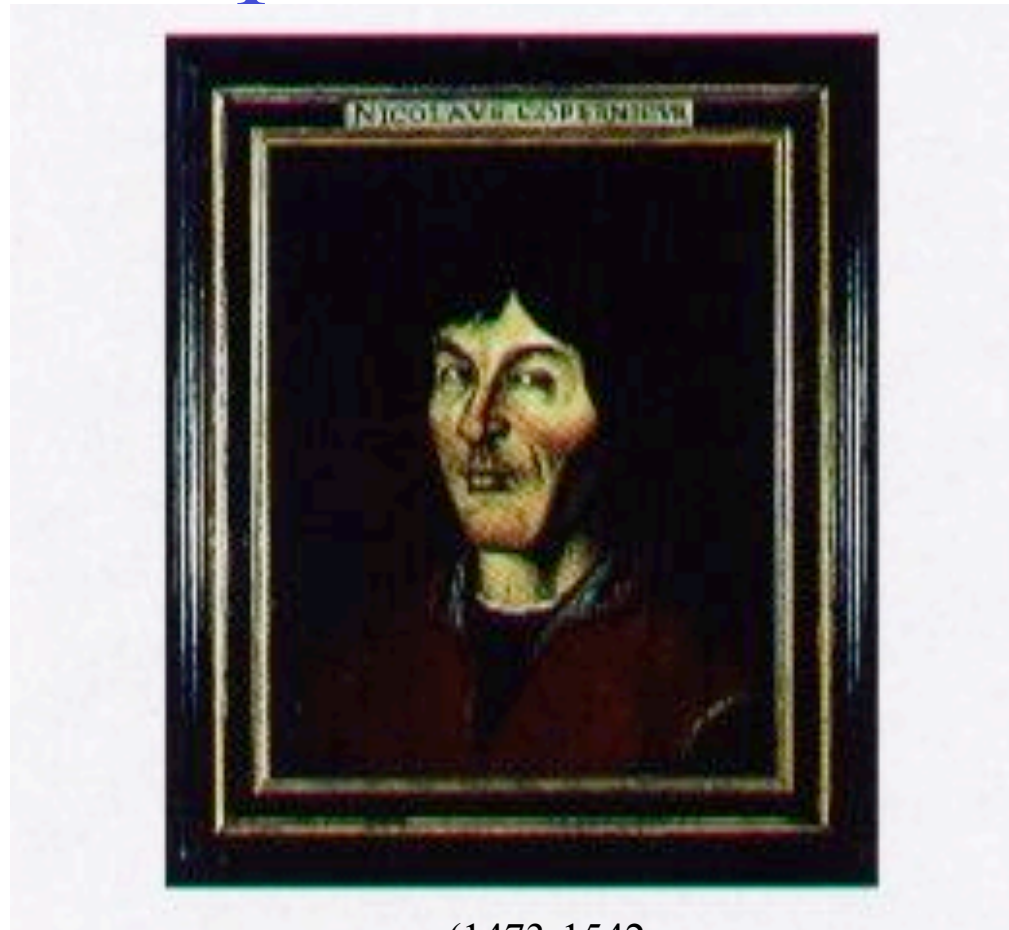


Lecture 4

The Copernican Revolution

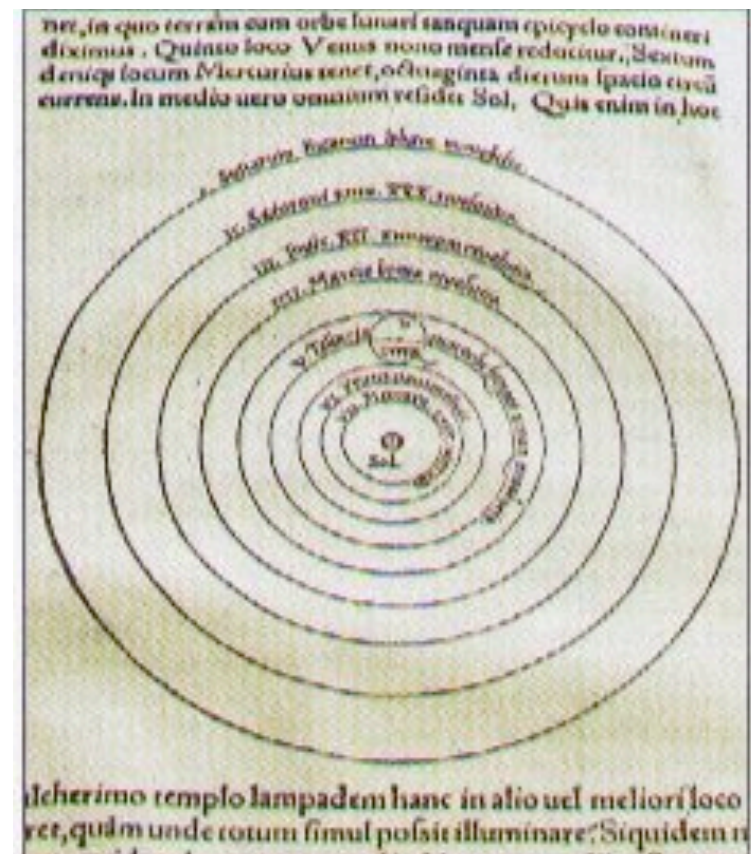
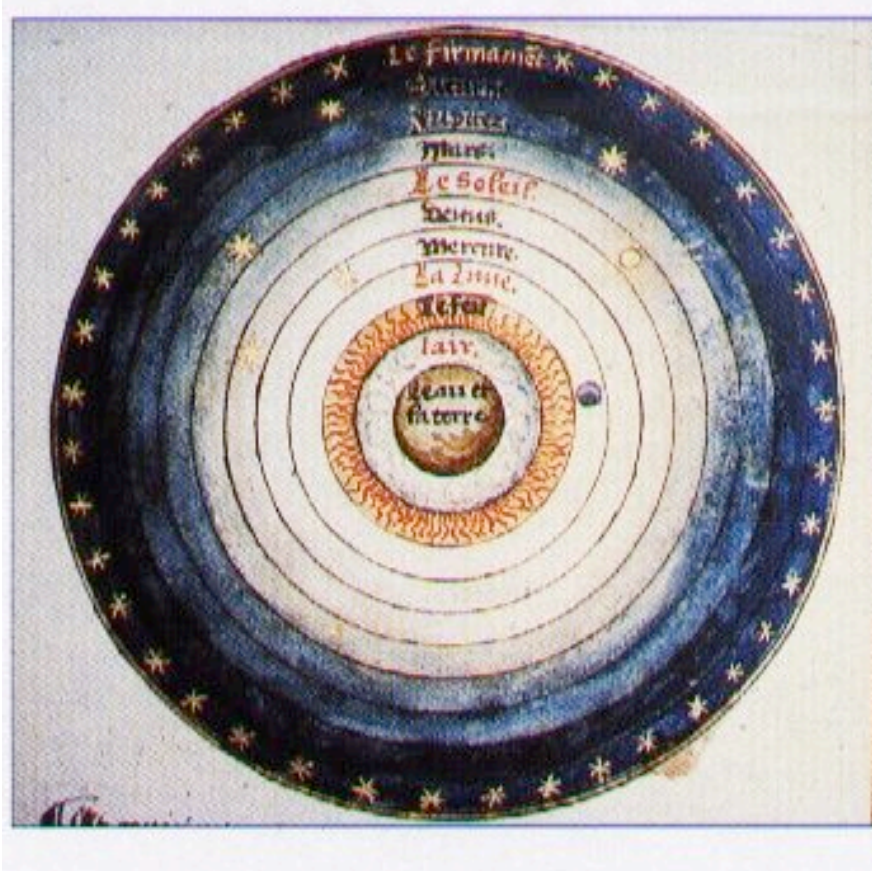


(1473-1542)

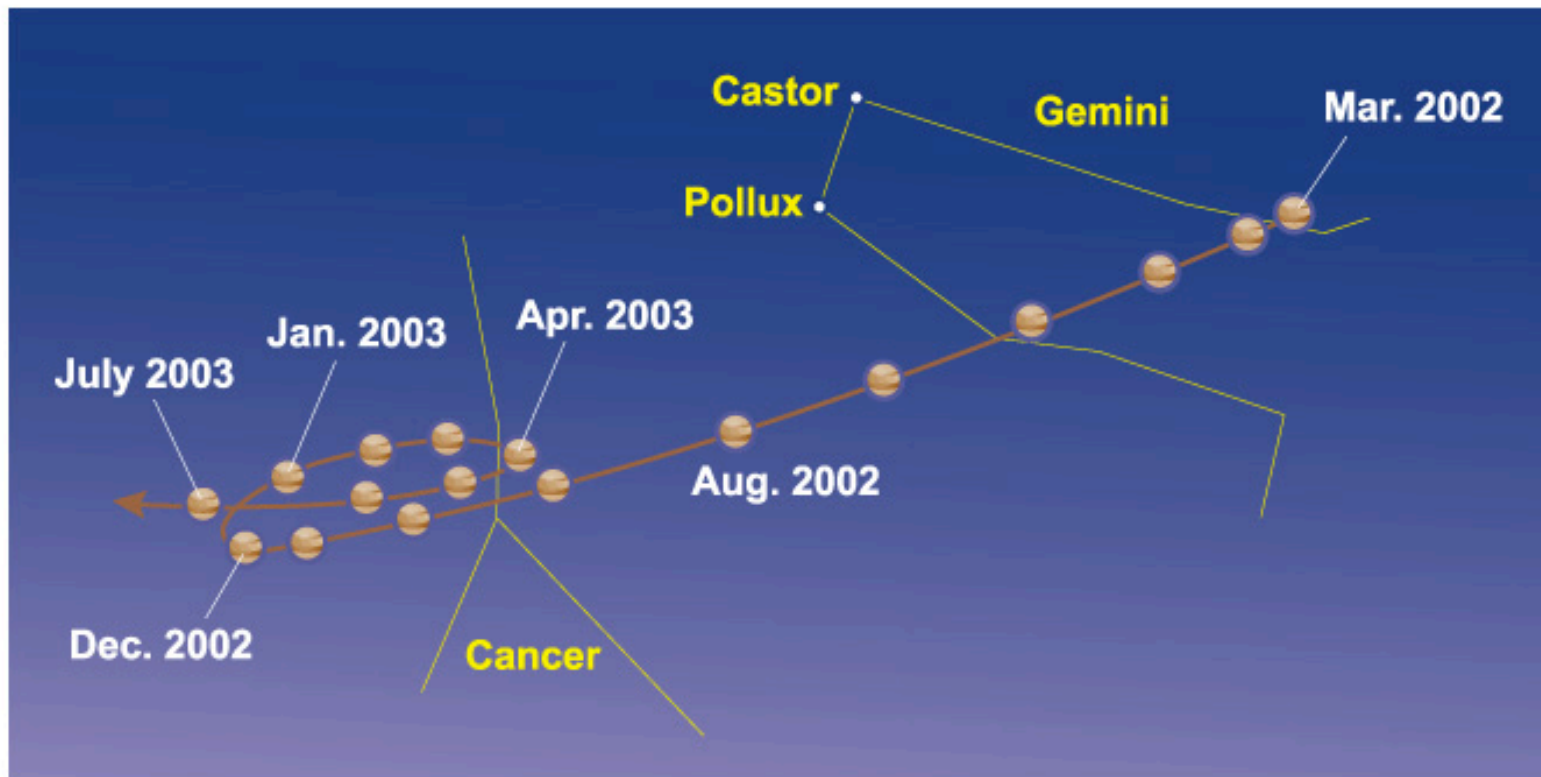
Outline of Lecture 4

- Ptolemaic System:
 - The planets travel around the Sun via guiding centers and epicycles.
 - Eighty epicycles are needed to fit the observations then existing.
- Copernican Revolution:
 - The Sun, not the Earth, lies at the center of the planetary system.
 - The Earth is a planet, yielding a simple explanation of retrograde motion.
 - The Moon still goes around the Earth.
 - Epicycles are still needed for an accurate description, but reduced to thirty.
- Kepler's Three Laws of Motion:
 - Planetary orbit is an ellipse in a plane with Sun at one focus.
 - Radius sweeps out equal areas in equal times.
 - Square of orbital period is proportional to cube of semimajor axis, with constant of proportionality the same for all planets.

Ptolemaic (Geocentric) vs. Copernican (Heliocentric) Universes

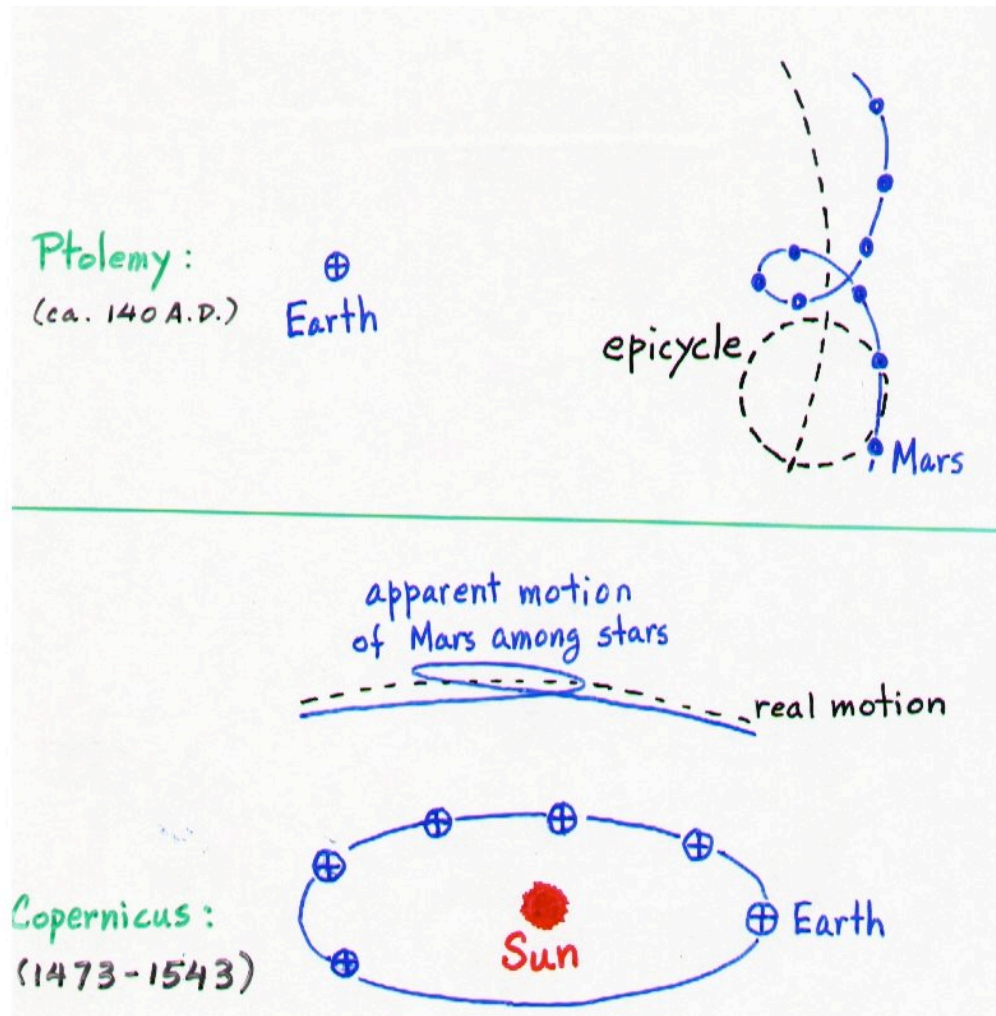


Retrograde Motion of Planets



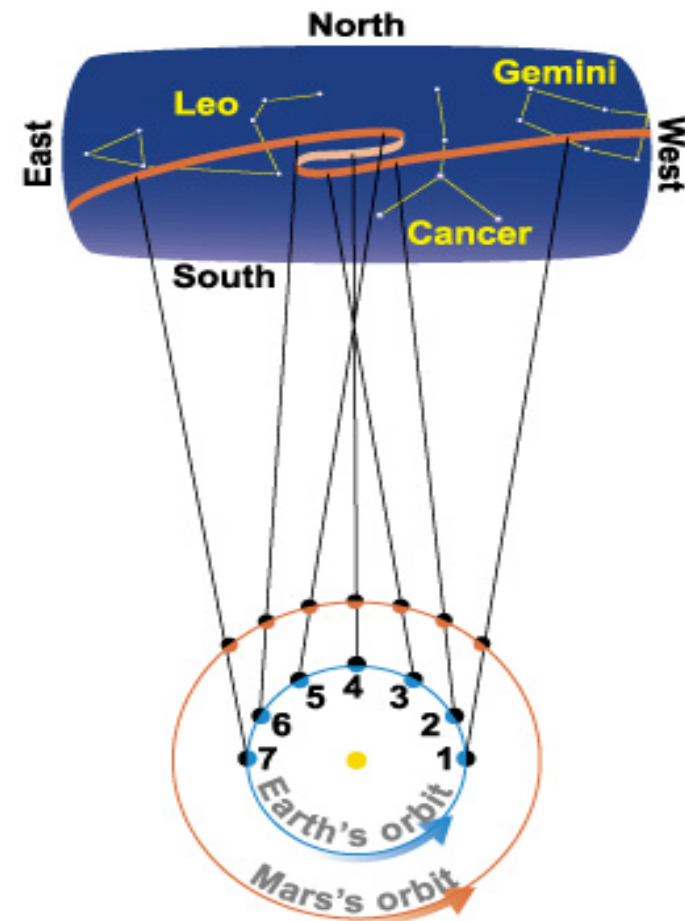
**Dots represent Jupiter's approximate position at 1-month intervals.
(Jupiter not to scale.)**

Geocentric & Heliocentric Descriptions



Mars's Apparent Motion Against Background Stars

- Advantages of Copernican System
 - No need for equant although still uses 30 epicycles for 7 planets (with Earth replacing Sun as a planet)
 - Explains why “superior” planet which shines by reflected light from Sun is brightest during period of retrograde motion
 - Center of motion the largest and brightest body in the system, the Sun
- Disadvantages of Copernican System
 - No observed stellar parallax
 - Moon still needs to go around Earth
 - Numerical fit not any better than Ptolemy's scheme



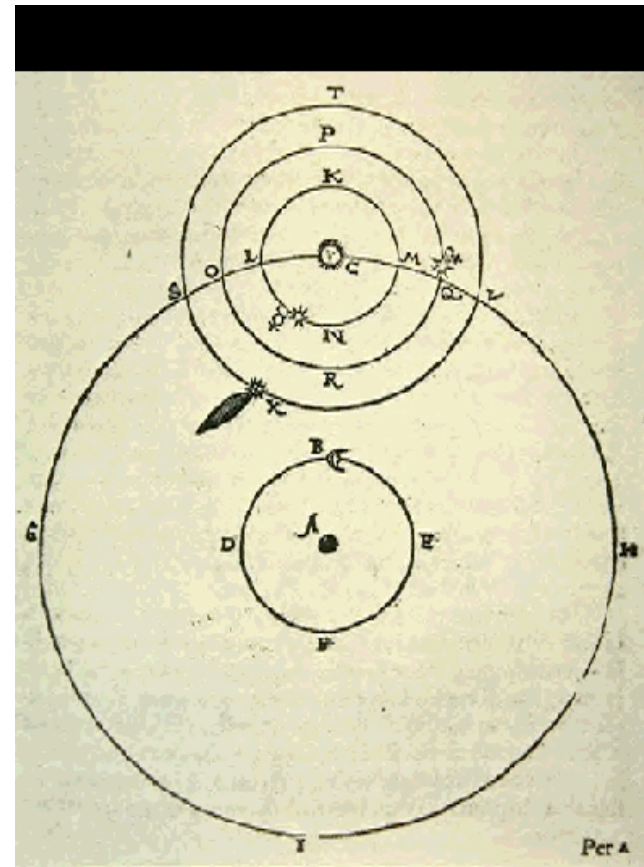
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Reaction of Contemporaries

- Martin Luther (1483-1546): [Copernicus] “is a fool who wishes to reverse the entire scheme of astronomy; but sacred scripture tells us that Joshua commanded the Sun to stand still, not the Earth.”
 - Conservative who wanted to reform Church by returning it to a simpler, less corrupt time.
 - Agitator for the abolishment of indulgences (payment to lessen time of deceased in purgatory).
 - A founder of the Protestant branch of Christianity.
- Response of Catholic Church to threat posed by the Reformation Movement:
 - At first, tolerance of dissent and liberal treatment of new ideas.
 - Later, institution of the Counter-Reformation and the Inquisition.
- Giordano Bruno (1548-1600): burned at the stake for advocating that stars are suns in their own right, and that there is a plurality of worlds like the Earth.

Tycho Brahe (1546-1601)

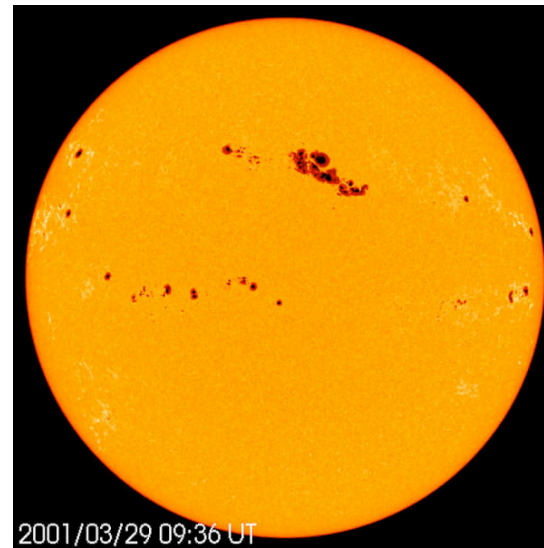
- Observed supernova, which he showed lay beyond orbit of Moon.
- Showed comets had wild orbits (about the Sun) beyond the orbit of the Moon.
- Best naked-eye observer in human history (positional accuracy twice as good as Hipparchus).
 - Still, Tycho was unable to see stellar parallax.
 - Proposed compromise “Tycho system,” where Moon and Sun circle a stationary Earth, but all the other planets and comets orbit the moving Sun.



Tychonic System of the World

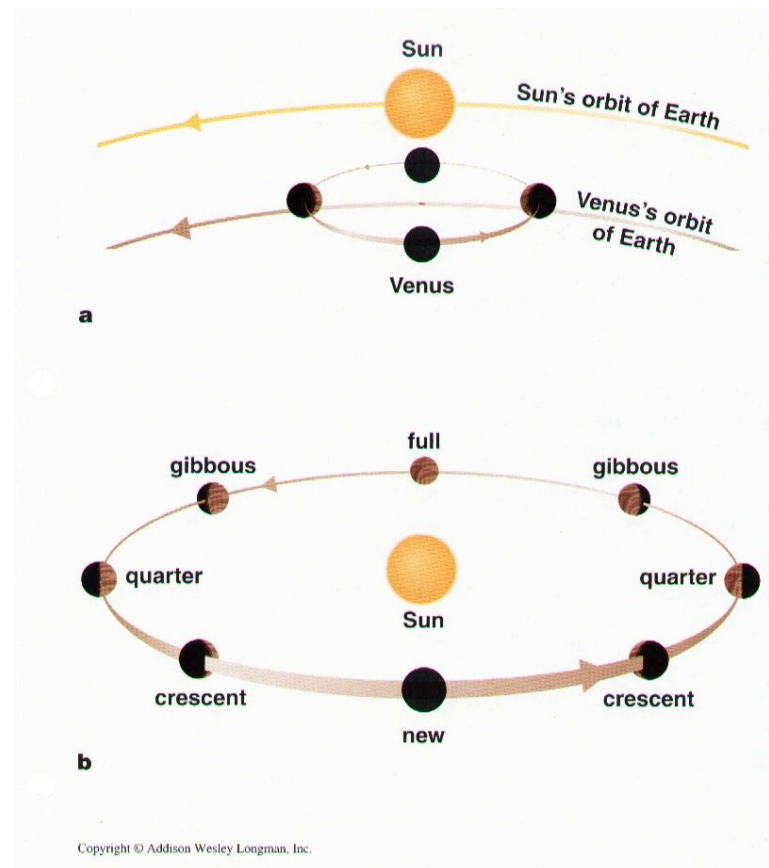
Galileo Galilei (1564-1642)

- Construction of first astronomical telescope.
- Observations of mountains and valleys on the Moon, phases of Venus, moons of Jupiter (Galilean satellites), rings of Saturn, stars of Milky Way, dark spots on the Sun
- Strongest proponent of Copernican System
- Wrote *Siderius Nuncious* (*Starry Messenger*) to popularize findings

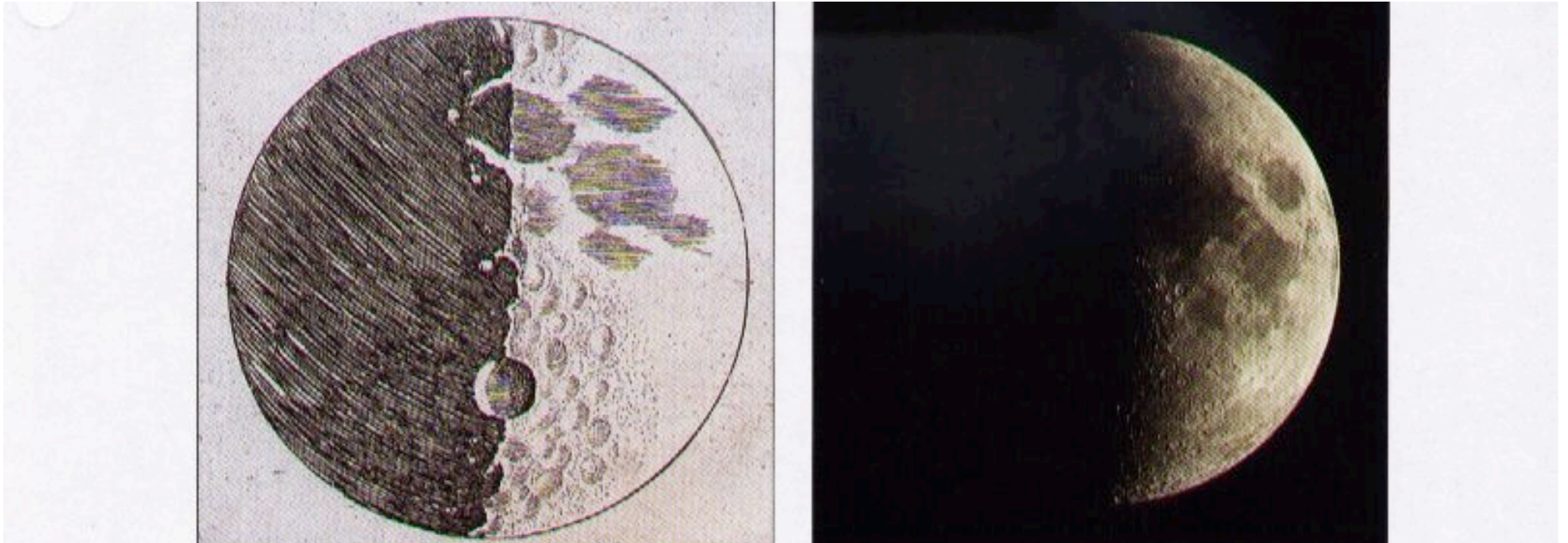


Galileo: Phases of Venus

- Top: Ptolemaic diagram
- Bottom: Copernican diagram
- Although observed phases of Venus are not explicable in Ptolemaic System, they can be accommodated by the Tychonic System. Indeed, on the basic issue of whether the Sun circles the Earth or the Earth circles the Sun, without demonstrated stellar parallax, there is no *kinematic* way (how things move) to distinguish between the two; only *dynamical* reasons (why things move) can provide a distinction.



Galileo: The Moon Has Mountains and Valleys -- like the Earth



Aristotle: Moon, being a heavenly body, is a perfect sphere (no topography). Its discoloration is due to “pollution” from being too close to a filthy Earth. Galileo (*Starry Messenger*): Seen through a telescope, isolated peaks lit up by sunlight at lunar dawn before valley floors are flooded with light.

During new moon, when the lit side of the Moon faces away from us, we can still see the dark side.

Explanation (due originally to Da Vinci): Lunar night side is illuminated by earthshine from “Full Earth.”

Earth is a heavenly body like the Moon; the Moon is a terrestrial body like the Earth.

Galileo: Jupiter Has Four Large Moons

Adi 7. di Gennaio
Giorno si vede così
Adi 8 così
Adi 12. si vede in tale costituzione
Adi 13. si vede in questa
Adi 14. è angusto
Adi 15. si vede in questa

On the 7th of January
 Jupiter is seen thus

On the 8th thus
 it was therefore direct and not retrograde

On the 12th day it is seen in this arrangement

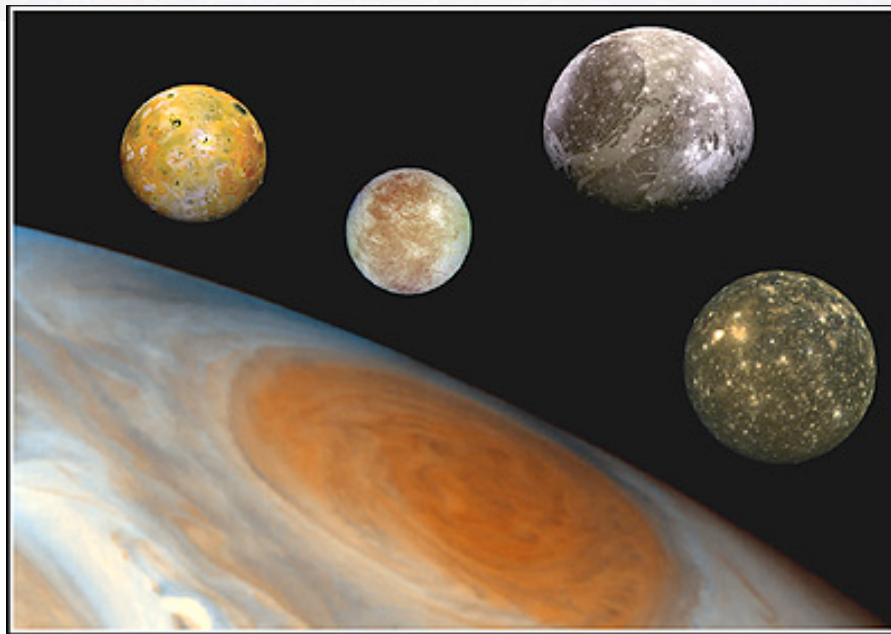
The 13th are seen very close to Jupiter 4 stars
 or better so

On the 14th it is cloudy west

The 15th the nearest to Jupiter was smallest
 the 4th was distance from the 3rd about double

The spacing of the 3 to the west was
 no greater than the diameter of Jupiter
 and they were in a straight line.

long. 71°38' lat. 1°13'



Earth is not only
 heavenly body with a
 moon. There are
 other centers of
 revolution besides the
 Sun and Earth.

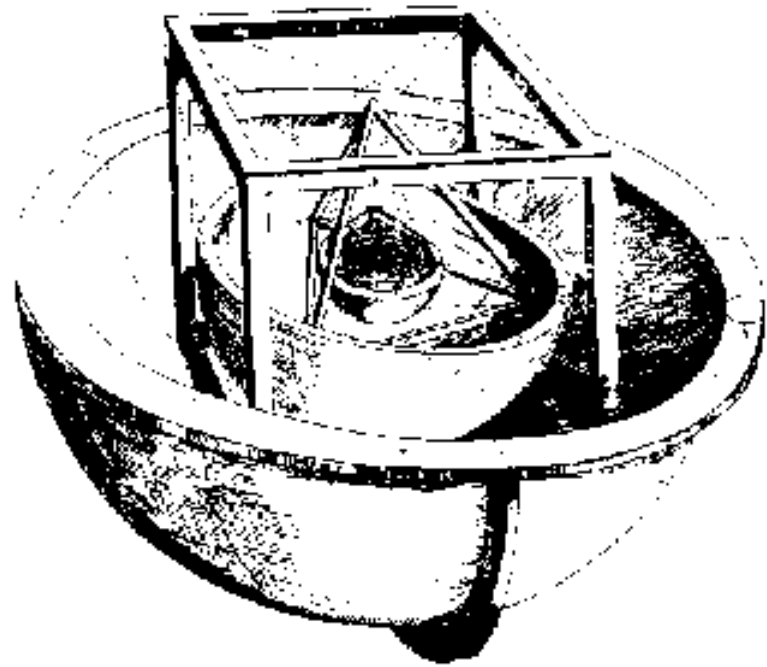
Galileo as Scientific Martyr

- Claim of “proof” for Earth’s motion (erroneous theory of tides).
- Publication of the “Dialogues of Two World Systems” (in Italian rather than Latin), trial by Church (shown instruments of torture), forced to abjure. “And yet it moves.” (see Bertolt Brecht’s play on the trial of Galileo)
- Confined to house arrest. Formulates “new science” of mechanics.
- Most influential combination of experimentalist and theorist world has ever seen.
- Credited rightly with having started modern science.

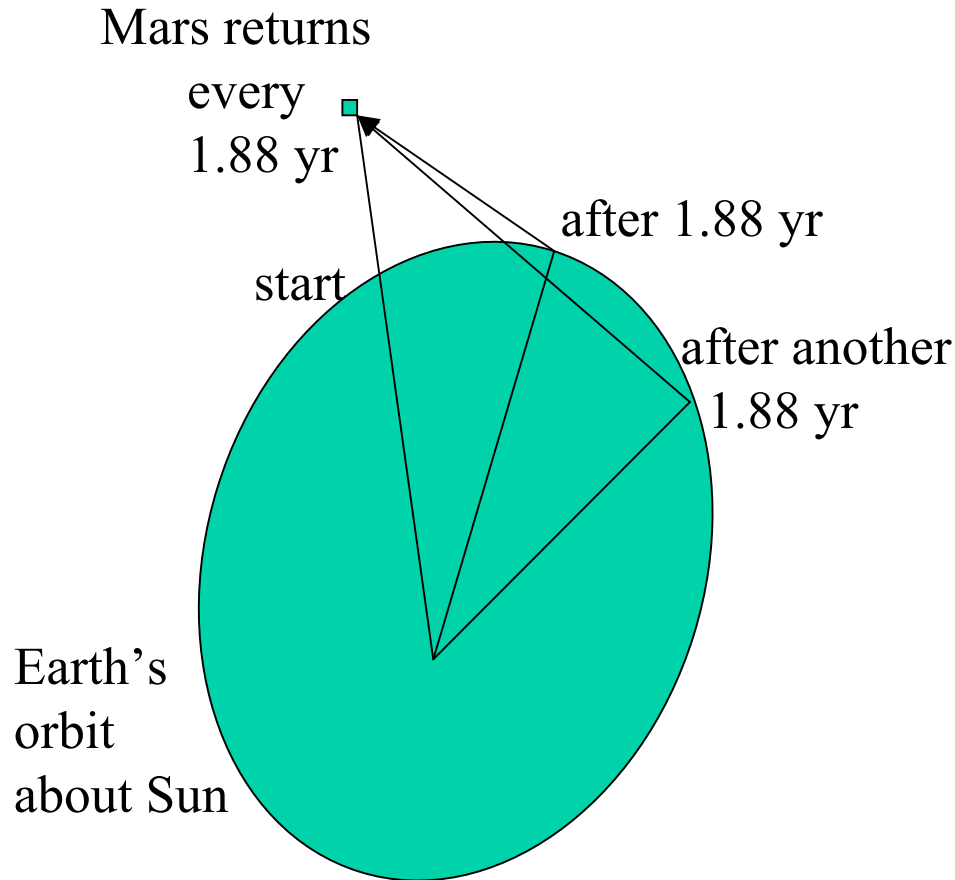


Kepler (1571-1630)

- Copernicus content to explain Ptolemy, not nature.
- Brilliant wrong idea: Perfection of regular geometric solids (five “Platonic” solids).
- Later, correct three laws of planetary motion (to explain data of Tycho Brahe):
 - Each planet, including the Earth, goes around the Sun in a plane, with the Sun at one focus of an ellipse.
 - The radius vector from the Sun to the planet sweeps out equal areas in equal times.
 - The square of the orbital period of a planet is proportional to the cube of the semi-major axis of its elliptical orbit, with the proportionality constant being the same for all the planets of the solar system.

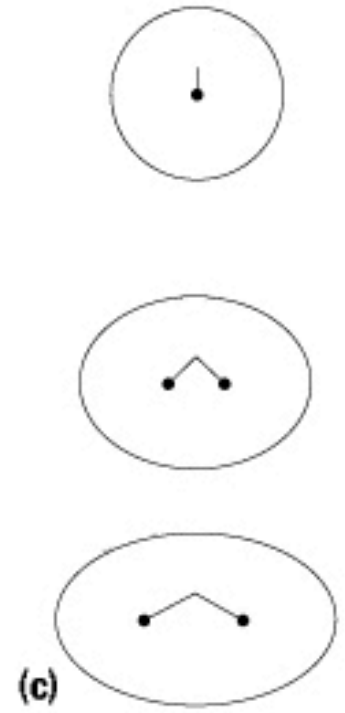
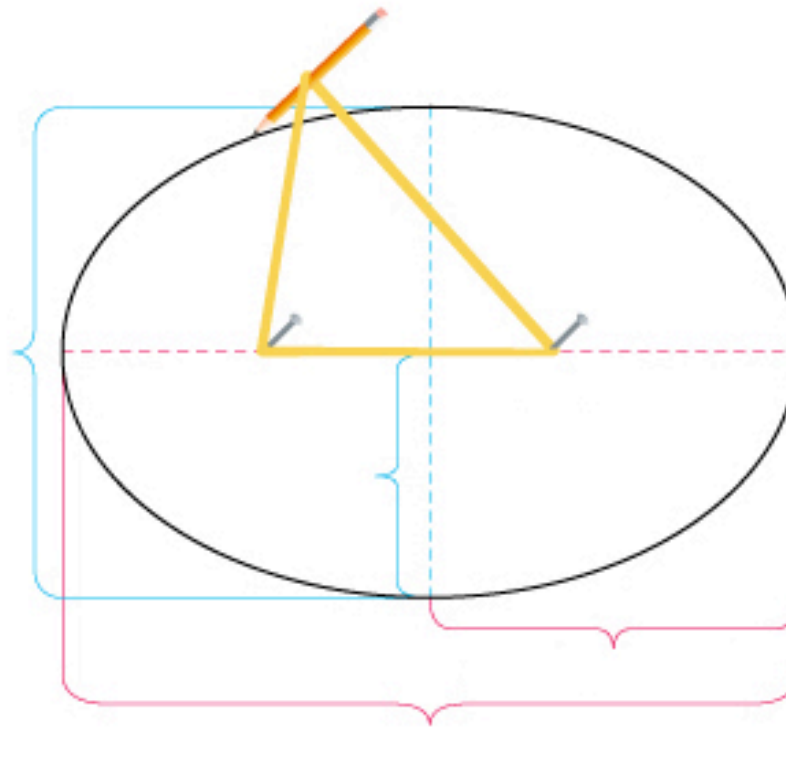
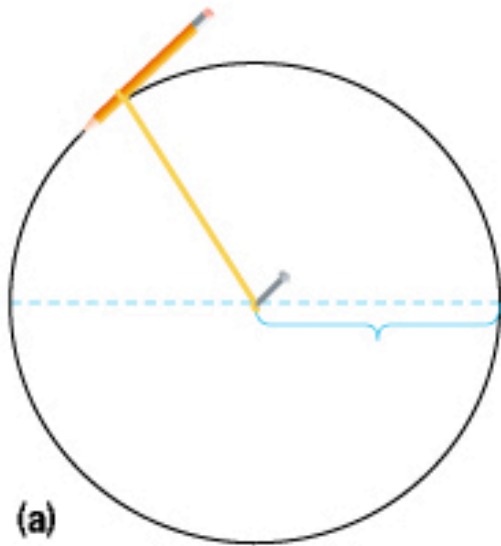


Difficulty: Observations Are Carried Out on a Moving Platform

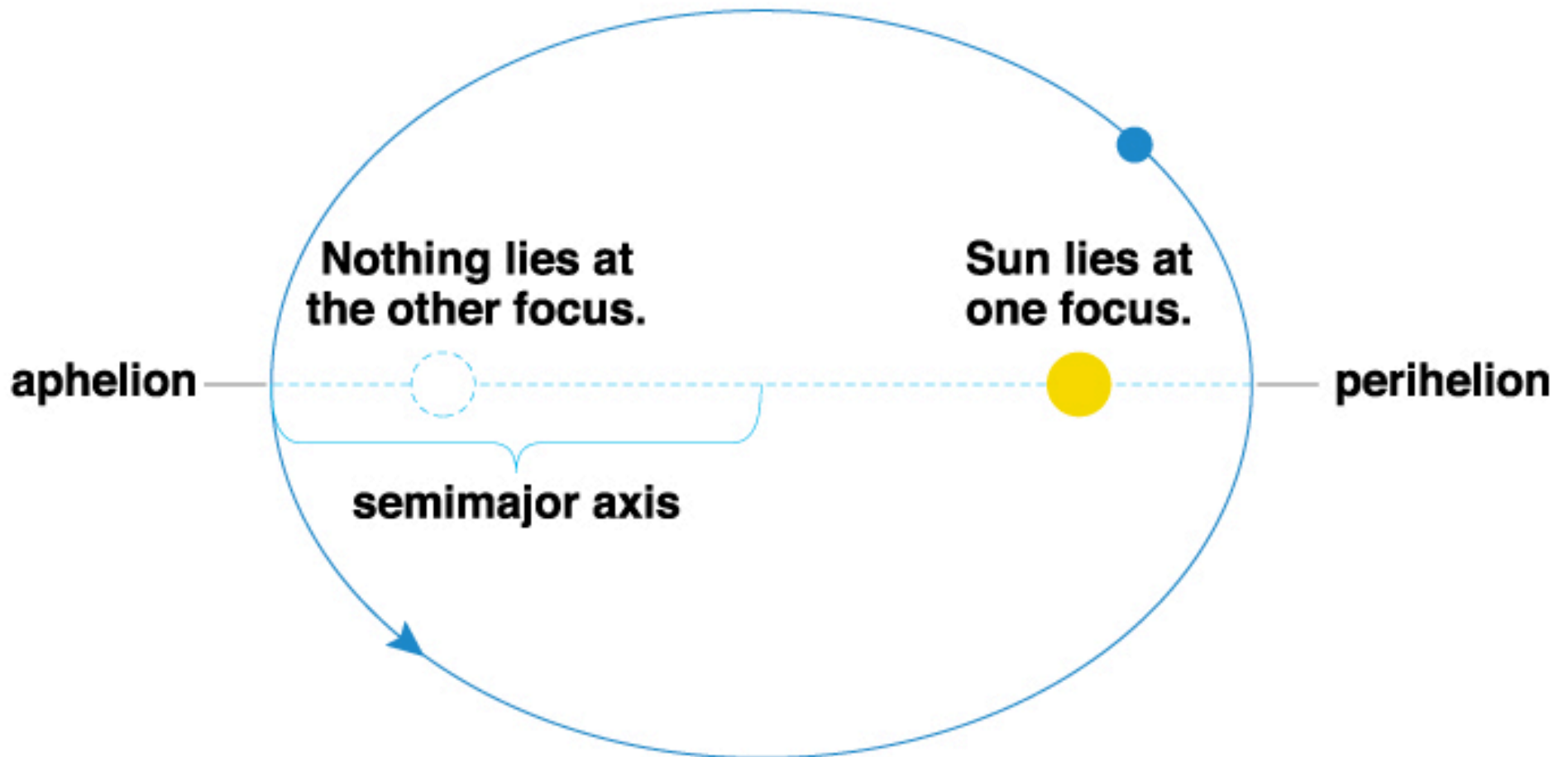


- Assume closed orbits that are periodic in time.
- Guess orbital period of Mars about Sun (in diagram, 1.88 yr).
- Construct trial Earth's orbit, starting at a time when Sun, Earth, Mars are lined up in a straight line. Fix Earth-Sun distance then arbitrarily.
 - After 1.88 yr, Earth's line of sight to Mars and Sun will point to different constellations. This fixes second point on Earth's orbit relative to first.
 - Repeat after another 1.88 yr.
 - Go all the way around, until the Earth has returned to its original point. The Earth's orbit has now been traced.
 - If the Earth's orbit is not closed when go all the way around, then reguess Mars's orbital period.
- To fill in missing points, start at somewhat different time for initial configuration.

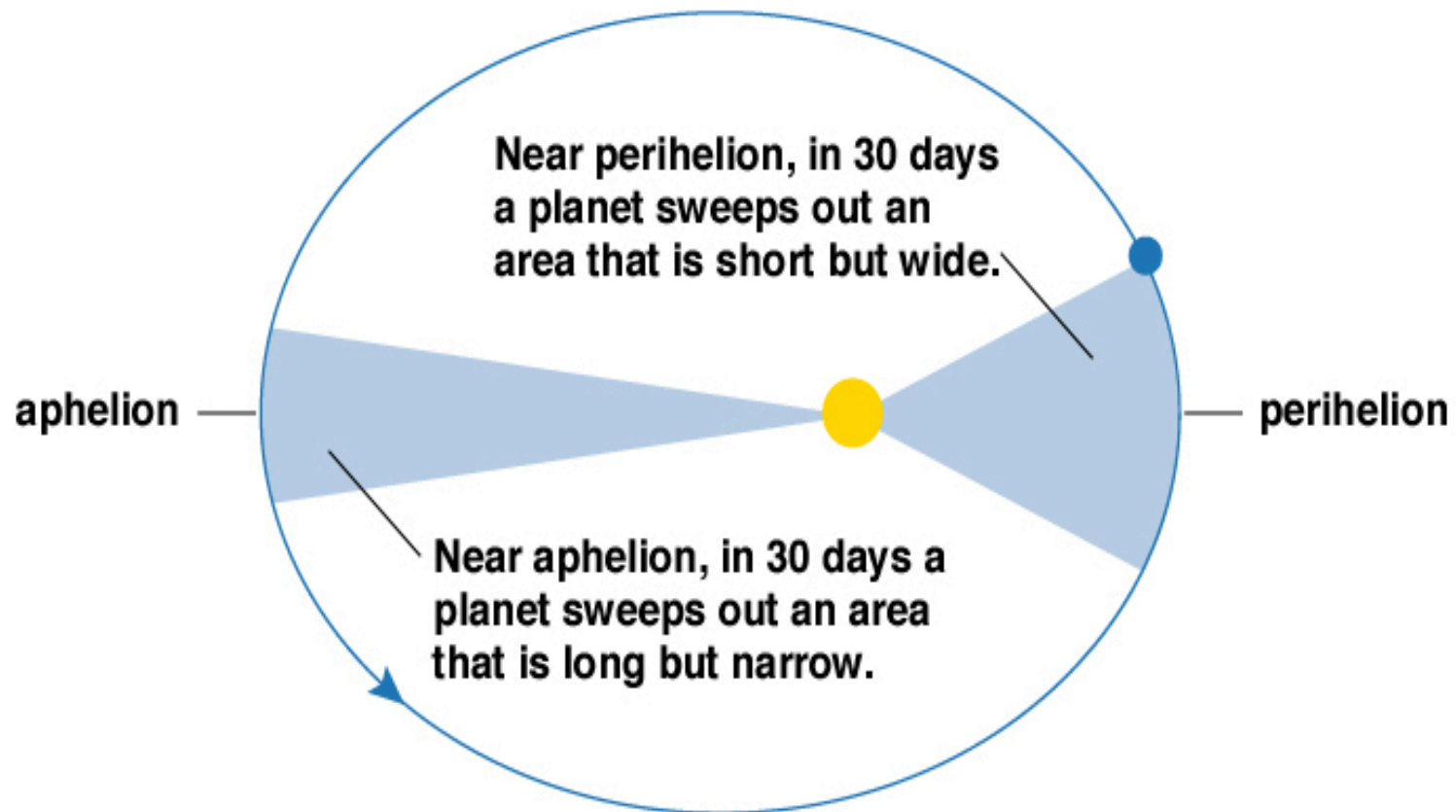
Drawing Ellipses



Kepler's First Law



Kepler's Second Law



The areas swept out in 30-day periods are all equal.

Kepler's Third Law

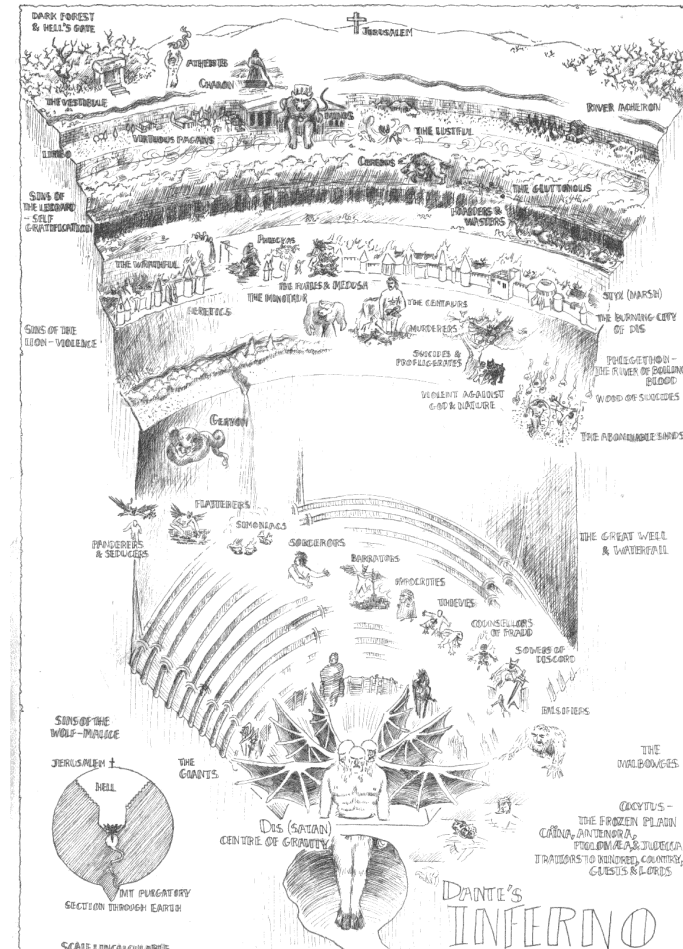
- Of Kepler's three laws, the third was last to be discovered.
- It is the most peculiar, since it relates two unlike quantities (orbital period and semi-major axis) in a completely unexpected and unprecedented way (squares combined with cubes).
- Kepler's motivation: "music of the spheres." Crazy enough to be right: planetary system and musical instruments are both mechanical systems.
Pythagoras: the tone produced by a vibrating string (how fast it vibrates) is related to the length of the string that is tied tautly between two ends.

Object	a (AU)	P (year)	a^3	P^2
Mercury	0.387	0.241	0.058	0.058
Venus	0.723	0.615	0.378	0.378
Earth	1.00	1.00	1.00	1.00
Mars	1.52	1.88	3.51	3.53
Jupiter	5.20	11.9	141.	142.
Saturn	9.54	29.5	868.	870.
Uranus	19.2	84.0	7,080.	7,060.
Neptune	30.1	165.	27,300.	27,200.
Pluto	39.5	248.	61,600.	61,500.


 No longer a planet!

Social & Philosophical Impact of Copernicus, Kepler, & Galileo

- Removal of humans from the center of God's attention: This is especially true if there is a "plurality of worlds" a la Bruno.
- Earth transported to the heavenly realm: Its center is not Hell, into which all filth and heavy things tend to fall.
- Motion of the planets not complex: It does not involve many circles & epicycles, but only single ellipses (subject of Greek study as "conic sections").
- Possibility of explaining motion, the agent of change, in terms of physical causes: We do not need to invoke a "first mover" (Aristotle's "primus mobilium," Aquinas's "God"), although one may still exist for other reasons.



Depiction by Daniel Heald of the nine circles of Hell in Dante's *Inferno*