PHYS 275 Planets

Fall 2017

Lecture 2 Historical Development

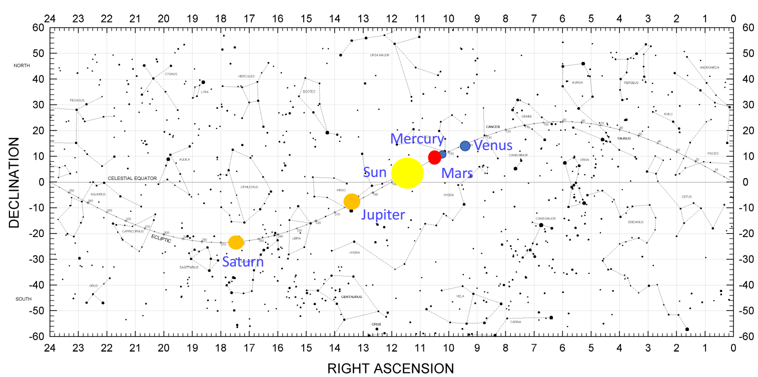
Johannes Kepler's Uphill Battle

Today's Class

Most of pre-science astronomy is studies of the Solar System

1. Prehistoric astronomy
2. Greek (beginnings of "science"?)
3. Chinese, Hindu, Arabic contributions to astronomy
4. Astronomy becomes a science

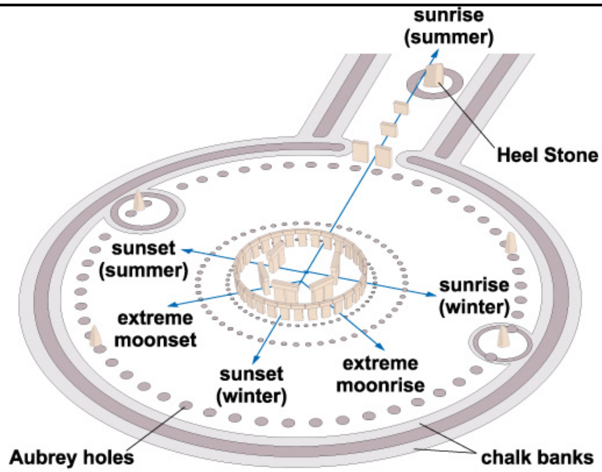
EQUATORIAL SKY CHART Planets on Sept 13, 2017



"Stone-Age" Astronomy

Primarily to mark seasons, special times of year … the world's largest calendars…

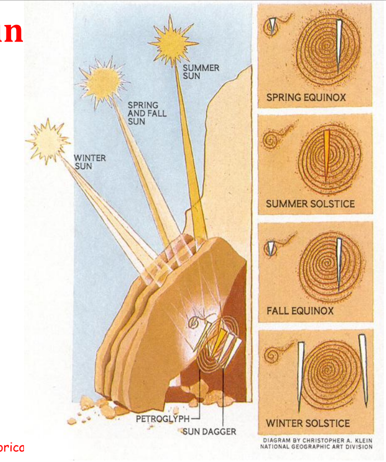
1. Stonehenge "stone circles", and standing stones
2. pyramids
3. Mayan, Peru
4. Medicine Wheels
5. also: sundials to give time of day



Sunrise over Stonehenge: June 21, 2005

<u>sun dagger</u> at noon in Chaco Canyon, NM

A calendar!
Very important in an agrarian society



Ancient Greek Astronomy

1. The world (didn't really use the word "Universe") was the Sun, moon, and planets on a fixed (unchanging) sky
   - planet = "wanderer" – there were 7 planets (Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn), those visible with the naked eye
2. A succession of philosophers who thought about astronomy:
   - Pythagoras (~560-480BC)
   - Aristotle (384 - 322BC)
   - Aristarchus of Samos (310-230BC)
   - Eratosthenes (276-195BC)
   - Hipparchus (~190-120BC)
   - Ptolemy (~140AD)

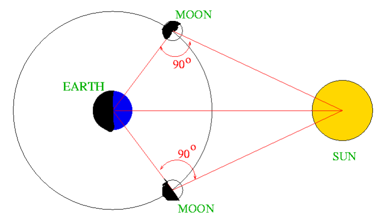
Ancient Greek Astronomy

1. Philolaus: non-geocentric cosmology: Earth moves around central fire (not the Sun!) & "counter Earth" on opposite side of this fire
2. Pythagoras: the "heavenly bodies" are spherical
3. Aristotle
   - How can the Earth move? → **Geocentric Universe**
   - Correct explanations of phases of Moon and of eclipses
   - Sun much more distant than the Moon
   - Earth spherical

Ancient Greek Astronomy

Aristarchus of Samos
- Used newly discovered geometry tools
- Measured the relative distances of the Moon and Sun and found the Sun was 18-20 times further away then the Moon
- Determined relative sizes of Earth, Moon, and Sun from lunar eclipse data (Moon diameter= 1/3 × Earth, Sun diameter = 7 × Earth)

Aristarchus's method of distances

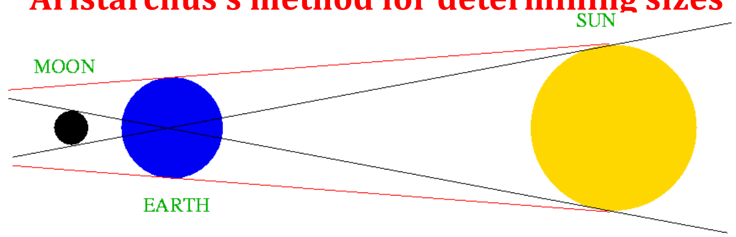


Determine (measure) the **length of time** from third quarter (at bottom) to first quarter (at top)

$$\frac{1}{2}\frac{\textit{length of time}}{\textit{length of a month}} \times 360 = \text{angle(Moon} \rightarrow \text{Earth} \rightarrow \text{Sun) in degrees}$$

$$\frac{\text{Earth to Moon distance}}{\text{Earth to Sun distance}} = \cos(\text{angle})$$

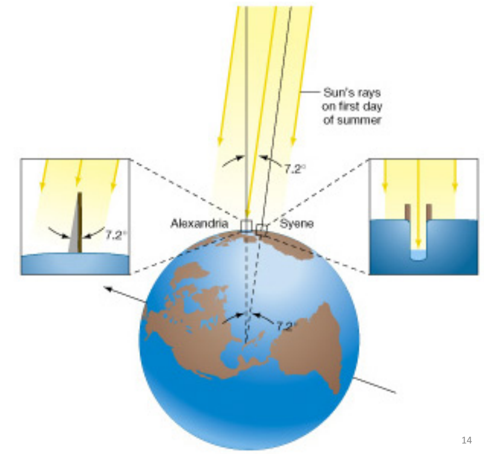
Aristarchus's method for determining sizes



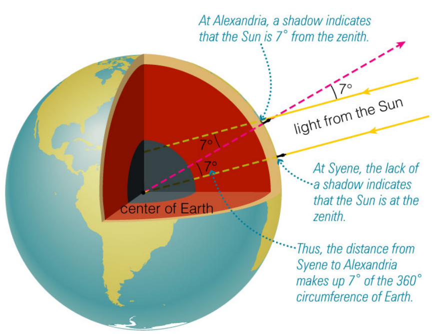
Moon and Sun are the same (angular) size in the sky (1/2 deg.) => they must fit within the same (1/2 deg) pair of lines: so their relative distances are known.

From eclipse timing it was known that the Earth's shadow is 8/3 the size of the moon. Combine these to get relative sizes of Earth, Moon, Sun

Eratosthenes measured the size of the Earth from "shadows": sun angles



Eratosthenes measured Earth's diameter



$$\frac{7^\circ}{360^\circ} = \frac{d_{Alexandria-Syene}}{circumference_{Earth}}$$

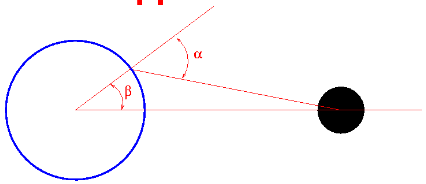
if $d_{A\text{-}S}$=5000 stadia => circumference of Earth = 250,000 stadia

or… ~42,000km (true ~40,000km)

Ancient Greek Astronomy

Hipparchus
- invented trigonometry
- measured positions and brightnesses of 850 stars – high precision, valuable today
- celestial coordinate system, magnitude system, discovered precession
- estimated Moon's size and distance
- measured length of year (to within 6 minutes of correct value!)
- explained eclipses
- "invented" epicycles

Parallax: Hipparchus and Ptolemy



First, measure the angle to the centre of the Moon from two positions on the Earth at the same time. Here the Moon is overhead at one place and at angle α from another place.

In the triangle formed with centres of both Moon and Earth and the position of the "other place" we know all of the angles (we know where we are on the Earth – therefore know β), and the length of one side is the radius of the Earth…

This is enough to get the distance to the Moon!

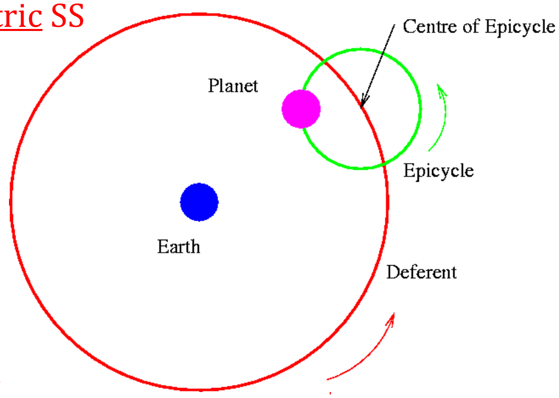
Solar distance was too small by ~10

Retrograde Motion

1. tracking planetary positions had shown that some – most notably Mars – did not follow simple paths across the sky
2. superior planets make a loop in the sky once every year
3. the part of their path when a planet is moving "backward" in the sky is called "retrograde motion"
4. normally planets appear to move from west to east in the sky but, at times, superior planets reverse direction briefly before resuming EW motion

Retrograde Motion

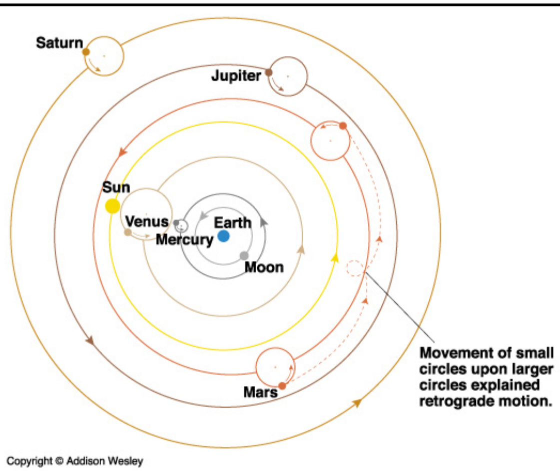
epicycles "invented" to explain retrograde motion in a geocentric SS



Ancient Greek Astronomy

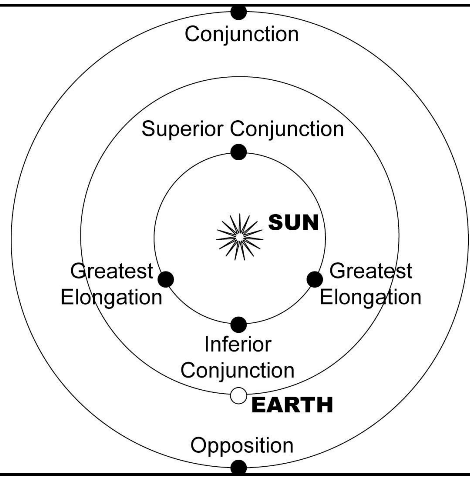
Ptolemy (140BC)

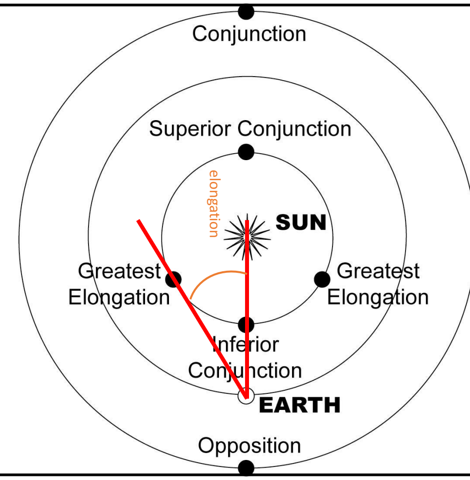
- circles are perfect
  - → **Epicyclic Theory of Solar System**
- Needed epicycles on epicycles
  - → **complicated model**
- Used parallax to measure distance to Moon
- Published a 13 volume summary of all astronomical knowledge: the "Almagest"



Synodic versus Sidereal Periods

1. The time from noon to noon (next day) is a Synodic period (based on Sun)
2. The time from Full Moon to Full Moon (next month) is Synodic period
3. The time from when a planet is in the sky on the (opposite, same, right angle) side of Sun to the next is a Synodic period



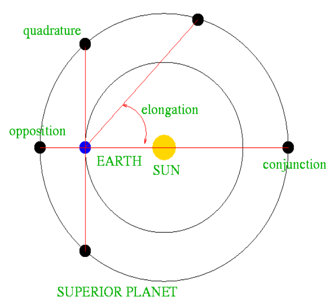


Planetary Positions/Motions: Superior Planet

Conjunction – planet is at an elongation of 0°
- The planet is behind (superior conjunction) or in front of (inferior conjunction) the Sun

Opposition – planet's elongation is 180°
- planet is in the opposite part of the sky from the Sun

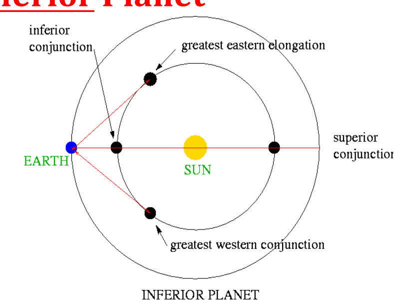
Quadrature – elongation (superior planet only!) is 90°



Planetary Positions/Motions: Inferior Planet

IMPORTANT!!!

definition: mean distance from Earth to Sun = 1 Astronomical Unit (A.U.)



Planetary Positions/Motions (SYNODIC!)

1. Superior planet – one that is further from the Sun than the Earth is
2. Inferior planet – one that is closer to the Sun than the Earth is
3. Elongation: angle of a planet with respect to the Sun
4. Conjunction – planet is at an elongation of 0^o
   - The planet is behind (superior conjunction) or in front of (inferior conjunction) the Sun
5. Opposition – planet's elongation is 180^o
   - planet is in the opposite part of the sky from the Sun
6. Quadrature – elongation (superior planet only!) is 90^o
   - largest elongation of an inferior planet is the "greatest eastern" or "greatest western" elongation

Pre-scientific Astronomy in "the rest of the World"

1. Hindus
   - measurements of Moon
   - systems of numbers
2. Islamic
   - algebra
   - records of positions of planets
   - eclipse records
3. Babylonians, Assyrians, Egyptians:
- calendar, time-keeping, surveying

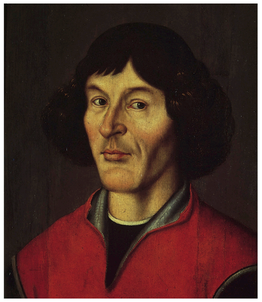
Pre-scientific Astronomy in "the rest of the World"

Chinese
- Oldest records: 2159BC - two astronomers executed for calendar errors
- good records of comets, meteorites and supernova ("new stars")
- 350BC: Shih Shen makes first star catalogue with 800 entries

Old astronomical records are invaluable!

Normally things change in the sky so slowly that the timescale is >> than a person's lifetime

European Development of Astronomy



Copernicus (1473-1543)
- **Heliocentric model**
- planets closer to the Sun than the Earth revolve around the Sun faster than the Earth
- the Earth rotates on its own axis
- all planets' orbits are circular
- sidereal vs. synodic periods
- relative distances of planets

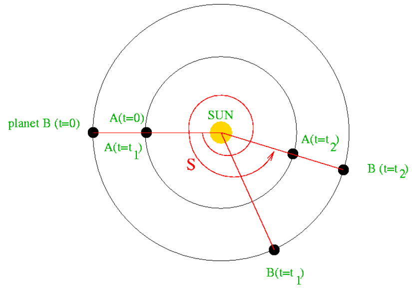
Sidereal vs. Synodic Periods

Sidereal period = P
Synodic period = S

in S years the Earth goes around the Sun S times

another planet takes P years to go around the Sun,

so in S years it will make S/P trips around the Sun

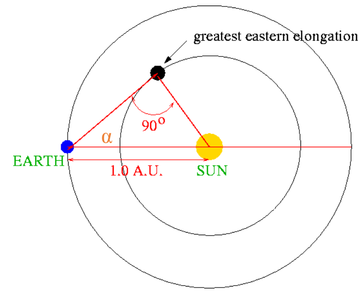


For a superior planet: S = 1 + (S/P)

for an inferior planet: S+1 = S/P

Relative distances of planets: inferior planet

scaled to AU

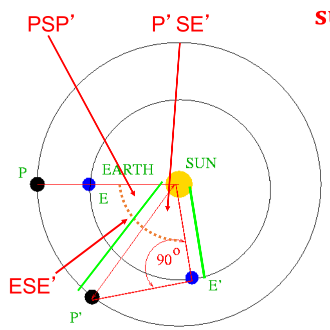


at greatest elongation (α) an inferior planet is in a 90º angle triangle between Earth and Sun.

distance from the Sun to the planet is:

d(AU) =1.0 A.U × sin (α)

Relative distances of planets: superior planet



want to know P' SE'

angle P' SE'= ESE' - PSP'

Given: we have measured the sidereal periods…

Earth-planet relative position goes from opposition to quadrature; making angles PSP' and ESE'

we know these angles from orbital periods and elapsed time between orientations

cos(P' SE') = SE' /SP'

SP' = 1.0AU/cos(P' SE')

(scaled to AU)

Copernicus' determination of the scale of the Solar System

	Sidereal Period		Sun to planet distance	
Planet	Copernicus	Modern	Copernicus	Modern
Mercury	88d	87.91d	0.38 AU	0.387 AU
Venus	225d	225.00d	0.72	0.723
Earth	365.25d	365.25d	1.00	1.00
Mars	687d	686.98d	1.52	1.524
Jupiter	12yr	11.86yr	5.2	5.204
Saturn	30yr	29.51yr	9.2	9.582

A curiosity: Bode's Law:

$a = 0.4 + 0.3 \times 2^{n-2}$

planet	n	Bode	a (A.U.)
Mercury	1*	0.4*	0.39
Venus	2	0.7	0.72
Earth	3	1.0	1.00
Mars	4	1.6	1.52
?	5	2.8	---
Jupiter	6	5.2	5.20
Saturn	7	10.0	9.58
Uranus	8	19.6	19.1
Neptune	9	38.8	30.2

European Development of Astronomy: observations

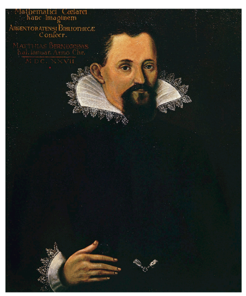
Tycho Brahe (1546-1601)

- extremely detailed, high precision observations
- used large, carefully-built instruments of his own design
- Parallax of comets, SN => farther from Earth than Moon

European Development of Astronomy: analysis

Kepler (1571-1630)

- worked as assistant to Tycho
- given Mars data to take with him when he left for new job
- analyzed Mars' orbit and discovered his 3 "Laws"

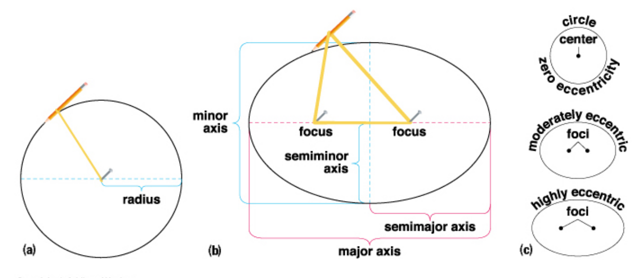


1. orbits are elliptical
2. equal areas are swept out in equal time
3. period² 'proportional to' distance³

$\boxed{P^2 = a^3}$

where **P** is period in years and **a** is the orbital semimajor axis in A.U.

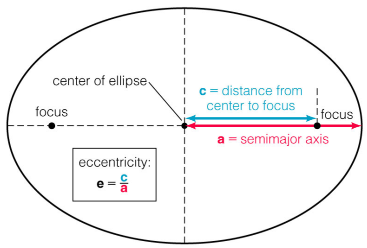
Kepler's First law (KI): orbits are ellipses

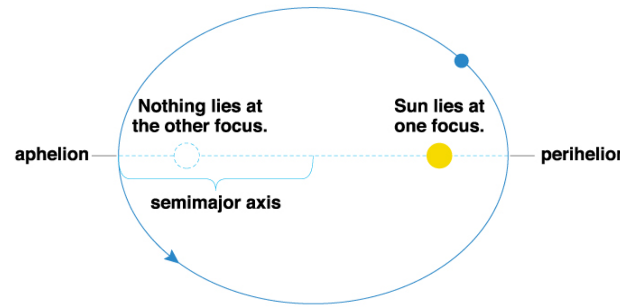


Properties of an ellipse

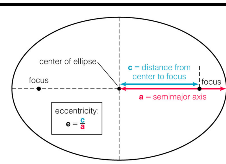
semimajor axis is the average distance of a body from the orbit's focus

an orbit's focus is at the location of the centre of mass of the system





Elliptical Orbit



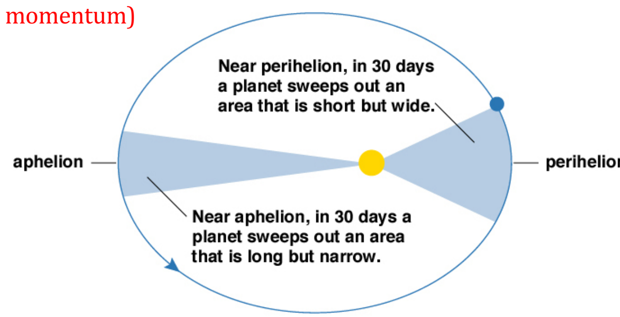
Question: A comet is seen with an orbit of semi-major 20 A.U. If the eccentricity of the orbit is 0.80 how close will it be to the Sun at perihelion?

Answer: a = 20 AU. e = 0.8

e = c/a therefore c = a × e = 16 A.U.

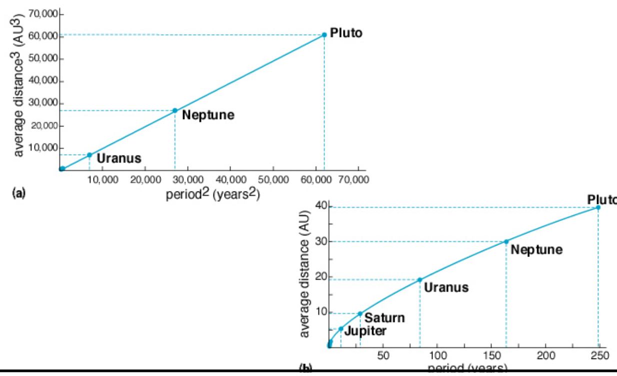
The distance from the focus to the orbit at closest approach is 20 – 16 A.U. or **4.0 A.U.**

Kepler's Second Law (KII): planet sweeps equal area in equal time (from conservation of angular momentum)

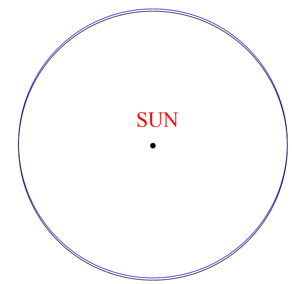


The areas swept out in 30-day periods are all equal.

Kepler's Third Law(KIII): P^2(years)=a^3(AU)



The shape of the Earth's orbit (blue) and a circle with the same radius(black) as the semi-major axis.



Kepler's Law examples

Question: A comet is observed to have an orbit with a semi-major axis of 20 A.U. What is the period of the comet's orbit?

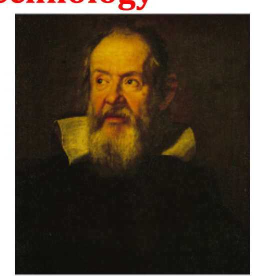
Answer: P^2 (years) = a^3 (A.U.) (Kepler's 3rd Law)

$P^2 = 20^3 = 8000$ or $P = 89$ years

(Note: answer only to two significant figures)

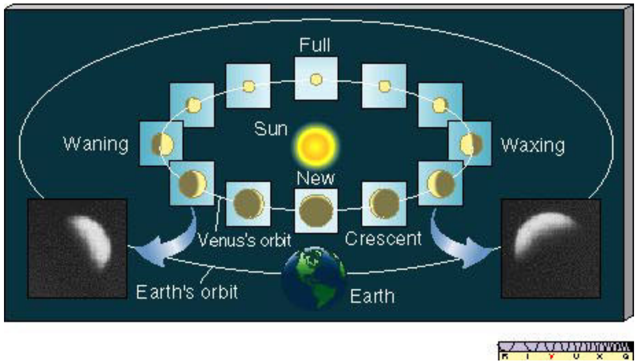
European Development of Astronomy: new technology

1. use of a telescope to do astronomy
   1. phases of Venus
   2. mountains on Moon
   3. sunspots
   4. moons of Jupiter
   5. Milky Way is made of stars
2. Forced confrontation with Pope → confined to his home for life in 1633 for heresy
3. "forgiven" in 1992



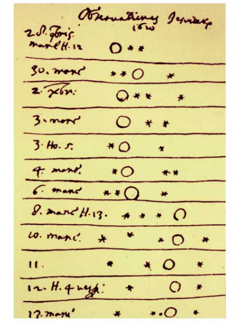
Galileo (1564-1642))

observed phases of Venus => Venus must orbit the Sun



Galileo and the Moons of Jupiter

- page from Galileo's notebook (1610)
- sketches show four "stars" near Jupiter
- different positions at different times, repeatable
- Galileo realized these were moons of Jupiter
- showed that objects could orbit a moving body



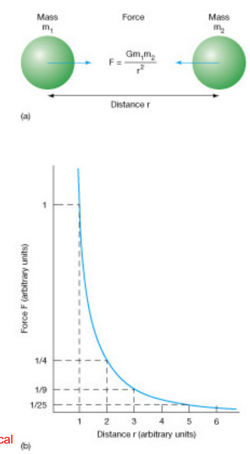
European Development of Astronomy: Physics

1. Newton
   - Laws of Motion (F=ma)
   - Law of Gravity
   - optics
   - Calculus
2. these "Laws" were the first to provide universal rules that governed motions of planets and of everyday objects on the Earth

Isaac Newton (1642-1727)

universal law of gravity: describes the forces acting between bodies due to gravity

$$F = \frac{Gm_1m_2}{r^2}$$



Summary: Development of Astronomy as a Science

1. Early Astronomy is an era of detailed record-keeping of the motions of the planets (and Moon)
   - Astrology was often the motivation for these observations
   - Mathematical tools (such as geometry) were invented and useful for the measurements being made
2. BUT a "scientific method" was not in use to understand this data
   - Philosophy was often the source of explanations about the Universe
   - Mathematical tools and simple physical laws were needed
3. With Newton's work both the math and the physics became available to provide testable ideas about the underlying causes of the observations of the Solar System