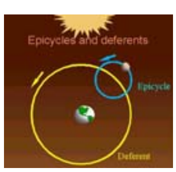
Some Basic Facts to Know

- What is the age of the solar system? How do we know?
- What is the Age of the universe? How do we know?
- What fraction of the mass within the solar system is contained in the sun? How do we know the mass of the Sun? How do we know the masses of the planets?

Motions of Objects

- Kepler's Laws:
  1. Each planet moves around orbit in ellipse, with sun at one focus.
  2. The straight line joining the planet and the sun sweeps out equal areas of space in equal amounts of time.
  3. $P^2 = a^3$ or Newton's version: $P^2 = a^3/(m_1+m_2)$
- Newton's Laws of Motion:
  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).
  - Gravitational force = $\frac{Gm_1m_2}{r^2}$
  - Angular momentum. Both amount & direction are *conserved.*
- General Relativity
  - Objects move in straight lines through curved space time.
  - Principal of Equivalence: *You cannot tell the difference between acceleration and gravity. You cannot tell the difference between freefall and lack of gravity.*

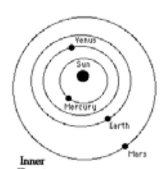
The Motions of the Planets



Ptolemy 140 AD

Copernicus 1543

Simpler model



Kepler 1609

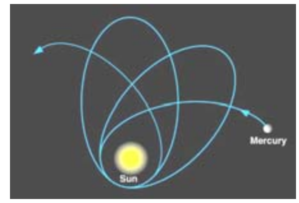
More accurate description of data

Newton's laws:
- Much more accurate yet.
- General description of everything.

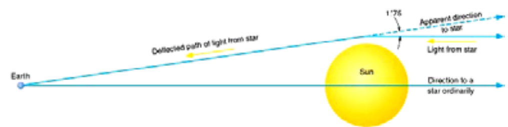
Special & General Relativity:
- Accurate in extreme situations:
  - High velocities.
  - Strong gravity.

Proofs of General Relativity

- Rapid precession of Mercury's orbit.
  - Phenomenon known before.
  - G.R. offered the explanation.

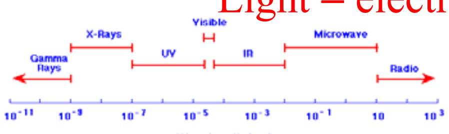


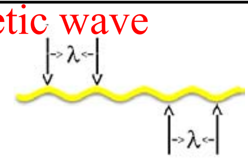
- Bending of light rays passing near Sun.
  - First measured in 1919



- Time dilation in gravitational fields.
  - Measured using real clocks, on Earth.
- Gravitational redshift in strong gravitational fields
  - Observed in spectra of white dwarfs.

Light = electro-magnetic wave





- *frequency* = rate at which crests pass a stationary observer.

  $f = \text{velocity/distance} = c/\lambda$ (cycles/second)
- *Energy* of each photon:

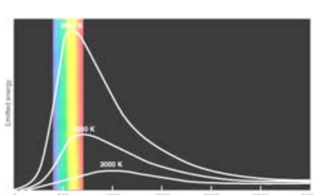
  $E = hf = hc/\lambda$ (h = Planck's constant)

Inverse square law: $F = L / 4\pi r^2$

Black Bodies:

- Wien Displacement Law.
  - $\lambda_{max} = 3x10^6 / T$
- Total energy emitted *per unit surface area*:

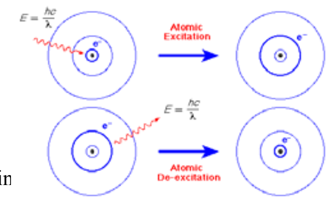
  $E = \sigma T^4$ (Steffan-Boltzmann Law)

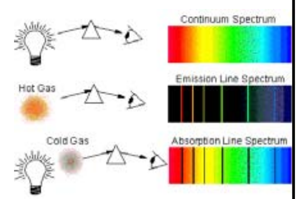


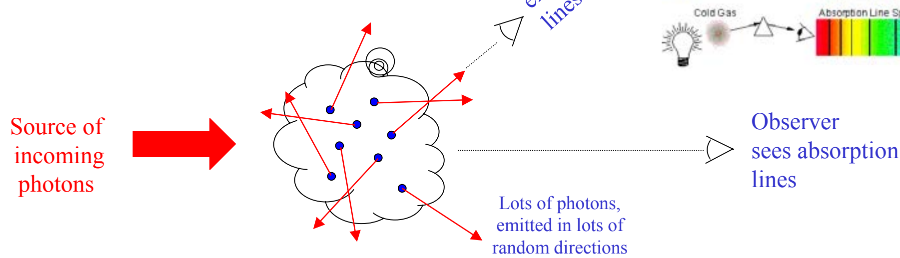
Wavelength →
← Energy

Emission & Absorption Lines

- Bohr Atom:
  - Electrons can only be in orbits at certain special radii.
  - Only one electron can be in a given orbit at one time.
  - Electron's energy stays constant while it is in orbit.
- Each Bohr orbit has its own distinct energy.
- For electron to move from inner orbit to one further out, it must gain exactly the energy difference between the orbits ➔ Absorb photon with correct energy
- Electron falling to lower level ➔ can emit photon with energy
  = exact energy difference between levels.

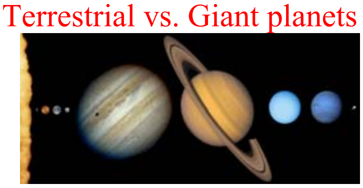




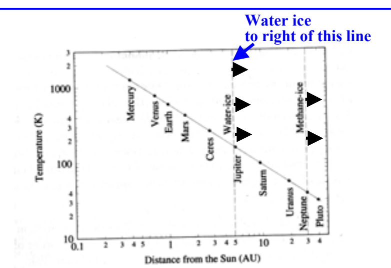


Overview of Solar System

- The solar system is a disk
  - Rotation of sun, orbits of planets all in same direction.
  - Most planets rotate in this same sense. (Venus, Uranus, Pluto are exceptions).
  - Angular momentum of pre-solar gas cloud.
- Terrestrial vs. Giant planets



  - High vs. low density
    - Rocks vs. mostly gas
  - Composition
    - heavy elements vs. primarily H/He
  - Difference due to distance from Sun.



In the Solar Nebula, while the planets were forming:
Presence of ice
➔ more material for core
➔ could gravitationally attract large masses of hydrogen & helium gas.

Terrestrial Planets

- Earth
  - Differentiated:
    - Iron/nickel core
    - Mantle of lighter rock
    - Thin crust on top
  - Plate Tectonics
    - Plates formed at rifts, usually in mid-ocean.
    - Drift & collide
      - Subduction
      - Volcanic activity
      - Mountain building
  - Evolution of atmosphere
    - Thick CO_2 → life → N_2, O_2
    - Current global warming
      - Greenhouse effect
      - Man-made CO_2

- (Moon)
  - Impact craters as clocks
  - Old highlands (4.1-4.4 billion yrs)
    - Heavily cratered
  - Maria (3.3- 3.8 billion yrs)
    - Fewer craters
  - Rocks from each brought back by Apollo astronauts.
    - Age dating
    - Chemical composition
  - Tidally locked to Earth
  - Formation of Moon
    - 4 theories
    - Giant Impact is current favorite.
- Mercury
  - Closest to Sun, eccentric orbit.
  - Airless, heavily cratered.
  - Hot, but (slightly) colder than Hell.
  - Very dense - mostly iron-nickel core.
  - Geologically dead (probably)
    - But rupes → shrinkage at early time.
  - Rotates in 2/3 of its orbital period
    - Tidal locking with a twist.

Terrestrial Planets (continued)

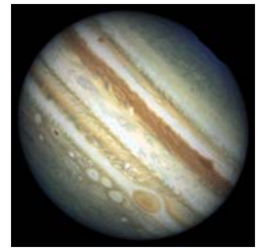
Venus
- Differentiated like Earth
  - But no tectonic plates.
- Surface mostly studied by radar
  - Large volcanoes
  - "Continents" pushed up by tectonic flows in mantle.
  - Recent lava flows, constant resurfacing.
  - Crater density → very young surface
    - only 800 million yrs old.
- Thick CO_2 atmosphere
  - Result of runaway greenhouse effect.
  - Keeps surface very hot (900F).
    - Lead, brimstone (sulfer) are molten.
- Retrograde rotation
  - Probably due to giant impact.

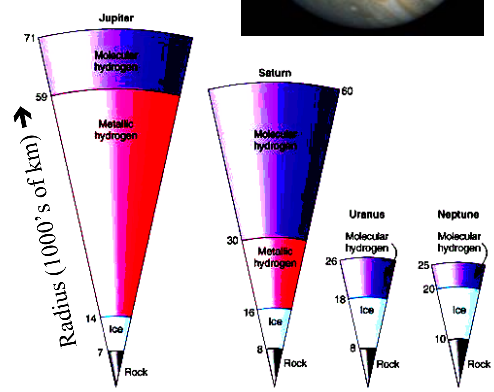
Mars
  - 50% smaller diameter than Earth
  - 1.5 times further from Sun.
  - Many visits by spacecraft.
- Small metal core, but much activity in mantle.
  - Gigantic volcanoes.
  - 50% highland "continents"
    - Tharsis bulge.
    - Cracked open to form Valles Marineris.
  - 50% low-lying lava plains.
    - 4 billion yrs old (crater counts)
- Atmosphere
  - CO_2, like Venus, but very thin.
  - Runaway refrigerator effect
    - Atmosphere gradually escaped
    - Could not retain heat
    - Water froze out
      - even less heat retained
- Life?
  - Viking landers found no sign.
  - In meteorites from Mars? Very questionable.

The Giant Planets

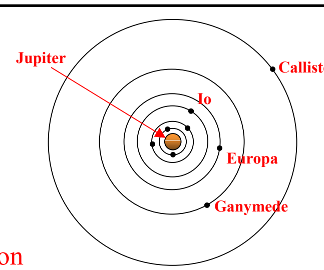
Jupiter – Saturn – Uranus - Neptune

- 14-300 x more massive than Earth.
- Massive H, He atmospheres
  - By far the most abundant elements in the solar system.
- On top of rock/ice core with 10-15 x mass of Earth.
- Lots of weather on Jupiter & Saturn.
  - Ammonia (NH_3) clouds.
  - Strong winds at different latitudes. (differential rotation)
  - Cyclonic storms
    - Great Red Spot
      - 2 x size of Earth
      - 400 yrs so far
  - Investigated by Galileo probe.
- Uranus, Neptune have methane reflective layers (blue-green color).
  - Neptune has high altitude clouds of methane ice crystals.





Moons



- Jupiter's Galilean moons, as we get closer to Jupiter:
  - Callisto – ice, geologically dead.
  - Ganymede – ice, but geologically active.
  - Europa – rock, but covered by ice pack over liquid water.
  - Io – rock, extreme volcanic activity.
- Gradient of properties due to increased tidal effects & heating from Jupiter.
- Jupiter's 24 other moons are much smaller.
- Saturn: 31 known moons
  - largest is Titan
    - N_2 atmosphere.
    - Similar to Earth's, but very cold (ethane oceans).
    - Cassini/Huygens probe to land in 2004.
- Triton
  - Neptune's largest moon.
  - Retrograde orbit.
  - 75% rock, 25% ice.
  - Very thin N2 atmosphere.
- Pluto (& Charon)
  - No spacecraft visits, so little is known
  - Pluto probably quite similar to Triton.
  - Charon is half as big as Pluto.
  - Debate about whether Pluto should be called a planet.
    - Very low mass.
    - Eccentric, tilted orbit.
    - Similar to some comets.

Rings

- All 4 giant planets have rings.
- Rings form inside Roche limit:
  - $P^2 = a^3$ ➔ different parts of a moon try to move in orbits with different periods.
  - This tears bodies apart unless gravity (+ internal tensile strength) can hold them together.
  - For orbits inside Roche limit, prospective moons are torn apart.
- Jupiter, Uranus, Neptune have very thin rings. Saturn has much larger rings.
- Rings made of gravel and small bits of ice.

Asteroids

- Small rocky bodies in orbit about sun.
  - Left over from formation of Solar System.
- Most, but not all, in asteroid belt.
  - Some cross Earth's orbit

Meteorites

- Asteroids that hit Earth and don't burn up in atmosphere.
- Analyzing them ➔
  - Age of solar system (4.5 billion yrs)
  - Initial chemical composition of solar system.

Comets

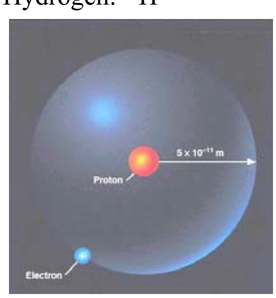
- Mostly ice
- Some on highly eccentric orbits
  - Spectacular tails when close to Sun.
  - Melted ice is driven off by solar radiation, solar wind.
- Most come from Oort Comet Cloud at edge of solar system.
  - Some from Kuiper Belt, just beyond Pluto.

What Powers the Sun?

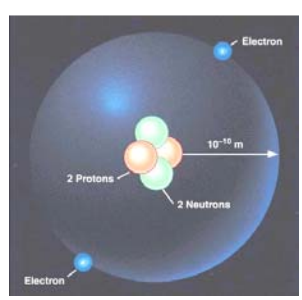
- Need to provide
  - 4×10^{26} watts
  - $< 2 \times 10^{33}$ grams (mass of Sun)
  - $>$ 4.5 billion years (age of Earth)
- Nuclear fusion reactions:
  - $4 \times {}^1H \rightarrow {}^4He$ + neutrinos + energy

Hydrogen: ^1H

4 x



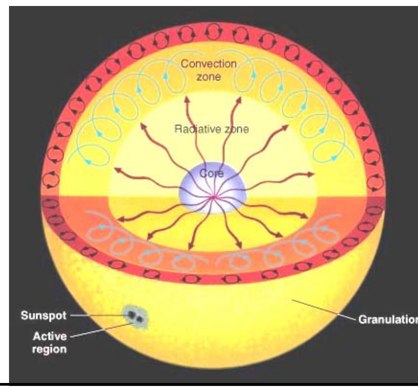
Helium: ^4He

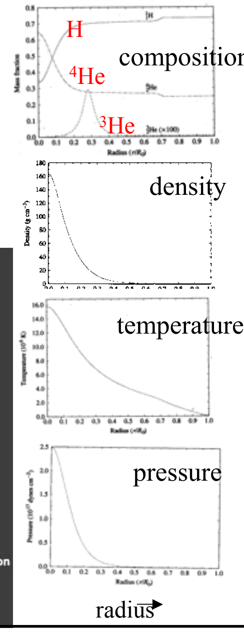


Computing the structure of the sun

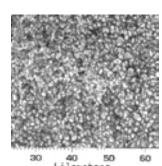
See [15.3]

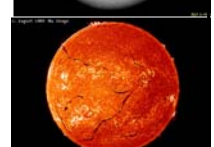
- For every point in the Sun, we want to compute
  - temperature
  - pressure
  - density
  - composition
  - energy generation
  - energy transport mechanism
- We can write 4 equations expressing the following ideas:
  - The Sun is a gas.
  - The sun is neither contracting nor expanding.
  - The sun is neither heating up nor cooling down.
  - Specify method of energy transfer.

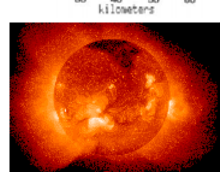


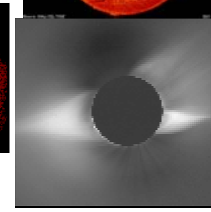


- Photosphere
  - Deepest layer from which light directly escapes into space.
  - Low density and pressure, but *hot* (5800° K)
  - Granules = Tops of convection currents.
- Chromosphere
  - Transparent gas layer above photosphere.
- Corona
  - T > 1,000,000° K
  - Very low density: 10^{-10} bar.
  - Heated by magnetic energy.





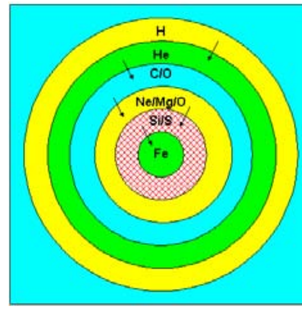




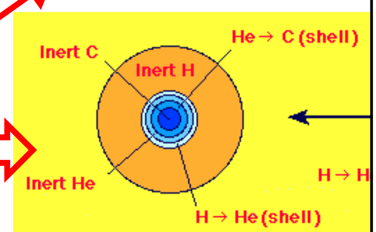
- Magnetic Fields Control Much of Sun's Surface Activity
  - Sunspots:
    - Cooler regions where lines of force enter/leave surface.
  - Solar Wind
    - Charged particles with greater than escape velocity, escaping through holes in magnetic field.
  - Prominences
    - Charged particles following magnetic lines of force.
  - Flares
    - Magnetic field lines short out ➔ Huge burst of charged particles
  - 11/22 yr. Solar cycle
    - Due to "winding up" of Sun's magnetic field.

Nuclear burning in stars

Reaction	Min. Temp.
4 ^{1}H → ^{4}He	10^{7} ° K
3 ^{4}He → ^{12}C	$2x10^{8}$
^{12}C + ^{4}He → ^{16}O, Ne, Na, Mg	$8x10^{8}$
Ne → O, Mg	$1.5x10^{9}$
O → Mg, S	$2x10^{9}$
Si → Fe peak	$3x10^{9}$



Evolution through nuclear burning.	
$M_{initial} > 3M_{\odot}$	Nuclear burning all the way to iron.
$M_{initial} < 3M_{\odot}$	Nuclear burning shuts off after He-flash.



How do stars get from here to there?

Here: Evolution through nuclear burning.	
$M_{initial} > 3M_{\odot}$	**Nuclear burning all the way to iron.**
$M_{initial} < 3M_{\odot}$	**Nuclear burning shuts off after He-flash.**

Mass loss:

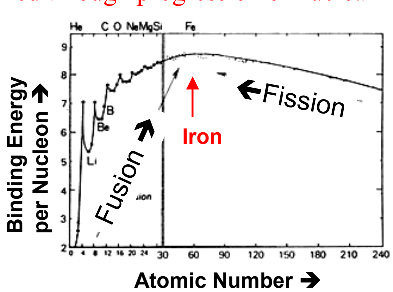
- Planetary nebulae
- Eta Carinae
- Supernovae

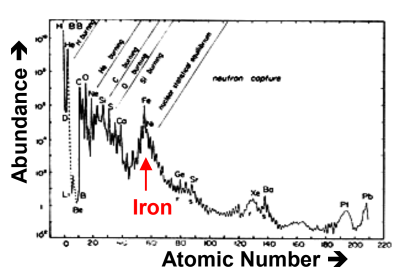
There: Final state.	
$M_{final} > 3M_{\odot}$	**Black hole.**
$1.4 < M_{final} < 3M_{\odot}$	**Neutron star.**
$M_{final} < 1.4M_{\odot}$	**White dwarf.**

The Chemical Enrichment of the Galaxy:

All elements heavier than Hydrogen, Helium & Lithium formed through progression of nuclear reactions in stars.

Interstellar Gas
Stars





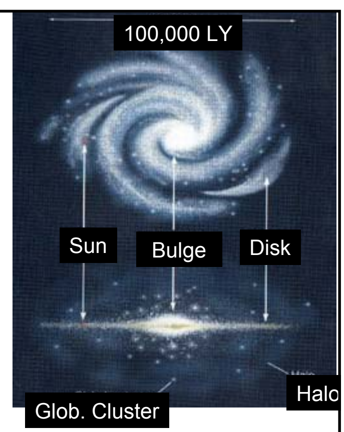
Star Formation

- Stars form in dense gas clouds = molecular clouds
  - Shielded from UV radiation by dust ➔ atoms are combined into molecules.
  - H_2 …and also H_2O, NH_3, CO plus much more complex molecules.
- Star formation ➔ disks around stars
  - ➔ channels outflows into double-lobed patterns
  - Planets form in these disks.

What types of planets are out there?

- Current search methods ➔ easiest to detect giant planets close to parent star.
  - ***But…why do giant planets exist at less than 1 AU?***
    - spiraling into the star, as a result of friction.
- Also - 3 Earth-sized planets circling pulsars
  - inhospitable environment.
  - These planets are thought to have formed *after* the supernova.
- Future space-based searches
  - Earth-sized planets in habitable zone around G stars like the Sun??????

Galaxies



- Composed of 100 billion stars or more.
- Main types are
  - Ellipticals
  - Spirals
    - Regular spirals
    - Barred spirals
  - Irregulars
- Our galaxy (the Milky Way) is a spiral with a weak bar.
- Spiral arms
  - Density waves vs. winding up due to differential rotation.
  - Site of increased gas density, star formation.
- Theories of galaxy formation: top-down vs. bottom-up.
- Mass of galaxies dominated by Dark Matter.
  - Detected by studying motions of stars around galactic centers.

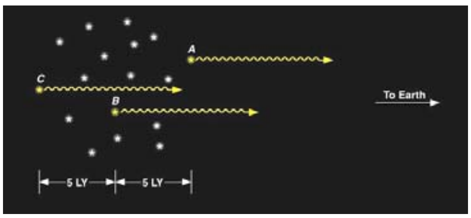
Quasars & Active Galaxies

- Large redshift ➔ large distance

$$F = L/4\pi d^2$$

$$4\pi d^2 F = L$$

- Measured flux + distance ➔ huge luminosity
  - Up to 1000 x luminosity of an entire galaxy of stars.
- Rapid flux variability ➔ small volume.

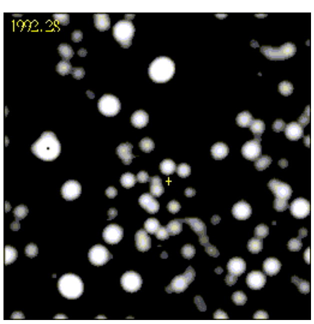


Some luminous quasars vary in *few days* ➔ same size as solar system.

Black Hole
- Result of extremely strong gravitational field
- Schwarzschild radius.
  - $R_S = 2GM/c^2$

- Energy Source:
  - Gas, stars fall into $10^8\ M_\odot$ black hole.
  - Gravitational potential energy ➔ thermal energy ➔ light

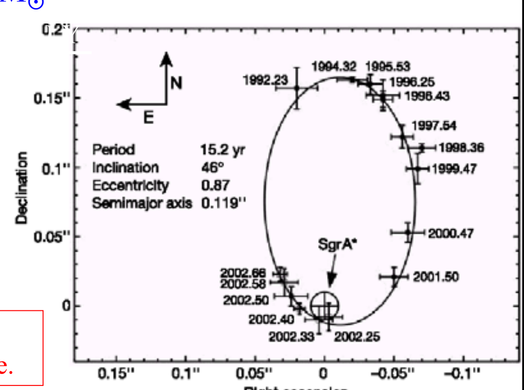
The Black Hole at the the Galactic Center



$$P^2 (M_1 + M_2) = a^3$$

Velocities of stars in very center
➔ black hole at position of Sagittarius A*

$10^6\ M_\odot$



Infrared observations over 6 years show proper motion.

Latest data (2002): follows complete orbits to within 60AU from black hole.

Possible Geometries of the Universe

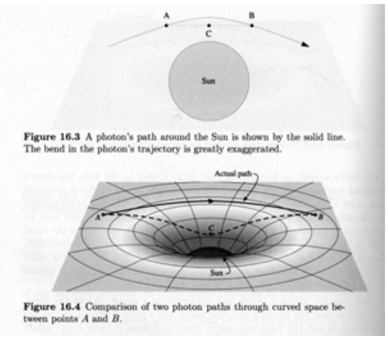
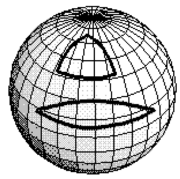
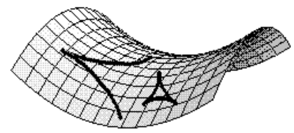


Figure 16.3 A photon's path around the Sun is shown by the solid line. The bend in the photon's trajectory is greatly exaggerated.

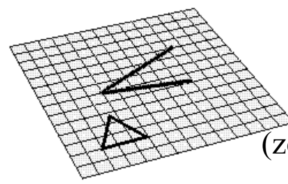
Figure 16.4 Comparison of two photon paths through curved space between points *A* and *B*.



Positive Curvature



Negative Curvature



Flat (zero curvature)

An Expanding, Evolving Universe

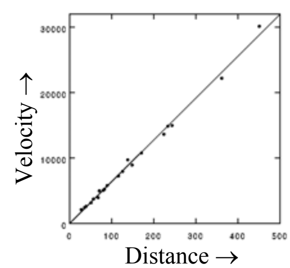
Hubble's Law:

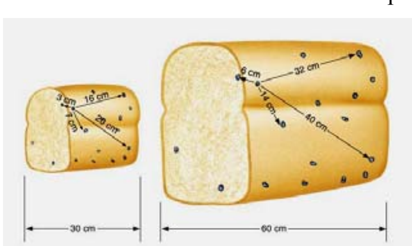
- Galaxies all recede from us.
- Velocity proportional to distance.

  $v = H_o\, d$

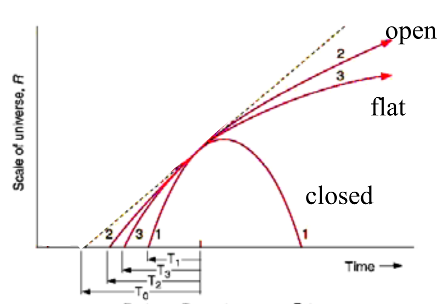
- We are unlikely to be at exact center.

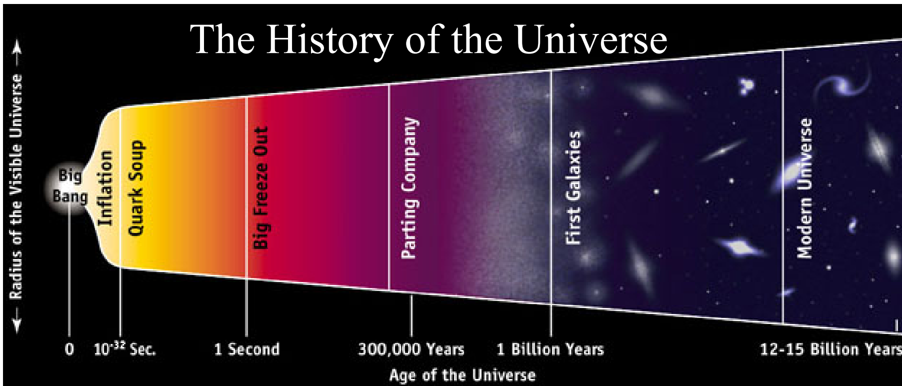
  ➔ Scale of the whole universe is expanding.





Energy balance	Ω_0	Curvature	Future
kinetic > gravitational	< 1	negative	open
kinetic = gravitational	1	flat	critical
kinetic < gravitational	> 1	positive	closed





Planck time

Inflation

Nucleosynthesis of H, He, Li

Decoupling of CMB

Galaxy Formation

Now

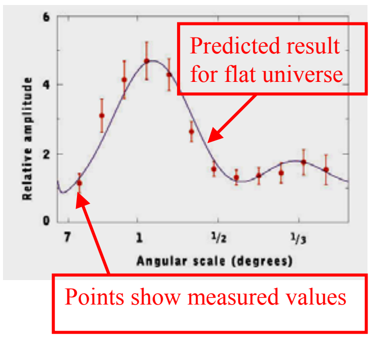
Hot → Cool

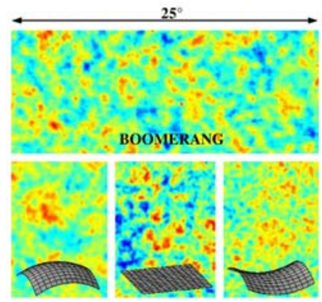
High density → Low density

How do we know the universe is expanding from a very much smaller size?

- Hubble's Law
- Cosmic Microwave Background (CMB)

Size scale of Structure in the CMB ➔ Universe is flat.



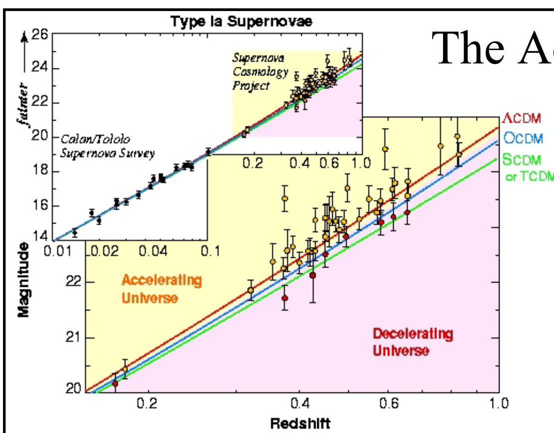


But there is not enough matter.

- Total detectable matter (luminous + dark) is only about 1/3 of "critical" density needed for flat universe.

Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014
Dark Matter	0.3

The Accelerating Universe



- Type Ia Supernovae as "standard candles" ➔ accelerating expansion.
- Two-parameter diagram ➔ mysterious extra "force" pushing things apart.