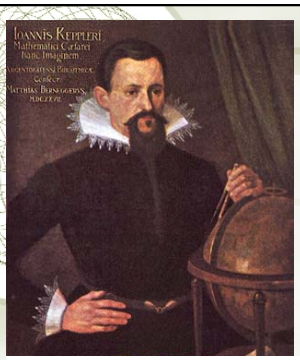
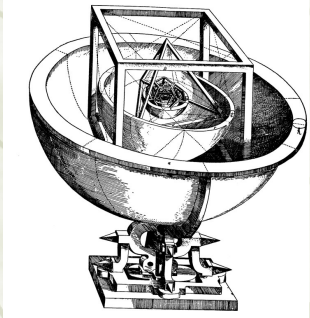
Lecture 3: Cosmology of the Scientific Revolution

- Kepler
- Galileo
- Newton





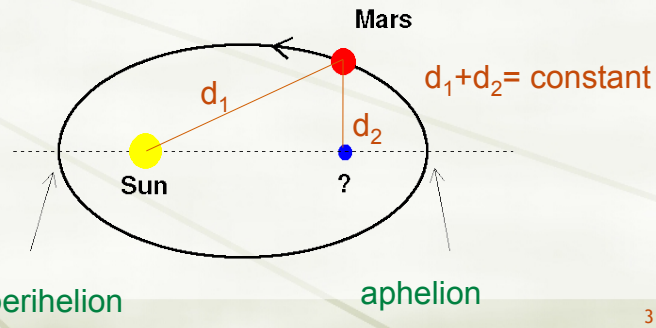
The Polyhedra inscribed into the planetary orbits. Kepler's drawing is a pure geometrical fancy, but it is meant to correspond to the actual relation between the radii of the planetary orbits. Most important here is the cube, fitted into the outermost sphere of Saturn.

Johannes Kepler (1571-1630)

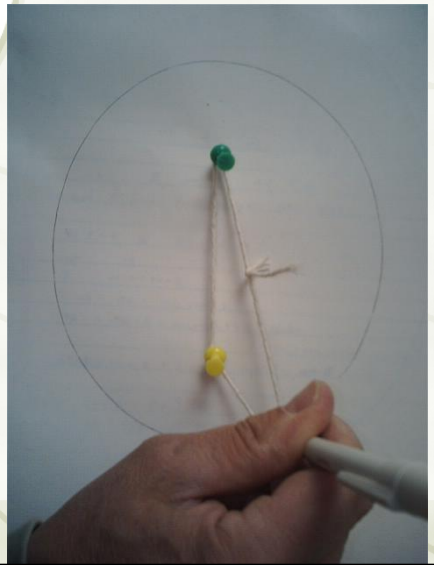
- Born in Germany; originally planned to be ordained as Lutheran minister
- Convinced God made the Universe according to a mathematical plan; saw his Christian duty as understanding works God had created
- Was hired as Tycho Brahe's assistant in Prague; his job was to make sense of Brahe's extremely accurate observations of Mars
- Let to the publication of three laws of planetary motion (1601, 1609, 1619)

Kepler's first law

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



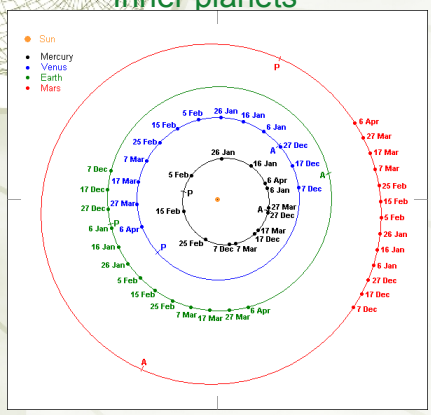
Kepler's first law



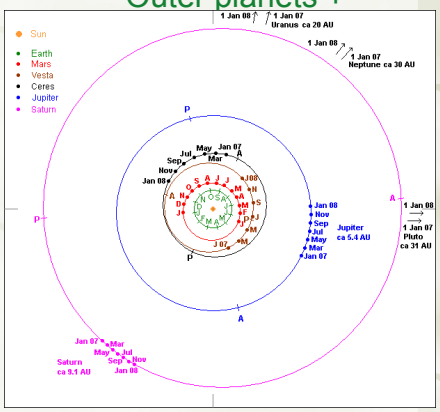
Drawing an ellipse is easy: use two tacks for the focii and a string

Solar system orbits

Inner planets



Outer planets +

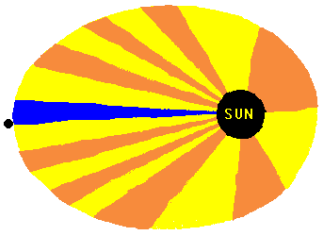


http://www.rasnz.org.nz/SolarSys/Orbits07.htm

Note the low eccentricities!

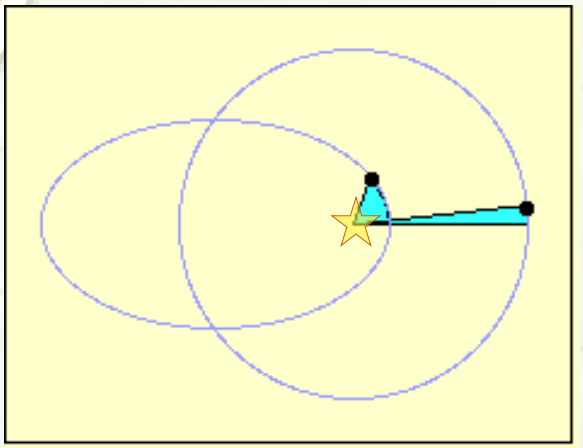
Kepler's second law

- **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.



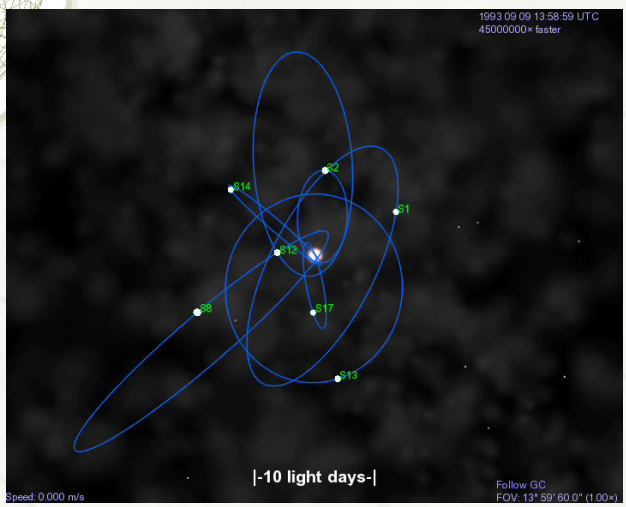
http://home.cvc.org/science/kepler.gif

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



Time-lapse movies of orbits

Stars around the Galactic center's black hole



www.mpe.mpg.de/ir/GC/index.php

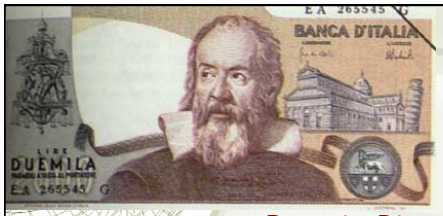
Kepler's third law

- **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.

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

- 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,

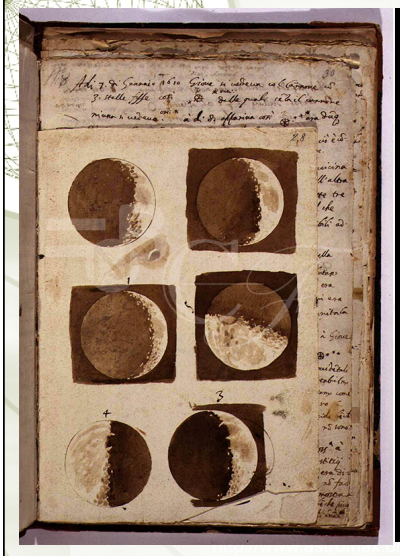
$$\left(\frac{P}{yr}\right)^2 = \left(\frac{R}{AU}\right)^3$$

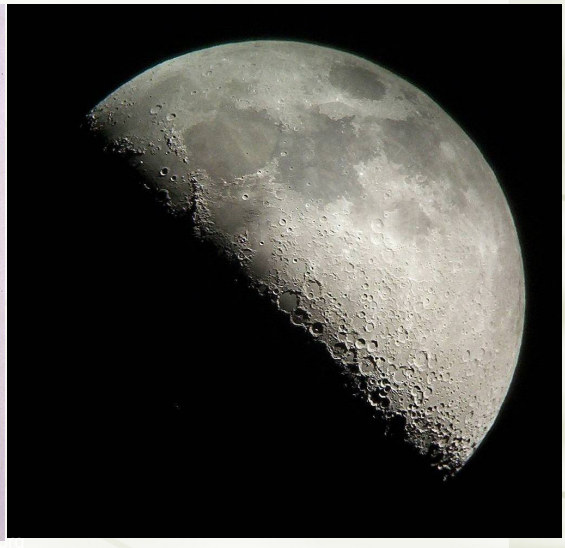


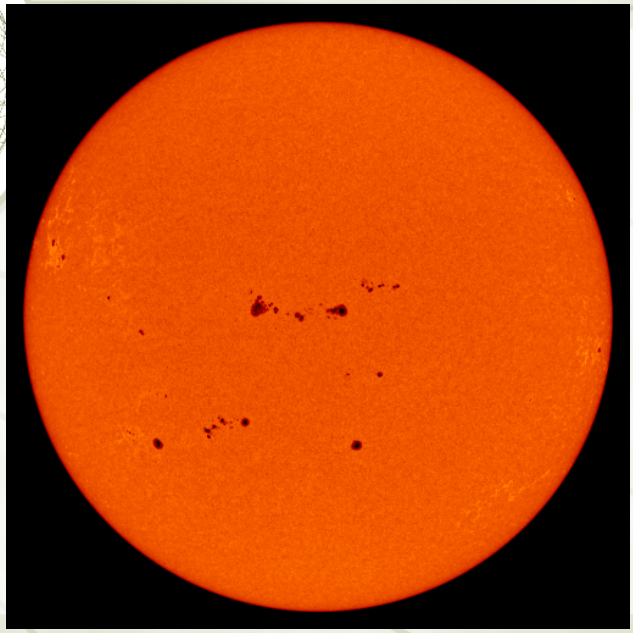
Galileo Galilei (1564-1642)

Considered the father of modern science

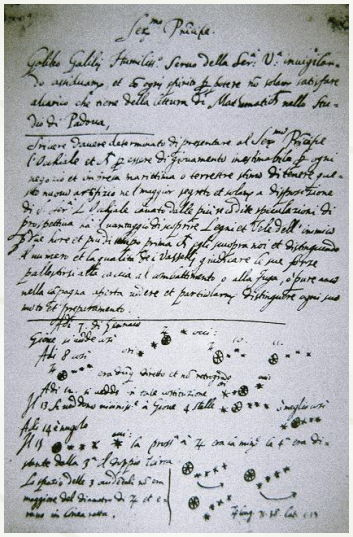
- Born in Pisa; worked as professor of mathematics
- Built one of the first telescopes in 1609
- Published *"The Starry Messenger"* with first telescopic discoveries in 1610
- Telescopic observations:
  - Saw craters and mountains on the Moon
  - Realized sunspots were on surface, not foreground; rotated 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…



SIDEREUS NUNCIUS 75

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

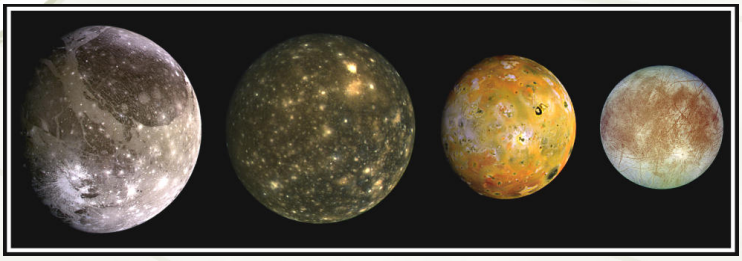
in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

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!)

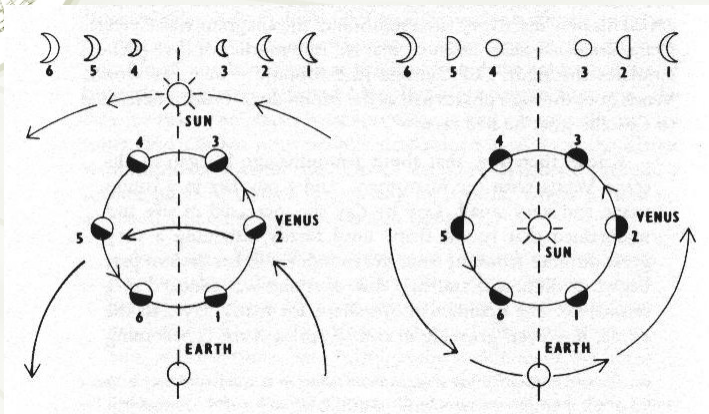


NASA

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

Phases of Venus: the test of the Heliocentric system



Galilean physics

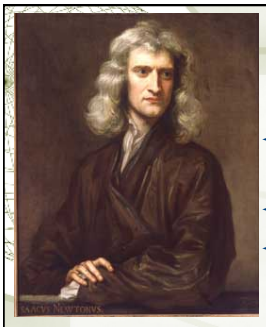
- After 1633 trial, Galileo returned to work on physics of mechanics
- Published *Discourses and mathematical demonstrations concerning the two new sciences (1642)*
- Made experiments with inclined planes; concluded that distance *d* traveled under uniform acceleration *a* is $d=a\,t^2$
- Used "thought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

Museum of Science History in Florence

Experiments with Inclined plane

(Middle?) Finger of Galileo !

Tomb of Galileo in Santa Croce



Isaac Newton in 1689, by Sir Godfrey Kneller.

The *Principia* is recognized as the greatest scientific book ever written!

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

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
- Retired from research in 1693, becoming active in politics and government
- Lost lots of money on the stock market ☺