SCI 238 — Introduction to Astronomy
Final Notes

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Contents

1 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.

1.1 White Dwarfs

1.1.1 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**

1.1.2 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.

1.1.3 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 $1.4M_Sun$ 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.

1.1.4 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.

1.2 Neutron Stars

1.2.1 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.

1.2.2 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.

1.2.3 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.

1.3 Black Holes

1.3.1 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:

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

1.3.2 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.

1.3.3 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.

1.3.4 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.

1.4 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.

2 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.

3 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. bf 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.*

3.1 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.

3.2 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.

3.3 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.

3.4 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.*

3.4.1 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.

4 Chapter 17: The Beginning of Time

4.1 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.

4.1.1 Conditions of the Early Universe

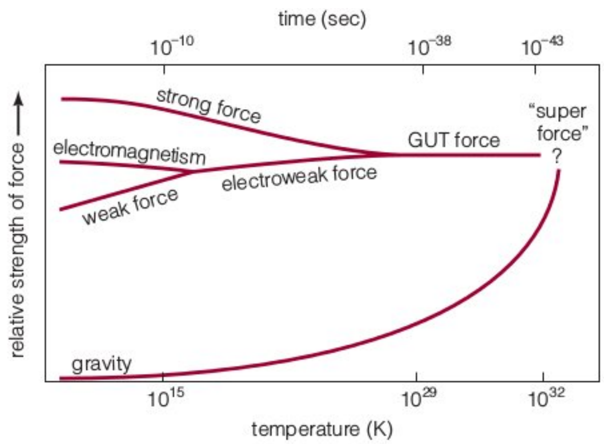
During the first few seconds the universe was so hot that photons could transform themselves into matter and back. When two photons collide with energy twice that of a electron (its mass times c^2*) they make a electron (matter) and positron (antimatter). When these two meet they annihilate each other 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)*

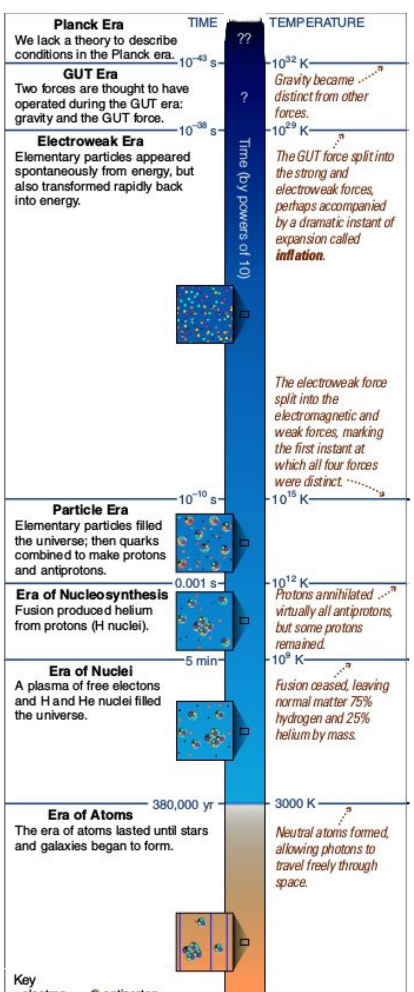
- *Electromagnetism: holds particles together (dominant on atoms and molecules)*
- *Strong nuclear: holds atom nucleus together*
- *Weak nuclear: deals with fusion and fission*

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.



4.1.2 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.*

4.2 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.*

4.2.1 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).*

4.2.2 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.

4.3 Inflation

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

4.3.1 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.

4.3.2 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.*

4.4 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.*

5 Assignments

6 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.

7 Assignment 12

7.1 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 protogalactic 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

7.2 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.

7.3 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

7.4 Eras of the Universe

Era name	description	ended after	t
Planck	all 4 forces operated as one	$10^{-43}s$	
GUT	strong electroweak forces unit as GUT force	$10^{-38}s$	
Electroweak	3 forces operated: gravity, strong, electroweak	$10^{-10}s$	
Particle	Protons, neutrons both common	$10^{-3}s$	
Nucleosynthesis	fusion create helium nuclei	5 minutes	
Nuclei	H, He nuclei and electrons existed, but no neutral atoms	380,000 years	
Atoms	Neutral atoms existed, but not stars		
Galaxies	Stars and galaxies common		

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

7.5 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.

8 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** $= hf = \frac{hc}{\lambda}$
- $v_{\textbf{radial}} = \frac{\Delta\lambda}{\lambda}\ c$

- $F = G\frac{m_1 m_2}{r^2}$
- $p^2 = \frac{4\pi^2}{(M_1+M_2)*G}\ a^3$ **(in our solar system years^2 = A.U.^{3})**
- $L = 4\pi^2 R^2 \sigma_{SB} T^4$
- **Angular separation (rad)** $= \frac{\textbf{semi-major axis (AU)}}{\textbf{distance parsecs}}$
- $r_{\textbf{planet}} \approx r_{\textbf{star}} * \sqrt{\textbf{fraction of light blocked}}$
- **Eccentricity of an ellipse:** $e = \frac{f}{a}$ **where f is the distance from the center to a focus**
- **momentum** = **mass** $*$ **velocity**
- $\textbf{SA}_{\textbf{sphere}} = 4\pi r^2$
- $\lambda_{\textbf{peak}} T = 2.898 * 10^{-3} m \cdot K$
- **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**