Quiz 1

* Overview of the Sun
- $D_\odot \approx 100 \times D_\oplus$
- sunspots are cooler & produce less light than the rest of the surface
- $V = \frac{4}{3}\pi r^3$
- $V_\odot = 10^6\ V_\oplus$
- $M_\odot = 330{,}000\ M_\oplus$
- 2×10^{30} Kg = solar mass
- earth has a bigger density than sun
- sun = $1.4 \frac{g}{cm^3}$
- earth = $5.5 \frac{g}{cm^3}$
- sun is mostly hydrogen & helium (74% hydrogen, 24% helium)
- gravity keeps sun together
- gas pressure pushes outward
- it is in equilibrium
- light comes from photosphere, or "surface"
- produces light by thermal radiation

* Properties of light
- it is a wave
- different colors → different λ
- red 7×10^{-7} m
- blue 4×10^{-7} m
- violet 3.8×10^{-7} m
- radio, infrared, UV, x-rays, γ rays
- EM spectrum

* Thermal Radiation
- heat or black body radiation
- from hot solid gas or dense gas
- the hotter the object the more light it produces
- the hotter the object the shorter the λ of light
- 1st rule - Stefan's Law
- 2nd rule - Wien's Law

- Wien's Law = $\lambda_{max} \propto \frac{1}{T}$
- can be written $\lambda_{max} = \frac{0.0029}{T}$, but λ
- is in m and T is in Kelvins
- brightness $\propto 4\pi r^2 T^4$ (luminosity actually)
- distance affects brightness also
- brightness $= \frac{1}{4\pi r^2}$
-

1.22.07 * Brightness vs. Luminosity

- $B \propto \frac{L}{4\pi d^2} \propto \frac{L}{d^2}$
- light carries energy, depends upon λ

* Types of Energy
- radiative energy - energy of light
- kinetic energy - energy of motion
- potential energy - stored energy
- in nuclear reactions, mass converts to energy
- $E = mc^2$, rest mass is potential energy

* Fusion & Fission
- fusion is binding
- fission is splitting
- in sun, hydrogen goes to helium

* Sun ~~& Fusion~~
- density is $1.4 \frac{g}{cm^3}$ as whole
- photosphere is about 5800 K
- reactions only occur in core of sun
- in core, density is 100 g/cm^3 and is 10,000,000 K

* Subatomic Particles
- positron - positively charged electron
- neutrinos - neutrally charged, very low mass, even less than an electron, don't know mass exactly
- atomic mass is average of isotopes' mass

* Fusion in sun
- $^1H \rightarrow {}^4H$ net reaction
- $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$
- $p \rightarrow n + e^+ + \nu$. ν is neutrino
- $^2H + {}^1H \rightarrow {}^3He$ + energy (light γ rays)
- $^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$
- $6\,{}^1H + 2e^- \rightarrow {}^4He + 2H^1 + 2\nu + \gamma$ rays

1.24.07 * Review
- proton - proton chain
* Forces
- strong force - holds atoms together
- weak force - involved in radioactive decay
- gravity -
- electromagnetic -
- strong only acts over very short distances
- weak is just another electromagnetic forces
- they are called the electroweak force
* The Solar Neutrino Problem
- neutrino's left over from reaction fly out of sun
- they are very hard to detect
- but will interact with chlorine, gallium,
& H_2O & D_2O
- scientists have built neutrino observatory
- tank filled with one of these compounds
- these will also interact with the solar wind
- solar wind is mostly protons & electrons
- Humstake Gold Mine in South Dakota contains
dry cleaning fluid
- Super - Kamiokande Neutrino Detector, Japan - water
- Gallex Neutrino Detector, Italy - uses Gallium
- Sudbury, Ontario - heavy water
- the problem was that everything was detecting too less (≈ 1/3)
- so either our calculations are wrong or something has happened
to the neutrinos
- neutrinos can change to another type
- 3 types -
electron - produced in sun
tau
muon

- neutrino oscillation was occuring
- heavy water can detect all 3 types
* Stellar Parallax
- $b \propto \frac{L}{D^2}$
- joule/sec = watt
- solar luminosity = $L_\odot = 3.9 \times 10^{26}$ W
- Stefan's law - $L \propto 4\pi r^2 T^4$
- so $b \propto \frac{r^2 T^4}{D^2}$
- most stars have angular sizes less than an arcsecond
- we could calculate size if we know distance
- find distance with stellar parallax
- uses geometry
- parallax = apparent motion of a near by object relative to background objects due to a change in position of the observer
- parallax shift $\propto \frac{1}{D}$
* Parsec
- 3.26 LY = 1 parsec
- stands for parallax arcsec
- the distance of an object if its parallax shift was one arcsec
- $p = \frac{1}{2}$ angular shift over 6 months
- $p = \frac{1}{D}$ if in arcsecs and parsecs
- if total shift was $0.2''$, then $p = 0.1''$, so $d = \frac{1}{0.1} = 10$ pc.
- proper motion = true motion of the stars through space in the plane of the sky
- use a one year time span instead of 6 months
-

Quiz 2

* The Luminosity of the Sun
- $D_{bulb} = 12.5$ cm
- $b \propto \frac{L}{4\pi d^2}$ or $b \propto \frac{L}{D^2}$
- $b_B \approx b_\odot$
- $1 = \frac{100W}{L_\odot}\left(\frac{1.5\times10^{13}\text{ cm}}{12.5\text{ cm}}\right)^2$
- $L_\odot = 100W(\cdot 10^{12})^2$
- $L_\odot = 10^{26}$ W
- watt $= \frac{\text{joule}}{\text{sec}}$
- brightness $= \frac{\text{energy}}{\text{sec}\cdot\text{cm}^2}$

* Magnitude System
- system dates back about 2000 years to Ancient Greece
- Hipparchus made it, had a catalog of stars
- contained about 850 stars, gave positions and estimate of brightness
- he used eyes and classified stars
- brightest stars were first magnitude
- 6^{TH} mag were the faintest stars in the sky
- brightest stars have a low magnitude
- a first magnitude star is about 2.5 times brighter than a second
- $(2.5)^5 \approx 100$
- first magnitude is about 100 times that of a 6^{TH}
- by definition now, 5 steps of brightness = 100x
- each step equals $\sqrt[5]{100}$ or 2.512
- in modern system, we use fractional magnitude
- Betelgeuse has a magnitude of 0.4
- Sirius has mag of −1.5
- Deneb is 1.3
- Venus is −4.2 mag (variable though)
- Jupiter = −2.6 mag (variable)
- Saturn = 0.7 mag
- Neptune = 7.9 mag
- Pluto = 14.9 mag $(2.512)^7 \approx 620$

- sun is about -26.7 mag
- moon is about -12.7 mag after full
- these are apparent magnitudes
- This is how they appear to us
-

Quiz 2

* Energy levels
- in core of sun, atoms are ionized
- electrons can jump by absorbing photon, impact with another atom
- to jump down, it emits a photon of light

* Sun
- core - 28% - nuclear reactions
- radiative zone - 44% - absorption + reemission
- convective zone - 28%
- photosphere - about 300 km thick
- about 1/1000 radius of sun
- atmosphere - low density gas (below are part of)
- chromosphere - 2000 km thick
- corona - 15x radius of sun - very low density
- corona is hard to see
- distance from Earth to sun = 100 $D_{\odot}$
- radius of corona = 0.15 AU
- solar wind - particles from sun
- extends way out beyond planets

* Radiative Zone
- when photon is emitted, it goes in random direction
- random walk process - each step changes direction randomly
- on average, photons are emitted 10^{22} times
- takes about a million years for light to get out of sun
- moving from core to outer part, opacity increases
- steps get smaller also
- by the time it gets to edge of radiative zone, it is very hard to leave since atoms are neutral
-

* The Convection Zone
- hot air rises & cold air sinks because of gravity
- hot atoms push up to surface and cooler gas falls down
- photosphere is top of convection zone
- granules - convective cells on the sun
- about 1000 Km across each
- lighter spots are hotter & darker spots are cooler
- we can measure the velocity of gas coming near or going away from us
- change on time scale of 5-10 minutes
- there are layers of convective cells
- small ones on top & large ones on bottom
- big regions are called supergranules
* Spectrum & Absorption lines
- the low density gas of the sun absorbs light
- sun & most stars have absorbtion line spectrum
* Uncertainity Principle
- cannot know location & position of a particle
- lines have widths
- doppler shift also affects it
- number of protons, ionized can change spectrum
- isotopes works also
-

Quiz 2

* Doppler Shift
- towards us - blueshift
- away from us - redshift
- doesn't matter which observer moves
- proper motion measures motion of stars traverse to the line of sight of the observer
- use proper motion & doppler shift to get motion through space

* Solar Eclipses
- by chance, angular size of moon & sun are about half a degree across
- $D_{\odot} = 400\ D_{moon}$
- distance & diameter
- this means moon covers sun at solar eclipse
- angular size $\theta \propto \frac{1}{D} \propto$ physical size
- annular eclipse - when moon is small, but cannot cover sun
- if moon totally blocks, then chromosphere can be seen
- spicules - spikes on the sun that change 5-10 minutes
- about 10,000 km
- caused by magnetic activity
- chromosphere has a reddish tint
- if θ of moon is bigger than sun, then corona can be seen
- coronagraphs or devices will block out sun
- sun has absorption line spectrum, unless it is eclipsed, then an emission line spectrum exists

*

Quiz 2

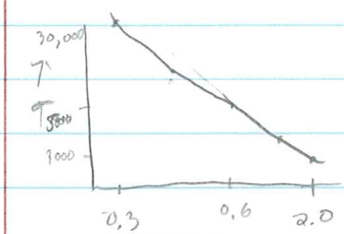
* Magnetic Dynamo

- magnetic field of sun is 1000s of that of Earth
- magnetic field generated by magnetic dynamo
- moving charged particle encountered a magnetic field will be deflected
- a moving charged particle creates its own magnetic field
- in inner regions of sun, most of the H & He is ionized
- sunspots are created by magnetic field
- sunspots are around 4700 K - 5500 K
- sunspots have magnetic field about 1000x that of rest of photosphere
- it inhibits convection, thus are cooler
- an atom in a magnetic field will change energy and thus, its spectrum
- sunspots tend to come in pairs and tend to be east and west
- the two in a pair have different polarity
- all spots in the same hemisphere have same polarity
- in other hemisphere, it would be opposite
- period of variation of number of sunspots is about 11 years
- cycle is not exactly regular though, could be 7-15 years
- during solar maximum, there could be between 50-150 sunspots
- sunspot can last 1-100 days
- at solar minimum, spots are usually high latitude 25°-30°
- at solar maximum, spots are closer to equator 15°-20°
- few years later, could be 10°
- next cycle, sunspots will have reverse polarity in their respected hemisphere
- sunspot cycle is really 22 years (for both polarity)
-

* Differential rotation
- sun rotates faster at equator than poles
- rotation at equator is about 25 days
- higher latitudes take longer
- field lines will be stretched
- they will poke up through the photosphere
- sunspots are just where the field lines comes out & goes back in
- eventually, the field lines dissolve and new ones form, however, it is upside down
- there is a loop of gas that will form on it
* Prominence
- arc of gas between two sunspots where gas is being carried
- can last 1 day to months
- if field line breaks, it is an eruptive prominence
- not the same as a solar flare, SF is more energetic
- solar flares are associated with sunspots
- when many field lines ~~cross~~, an explosion occurs
- alot of material will be blasted into space
- during solar max, more prominences & flares happen
- this means more solar wind
* Pictures
- first US space station = Skylab
- occupied 1973 - 1979
- looked at sun's x-rays & ultraviolet
- Maunder minimum - hardly any sunspots - 1650-1700
- Solar Maximum Mission - 1980 - 1989
- coronal spikes - 0.1 AU

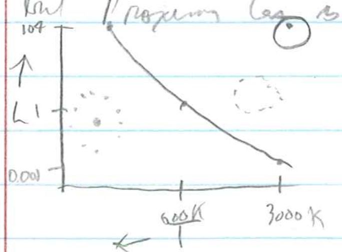
Quiz 3

* Magnitude
- brighter the star lower the magnitude
- each step is 2.512
- every five steps is 100
- Hipparchus made it, used his eyes
- as temperature increases, B-V goes down
-



curves upward

- gives us an easy way to find temperatures of stars
- can also use Wien's law to find temperature
- $\lambda_{max} \propto \frac{1}{T}$
* Stefan's Law
- $L \propto 4\pi r^2 T^4$
- Betelgeuse & Proxima Cen are about 3000 K
but Proxima Cen is less luminous because it is smaller
-



solid line = main sequence
O = supergiants
◌ = giant
⋯ = white dwarf

- $R_B = 400\ R_\odot$
- $T_B = 0.5\ T_\odot$
- $L_B \propto 4\pi r_B^2 T_B^4$
- $L_\odot \propto 4\pi r_\odot^2 T_\odot^4$
- $L_B = 10{,}000\ L_\odot$
- Sirius B is a white dwarf ≈ size of Earth
- main sequence has hydrogen fusion reactions
- diagram is Hertzsprung - Russell Diagram, or HR

* Luminosity Classes
- supergiants = I
- giants = III
- main sequence = V
- white dwarfs = not given a numeral
- bright giants = II
- subgiants = IV
-

Quiz 3

* HR Diagram
- relates temperature and luminosity
- B-V is in magnitude
- as temperature goes up, B-V goes down
- can use spectrum of a star to get its temperature
- H_α is strongest in stars about 10,000 K
- H_α is $3 \to 2$
- to have a strong $H\alpha$ absorption line, alot of H
  with electrons in level 2 is needed
- absorption lines are made in lower chromosphere
  and upper photosphere
- in the hottest stars, most atoms are ionized
- therefore, it cannot produce absorption lines
- cold stars - around 3000K
- most electrons are in ground state
- stars around 10,000 K, electrons are excited, but
  not ionized
- only in hottest stars is helium ionized found
- lines for neutral He also is hard to excite
* Spectral Classes - Seven
- hottest - 30,000K - O
- 20,000 K B
- 10,000 K A
- 7,000 K F
- 6,000 K G
- 4,000 K K
- 3,000 K M
- late 1800s for spectral class starting
- strongest hydrogen lines were A, then B, all the way to P
- Annie Jump Cannon - classified 250,000 stars and found the new order
- Oh Boy, An F Grade Kills Me"
- we now have 10 subclasses

- 0 subclass is hottest, 9 is coldest
- our sun is a G star - G2 V
- Alpha Centauri A = G2 V
- B = K0 V
- Proxima Cen = M5 V
- Betelgeuse = M2 I
- Aldebaran = K5 III
- spectral type + luminosity class
- an M2 I + M2 V is have different lines
- a main sequence star has broader lines
- bigger stars have narrower lines
- weak gravity field out where lines are produced
- masses ∝ the same
- from spectrum, get spectral type + luminosity class
- get location on HR diagram
- get approx. luminosity
* Spectroscopic Parallax
- figure out luminosity & spectral class from
- use HR diagram
- gives approximate luminosity
- measure brightness & use formula of
- called automobile headlight method
* Parallax
- another way to get distance of stars is stellar parallax
- take measurement on other side of sun
- $P = \frac{1}{D}$, parallax shift ↑, distance ↓
- P = arcseconds and D is parsecs
- very accurate, but only works for nearby stars
- Hipparcos Spacecraft = measured parallax for 112,000 stars
- our galaxy contains 400 billion stars
-

* Newton's Laws
- 1ST - objects in motion stay in motion
- 2ND - $F = ma$
- 3RD - every action has an equal and opposite reaction, or $F_1 = F_2$
- sun is 330,000x larger than Earth
* Newton's Law of Universal Gravitation
- $((M_1 M_2)/R^2) G = F_{grav}$
- G = gravitational constant $= 6.67 \times 10^{-11} \frac{Nm^2}{kg^2}$
-

Quiz 3

* Newton's Laws
1. inertia
2. $F = ma$
3. $F_1 = F_2$
4. $F = GM_1M_2/R^2$
* Binary Stars
- more than half of the stars we see are binary
- $(M_1 + M_2) P^2 = R^3$
- Newton's revision of Kepler's Third Law ←
- distance must be AU, period in years, and mass in solar mass
* Center of Mass
- "balance point of gravity"
- center of mass is closer to the more massive object
- $M_J = 10 M_L$
- $X_J = \frac{1}{10} X_L$
- $M_J X_J = M_L X_L$
- some cases where both stars can be seen
- this is called a visual binary
* Visual Binary Stars
- maybe LYs away from each other
- period in 100s of years
- star at bottom of Cygnus - Albireo
- it is a pair of B + K stars, about 3.5" apart
- B is hotter, color is blue
- K is red, more orangish
- an optical double, not binary, but may look like it
- parallax will be different for optical double
* Astrometric Binary
- one star is too faint to see, so visible star dances
- astrometry - measuring positions of objects in sky
- used for stellar parallax and 3d motion, and whether or not it is binary

- Sirius A first called an astrometric binary
- Sirius B is a white dwarf
* Spectroscopic Binary
- O stars have strong ionized He lines (He II)
- M stars have titanium oxide (TiO)
- if both lines were seen, then two stars are there
- can tell there are two stars based on spectrum
- double-lined spectroscopic binary - hot and cold star
- 2 A stars = 10,000 K, H lines are strong
- when two stars are of the same type, then the lines will split into two different lines
- from this you can find the period of orbit, and find mass by the relative shifts of the lines
- a single line spectroscopic binary is when only one star's lines can be seen, but lines are still moving from redshift to blueshift and back
* Eclipsing Binary Stars
- when one star eclipses another
- star will be dim & bright
- regular pattern of dips
- brightness vs. time - bright curve
- we can get physical sizes of stars from time of eclipse
- in most cases, we cannot measure star's size directly
- Algol - "the ghoul", the demon star", in Perseus, it is one
- Algol is supposed to be the eye of Medusa
* Three Ways to Find Binaries
- measure wobble of star in sky
- measure Doppler shift
- rare, but could see eclipsing
* Extrasolar Planets
- can use these three techniques to find these
- can't detect these yet directly

- we can see their influence on a star though
- best one is Doppler shift
- almost 200 ES planets found
- can't detect wobble of stars due to planet orbiting yet
- planetary transit : when planet moves in front of star and eclipses the star
- it is easier to find big planets near the stars

* Brown Dwarfs
- a failed star
- a ball of gas that doesn't start H fusion because it doesn't have enough mass
- if mass is less than 8% of sun, then it won't become a star
- brown dwarf ≠ planet
- brown dwarfs are larger than planets, about 13x of Jupiter
- deuterium will happen on a brown dwarf
- $^2H + {}^1H \rightarrow {}^3He$
- not all of energy though
- spectrum peaks in IR
- brown dwarf ≠ white dwarf
- white dwarf is burned out core of a star
- brown never made it

Quiz 3

* Mass - Luminosity Relation
- as you go up the main sequence, mass increases
- bottom - $\frac{1}{10} M_{\odot}$
- top - 30 - 40 $M_{\odot}$
- mass is the most fundamental
- mass determines the gravity field, the Temperature, and luminosity
- main sequence - $H \rightarrow He$
- bottom 0.001 $L_{\odot}$
- top - 10,000 $L_{\odot}$
- a small change in mass makes a big change in luminosity, but not directly proportional
- $L \propto M^{3.1}$ (approximately)

* Stellar Lifetime
- main sequence stars = how long it takes for the star to deplete its hydrogen
- a star the mass of the sun can last about 10 billion years
- lifetime = mass of fuel / rate of fuel used up
- in general lifetime $\propto \frac{\text{mass}}{\text{luminosity}} \propto \frac{1}{M^2}$
- the bigger the MS star, the shorter the lifetime
- O stars (hot) only lasts a few million years
- M stars (cold) lasts a trillion years
- universe is only 13.7 billion years old
- No M star has gone away, will be fusing for a while
- a massive star, about 8x of ours, will become a supernova
- lower mass stars will blow off outer layers and have expanding shell of gas, core will become a white dwarf
- the rings of gas are called planetary nebula

* Interstellar Matter
- about 99% gas by mass, only 1% dust
- dust is small, some microscopic, made up of silicates, silicon / oxygen
- 75% hydrogen by mass

- 24% He, 1% all other chemical elements
- in Milky Way, there is about $10^9\ M_\odot$ of interstellar matter
- about 10% of all stars in galaxy by mass
- contained in clouds, very gigantic, 100s of LYs
- can contain 10^6 or more solar masses

* Three Types of Clouds
- molecular clouds, atomic clouds, + ionized clouds
- in molecular, mostly H_2, 10-20 K, about 10^6 molecules/cm^3
- air on Earth = 10^{19} molecules / cm^3
- in atomic, neutral atoms, HI clouds, about 100K, 1 atom / cm^3
- in ionized, 10,000 K, 1 atom per m^3
- produces an emission line spectrum

* Ionized Clouds
- three types
- O star peaks in UV, which ionizes the hydrogen around it
- called H II region, which looks red due to $H\alpha$
- supernova remnant - gas is moving at a fast speed and becomes collisionally excited, which glows $H\alpha$
- planetary nebula - similar to the O star, but with white dwarf instead

* Clouds - Atomic
- harder to find the colder clouds
- the ground state of H is because it is split into because of electron's spin
- electron can spin parallel or anti-parallel
- those two states have slightly different energies
- it produces radio waves if it jumps down
- it is 21 cm for the λ

* Molecular Clouds
- even harder to find, doesn't produce strong line because it is so cold
- we can't detect the H_2, but we can detect CO

- CO has emission line at 2.6 mm – microwave
- very easy to detect
* Interstellar Dust
- blocks light from behind, called dark cloud
- about 10 - 100s K
- solid particles, and produce light, continuous spectrum
- produces long wavelength infrared – far infrared
- to see the dust, use a long λ IR telescope
- the shorter the λ of light, the easier it is to be scattered or reflected
- a reflection nebula – O star with H II region, but with a B star, the star looks blue, with a blue hazy glow around it, because B stars make blue light
-

Quiz 3

* Clouds
- C_2H_5OH has been found in molecular clouds
- polycyclic aromatic hydrocarbons are also found in molecular & atomic, but not ionized because of UV light
- (*) → blue light, called a reflection nebula
- reflection nebula are with B stars
- molecular clouds are densest, stars form from this
- needs extra force to turn into stars
- a supernova, collide with another cloud, or strong stellar wind can compress cloud
- star formation tends to happen in spiral arms of Milky Way
- arms trail behind spin of galaxy

* Spiral Density Waves
- "arms of galaxy"
- gravity field is stronger near arms
- density of arms is higher than surrounding region
- some stars & gas don't stay in arms
- stars move into arms and then move out
- spiral arms are like traffic jams
- clouds are likely to collide, but not stars

* Formation of Stars
1. - trigger for collapse
2. - break up of cloud
3. - collapses more and spins faster
- angular momentum $\propto$ velocity · mass · size of object
4. - flattens to a disk
5. - core gets hot
6. - clumps of dust form dust grains stick together
7. - core gets hotter & nuclear reactions start (starts with H fusion)
- officially a star, once formed, it is main sequence
8. - new star has very strong wind; blows out gas & dust

+ Finding Protostars
~ protostars mostly produce IR light
— generally inside molecular clouds, thus blocking our view of the star
* Misc - Picture
~ globules - small dense molecular clouds where stars will form soon

Quiz 4

* HR Diagram
- a top - 10,000 $L_\odot$ + 30 $M_\odot$
- as T goes up, lifetime goes down
- stellar evolution is the change of stars over its lifetime

* HR Diagrams of Star Clusters
- useful for studying stellar evolution
- - reasons
1. - all stars in same cluster formed at about the same time
2. - all stars in the cluster are at the same distance from us
- stellar evolution is a slow process

* Types of Star Clusters
- open clusters - loosely bound group of stars, made up of young stars
- globular cluster - dense balls of stars, spherical in shape, are old
- when clusters are formed, all types of main sequence stars are in there
- if it has a full main sequence, then it is young
- age of cluster is related to its main sequence
- the top is called the main sequence turnoff
-

Quiz 4

* The Evolution of a 1 solar mass star
1. - formation - takes about 90 million years
2. - main sequence - hydrogen fusion, ~10,000,000°, lasts 10 billion years
- when core runs out of fuel, it gets cold, and gravity begins to shrink star
- H fusion is also called H burning
3. - core shrinks, but outer layer expands and cools off
- $L \propto R^2 T^4$, T goes down, but R goes up higher, so star becomes brighter
- T goes down by 2 but R goes up to about 100x
- core shrinks until it can no longer, called the electron degenerate limit
- Pauli Exclusion Principle - no two electrons can be in the same quantum state
- i.e. - there is a limit on how close two electrons can be
- called electron degeneracy pressure - electrons resist being compressed
- core will eventually get hot enough so that He fusion starts ~100 million K

* Helium Fusion
- $^4He + {}^4He \rightarrow {}^8Be$ - ^8Be is unstable, but will fuse with ^4He
- $^8Be + {}^4He \rightarrow {}^{12}C$
- called the triple alpha process

* Evolution (cont.)
- core gets hot, so it expands and leaves degenerate state
- star outer layers will shrink in and heat up
- it then becomes a horizontal branch star, because it moves to the left on the HR diagram
- only lasts about 50 million years
- then core starts to shrink again

- outer layers move out
- the star becomes even larger & more luminous
- called asymptotic giant branch - just means star moves in that direction twice
- core never gets hot enough for reactions to stay
- star starts to pulsate in size, so luminosity changes
- it becomes a variable star
- most extreme example - Mira variable stars
- asymptotic stage last only 10,000 years
- eventually, star sheds its outer layers
- core still hot from left over heat ~30,000 K

* Planetary Nebulae
- just outer layers of a dead star
- core becomes a white dwarf
- from second giant to white dwarf in < 10,000 years
- white dwarf eventually becomes black dwarf & black dwarf ≠ brown dwarf
- black dwarf is core of dead star, or cooled white dwarf
-

Quiz 4

* Evolution of Massive Stars
- limit of mass of white dwarf = Chandrasekhar limit
- more massive stars evolve faster
- in 1 $M_\odot$ stars on main sequence, proton-proton chain occurs
- in a high mass star, the CNO cycle occurs

* CNO Cycle
- Carbon Nitrogen Oxygen
- $^{12}C + {}^{1}H \rightarrow {}^{13}N$
- $^{13}N \rightarrow {}^{13}C + e^{+} +$ neutrino
- $^{13}C + {}^{1}H \rightarrow {}^{14}N + {}^{1}H \rightarrow {}^{15}O \rightarrow {}^{15}N + e^{+} +$ neutrino $\rightarrow$ $^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$
- ^{12}C is a catalyst because it is not used up
- net reaction is $4\,{}^{1}H \rightarrow {}^{4}He$

* Evolution (cont.)
- when core runs out, it shrinks
- outer layers are shed & cool off
- star moves to the right, luminosity stays the same
- it then it a supergiant
- core heats up, triple alpha process happens
- it moves to the left
- since it is more massive, carbon fuses with helium
- $^{12}C + {}^{4}He \rightarrow {}^{16}O$
- it would then cool off again, and become hot
- $^{16}O + {}^{4}He \rightarrow {}^{20}Ne$
- if its hot enough, $^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg$ and $^{24}Mg + {}^{4}He \rightarrow {}^{28}Si$
- this set of reactions is called alpha capture
- these are the dominant reactions, but others happen
- side reactions produce odd numbered elements
- as you go up periodic table, it takes more energy to fuse

- heavier chemical elements are produced by more massive stars
- alpha capture continues up until ^{52}Fe
- $^{52}Fe + {}^{4}He \rightarrow {}^{56}Ni$ unstable $\rightarrow {}^{56}Co$ unstable $\rightarrow {}^{56}Fe$
- if you fuse anything with ^{56}Fe, energy is lost
- every time reaction period stops, the core gets colder and shrinks
- the ^{56}Fe reaction cools down core and it continues to shrink
- core collapses down beyond electron degeneracy limit (mass core > 1.4 $M_\odot$)
- this happens because electrons fuses with protons
- $e^- + p^+ \rightarrow n +$ neutrino
- net effect → ball of neutrons
- called a neutron star
- > 1.4 $M_\odot$, but only about 20 km across
- very dense object
- before collapse, shells of reactions happen
- as chemicals get heavier, times of fusions get smaller
- core collapses until neutron degeneracy limit
- limit how close neutrons will come together
- collapse will stop
- upper limit for this force is 3 $M_\odot$, any higher, and a black hole forms
- collapse happens so fast, it gets too compressed
- this causes it to bounce back
- outer material shrinks, and if it hits bouncing core, then a supernova happens
- during supernova explosion, heavier chemicals are made because of high energy
- heavy elements, like U, are formed during supernova
- only created during supernova, and supernova are rare events

- few O stars form
- only ≈ 6 SN in Milky Way galaxy around last 1000 years
- abundance of elements in universe changes with time
- during a supernova, the star will increase in brightness by 10^6 times
- a supernova in its peak is about $10^9 L_\odot$
- ≈ 100 supernovae seen in other galaxies per year
- SN1987A was a blue supergiant
- after supernova, core can remain behind as a neutron star, it could become a black hole, or core can be destroyed
- some neutron stars are also pulsars
- a pulsar has regular pulses of light
- neutron stars have strong magnetic fields
+ laws of Electricity and Magnetism
- a moving charged particle will get trapped and spiral along a magnetic field line
- moving charged particle itself produces magnetic field
- a moving charged particle that is accelerated produces light
- called synchrotron radiation (in the direction of motion of moving charged particle)
- if Earth is in path of that light, we seeing blinking effect
- pulsars may not be lined up towards us, so we wouldn't see them
- synchrontron radiation is strong in radio
- Jocelyn Bell discovered pulsars
- nickname for pulsars is L.G.M, or little green men

Apr 4

* Mass Transfer Binary Stars
- disk of gas around star is called accretion disk
- when the one star looses mass, the star will cool down and evolve more slowly, however, the star getting mass evolves faster and moves up the HR diagram (the main sequence)
- star moves because of mass transfer
- Algol is eclipsing binary star, but has been a mass transfer binary star
- Algol is BV + GIII, B is more massive
- in binaries, we assume stars formed at same time
- GIII was originally more massive
- there is a special point, the Lagrange point, in which gravity is equal
- the point is closer to the less massive star in the pair
- this point is not same thing as center of mass
- center of mass is closer to more massive star
- if a star expands out past the L point, then mass transfer happens
* White Dwarf in Mass Transfer Binary
- white dwarf is mostly carbon, He, oxygen, maybe Ne
- no reactions are happening
- can be up to 1.4 $M_\odot$ - Chandrasekhar limit
- ≈ size of Earth or few larger
- about 10^6 g/cm^3
- gas going around gets hot & nuclear reactions happen
- a nova is a flare of nuclear reactions on a white dwarf
- during a nova, the star can get 10 to 100,000 times
- if star becomes overloaded, then a supernova occurs

- this kind of SN is a SN-type I
- type II is explosion of a massive star
- type II has strong hydrogen lines
- type I don't have strong H lines

* Neutron Stars in Mass Transfer Binary Stars
- gas falling into it gets hot and reacts
- x-rays are usually formed from the reactions
- called x-ray bursters
- alot of energy is involved

* Gamma Ray Bursters
- thought to be related on creation of black holes
- sudden bursts of γ rays
- GRB was not localized the plane of galaxy
- coming from very distant galaxies
- most luminous objects in universe, about 100x of a supernova
- could be that neutron stars orbiting around each other merge and give this light off
- also could be a really massive star whose core collapse to black hole + a hypernova occurs

* Einstein's Theory of General Relativity
- photons of light feel gravity from other objects
- mass of photon = 0
- verified experimentally
- first experiment was done in 1990 during solar eclipse
- light from stars behind sun should be bent due to sun's gravity - Einstein predicted
- during eclipses, stars can be seen near suns
- gravitational arcs - we could see the same star 4 times in 3-D space because an object in front bends light

- we would see galaxies with arcs around it
- the presence of mass in the universe warps the universe and distorts space

2. Black Holes
- no object can escape gravity field, not even light
- everything is compressed to a single point called the singularity
- singularity has density of ∞ because its radius is 0
- event horizon - boundary of black holes influence
- the bigger the mass, the bigger the radius
- the Schwarzschild radius is distance from event horizon to singularity
- a black hole of Earth is 1cm event horizon radius
- Jupiter - 3 meters, Sun - 3 km
-

Quiz 4

* Strange Phenomena Near Black Holes
- Schwarzschild radius $\propto$ mass of BH
- $1 M_\odot$ BH = 3 km R_{SCH}
- light from background stars would be very distorted
- very strong tidal forces
- can rip things apart even outside of event horizon
- tidal forces are the fractional difference between forces
- a BH of $10^6 M_\odot$ to survive tidal force
- time runs more slowly in a stronger gravitational field
- mass warps time & space
- proven experimentally
- clocks in space run faster because they are in a weaker field
- light from nearby stars is redshifted or blueshifted, not a Doppler Shift
- it is a gravitational shift, verified by studying white dwarf stars

* Wormholes
- a break in space where you go in & come out somewhere else
- go in the black hole and go out the white hole

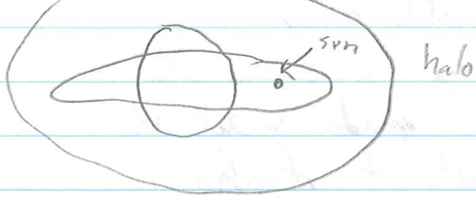
* How To Find A Black Hole
- one can see the gravitational effect on other objects
- as in a binary star with one a BH, thus it is a single-lined spectroscopic binary
- one could also look for X-rays
- Cygnus X-1 - single-line SB, strong x-ray sources, mass of invis object is at least 10 $M_\odot$, meaning it must be a black hole

- the BH at the center of Milky Way is 2×10^6 $M_\odot$
- it is called Sagittarius A*
- to measure, we some get Doppler shift or proper motion
- almost all massive galaxies have black holes in the center in range to 10^6 to 10^9 $M_\odot$
- light varies on very short timescales, like minutes or hours
- this means the physical size of object is small
- very high luminosity from very small region, best explanation is accreation disk around BH

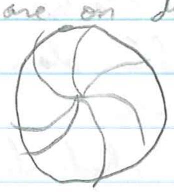
* Jets of Particles from BH
- some BH have these jets
- the jets can be millions of LY in length
- these are called radio galaxies
- BHs of same mass may or may not produce jets
-

Quiz 5

* The Structure of the Milky Way
- 100,000 LY across (about 30K parsecs)
- 3.26 LY = 1 parsec
-



- interstellar clouds are confined to the disk
- newer stuff is in disk, older stuff is in bulge & halo
- H II regions are on disk, because they are around new stars
- face on



- may be a bar inside of galaxy
- star formation happens in spiral arms
- planetary nebulae can be found in bulge, disk, & halo
- white dwarfs can be found throughout
- supernova type II can be in disk
- SN type II is a star that collapse
- SN type I found in all
- mass-transfer system with white dwarf that exploded is SN type I
-

Quiz 5

* Distances
- to get distance to an object, use stellar parallax and spectroscopic parallax
- a third way is to use variable stars
- pulsating variable stars change their opacity
- light can't escape, so star expands until it can escape, and star cools + shrinks

* Variable stars
- Mira variable - asymptotic giant branch stars
- period can be off + variation changes
- RR Lyrae + Cepheid variable stars are easier to get distances from; are hotter
- they lie on instability strip, which starts above A stars
- goes up diagonally up to G (off of Main sequence)
- RR Lyrae are at bottom - about 100 $L_\odot$
- Cepheid have a range of luminosity
- look at light curve to determine which is which
- graph is sawtooth shape, but RR Lyrae can be about a day, and Cepheid is about 1-100 days (period)
- as L goes up, period goes up on a Cepheid star
- 2 types of Cepheid - type I has chemicals like our sun, type II has very low amounts of heavier elements

* Historical Background
- before 1500s, Earth was thought to be center of universe
- Copernicus challenged idea by saying sun is center of universe
- in 1610, Galileo used telescope to look at Jupiter and saw moons
- saw Venus like the moon with its phases
- saw Milky Way and saw many more stars

- galaxy was bigger than thought
- William Herschel tried to make 3-d maps of galaxy in 1785
- he counted stars through about 3,000 places in the sky
- he tried to estimate magnitude
- he assumed that all stars were the same luminosity as the sun
- used inverse square law of light to estimate distance
- he didn't know about interstellar dust though and
- assumed was in the center
- 1838 - stellar parallax was measured by Frederich Bessel
- 1908 - period/luminosity relation for Cepheid variables discovered by Henrietta Leavitt
- 1917 - Harlow Shapley used relation to measure distance to globular clusters within Milky Way (old clusters)
- 3D distribution of center was centered on Sagittarius
- he concluded that sun was not center of galaxy
- he also concluded that galaxy was about 10 times bigger than what people used to think
- 1930 - existence of interstellar dust by Robert Trumpler
- he studied open clusters (young), found in disk
- he used two methods, assumed they had the same total luminosity, & used $b \propto \frac{L}{D^2}$
- second method is he assumed they had about the same angular size
- to his surprise, he got different distances
- first method distances were bigger than second method
- he neglected interstellar dust
- so because they were dimmer, he thought they were further away

- dust doesn't affect angular size much
- 1^{st} evidence for lots of dust absorption
- the spiral things were called spiral nebulae, some thought they were small objects within our galaxy, some said they were outside of galaxy
- 1916 - Adrian van Maanen claimed he could see the spiral rotate on the plane of the sky
- he thought they would have to be rotating at the speed of light
- he concluded they had to be inside our galaxy
- his observations were not accurate
- 1923/24 - Edwin Hubble - observed spirals and realized they were Cepheid variables in the spirals and concluded that they were outside of our galaxy
- they are galaxies also

* Rotation of Galaxies

- rotate about 200 - 300 km/s, compare to 300,000 km/s
- can measure doppler shift velocities
- it takes about 225 million years to orbit Milky Way
- our sun has taken about 20 trips around MW since it was born
- our galaxy has differential rotation
- everything goes around center of galaxy about circular orbit (in disk)
- in bulge + halo, elongated orbits

* Distribution of Mass in Galaxy

- $v^2 = \frac{GM}{R}$
- v is circular velocity, M is mass of object that is being orbited, R is distance
- mass in a radius of 15 K parsecs is 200×10^9 $M_\odot$
- 90 $M_\odot$ = 600×10^9 $M_\odot$
- that means 400×10^9 is missing

- we can measure its gravitational effect, but don't see it
- this is called dark matter
- it is not producing light
- could be big objects that don't produce light
- could also be subatomic particles, not normal matter
- could be a neutralino + axions or supersymmetric particles
- our ideas about gravity could be wrong

Quiz 5

* Formation of Milky Way
- start with a large interstellar cloud, may be millions of LY across
- it will collapse, fragment, + stars will form
- stars formed are distributed equally in bulge + halo
- gas left over concentrates toward center and spins faster and flattens to a disk
- a new generation of stars form in disk
- other gas clouds could fall into galaxy
- galaxies could also merge

* Types of Galaxies
- spirals -

- barred spirals -

- elliptical - spheroidal balls of stars, no disk, not alot of interstellar matter, mostly old stars, tend to be re
- irregular - don't have a bulge, don't have spiral arms, amorphous blobs of stars and gas, tend to have alot of gas + star formation, have blue tint

* Hubble Types
- are subtypes
- spirals - ratio of bulge to disk, how tightly wrapped arms are
- Sa -

- Sc -

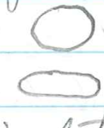
- Sb -

- middle
- Sd -

- have fragments of arms
- Sab - between Sa + Sb
- Sbc - between Sb + Sc
- Scd - between c + d

- barred galaxies
- SB_a –
- SBb –
- SBc –
- SBd –

- also are SBab, SBbc, SBcd
- spirals – classified according to flatness of sphere
- E0 –
- E7 –



- E1 – E6 – in between
- classification used to be done by eye
- Allan Sandage & Gerald deVaucouleurs both cataloged galaxies
- NASA Extragalactic Database contains about 350,000 galaxies
- how a galaxy looks like depends on what ∠ you view it at
- lenticular galaxies look like lenses, in between elliptical & spirals

* Galaxy Interactions
- even normal galaxies interact
- when galaxies collide, stars don't necessarily collide, but clouds do
- interacting galaxies have a lot of new stars
-

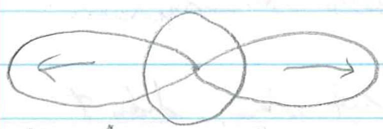
Quiz 5

* The Local Group
- group of 36 galaxies, we are in it
- two biggest galaxies - Milky Way & Andromeda
- M33 is next biggest - "Pinwheel Galaxy"
- Sagittarius Dwarf Galaxy - closest to Milky Way, it is falling into our galaxy
* Dark Matter in Elliptical
- we look at range of velocities for stars orbiting
- the total mass of the galaxy can be calculated with velocities
* Dark Matter in Galaxy Clusters
- galaxies are bound to clusters
- galaxies move like stars in ellipsoidal
- the mass of cluster is 100x that of sum of galaxies' mass
- there is intracluster gas between galaxies, about 1,000,000 K and produces X-rays
- mass of gas doesn't account for dark matter
- cluster holds on to gas by gravity, so DM is there
- from temperature of gas, we can get a limit to mass of clusters
* Active Galaxies
- discovered using radio telescopes
- radio astronomy began in 1932 - Carl Jansky worked at Bell Telephone and noticed hissing on the line
- radio waves were coming from interstellar matter in plane of Milky Way
- accelerated charged particles caused this by synchrotron radiation, which is brightest in radio
- stars are faint in radio waves
- sun was not detected by radio waves until 1942
- happened during WWII, British operators noticed interference

- they noticed it happened during solar flares
- after, they found point sources that weren't in plane of Milky Way
- Allan Sandage - looked for optical counterparts
- he found things that looked like stars
- when he looked at spectrum, he couldn't ID it
- they called them quasi stellar radio sources
  AKA quasars
- he also found objects that looked like stars, didn't emit radio but did have weird spectrum
- called them quasi stellar objects or QSOs
- now used interchangably
- found quasars in 1961
- Martin Schmidt ID lines to elements, but lines were very redshifted
- this means they were moving away from us very fast
- objects are so big, they could not be bound to galaxy
- the further away an object is to us, the faster it is moving
- happens because expansion of universe
- velocity $\propto$ distance
- this is called Hubble's law
- these objects have luminosity of $10^{15}\ L_{\odot}$
- the entire MW galaxy only has $10^{11}\ L_{\odot}$
- about 10,000 times bigger than our galaxy
- they also vary with time, with periods less than a year
- this means they are less than 1 LY across
- we can only explain this by black hole
- BH of a million or a billion solar masses
- these black holes are in center of galaxies
- we can see fuzz around light

- galaxies within the ranges of $10^{15} L_\odot - 10^{6} L_\odot$
are called active galaxies or active galactic nucleus
- nucleus may have $10^{9} - 10^{10}$ $L_\odot$

Types of active galaxies
- Seyfert - spirals with bright nuclei - don't have BH jets
- radio - giant ellipticals with alot of radio emissions
-


charged particles

- the two things are jets coming out of BH
- double-lobed radio galaxies
- we may also see -

- same thing, but we are looking down toward lobes
- some BHs have jets and some don't
- spin of BH may cause material to be flung out
- 2 spirals about the same mass merge, get ellipticals
- the BHs may merge and go faster because of merge
- spiral galaxies just have slower BHs
- spirals have alot of matter, but ellipticals don't
- jets may be smothered by interstellar mass
-

Quiz 6

* Distribution of Quasars

- the closest quasar to us is 240 million parsecs, or 800 million LY
- most quasars are more than a gigaparsec away, or 3.3 billion LY
- there are more quasars per volume of space than nearby
- could be because we live in a special place in space
- more likely, number of quasars in universe has decreased with time
- we are seeing the quasars as they were a long time ago
- this means that the BH at center of galaxy eats up material and then will go black when material is gone
- quasars have evolved to seyfert → radio → normal galaxy
- a problem exists because the universe expands with time
- density of galaxies is going down
- in the past, galaxies were closer together
- they were more likely to interact
-

Quiz 6

* Superclusters
- cluster of clusters
- The Local Supercluster is 40 Mparsecs across or 120,000,000 LY
- contains the local group & the Virgo Cluster
- coordinates are in right ascension & declination
- declination is projection of Earth's latitude lines on sky
- zone of avoidance - it looks like galaxies avoid that part of sky, but dust from MW blocks light
- another SC is the Pisces-Perseus SC, about 80 Mparsecs away
- SC are not balls, they are flattened disks
- a slice of the universe plot maps velocity to R.A. or declination
- the Coma Cluster is about 100 Mparsecs away
- the Great Wall extends very far
- the Voids are places were nothing is seen, about 100 Mparsecs across
- voids are about spherical in shape
- walls are walls of voids
- V = Hd, where H is Hubble's constant
- to get Hubble's constant, you need both V and d
- can get distance from stellar parallax, variable stars, and spectroscopic parallax
- stellar parallax only works for nearby objects

* Astronomical Distance Ladder
- stellar parallax - geometric, accurate up close, only works to about 500 parsecs
- spectroscopic parallax - works up to 10K parsecs

- not as accurate
- variable stars - 40M parsecs
- depends upon previous technique
- standard candle method - uses class of objects for which have about the same luminosities
- used for H II regions, supernova
- measure brightness and use $b \propto \frac{L}{D^2}$
- Hubble's law is last, or expansion of universe

* The Expansion of the Universe

- distant galaxies move away from us
- the space between galaxies is getting bigger
- the redshift from expansion is called cosmological redshift
- galaxies can move relative to space, but space also increases
- true motion in space is peculiar velocity because it deviates from Hubble's law
- Hubble's law assume cosmological redshift
- if galaxy is far away, Hubble's law dominates
- observed velocity for nearby object dominates
-

Quiz 6

* Cosmology
- study of the cosmos or universe as a whole
- expansion of universe is described as $V = Hd$
- Big Bang is the point in time where all matter was at a single point
- age of universe = $t = \frac{1}{H}$
- H is 70 km/s/mparsec, accurate to ±5 km/s/mparsec
- we end up with 14 billion years
- we assume that things did not speed up or slow down
* Was Universe Going Faster or Slower In Past?
- if density of universe is high, then expansion can slow down with time
- dark energy makes universe accelerate
- we can measure amount of dark matter in galaxies, which gives us an upper limit
- 2×10^{-27} kg/m³
* Fates of Universe
- everything slows, then it comes back in on itself
- this is called a closed universe
- happens when there is a high density in universe, but needs to be ≥ 9×10^{-27} kg/m³
- Big Crunch is name of the collapse
- or maybe universe will expand forever
- called an open Universe
- or a flat universe, where it slows down, but doesn't collapse back
- happens at exactly 9×10^{-27} kg/m³
- it is called the critical density
- evidence from cosmic microwave background says universe is expanding
-

* Dark Energy
- thought to push the universe to accelerate
- Einstein applied his general relativity to universe as a whole
- his equations told him that universe is not static
- he found that it had to be expanding or contracting
- he thought that universe didn't change though
- he added a constant to make universe not change with time
- he added the cosmological constant
- he said he made a mistake - "his biggest blunder"
- recently, cosmological constant was added back into equations as a measure of acceleration
- there is a limit on how much space there is in the universe
- in theory, you can come back on itself if the universe is closed
- an open universe is a hyperbolic universe
- flat would be like a sheet of paper
- in a closed universe, angles add up > 180°
- in an open universe, angles add up < 180°

* Lookback Time
- time it takes light from an object to reach us
- that is not the same as distance in LY
- most distant objects have LB time of 9 billion years, but are about 18 billion LY away

* Age of Universe
- 13.7 billion years
- includes acceleration changes
- the observable universe is area of space with a look back time < age of universe
- observable ≠ observed
-

* Olbert's Paradox
- assuming universe is infinite and filled with galaxies, then why isn't sky full of light?
- if you go in a line, you will eventually run into another galaxy
- light needs time to get to us & we can't see outside of observable universe
- universe is finite in time
-

Quiz 6

* The Big Bang
- beginning of universe
- space itself flew out
- multiverse idea is the idea of multiple universes
- there is evidence that Big Bang happened
- one piece is expansion of universe
- another is the cosmic microwave background
- the early universe was filled with light of high energy (gamma)
- it is no longer γ rays, it is now mostly microwaves
- discovered by accident in 1960s by Robert Wilson & Arno Penzias
- they worked at Bell Telephone Labs
- they were testing a microwave antenna being used for satellite communication
- they found a strange signal in every direction
- the radiation is a thermal spectrum, peaks at 1 mm
- 2.7K is it temperature

* Pair Production
- $e^- + e^+ \rightarrow$ gamma rays
- p + anti-proton $\rightarrow$ γ rays
- called pair annilation
- $\gamma \rightarrow e^+ + e^-$
- called pair production
- in the early universe, alot of pair production happened
- as well as annihilation
- proton stopped forming first, then electrons
- protons stopped after 1/10000 seconds after BB
- electrons continued until about a minute into BB
- pair annihilation continued though
- in the end, matter dominated over antimatter
- after 1 minute, nuclear fusion happened

- called primordial nucleosynthesis
- $^1H + n \rightarrow {}^2H$
- $^2H + {}^1H \rightarrow {}^3He$
- $^3He + n \rightarrow {}^4He$
- this different from the proton-proton chain found in stars like the Sun
- neutrons by itself can change to a proton + electron in about 15 minutes
- some lithium was made, but not that much
- other elements were not created in early universe
- nuclear reactions stopped at 15 minutes into BB
- at that point: 75% H & 25% He
- only includes baryonic matter (matter from p + n)
- ratios of elements tell us about early Universe
- ratios are a third piece of evidence
- ^2H abundance gives info on baryonic density in early Universe
- in stars: almost all ^2H is converted
- all ^2H we have now was formed in early Universe
- density of baryons in early Universe $\approx$ 4% of critical density
- critical density = density required to make a closed universe
- doesn't tell us about dark matter
- density from cluster masses $\approx$ 1/3 critical density
- implies dark matter is not baryonic and there is about 10x more of it
- dark energy may provide that the universe is flat
- universe is still ionized after 15 minutes
- ionization stopped after 400,000 years old
- this is called recombination
- CBR peaked at 3000 K at near infrared

- before this point, matter + energy was always interacting
- the universe became transparent at recombination
- matter + energy became decoupled
- when we look at CBR, we are looking at recombination
- CBR is not uniform, but almost uniform
- not sure of exact time of galaxy formation, but it was less than 10^9 years old
-