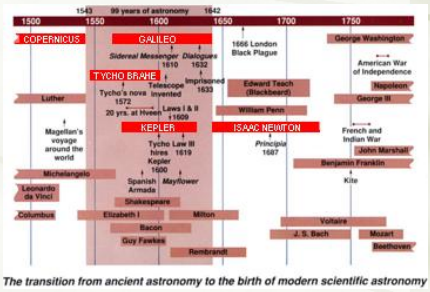
Lecture 3: Cosmology of the Scientific Revolution

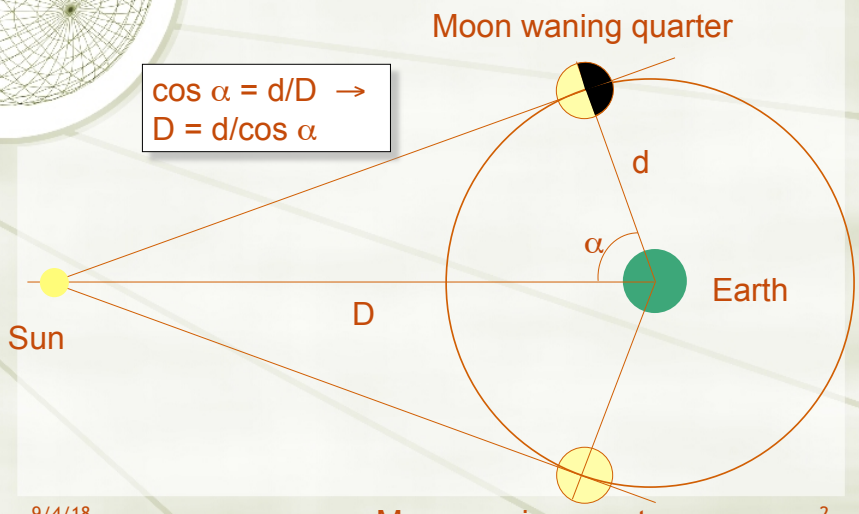
- Tycho Brahe
- Kepler
- Galileo
- Newton



The transition from ancient astronomy to the birth of modern scientific astronomy

http://www.physics.fsu.edu/users/Lind/AST1002/

Aristarchus Earth-Sun distance

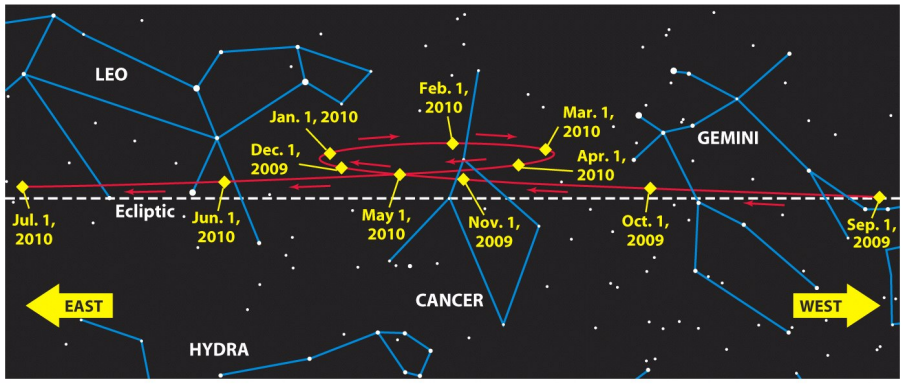


Heliocentric model of Aristarchus

- Observations implied Sun is much larger than Earth
- Therefore proposed the first **heliocentric** model
  - Sun is the center of the Universe
  - Everything goes around the Sun
- Never accepted by others of his time
  - inconsistent with *apparent* perception of stationary Earth
  - No *apparent* shift in stellar positions could be observed over course of seasons
  - Prevailing culture was uncomfortable with the idea that Earth was not central to the Cosmos

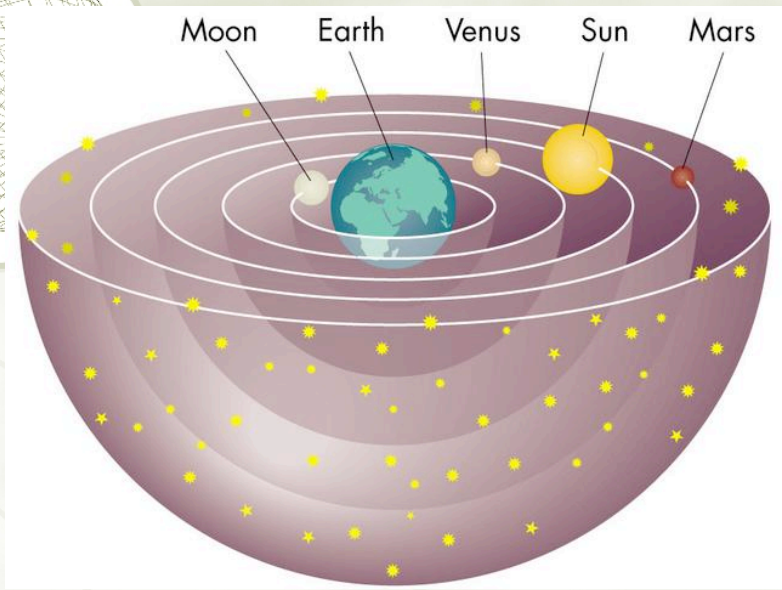
Ptolemy (100-170 A.D.)

- Worked at observatory in Alexandria, both as observer and theorist
- Developed theory to accommodate detailed planetary observations:
  - Variations in brightness over months
  - Retrograde motions
  - Variations in observed orbital speed
- Theory involved motion along small circles superposed on top of motion along large circles (think Spirograph!)
- Successors added additional "epicycles" to model to improve agreement with observations
  - Very complex!
  - No underlying law; no predictive power for new planets



Retrograde motion

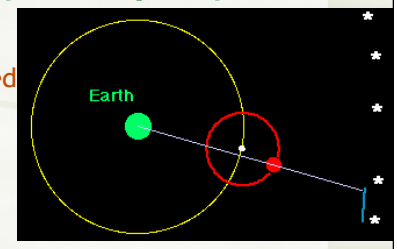
Motion of Mars over 1 year- notice 'reversal of direction'



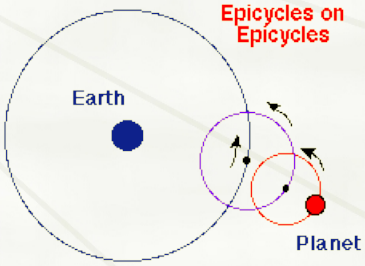
Geocentric model

Ptolemy's epicycles

- 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")

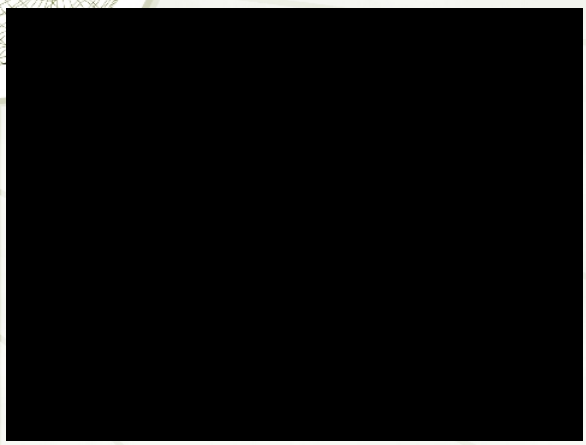


Dept. of Physics and Astronomy Univ. of Tennesse



Needed more and more epicycles to fit observed angular motion

Ptolemy and Homer

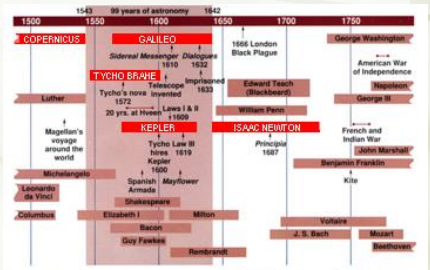


Carman & Serra, from YouTube

- This particular "orbit" required 1000 epicycles
- What do you think this translates to in terms of falsifying the theory?

Renaissance cosmology

- Pre-Renaissance
- Copernicus
- Tycho



The transition from ancient astronomy to the birth of modern scientific astronomy

http://www.physics.fsu.edu/users/Lind/AST1002/

Before the Renaissance

- During European "dark ages," Arab astronomers preserved and extended Ptolemy's work
- Aristotelian/Ptolemaic view prevailed in Europe, 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 Earth"ers is myth!)

Copernicus (1473-1543)

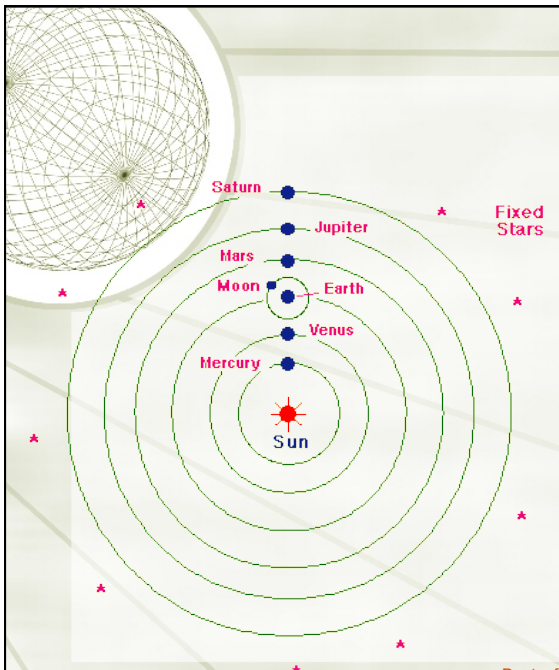
- Nicholas Copernicus was modern founder of the heliocentric (Sun centered) model for the solar system
- Copernicus was born in Poland; studied in Krakow, Bologna, Padua, Ferrara
  - canon law, medicine, mathematics, astronomy
  - Worked as church canon, physician
- Rejected Ptolemy's geocentric model because it was too complicated
- Preferred heliocentric model with perfect circular motions
- **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.**

Copernicus's first work

- Wrote and distributed to friends the *Little Commentary* (1514)

Axioms:

1. *There is no one center in the universe.*
2. *The Earth's center is not the center of the universe.*
3. *The Earth and planets revolve around the Sun.*
4. *The distance from the Earth to the Sun is imperceptible compared with the distance to the stars.*
5. *The rotation of the Earth accounts for the apparent daily rotation of the stars.*
6. *The apparent annual cycle of movements of the Sun is caused by the Earth revolving round it.*
7. *The apparent retrograde motion of the planets is caused by the motion of the Earth from which one observes.*



Portrait from 1597
by Teothor de Bry

Copernicus's *de Revolutionibus*

- Full title: *De Revolutionibus Orbium Coelestium*
- Printed Nuremberg, 1543, in last year of life
- Spelled out, using observations and mathematics, evidence for his heliocentric model
  - Simple and natural explanation for retrograde motion of planets
  - Included accurate relative spacings of planetary orbits
  - Showed that planetary speeds decrease outward from Sun
  - Still had to include some epicycles to improve agreement with observations
- Book was widely read and appreciated by 16th C. astronomers
  - some believed in Copernicus's heliocentric physical model
  - others considered Copernicus's approach superior for calculating orbits, but believed in geocentric Universe
- No official position by Catholic church up to 1600

Tycho Brahe (1546-1601)

- Flamboyant and tyrannical aristocrat, but devoted to science
- Lived and observed on an island (Ven) off the coast of Denmark
- Last of the great "naked eye" observers
- Made planetary observations much more accurate than any previous
- Observed "new star" (Tycho's supernova) in 1572
- Demonstrated that a comet was beyond Moon's orbit
- From parallax observations of new star, comet:
  - knew they were not in Earth's atmosphere
  - evidence that heavens were not immutable

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Large quadrant at Uraniborg

9/4/18

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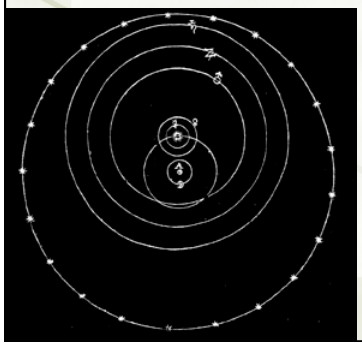
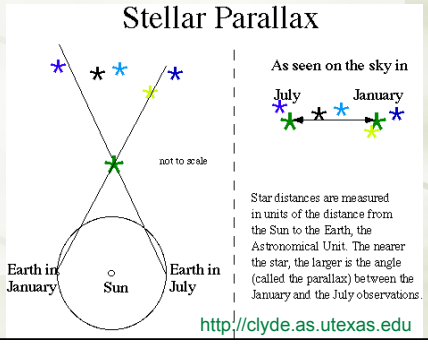
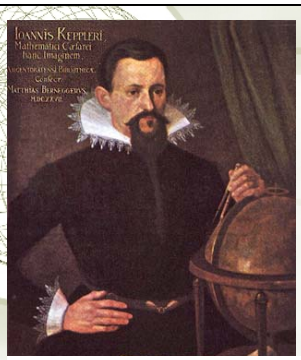
Tycho's cosmological model

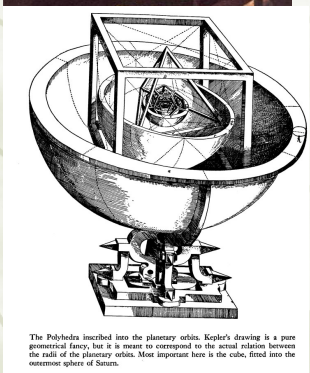
- Tycho used parallax observations to explore heliocentric model:
  - If Earth moves, then parallax of stars *should* be observable
  - Tycho could not detect any significant parallax; he concluded Earth is stationary
  - In fact, stellar parallax is 100× too small for naked-eye observation to measure; largest values are about 1 arcsecond=(1/3600)°
- Tycho settled on combined geo/helio-centric model
  - Sun orbits Earth; all other planets orbit Sun





Johannes Kepler (1571-1630)





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.

- Born in Germany; originally planned to be ordained as Lutheran minister
- Convinced God made the Universe according to a mathematical plan; saw his Christian duty as understanding works God had created
- Studied mathematics; published in 1596 his ***Mystery of the Cosmos*** proposing that planetary orbits lie in spheres nested within a series of the Platonic solids (wrong!)
- Was hired as Tycho Brahe's assistant in Prague; his job was to make sense of Brahe's extremely accurate observations of Mars
- Kepler became Imperial Mathematician after Brahe's death (1601)
- Kepler's "war with Mars" amounted to a thousand sheets of arithmetic; resulted in publishing Kepler's "First Law" and "Second Law" in 1609 as part of his ***New Astronomy***
- Kepler's "Third Law" was published in 1619 as part of his ***Harmony of the World***

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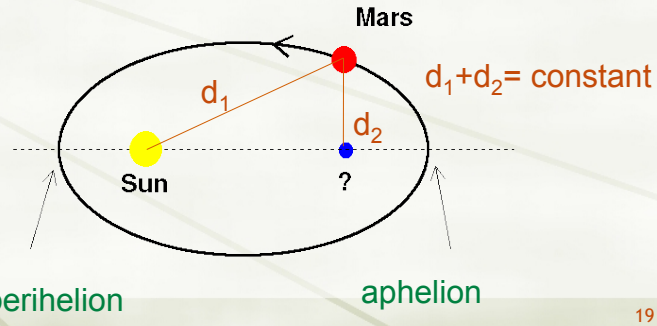
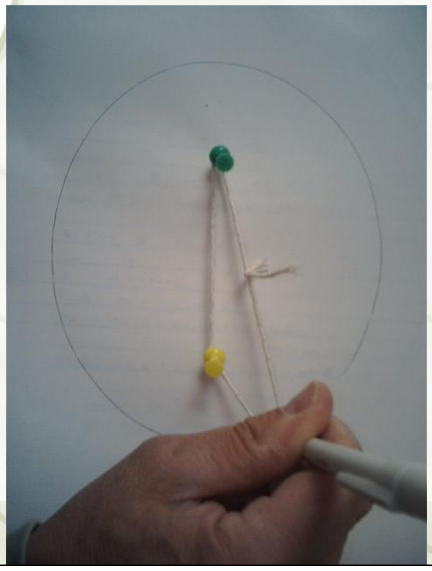
Kepler's first law

- Planets move around the Sun in ellipses, with the Sun at one focus.



Kepler's first law

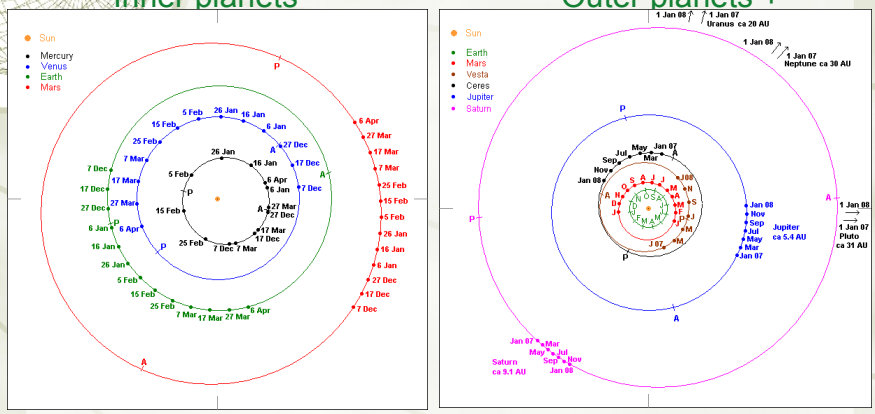


Drawing an ellipse is easy: use two tacks for the focii and a string

Solar system orbits

Inner planets

Outer planets +

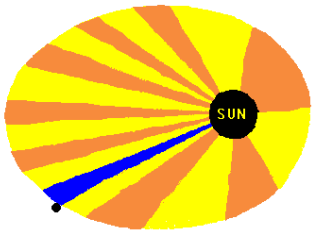


http://www.rasnz.org.nz/SolarSys/Orbits07.htm

Note the low eccentricities!

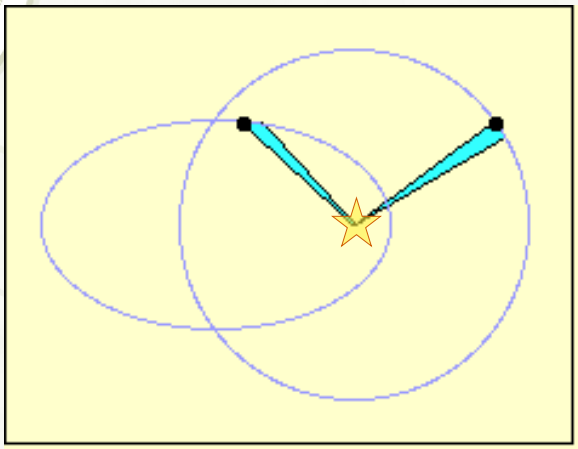
Kepler's second law

- **The line connecting the Sun and a given planet sweeps out equal areas in equal times.**
  - Therefore, planets move faster when they are nearer the Sun
  - Consequence of angular momentum conservation.



http://home.cvc.org/science/kepler.gif

Kepler's second law with high- and low- eccentricity orbits



Time-lapse movies of orbits

Stars around the Galactic center's black hole

http://www.galacticcenter.astro.ucla.edu/animations.html

Time-lapse movies of orbits

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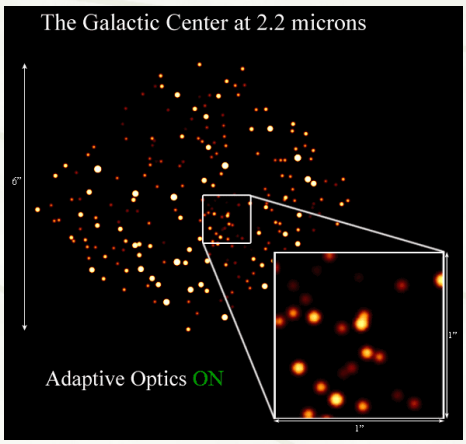


http://www.galacticcenter.astro.ucla.edu/animations.html

Kepler's third law

- **The square of the period *P* of the orbit is proportional to the cube of the semi-major axis *R***
- Period (*P*) = time it takes for planet to complete one orbit
- Semi-major axis (*R*) = half of the length of the "long" (i.e. major) axis of the ellipse.

$$P^2 = constant \times R^3$$

$$P^2 = 4\pi^2/G(M+m) \times R^3$$

(Newton)

- For the Earth, we know that:
  - P= 1 year = 3×10^7 seconds
  - R= 150 million km (1 Astronomical Unit, A.U.)
- Kepler's 3rd law says that, for other planets,

$$\left(\frac{P}{yr}\right)^2 = \left(\frac{R}{AU}\right)^3$$

- For the Earth, we know that:
  - P= 1 year = 3×10^7 seconds
  - R= 150 million km (1 Astronomical Unit, A.U.)
- Kepler's 3rd law says that, for other planets,

$$\left(\frac{P}{yr}\right)^2 = \left(\frac{R}{AU}\right)^3$$

- Newton will show (lect# 5) that in general

$$P^2 = \frac{4\pi^2}{GM_{sun}}R^3$$

Where G is the "gravitational constant"

An imprecise version of Kepler's laws

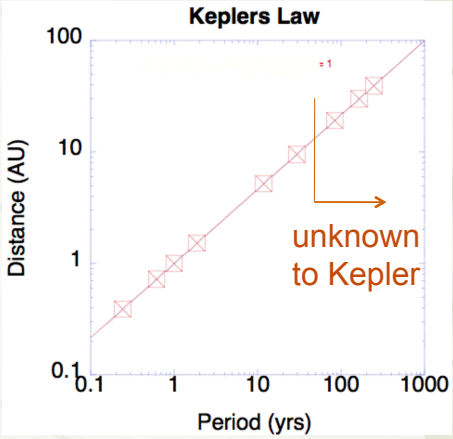
- Orbits are not circular
- A planet's speed changes during its orbit
- There is a definite relationship between orbital period and the distance from the star

Kepler in perspective

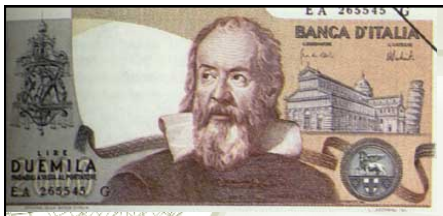
- Based on Tycho Brahe's accurate observations, Kepler calculated and thought his way to a major breakthrough in cosmology
- Kepler's three laws of planetary motion
  - Represented a very simple (and correct!) model of the solar system
  - Swept away thousands of years of prejudice – and his own previous pet theory!
  - Were driven fundamentally by the **data**, including Tycho's error estimates
- Unlike previous models which quantified only what was observed already, Kepler's Laws had predictive power, consistent with modern idea of a meaningful scientific theory

This is what we mean by "predictive power"

- Line is Kepler's third law
- Boxes are planets in the solar system

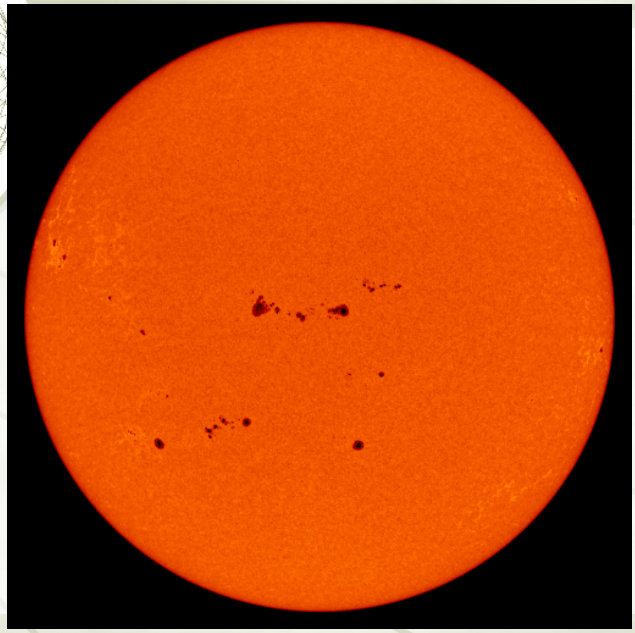


Exoplanets discovered by the Kepler observatory

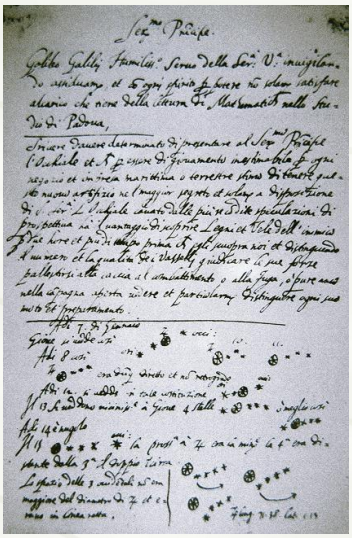


Galileo Galilei (1564-1642)

- Born in Pisa; worked as professor of mathematics
- Built one of the first telescopes in 1609
- Published *"The Starry Messenger"* with first telescopic discoveries in 1610
- Telescopic observations:
  - Saw craters and mountains on the Moon
  - Realized sunspots were on surface, not foreground; rotated with Sun
  - Identified four satellites of Jupiter ("Galilean moons")
  - Saw rings of Saturn
  - Resolved the diffuse Milky Way into many faint stars
  - Observed phases of Venus including gibbous and full



Letter from Galileo reporting the discovery of Jupiter's moons…



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On the third, at the seventh hour, the stars were arranged in this sequence. The eastern one was 1 minute, 30 seconds from Jupiter; the closest western one 2 minutes; and the other western one was

East * ○ * * West

10 minutes removed from this one. They were absolutely on the same straight line and of equal magnitude.

On the fourth, at the second hour, there were four stars around Jupiter, two to the east and two to the west, and arranged precisely

East * * ○ * * West

on a straight line, as in the adjoining figure. The easternmost was distant 3 minutes from the next one, while this one was 40 seconds from Jupiter; Jupiter was 4 minutes from the nearest western one, and this one 6 minutes from the westernmost one. Their magnitudes were nearly equal; the one closest to Jupiter appeared a little smaller than the rest. But at the seventh hour the eastern stars were only 30 seconds apart. Jupiter was 2 minutes from the nearer eastern

East ** ○ * * West

one, while he was 4 minutes from the next western one, and this one was 3 minutes from the westernmost one. They were all equal and extended on the same straight line along the ecliptic.

On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Jupiter, as is seen

East * ○ * West

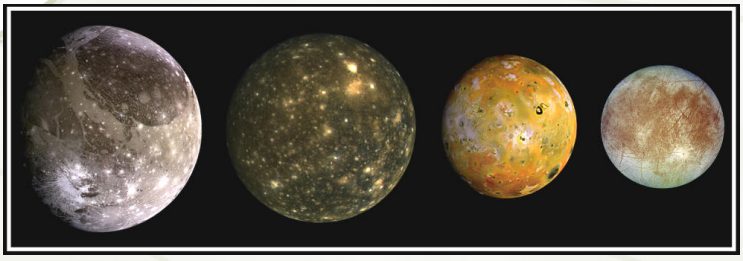
in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

On the seventh, two stars stood near Jupiter, both to the east, arranged in this manner.

Galilean Moons

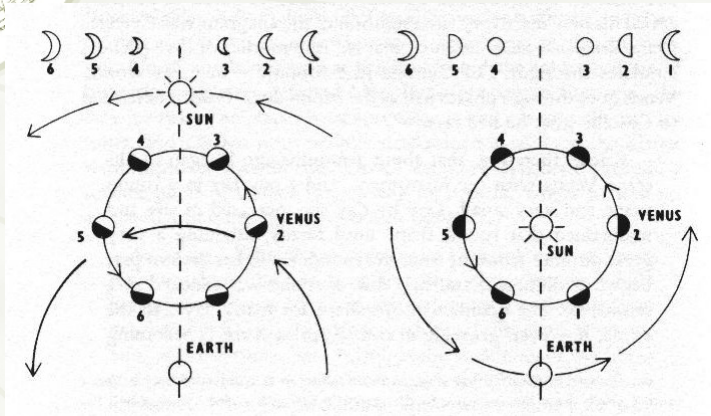
http://www.ladeltascience.com/astronomy/kisatchie04/

Galilean moons (from Galileo spacecraft!)



NASA

Phases of Venus: the test of the Heliocentric system



Galileo's lens, Florence

Museo di Storia della Scienza, Florence

41

Impact of Galileo's observations

- Chipping away at Aristotelian point of view:
  - Features on Sun, Moon, Saturn indicated they are not "perfect" orbs
  - Faint stars resolved in Milky Way indicates stars at many distances -- not just single sphere
  - Moons of Jupiter showed that Earth was not sole center of motion
- Crucial experiment ruling out Ptolemaic model:
  - Possible phases of Venus in Ptolemaic model are only crescent or new -- but Galileo *observed full phase*
  - Observation supported Copernican (or Tycho's) model (Venus on far side of Sun when full)
- As a result of his observations, Galileo became ardent supporter of Copernican viewpoint
- In 1632, published *Dialogue Concerning the Two Chief Systems of the World - Ptolemaic and Copernican*
- The Inquisition banned the book; Galileo was found guilty of heresy in supporting Copernican view, and sentenced to house arrest

Galilean physics

- After 1633 trial, Galileo returned to work on physics of mechanics
- Published *Discourses and mathematical demonstrations concerning the two new sciences (1642)*
- Made experiments with inclined planes; concluded that distance *d* traveled under uniform acceleration *a* is $d=a\,t^2$
- 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"
- 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.

Quiz: Write your name and answer in the card

- In the first lecture we talked about the characteristics of a scientific theory. This lecture we pointed out a fundamental problem (in terms of modern scientific thinking) with Ptolemy's system of epicycles to explain planetary motions.
  - What was it?

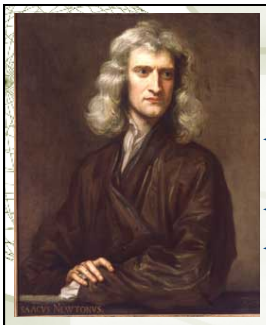
Next time…

- Newton and his laws
  - Laws of motion
  - Law of universal gravitation

Start reading Chapter 3 of text

First Homework will be posted tomorrow!!!!

HW #1 due on Sept 20th!



Isaac Newton in 1689, by Sir Godfrey Kneller.

Isaac Newton (1643-1727)

- Attended Cambridge University, originally intending to study law, but reading Kepler, Galileo, Descartes
- Began to study mathematics in 1663
- While Cambridge was closed due to plague (1665-1667), Newton went home and
  - began to work out foundations of calculus
  - realized (contrary to Aristotle) that white light is not a single entity, but composed of many colors
  - began to formulate laws of motion and law of gravity
- Became professor of mathematics starting in 1669 (age 27!)
- Worked in optics, publishing "Opticks" (1704)
  - invented reflecting telescope
  - showed color spectrum from prism recombines into white light with a second prism
  - analyzed diffraction phenomenon

Father of modern physics and cosmology

Newton's history, cont.

- In 1687, published *Philosophiae naturalis principia mathematica*, or *"Principia"*
  - publication was prompted (and paid for) by Halley
  - partly in response to claim by Hooke that he could prove gravity obeyed inverse-square law
  - included proof that inverse square law produces ellipses
  - 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
  - many other applications, including tides, precession, etc.
  - laid out general physics of mechanics -- laws of motion
  - showed that Kepler's laws follow from more fundamental laws
- The *Principia* is recognized as the greatest scientific book ever written!
- Retired from research in 1693, becoming active in politics and government