggest stellar parallax is only ~1.0", so the Greeks had no hope of detecting it.

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

Knowledge of the Ancient Greeks



Aristarchus (310-230 BC)

The Earth orbits around the Sun (!)

Eratosthenes (276-195 BC)

–Measured circumference of the Earth.

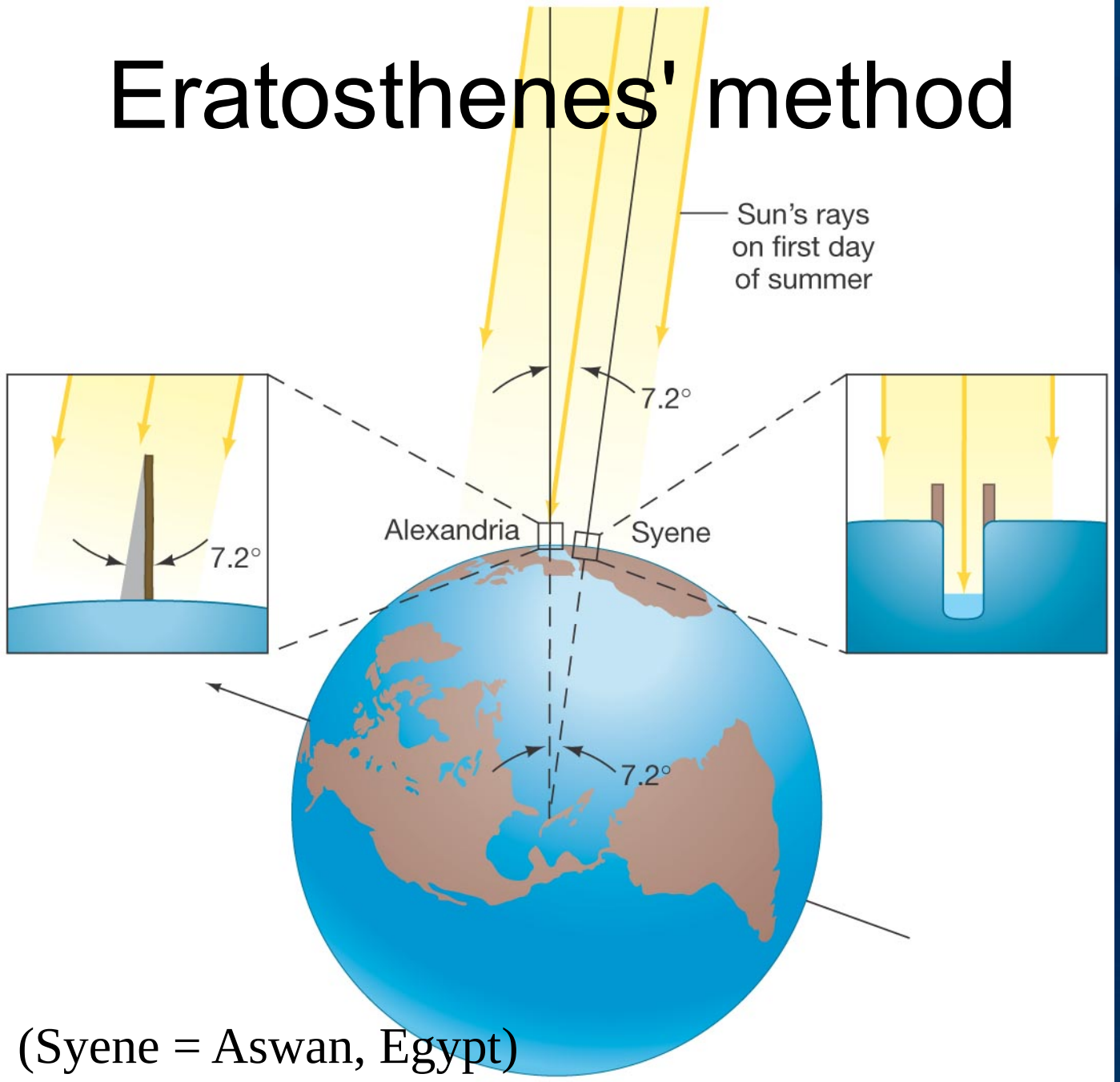
–Invents armillary sphere

- Hipparchus (190-120 BC)

–Discovered precession of Earth's spin axis

–Uses epicycles, deferents and eccentrics in modelling motion of Sun and Moon.

Eratosthenes' method



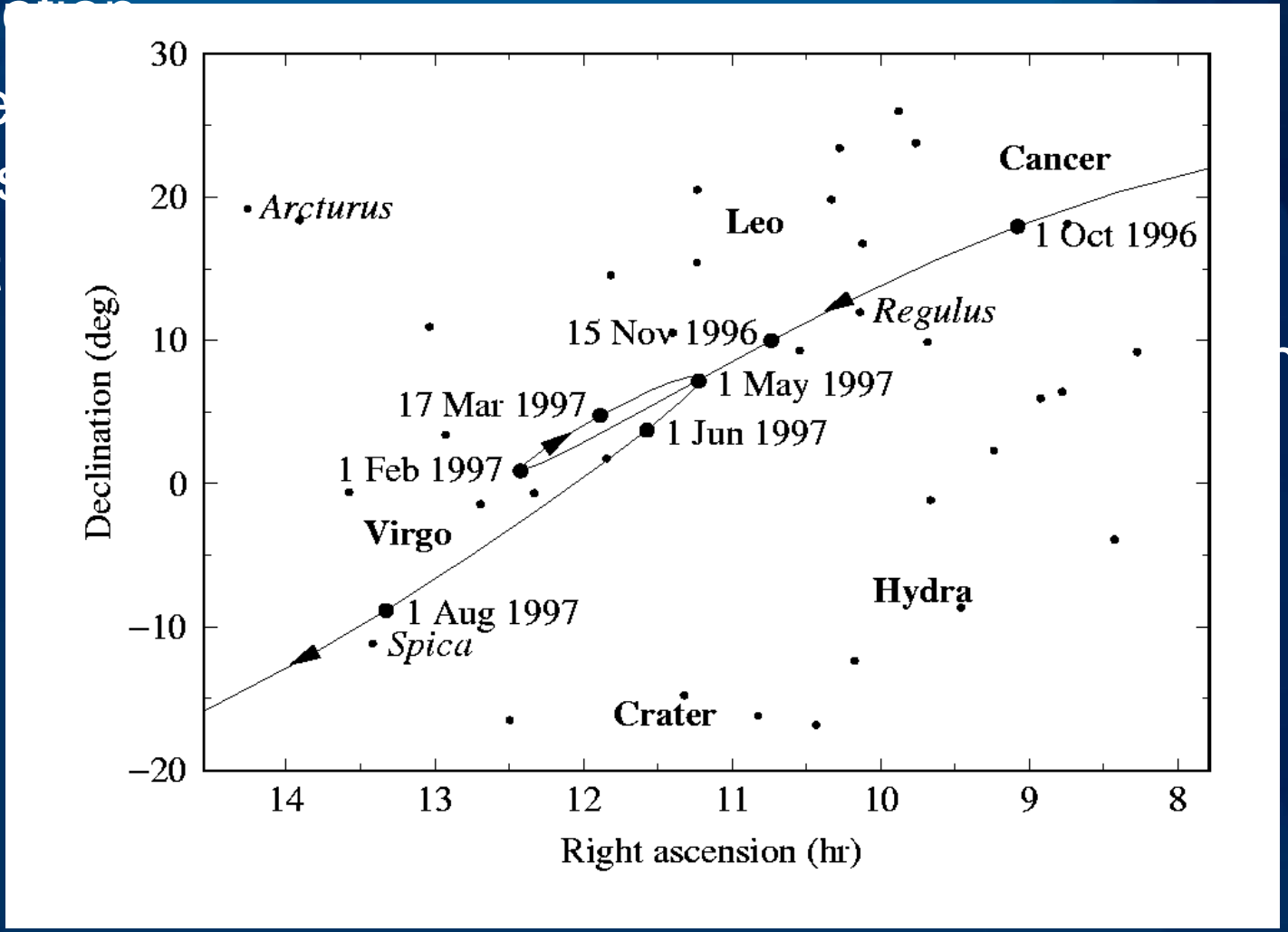
(Syene = Aswan, Egypt)

Knowledge of the Ancient Greeks

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

The Appearance of the Planets

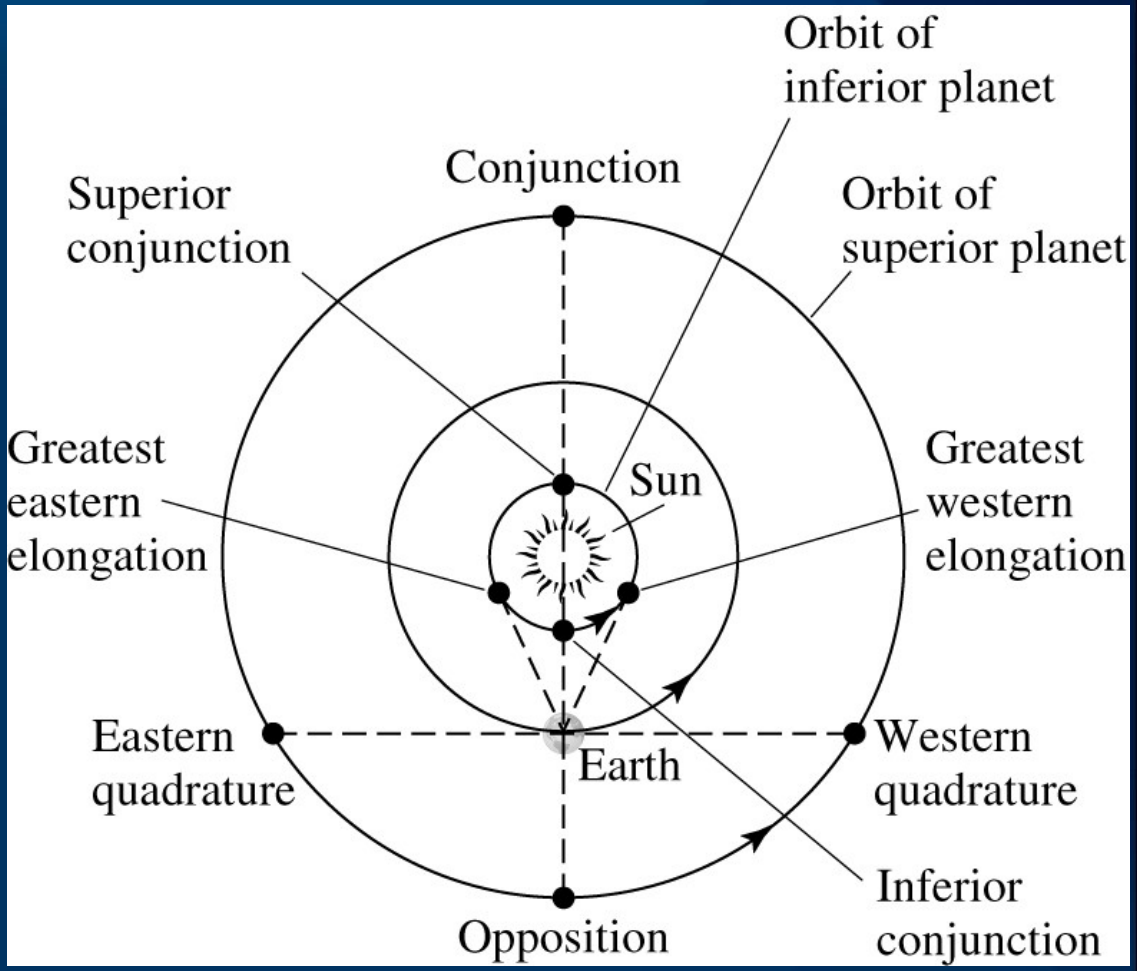
- Daily m
- Change across s
- All orbit
- Usually we call



Retrograde Motion!

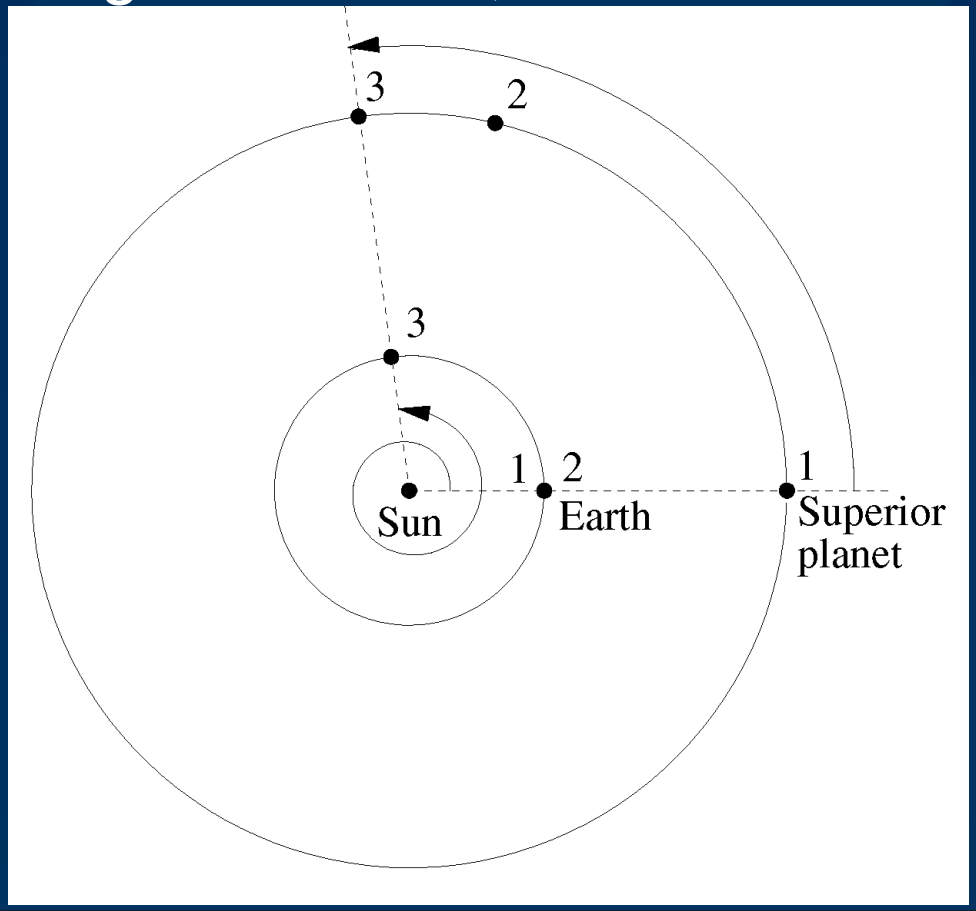
Planetary Configurations

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



Synodic and Sidereal Periods

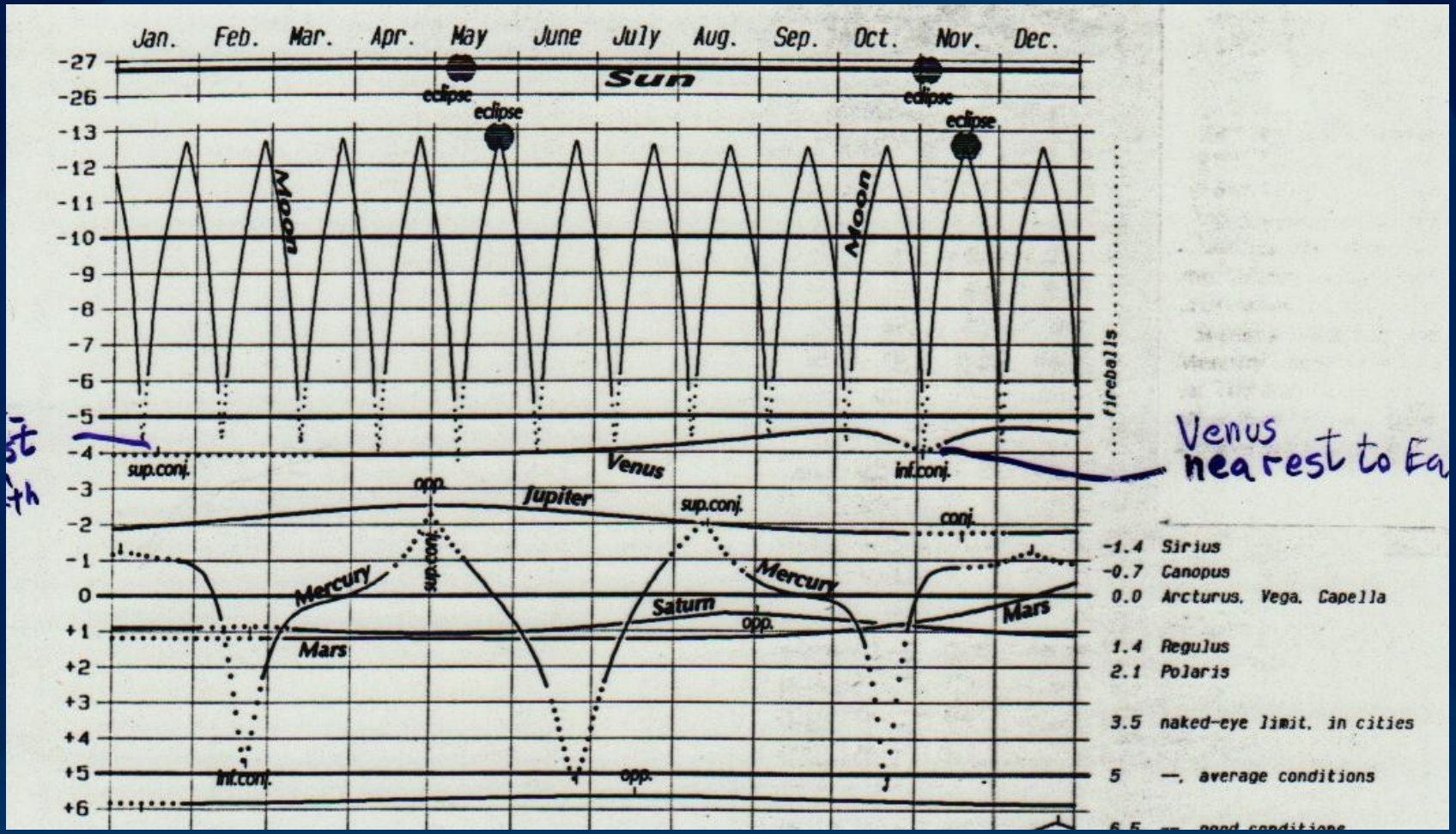
- Synodic period: time interval between successive conjunctions or oppositions, 1→ 3
- Sidereal period: time interval for one complete orbit relative to background stars, 1→2



The Appearance of the Planets

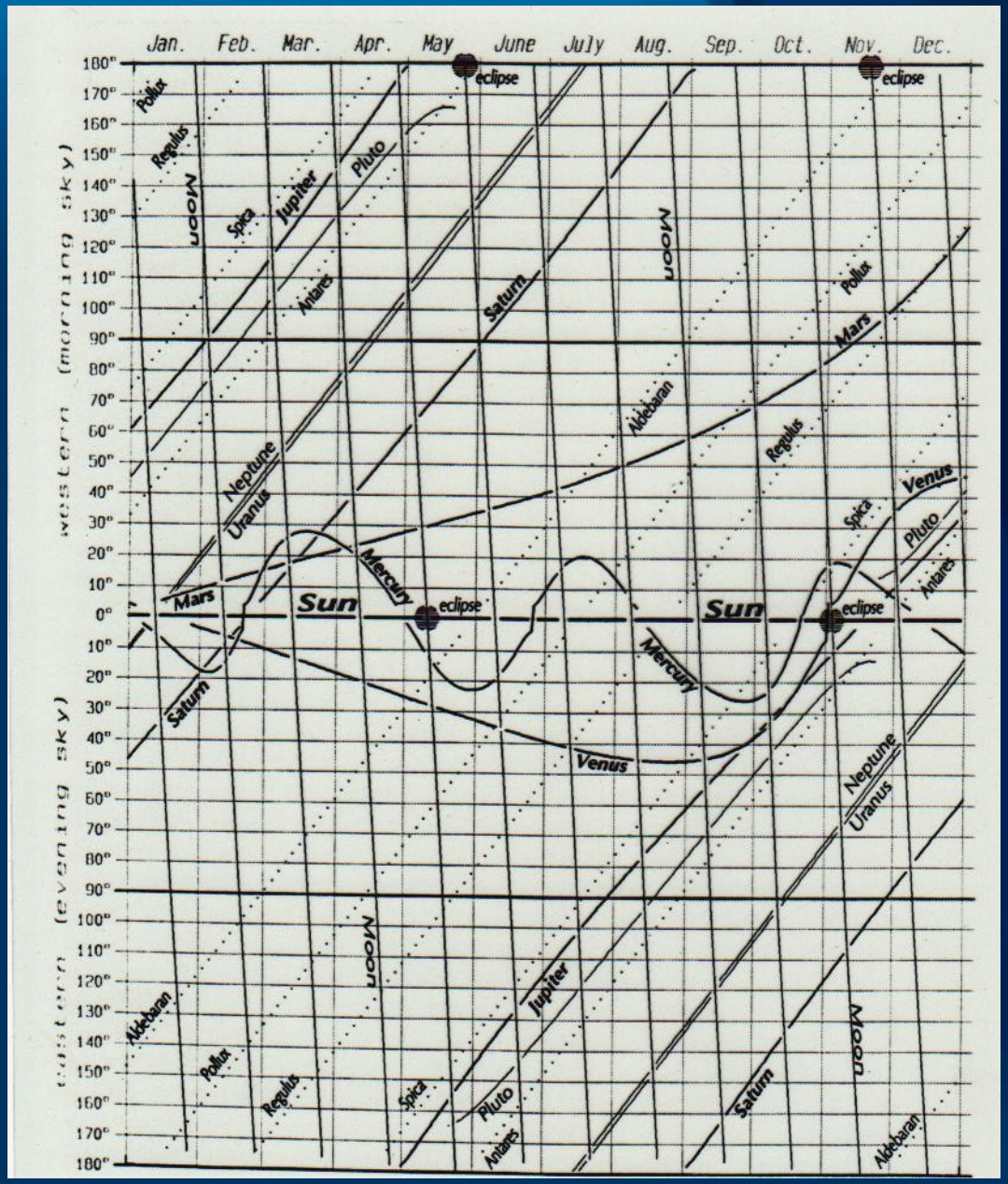
Brightness, measured in magnitudes.

- Smaller magnitude → brighter.



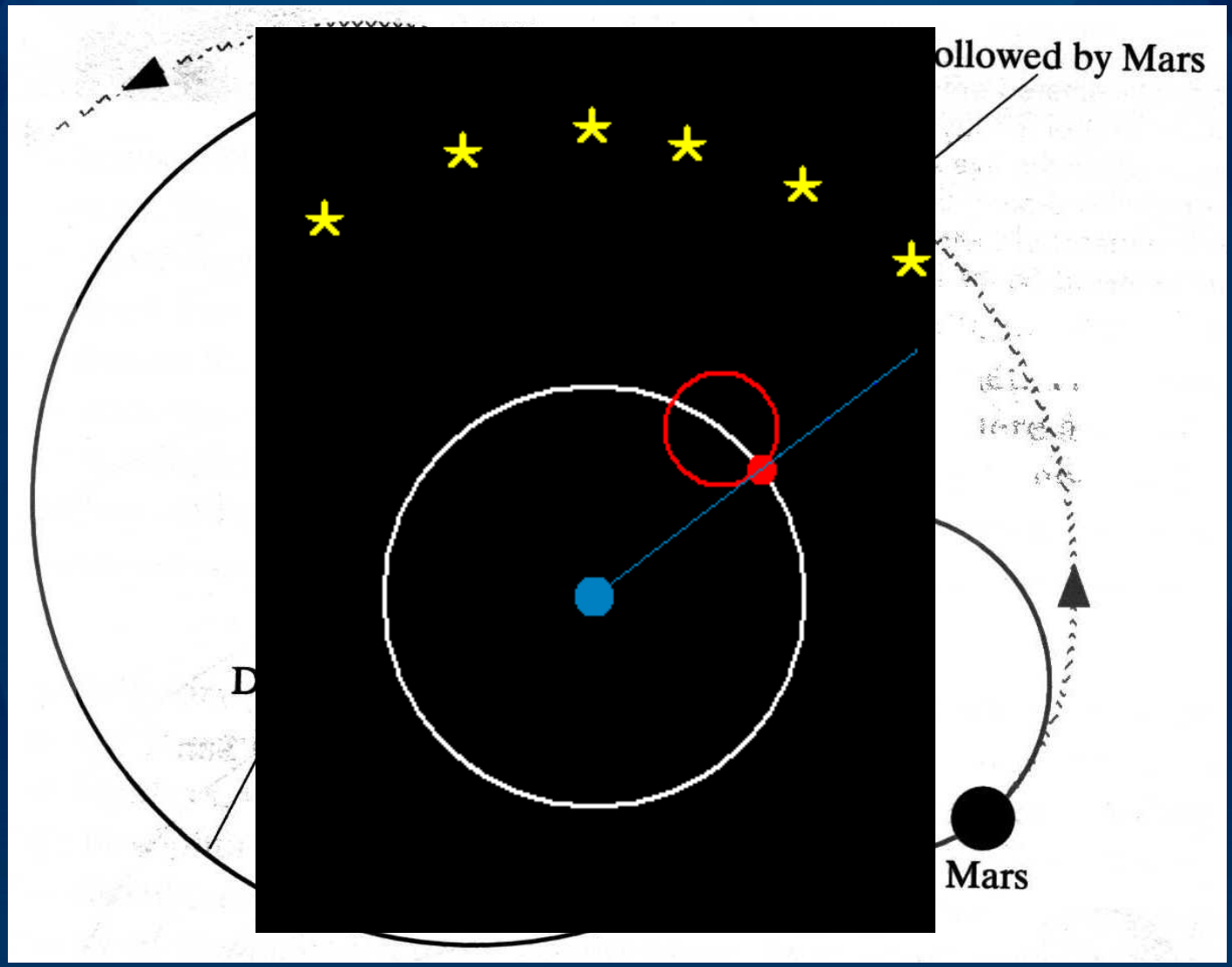
The Appearance of the Planets

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



Epicycles on Deferents

- Ptolemy et al. desired uniform circular motions



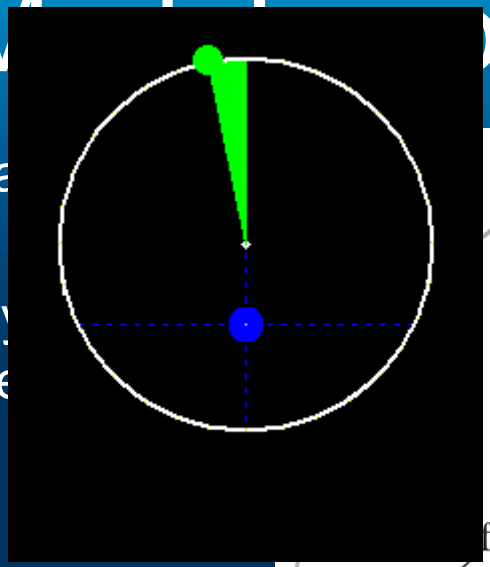
Ptolemy's M[illegible]omple[illegible]

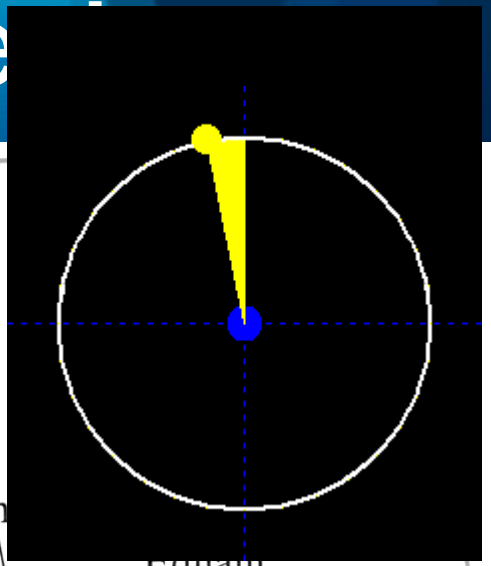
- Eccentric - displaces Ea[illegible] from center
- Equant – center of epicy[illegible] has uniform angular spe[illegible] when viewed from this point

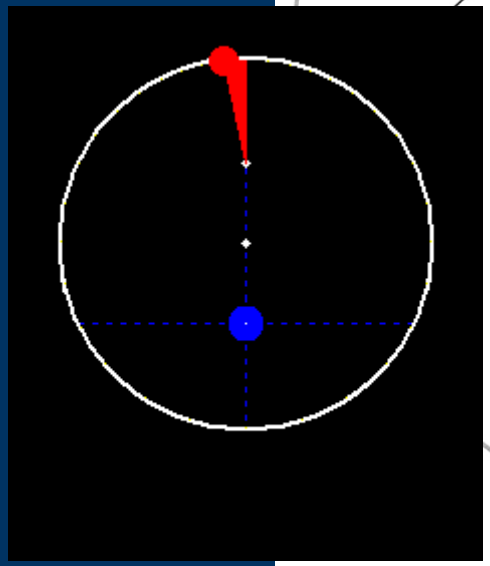
- 80+ epicycles
- It works pretty well!

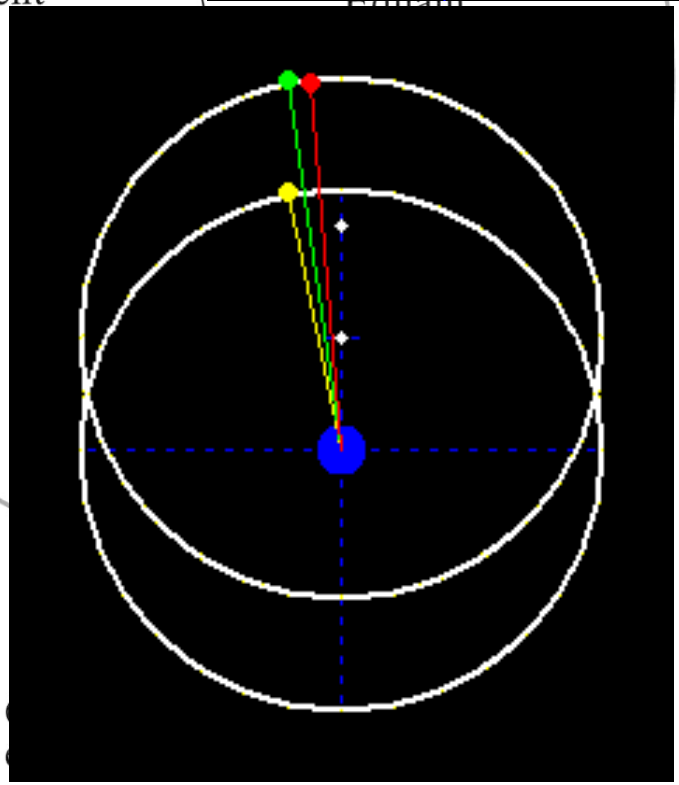
- Occam's Razor (1348)
  - Accept the simplest explanation

See "marsorbit.swf".





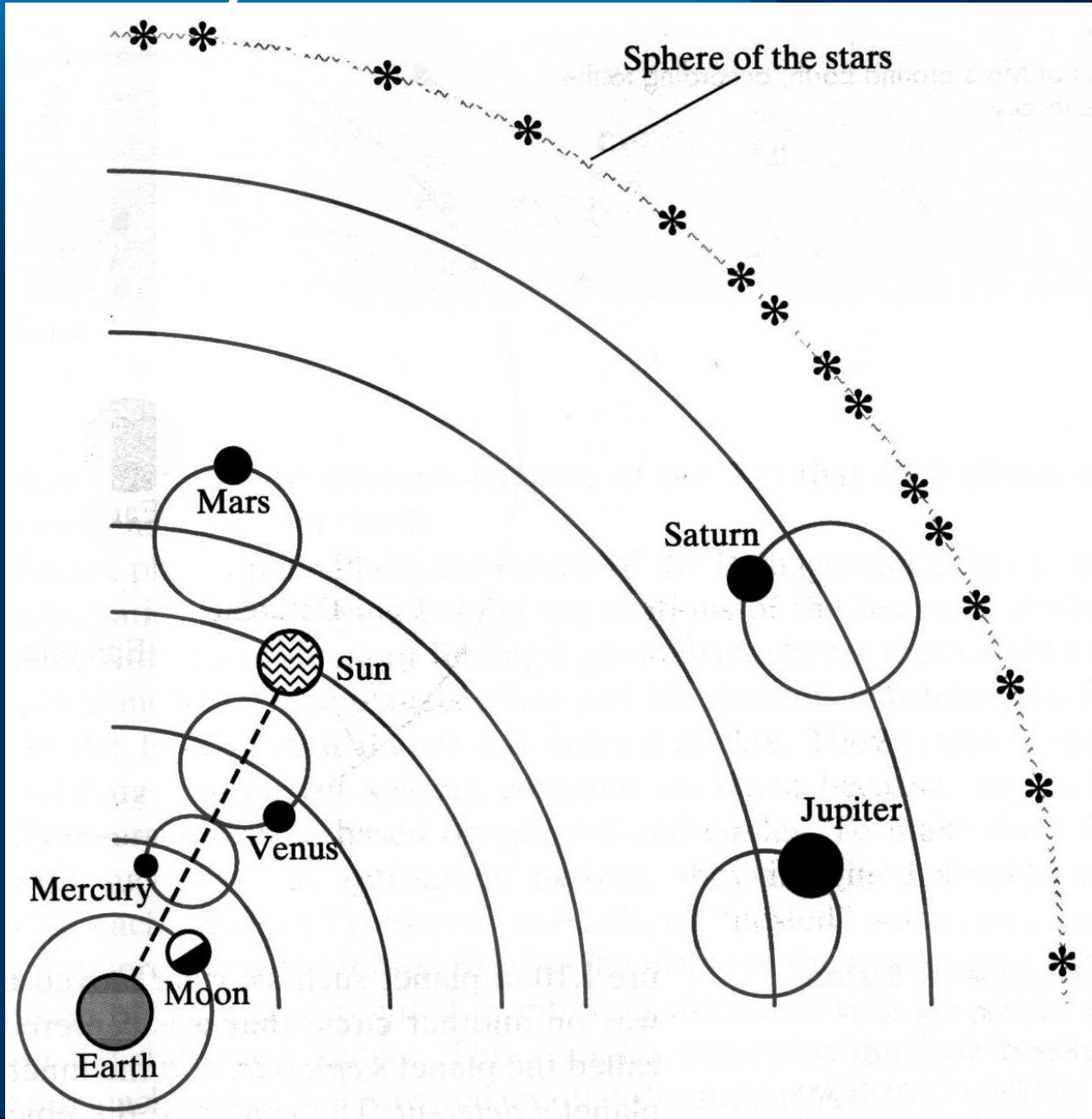




Ptolemy's Model

- 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

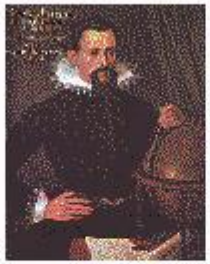
. 1546

TYCHO BRAHE

. 1601

JOHANNES KEPLER

. 1571



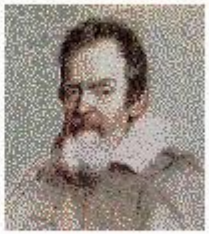
. 1609 New Astronomy

. 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

. 1571

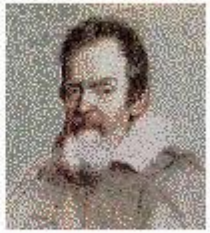
. 1609 New Astronomy

· 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

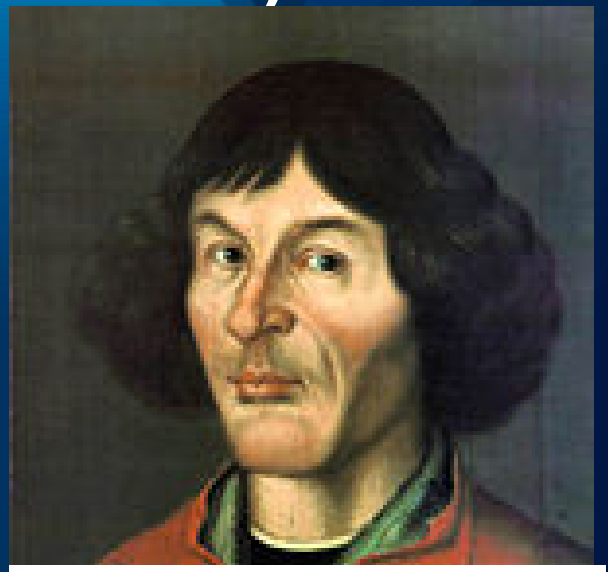
SIR ISAAC NEWTON

. 1686 Principia

. 1727

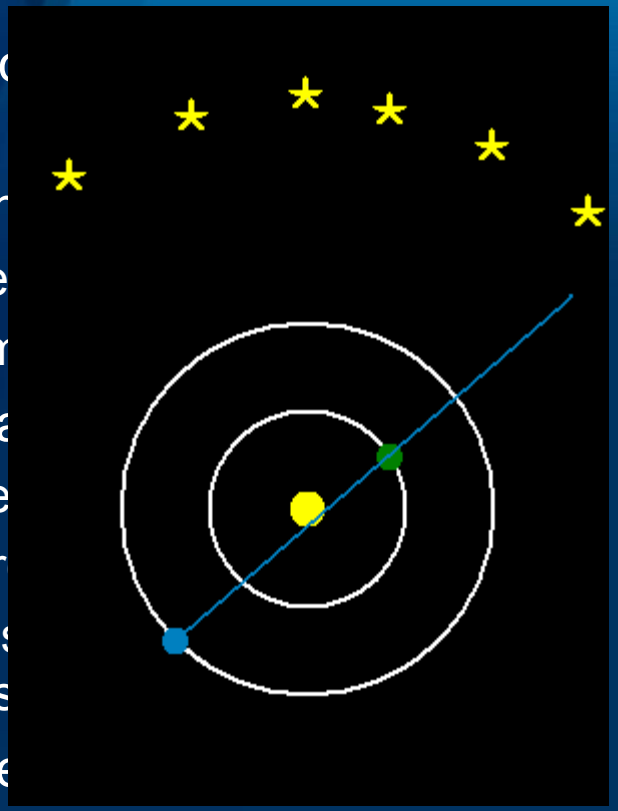
Copernicus (1473-1543)

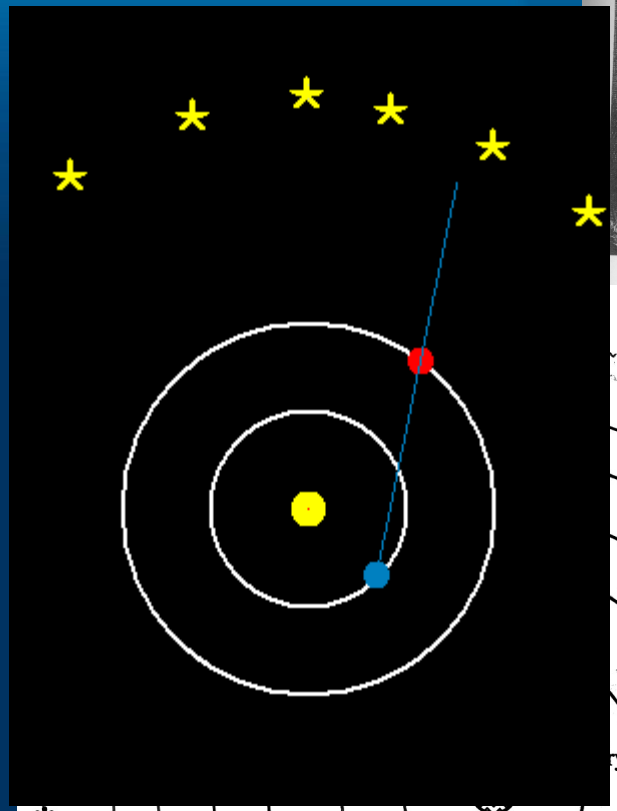
- Polish Son of merchant
- a mathematician, astronomer, physician, classical scholar, translator, Catholic cleric, jurist, governor, military leader, diplomat and economist
- Astronomy is avocation
- Publications
  - On the Revolutions of the Heavenly Spheres (1543)
  - Little Commentary (1514)
  - Trigonometry,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

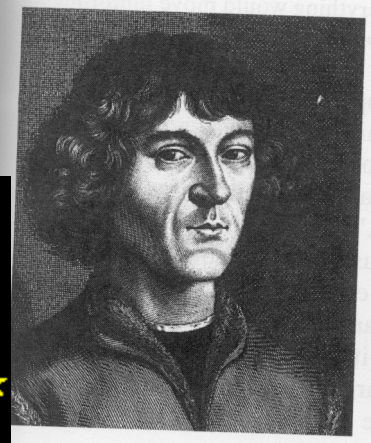


Copernicus

- Is there s
  about the
- Keep som
  - sphere
  - uniform
- Major Cha
  - Sun ce
  - Earth r
  - Earth i
    planets
- Establishe
- Less complicated explanation for retrograde motion







Copernicus

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

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

Copernicus

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

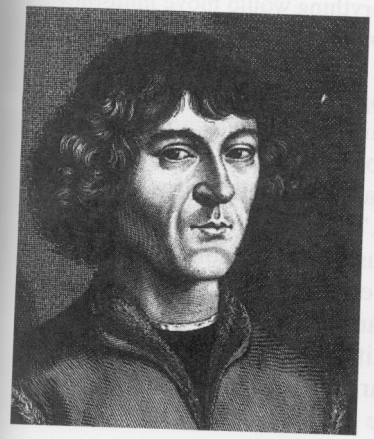


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd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

Tycho Brahe (1546-1601)

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

Tycho Brahe

- Left Kepler with 20 years of meticulous planet measurements.
  - 5x better precision
    - 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 duce the ons!

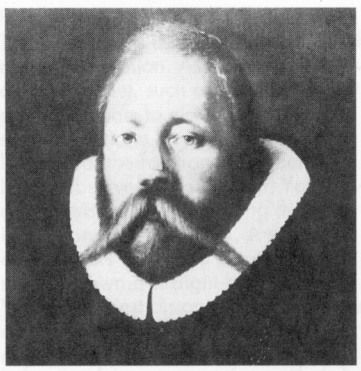


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

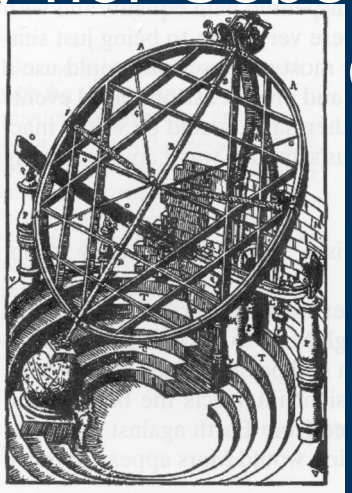


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

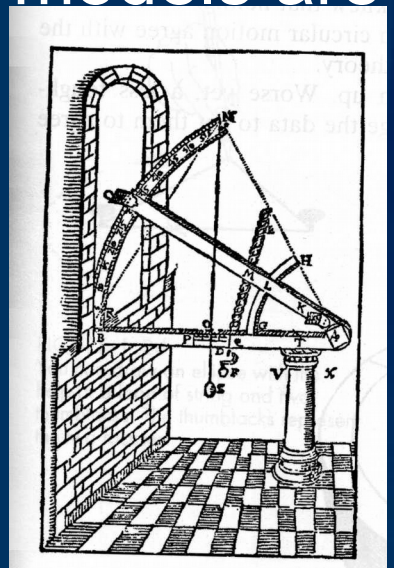


FIGURE 1.20
An instrument that Brahe used for

Johannes Kepler (1571-1630)

- Mathematician, astronomer, astrologer
- Had religious convictions - *God had created t… intelligibl… the natur…*
- Geometr… regular s…
- Mysteriu…
- Astronon…
- The Harr… Law

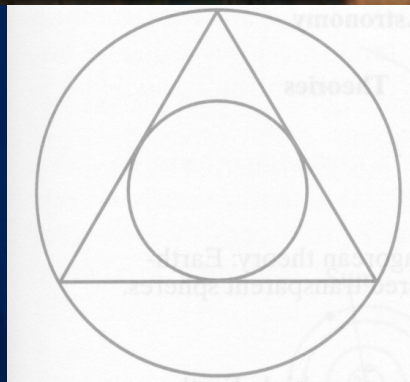
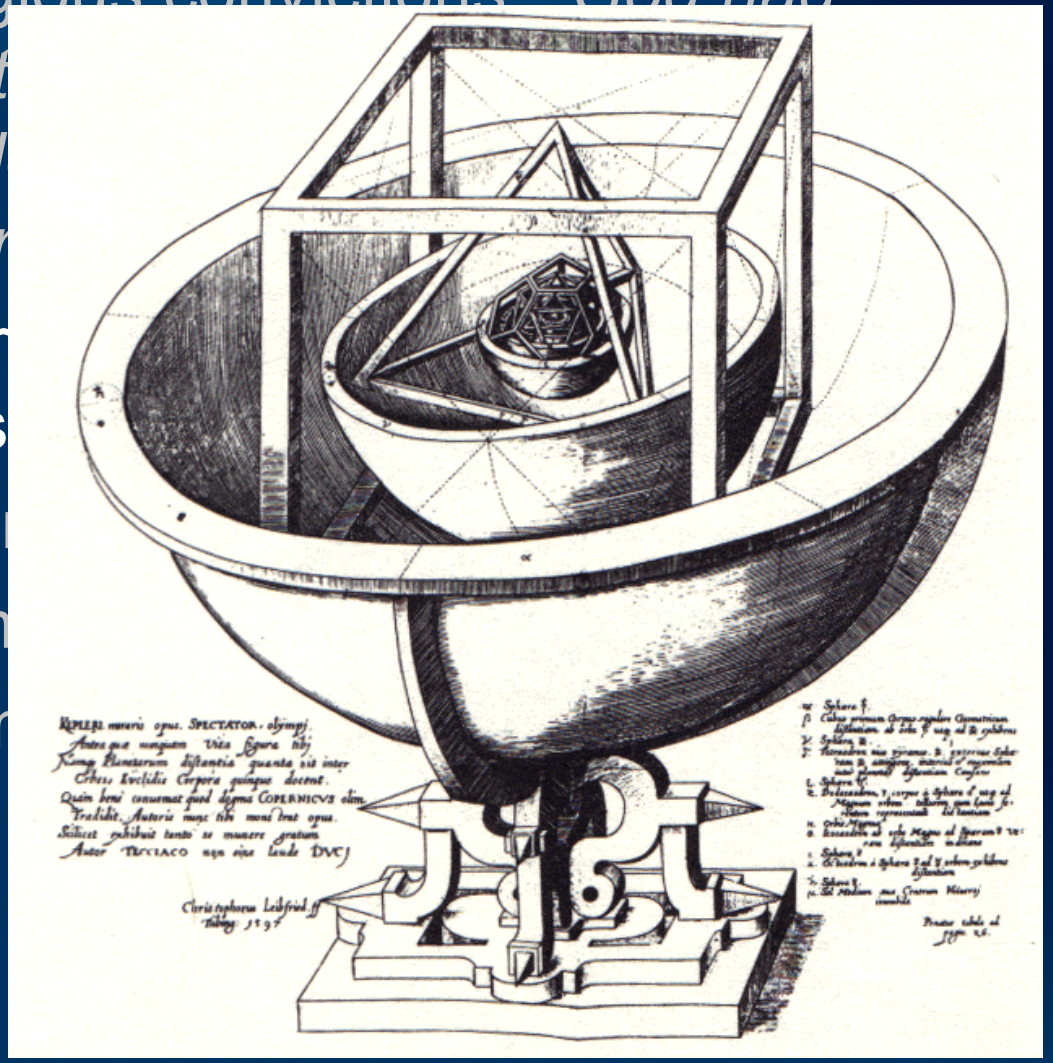


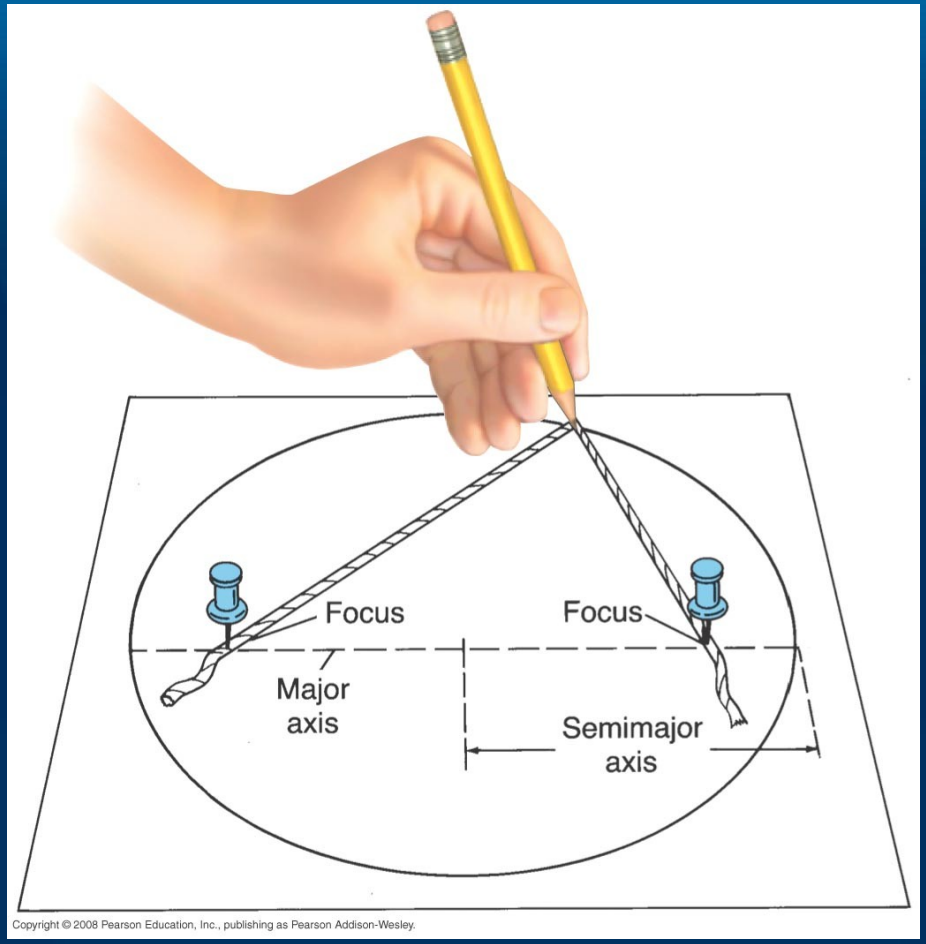
FIGURE 1.23
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.



Johannes Kepler

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

Kepler's 1st law



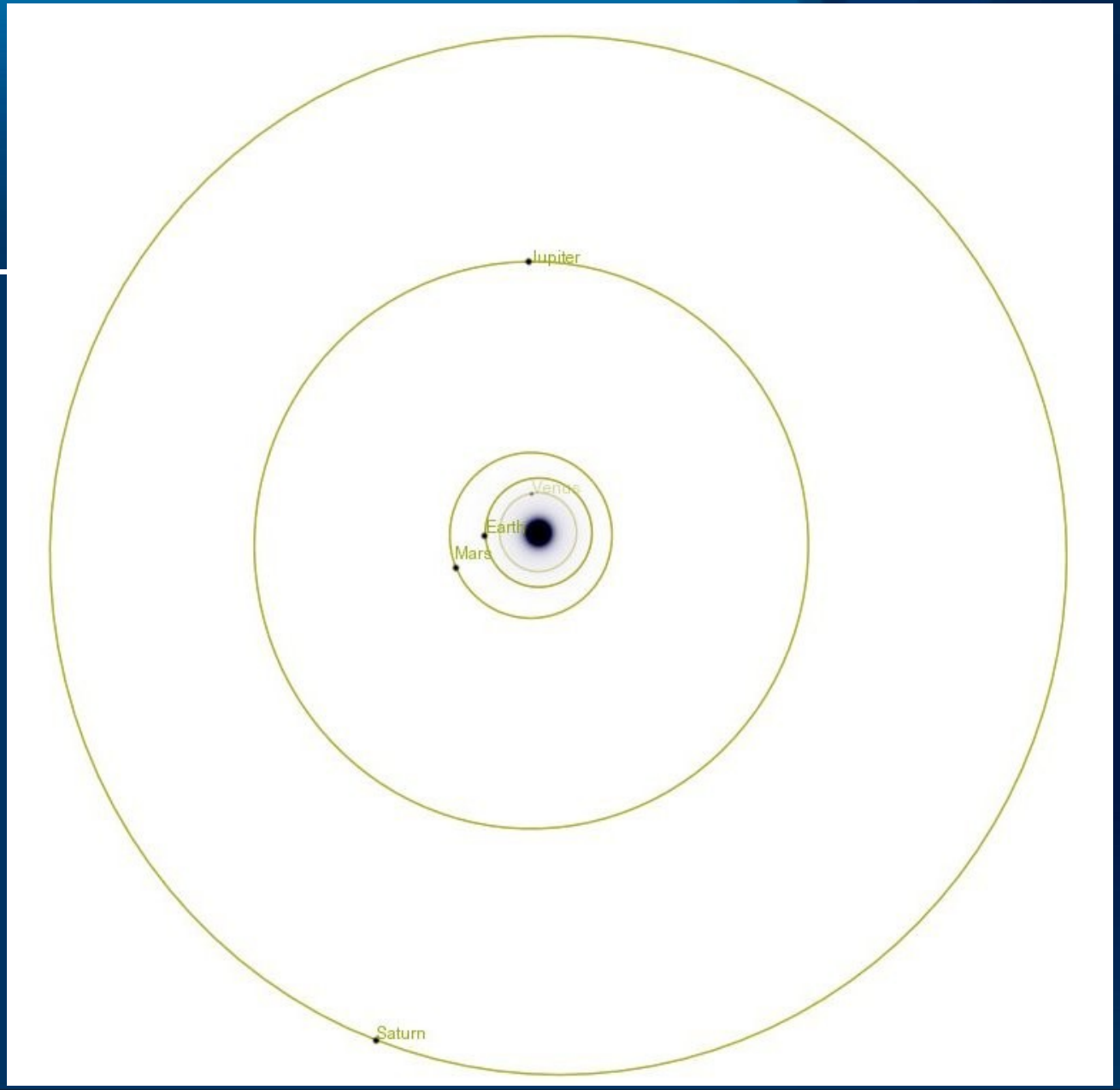
The planets follow elliptical paths with the Sun at one focus.

Johannes Kepler

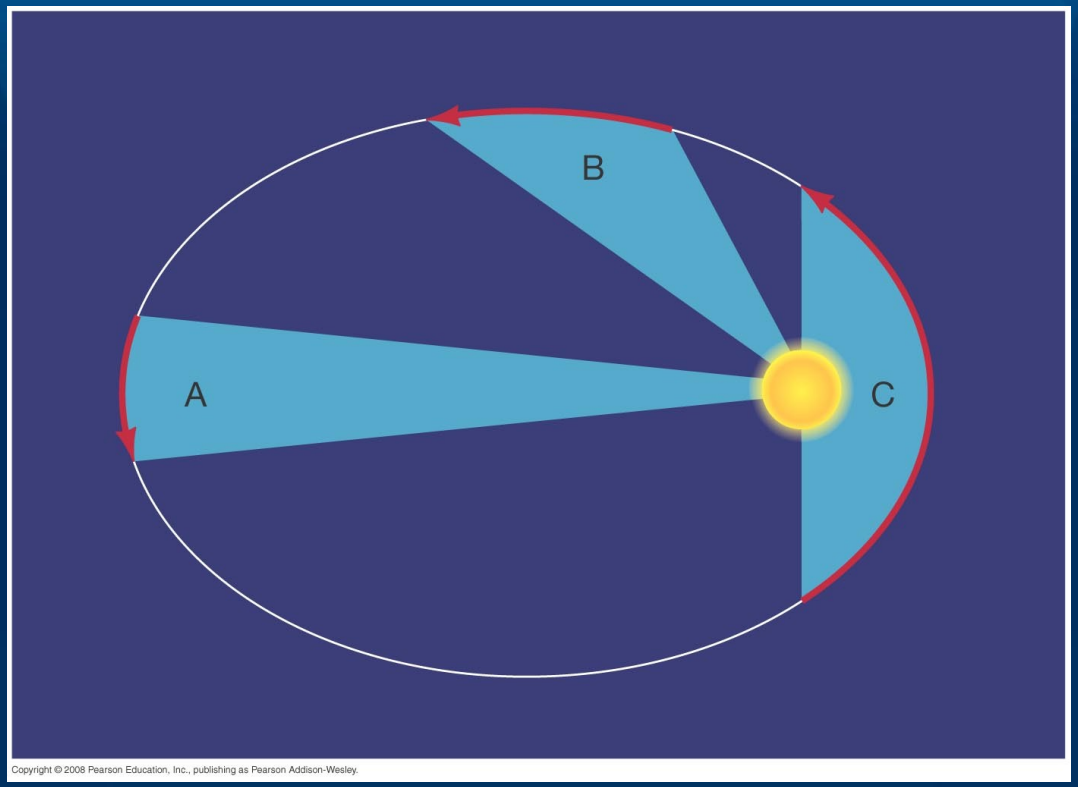
Inner Planet orbits
- Mercury most eccentric (0.206)
- Almost same as off-centered circles, but not.

Outer planets
- Mars most eccentric (0.09)

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

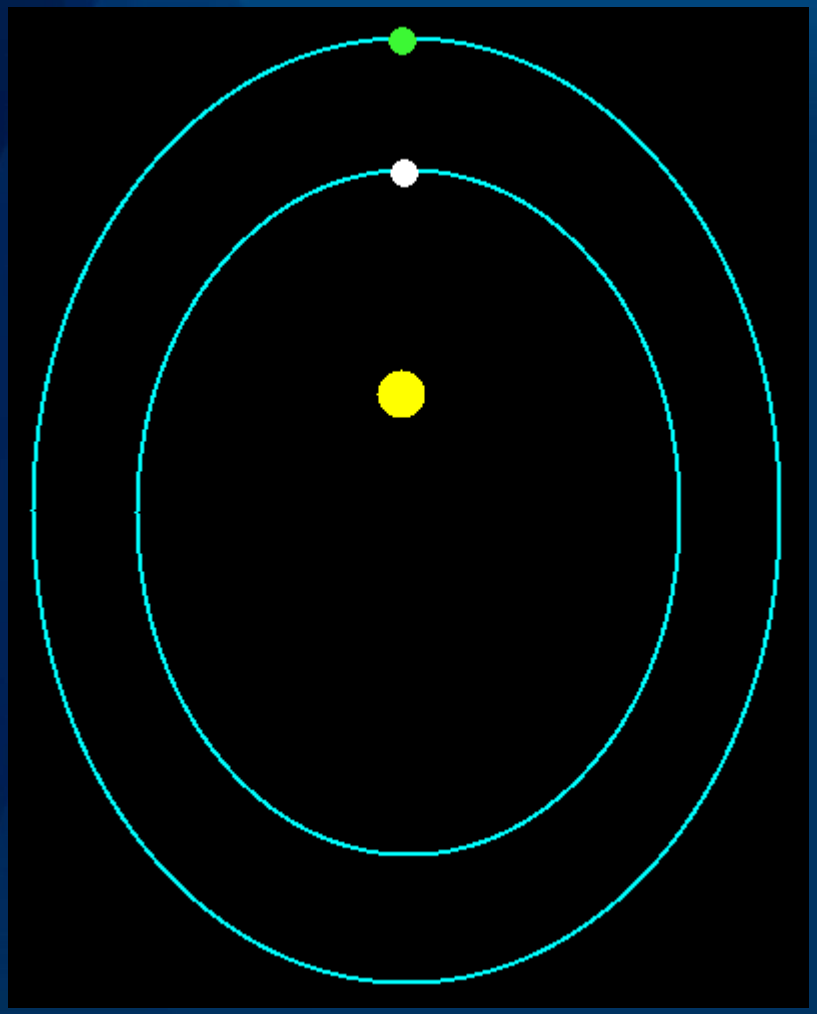


Kepler's 2nd Law



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

Kepler's 3rd law



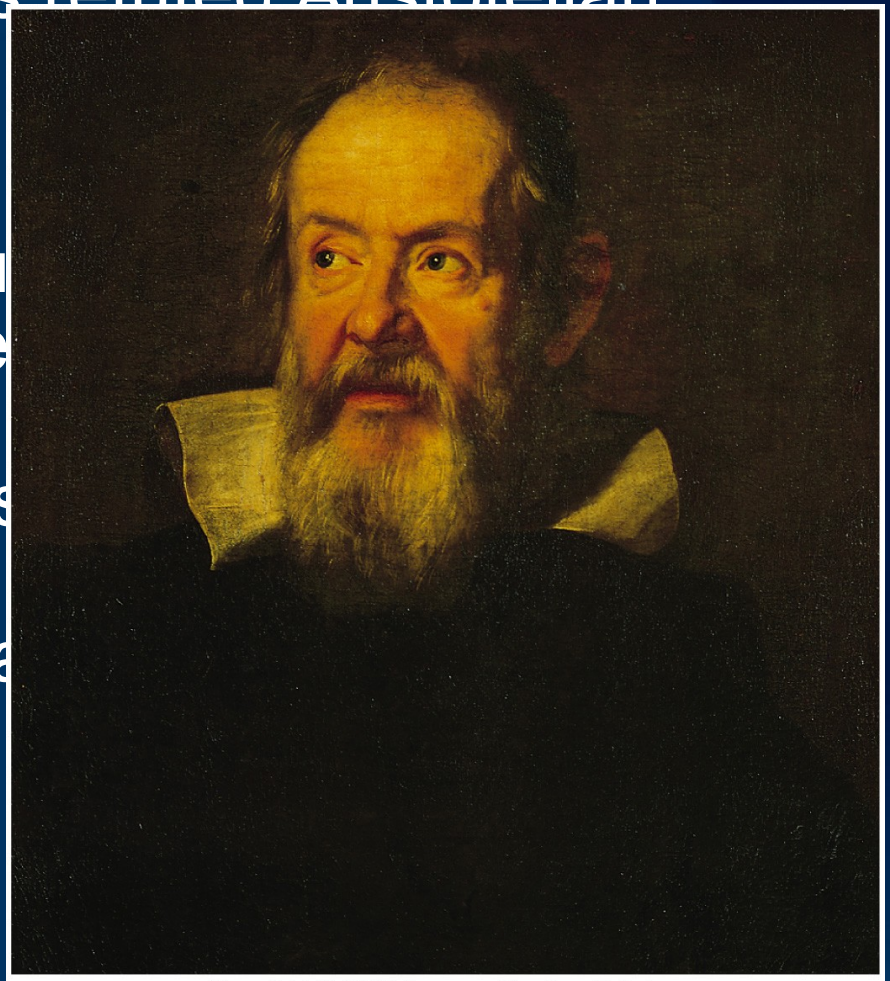
$P^2=a^3$

Period increases with distance from the Sun.

P=period, in years
a=semi-major axis, in AU.
See kepler.swf.

Galileo (1564-1642)

- He supports Copernicus, Kepler
- 1609 - uses telescope for astronomical observations
- Experiments & observations refuted Aristotelian physics
  - –Free-fall, inclined plane, experiments
  - –Moons of Jupiter orbit 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

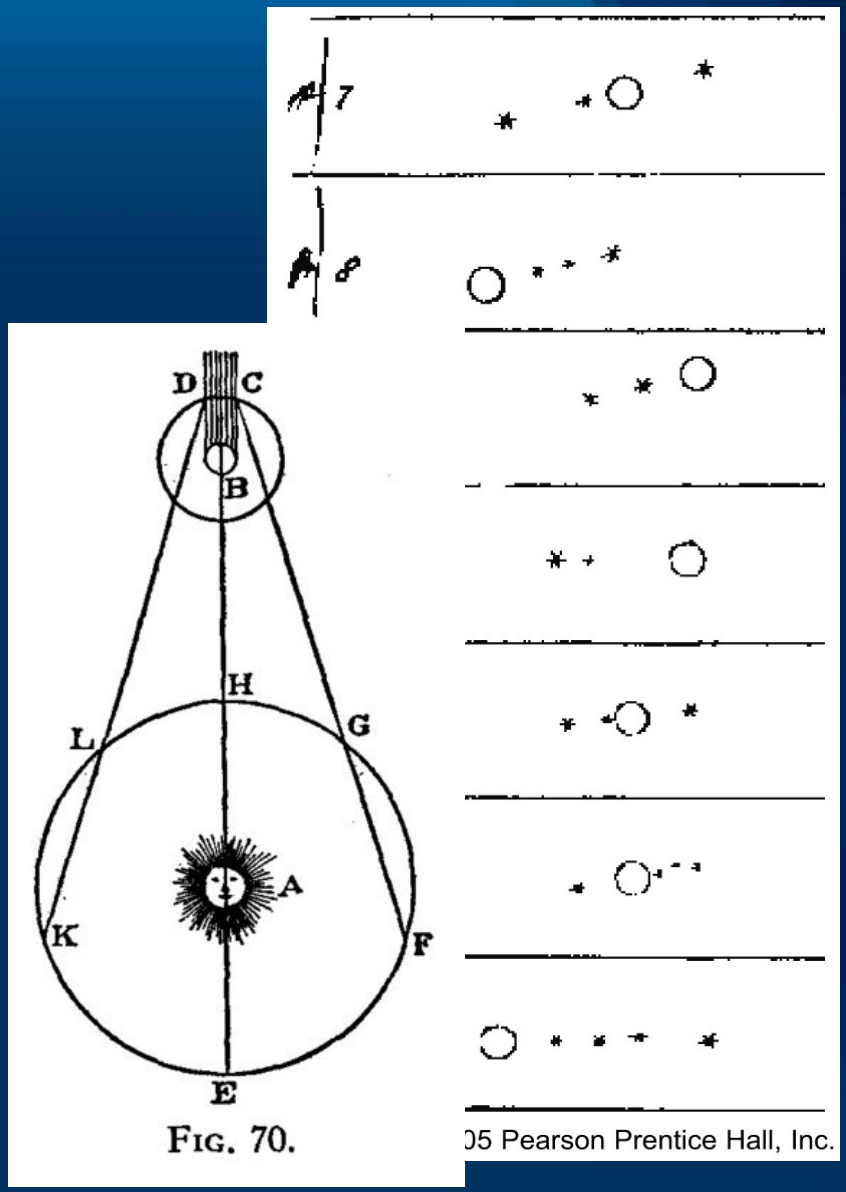
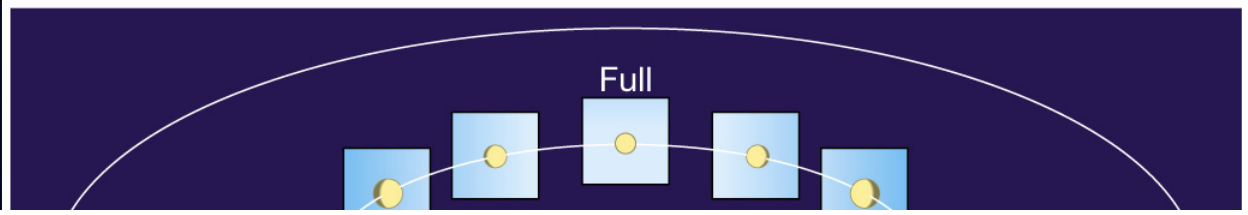


FIG. 70.



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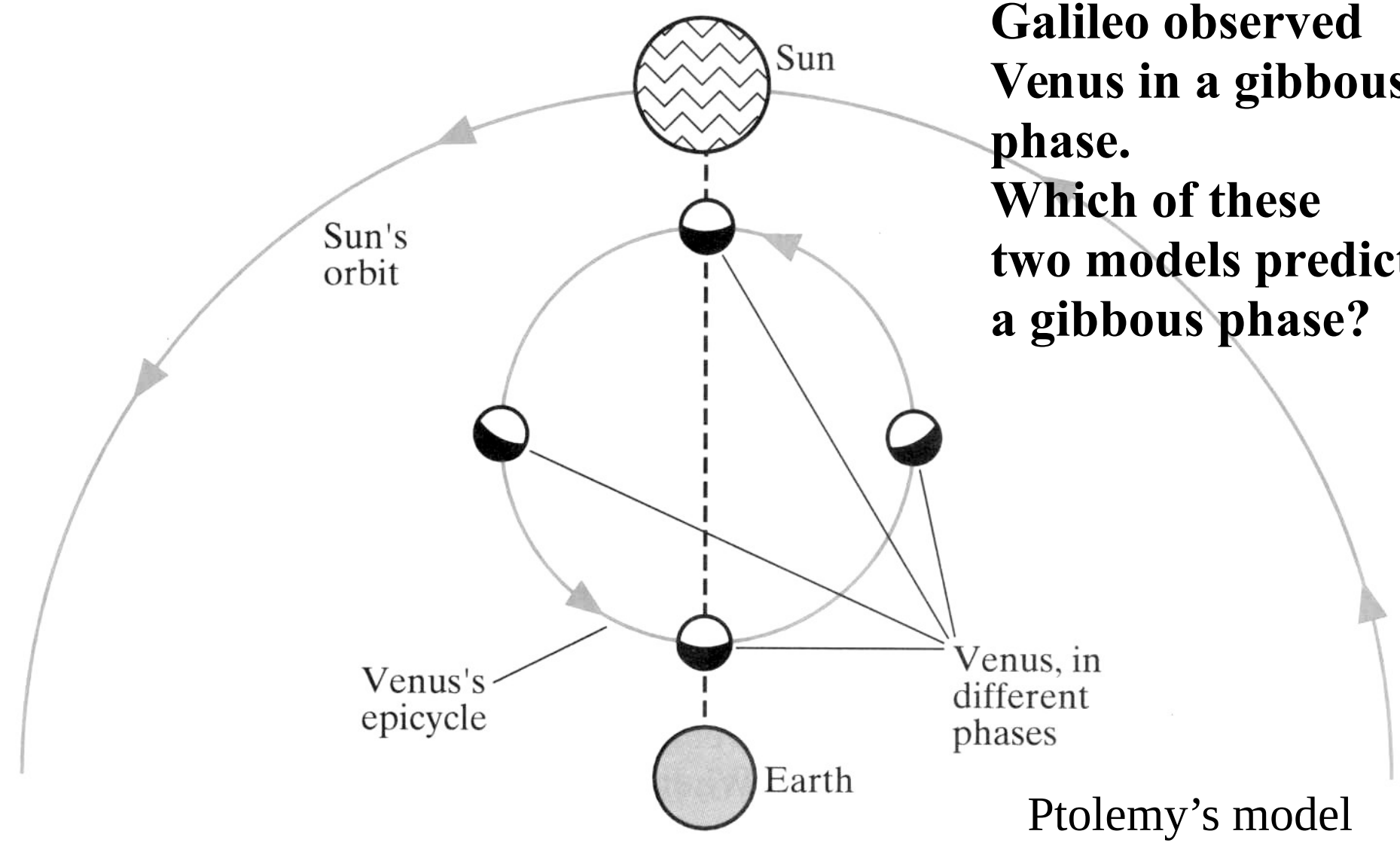

Galileo observed Venus in a gibbous phase.
Which of these two models predict a gibbous phase?

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.
- 1992: Catholic Church acknowledges their error

I

- Englis
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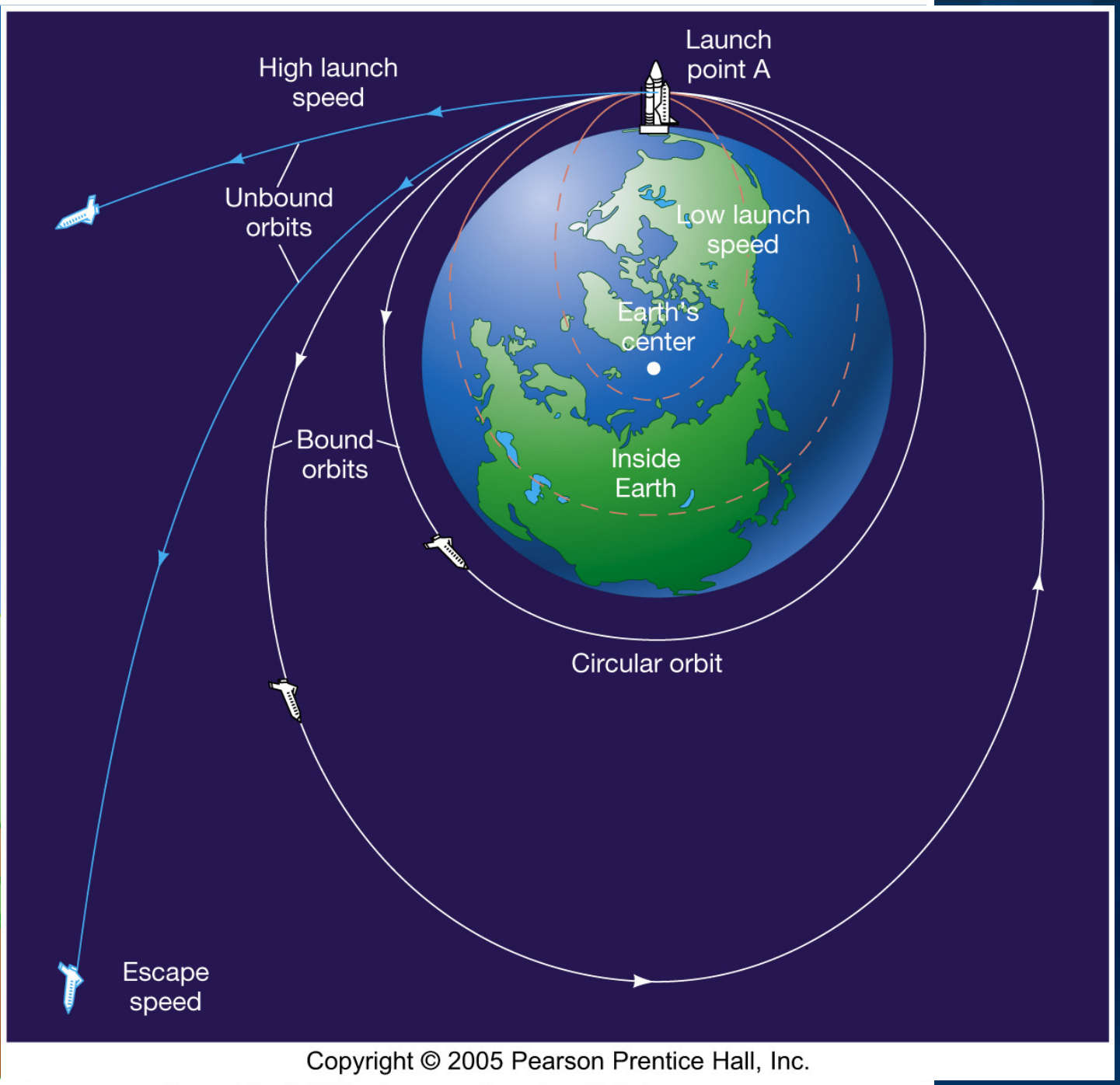
- Invent
- Urgec
  Philoso
- 3 laws
- Unive
  - –Can
  - –Fina
- *"God g*
  can be



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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

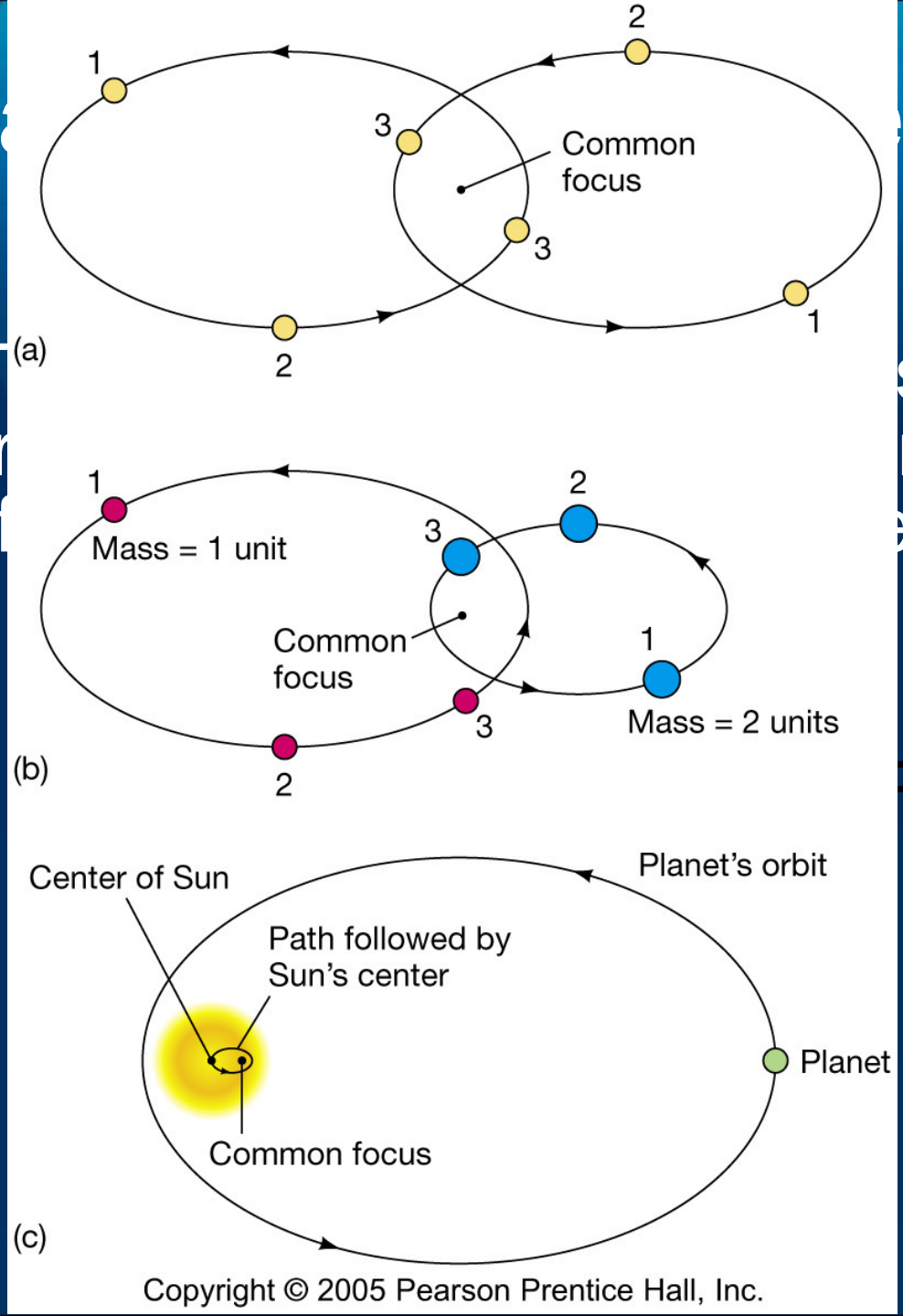
$$F = G\frac{m_1 m_2}{r^2}$$

  - –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."*

Isa ... es”

- Kepler I: T ... s with the pr ... r of mass of ... e Sun)
- Kepler III: ... system to

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



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

Fi

- Ve
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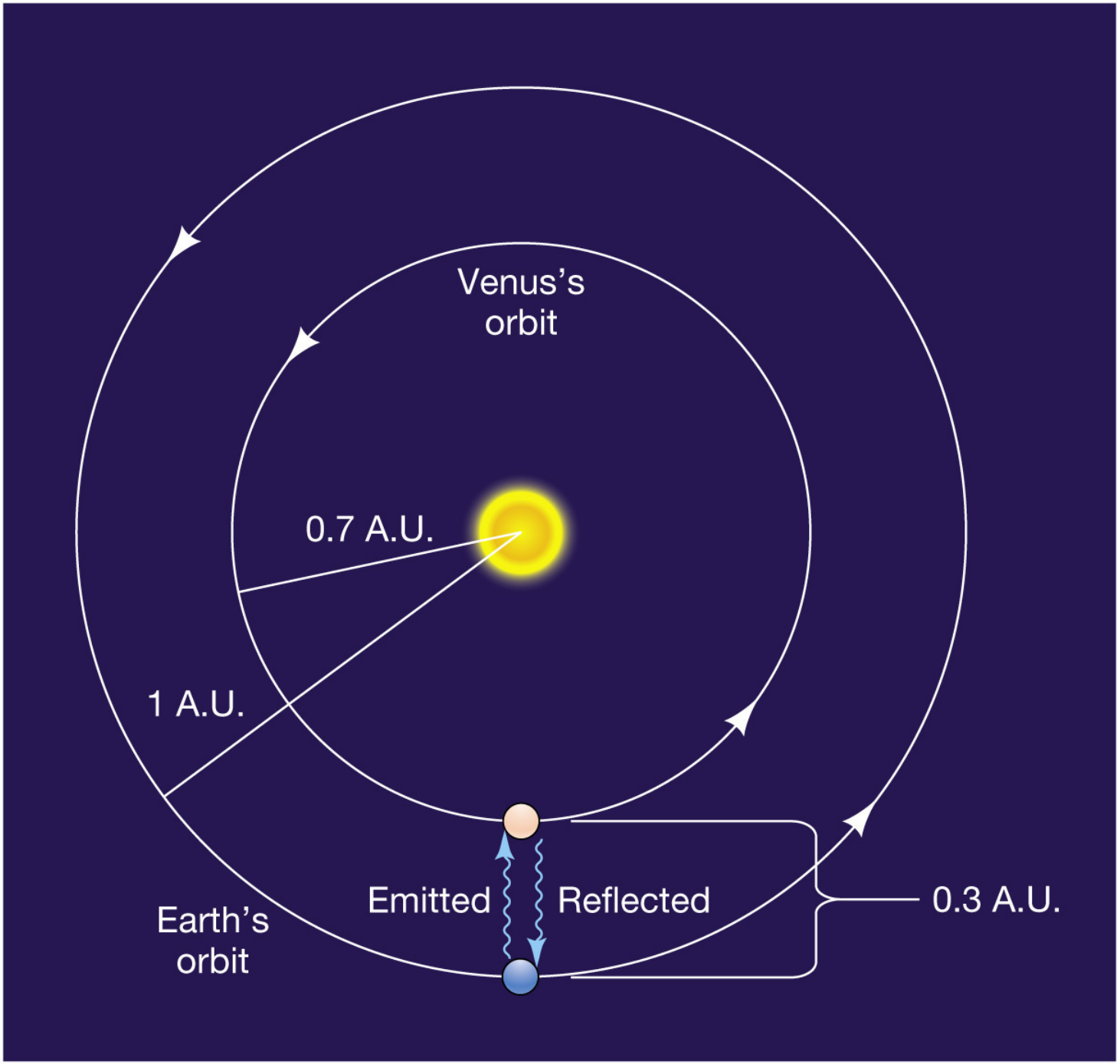

's view out
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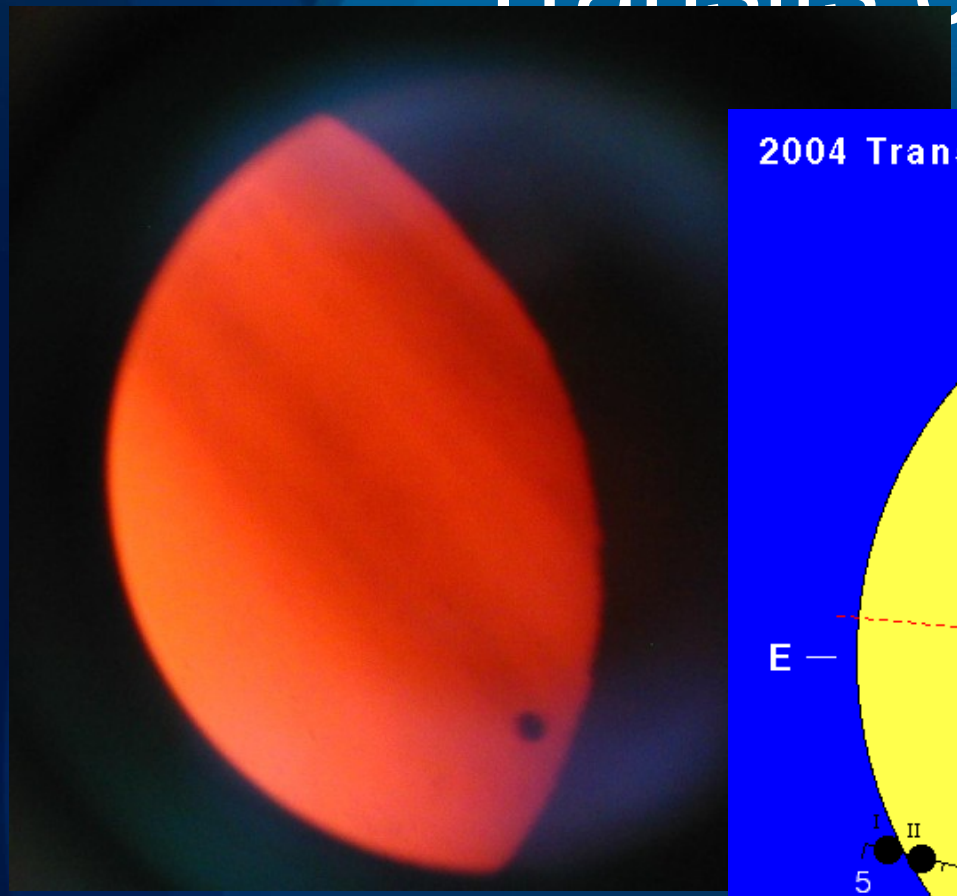
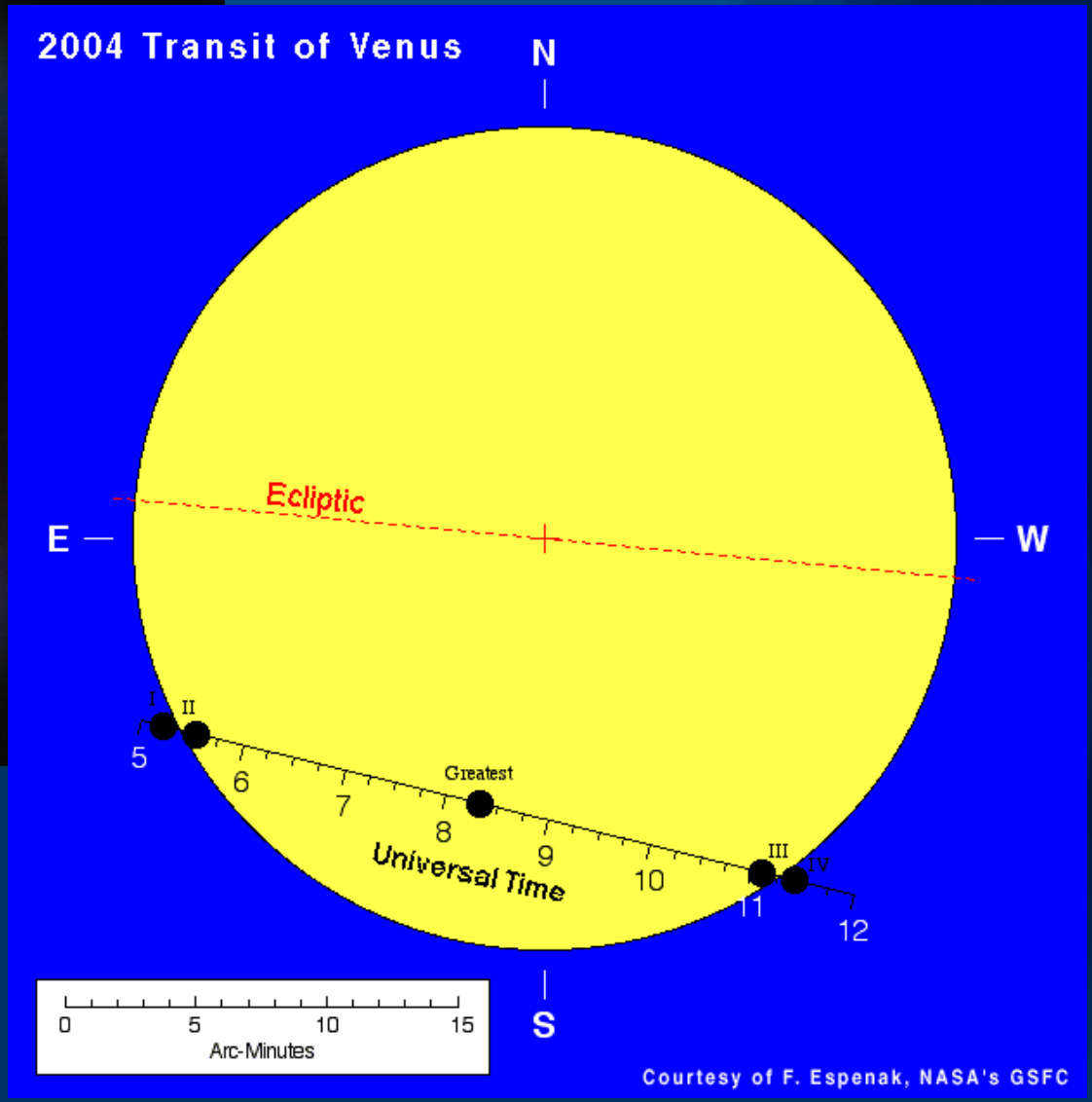
Figuring out the remaining loose ends of the Solar System

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

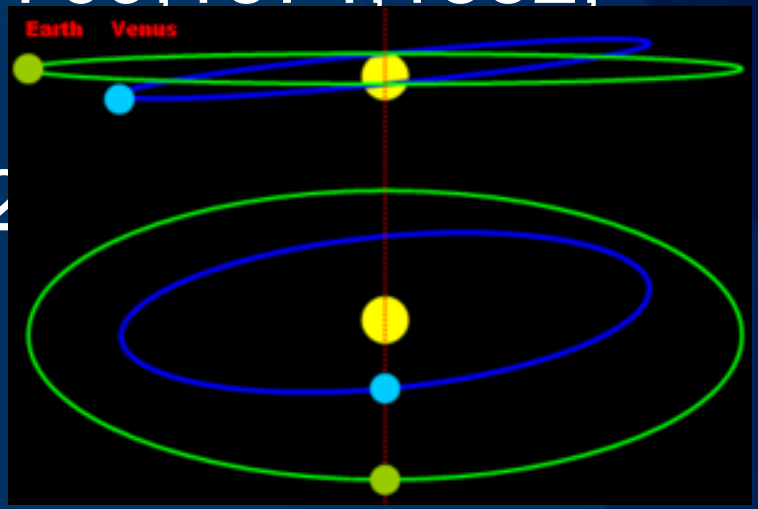
Transits of Venus





Transits of Venus

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



Last transit: June 6, 2012

Next transits: 2117, 2125

How it works: 3.4° tilt, 8:

243 yr cycle.

Inferior conjunction while both planets on line

of nodes.

Science vs Superstition – it never ends

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

General philosophy of science

Karl Popper: Logic of falsification

Theories can never be verified by observation.

Theories can be falsified by observation, and so discarded.

The only acceptable theories are those which are falsifiable.

Thomas Kuhn: Paradigms and paradigm shifts

"Normal science" -- investigation within a paradigm

Revolutions -- paradigm shifts driven by anomalous data

Niels Bohr: Correspondence principle

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

A Summary of the Early History of Astronomy