The spherical Earth

- Greeks knew the Earth was a sphere
  - View of constellations changes from N→S
  - Observations of ships sailing over the horizon (mast disappears last)
  - Observations of the Earth's shadow on the Moon during lunar eclipses
  - The myth of the Flat Earth is a modern misconception about ancient and medieval thought

Earth's shadow on the Moon during a lunar eclipse

Earth radius ~ 4x Moon radius

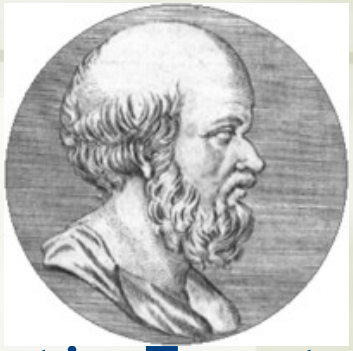
Distance of Moon From Earth

- Suggest a method for determining this distance; hint: use the Sun. Twice if you like.
- Start with:
  - The size of the Earth (radius *R*)
  - The Sun is *very* far away
  - You've seen lunar eclipses…
- (Work in your groups of 3)
- I'll get you started…

Distance of Moon From Earth

- Moon moves in a large circle of radius *R*
- Moon goes around one circle per month *T*
- Earth's shadow is about twice its radius *r*
- Time it takes Moon to cross the shadow *t* *(maximally, about 3.6 hours)*
- v = v it's the same "velocity"!
- $2\pi R/T = 2\ r/t \rightarrow R/r \sim 1$ month / (3 hr * π)
- Average distance of the Moon ~ 60 Earth radii
- Aristarchus, 270 BC…
- But how big is *r*?

Eratosthenes



- Astronomer/mathematician in Hellenistic Egypt (c.275-195 BC)
- Calculated circumference of Earth
  - Measured altitude of Sun at two different points on the Earth (Alexandria & Syene about 800 km apart): found 7° difference
  - How did he do it? (What do you do with those numbers?)
  - Multiplied (360°/7°)×800km (distance between the 2 sites) to obtain circumference~40,000km

- This is a bit oversimplified!
- Note mountains not shown to scale.

Eratosthenes

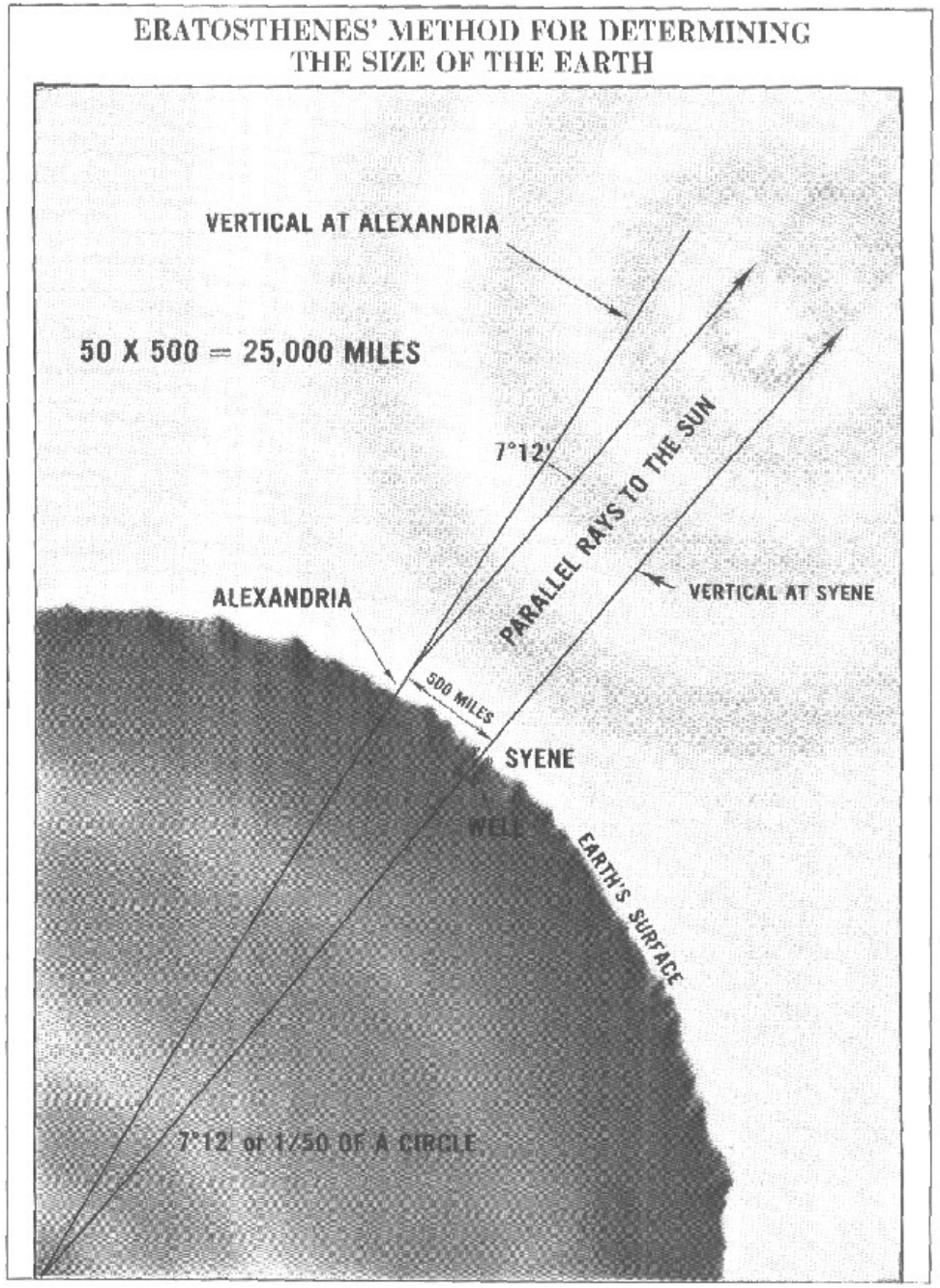


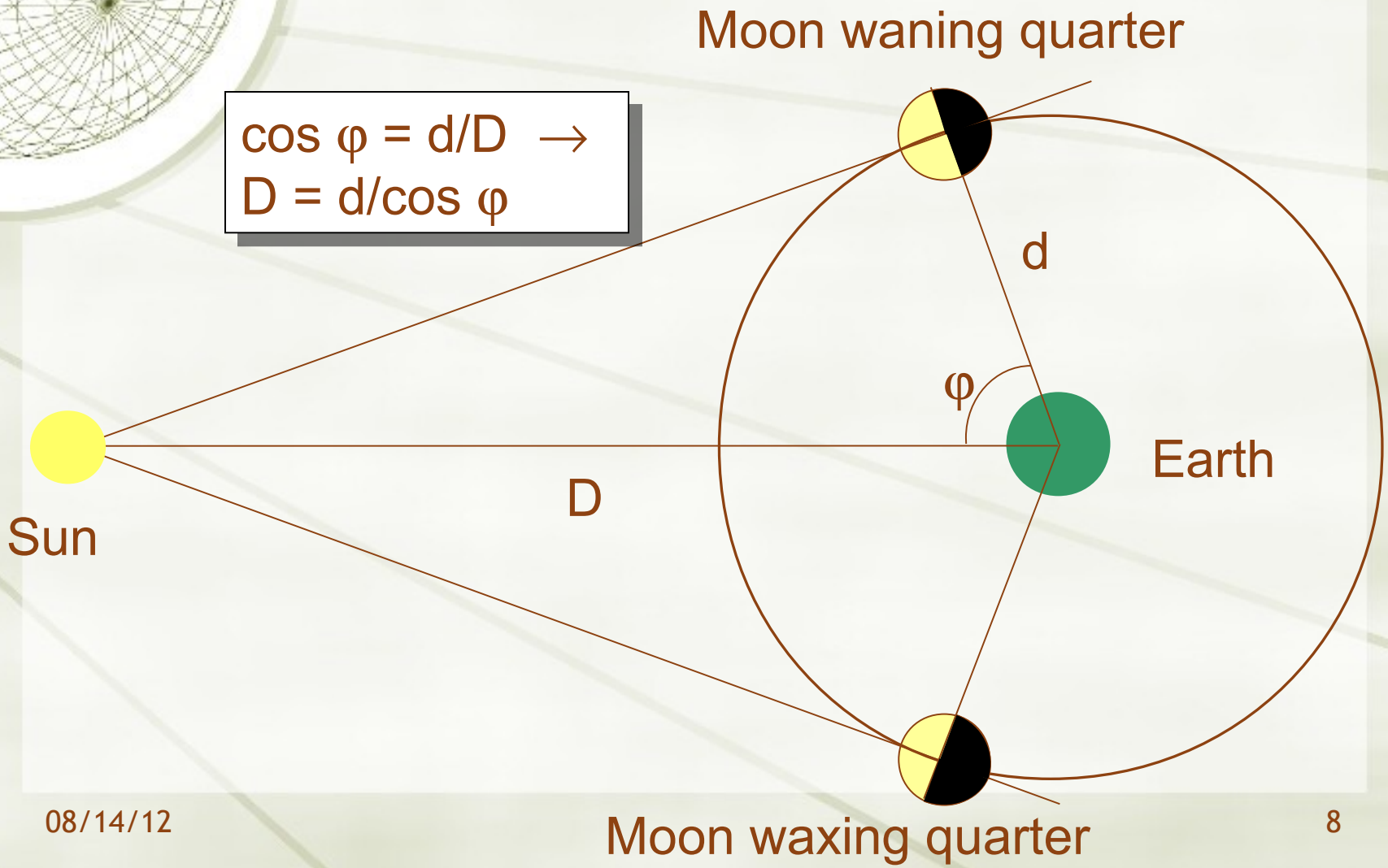
Figure 1

Aristarchus of Samos (310-230 B.C.)

- Using eclipse data and geometry:
  - Measured *relative* sizes of Earth, Moon
- Attempted to measure distance to Sun
  - Size of shadow?
- Need to measure the angle of Sun and Moon when Moon is exactly at 1st or 3rd quarter ("half")

Aristarchus Earth-Sun distance

- Measure angle of Sun & Moon 1st or 3rd quarter (“half”)



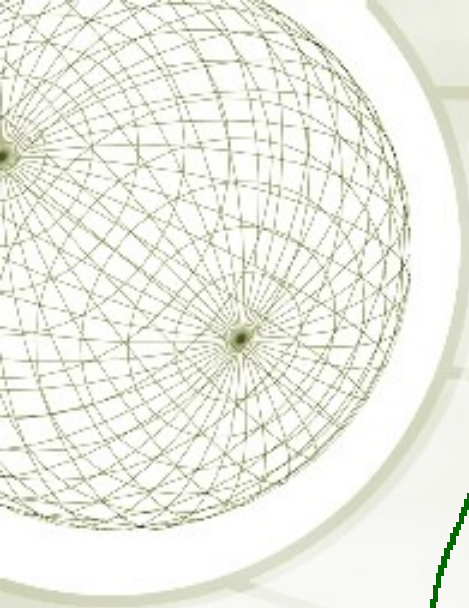
Aristarchus of Samos (310-230 B.C.)

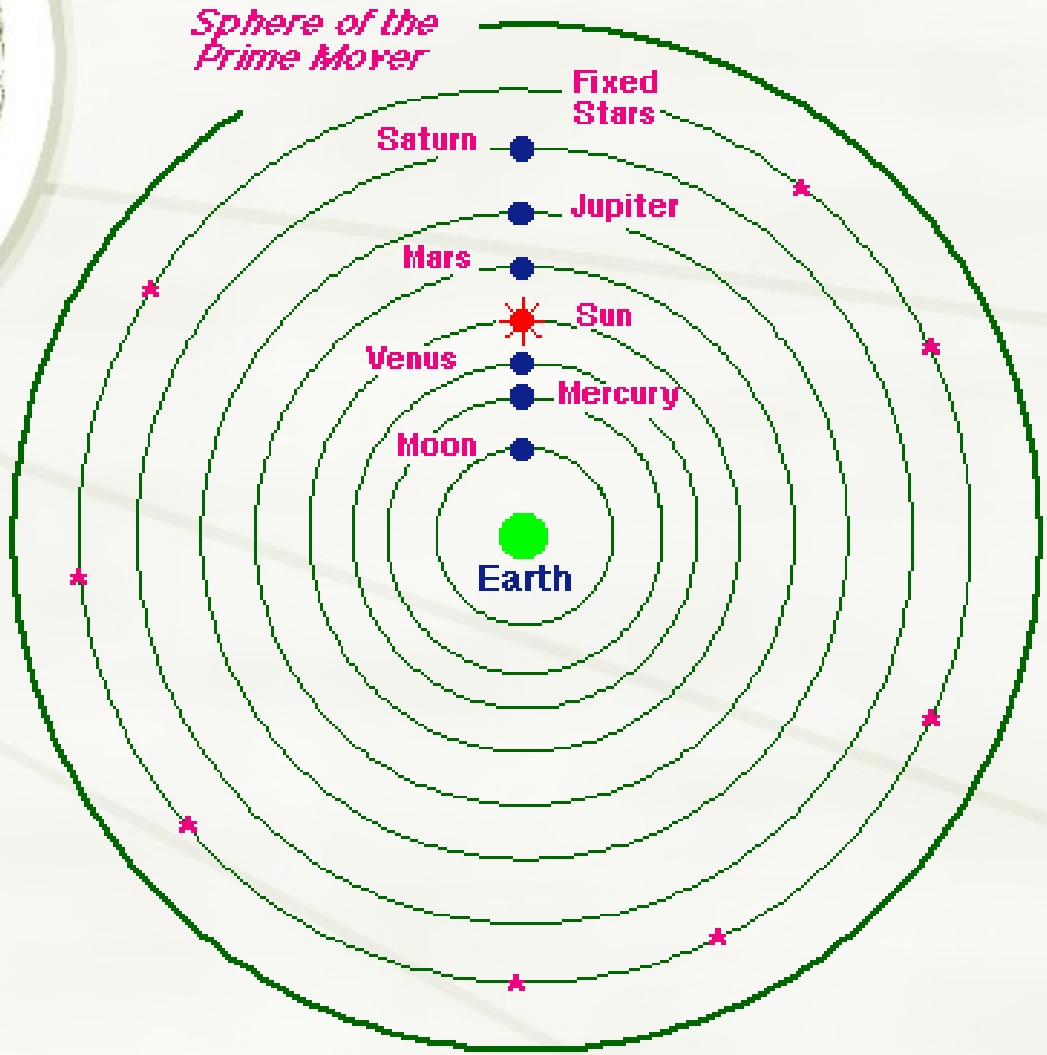
- Use angles and known Earth-Moon distance to get Sun's distance
- Precision very difficult!
- Deduced Sun is 20 times further from Earth than Moon… [actual answer is 400 times…]
- Sun must be huge! Bigger than the Earth!
- ***First to propose a heliocentric model!***

Cosmology of Eudoxus and Aristotle

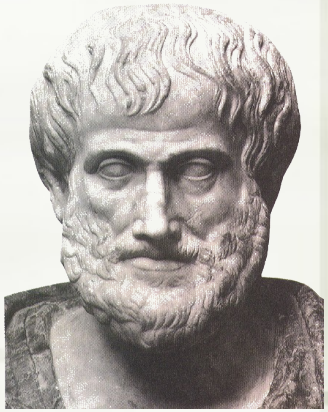
- Fundamental "principles":
  - Earth is motionless
  - Sun, Moon, planets and stars go around the Earth: *geocentric model*
- Eudoxus* (408-355 B.C.)
  - Proposed all heavenly bodies embedded in giant, transparent spheres that revolve around the Earth.
  - Eudoxus needed 27 interlocking spheres to explain observed celestial motions
  - e.g., need to have 24-hr period = day *and* 365-day period=year for the Sun

*most renowned astronomer and mathematician of his day.





Aristotle's Universe

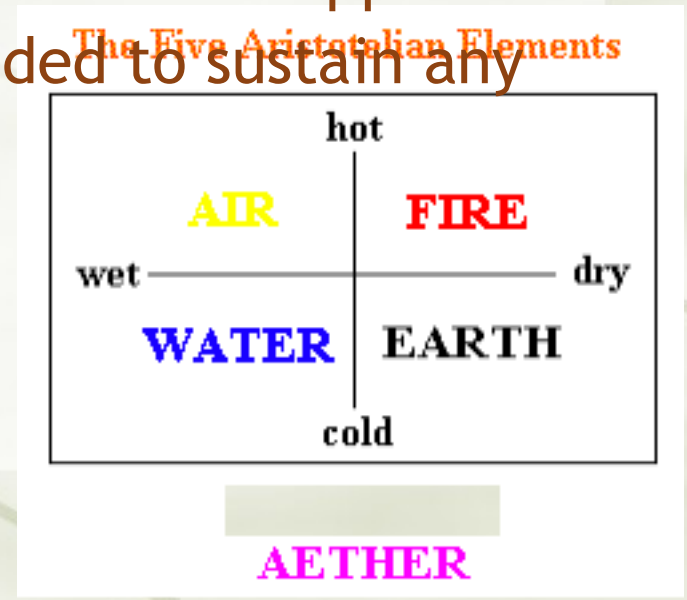


http://graduate.gradsch.uga.edu/archive/Aristotle.html

Aristotle's (384-322 B.C.) physics

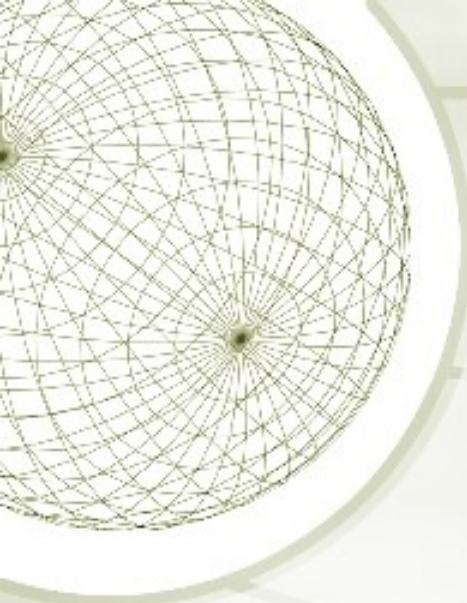
- Four basic (earthly) elements: earth, water, air, fire
- Each element *tends to move* toward its "natural" place:
  - E.g., rock (earth) falls in air/water, air bubble in water rises
  - "Natural motions" of earthly objects
    - straight lines toward center of Earth
    - bodies in motion naturally tend to come to rest
    - applied force causes deviation from natural motion
    - body at rest will remain so unless a force is applied
    - continual application of force needed to sustain any motion *other* than natural motion
  - Why is this in a Cosmology class?

Codification of our experience!



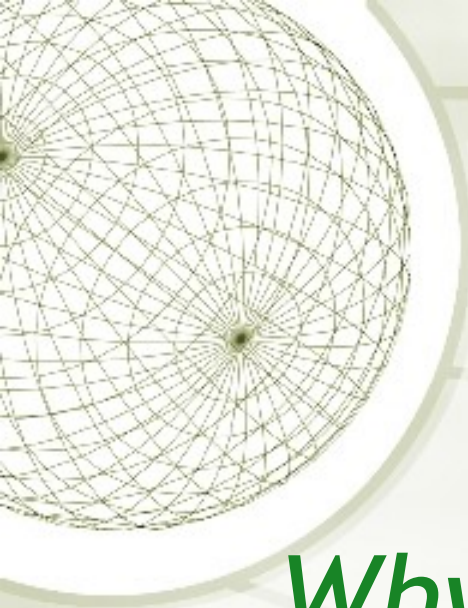
Aristotle's celestial physics

- Heavens are governed by *different* laws from Earth
- Celestial bodies composed of "aether," a fifth element not present on Earth*
- **turns out there might a quintessence! (later…)*
- "Natural motions" of celestial spheres are different from terrestrial motions:
  - circular, constant, and eternal
  - Aristotle needed 55 spheres to explain observed motions of Sun, Moon, planets, stars
- Space is finite, bounded by outer sphere
- Edge is unreachable: motions become circular in the ethereal
- Time is infinite
- Why is such a perfect universe centered on such an imperfect Earth?

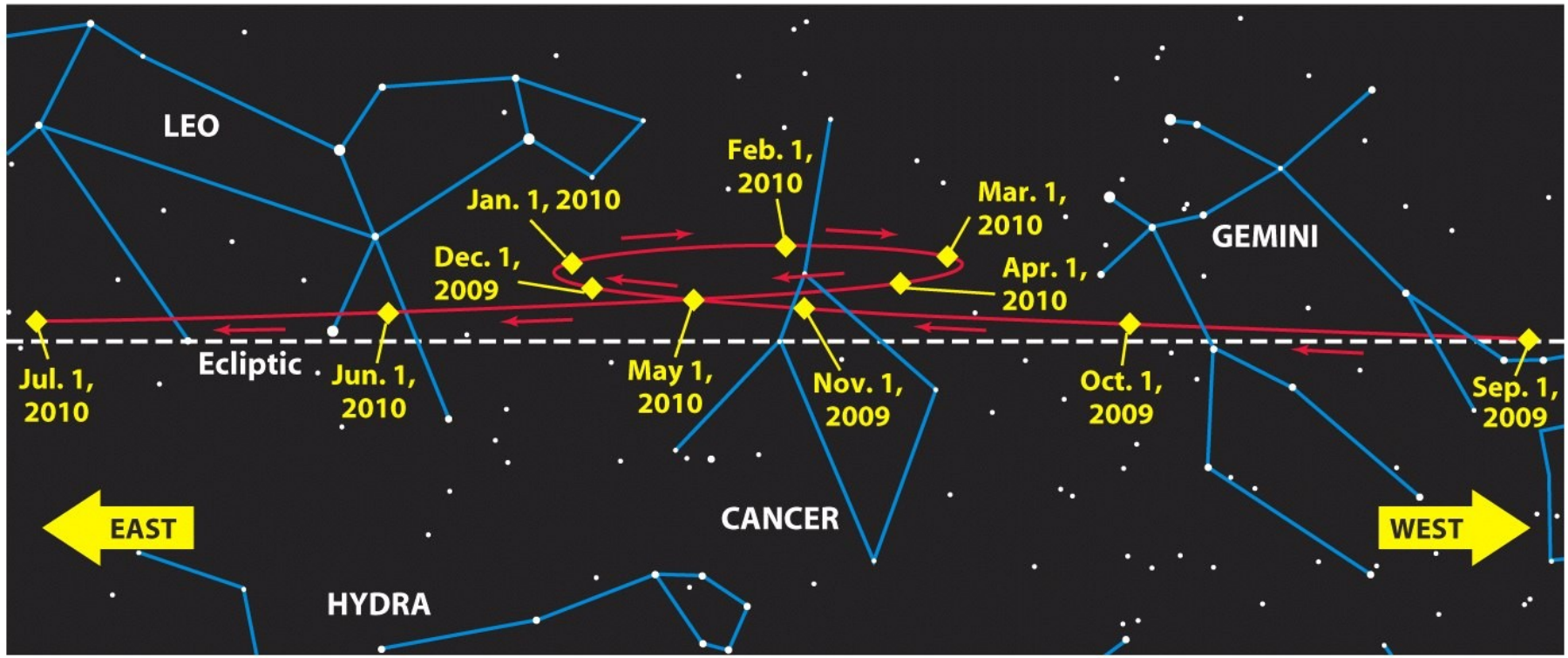


Because you're all sinners!

Just kidding!
(But I wouldn't be kidding in the Middle Ages…)



Why do you care what a bunch of dead Greeks did?



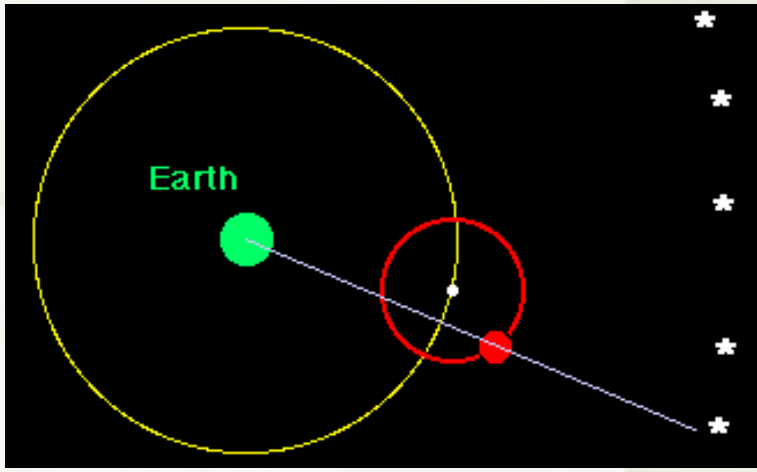
Retrograde motion

Motion of Mars over 1 year- notice 'reversal of direction'

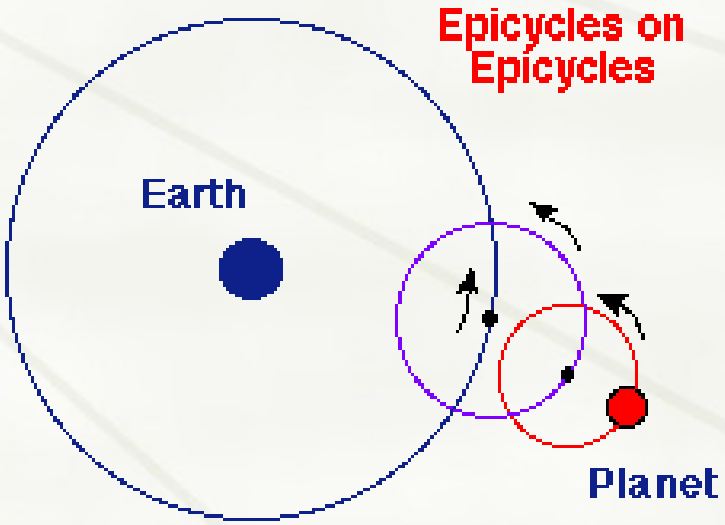
Ptolemy's epicycles-how to calculate the positon of the planets

Ptolemy's original "epicycles"

- Larger circle ("deferent") not centered on the Earth
- Motion appeared uniform from "equant" (offset from Earth and from center of "deferent")



Dept. of Physics and Astronomy Univ. of Tennesse



Needed more and more epicycles to fit observed angular motion

Epic Epicycles

- Aristotelian/Ptolemaic view prevailed in Europe and Islamic empire, through 1400's
  - Geocentric model
  - Creation at finite time in past, for consistency with Christian theology
  - Earth known to be round (Columbus battling against flat Earthers is myth!)

Copernicus (1473-1543)

- Nicholas Copernicus was modern (re)founder of the heliocentric (Sun centered) model for the solar system
- Rejected Ptolemy's geocentric model because it was too complicated (Occam's razor)
- Heliocentric model …
- …with perfect circular motions (model bias!)

Copernicus

- Mathematics was not simpler than Ptolemy's, but it required fewer basic assumptions
- By Copernicus assuming only
  - the rotation of the Earth,
  - revolution about the sun,
  - tilt of Earth's rotational axis,
- he could explain observed “motions” of the heavens
- Because he retained *circular* orbits, his system required the inclusion of epicycles

Copernicus (1473-1543)

- ***The Copernican Principle: The Earth is not at a special location in the Universe.***

- Later, we will come across the **Generalized Copernican Principle: There is no special place in the universe, i.e., the universe has no center**
- Death of Anthropocentrism?
- (Where is the center of the Universe?)
- (YOU!)

Tycho Brahe (1546-1601)

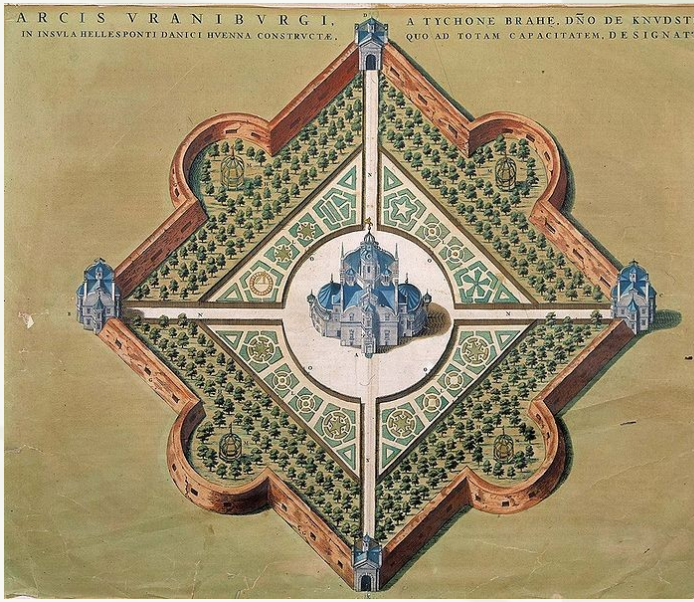
Tycho Brahe (1546-1601)

- Born 3 years after Copernicus' death
- Last of the great "naked eye" observers
- Observed *nova* "new star" (1572)*
- From parallax observations of comet:
  - knew they were not in Earth's atmosphere
  - Showed they *crossed* the spheres!
  - Beyond Moon's orbit!
  - evidence heavens not immutable!
- **Collected the premiere dataset on the motion of the planets**

*Chinese had known of 'new stars (novae) for millenia

Tycho Brahe and the Origin of Scientific Funding

- He received an annual pension of five hundred dalers.
  - This was far more than the income of any other man of learning in Europe, and even for an aristocrat, it was a substantial income.
  - **Tycho set a new European standard for the financial support of scientific research.**
  - It is estimated that Brahe's observatory cost about 1% of the **Danish government budget** during construction.



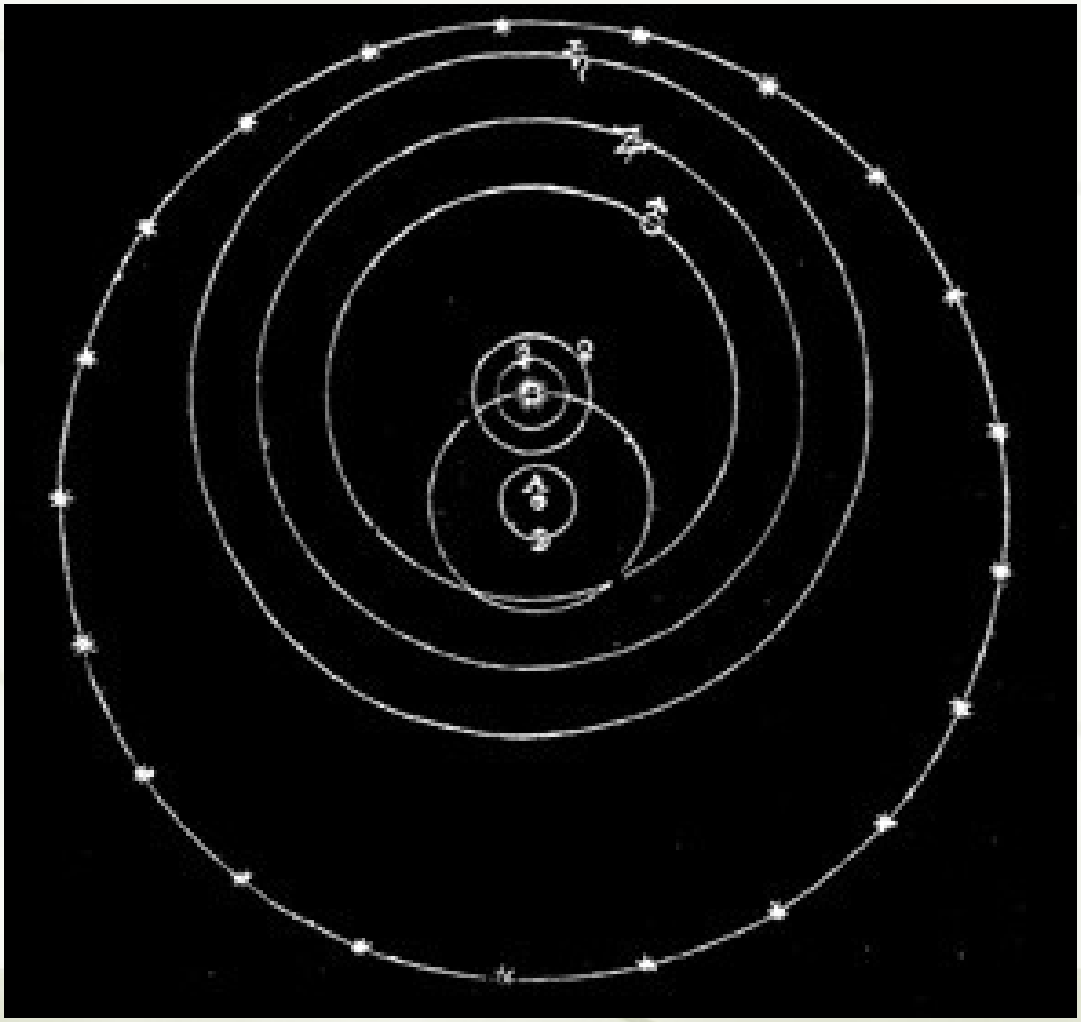
Uraniborg

Large mural quadrant at Uraniborg ~2.6m in diameter (to measure angles precisely)

Tycho's cosmological model

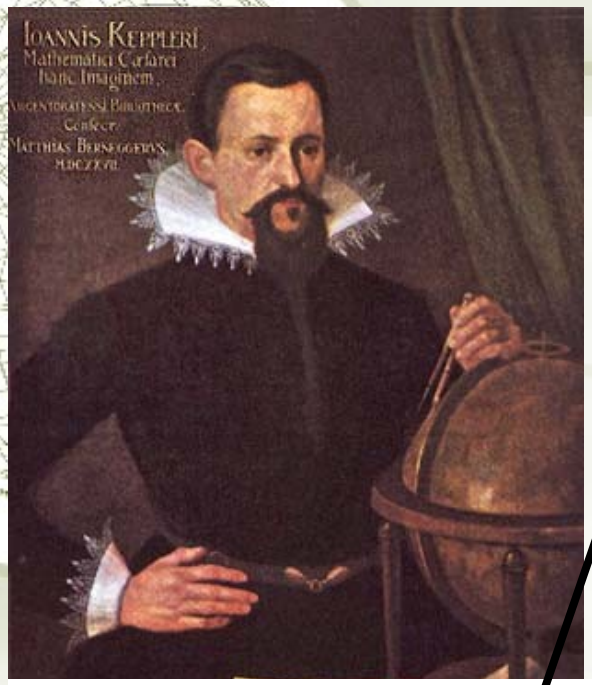
- Tycho used parallax to test heliocentric model:
  - If Earth moves, parallax of stars ***should*** be observable
- Couldn't detect parallax; concluded Earth is stationary
- Settled on combined geo/helio-centric model
  - Sun orbits Earth; all other planets orbit Sun

Tycho's cosmological model



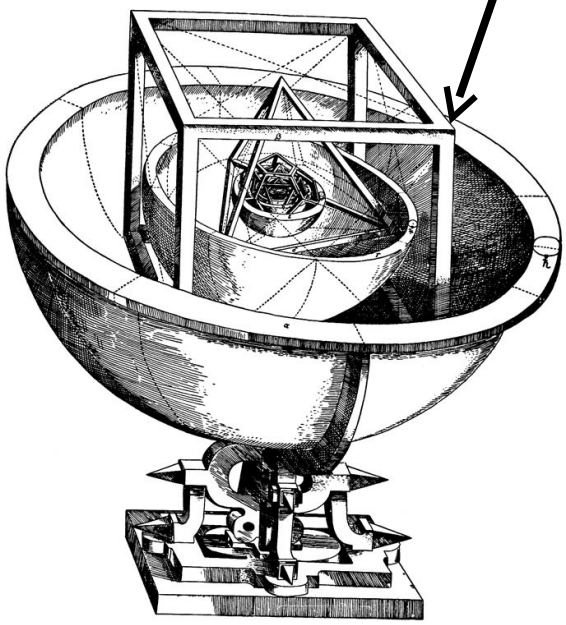
Tycho's Compromise

- Alas, stellar parallax is 100× too small for naked-eye observation to measure; largest values are about 1”
- 1 arcsecond=(1/3600)°
- What's 1” in radians? *Board digression*
- How many AU away is 1 arcsecond?
- What is the parallax of α-Centauri, 4 ly away?



Johannes Kepler (1571-1630)

- Convinced God made the Universe according to mathematical plan
- Was hired as Tycho Brahe's assistant in Prague to make sense of Brahe's extremely accurate observations of Mars
- Led to the publication of three laws of planetary motion (1601, 1609, 1619)



The Polyhedra inscribed into the planetary orbits. Kepler's drawing is a pure geometrical fancy, but it is meant to correspond to the actual relation between the radii of the planetary orbits. Most important here is the cube, fitted into the outermost sphere of Saturn.

An imprecise version of Kepler's laws

Orbits are not circular

A planet's speed changes during its orbit

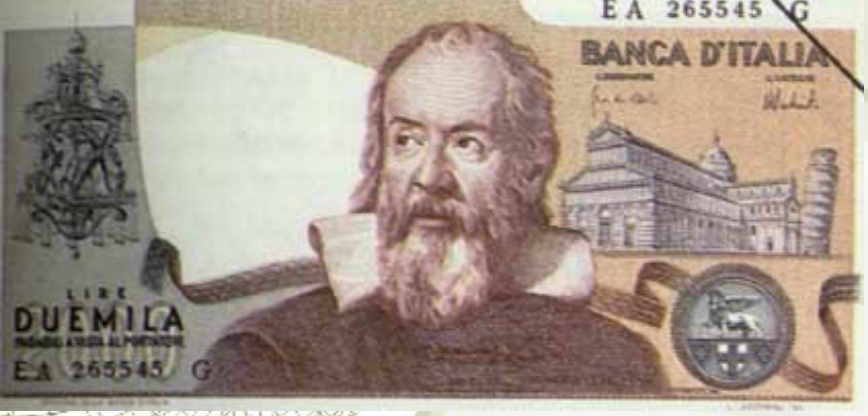
There is a definite relationship between orbital period and the distance from the star

Kepler in perspective

- Based on Tycho Brahe's accurate observations, Kepler calculated his way to a major breakthrough in cosmology
- Kepler's three laws of planetary motion
  - Represented a simpler model of solar system and can be generalized
  - Swept away thousands of years of prejudice – and his own previous pet theory!
  - Were driven fundamentally by the ***data***, including Tycho's error estimates
- Data will lead theory again in cosmology!

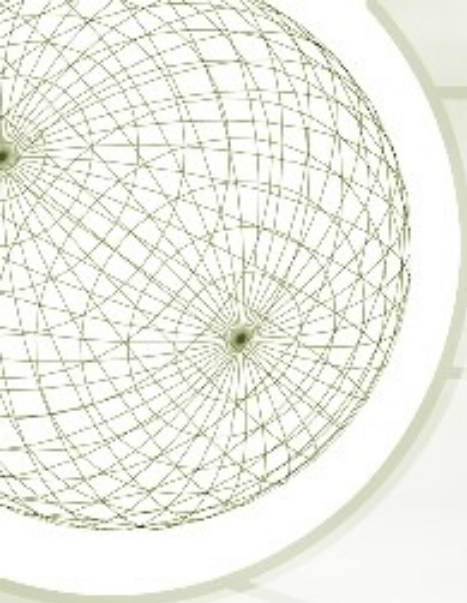
Kepler in perspective

- Unlike previous models, Kepler's Laws had predictive power, consistent with modern idea of a meaningful scientific theory
- Newton's derivation (i.e., deeper underlying theory) of Kepler's laws from even more general principles comes later…
- 19th century observations of small deviation of Mercury's orbit from Newton's/Kepler's laws spur theoreticians again… more on that later



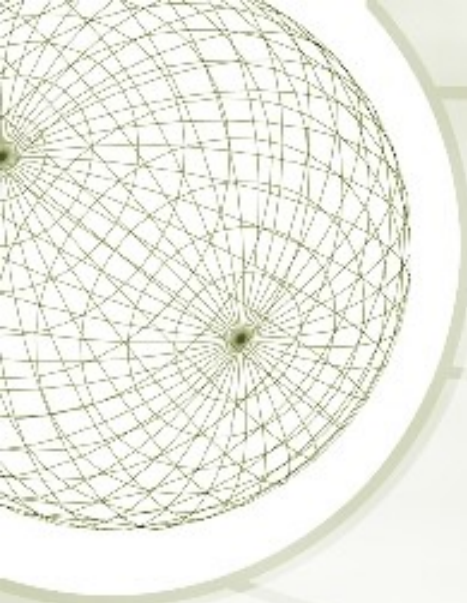
Galileo Galilei (1564-1642)

- Built one of the first (astronomically useful) telescopes in 1609
- Published "*The Starry Messenger*" with first telescopic discoveries in 1610
- Telescopic observations: objects in the sky were not perfect!

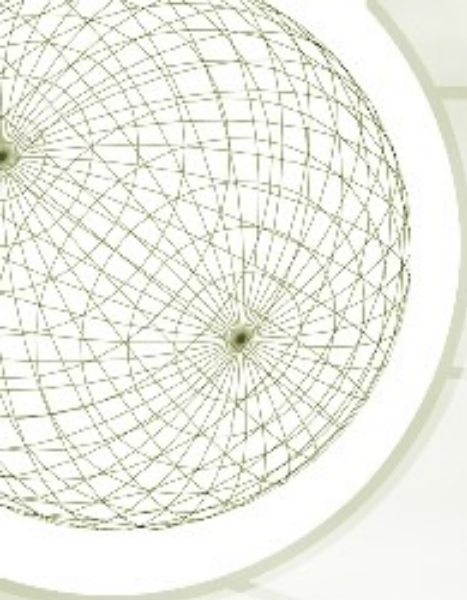


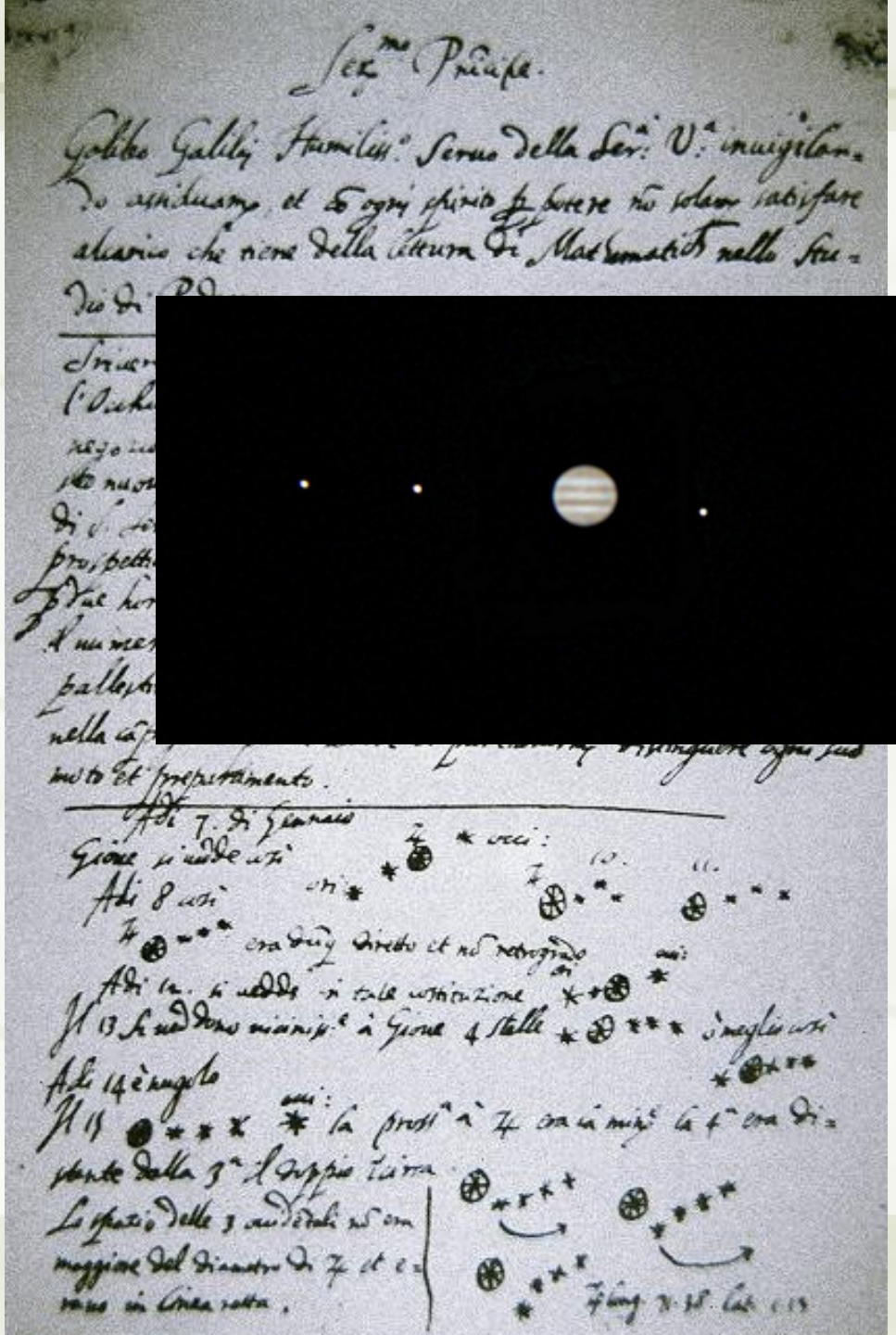
Moon is not smooth, but covered by mountains and craters.

http://www.astromax.org



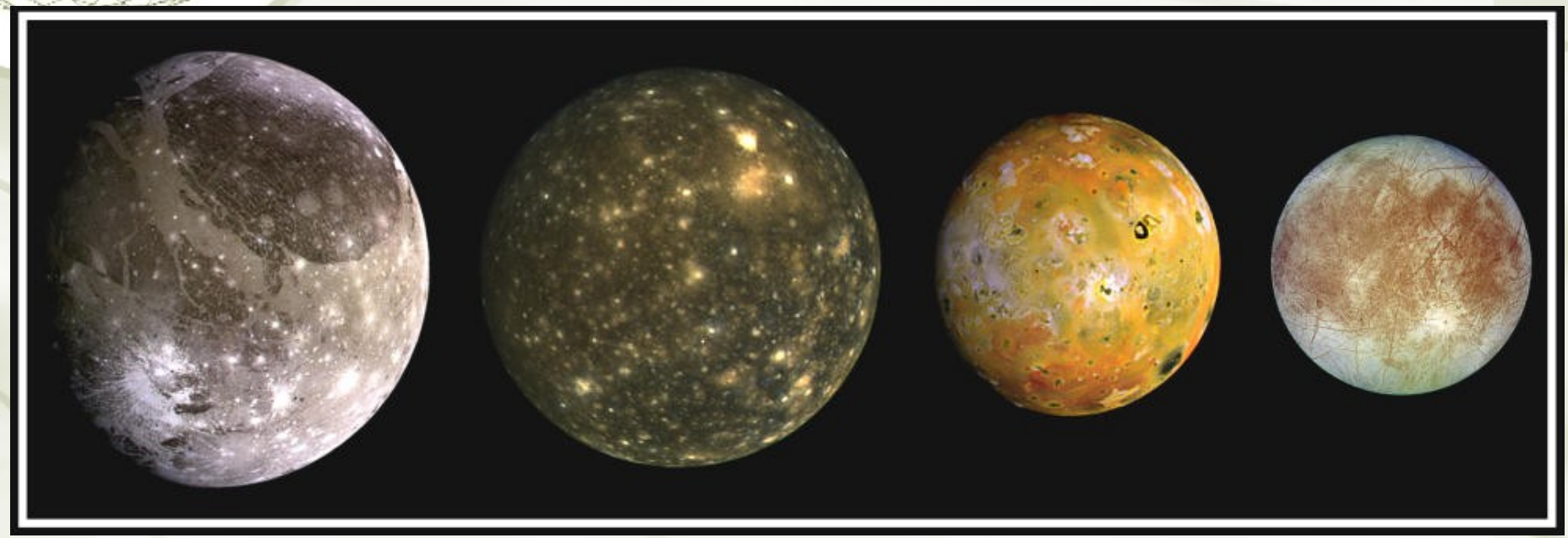
- Galileo observed sunspots moved = Sun was rotating on an axis.
- The doctrine of an unchanging perfect substance in the heavens (aether) starts to crumble!





Letter from Galileo reporting the discovery of Jupiter's moons… Not everything goes around the Earth!

Galilean moons (from Galileo spacecraft!)



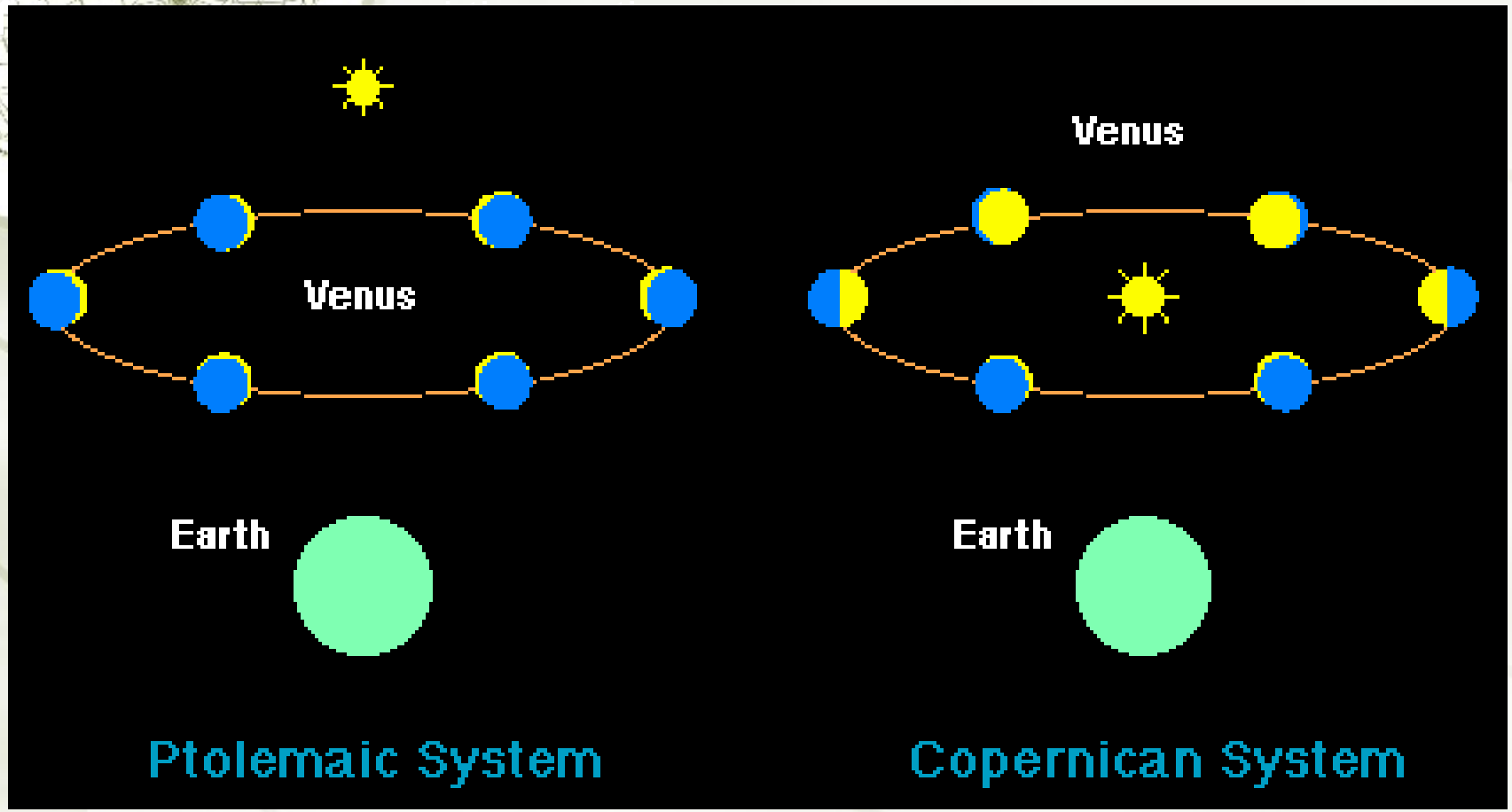
NASA

Impact of Galileo's observations

- Crucial experiment ruling out Ptolemaic model:
  - Possible phases of spherical Venus in Ptolemaic model are only crescent or new -- but Galileo *observed full phase*
  - Observation supported Copernican (or at ***least*** Tycho's) model

Phases of Venus: a test of the Heliocentric system

In the heliocentric model Venus can show certain phases impossible



http://www.telescope1609.com/Galileo.htm

http://csep10.phys.utk.edu/astr161/lect/history/galileo.html

Impact of Galileo's observations

- Galileo became ardent supporter of Copernican viewpoint
- In 1632, published *Dialogue Concerning the Two Chief Systems of the World - Ptolemaic and Copernican;*
  - Inquisition bans book
  - Galileo found guilty of heresy; sentenced to house arrest
- Giordano Bruno did not fare well (1548-1600 – burned at t

Galilean physics

After 1633 trial, Galileo works on mechanics

Used “thought experiments” to conclude that all bodies, regardless of mass, fall at the same rate in a vacuum – contrary to Aristotle

Now known as “equivalence principle” – will pop up later

https://www.youtube.com/watch?v=5C5_dOEyAfk

Galilean physics

Realized full principle of inertia:

body at rest remains at rest;

body in motion remains in motion (force *not* required)

Realized principle of relative motion ("Galilean invariance"):

If everything is moving together at **constant** velocity, there can be no apparent difference from case when everything is at rest

Ball dropped from top of moving ship's mast hits near bottom of mast, not behind on deck (ship not big enough to notice Coriolis force!)

Isaac Newton in 1689, by Sir Godfrey Kneller.

Father of modern physics and cosmology

Isaac Newton (1643-1727)

Attended Cambridge University, originally intending to study law, but reading Kepler, Galileo, Descartes

Cambridge closed due to plague (1665-1667), Newton went home and

began to work out calculus

realized (contrary to Aristotle) that white light is composed of colors

began to formulate laws of motion and law of gravity

What have ***you*** done lately?

Newton's history, cont.

In 1687, published *Philosophiae naturalis principia mathematica,* or *"Principia*

included proof that inverse square law produces ellipses (Kepler!)

generalized Sun's gravity law to universe law of gravitation: *all matter attracts all other matter with a force proportional to the product of their masses and inversely proportional to the square of the distance between them*

$$F_G \propto mM/r^2$$

Newton's history, cont.

"Principia":

laid out general physics of mechanics – laws of motion

Principia is possibly greatest scientific book ever written ("Origin of Species" anyone?)

Newton's physics good enough to explain all astronomy until late 19th century (Mercury); good enough to land on the Moon.

Not good enough for GPS accuracy…