ISP 205
Visions of the Universe

- Instructor: Dr. Jack Baldwin baldwin@pa.msu.edu
  - Office hours (3270 BPS):
    - 2-3 Monday
    - Noon-2PM Wednesday
    - or by appointment (phone 355-9200, ext. 2411)

These are listed in the syllabus

- ISP 205 Lab Course
  - *Not* required in order for you to be in this lecture course.
  - ~ 50% of you are taking it.
  - Deborah Frank, the TA, is in charge of the lab course.
    dfrank@pa.msu.edu

Grading

- You should know the materi
  - it's mostly from the book, but
  - I will cover only a part of wha

  so come to class.

The TA: Deborah Frank
Office hrs just before each quiz.
10-12 Tuesday
BPS 3265
Phone 355-9200, ext 2446

- Tests:
  - Quiz every Tuesday 2/3 of grade
    - (Drop lowest two)
  - (cumulative) Final 1/3
  - Occasional extra credit questions in class.

- Final grade will be on a curve, although there is a guaranteed worst-case curve.

Also in the syllabus

NOTE: this is an example from a previous year – wrong dates.

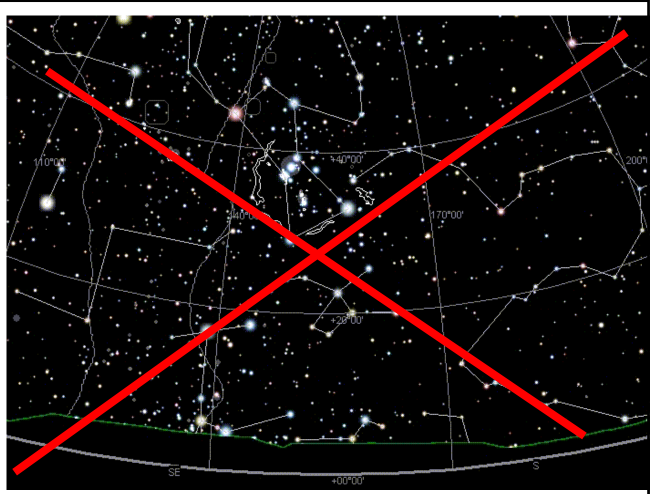
Interpreting the course schedule

Numbers in square brackets are chapters from text "Voyages through the Universe".

- **Aug 28,30.** The size of the Universe. The scientific method, "laws" in p [Prologue].
-
- **Sept 4,6.** Laws of motion: Ptolemy, Copernicus, Kepler, Newton [1,2].
-
- **Sept 11,13.** Radiation and spectra [4.1,4.2]. Maybe a bit about telescop
-
- **Sept 18.** The solar system [6 briefly]. Earth as a planet [7]. The seasons

This course is *not* about:

The night sky.



Sorry…

•*Not* about the constellations.

•*Not* about signs of zodiac

•Try AST 101 "Celestial Clockworks", in Planetarium each Spring

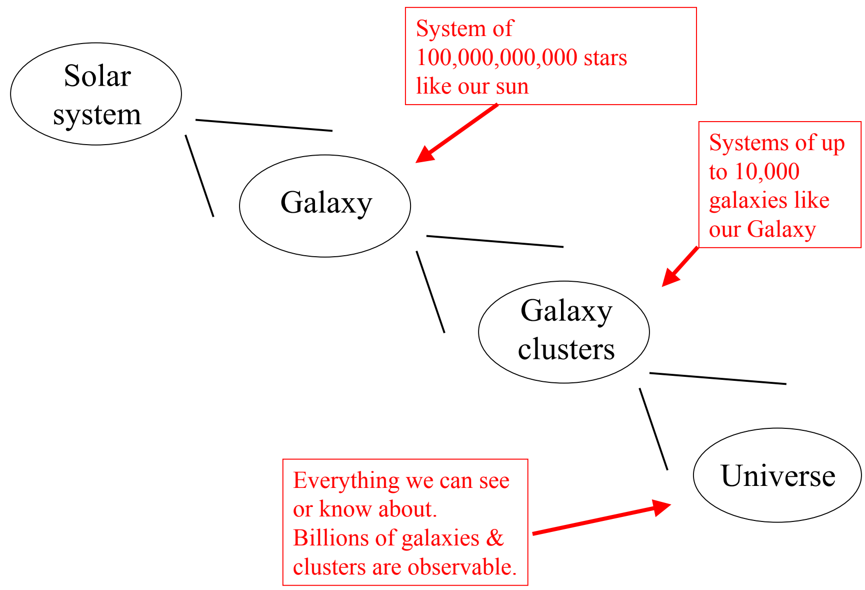
This course *is* about:

- The scientific approach.
- What we know about the Universe, from the scale of planets on up.
- How we have come to know it.

3 Major Sections

1. **Background: The Laws of Physics.**
   - Laws of Motion
   - Radiation
   - (Telescopes)
2. **The Solar System:**
   - The Sun (an example of a star)
   - Exploring the Planets.
3. **The Universe: Where Did It Come From & Where Is It Going?**

Quick tour of the Universe



Units of astronomy

- Numbers ranging from very big to very small

  ==> use scientific notation

  $100{,}000{,}000{,}000 = 10^{11}$ $\quad$ $0.001 = 10^{-3}$ etc

  $200{,}000{,}000{,}000 = 2\text{x}10^{11}$ $\quad$ $0.003 = 3\text{x}10^{-3}$

  $2\text{x}10^{11} \text{ x } 3\text{x}10^{-3} = 2 \text{ x } 3 \text{ x } 10^{11-3} = 6\text{x}10^{8}$

- but also……

  $6\text{x}10^{8}$ = 6E8

  $3\text{x}10^{-3}$ = 3E-3 etc.

Distances

- metric units: 1 km = 0.6 miles
  - diameter of Earth: 13,000 km (8,000 miles)
  - circumference of Earth: 40,000 km (25,000 miles)

- astronomical unit (au): radius of Earth's orbit
  - = 1.5×10^8 km

- Parsec (pc): distance to object that has parallax of 1 arcsec
  - *parallax? Arcsec?* What does *those* mean???

- light years (ly):
  - distance light travels in 1 year = 9.5×10^{12} km
  - 1 parsec (1 pc) = 3.26 ly

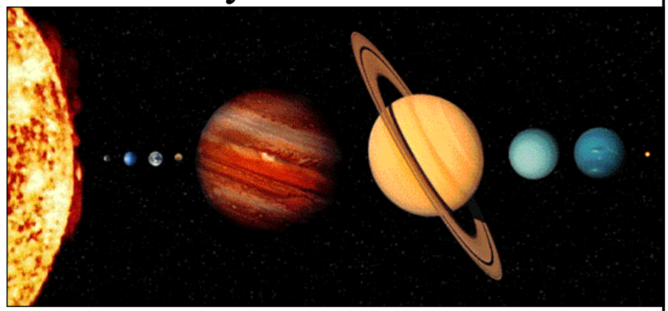
Time

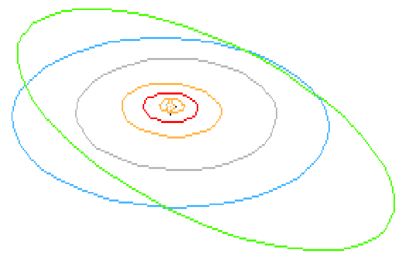
- seconds (s), years (yr), Gigayears (Gyr = 10^9 yrs)

- Lookback time
  - light travels 1 ly/yr
  - most distant observable objects (QSOs) are $\sim 10^{10}$ ly away
  - we see them as they were $\sim 10^{10}$ yrs ago

The Solar System

- Sun
- 9 planets
- 65+ moons
- comets
- asteroids
- dust
- gas
- cosmic rays
- other non-descript junk





A model solar system

(scaled down by a factor of 6 million)

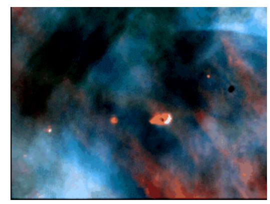
	(meters)	
Object	**Diameter**	**Distance**
Sun	0.241	0
Mercury	0.001	10
Venus	0.002	19
Earth	0.002	26
Mars	0.001	40
Jupiter	0.025	135
Saturn	0.021	247
Uranus	0.009	498
Neptune	0.009	780
Pluto	0.000	1025
Nearest star (Proxima Centauri)	0.241	6.9E+06
Center of our Galaxy	---	4.2E+10

70% of diameter Of Earth!

100x the real distance to the moon!

The Orion Nebula
a present-day site of star formation

1500 ly away from us.
Recently-formed stars heat dense, opaque gas cloud.
A cavity has blown-out, so we can see in.



Hubble Space Telescope image of "proto-star" with surrounding disk.

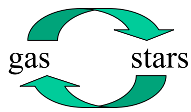
The oldest stars

The globular cluster M10

- ~10^5 (100,000) stars
- formed ~10^{10} years ago.

The galaxy

- Originally all gas
- Now ~10^{11} stars similar to our sun.
- Stars are borne, evolve, then die.
- Material processed through stars.
  - Galactic ecology

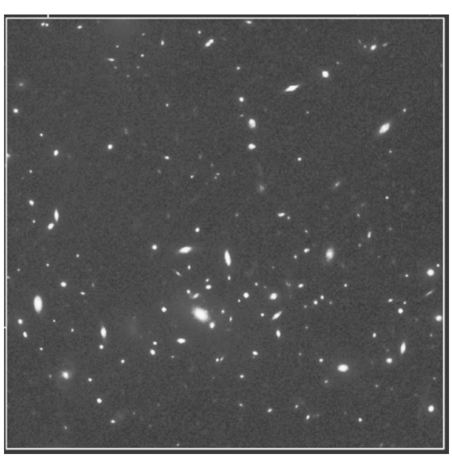


- This is source of all chemical elements

except Hydrogen (H)
Helium (He)
Lithium (Li)

made in "big bang"

Clusters of galaxies

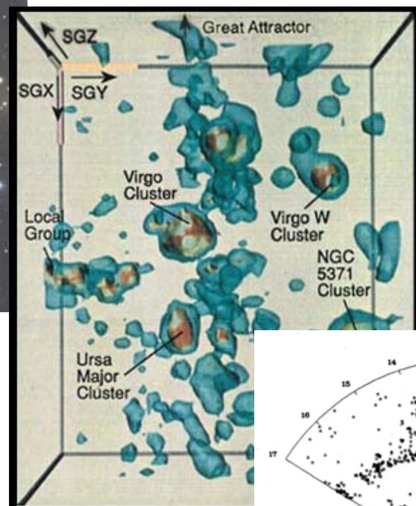


Hubble Space Telescope image

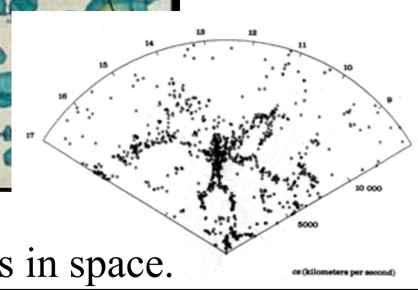
The distant galaxy cluster MS1054-0321

- Contents: thousands of galaxies and trillions of stars
- Mass: the equivalent of several thousand of our Milky Ways
- Distance:8 billion light-years from Earth.

Clusters of thousands of galaxies



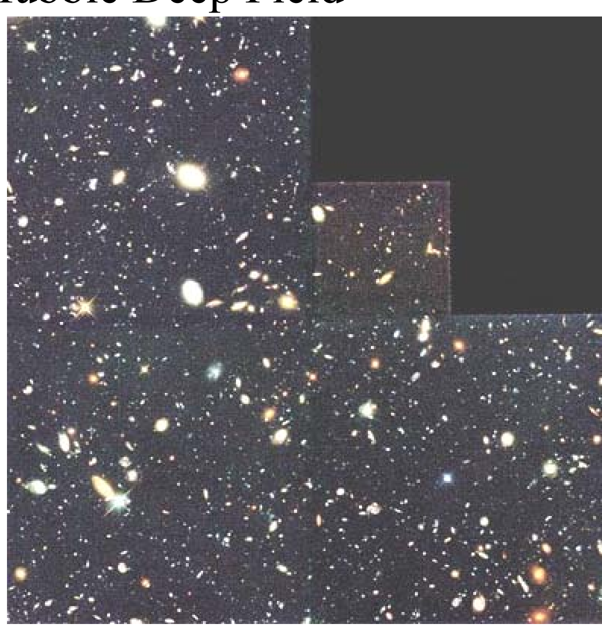
Superclusters



…and giant soap bubbles in space.

The Hubble Deep Field

- Tiny area of sky.
  - 1/12 angular size of full moon.
- Faintest objects ever measured.
- 10 days' exposure with Hubble Space Telescope.
- Only 20 stars.
- Remaining 5000 objects are galaxies.



The Universe

- = all the places we could possibly get to, disregarding problems about travel time.
  - We don't see to any edge, just out to where light-travel time = age of oldest observable object.
  - For all we know, it goes on forever.
- There may well be *other* universes, inaccessible from our own.
- Space is *curved* because of matter and energy contained in it , as per General Relativity.
- Our universe has expanded from a "singularity" that occurred $\sim 10^{10}$ years ago.
  - The "Big Bang"

Evidence for Big Bang

- Expanding universe
  - (on average) all galaxies flying away from all other galaxies.
- Microwave background radiation
  - relic glow from earlier, hotter phase of Universe
  - visible only at microwave wavelengths
  - comes uniformly from all directions.
- Presently-seen hydrogen, helium were synthesized in the first 3 minutes of life of Universe.

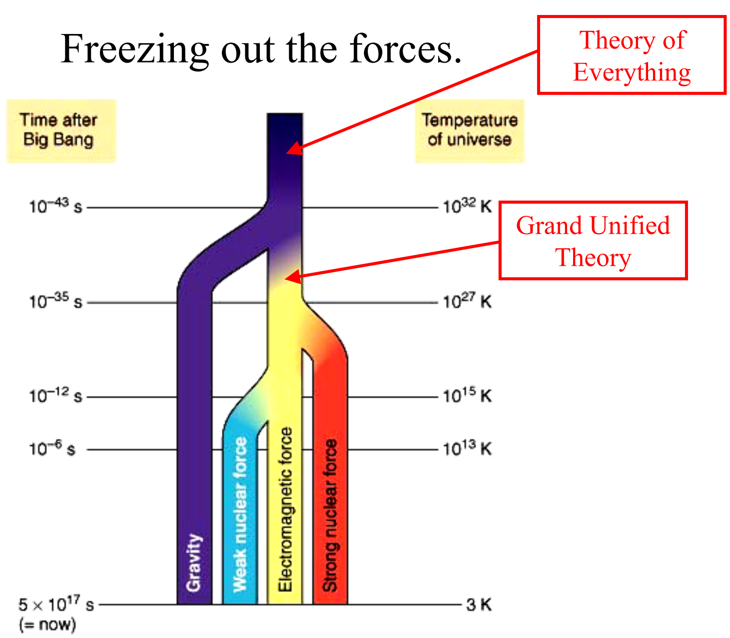
The scientific method

- Cause and effect.
- Hypothesis ←→ test.
  - models
- Laws of physics
  - describe what we see happening
  - usually mathematical
  - thought to be same everywhere in universe
    - → measure what happens in lab on earth, then predict what will happen in distant galaxies
    - and vice-versa

The 4 forces

- Gravity
  - attraction of all matter for all other matter
  - very weak force, but there's lots of matter.
- Electromagnetic
  - electricity
  - magnetism
  - light
- Strong nuclear force
  - Holds nuclei of atoms together, against electromagnetic force.
- Weak nuclear force
  - important for subatomic particles such as neutrinos

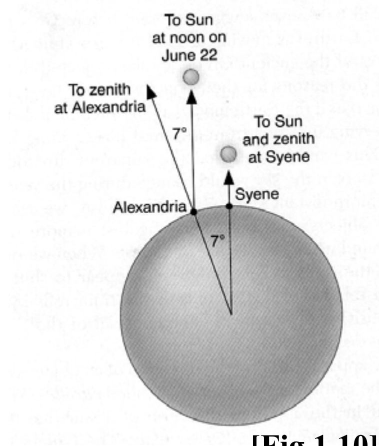
Freezing out the forces.



[Fig 28.16]

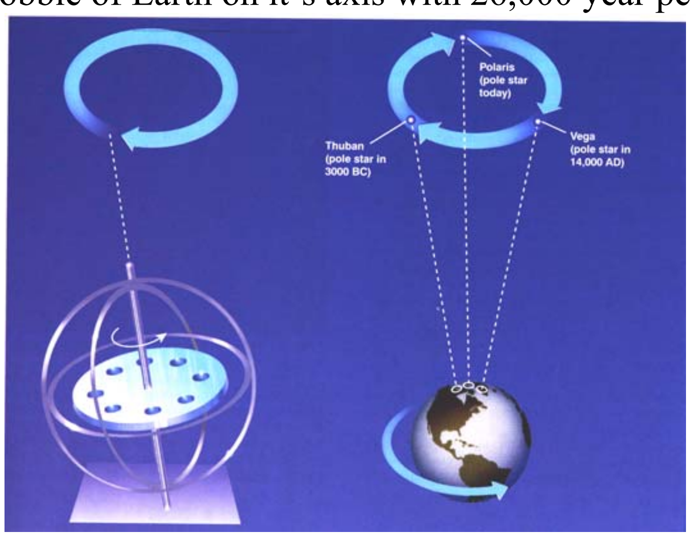
The Laws of Motion [1.2]

- History of Astronomy
  - 2000 years' worth of wrong models.
  - we certainly still don't have it exactly right.
    - but we've gotten closer (we think).
- Early Greeks:
  - Some remarkable successes
    - Knew Earth is round
    - Measured Earth's diameter (Eratosthenes, in 200BC)



[Fig 1.10]

Measured "precession" (think of gyroscopes):
…wobble of Earth on it's axis with 26,000 year period

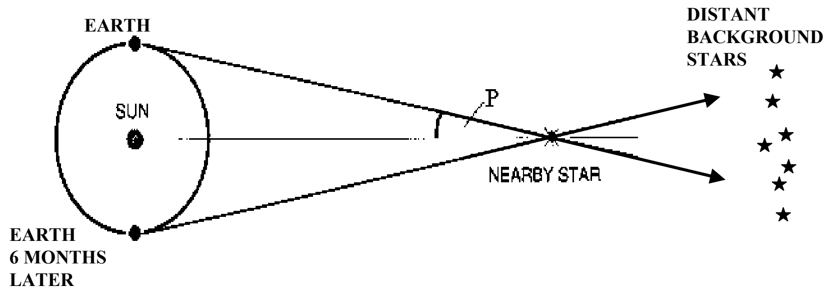


[Fig 1.11]

Hipparchus, 150BC

But one major error

- Greeks thought Earth was at center
  - tried, but could not detect *parallax* of nearer stars



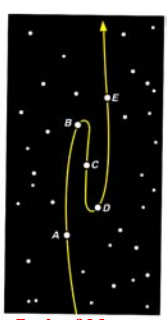
- No parallax detected…

Wrong!

- Could not imagine stars too far away to detect parallax
==> Earth does not move.

Retrograde Motion & Ptolemy's Epicycles

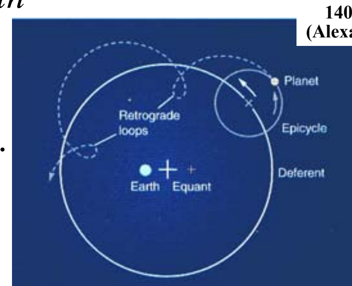
Ptolemy. 140 AD (Alexandria)

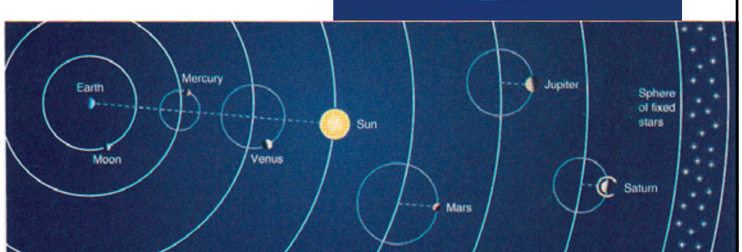


Path of Mars, etc. as seen from Earth

- Trying to place *Earth* at center.
- Led to very complicated system.

epicycle





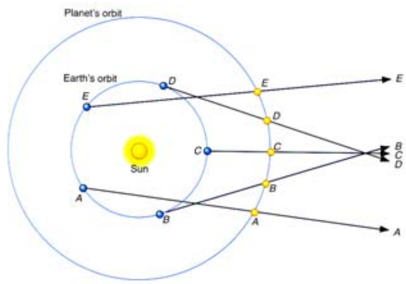
Blue figures are from Seeds, *Horizons: Exploring the Universe.*

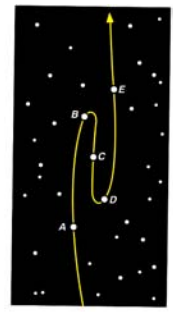
What Ptolemy didn't know:

epicycle

- Earth moves in orbit around sun.
- The other planets move on their own orbits around the sun.

[Fig 1.12]





http://web.cuug.ab.ca/~kmcclary/ORRERY/fastsolar.html
shows why this really happens (click "Center", "Earth") simulation

1543: Copernicus showed sun is at center

WE ARE NOW HERE!

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum ſpacio circu currens. In medio uero omnium reſidet Sol. Quis enim in hoc

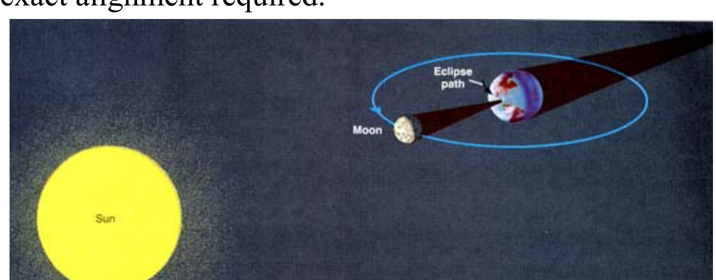
pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum ſimul poſsit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegiſtus uiſibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in ſolio regali Sol reſidens circum agentem gubernat Aſtrorum familiam. Tellus quoque minime fraudatur lunari miniſterio, ſed ut Ariſtoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur ſub hac

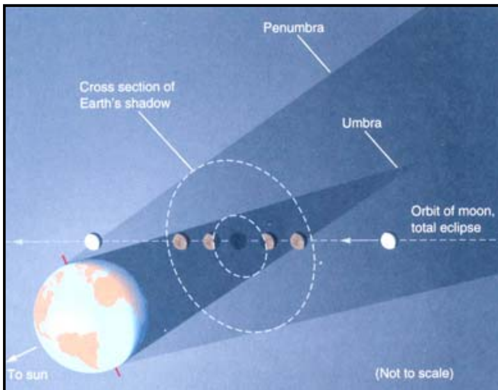
- Copernicus assumed each planet is on circular orbit about sun.
  - We cannot tell difference between apparent motion of Earth around Sun *vs.* Sun around Earth.

[Fig 1.15]

Eclipses [3.7]

- Lunar eclipse
  - Earth's shadow much larger than entire Moon.
  - But 5º tilt between orbits limits this to twice per year.
- Solar eclipse:
  - Moon can block our view of Sun.
  - Weird coincidence: Sun and Moon have same angular size. Moon can block out view of Sun.
  - But exact alignment required.





Lunar Eclipse Tonight

- Starts 10:03
- ½ covered: 10:35
- Fully covered: 11:14-12:06

Table 3-1 Total and Partial Eclipses of the Moon, 1999–2010

Date	Time* of Mideclipse (GMT)	Length of Totality (Min)	Length of Eclipse (Hr:Min)
1999 July 28	11:34	Partial	2:22
2000 Jan. 21	4:45	76	3:22
2000 July 16	13:57	106	3:56
2001 Jan. 9	20:22	60	3:16
2001 July 5	14:57	Partial	2:38
2003 May 16	3:41	52	3:14
2003 Nov. 9	1:20	22	3:30
2004 May 4	20:32	76	3:22
2004 Oct. 28	3:05	80	3:38
2005 Oct. 17	12:04	Partial	0:56
2006 Sept. 7	18:52	Partial	1:30
2007 Mar. 3	23:22	74	3:40
2007 Aug. 28	10:38	90	3:32
2008 Feb. 21	3:27	50	3:24
2008 Aug. 16	21:11	Partial	3:08
2009 Dec. 31	19:24	Partial	1:00
2010 June 26	11:40	Partial	2:42
2010 Dec. 21	8:18	72	3:28

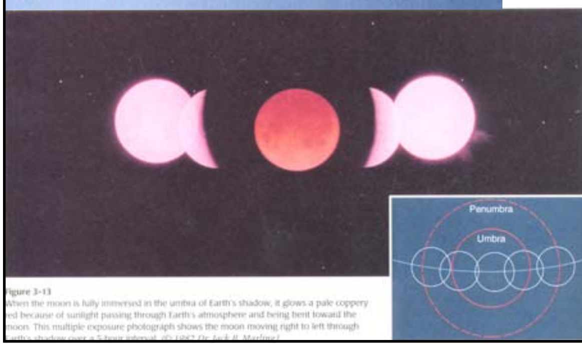


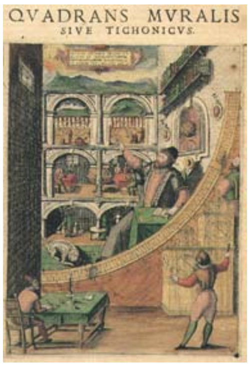
Figure 3-13
When the moon is fully immersed in the umbra of Earth's shadow, it glows a pale coppery red because of sunlight passing through Earth's atmosphere and being bent toward the moon. This multiple exposure photograph shows the moon moving right to left through Earth's shadow over a 5-hour interval.

The *heliocentric* model

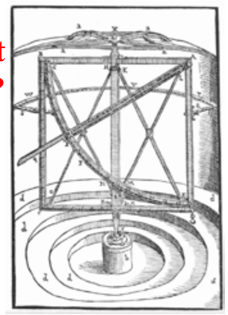
- Equally good fit to data about planet's motions
- But fewer "degrees of freedom" (fewer arbitrary constants to specify)
- Occam's razor (William of Occam; 1284-1347)
  - the simplest of two or more competing theories is preferable
  - an explanation for unknown phenomena should first be attempted in terms of what is already known.
- KEY RESULT: Earth just one of several planets, *not* center of Universe.

Tycho's Observatory
Tycho Brahe (1546-1601)

Fake
What nose?

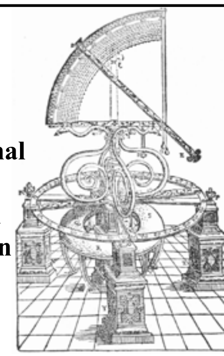


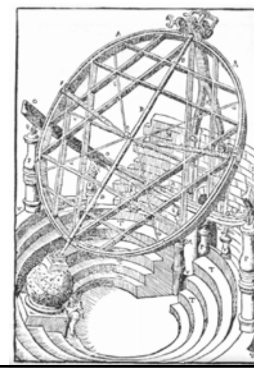
Tycho and his great quadrant at Uraniborg. 1582



Revolving steel quadrant, 2 meters in radius. Built in 1588.

Brass azimuthal quadrant, 65 centimeters in radius. Built in 1576 or 1577





Great equatorial armillary, 3 meters in diameter. 1585.

Early 1600's: Galileo [pp. 32-33]

- First to use telescope to look at night-time sky.

Discovered:
- Milky Way = myriads of stars.
- Phases of Venus
  - confirmed heliocentric model.
- Sunspots.
- Craters, maria on Moon.
- Rings of Saturn
- 4 Moons orbiting Jupiter.

Galileo's telescopes: ~1" in diameter x 24-30" long

The Scientific Approach:
The explanation *must* fit the observed facts.

What Galileo Saw:

The milky way = jillions of stars

What Galileo Saw:
4 moons orbiting Jupiter

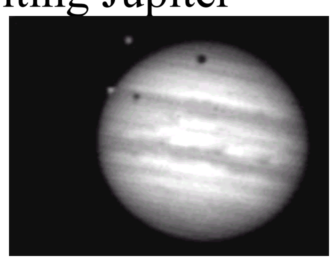
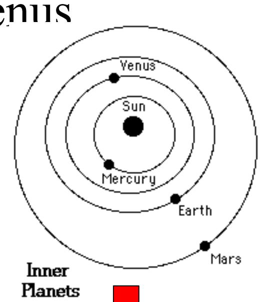
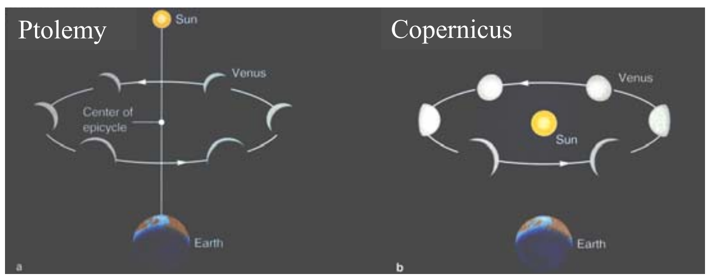


Image through modern telescope showing 2 of Galileo's satellites and their shadows

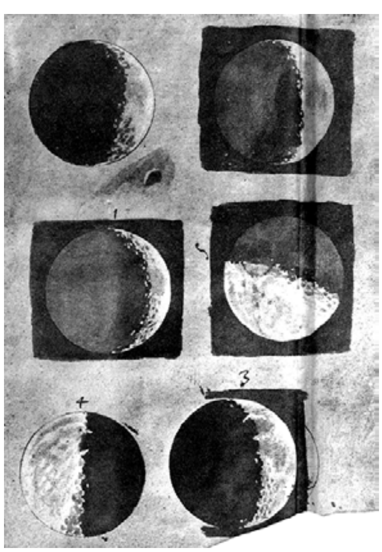
The old boy's observing notes

What Galileo Saw:
The phases of Venus





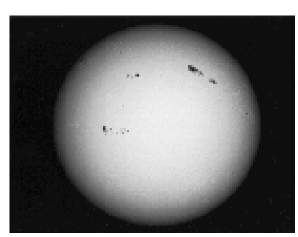
More Galileo discoveries



Craters, maria on moon

Galileo's sketch.. 1616

Rings of Saturn



Sunspots

Johannes Kepler
(1571-1630)

- Tycho was Kepler's "thesis advisor"
  - 20 yrs' data on planetary motions.
  - Wouldn't let Kepler near 'em.
  - Tycho tried to fit data with Ptolemy-like model.
- Kepler analyzed data after Tycho died
  - Concentrated on orbit of Mars.
  - Had to subtract off Earth's (imperfectly known) orbit.
- Discovered 3 "laws" that together describe the motions of all the planets.

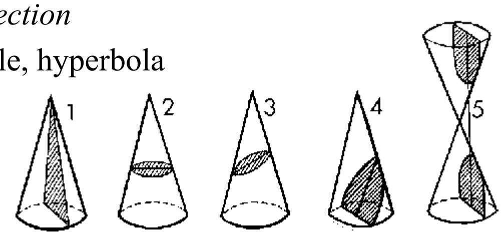
Kepler's 3 Laws [2.1]

- Each planet moves around orbit in ellipse, with sun at one focus.
- The straight line joining the planet and the sun sweeps out equal areas of space in equal amounts of time.
- $P^2 = a^3$

Kepler's first law:

Each planet moves around orbit in an ellipse, with the sun at one focus.

- Ellipse is a *conic section*
  - Along with circle, hyperbola



- This is an unexpected result…
  - Why an ellipse?
  - Why is sun at focus rather than at center??

Kepler1 simulation

Kepler's second law:

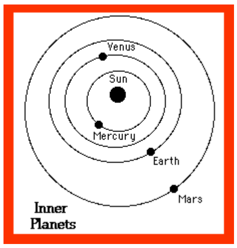
The straight line joining the planet and the sun sweeps out equal areas of space in equal amounts of time.

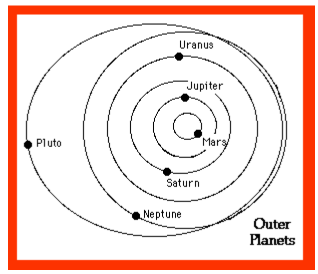
- planet moves more slowly when it is far from sun
- more rapidly when close to sun

- see the Kepler2 simulation

Kepler's third law: $P^2 = a^3$

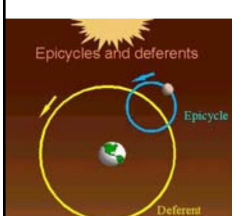
- P = period of orbit, in years
- a = semi-major axis of orbit, in au.





Fastsolar simulation

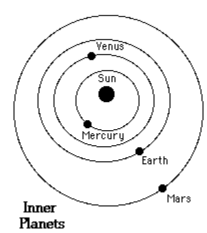
The Motions of the Planets



Ptolemy
140 AD

Copernicus
1543

Simpler model



Kepler
1609

More accurate description of data

Kepler's 3 Laws [2.1]

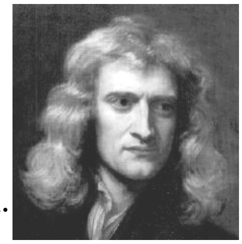
- Each planet moves around orbit in ellipse, with sun at one focus.
- The straight line joining the planet and the sun sweeps out equal areas of space in equal amounts of time.
- $P^2 = a^3$

But why??

These are descriptive laws,

but there must be deeper reasons for the planets to do this.

Isaac Newton
(1643-1727)



- One of the great geniuses of the millennium.
  - Invented *calculus*
  - *Mechanics* (the description of how things move)

- Kepler's laws can be derived from Newton's laws
- But Newton's laws are a general descriptions of a far wider range of phenomena
  - universally valid
    - except on the smallest or largest scales, or in extreme situations (strong gravity, high velocities).

Newton's laws of motion (*Principea*, 1687)

The Harvard Law School version…. See [pg. 43]

1. Every body continues doing what it is already doing --- being in a state of rest, or moving uniformly in a straight line --- unless it is compelled to change by an outside force.

2. The change of motion of a body is proportional to the force acting on it, and is made in the direction in which that force is acting.

3. To every action there is an equal and opposite reaction (or, the mutual actions of two bodies upon each other are always equal and act in opposite directions).

Newton's First Law

- *Momentum stays constant unless there is a force*

- Momentum = m x v = mass x velocity
  - *Mass* is a property of all matter.
  - *Velocity* is a vector: speed + direction
  - Momentum also a vector (i.e. it has a direction)

Newton's Second Law

- *F = m x a*
  Force = mass x acceleration
  - "change of motion" = acceleration
    = change in velocity per unit time.
    - 2x more force ➔ 2x more acceleration, etc.
    - Force is another vector: amount + direction

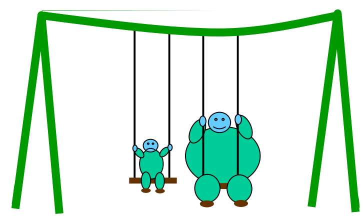
Newton's Third Law

Action <---> Reaction

- Or, since F=ma:

$$m_1 a_1 = - m_2 a_2$$

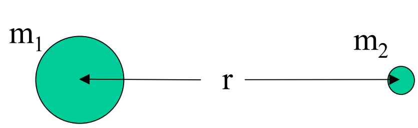
Relative accelerations in inverse proportion to relative masses

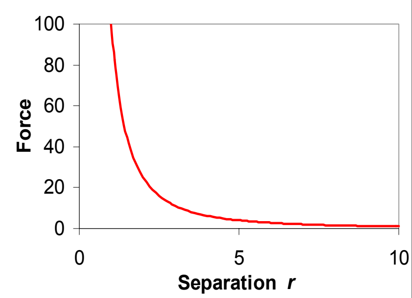


- Or… total momentum of system is *conserved* (stays constant).
- Rockets and jet engines use this principle.

Gravity

- Universal attraction of all matter for all other matter
- Gravitational force = $\dfrac{Gm_1m_2}{r^2}$





- Newton deduced this from his 3 laws of motion + Kepler's 3rd law.

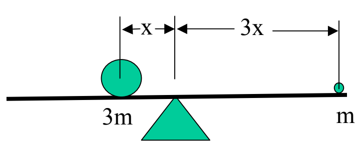
Newton's 3 laws of motion
(The Short Form)

1. Object's *momentum* does not change unless acted on by a *force*.
2. F = ma
3. Conservation of total momentum of system (Action - Reaction).

+ Gravity

$$\text{Gravitational force} = \frac{Gm_1m_2}{r^2}$$

- Center of mass
  - 3-D teeter-totters:



This globular cluster of 10^5 (100,000) stars also has a center of mass.

- Bound systems of objects (like the globular cluster, or like your car…)
  - Just figure out force on center of mass
  - System moves as if total mass were concentrated at that point.

Orbits of Planets *a la Newton* [2.4]

Kepler's first law becomes:

Planets move in ellipses with solar system's center of mass at one focus.

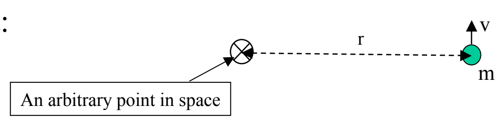
… but 99.9% of Solar System's mass is in Sun.

center of mass located slightly beneath the surface of the Sun.

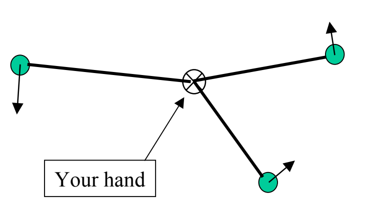
simulation with planets 45 times more massive

Angular momentum [pg. 45]

- Momentum = m x V
- Angular momentum = m x V x r
  - a single object:



  - system of 3 objects attached by strings:



Total angular momentum
= sum of values
for individual objects.

Total angular momentum of a system is also *conserved*

- Unless acted on by outside forces.
- Angular momentum is another vector
  - amount + direction important
- Everyday examples of conservation of angular momentum at work:
  - precessing tops
  - bicycles, motorcycles
  - daring university students going for a ride on “the stool”

Interpreting Kepler’s second law

Kepler2 simulation

- This is just *conservation of angular momentum* in Sun-planet system.
  - mvr = constant
  - smaller r ➔ larger v

Kepler’s 3rd Law

- Newton used this law to derive nature of Gravitational Force.

- But using Newton’s laws + gravity to derive Kepler’s 3rd law shows:

$$P^2 = \text{constant} \times \frac{a^3}{m_1 + m_2}$$

  - contains total mass = $m_{Sun} + m_{planet}$
    - Kepler missed this because 99.9% of mass is in Sun.
    - This is how we determine masses in orbiting systems.

Energy = ability to do work

- Energy = force x distance

- Kinetic energy = $\frac{mv^2}{2}$

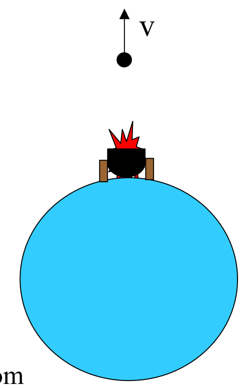
- Other kinds of energy
  - Gravitational potential energy
  - Electrostatic/magnetostatic potential energy
  - Electromagnetic (light) energy
  - Mass-energy: $E=mc^2$ (Special Relativity)

- Total energy of system stays constant unless acted on by outside force.
  - *Conservation* of energy.

Important concept

Gravitational Energy & Escape Velocity

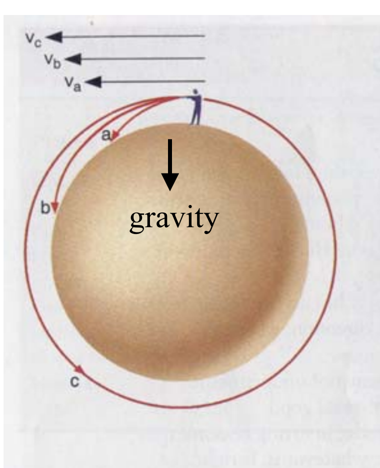
- For a canon ball shot straight upwards:
  - Total energy = kinetic energy
    + gravitational potential energy.
  - kinetic energy ➔ potential energy,
    Canon ball slows down
    (like a pendulum on its upswing).
  - Large initial velocity
    ➔ will escape Earth's gravity and keep going.
  - Escape velocity = minimum velocity for escape



$= \sqrt{2GM/r}$ M = mass of Earth
r = initial distance from center of Earth

Don't worry about the exact formula...

Circular vs non-circular orbit

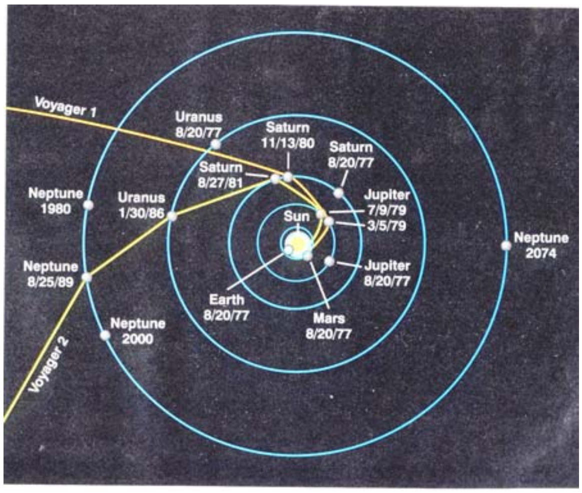


Newton's Cannon

- Gravity pulls bullet towards center of Earth.
  - Same for satellite, moon, etc.
- Bullet tries to keep going in straight line
  - momentum… Newton's first law.
- Result is bullet moves in curved path.
- Choosing correct velocity leads to circular orbit.
  - 8 km/s = 17,500 mph at Earth's surface.
- lower velocity
  (less total energy)
  ➔ elliptical orbit
  (which collides with Earth).

The Grand Tour of the Solar System (late 1970's)

courtesy of Isaac Newton's work in the 1660's



- *You too* can figure out how to do this.
- Just use
  - Newton's 3 laws.
  - Law of gravity.
  - Lots of computer time.
- But you must take into account gravitational attractions of Sun + all the planets.

An amazing 140 years

	Lived	Work became known
Copernicus	1473-1543	1543
Tycho	1546-1601	1601
Kepler	1571-1630	1609
Galileo	1564-1642	1610
Newton	1642-1727	1687

The next big jumps:

- Electromagnetism 1860
- Relativity 1910

} **Physics**

- Nature of our Galaxy and other galaxies 1920
- Expanding Universe 1929
- Understanding the energy source of stars 1938

} **Astronomy**

Some Important Concepts

- Newton's 3 laws of motion
  - Object's *momentum* does not change unless acted on by a *force*.
  - F = ma
  - Conservation of total momentum of system (Action - Reaction).
- Gravitational force

⇩

- Conservation of total *angular momentum* of system.
- Conservation of total *energy* of system.

⇩

- Kepler's laws and almost everything else about orbits and motions in general are contained in the above.

Limits of Newton's Laws

Well established

- Very high velocities ➔ Special Relativity
- Very strong gravitational fields ➔ General Relativity
- Very small scales ➔ Quantum mechanics

Highly speculative

- Inertial mass *vs.* Gravitational mass??
  - Inertial: Momentum = m x v
    F = m x a
  - Gravitational: $F = \frac{Gm_1m_2}{r^2}$

Are these two kinds of masses really proportional to each other?

Some theories postulate that they are not.