SCI 238 — Introduction to Astronomy
Final Notes

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1 Chapter 10 – Our Star

1.1 A Closer Look at the Sun

1.1.1 History

Our first views of the sun were that it was a ball of fire. In the 19^{th} century we had found the Sun's radius and distance and found that its energy could not have come from burning fuels or other chemical processes.

The first real idea was that the Sun generates energy by slowly contracting in size through **gravitational contraction**. Gravitational potential energy is converted into thermal energy as mass moves inward. This would keep the inside of the Sun hot. The amount of contraction required would be small enough to go unnoticed until the 19^{th} century. This theory shows that the Sun could continue contracting for 25 million years. The problem: geologists had already calculated the earth's age as much higher than that.

The next idea was based on Einstien's theory of relativity ($E = mc^2$). Calculations showed that the Sun had enough mass to shine for billions of years. This explained where sunlight came from, but not the thermal energy. Eventually in the 1930's the discovery of nuclear fusion was found and we use that to explain where thermal energy comes from.

1.1.2 Nuclear Fusion

Nuclear fusion requires very high temperature and density to start. This started in the sun through gravitational contraction. The sun was formed from a collapsing gas cloud. This released gravitational potential energy raisin the core temperature. This continued to happen until sustained nuclear fusion started.

The sun has a fairly steady size and energy today because it has reached equilibrium. **Gravitaitonal Equilibrium** is the balance between the outward push of hot internal gases trying to escape and the inward push of gravity. This allows the sun to have a steady size. This also means that **pressure increases with depth** in the sun. **Energy Balance** is the balance between the rate of fusion and the rate of energy being released from the Sun's core into space.

1.1.3 Structure

The sun is essentially a ball of plasma (gas in which atoms are ionized) which moves like a gas, but also reacts to magnetic fields.

Basic Properties:

Radius (R Sun)	696,000 km (about 109 times the radius of Earth)
Mass (M Sun)	2 10 30 kg (about 300,000 times the mass of Earth)
Luminosity/Power Output (L Sun)	3.8 10 26 watts
Composition (by percentage of mass)	70% hydrogen, 28% helium,2% heavier elements
Rotation rate	25 days (equator) to 30 days (poles)
Surface temperature	5800 K (average); 4000 K(sunspots)
Core temperature	15 million K

Layers (outside in):

- Solar wind
- Corona
- Chromosphere
- Photosphere
- Convection zone
- Radiation zone
- Core

Solar Winds is a stream of charged particles blown outward from the Sun. These help shape the magnetospheres of planets and the tails of comets.

Corona is suprisingly hot (1 million K) and emits the most X-ray radiation, the density is very low

Chromosphere is much cooler here (10,000 K), radiates UV radiation

Photosphere temperature is 6,000K, surface churns like boiling water, home of sunspots and intense magnetic fields

Convection Zone region of hot gas rising and cool gas sinking caused by energy from the core rising to the surface (called convection, duh)

Radiation Zone less turbulent than the convection zone, energy moves outwards as photons instead of hot gas, temperature rises to 10 million K, shit ton of X-ray radiation

Core where nuclear fusion is making energy, temperature 15 million K, density 100 that of water, pressure 200 billion times earth's surface, energy takes hundreds of thousands of years to get to the surface

1.2 Nuclear Fusion in the Sun

Note nuclear fusion (the Sun) $\neq$ nuclear fision (nuclear reactor).

Within the Sun's core there is a soup of hot fas funn of psitively charged atom nuclei flying about. When these collide (most of the time electormagnetic forces deflect them) they stick together to form a heavier nucleus. This is caused by **strong force** (binds protons and neutrons together) overriding the electromagnetic deflection force. It's only strong enough to do this at very small distances which happens due to the high speed of the particles (which is in turn caused by the high temperature which is caused by the high pressure which is caused by high gravitational force which is caused by large mass).

This is explained by the **Ideal Gas Law**

$$P = nkT$$

where P is the pressure, n is number density (particles per volume), T is temperature, and k is **Boltzmann constant** $= 1.38 \times 10^{-23}$ joule/K

1.2.1 Proton-Proton Chain

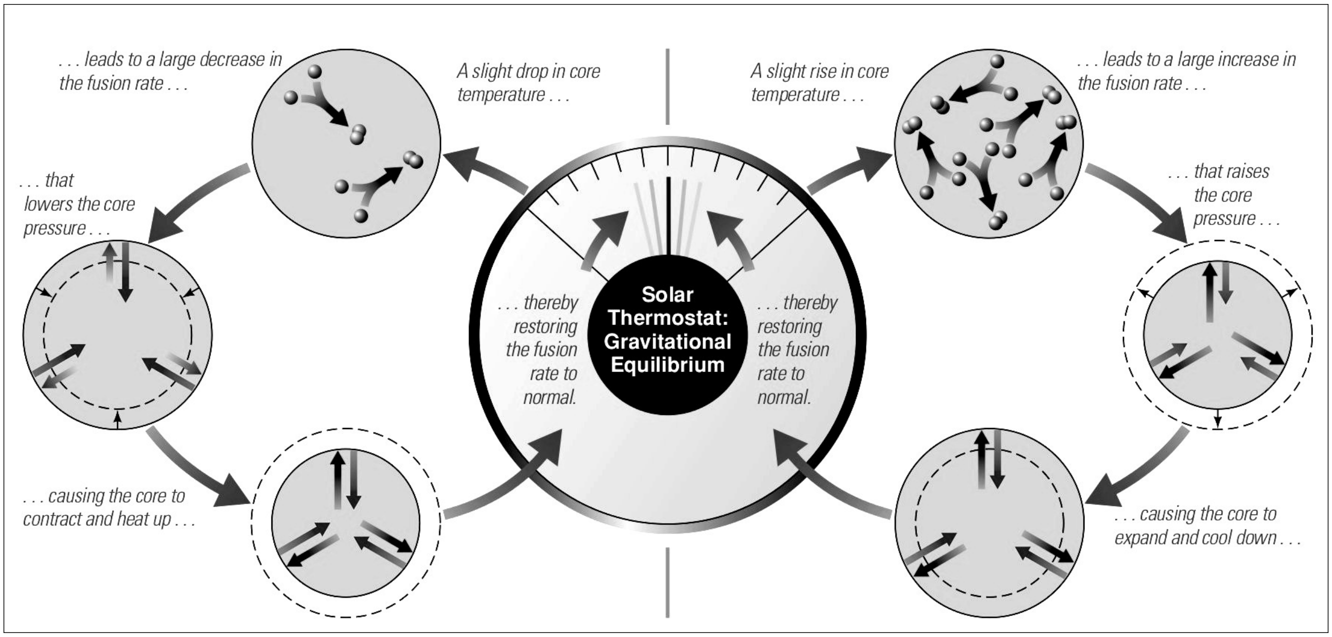
Most hydrogen comes in the form of a single proton, but we need to fuse it into a helium atom which is two protons and two neutrons. So what we have to do is fuse four hydrogen atoms into one helium atom. This is through a sequence of events called the **proton-proton chain**.

1. Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice
2. The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step occurs twice
3. Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

In total four protons collide to make a helium atom, two positrons, and two neutrinos.

1.2.2 Solar Thermostat

Life on earth relies on the Sun's steady fusion rate. If we were to increase the core's temperature slightly, this would cause an increase in fusion rate. The increased fusion rate would make more energy, but energy moves very slowly through the sun so it would get bottled up in the core. This would increase the core pressure to exceed the balancing force of gravity so the core would expand and cool. Cooling lowers the fusion rate and equilibrium is reached again.



1.2.3 Path of Energy Through the Sun

Energy starts as photons in the Sun's core. They zigzag at the speed of light so it takes them a while to get out. In the dense interior a photon can only ravel a fraction of a millimeter before it collides with electron and gets deflected in a new direction causing its zigzag path. Eventually it makes its way through the core and radiation zone into the convection zone where the temperature drops to 2 million K and the photon is absorbed into cooler solar plasma. This creates the convection that happens in the convection zone. Eventually it rises to the top and enters the photosphere. Here the density is low enough that photons can escape into space as sunlight.

How do we know about the interior of a star:

- Mathematical models: based on laws of physics and observed properties
- Solar Vibrations: the Sun's surface vibrates like with earthquakes which we can see in Doppler Shifts.
- Solar Neutrinos: these are formed during nuclear fusion, these can pass through almost anything without reacting (including the Sun's layers), so we can see whats going on right now (well, 8 minutes ago)
  - these fuckers are hard to catch, need detectors deep in mines
  - initially we only caught a third of what we expected (solar neutrino problem) due to neutrinos changing properties during their journey (electron neutrino, muon neutrino, or tau neutrino)

1.3 The Sun-Earth Connection

1.3.1 Sunspots and Magnetic Fields

Sunspots are dark spots on the sun where things are cooler. They are formed when magnetic fields keep hot gas from entering a section of the photosphere. Magnetic fields can alter the energy levels of atoms (Zeeman effect), mucking with their spectral lines. The particles in solar plasma move along magnetic lines (usually spiraling along them).

Sunspots form where magnetic fields extend from the Sun's interior. The magnetic lines there are strong enough to suppress convection making the spot cool. They usually last a few weeks until their magnetic fields weaken. Sunspots tend to appear in pairs connected by a magnetic loop. Gas getting trapped in these loops makes **solar prominences**.

1.3.2 Solar Storms

These are sudden changes in the Sun's magnetic fields. The most dramatic example is **solar flares** which send bursts of X rays and fast moving particles into space. Flares tend to happen near sunspots. The current theory is that solar flares are caused when magnetic fields become so twisted they cannot bear the tension and snap into a better shape.

1.3.3 Heating the Chromosphere and Corona

Some weird shit goes down on the sun where its atmosphere gets hotter the farther you go out. The current theory is that magnetic fields carry energy upward to heat the chromosphere and corona.

The churning that happens in the convection zone probably shakes with tightly wound magnetic lines which carry this energy into the atmosphere and deposit it as heat.

Its very hard to investigate this because the solar atmosphere is not dense enough to see at that point (except during an eclipse). We can watch them through X-rays and UV rays.

In X-ray images of the chronosphere:

- bright spots is where hot gas is trapped below a sunspot where magnetic lines loop back to the Sun
- dull spots (**coronal holes**) are under magnetic lines that escape into space
- the stuff blown out by flares are huge bubbles called **coronal mass ejections**
  - have strong magnetic fields
  - causes auroras
  - fuck with satellites

1.3.4 Solar Cycles

Sunspots have a 11 year cycle. The solar maximum has most sunspots and solar minimum has fewest. At each solar maximum the Sun's magnetic fields start to flip. This is because all magnetic lines connecting pairs of sunspots point the same direction. This means that magnetic fields have a 22 year cycle.

2 Chapter 11 – Surveying the Stars

2.1 Properties of Stars

2.1.1 Luminosity

The **apparent brightness** of a star is how bright it appears to us, or the amount of power reaching us per unit area (units are watts per square meter). The **luminosity** of a start is is the total power that the star emits (units are watts). Apparent brightness follows a inverse square law to distance.

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

The most direct way to measure a star's distance it through measuring its stellar paralax. This is found by comparing a star's shift against its background over 6 months. We calculate its **paralax angle**

$$d = \frac{1}{p}$$

Where d is the distance to that star in light years and p is the paralax angle (Note: 1 arcsecond $\rightarrow$ 3.26 lightyears = 1 parsec)

We tend to measure luminosities as orders of magnitude of our sun's luminosity, called **apparent magnitude** instead of apparent brightness and **absolute magnitude** instead of luminosity. For every 5 magnitudes we have a brightness factor of 100. So a magnitude 1 star is 100 times brighter than a magnitude 6 star. We define the absolute magnitude as the apparent magnitude if owould have itf it were at a distance of 10 parsecs.

2.1.2 Temperature

The temperature of a star usually means its surface temperature since its the easiest to measure. A star's temperature is easier to measure than luminosity since it does not vary with distance. We can measure a star's temperature with reasonable accuracy by measuring its color. This is done by comparing its apparent brightness in two different colors of light (usually blue and red).

We run into problems when interstellar dust interferes with the color of a star so astronomers use a star's spectral lines instead. Stars showing spectral lines of ionized elements are fairly hot because it takes high temperature to ionize atoms. In contrast, stars displying spectral lines of molecules are relatively cool. Stars are classified by their **spectral type** OBAFGK in decreasing order of temperature. These are often divided farther using numbers. For example our sun is a G2 star meaning its hotter than a G3 but cooler than a G1.

Type	Example(s)	Temp.	Key Absorption Line Features	Brightest (color)
O	Stars of Orions Belt	>30k K	Strong ionized He, weak H	>97 nm (ultraviolet)
B	Rigel	30k-10k K	Strong neutral He, some H	97-290 nm (ultraviolet)
A	Sirius	10k-7.5k K	Very strong H	290-390 nm (violet)
F	Polaris	7.5k-6k K	Some H, some ionized Ca	390-480 nm (blue)
G	Sun, Alpha Cent. A	6k-5k K	Weak H, strong ionized Ca	480-580 nm(yellow)
K	Arcturus	5k-3.5k K	some metals, some molecules	580-830 nm (red)
M	Betelgeuse, Prox. Cent.	<3.5k K	Strong molecules	> 830 nm (infrared)

History of Spectral Types Spectral types were made at Harvard College by Edward Pickering's computers (women who'd studied physics or astronomy). The first was Williamina Flemming who classified A-O by the descending strength of hydrogen lines. Annie Jump Cannon modified this existing classification by reordering and removing classes until the OBAFGKM that is used today was left. Finally Cecilia Payne-Gaposchkin discovered that stars were all made of the same material and the lines reflected ionization levels which indicated surface temperature.

2.2 Mass

Measuring mass is very difficult and we can only really do it on binary star systems. We do this by applying Newton's version of Kepler's third law

Binary star types:

- **visual binary:** we can see each star distinctly, sometimes one star is too dim to see but we can observe the shift of the visible star
- **eclipsing:** a pair of stars that orbit in a plain of our line of sight, we rotate between seeing the combined light of both stars (no eclipse) and only the light of one star (full eclipse)
- **spectroscopic:** we need to use Doppler shifts to detect its nature

2.3 Patterns Among Stars

These are ways of charting stars, the x-axis is the surface temperature (OBAFGKM) and the vertical axis is luminosity (L_{sun}) on a logarithmic scale. We can also infer the star's radius from the chart because a star's luminosity is based on its surface temperature and radius.

$$L = 4\pi r^2 \times \sigma T^4$$
$$\sigma = 5.7 \times 10^{-8} W/(m^2 \times \text{Kelvin}^4)$$

Where L is luminosity, r is radius, σ is amount of thermal radiation emmited per unit area constant, and T is the star's temperature. This means that the radius of a star increases along a diagonal from lower left to upper right.

Stars cluster on the H-R diagram:

- **main sequence:** streak running from upper left to lower right
- **supergiants:** upper right
- **giants:** between supergiants and main sequence
- **white dwarfs:** lower left

Like with spectral classes, astronomers assign luminosity classes describing the region of the H-R diagram that a star falls in. I is for super giants, III is for giants and V is for main sequence. II and IV are for those that fall inbetween. White dwarfs fall outside the classification and are called wd. Stars with higher luminosity have larger radii as well.

We combine spectral type and luminosity class together to identify stars.

2.4 Main Sequence

Main sequence stars are the majority of stars that we observe and because of that we have found more patterns within them. Mass increases as we go up the strip of main sequence stars on the H-R Diagram. We also see that low mass stars are much more common than high mass stars. Mass is the most important attribute of hydrogen fusing stars because it determines the balance point at which energy released by fusion equals the energy lost from the star's surface. This is what allows for the wide range of luminosities. Luminosity is very sensitive to mass (example a star 10 times as massive as the sun is 10000 times as luminous).

A luminous star must be very hot or very large. But a very small mass change is required to greatly increase the luminosity of a star, so their surface temperature must be much higher to account for this large increase in luminosity. This fits the H-R Diagram pattern of temperature increasing with luminosity. We can use the mass-luminosity-temperature relationship to estimate a star's mass just by knowing its spectral type.

A star is born with a set amount of hydrogen fuel, the amount of time that it can burn this fuel for is the star's **main sequence lifetime**. Lifetime is inversely proportional to the mass of the star. This is because as mass increases luminosity increases exponentially, so stars with higher masses may have more fuel but they burn it waaaay faster.

2.5 Giants, Supergiants, and White Dwarfs

2.5.1 Giants and Supergiants

These are much cooler but more luminous than the sun which tells us that they are huge. These stars have almost exhausted their hydrogen fuel supply and are trying not to collapse under their own weight. They do this by releasing fusion energy at a high rate which explains their high luminosity, and the need to radiate all this energy expands them to enormous size.

2.5.2 White Dwarfs

This is what happens when a giant runs out of fuel completely. The star ejects all of its outer layers and is left only with a dormant core. They are hot because they are still the core of a star, but dim because they have no way to radiate their energy.

2.6 Star Clusters

Stars are born from giant clouds and many stars can be born from the same cloud, so they tend to cluster.

- all stars in a cluster are about the same distance from earth
- all stars in a cluster are about the same age

2.6.1 Types of clusters

- **open cluster:** found in disk of galaxy, young stars, up to several thousand stars, about 30 light years across
- **globular cluster:** found in halo of galaxy: oldest stars, more than a million stars, 60-150 light years across

2.6.2 Age of a Cluster

We plot a cluster's stars on the H-R Diagram, and this tells us its age. For instance the Pleides open cluster has no stars of the O spectral class. This means that Pleidas is old enough that its O stars have finished their hydrogen fission and 'died'. We call the point at which a cluster's main sequence diverges from the standard main sequence the **main sequence turnoff**. The age of the cluster is equal to the lifetime of stars at its main-sequence turnoff point (at its most massive star).

3 Chapter 12 – Star Life Cycle

All elements heavier than hydrogen and helium were created through fusion or supernova

3.1 Star Birth

gravity causes a gas cloud to contract until center is hot enough to sustain -fusion heat generated from gravitational potential clouds internal gas pressure resists gravity

gravitational equilibrium: gas pulling inward matches pressure pushing out, star size is stable two factors: 1. higher density, more material per space (still low enough to be strong vacuum on earth) 2. lower temperature, reduces pressure (typically 10-30 K)

$M_min = 18 * M_Sun * sqrt(T^3/n)$

T = temp of gas in K n = density of gas in particles per cubic meter

referred to as molecular clouds, cold enough for H atoms to pair up very large, many stars generally born in simulatneous clusters

3.1.1 Protostar Stage

as it compresses gas starts to heat up, lumpy clumpy shape energy radiates away until its dense enough to trap heat, temp rises hard still not hot enough for fusion rotate rapidly from conservation of momentum of particles flattens to a disk from particle collisions (plantes may form here eventually) may shoot jets perpindicular to disk (not sure why, suspect magnetic fields due to rotation) field also generates protostellar wind (stronger version of solar wind) wind and jets shed momentum by expelling material, slowing rotation

angular momentum also cause of binary star systems (stars form close together, orbit instead of crash, more momentum = larger orbit)

becomes true star at 10 million K, continues to rise until balance achieved (energy from fusion = energy radiated) time to reach main sequence phase proportional to mass, large stars are faster

stars range in size, over 99% are within 0.5 and 2 M_Sun (leaning below 1) large ones burn out faster

stars cant be more than 300 M_Sun because it would blow off its outer layers cant be less than 0.08 M_Sun or it wont get hot enough, stabilizes as a brown dwarf brown dwarf gravity collapse halted due to degeneracy pressure, restriction on how close elections can be together

3.2 Low Mass Stars (< 8 M_sun)

Main-Sequence stage 90% of star's lifetime star regulates itself: if fusion works too fast, core expands until it cools again

3.2.1 Red Giant stage

when core hydrogen is depleted, fusion will cease no more radiation pushing outwards, core shrinks from gravity core is inert helium, small shell of hydrogen around it fuses (higher rate than core), outer layers expand star is 100 times larger and 1000 times brighter than main sequence stage weaker gravity at surface, increased stellar wind fusion shell makes more helium, core gets heavier and shrinks more, shell gets even hotter and denser

3.2.2 Helium Core Fusion stage

feedback loop until core reaches 100 million K, helium start fusing into carbon at this point thermal pressure is too low (gravity is fucking intense) core sustained by degeneracy pressure, which does not increase with temperature helium fusion heats the core without causing it to inflate, fusion rate spikes (called helium flash) so much so that thermal pressure becomes dominant and core increases in size, lowering temp and fusion outer layers shrink again, stabilizes back at yellow this stage is short, 1% of star lifetime

3.2.3 Last Gasps

when helium runs out carbon core shrinks again outer layer expansion again from helium shell fusion (hydrogen shell still going, core double layered) now even larger than red giant stage star is too low mass to fuse carbon, will not reach 600 million K too large for its mass, gravity too low on surface, outer layers start being blown off forms planetary nebula (nothing to do with planets), bright glowing ring will combine into interstellar dust when cooled exposed core remains as a stable white dwarf, gas recycled into a new star will cool until it no longer emits light, then sit in the dark of space

3.3 High Mass Stars

3.3.1 Hydrogen Fusion

once in main stage, protons can slam into carbon, nitrogen, oxygen molecules with enough energy follows CNO cycle of fusion and decay 1. C12 + H -¿ N13 2. N13 -¿ C13 3. C13 + H -¿ N14 4. N14 + H -¿ O15 5. O15 -¿ N15 6. N15 + H -¿ C12 + He4

this cycle allows hydrogen fusion to proceed much faster than proceed much faster than typical proton chain (more valid things to bump into) makes these stars much brighter, lives much shorter

3.3.2 Becoming a Supergiant

reaches hydrogen fusing shell stage much faster, outerlayers expand temperatures so high that degeneracy pressure never takes over, no helium flash (gradual, like hydrogen was) fuses helium into inert carbon core in just a few thousand years core fusion stops, core shrinks, helium shell forms, surface expands alternates between shrinking and expanding as core reaches next level of fusion hydrogen ¿ helium ¿ carbon ¿ oxygen ¿ neon ¿ magnesium ¿ silicon ¿ iron the biggest stars transitions so quickly other layers dont have time to resond, become red supergiant

eg Betelgeuese, Orion's left shoulder. 500 solar radii, 2 AU

3.3.3 Heavier Nuclei

simplest heavy fusion is helium-capture reaction 1. C12 + He4 -¿ O16 2. O16 + He4 -¿ Ne20 3. Ne20 + He4 -¿ Mg24 note that each transition upwards drains the core and causes another shell to form all shells will be active simultaneously once hot enough, can start fusing those heavy nuclei 1. C12 + O16 -¿ Si28 2. O16 + O16 -¿ Si31 + H 3. Si28 + Si28 -¿ Fe56

3.3.4 Iron, the Dead End

iron is the only element where it is not possible to generate nuclear energy, fusion or fission lowest mass per nuclear particle of all elements iron core can only resist gravity through degeneracy pressure, but more iron keeps piling on then gravity pushes past the quantum mechanical limit

3.3.5 Supernova

electrons disappear by combining with protons to form neutrons, realeasing neutrinos iron core with a mass near M_Sun and radius larger than Earth collapses into a ball of neutrons just a few kilometers across in a fraction of a second stops due to neuton denegeneracy pressure this neutron star is similar to an atom nuecleus the size of Kitchener the gravitational collapse of the core releases an enormous amount of energy, more than 100 times than the Sun will radiate over its entire 10 billion year lifetime old theory was that supernova was caused by matter collapsing into neutron star and bouncing new theory is collapse causes so many neutrinos to be formed that, despite how rarely they interact with matter, entire star is blown away so hot that it's as bright as moderately sized galaxies for a few weeks, continue to expand and cool will eventually be incorporated into new stars in other gas clouds

Crab nebula is remnant of supernova from 1054 AD

if gravity is still strong enough to overcome neutron degeneracy pressure, collapses continues further to a black hole

interesting note: due to larger stars dying and adding heavier elementss to the interstellar dust, newer stars have higher percentages of heavy elements than older stars (2-3% vs 0.1%)

interesting note: most heavy elements are made in helium capture which adds two protons, so even numbered elements are more abundant in the universe

3.4 Binary Systems

the two stars exert tidal forces on eachother, create football shapes when the more massive star begins to expand, the gas on the surface experiences strong pull to the other star than its own core, begins a mass exchange may transfer back when "soon to be as or more massive" star begins expanding too

4 Chapter 13 – White Dwarfs, Neutron Stars, Black Holes

To scientists, dead stars are ideal laboratories for testing the most extreme theories of general relativity and quantum theory.

4.1 White Dwarfs

4.1.1 What is a white dwarf?

A white dwarf is essentially the exposed core of a low-mass star that has died and shed its outer layers in a planetary nebula. It is quite hot when it first forms (it was the inside of a star) but it slowly cools with time. White Dwarfs have masses like those of stars but sizes like that of Earth which is why they are generally quite dim compared to stars like the sun. THe hottest white dwarfs can shine brightly in high-energy light such as ultraviolet and X-rays.

A white dwarf's combination of starlike mass and a small size makes gravity near its surface very strong. Because there is no fusion to maintain heat and pressure, **degeneracy pressure** combats the gravitational force. The same pressure supports brown dwarfs, it arises when particles are packed as closely as the laws of quantum mechanics allow. More specifically, in white dwarfs arises from electrons so it is called **electron degneracy pressure**

4.1.2 Composition, Density and Size

Composition of a White Dwarf reflects product's of stars final fusion stage. A white dwarf from something resembling our sun would consist mostly of carbon. (stars like the sun fuses helium into carbon in final stage of life). The **bf denisty** of a white dwarf is so high that a teaspoon of its material would weight several tons. More massive white dwarfs are also smaller in size (the most massive being the smallest). The more massive a white dwarf is, the greater gravity compresses matter to a much greater density. Electrons in a white dwarf respond to compression by moving faster.

4.1.3 The White Dwarf Limit

The fact that electron speeds are higher in more massive white dwarfs leads to a fundamental limit on the maximum mass of a white dwarf. The **White Dwarf limit** is $1.4 M_S un$ because anything larger than this would have electrons moving faster than the speed of light. Also called Chandrasekhar limit. In every observed case this limit holds true.

4.1.4 White Dwarf in a binary System

A white dwarf in a binary system can slowly gain mass if its companion is a main sequence of giant star. Matter coming from the other star forms a whirlpool like disk as it makes its way to the White Dwarf's surface (called an **accretion disk**). In this way, a white dwarf can get Hydrogen.

Novae: Hydrogen spilling towards the white dwarf heats up. If the temperature reaches 10 million K hydrogen fusion suddenly ignites. This thermonuclear flash causes the binary system to shine for a few weeks as a nova. (far less luminous than a supernova but can still shine as brightly as 100,000 suns). Accretion resumes after nova explosion subsides so process can repeat itself

White Dwarf SuperNovae: Through repeating the previous process it is believed that a white dwarf gains mass. When it reaches the **white dwarf limit** carbon fusion begins and explodes completely into what we call a **White Dwarf Supernova**. This is however quite different from a **massive star supernova**. Both shine with luminosities of 10 billion times that of the Sun but white dwarfs supernovas fade steadily and massive stars are more complicated. White Dwarf supernovas also lack hydrogen lines.

4.2 Neutron Stars

4.2.1 What is a neutron star?

A ball of neutrons created by the collapse of the iron core in a massive star supernova. Typically 10km in radius yet more massive than the sun. **Neutron degeneracy pressure** supports neutron stars. The gravity on the surface makes the escape velocity about half the speed of light. Neutron stars spin rapidly when they are born and strong magnetic fields can direct beams of radiation that sweep through space.

4.2.2 How were they discovered?

First observational evidence 1967, radio waves at precise intervals (now refered to as **pulsars**). Signal came from gaseous remains of supernova. It was a neutron star, pulsations arise becuase of conservation of angular momentum (rotation increases as size decreases). Neutron star's rotation slows over time. **Pulsars** must be neutron stars because no other object could spine that quickly without tearing itself apart. White Dwarf 1/sec. Pulsar as fast as 625/second.

4.2.3 Neutron Star in a binary System

Like white dwarfs, neutron stars can burst back to life. Due to stronger gravity, the accretion disk on a neutron star is much hotter and denser than a white dwarf's. High temperatures in inner regions of the disk make it radiate powerfully in x-rays. Due to this emission these are often called **X-ray binaries** and hundreds have been detected in the Milky Way. Pulsars of X-ray binaries accelerate with time, some rotating every few thousandths of a second. (called **millisecond pulsars**).

Helium fusion can happen at a layer of the disk builds to 100 million K. Helium fuses rapidly and generates an **X-ray burster** which lasts a few seconds and flares every few hours to every few days. Energy relased is 100,000 times more powerful than sun output, all in X-rays. After burst, accretion resumes.

4.3 Black Holes

4.3.1 What is a Black Hole?

A black hole is so compact that it has an escape velocity greater than the speed of light, neither light nor anything else can escape from within a black hole. They are actually spherical and not funnel shaped.

The Event Horizon: The boundary between the inside of a black hole and the universe outside is called the event horizon. It marks the point of no return for objects, the boundary at which escape velocity equals the speed of light. Gets the name because we have no hope of learning about events that occur within it.

The **size** of a black hole is usually the size of its event horizon, defined by the **Schwarzschild radius**. Black hole with mass of the Sun has a Schwarzschild radius of about 3km. More massive black holes have a larger Schwarzschild radius.

A collapsing stellar core becomes a black hole at the moment it shrinks to a size smaller than its Schwarzschild radius.

Schwarzschild radius:

$$R_s = \frac{2GM}{c^2}$$

4.3.2 Singularity and Limits of Knowledge

Because nothing can stop the crush of gravity in a black hole, we might expect all matter that forms a black hole must ultimately be crushed to an infinitely tiny area and dense point in the center called a **singularity**

According to Einstein's theory from your point of view a friend would never cross the event horizon even though he would vanish from view due to redshifiting. You would not survive to cross the event horizon due to gravity, however with supermassive black holes, tidal forces are weaker so it would be possible to enter the event horizon.

4.3.3 Formation of a Black Hole

Most massive stars may not succeed in blowing away all upper layers in supernova. If enough mass falls back to neutron star, it could exceed neutron star limit (3M Sun). Gravity would exceed degeneracy pressure and core collapses again with no known force to keep it from collapsing into a black hole.

4.3.4 Observational Evidence

Gravity alters its surroundings. Compelling observational evidence comes from studying X-ray binaries, some may contain black holes instead of neutron stars. The trick to learn is by measuring mass.

4.4 Origin of Gamma Ray Bursts

By far the most powerful bursts of energy we observe in the universe. Some appear to come from extremely powerful supernova explosions. A supernova from a neutron star does not release enough energy, however a supernova that forms a black hole (**hypernova**) might be powerful enough to explain it.

4.5 Summary Notes

- Observation evidence exists for white dwarfs and neutron stars, is strong for black holes
- All three can have close stellar companions in which they can accrete matter.
- Black holes are holes in the universe that strongly warp time and space around them. Nature of singularities beyond frontier of current understanding.

5 Chapter 14

5.1 Milky Way

5.1.1 Appearance

The Milky Way Galaxy has over 100 billion stars. It is a vast **spiral galaxy** consisting of spiral arms in a flat disc converging at a bugle in the center. The disc is surrounded by a dimmer halo (it is dimmer because most of the very bright stars are in the disc). The galaxy is 100 000 light years in diameter and 1000 light years thick. Our solar system is about 27 000 light years from the center.

It is difficult to view the galaxy because of clouds of interstellar gas and dust (called the **interstellar medium**) get in the way.

The Milky Way is one of the larger galaxies in our Local Group and its gravity influences smaller galaxies in the area. The Small and Large Magellanic Cloud galaxies actually orbit the Milky Way. Two even smaller and closer galaxies (Canis Major and Sagittarius Dwarf) are in the process of colliding with the Milky Way which will rip them apart.

5.1.2 Stars in Orbit

Stars in the disc of the galaxy orbit in roughly circular paths in the same direction and roughly the same plane. They orbit a bit like marry-go-rounds where the stars orbit the center but also bob up and down as they do. This bobbing happens because of localized gravity within the disc. When a star is to high the disk pulls it downwards, but it overshoots and becomes too low, repeat. The stars at the edge of the galaxy orbit at roughly the same speed as the stars at the center of the galaxy which is what gives it that swirl look.

Stars in the bulge and halo have randomly oriented orbits. Bulge stars move around the galactic center in elliptical paths with random orientations. Halo stars have much more exaggerated orbits, swooping high and low the disc at such high velocities that the disc's gravity barely effects them.

The Orbital Velocity Law:

$$M_r = \frac{r \times v^2}{G}$$

Where M_r is the amount of mass contained with this orbit (kg), r is the radius of the orbit(m), v is the object's orbital velocity (m/s) and G is the gravitational constant ($6.67 \times 10^{-11} \frac{m^3}{kg \times s^2}$).

5.2 Galactic Recycling

Interstellar mass is recycled within the galaxy's interstellar medium. This also changes the composition of the medium (stars make much heavier elements in their deaths).

5.2.1 Gas Recycling

- **atomic hydrogen clouds** - interstellar gas clouds fill the galactic disk
- **molecular clouds** - gas in the disk gradually cools and forms molecules
- **star formation** - gravity makes stars form molecular hydrogen mass
- **nuclear fusion in stars** - fusion in the cores of stars makes new elements from hydrogen
- **hot bubbles** - supernovae and stellar winds return gas and new elements to interstellar space
  - the strong solar winds from supernovae sweep surrounding material into a hot bubble, these continue to expand until the breach the galactic disk where they erupt, the erupted gas cools and rains back down onto the disk
  - supernovae also create shock waves that create walls of fast moving gas that heats and ionizes interstellar gas
- **returning gas** - returning gas cools and then blends into atomic hydrogen clouds
  - longest stage so its where most of the hydrogen lives
  - the matter rained down onto the disk cools and condenses into clouds (these may contain dust grains of carbon or silicon which are what blocks our view)
  - as the cloud cools hydrogen combine into molecules making it a molecular cloud
- repeat
  - in molecular clouds stars are formed
  - these stars' solar wind erode the clouds and keep more stars from forming
  - molecules fall apart and become ionized and join the near by atomic hydrogen clouds

Different parts of the Milky Way are at difference stages of the cycle so we can view the whole cycle via different wavelengths.

- radio emissions show atomic hydrogen (has a 21cm spectral line)
- radio emissions of carbon monoxide show the distribution of molecular clouds
- long-wavelength infrared emissions from interstellar dust show molecular clouds where stars are forming

- short-wavelength infrared emissions show the light from stars
- visible light shows how the galaxy looks and where dust blocks our view
- X-rays show where hot gas bubbles are
- gamma-rays show where gas densities are highest (most number of collisions) in molecular clouds

5.3 Location of Star Formation

Stars form in molecular clouds, duh. Locations where there are hot massive stars are indication of star birth places (those stars dont live very long). These areas also tend to be very colorful due to wisps of hot gas called **ionized nebulae**. These tend to be redder because electrons falling a level in hydrogen give off red photons. Nebulae that are bluer tend to be that color from dust grains reflecting light.

The spiral arms of our galaxy are full of new stars since they house many mollecular clouds and lots of young bright stars. Spiral arms form because molecular clouds collide quite often, these continue to compact until they become a birthing zone for stars.

5.4 History of the Milky Way

Unlike the disk that has stars of all ages, the halo has only old stars that contain fewer heavy elements. This is because the halo does not contain molecular clouds used for star formation so there can be no new stars in the halo and the halo is the oldest part of the galaxy before heavier elements existed as much.

Our galaxy started as a **protogalacic cloud** containing tones of hydrogen and helium. Gravity causes the cloud to contract and fragment. The bulge and halo stars formed first. At this point the galaxy was not disk shaped so these new stars orbited however they wanted. The gas continued to contract until it flattened into a disk due to the conservation of angular momentum. The concentrations of heavy elements in the halo stars implies that the Milky Way formed in multiple clouds that collided. Some halo stars move in organizes streams that implies that they came from other galaxies that collided with ours.

5.5 Galactic Center

The galactic center lies in the direction of Sagittarius. When we look at within 1000 light year of the center of our galaxy we see very dense cloud of gas and several million stars. At the center of this is the source a bright radio emissions, Sagittarius A*. Several hundred stars cluster Sagittarius A* within a light year and their orbital paths indicate a massive object at the center, about 4 million solar masses with a volume smaller than our solar system. This must be a black hole.

6 Chapter 15 – Galaxies and the Foundation of Modern Cosmology

By taking a picture of a small section of the sky and determining how many such pictures would be necessary to cover the entire sky, we can extrapolate that there are well over 100 billion galaxies within the observable universe. Each of these galaxies has a different shape, size, color, etc.

6.1 Types of Galaxies

We have three major categories of galaxies:

Spiral galaxies are flat white disks with yellowish bulges near the center. The disks are fileed with cool gas and dust, as well as some sparse ionized gasses, and usually have a few spiral arms. The Milky Way is a spiral galaxy.

Elliptic galaxies are redder, rounder, and tend toward being longer than they are wide. They contain less cool gas and dust than spiral galaxies and more of the hot ionized gasses.

Irregular galaxies appear lke neither of these categories.

The reason the galaxies are different colors is based on the relative ratios of stars of different colors within them: spiral and irregular galaxies are white-ish since they contain stars of all colors and ages, while elliptic galaxies are reddish since they are populated mostly by old and red stars.

We also categorize galaxies by size: **dwarf galaxies** contain as few as 100 million stars and **giant galaxies** contain more than 1 trillion.

6.1.1 Spiral Galaxies

Spiral galaxies have a thin **disk** which forms outwards from a central **bulge**. The disk smoothly merges into a dim **halo** with a radius which can be upwards of 100 thousand lightyears. The **disk population** [**Population 1**] (population of stars within the disk) includes stars of all masses and ages. The **spheroidal population** [**Population 2**] consists of halo and bulge stars, the halo stars being generally old and low in mass.

We thus define:

- The **disk component** is the flat disk in which stars follow orderly, nearly circular orbits around the galactic center. The disk component always contains an interstellar medium of gas and dust, but the amounts and proportions of molecular, atomic, and ionized gases in this medium differ from one spiral galaxy to the next.
- The bulge and halo together make up the **spheroidal component**, named for its rounded shape. Stars in the spheroidal component have orbits with many different inclinations, and the spheroidal component generally contains little cool gas and dust.

All spiral galaxies have both of these components, though some **barred spiral galaxies** have a straight bar of stars cutting through the center, with arms spiralling off of the ends of the bar.

Lenticular galaxies are somewhat of a halfway between spiral galaxies and elliptical galaxies, as they have no spiral arms.

Approximately 75-85% of galaxies are spiral or lenticular.

6.1.2 Elliptical Galaxies

Elliptical galaxies have only a spherical component and no significant disk component. For this reason, they are sometimes called **spheroidal galaxies**. These galaxies tend to be small (and small elliptical galaxies are the most common of galaxies), though some are the most massive of galaxies: **giant elliptical galaxies**.

The composition of elliptical galaxies (ie. the ionized gasses) are much like the hot X-ray-producing gasses generated by supernovae and powerful stellar winds elsewhere in the universe.

Since these galaxies do not have many of the cool gasses found in other galaxies, they have very little ongoing star formation. This is why tese galaxies appear reddish: they tend to have very few young blue stars to counteract the color of the old red and yellow ones.

6.1.3 Irregular Galaxies

The irregular galaxies are all othre galaxies, which we can not easily classify. They are usually white and dusty and contain young massive stars. These also tend to be the oldest of galaxies: more irregular galaxies can be found the farther away we look. Though we aren't sure why, it seems that irregular galaxies were more common when the universe was younger.

6.1.4 Hubble's Galaxy Classes

Hubble designed a system for classifying galaxies: elliptical galaxies have a designation of E followed by a number from zero to seven, with a larger number signifying a larger eccenricity in shape: ie. an E0 galaxy is a sphere. Spiral and barred spiral galaxies have respective designations S and SB, followed by a lowercase letter from "a" to "c", where "c" corresponds to the smallest bulge and largest amount of dusty gas. Lenticular galaxies are designated S0 and irregulars are Irr.

6.2 Measuring Distance

We can measure the distance between the Earth and a galaxy using **parallax**. To do this, we must know the distance between the Earth and the Sun. This is done using **radar ranging**: by bouncing radio waves off of Venus and determining how long they take to return, we can find the distance to Venus. Keppler's laws, then, give us the distance to the Sun.

Since we can only measure within about a few hundred lightyears with parallax, we must also learn to measure distance by the inverse-square law of luminosity. Since similar stars should have similar luminosities (ie. a main-sequence G2 star like the Sun would have a similar luminosity), we can use the inverse-square law to determine how much farther it is from us than the Sun. For this approach, we must find **standard candles**: objects whose luminosity is known by which we can compare against.

Sun-like stars do not make very good candles since they are somewhat dim. To measure distances beyond a thousand lightyears, we need brighter candles. We thus have an approach by which we can get progressively better estimates: find a star within parallax distance, plot its HR, and establish luminosity from distance and brightness; then measure brightness of stars too far for parallax and use the inverse-square law to determine approximate distance.

Since we tend to use main-sequence stars for this, we refer to this technique as **main-sequence fitting**.

Unfortunately, this approach does not work well outside of our galaxy. We use brighter stars **cepheid variable stars**, or **cepheids**, for this task. These stars vary in brightness at some constant rate, from our perspective. The periods, though, are closely related to their luminosities: longer periods are found on more luminous stars. Cepheids, then, obey a **period-luminosity relation** which allows us to estimate their luminosity within 10% simply by measuring their period. A Cepheid with a period of 30 days is approximately ten thousand times brighter than the Sun.

Cepheids vary like this due to varying amounts of energy radiating from their surface: they have a peculiar problem in matching the amount of energy their surfaces radiate with the amount welling up from the core. The upper layers of a Cepheid variable star alternately expand and contract to attempt to find equilibrium, causing the stars luminosity to rise and fall. The periodluminosity relation holds because larger (more luminous) Cepheids take longer to pulsate in size.

We can use Cepheids as a stepping stone to find even brighter distant standard candles.

Some of the best distant standard candles are white dwarf supernovae, which are believed to be white dwarfs which have expanded beyond 1.4 times the mass of the Sun. Since these have a similar mass, these should all have comparable luminosities. Their luminosity is approximately ten billion times that of our Sun, and so we can detect them even in galaxies billions of lightyears away. The major disadvantage to this approach, of course, is that we can only measure the distance to galaxies with a supernovae-ing white dwarf; and this only happens once every few hundred years in the average galaxy. This technique, though, does allow us to calibrate an even better technique based on the expansion of the universe.

The spectra of most spiral galaxies tends to be redshifted; which occurs when a radiating object is moving away from us. When we measure the distance (using the above methods) as well as the redshifts of various galaxies, we notice that galaxies farther away from us are moving away at a faster rate. Thus, we determine that the universe is expanding. We express this with **Hubble's Law**

$$v = H_0 \times d$$

where v is an object's velocity away from us and H_0 is Hubble's constant. Note that astronomer's tend to use this law in reverse: using a galaxy's speed to measure its distance away from us.

Unfortunately, this is only an approximation, as the speed of a galaxy is impacted by the effects of gravity from nearby galaxies as well as from the expansion of the universe. In addition, we base our approximations upon how closely we can approximate Hubble's constant ($H_0 = 22\frac{km}{Mly \times s}$).

Note that the first of these issues impacts us most when measuring distances within the local group, as these are attracted to us by the Milky Way and thus move away from us at a much smaller rate than expansion would imply.

The major problem with measuring distances to galaxies is this chain of measurements; even today, based on the uncertainty at each step we can only be confident as to a galaxy's distance within about ten percent.

Remember, this chain is:

1. Radar Ranging
2. Parallax
3. Main-sequence Fitting
4. Cepheid Variables
5. White Dwarf Supernovae
6. Hubble's Law

6.3 Age of the Universe

All our observations are consistent with the **Cosmological Principle**: that the universe appears identical at all locations. In other words, it has no "edge" or "center". More specifically, the universe is expanding – but it is not expanding *into* anything, nor is it expanding into nothing. It itself is an infinite, three-dimensional surface which has no edges, sides, or center.

The Hubble Constant, then, changes as the universe ages: at any given time $\frac{1}{H_0}$ is exactly equal to the age of the universe. Technically, the Hubble Constant is non-constant, then, but it varies slowly enough as to be virtually constant.

Based on our current estimate of Hubble's Constant, the universe is between 12 and 15 billion years old. To be more precise, we would need to know whether the rate of expansion is accelerating, which could change these values immensely: if the expansion rate has been increasing, the age of the universe woulld be somewhat more than $\frac{1}{H_0}$, and vice-versa. Our current best-estimate is that the universe is 14 billion years old.

6.3.1 Lookback Times

Since the universe is expanding, it can be difficult to refer to the distances to objects. If we see light from an object which left that object 400 million lightyears ago, then it is currently more than 400 million lightyears away. An object's **lookback time** is the difference between the current age of the universe and the age the universe was when light left that object. The lookback time of an object, then, is unambiguous.

The lookback time of an object is directly related to its redshift. This is because the expansion of our universe also stretches out the photons within it, thus giving us a **cosmological redshift** as well as a Doppler redshift. This is a difference in perspective, mostly, as we can either think of galaxies as hurtling through space or being carried along by the expanding universe.

The **cosmological horizon** represents the limits of the observable universe as a boundary in time, instead of space: in a universe 14 billion years old, we can not see any objects with lookback times greater than 24 billion years.

6.4 Evolution of Galaxies

We know far less about the life-cycles of galaxies than we do of stars. That said, we can use galaxies of various lookback times to view galaxies of different ages. We can not see far enough back to watch galaxies being formed, but we can determine their likely early life based on some assumptions:

- Hydrogen and Helium gas filled space uniformly soon after the birth of the universe
- The distribution of matter in the early universe was not perfectly uniform

We assume the denser areas grew into galaxies based on our understanding of the laws of physics. These regions of enhanced density would have expanded along with the rest of the universe, gradually slowing their expansion due to ever-increasing effects of gravity. Within a billion years, their expansion would have reversed, the material within them forming **protogalactic clouds**, which eventually formed galaxies.

The clouds which would eventually form spiral galaxies cooled as they contracted, and the first stars grew from the coldest, densest clumps of gas. These stars were likely massive, with lifespans of only a few million years. Their supernovae seeded these clouds with heavier elements and heated the surrounding gasses. This heating would have slowed the collapse of the clouds and their rate of star formation, allowing time for the gasses to form rotating disks.

This explains the shape of spiral galaxies: the spheroidal center consists of stars formed in the early stages, before a definite rotational plane was established, and thus have verying planes of rotation. Those formed on the arms were formed after a rotation had been established, and thus all follow the same plane.

This model, though, does not explain irregular and elliptical galaxies.

6.4.1 Variances in Galaxies

We attempt to determine why these galaxies differ by examining their differences: why do spiral galaxies have gas-rich disks, while other galaxies do not?

Two plausible explanations for the differences between spiral galaxies and elliptical galaxies trace a galaxys type back to the protogalactic cloud from which it formed:

Protogalactic Spin A galaxys type might be determined by the spin of the protogalactic cloud from which it formed. If the original cloud had a significant amount of angular momentum, it would have rotated quickly as it collapsed. The galaxy it produced would therefore have tended to form a disk, and the resulting galaxy would be a spiral. If the protogalactic cloud had little or no angular momentum, its gas might not have formed a disk at all, and the resulting galaxy would be elliptical.

Protogalactic Density A galaxys type might be determined by the density of the protogalactic cloud from which it formed. A protogalactic cloud with relatively high gas density would have radiated energy more effectively and cooled more quickly, thereby allowing more rapid star formation. If the star formation proceeded fast enough, all the gas could have been turned into stars before any of it had time to settle into a disk, making it an elliptical galaxy. In contrast, a lower-density cloud would have formed stars more slowly, leaving plenty of gas to form the disk of a spiral galaxy.

The second theory is consistent with observations: young elliptical galaxies tend to have very few young stars, implying their stars were all formed very quickly and that new star formation is not ongoing for long.

Another possible avenue for determining why galaxies differ is by looking at what changes after they are formed. Galaxies are not formed in isolation, and their interactions with other galaxies may be the cause of the differences.

Sometimes, galaxies may collide. These are immense interstellar events which cause enormous changes to the objects involved. These collisions were much more common in the early universe – back when galaxies were much closer together.

Based on computer simulations, we see that the collision of two spiral galaxies can form an elliptical galaxy since tremendous tidal forces rip the disks apart and a large fraction of the gasses sink to the center of teh collision and rapidly form new stars. Little of the disks remain in the end, and the stars have randomized orbits.

Elliptical galaxies are most common in areas of the universe with a large number of galaxies – which would be the case if they were often formed by the collision of other galaxies. Our observations tend to lend creedence to elliptical galaxies being formed this way. Elliptical galaxies tend to have structures corresponding to likely violent pasts and by observing **central dominant galaxies** we see that elliptical galaxies can grow to a large size by consuming other galaxies through **galactic cannibalism**.

Galactic collisions could also ignite huge bouts of star formation – **starbursts** – which can form entire **starburst galaxies**. Since these would consume al ltheir gasses extremely quickly, they would rapidly burst and emit **galactic winds** which carry away all gasses capable of supporting the constant star formation of a spiral galaxy.

6.5 Quasars and Other Active Galactic Nuclei

Some stars have extreme amounts of radiation and jets of material from their cores. These very crazy cores are called **active galactic nulcei**, the most luminous of these are called **quasars**. Quasars are only found at great distances wich tell us that they were much more common billions of years ago, from this we infer that quasar production decreases as galaxies age.

6.5.1 Quasars

The current theory is that the energy in a quasar comes from the accretion disk around supermassive black holes. Quasars were discovered when a scientist was mapping radio sources with visible objects and found a blue star that have emission lines that didnt appear to belong to any known chemical element. It was eventually found that these emission lines were just those of hydrogen that had been hugley redshifted. From there the objects distance and luminosity were calculated and shit was bright.

While quasars only appear very far away, we can find active galactic nuclei closer to home. Unfortunatly these suckers are small (only about 100 light years across) so it is very hard to resolve them. Using interferometry with radio images we have found that they are even smaller (less than 3 light years across) and the way they flicker implies they are even smaller.

Certain galaxies also emit unusually strong radio waves, called **radio galaxies**. These waves come from huge radio lobes on either side of the galaxy. At the center of the galaxy is a active galactic nuclei with two gigantic jets of plasma shooting into the radio lobes. Recent discoveries imply that radio galaxies and quasars are actually the same thing veiwed in different ways.

6.5.2 Power Source of Quasars and Active Galactic Nuclei

Currently we think that the energy of quasars and AGN comes from matter falling into black holes. The matter falling converts gravitational potential into kinetic energy and matter colliding on the way down converts that to thermal energy, and that resulting heat emits the crazy radiation we see.

This explains their crazy luminosities, how they emit radiation over a broad range of wavelengths, and their jets. Accretion disks convert 10-40% of mass into energy (much greater than a stars 1% conversion) which explains the high luminosities. Hot gas near the accretion disk emits ultraviolet and X-ray photons. This radiation ionizes near by interstellar gas which emits visible light (and the emission lines that led to their discovery). Dust grains in surrounding molecular clouds absorbe this light and emit infrared ratiation. The fast electrons in the jet emit radio radiation. The prescense of jets is harder to explain. We think its related to twisted magnetic fields caused by the spinning of the accretion disks.

6.5.3 Supermassive Black Holes

Some astronomers doubt the existence of supermassive black holes, and finding them is very difficult. By observing matter orbiting the centers of nearby galaxies we find that supermassive black holes are very common and possibly at the center of every galaxy. We do this by looking at the doppler shifts on either side of where we think the black hole is. If it is red on one side and blue on the other it means that gas is orbiting some unseen object. We can use mass and distance calculations to get the mass of the object at the center of this orbit. Many objects (molecular clouds in particular) orbit very close to black holes (less than 1 light year), we can use this to guess the volume of it.

Black hole like objects appear in the center of a wide variety of galaxies with grossly different properties which implies that they are important to the formation of a galaxy, we just dont know how yet.

7 Chapter 16 – Dark Matter, Dark Energy, and the Fate of the Universe

The dominant source of gravity in the universe is **dark matter**, which is completely unobservable. **Dark energy** seems to be counteracting the effects of gravity on a massive scale.

In fact, the universe itself seems to be mostly composed of dark matter, rather than of atoms. Basically, dark matter is a theorized bunch of matter than may or may not exist but is necessary to create the effects our models predict. It is matter that gives off no light, ie. remains “dark”.

We predict that the expansion of the universe must slow over time due to the diminishing effects of gravity. If it does not, there must exist some “dark” energy fueling the expansion. Note that sometimes we refer to dark energy as **quintessence** or a **cosmological constant**. There is also no real correlation between dark matter and dark energy, other than that we have determined their existance through their being *necessary*.

7.1 Evidence

We know that distance from the center of a circle and an object’s orbital relation are related. It turns out if the center of the circle is the center of mass, the orbital speed *decreases* as we move away from the center. If the mass is distributed evenly, the orbital speed *increases*. Since the orbital speed of the stars within our galaxy increase as we move away from the galactic center, there must be a large amount of mass on the galaxy’s halo. Since we can detect no radiation from it, we call that dark matter.

For galaxies that are not our own, we can make a similar calulation: using the mass-to-luminosty ratio, we can determine the total mass of the galaxy. Then, we can measure the velocities of stars and dust clouds in that galaxy and use the laws of galaxy to caluclate their mass. The difference in mass is dark matter.

We find that the composition of a spiral galaxy is typically 98% or more dark matter.

We can apply these same techniques to galactic clusters. If we assume they orbit each other, the gravitational calculations predict a far greater mass than their luminosities would. Thus we see that Galactic clusters are even more than 90% percent dark matter!

We can also measure the temperature of the hot gas (interstellar medium) within a galaxy by measuring the X-rays that medium emits. Since temperature is related to mass in this case, we can determine a galaxy’s total mass with some calculations. Studies performed using this method see galaxies as containing more mass than luminosity would predict and thus agree with the above gravitational calculations.

We can also use **gravitational lensing** to make the mass measurements. This technique relies on large masses "bending" light as it travels by exerting gravitational influences on the photons. By measuring the perceived shift, we can determine the mass of the objects between us and a source of light. By using this technique, we can use Einstein's Laws instead of Newton's. Since these results agree, we can increase our confidence in dark matter.

We are pretty sure that there are two options:

- our understanding of gravity is correct and dark matter exists, or
- our understanding of gravity is incorrect.

That said, we are quite confident in our understanding of gravity. Furthermore, no one has been able to come up with an explanation which neatly explains our observations.

7.2 Composition

Dark matter may either be composed of particles we have already detected – but in some form as to be undetectable – or of exotic particles. At least most of it is likely exotic.

Dark matter could contain some non-exotic matter: if your body were in space, it would be undetectable as it would not be luminous enough to be visible. Similarly, planets, brown dwarfs, faint red M-sequence stars, etc are also classified as dark matter since they are too dim to be seen. That siad, if dark matter contained any of these objects, we could detect it: due to gravitational lensing, any of these objects passing in front of any source of light would be noticeable. The duration of this lensing would reveal the object's mass. We have discovered a few of these events, but not nearly enough to explain dark matter's prevalance or mass. Similar measurements agree dark matter can not be mostly comprised of black holes.

Models of nuclear fusion give us an estimate of the total number of protons, neutrons, etc in the galaxy. Their mass would comprise about one-sixth of the measured mass of the universe; thus there must be some exotic particles filling the five-sixths of the universe's mass.

We imagine dark matter to be composed heavily of **weakly interacting massive particles**, or **WIMPs**. These particles would be similar to neutrinos, in that they interact only with a couple of the four forces (ie. weakly interact) but far more massive and slower moving. Note that though these are refered to ass "massive particles", they are really subparticles and are thus only massive relatively speaking.

A large amount of WIMPs being present in the outer halo of a galaxy fits within our current understanding.

We have not yet detected any WIMPs, but through large-scale space particle detection and particle colliders, we are hopeful we will detect some soon.

7.3 Dark Matter's Role

Dark matter likely played an essential role in formating galaxies: by being os large in mass, areas high in dark matter likely attracted many other particles and eventually developed the mass to become a galaxy.

We also know that the universe is arranged into galactic clusters, superclusters, and even large sheets of superclusters. The reason mass in our universe is so highly divided is likely due to the effects of gravity from large amounts of dark matter. In fact, the current galactic structure likely mirrors the initial distribution of dark matter.

7.4 The Fate of the Universe

We can determine a **critical density** of our universe by which a universe with a larger density will eventually start contracting and one with a smaller density will simply expand forever. Including dark matter, our estimates of the universe's matter content fall short of this critical density (we measure mass approximately equal to 0.5% of the required amount and believe dark matter is 50 times more massive, thus we have 25% of the required mass). Thus the universe seems likel to continue expanding forever, as we are doubtful there is more dark matter than we have predicted.

In fact, the expansion of the universe is *increasing* over time, which should not happen based on our understanding of gravity. Thus we label dark energy as the force causing the expansion.

7.4.1 Expansion Patterns

Given future changes in expansion rates, we determine four possible expansion patterns:

recolapsing if there were no dark energy and the universe was above critical density, universal expansion would eventually reverse and end in a "big crunch". This is sometimes refered to as a **closed universe**, since it could be modelled by a mathematically closed sphere in more dimensions.

critical if there were no dark energy and the universe was at critical density, the universe's expansion would slow over time but never reverse. Mathematicall, we could call this a **flat universe**.

coasting if there were no dark energy and the universe was below critical density, the universe would keep expanding at its current rate forever. We could mathematically call this an **open universe**.

accelerating if dark matter exerts a repulsive force which causes the universe's expansion to acclerate over time, the universal expansion rate would increase over time. This type of universe may be closed, open, or flat. Current evidence points to our universe being an accelerating flat universe.

Based on the average distance between galaxies over time, we seem to be in an accelerating universe. We measure this by looking at white dwarf supernovae: their distance tells us the lookback time and their redshift tells us what rate the galaxy had been expanding at.

8 Chapter 17: The Beginning of Time

8.1 The Big Bang

We can use light from distant galaxies to see about a billion years into the past, beyond this we cannot see any objects bright enough. We also run into a problem with background radiation left over from the Big Bang. This radiation is from when the universe was 380 000 years old (before that light could not pass through). Most of our knowledge of the Big Bang is from mathematical models.

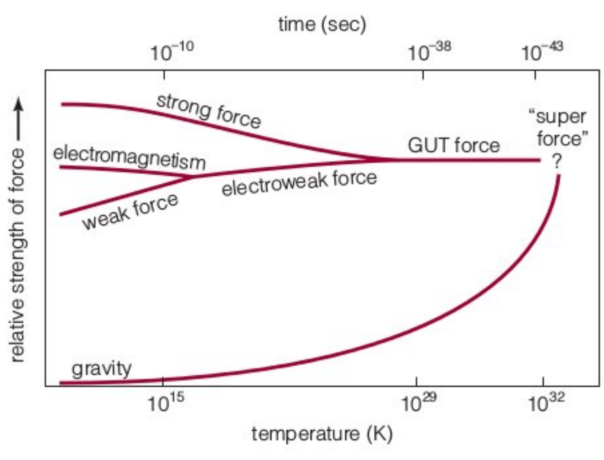
8.1.1 Conditions of the Early Universe

During the first few seconds the universe was so hot that photons could transform themselves into matter and back. When two photons collide with energy twice that of a electron (its mass times c^2) they make a electron (matter) and positron (antimatter). When these two meet they annihilate each other and release photon energy. Similar actions can be done for protons and neutrons. At its start, the universe was full of matter and antimatter jumping to and from energy.

Forces:

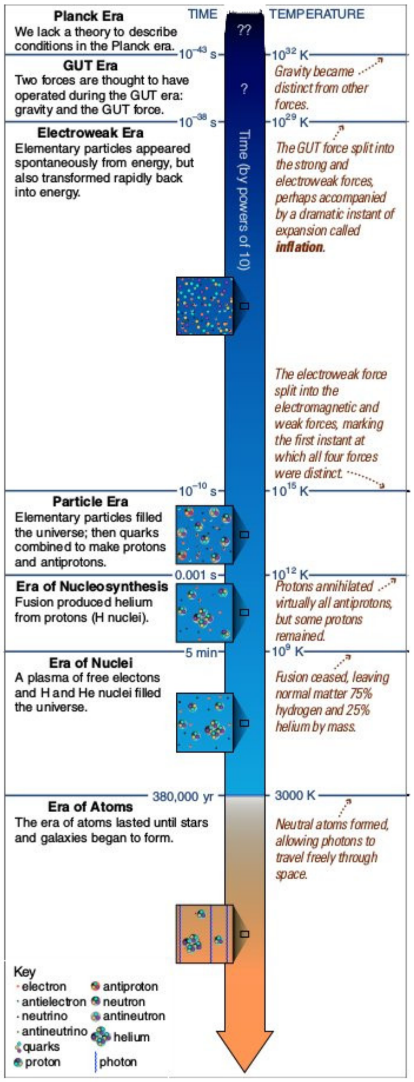
- Gravity: holds planets together (dominant on large objects)
- Electromagnetism: holds particles together (dominant on atoms and molecules)
- Strong nuclear: holds atom nucleus together
- Weak nuclear: deals with fusion and fission

At high temperatures (like at the birth of the universe) some of these meld into a different force. At its very start the universe was governed by one super force.



8.1.2 History of the Universe

We break the history of the universe into eras.



Planck Era This is the limit of what our current understanding of physics can explain. At this point we know that mass and energy were being converted back and forth rapidly. These energy fluctuations caused a changing gravitational field that warped space and time. A problem arises in that we have no theory to link quantum mechanics and general relativity. This era ended when the universe cooled enough for the super force to break into GUT force and gravity.

GUT Era We know barely more about this era than we do about the Planck era, and even then what we know is not well tested. We think that the separation of GUT into strong and electroweak forces released a ton of energy causing a dramatic expansion of the universe called **inflation** (we think expanding things of atomic size to solar system sized).

Electroweak Era At the end of this era the electroweak force breaks apart into the electromagentic and weak nuclear forces. This is the first point where we have experimental evidence of things actually fitting our models. Particle accelerators produced weak bosons that we predicted would exist during this era.

Particle Era This is the era right before the crazy energy-particle switching calmed down. All of the quarks created during this era had combined into protons and neutrons by its end. Since we were not spontaneously making matter and antimatter the two started permanently annihilating each other. We know that matter out numbered antimatter because matter exists. By comparing estimates on how many protons and photons there are we can get a rough estimate of the size of matter antimatter imbalance. The two numbers would have been similar at the start of the universe, but now photons outnumber protons a billion to one. This means that for every billion antiprotons there were a billion and one protons so when the billion annihilated themselves they made a billion extra photons.

Era of Nucleosynthesis Now that we had a steady amount of matter it started fusing into heavier elements but the heat of the universe kept breaking them apart. At the end of this era it had gotten too cool to fuse heavier elements.

Era of Nucleus At this point the universe consisted of plasma made of hydrogen and helium nuclei and electrons. Light didnt really go anywhere because it just bounced around between electrons (like it does inside a star). At the end of this era the universe had cooled enough for the nuclei to snag electrons and become stable. Once that happened light could travel in straight lines.

Era of Atoms and Era of Galaxies Now that we have stable atoms we can be in the era of atoms. The universe is now a mix of neutral atoms, plasma, and photons. Slight areas of higher density started attracting atoms and plasma to make protogalactic clouds. These went on to form stars and eventually galaxies. This is the era we are currently in.

8.2 Evidence

The big bang theory is widely accepted because it accurately predicts **cosmic background microwave radiation** as the radiation that started streaming through the universe at the end of the nuclei era. It also accurately predicts the amount of helium in the universe.

8.2.1 Left Over Radiation

Arno Penzias and Robert Wilson kept hearing noise on their microwave antenna, this was background radiation from the universes formation. They found that the noise was exactly the same from every direction (so it wasn't just coming from something). At the same time a group at Princton had found that the radiation created during the formation of the universe (predicted by George Gamow) would have to still exist and be detectable with microwave antennas.

Scientists predicted that cosmic background radiation would have a prefect thermal spectrum since it was from the start of the universe. Since it broke free when the universe was the temperature of a red giant it should have the same signature, but stretched by 1000 (since thats how much the universe has expanded since then). This shifted spectrum represents the temperature just above absolute 0. The Cosmic Background Explorer (COBE) satellite was launched to test these theories and it confirmed that cosmic background radiation has a perfect thermal spectrum and is about 3K. COBE also showed that background radiation is not absolutely the same in every direction. This had been a strike against the Big Bang Theory since the universe couldn't have been that smooth (it had to have pockets of slightly higher gravity for starts to form).

8.2.2 Abundance of Elements

Background radiation also explains a discrepancy in the amount of helium in a galaxy. No galaxy is $< 25\%$ helium, but star fusion can only produce 10% helium. This means that some helium must have been present during the formation of the universe, so the universe must have been hot enough at some point to fuse hydrogen. The temperature of the background radiation can be used to calculate how hot the universe was in the past and this can be used to calculate how much helium was fused (roughly 25%).

During the formation of the universe it was hot enough to switch between protons and neutrons, but as it cooled the universe favored creating protons since neutrons are heavier. During this time protons and neutrons combined to form deuterium (weird hydrogen nucleus containing a neutron). Deuterium fused to form helium. Most of these were blown apart by gamma radiation but as the universe continued to cool some stuck around. Here protons outnumbered neutrons seven to one. All neutrons were incorporated into helium-4 atoms resulting in one helium (weight 4) for every 12 hydrogen (weight 1 each), so 25% of the universe's weight was helium.

Rarely reactions could form lithium, but all other elements were created in stars. This is because by the time the universe has stable helium and hydrogen atoms to fuse into heavier elements it was too cool to fuse them.

8.3 Inflation

Lots of what we know about the origin of the universe is uncertain because we have no way to experimentally verify them.

8.3.1 Mysteries

Stuff we cannot explain with the Big Bang Theory without inflation:

- the structure: matter collected around areas of slightly higher density, where did these come from and why were they there
  - we can experimentally prove that the energy fields at any point in space fluctuate slightly, these might cause density enhancements
  - inflation would have increased the wavelengths of these fluctuations to be large enough to generate the density enhancements that existed (based on background radiation calculations)
- the uniformness: for something of its scale the universe is surprisingly smooth (varying by only 0.01%)
  - before inflation radiation was continuously bouncing around and interacting which lead to a normalization of it
  - inflation then flung this radiation far apart from each other very quickly so that they didn't have time to fuck with each other resulting in the smoothness we see
- density id close to critical density: if we sum dark matter and dark energy we find that the universe density is far too close to the critical density to be a coincidence
  - the universe is surprisingly flat which is only possible if its density was uniformly equal to the critical density (point at which kinetic expansion matched gravitational pull)
  - inflation explains this by expanding the universe so quickly that any curvature would not be noticeable on the scale of our universe

Note: inflation does not violate the speed of light since things aren't moving through a distance quickly, the distance itself is stretching.

8.3.2 Testing Inflation

We test inflation by using it to make predictions and seeing if its right (and it is);

- The overall geometry is flat, implying that the total mass-energy of the universe is equivalent to the critical density.
- The density of ordinary matter is 4.6% of the critical density, in agreement with observations of deuterium in the universe.

- The total matter density is 28% of the critical density. Subtracting the 4.6% for ordinary matter, we conclude that dark matter, probably in the form of weakly interacting massive particles, makes up about 23% of the critical density, in agreement with what we infer from measurements of the masses of clusters of galaxies.
- The combination of a flat geometry and a matter density lower than the critical density implies the existence of a repulsive force due to dark energy that currently accelerates the expansion, in agreement with observations of distant supernovae. Because the total mass-energy of the universe is the critical density, and matter accounts for only 28% of this, dark energy must account for the remaining 72% of the mass-energy of the universe.
- The universes age should be about 13.7 billion years at the current microwave temperature of 2.73 K, in agreement with what we infer from Hubbles constant and the ages of the oldest stars.

8.4 Observing the Big Bang

They sky is dark at night. Duh. But this actually makes no sense. **Olber's Paradox** is that if the universe is infinite and unchanging, then the sky should be as bright as the sun. Since the universe is infinite in every direction, there should be almost no part of the sky that doesn't have a source of light in the way. Even with the explanation of dust and black holes, the sky is too dark. The Big Bang Theory explains this by saying we can only see a finite number of stars because the universe began at a particular moment so our field of vision is limited.

9 Assignments

9.1 Assignment 9

Stages of birth of a star from first to last:
molecular cloud fragment, contracting cloud trapping infared light, protostar with jets, main-sequence star

From Highest to lowest temp:
main-sequence star, protostar with jets, contracting cloud trapping infared light, molecular cloud fragment

Fastest to slowest:
main-sequence star, protostar with jets, contracting cloud trapping infared light, molecular cloud fragment

Newly forming star has the greatest luminosity when it is a shrinking protostar with no internal fusion. Greatest energy source at this luminosity is gravitational contraction

Most of the gas remaining from the process of star formation is swept into interstellar space by a **protostellar wind**.

Planets may form within the protostellar disk that surrounds a forming star.

Main-sequence Phase

- lasts about 10 billion years
- surface radiates energy at the same rate that core generates energy
- energy generated by nuclear fusion

Protostar Phase

- pressure and gravity not precisely balanced
- energy generated by gravitational contraction
- luminosity much greater than the sun
- radius much larger than the sun

interstellar medium: the gas and dust that lies in between the stars in the Milky Way galaxy

Interstellar clouds called molecular clouds are the cool clouds in which stars form.

Most abundant in an interstellar molecular cloud: H_2.

Interstellar dust consists mostly of microscopic particles of carbon and silicon.

Part of electromagnetic spectrum generally giving best views of stars forming in dusty clouds: **infared**.

Looking by eye at a star near the edge of a dusty interstellar cloud. The star will look **dimmer and redder** than it would if it were outside the cloud.

Most interstellar clouds remain stable in size because the force of gravity is opposed by **thermal pressure** within the cloud.

A cold, dense gas cloud is most likely to give birth to star because this type of cloud has lower thermal pressure (due to the low temperature) and stronger gravity (due to the high density).

Core temperature required before hydrogen fusion can begin in a star: 10 million K

Smaller stars spend more time in the protostellar phase of life

Vast majority of stars in a newly formed star cluster are **less massive than the Sun**

Brown Dwarfs:

- form like ordinary stars but are too small to sustain nuclear fusion in their cores
- have masses less than about 8% that of our Sun
- supported against gravity by degeneracy pressure, which does not depend on the object's temperature

Radiation pressure prevents stars of extremely large mass from forming

Stages of a **high mass star** (first to last):
contracting cloud of gas and dust, protostar, main-sequence O Star, red supergiant, supernova, neutron star

Elements from first to last produced:
Helium, Carbon, Oxygen, Iron

The **CNO Cycle** is the process by which hydrogen fusion proceeds in high-mass stars.

If you returned to our solar system in 10 billion years you would most likely see a white dwarf

High Mass Stars ($> 8M_Sun$):

- have higher fusion rate during main sequence life
- late in life fuse carbon into heavier elements
- end in a supernova

Low Mass Stars ($< 2M_Sun$):

- final form is a white dwarf
- have longer lifetimes
- end life as a planetary nebula

The core of a high-mass star shrinks and heats up after it runs out of hydrogen.

9.2 Assignment 11

The Cosmic Distance ScaleCepheids

- Cepheids with longer periods have higher luminosities
- How to use Cephids to measure distance:
  - Step 1: Measure the period of the Cepheid's brightness variations.
  - Step 2: Use the period-luminosity relation to determine the Cepheid's luminosity.
  - Step 3: Calculate the Cepheid's distance from its luminosity and apparent brightness.

The Cosmic Distance ScaleFrom the Solar System to the Universe

- What baseline distance must we know before we can measure parallax?
  - the Earth-Sun distance
- Standard candle techniques
  - white dwarf supernovae (distant standards)
  - Cepheids
  - main-sequence fitting

The Cosmic Distance ScaleHubble's Law

- Hubble's law expresses a relationship between the distance of a galaxy and the speed at which it is moving away from us

- But before we can use Hubble's law, we must first calibrate it by measuring the distances to many distant galaxies with a standard candle technique
- meaning of Hubble's constant: It describes the expansion rate of the universe, with higher values meaning more rapid expansion

Understanding Hubbles Law

- Hubbles law tells us that the more distant a galaxy is from Earth, the faster it is moving away from us
- more distant galaxies move at higher speeds
- a steeper slope (distance vs speed) for Hubbles law would predict faster speeds for galaxies at particular distances

Visual Activity: A Graph of Hubbles Law

- galaxies with high speeds as measured from Earth are moving away from Earth and are farther from Earth than galaxies with lower speeds
- galaxies that have the lowest speeds are moving away from Earth and are closer to Earth than galaxies with high speeds
- galaxy B is twice as far from Earth as galaxy A. Hubbles law predicts that galaxy B will be moving away from Earth with approximately twice the velocity of galaxy A
- he slope of Hubbles law on the graph is actually steeper than that shown. In that case, the age of the universe would be younger than 14 billion years because the universe is expanding more rapidly than current data suggest

Which of these galaxies would you most likely find at the center of a large cluster of galaxies? a large elliptical galaxy

In which of these galaxies would you be least likely to find an ionization nebula? a large elliptical galaxy

If all the stars on the main sequence of a star cluster are typically only one-hundredth as bright as their main-sequence counterparts in the Hyades Cluster, then that cluster's distance is 10 times as far as the Hyades's distance.

Which of these galaxies is most likely to be oldest? a galaxy in the Local Group

About how many galaxies are there in a typical cluster of galaxies? a few hundred

When the ultraviolet light from hot stars in very distant galaxies finally reaches us, it arrives at Earth in the form of visible light.

Why do virtually all the galaxies in the universe appear to be moving away from our own? Observers in all galaxies observe a similar phenomenon because of the universe's expansion.

If you observed the redshifts of galaxies at a given distance to be twice as large as they are now, then you would determine a value for Hubble's constant that is twice as large as its current value.

Redshift of value z: $1+z = \frac{\lambda_{obsv}}{\lambda_{emit}} = \frac{d_{now}}{d_{past}}$ where obsv is wavelength observed and emit is wavelength emitted and d is distance.

Galaxy FormationSpiral or Elliptical

- A collision strips gas out of a spiral galaxy, this tend to change the spiral galaxy into an elliptical galaxy because a galaxy cannot have a disk if it does not have gas
- High density tends to lead to more rapid star formation in a protogalactic cloud which leads to an elliptical galaxy, rather than a spiral galaxy because rapid star formation means that there may not be enough gas left to make a disk.
- High angular momentum leads to faster rotation which leads to a spiral galaxy, rather than an elliptical galaxy because faster rotation leads to collisions among gas particles that cause the gas to settle into a spinning disk, rather than a more spread out cloud.

Which of these items is a key assumption in our most successful models for galaxy formation? Some regions of the universe were slightly denser than others.

A collision between two large spiral galaxies is likely to produce a large elliptical galaxy.

The luminosity of a quasar is generated in a region the size of the solar system.

The primary source of a quasar's energy is gravitational potential energy.

Supermassive black holes found at the centers of galaxies are related to the properties of those galaxies in which of the following ways? The mass of the black hole is related to the mass of the galaxys bulge.

A collision and merger of two large elliptical galaxies will eventually produce a large elliptical galaxy.

Starburst galaxies are especially bright in infrared light.

The rate at which supernovae explode in a starburst galaxy that is forming stars 10 times faster than the Milky Way is about 10 times higher than in the Milky Way.

9.3 Assignment 12

9.3.1 Dark matter

- Effects the orbits of stars and gas, causing faster motion than we can account for
- Stellar masses only account for most of the total mass close to the center of a galaxy
- total mass - luminous mass - mass of hot gas = dark matter
- Two main options
  - Ordinary - made of protons, neutrons, electrons. Simply can't be detected
  - Extraordinary - weakly interacting massive particles (WIMPs). Mysterious netruino-like particles. This is the best bet
- There isn't enough ordinary matter to explain ordinary dark matter
- Evidence:

  - Masses measured for galaxy motions
  - Temperature of hot gas (can be used to determine mass of galaxy)
  - Gravitational lensing

- WIMPs can't collapse because they don't radiate away their energy. They helped proto-galactic clouds collapse without collapsing themselves
- Dark matter lumps the universe together; accounting for expansion, galaxies are being drawn together into chains and sheet.

A rotation curve is a plot showing orbital speed versus distance form the center.

- Rigid disk = proportional
- Solar system = decreasing exponential
- spiral galaxy = increases as you move away from the center then levels off

Rotation curves show us that instead of velocity decreasing as you move away from the center of a galaxy, it increases, or remains constant. Both indicate that more mass is contained within the orbit than we would expect

- $v = \sqrt{\frac{M_r * G}{r}}$
- M_r = encircled mass
- r = radius of sphere containing the mass

Definitions

WIMPS: subatomic particles that have more mass than neutrinos but do not interact with light
Baryonic matter: Matter made from ordinary atoms
Gravitational lensing: The effect made when a massive object distorts the light coming from objects behind it

9.3.2 Dark Energy

Galaxies are expanding at an ever-increasing rate. This is impossible if gravity is the only force involved as it would cause the speed of galaxies to decrease.

The energy causing this repulsion is called dark energy.

Critical density: The average density of the universe such that:
density $<$ critical density $\Rightarrow$ the universe expands at an ever decreasing rate, but never stops.
density $>$ critical density $\Rightarrow$ the universe stops expanding the collapses.

If a critical universe has an average density of one, our universe is ≈ 0.3. So it should be coasting.

Dark energy makes it so that instead of the rate of expansion slowing, it is actually increasing. This also gives us the **oldest** model of the universe.

The is the age of the universe that would occur from each situation is ordered from youngest to oldest. Youngest = recollapsing, critical, coastingg, accelerating = oldest.

Dark energy fills the void needed to explain why CMB says the universe is flat.

9.3.3 Gravitational Lensing

The object being lensed is more widely separated when the object doing the lensing is

1. more massive
2. closer to the Earth

9.3.4 Eras of the Universe

Era Name	Description	Ended After	Final Temp.
Planck	all 4 forces operated as one	$10^{-43}s$	10^{32} K
GUT	strong electroweak forces unit as GUT force	$10^{-38}s$	10^{29} K
Electroweak	3 forces operated: gravity, strong, electroweak	$10^{-10}s$	10^{15} K
Particle	Protons, neutrons both common	$10^{-3}s$	10^{12} K
Nucleosynthesis	fusion create helium nuclei	5 minutes	10^{9} K
Nuclei	H, He nuclei and electrons existed, no neutral atoms	380,000 years	3000 K
Atoms	Neutral atoms existed, but not stars		
Galaxies	Stars and galaxies common		

The Planck era was the hottest era, the galaxy era the coolest.

9.3.5 Cosmic microwave background

In the era of nuclei electrons were free, and photons bounced among them. Once the age of nuclei ended the electrons were captured, and finally able to travel freely. The temperature of the universe was about 3000 K at this point and was the peak wavelength. Since then the wavelength has been decreasing linearly with the expansion of the universe.

Wavelength of CMB $\propto$ relative expansion of the universe.

The CMB has a perfect thermal radiation spectrum. Since it was originally all contained in a small area, where temperature and density could equalize.

Current temperature of the CMB is approximately 2.73 K.

10 Formulae and Values

Our solar system was formed 4.5 billion years ago, when about 2% of the galaxy's original Hydrogen and Helium had been converted to heavier elements. Thus the cloud which formed our galaxy was roughly 98% Hydrogen and Helium. The 2% of other materials form the core of the rocky planets in our systems, ie. the Earth.

The **Andromeda galaxy** is roughly 2.5 million light-years away and about $100,000$ light-years in diameter. **Sirius**, the brightest star visible in the night sky, is 8 light-years away. **Alpha Centauri**, the closest star system to our own (a three star system), is 4.4 light-years away.

- $E_k = \frac{1}{2}mv^2$
- $v = \lambda f$
- Energy $= hf = \frac{hc}{\lambda}$
- $v_{\text{radial}} = \frac{\Delta\lambda}{\lambda}\ c$
- $F = G\frac{m_1 m_2}{r^2}$
- $p^2 = \frac{4\pi^2}{(M_1+M_2)*G}\ a^3$ (in our solar system years^2 = A.U.^{3})
- $L = 4\pi^2 R^2 \sigma_{SB} T^4$
- Angular separation (rad) $= \frac{\text{semi-major axis (AU)}}{\text{distance parsecs}}$
- $r_{\text{planet}} \approx r_{\text{star}} * \sqrt{\text{fraction of light blocked}}$
- Eccentricity of an ellipse: $e = \frac{f}{a}$ where f is the distance from the center to a focus
- momentum $=$ mass $*$ velocity
- $\text{SA}_{\text{sphere}} = 4\pi r^2$
- $\lambda_{\text{peak}} T = 2.898 * 10^{-3} m \cdot K$
- Time dilation: $t' = t * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- Length contraction: $l' = l * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- Mass increase: $m' = \dfrac{m}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$
- Angular size, physical size, and distance are related as $\frac{l_{angular}}{360} = \frac{l_{physical}}{2\pi d}$
- $v = \sqrt{\frac{M_r * G}{r}}$
  - M_r = encircled mass
  - r = radius of sphere containing the mass