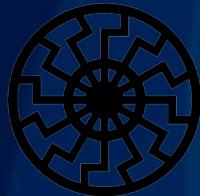


# The Copernican Revolution - Separating Science and Superstition

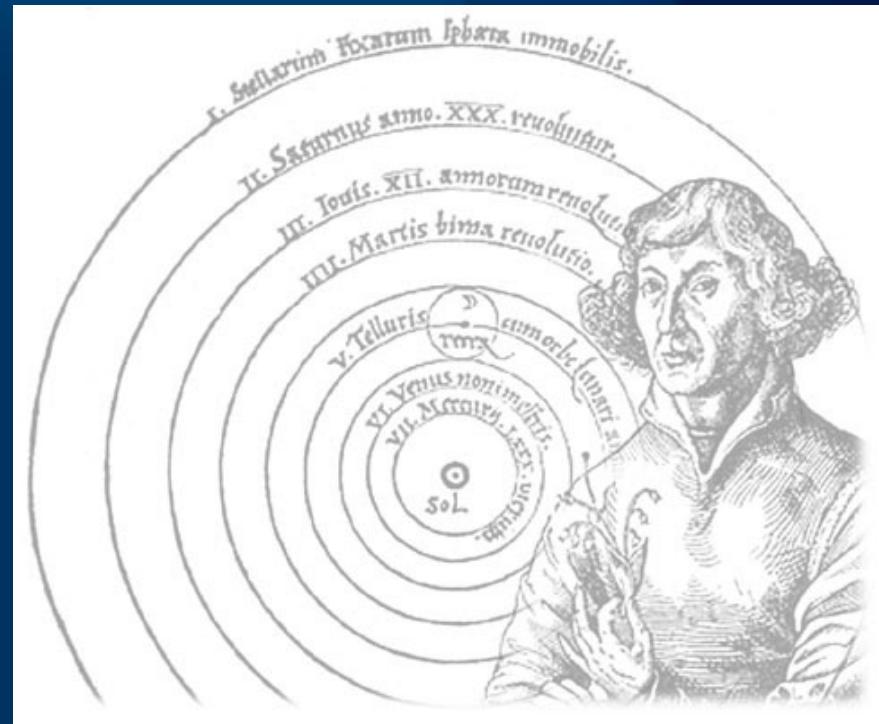


J. Pinkney  
ONU 2021



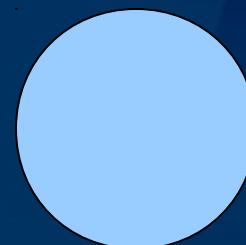
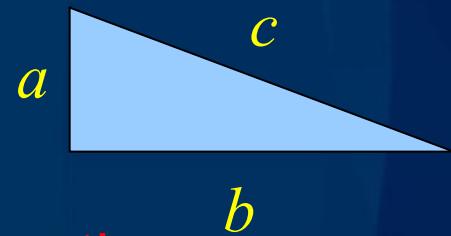
# Outline

- Our universe viewed by the ancients
- Greek astronomy
- Copernican Revolution
  - Nicolaus Copernicus
  - Tycho Brahe
  - Johannes Kepler
  - Galileo Galilei
  - Isaac Newton
- Loose ends: first parallax, aberration 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  $\sim 1.0''$ , 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)

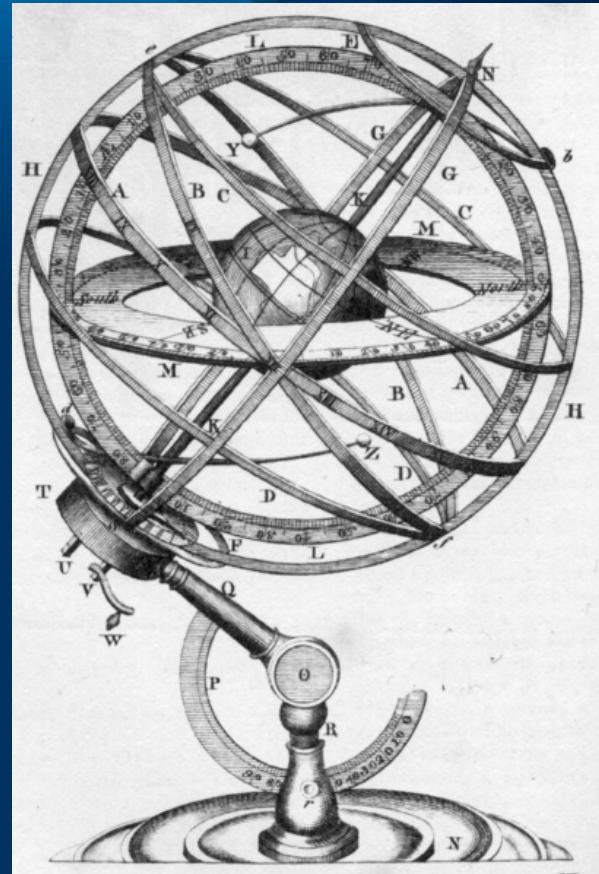
The Earth orbits around the Sun (!)

Eratosthenes (276-195 BC)

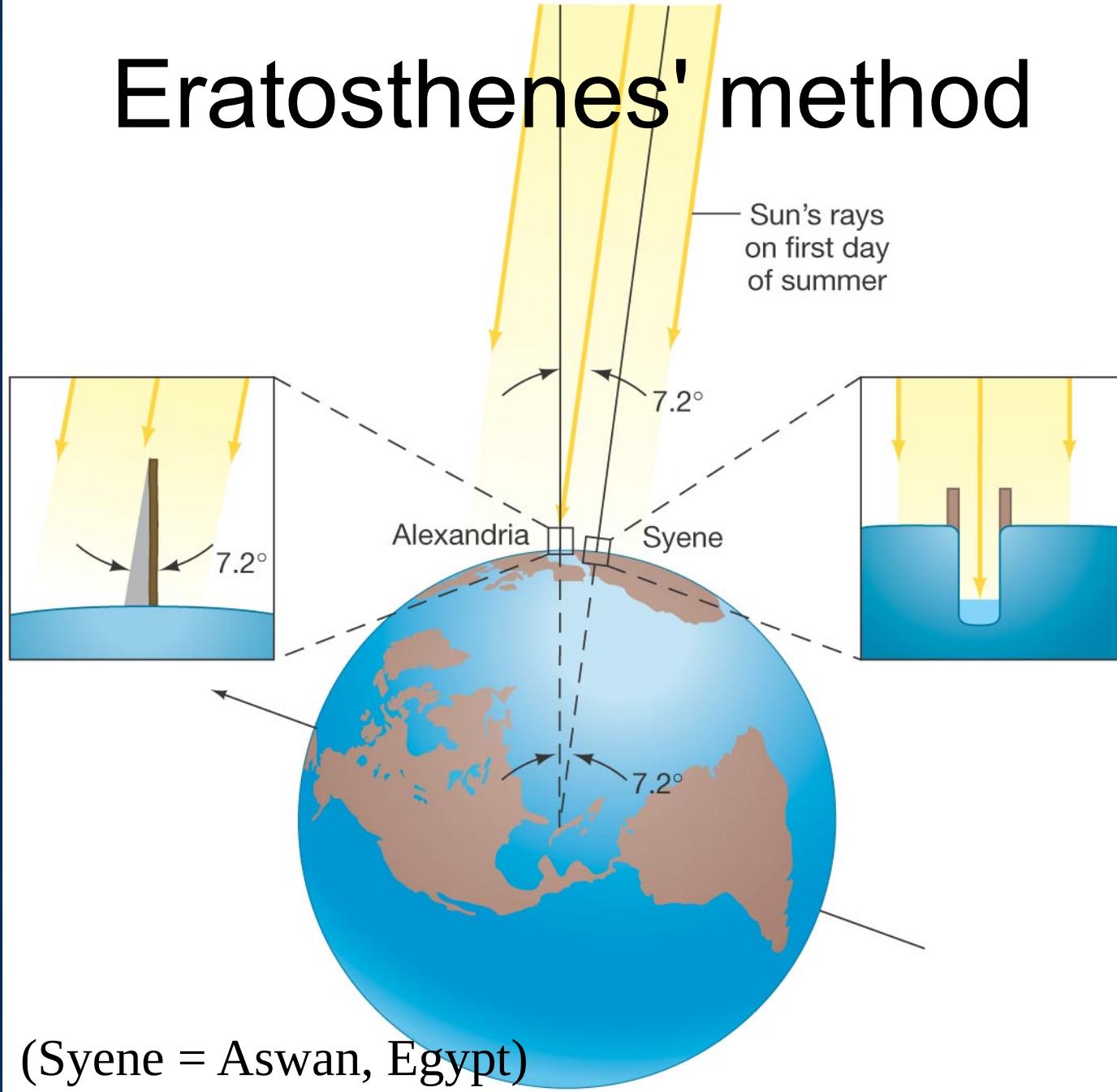
- Measured circumference of the Earth.
- Invents armillary sphere

• 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



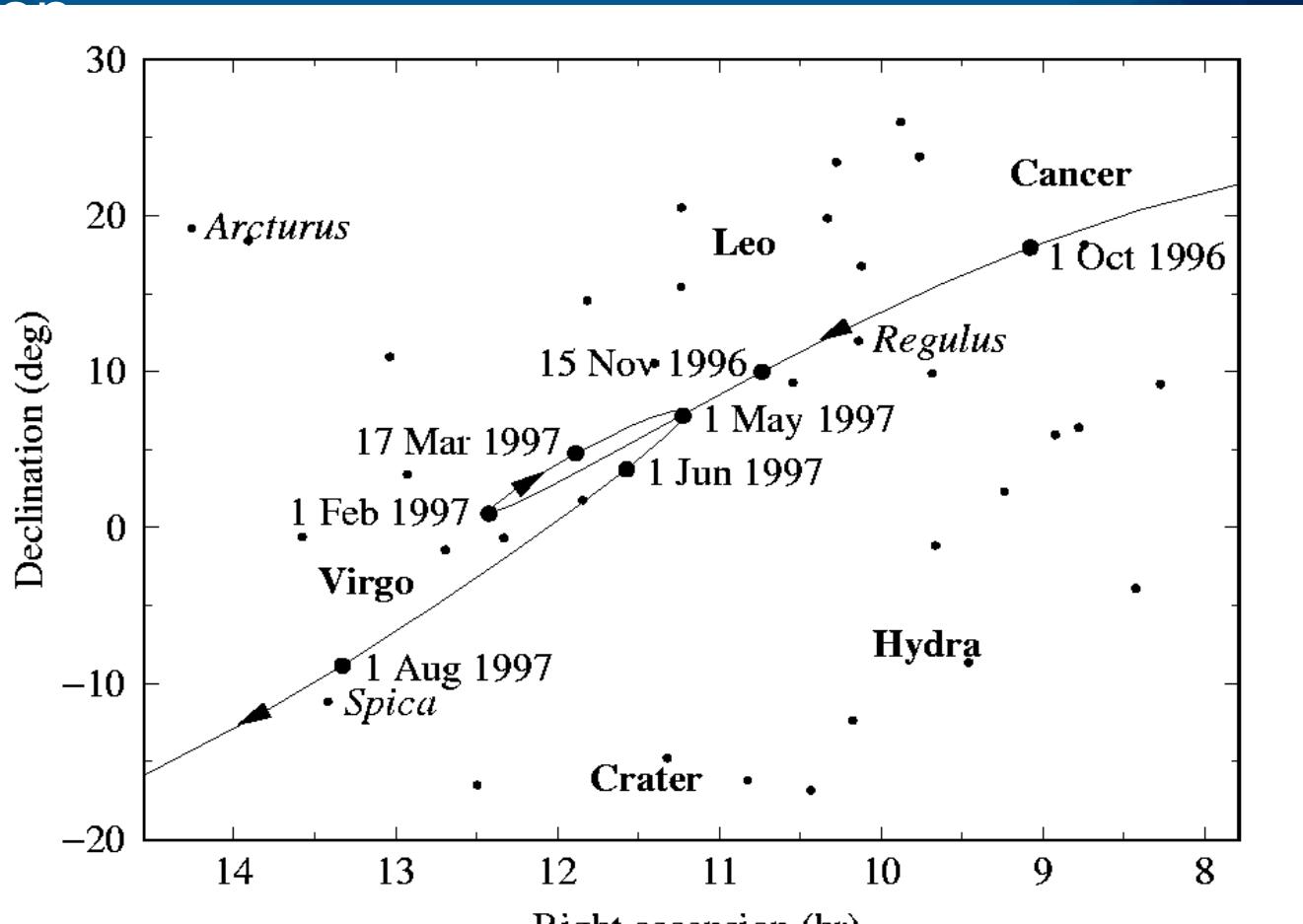
# Knowledge of the Ancient Greeks

- 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

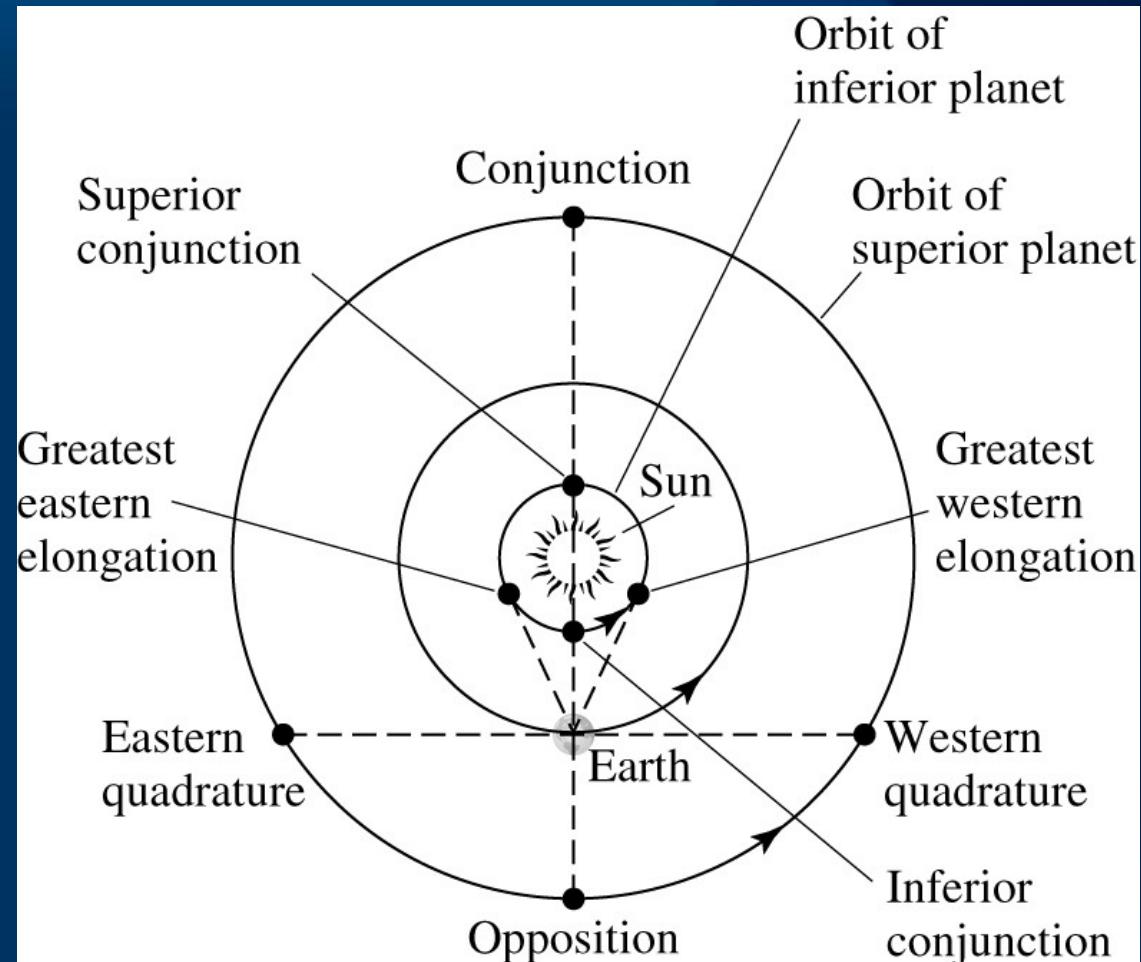
- Daily motion
- Change across sky
- All orbit Sun
- Usually we call



*Retrograde Motion!*

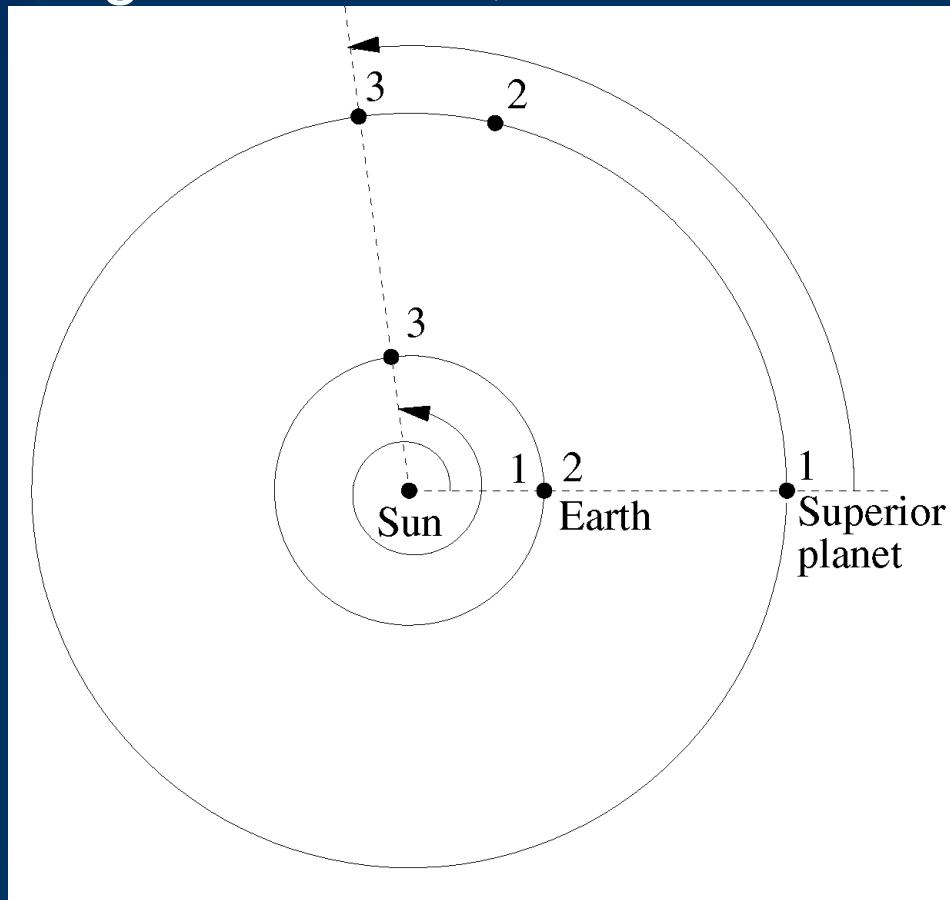
# Planetary Configurations

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



# Synodic and Sidereal Periods

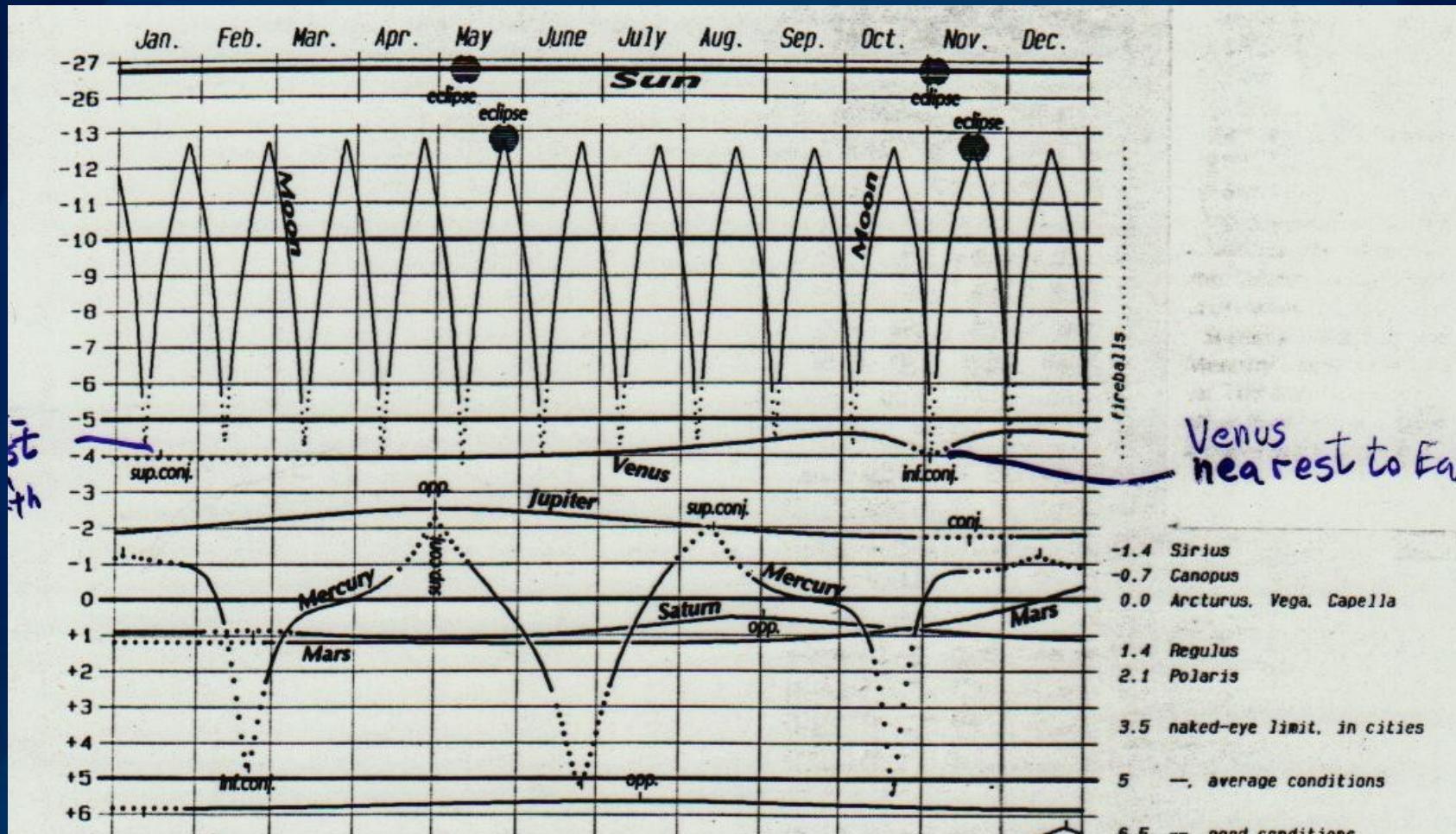
- Synodic period: time interval between successive conjunctions or oppositions, 1 → 3
- Sidereal period: time interval for one complete orbit relative to background stars, 1 → 2



# The Appearance of the Planets

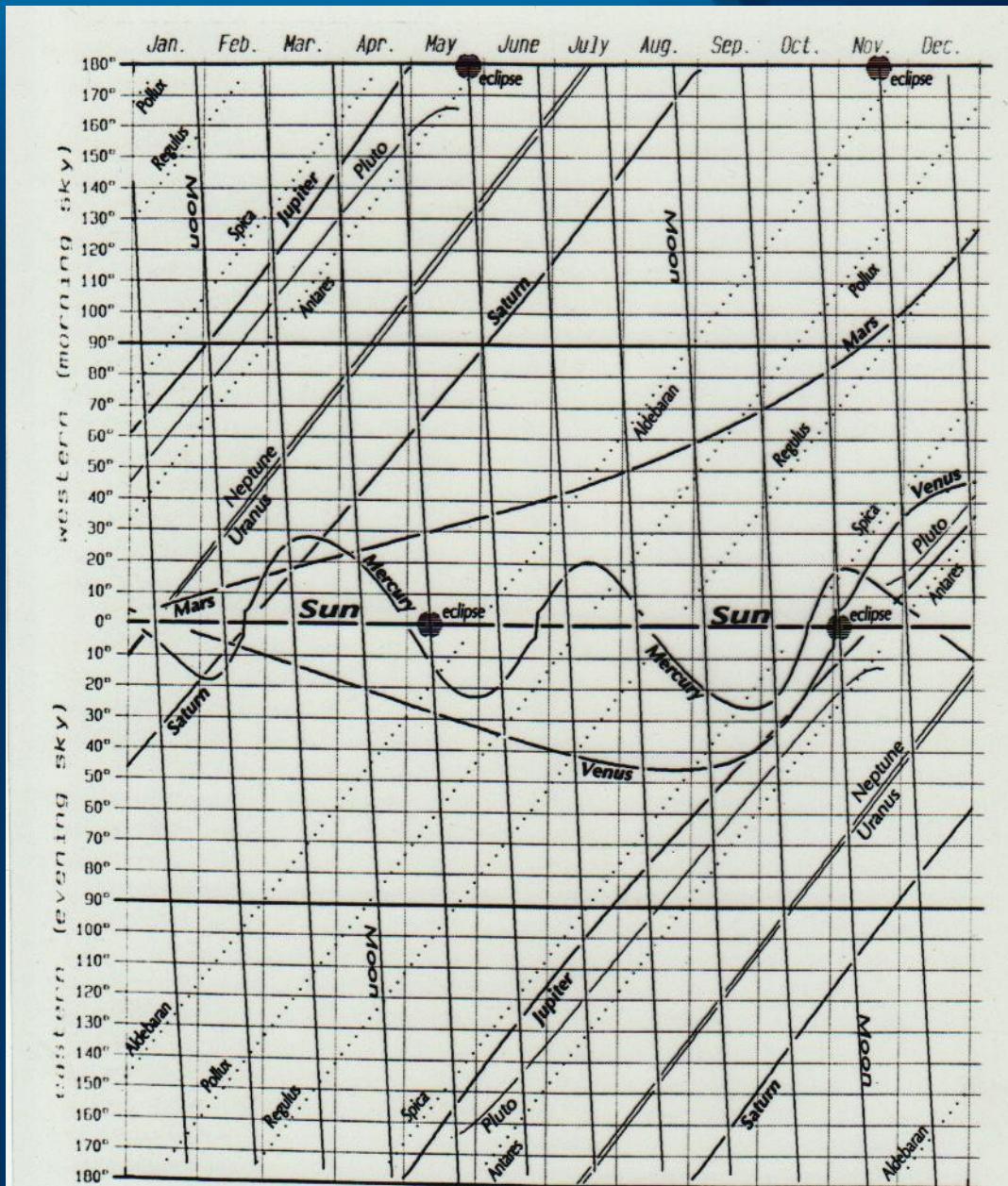
Brightness, measured in magnitudes.

- Smaller magnitude → brighter.



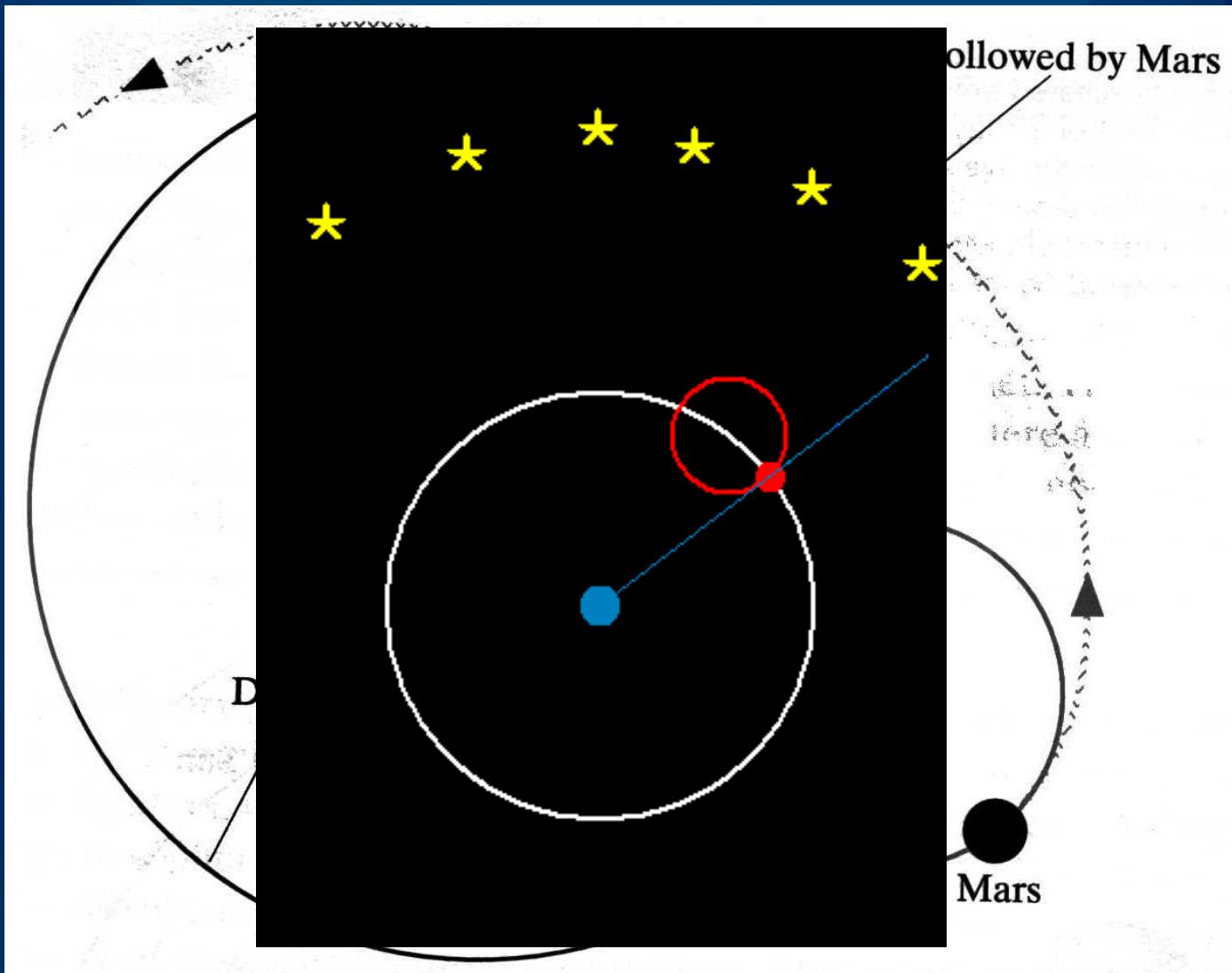
# The Appearance of the Planets

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



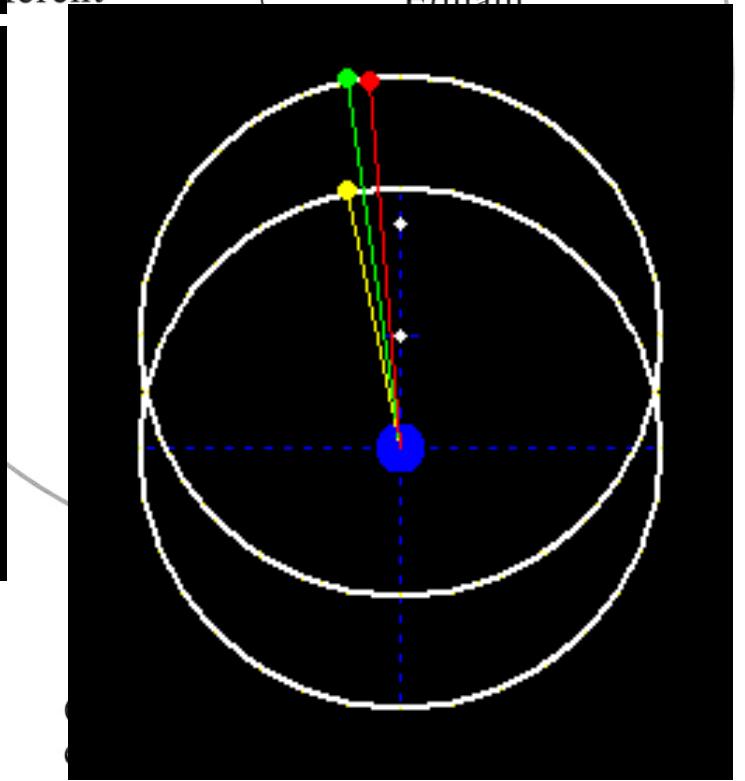
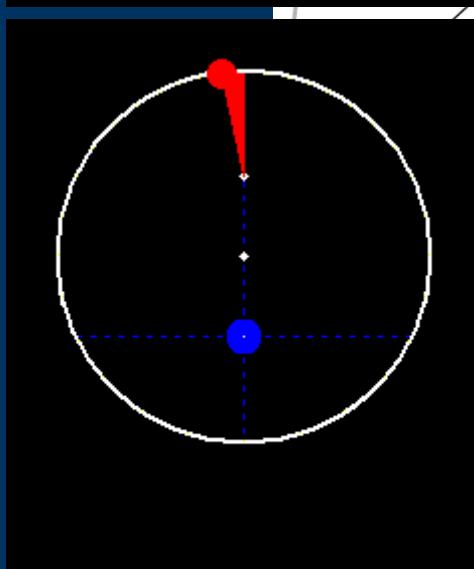
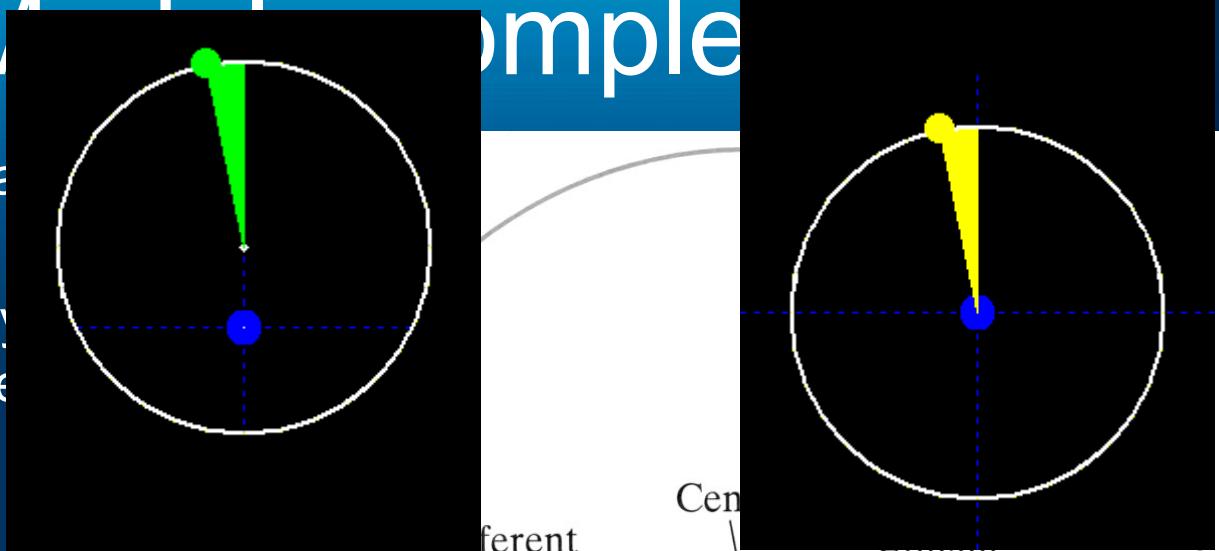
# Epicycles on Deferents

- Ptolemy et al. desired uniform circular motions



# Ptolemy's 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



See "marsorbit.swf".

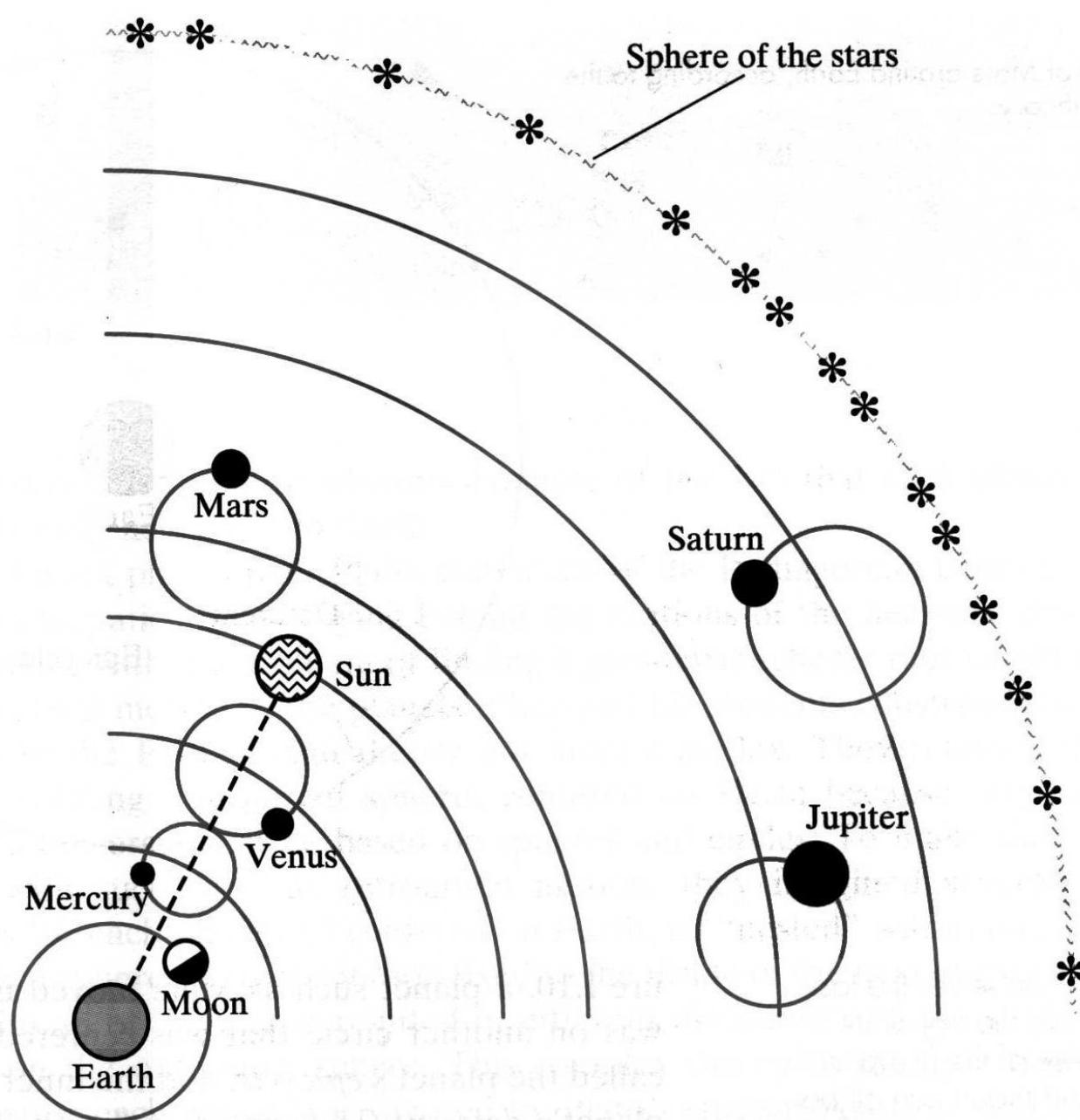
# Ptolemy's Model

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



# THE COPERNICAN REVOLUTION

· 1473

NICOLAUS COPERNICUS



· 1512 1st Comment

· 1543 *De Revolutionibus*

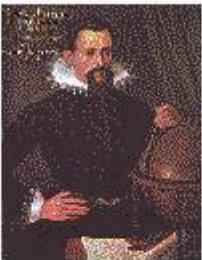
· 1546

TYCHO BRAHE



· 1601

JOHANNES  
KEPLER

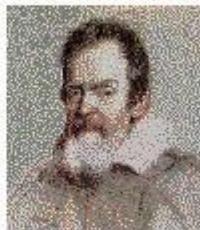


· 1571

- 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



1543 *De Revolutionibus*

1546

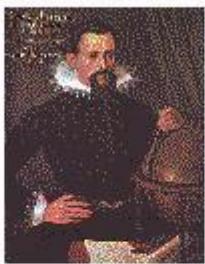
TYCHO BRAHE



1601

JOHANNES  
KEPLER

1571



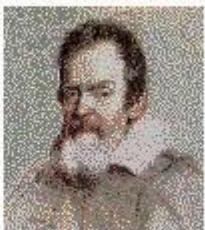
1609  
*New Astronomy*

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

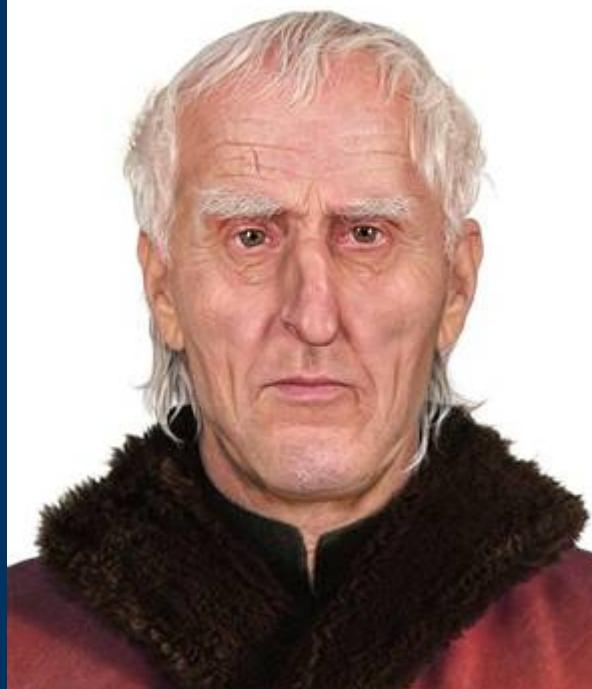
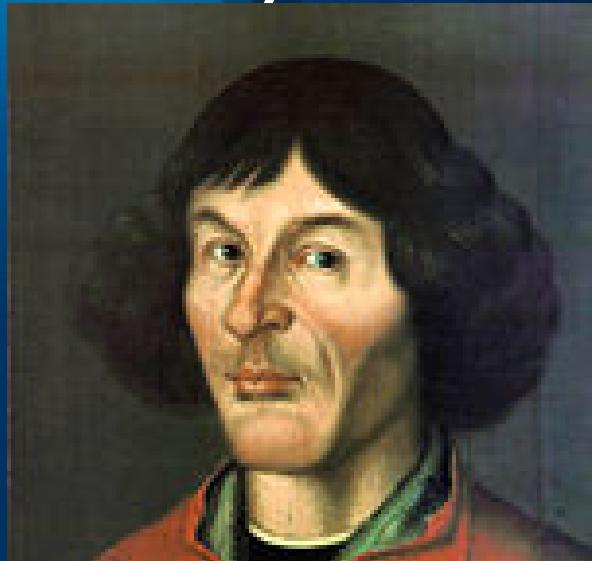


1686 *Principia*

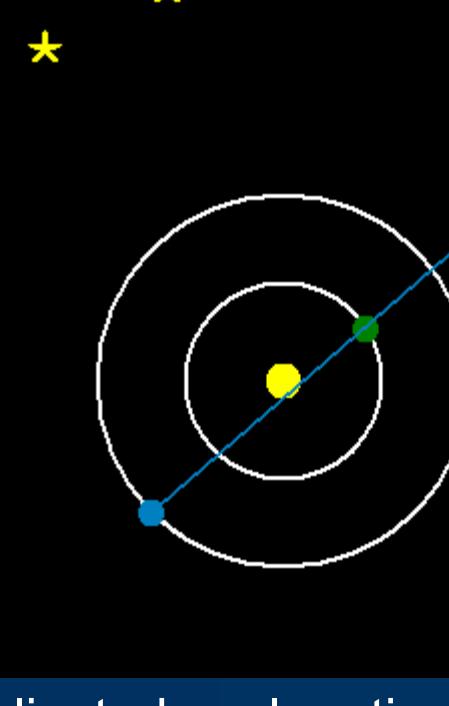
1727

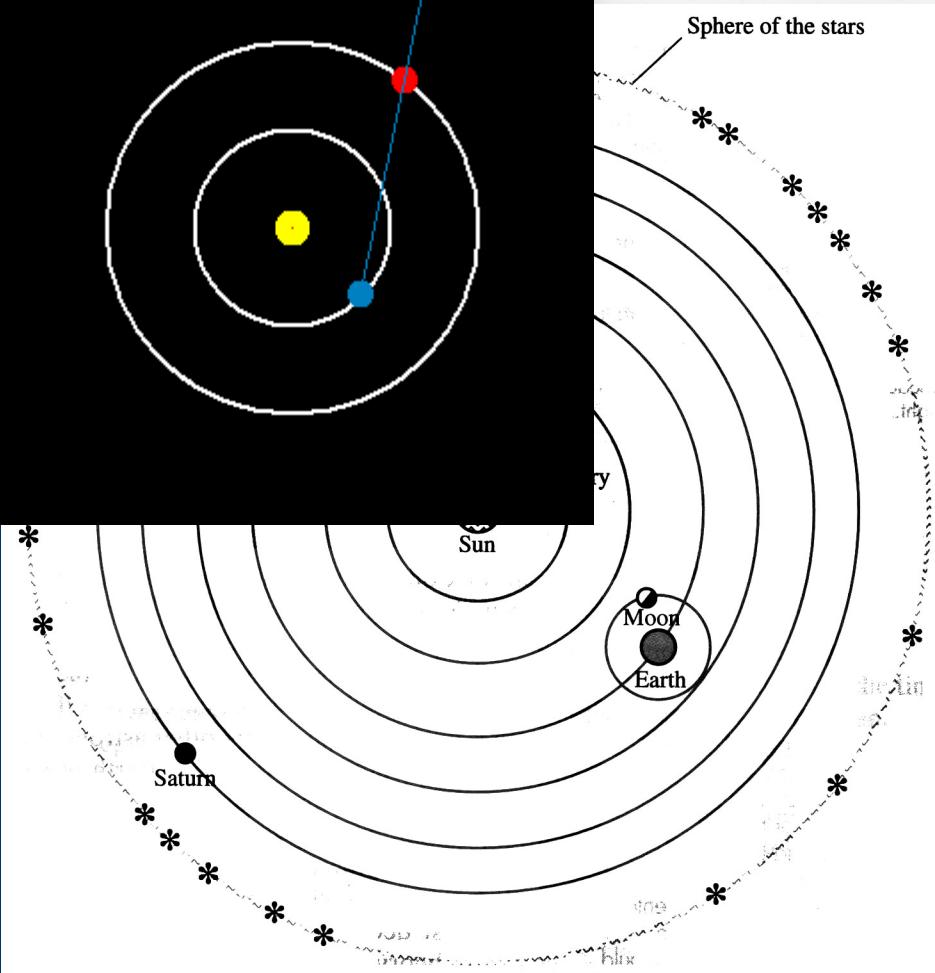
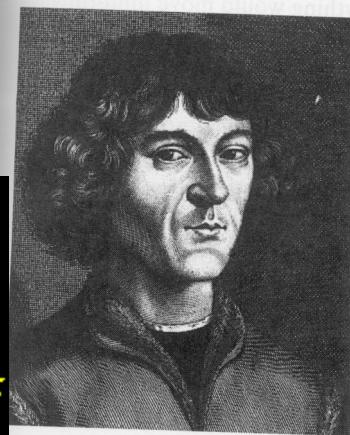
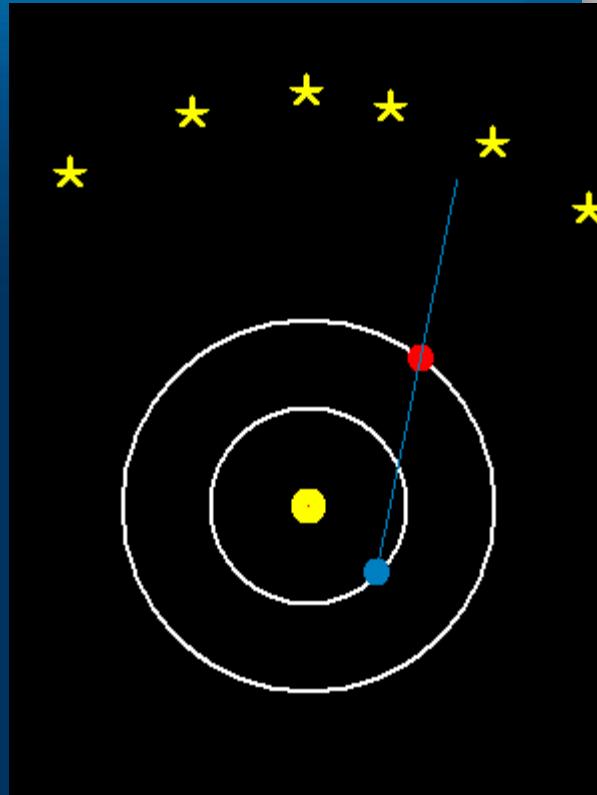
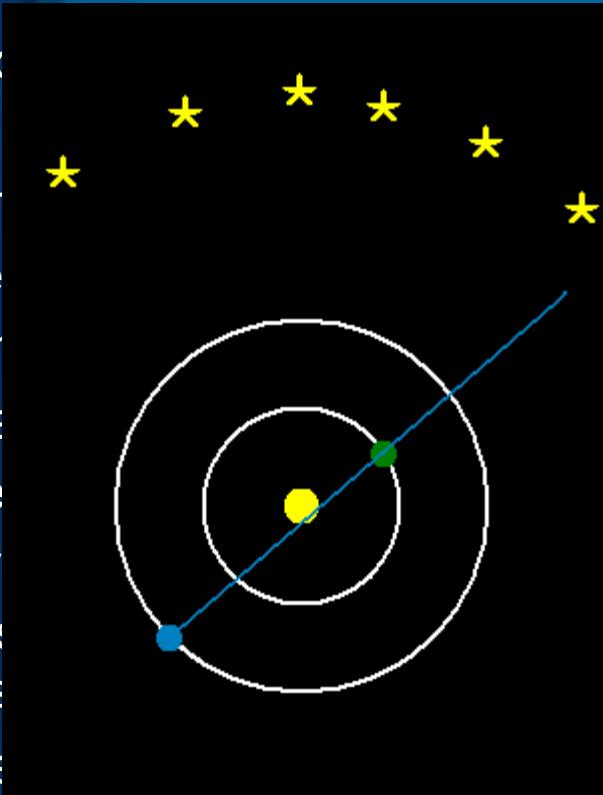
# Copernicus (1473-1543)

- 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 something about the Sun?
  - Keep some things simple
    - sphere
    - uniform
  - Major Changes
    - Sun centered
    - Earth rotates
    - Earth is one of the planets
  - Established by Ptolemy
  - 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

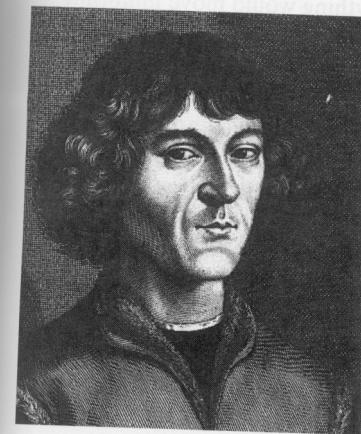
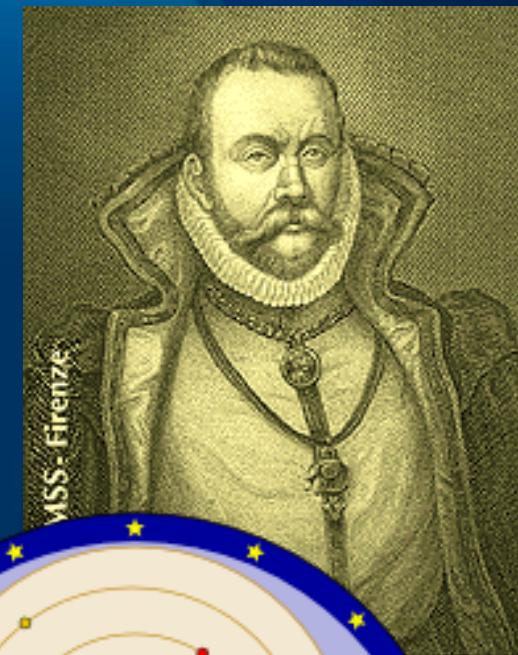


FIGURE 1.14  
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd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

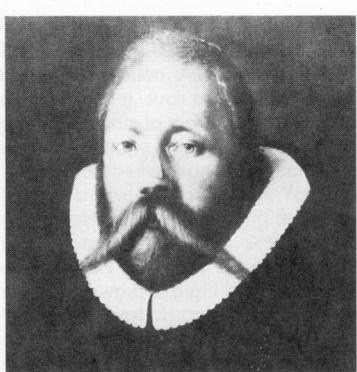


FIGURE 1.18  
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

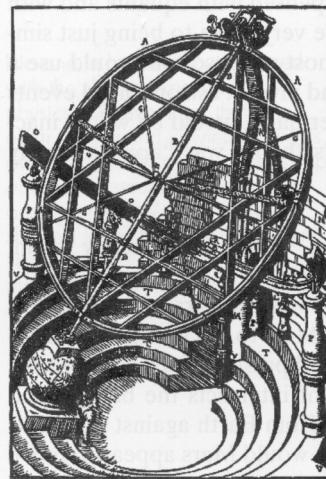


FIGURE 1.19  
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

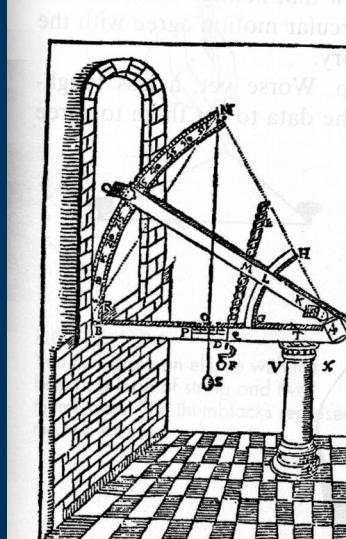


FIGURE 1.20  
An instrument that Brahe used for

# Johannes Kepler (1571-1630)

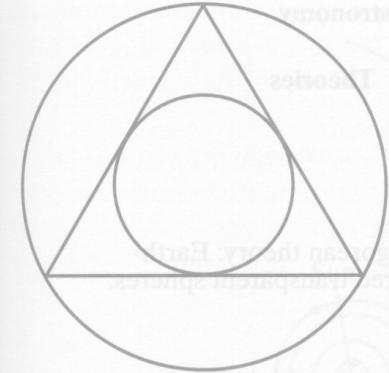
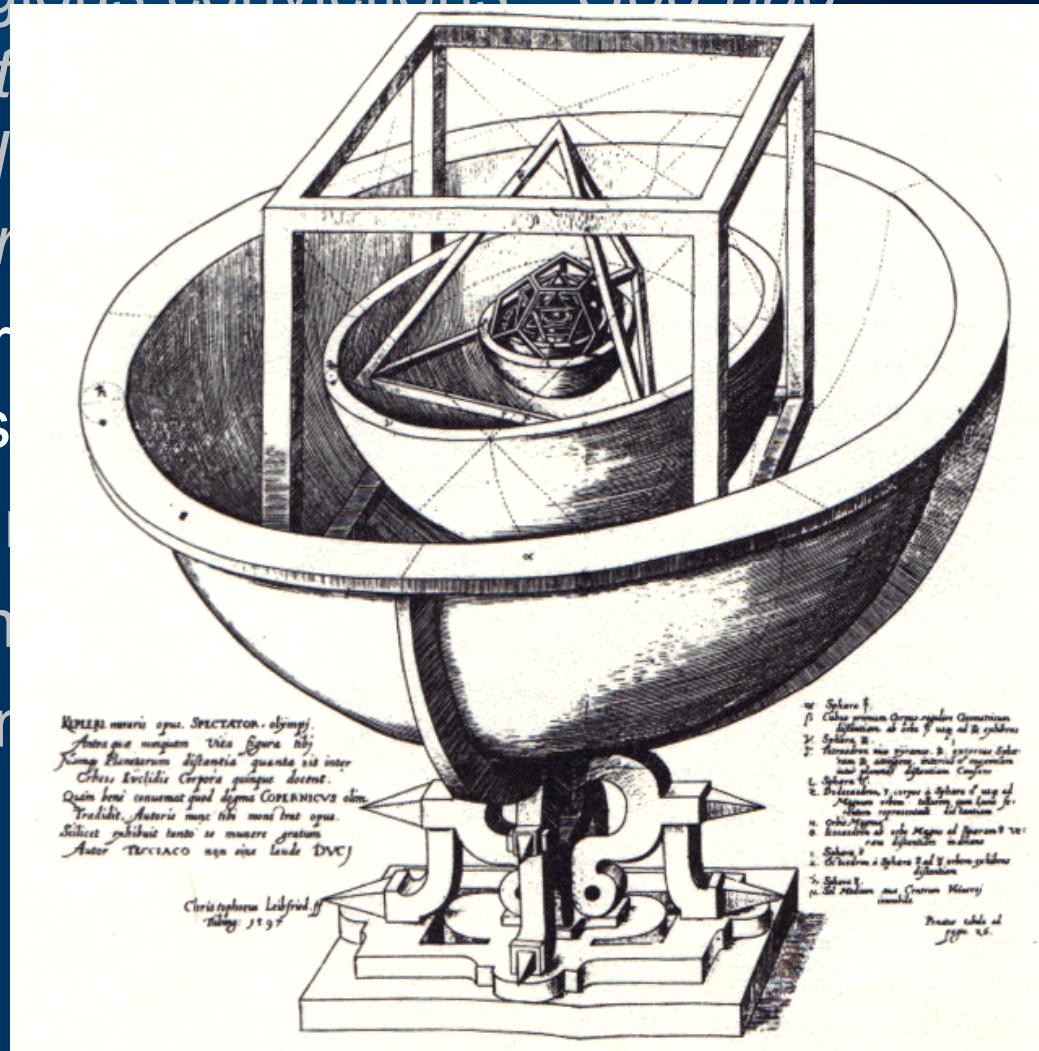


FIGURE 1.23  
A blackboard diagram similar to this gave Kepler the original inspiration for his planetary theory based on the five perfect solids. In this diagram, two circles are separated by a triangle.

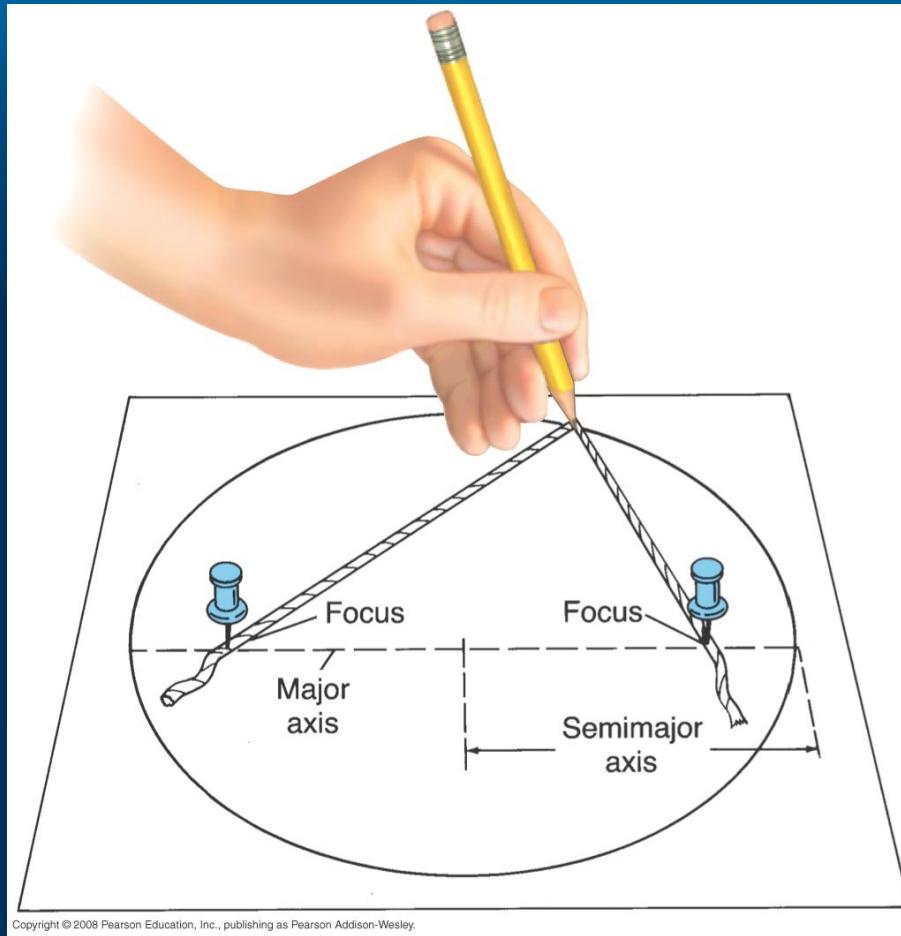
- Mathematician, astronomer, astrologer
- Had religious convictions - *God had created the universe according to a plan that is intelligible to reason*
- Geometric model of the solar system using regular solids
- Mysterious
- Astronomer
- The Harmonies of the World (Harmony Law)



# 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 1<sup>st</sup> law



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

# Johannes Kepler

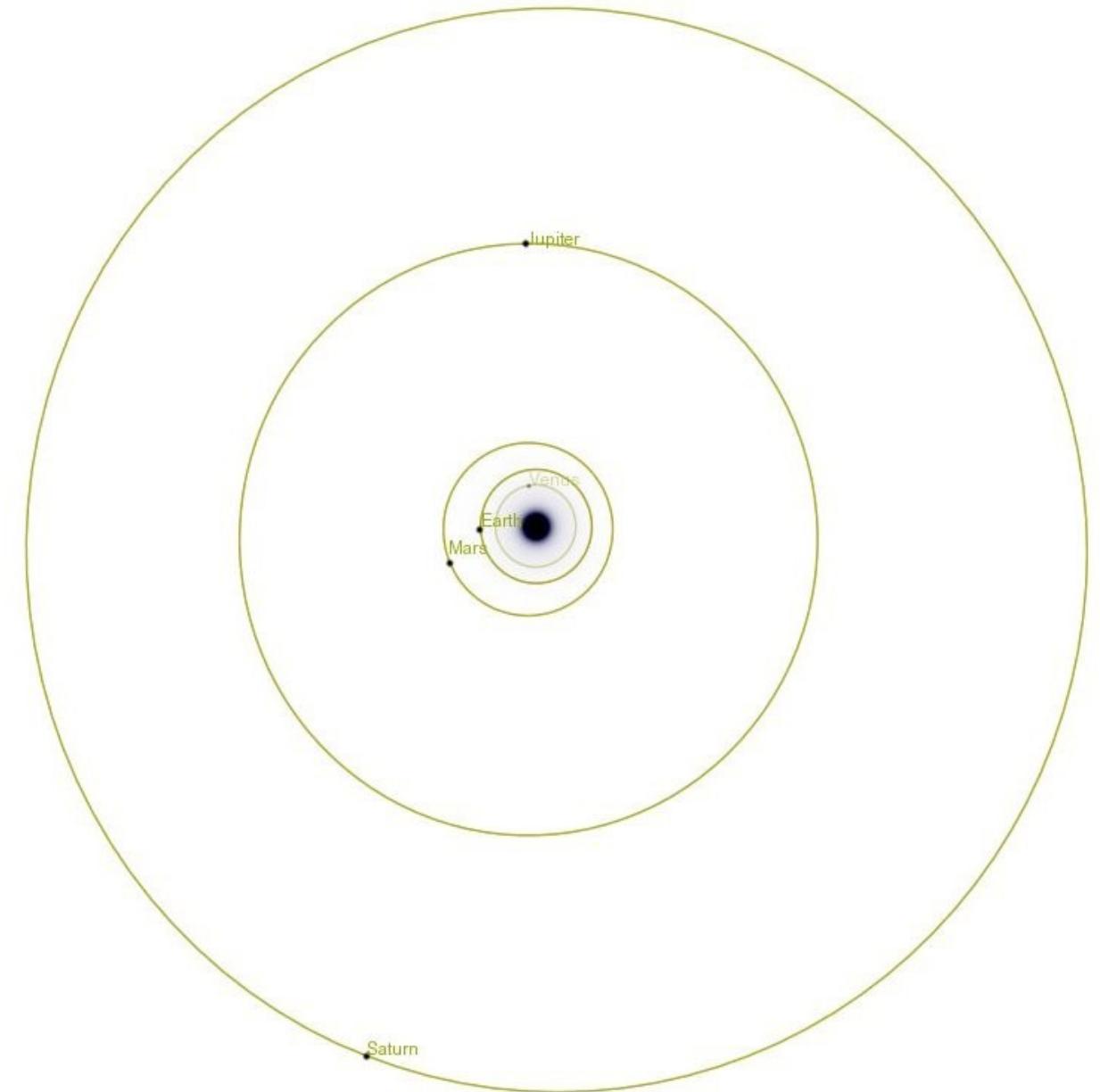
## Inner Planet orbits

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

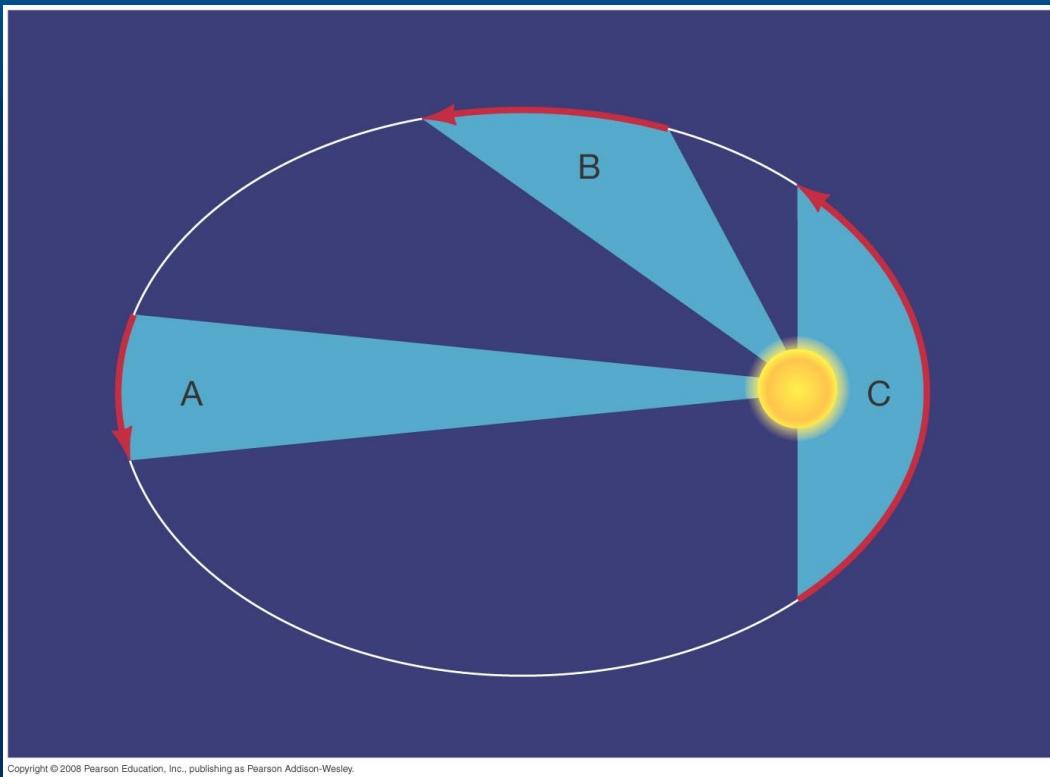
## Outer planets

- Mars most eccentric (0.09)

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



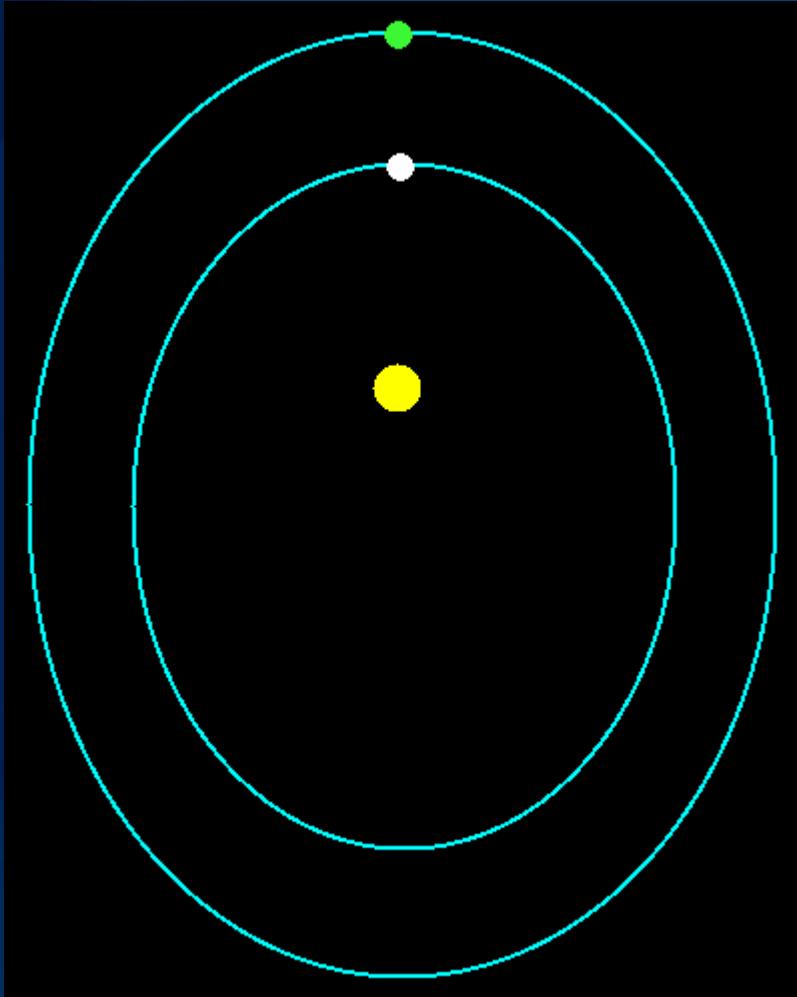
# Kepler's 2<sup>nd</sup> Law



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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 3<sup>rd</sup> law



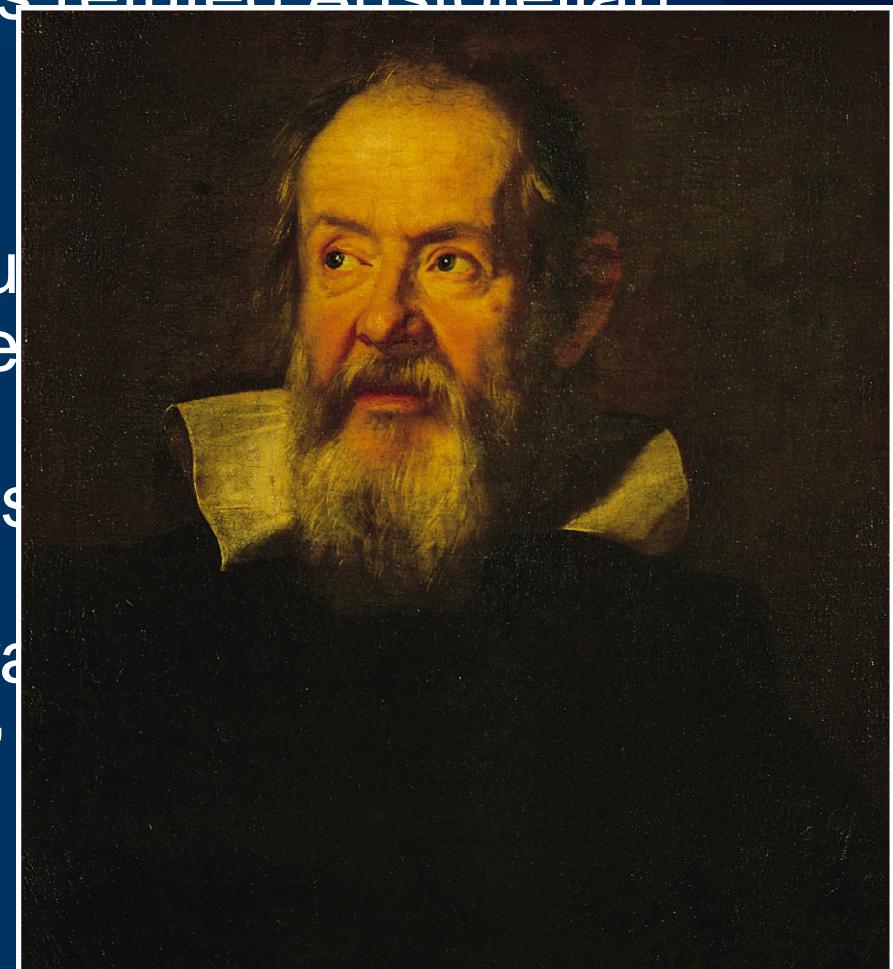
$$P^2 = a^3$$

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”



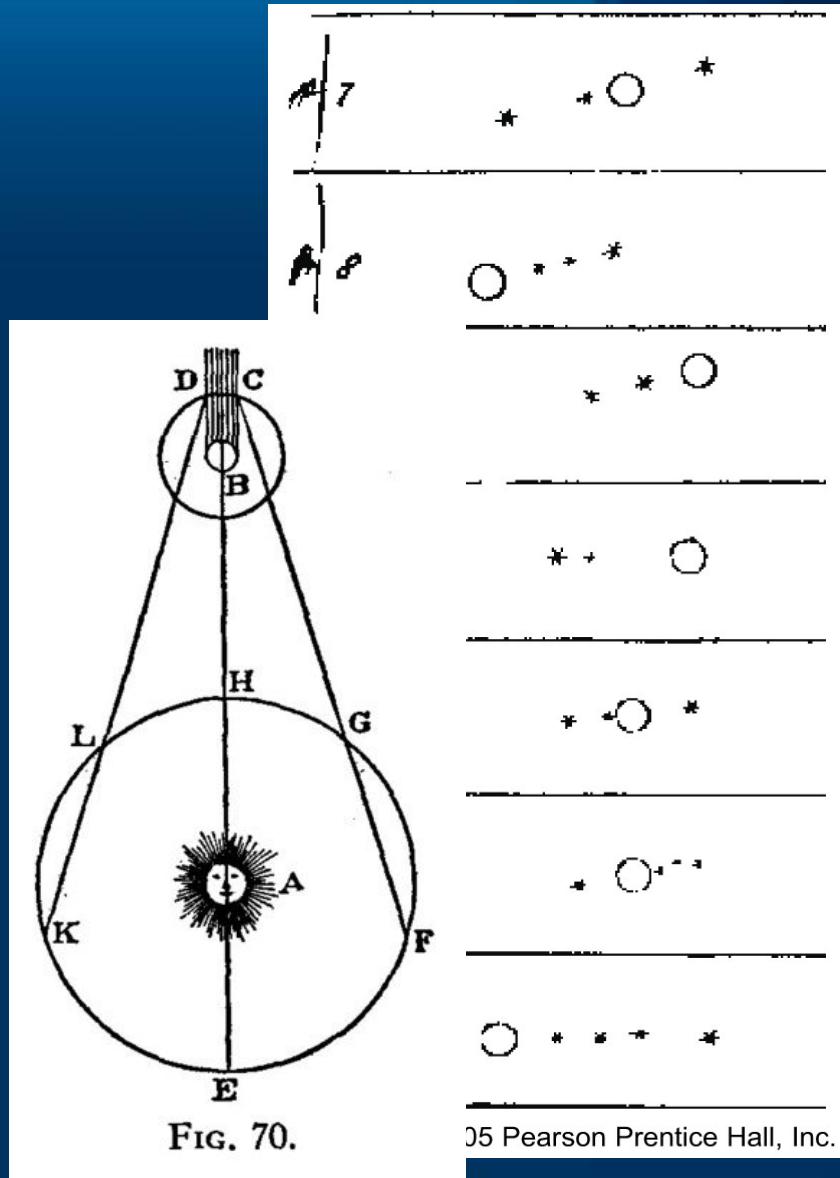
# Galileo and Jupiter

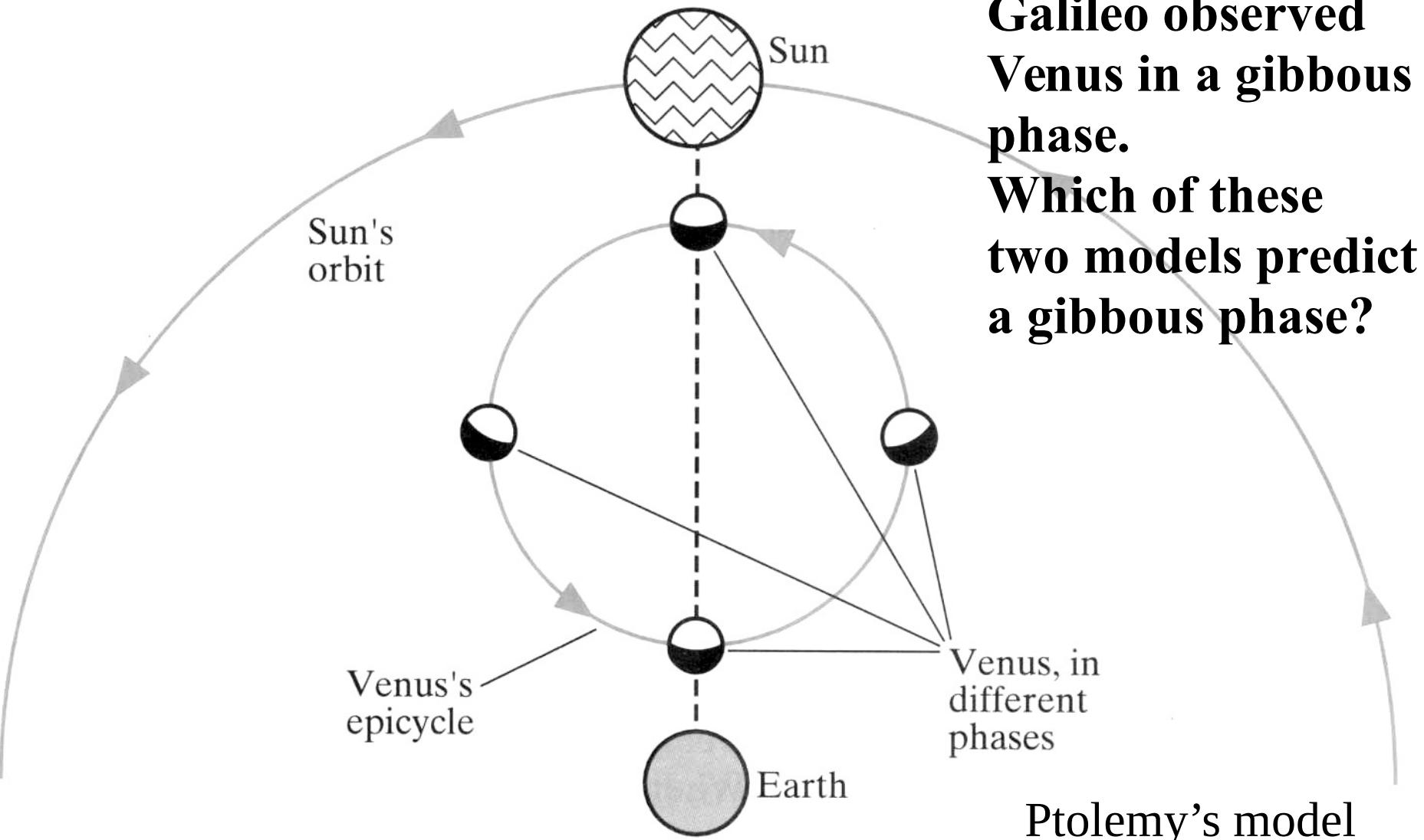
The “Galilean Moons”: Io, Europa, Ganymede, and Callisto.

Not everything orbits the Earth!

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

Ole Roemer 1677

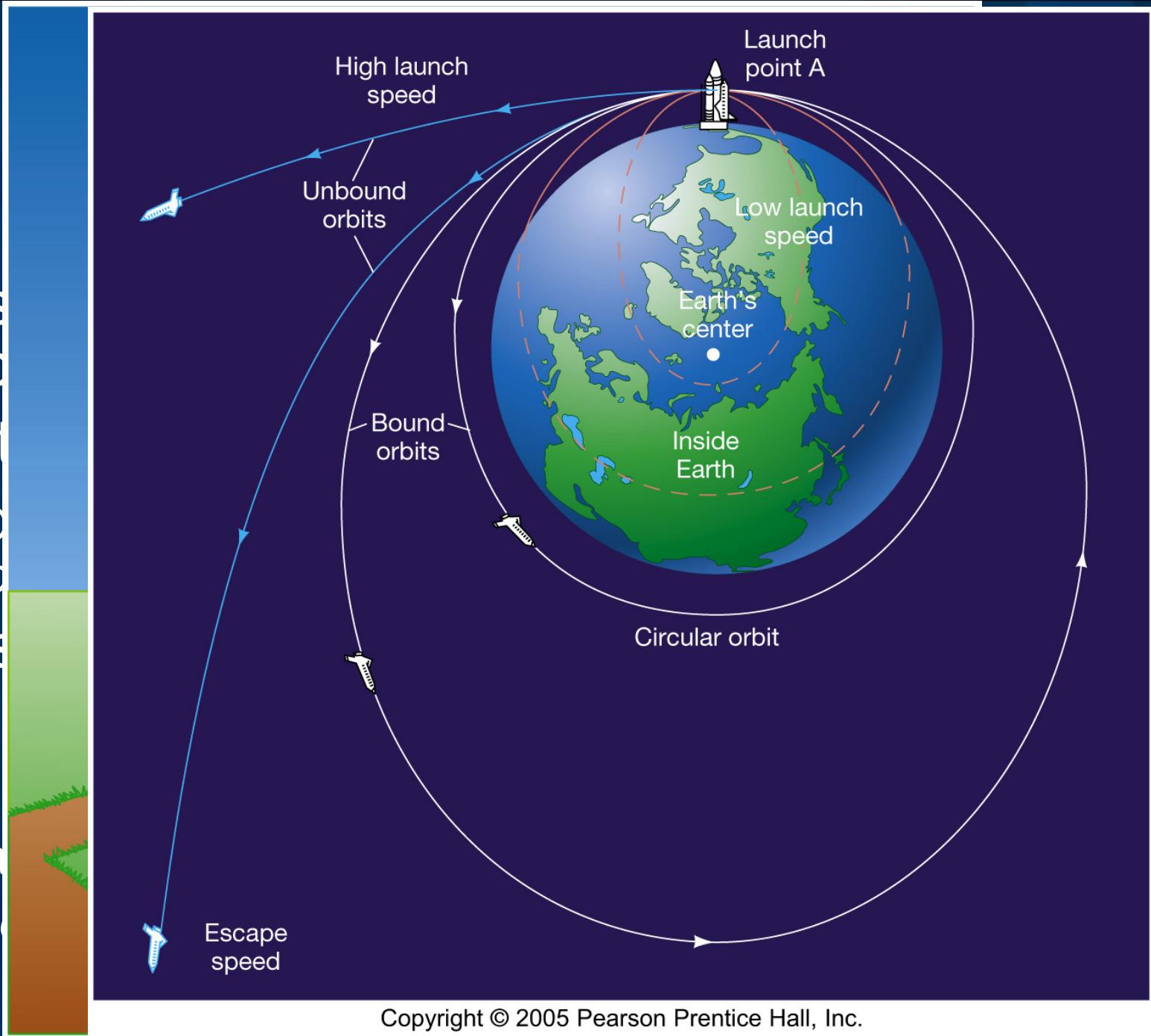




# Galileo's troubles

- Galileo was more vociferous and brash than Copernicus and Kepler.
- 1610: Published *Sidereal Nuncius* (Starry Messenger)
- 1616: Galileo (and Copernicus) judged to be heretical
- 1632: Published *Dialogue Concerning the Two Chief World Systems*.
  - Simplicio speaks words of Pope Urban VIII.
  - Published in Italian
- 1633: Sentenced to house arrest.
- 1642: Dies in house arrest.
- 1992: Catholic Church acknowledges their error

- English theologian
- Inventor
- Urged Isaac Newton to publish his Principia
- *Philosophiæ Naturalis Principia Mathematica*
- 3 laws of motion
- Universal gravitation
- Canons of gravitation
- Final theory of gravitation
- “God governs by the laws of nature which he himself has established, so that he requires no arbitrary power to overrule or destroy his works.”
- “God governs by the laws of nature which he himself has established, so that he requires no arbitrary power to overrule or destroy his works.”



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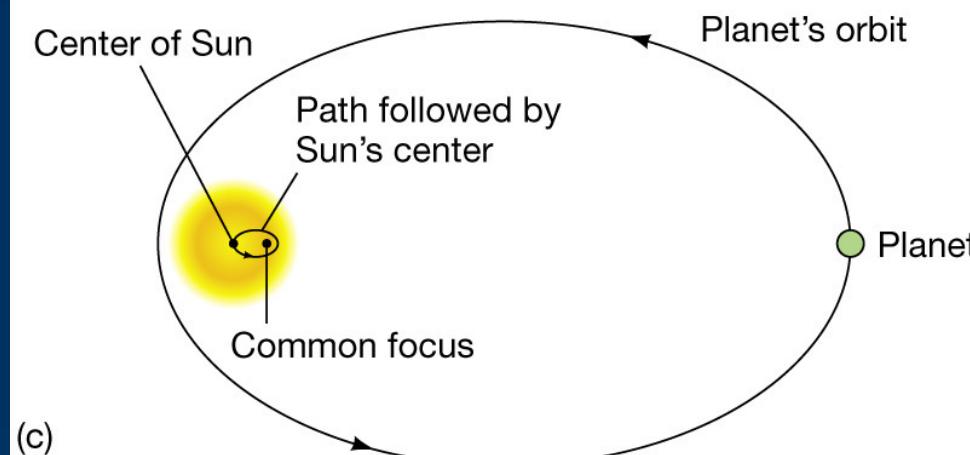
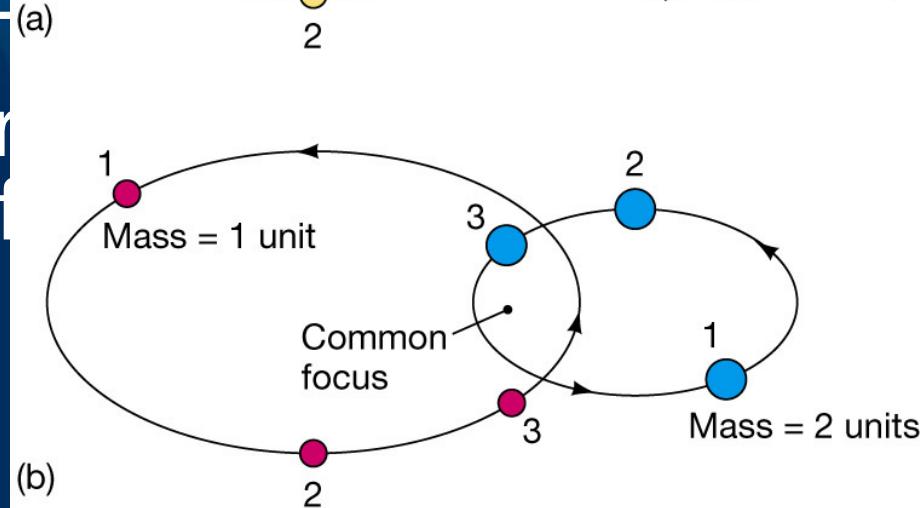
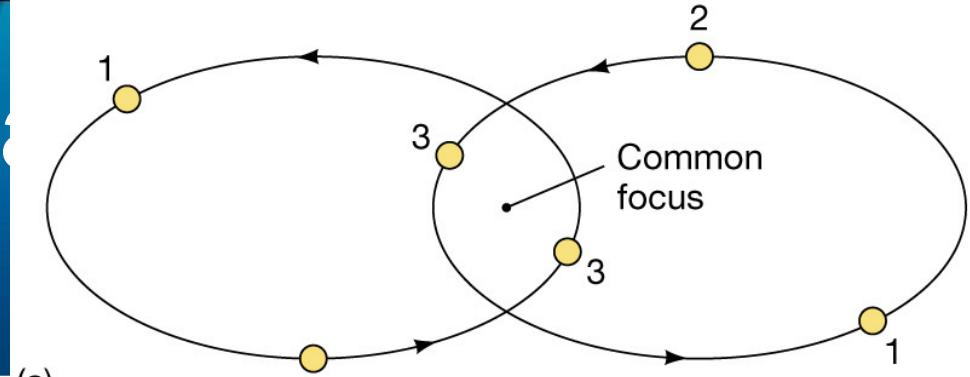
# Isaac Newton (1643-1727)

- 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.*”

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

# Is

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



S''

S  
r  
e

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

# Isaac Newton's “Fixes” to Kepler's Laws

- Kepler I: The planets orbit in ellipses with the principle focus on the center of mass of the solar system, (not the Sun)
- Kepler III: add the total mass of the system to the denominator ...  $P^2 = \frac{a^3}{M_{tot}}$

# The Copernican Revolution ... *matching!*

Nicolaus  
Copernicus

Tycho Brahe

Johannes Kepler

Galileo

Newton



*Observed gibbous phase of Venus*

*Made precision measurements of  
planets*

*Used ellipses to model solar  
system*

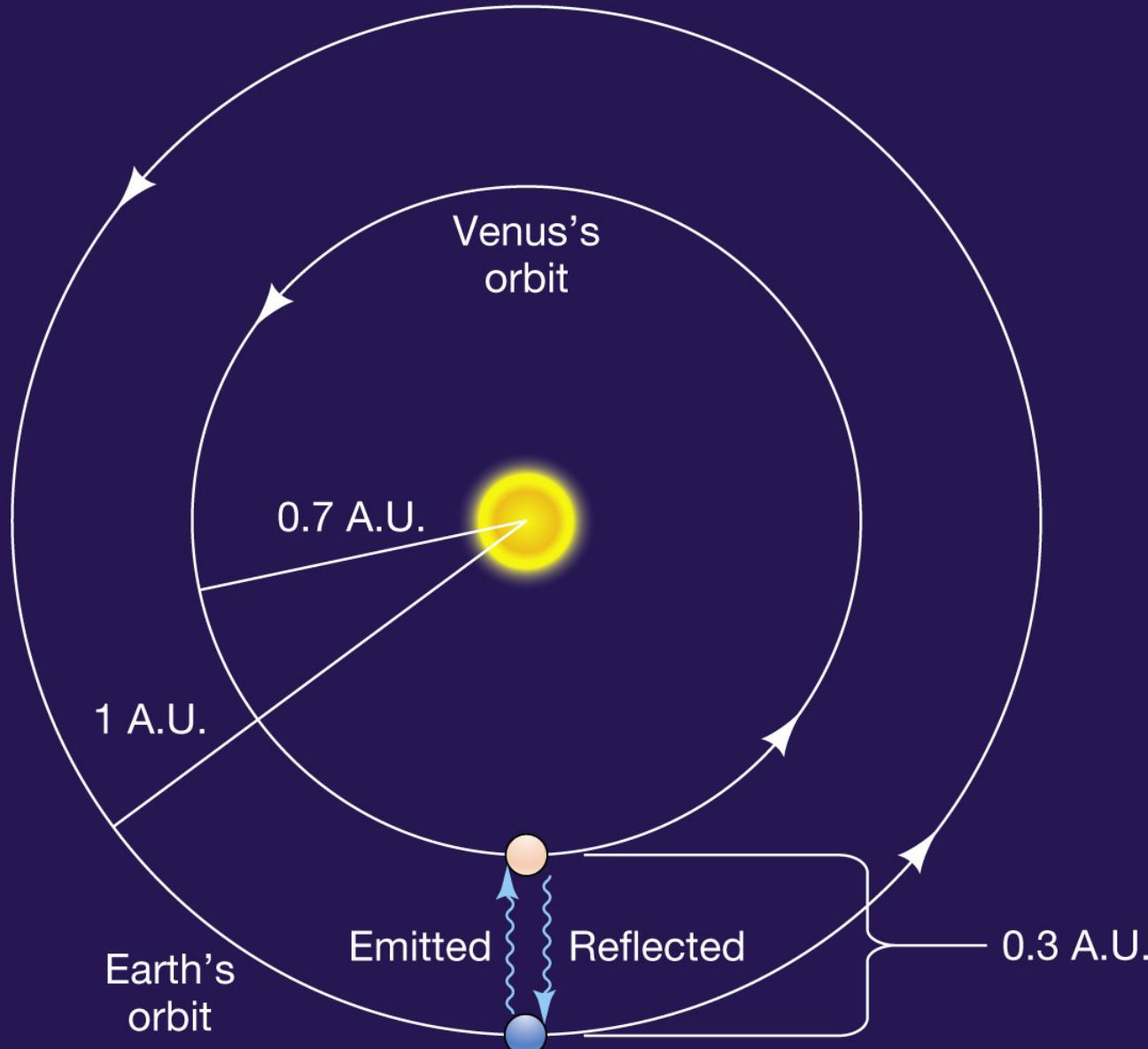
*Said gravity accelerates the  
planets*

*Revived the heliocentric model*

F

• Venus

• Water



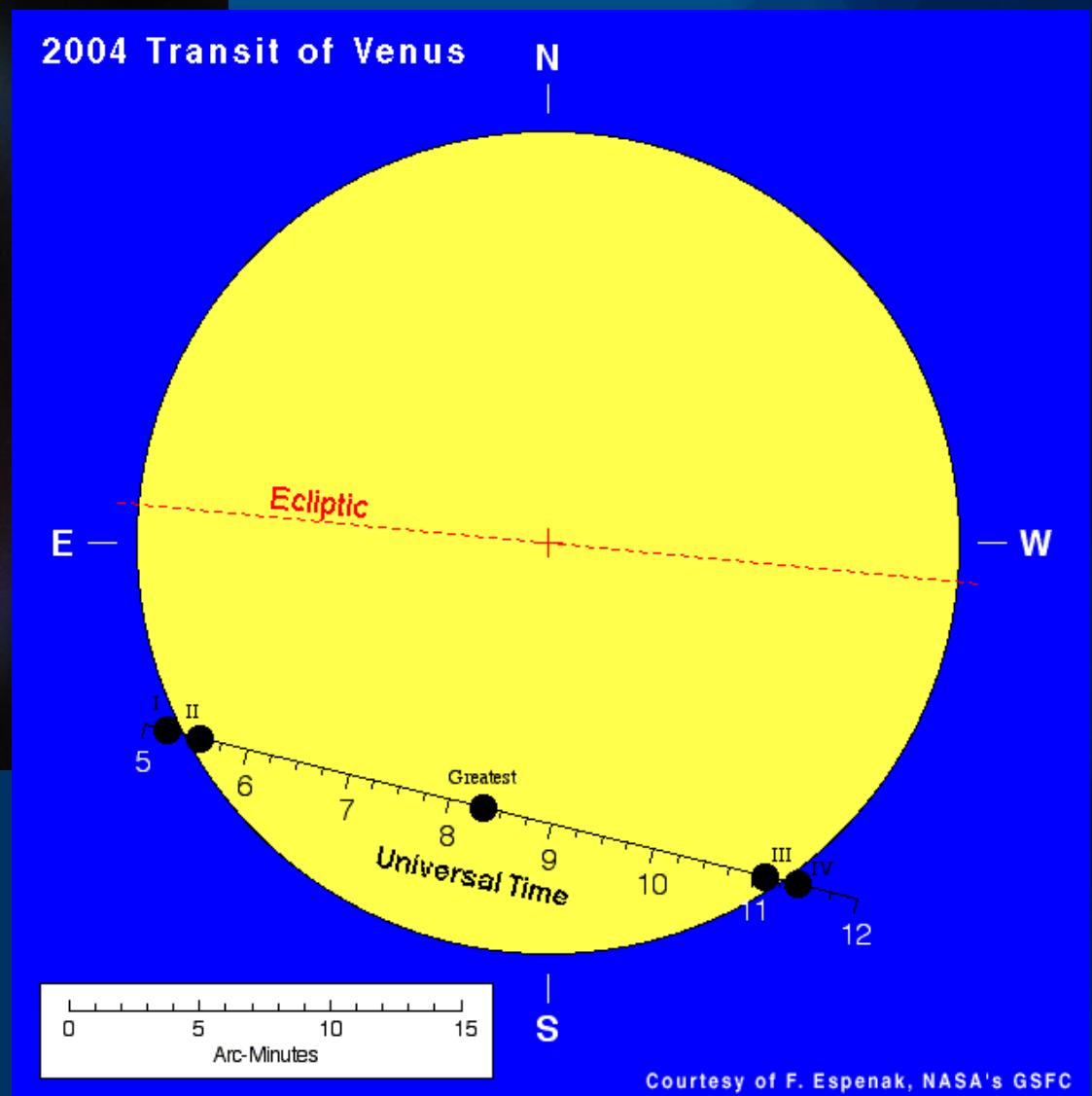
's view out  
window that  
ing left



# 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

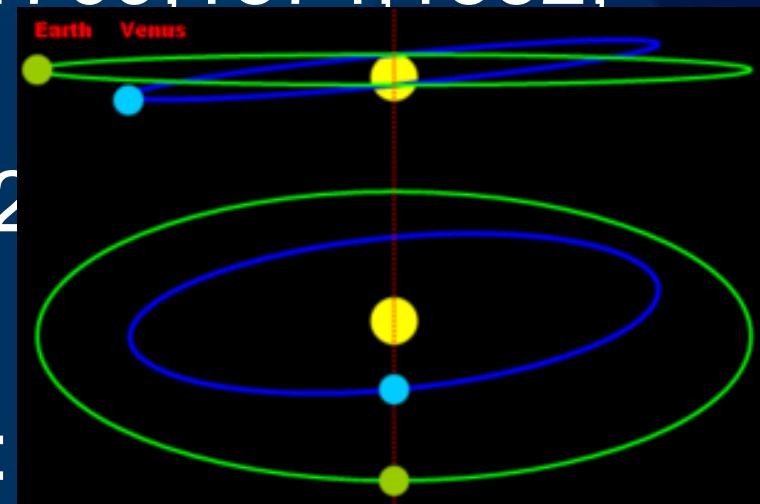
Next transits: 2117, 2125

How it works:  $3.4^\circ$  tilt, 8:

243 yr cycle.

Inferior conjunction while both planets on  
line

of nodes.

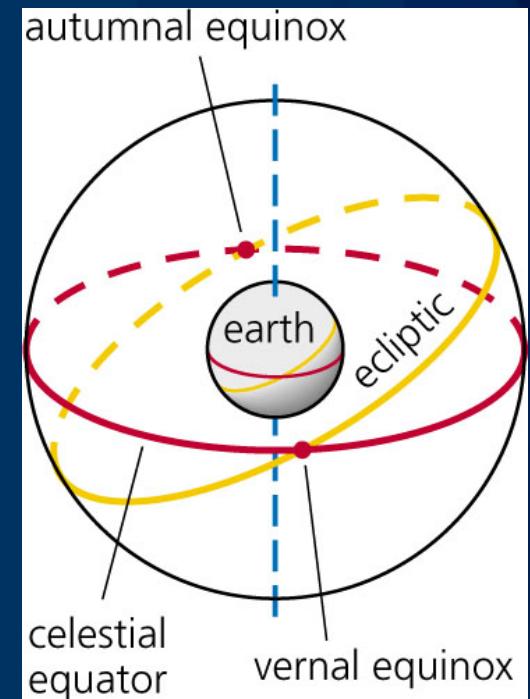
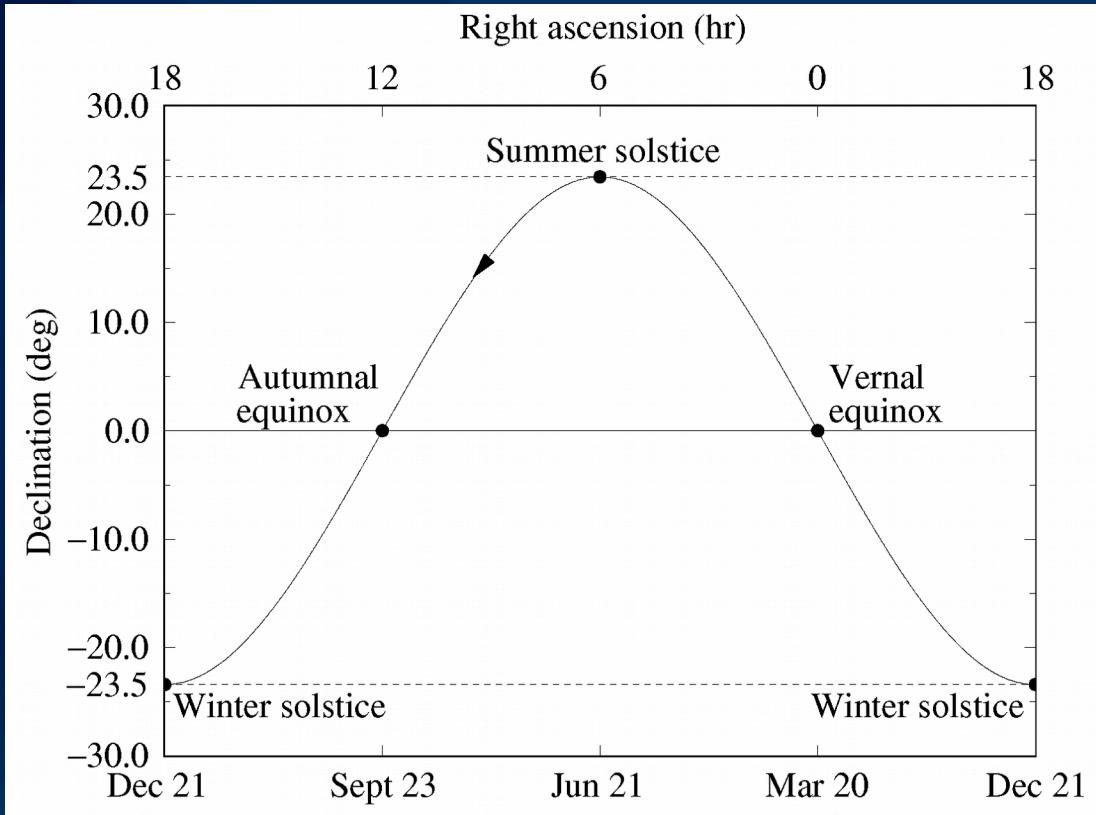


# Science vs Superstition – it never ends

- 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

# Ecliptic

- Seasonal variations due to orbital motion and the  $23.5^\circ$  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	
Each planet moves at a varying rate; retrograde motion.	400	Pythagorean theory: Earth-centered transparent spheres.
Heaven and Earth seem different; Earth seems motionless, apparently contradicting Aristarchus's theory.	300	Theory of multiple Earth-centered transparent spheres.
Planets are brighter during retrograde motion.	200	Aristarchus's theory: sun-centered circles.
Detailed quantitative measurements show need for small corrections.	100	Theory of Earth-centered epicycles.
Brahe's accurate measurements disprove Ptolemy's and Copernicus's theories.	0 ↓ A.D. 100 1500	Ptolemy's theory: Earth-centered epicycles, equants.
Galileo's telescopic observations disprove Earth-centered theories.	1600	Copernicus's theory: sun-centered circles.
		Kepler's theory: sun-focused ellipses.