SCI 238 — Introduction to Astronomy
Final Notes

Kevin James, Eric Pemberton, Lara Janecka, Nik Klassen, Tyler Babaran

Winter 2015

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 $1.4 M_S un$ 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.

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 Assignments

5 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.