ASTRO 2 In-Class Notes

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Updated May 4, 2011

Contents

1 Introduction to Cosmology: Where Did It All Come From?

This question has bothered mankind since prehistoric times. Why is there something instead of nothing? How did the universe come to be as it is now? The scientific pursuit of the answers of these questions is the study of the field of Cosmology. Over time, scientists have developed the tools of rational thought and science to help us answer these deep questions.

1.1 More specific Questions

- Is the Universe evolving?

- If so, how and when did it form?

- How big/old is the universe?

- How/when did galaxies/stars/planets form?

- Is there extraterrestrial life in the Universe?

1.2 Physical Cosmology

Cosmology is not an isolated science. Indeed, we use all the tools of physics to probe the nature of the universe. These tools are being used to probe even the most unknown topics in Cosmology, including the mysterious dark matter and dark energy. However, cosmology is unique in that we only have one universe to study. We cannot have a "control" universe and other universes to play around with in experiments. We are terribly limited by our position in space and time to study the universe. All data we gather is gathered from the here and now, on Earth and during our life time, which is very short on astronomical scales.

1.3 Telescopes as Time Machines

Light travels at a finite speed, so light that arrives on Earth was emitted from its source some time ago. Thus, the further away an object is, the further back in time we are looking when we view the object in a telescope. That being said, objects can only be seen at a *specific* time in their life time. We must then look at many galaxies at different points in their lives to figure out how galaxies and the universe have evolved in time. This is not unlike reconstructing a family history from a series of photographs taken at different times.

This is done by using telescopes that probe in all different wavelengths, not only the visible. Right now we are in a golden age of telescope varieties. The Chandra telescope is probing the sky for radiation in the X-Ray spectrum. The Spitzer Space Telescope is probing in the infrared, and Hubble is probing in the visible. In the near future, the James Webb telescope will be probing in an even wider range of wavelengths.

1.4   The Evolution of Cosmology

Cosmology is an ever-changing field of study. The ancient Greeks once believed that the Earth was at the center of the universe. However, observations have now made that theory difficult to support. Every year new discoveries similarly challenge and change our view on the universe. In 1929, Edwin Hubble proved that the universe was expanding, which was before an unheard of idea. In more recent years, this expansion was found to be *accelerating*, giving rise to dark energy. This notion is still not well-understood, and is analogous to throwing a ball in the air and having it accelerate upwards out of Earth's gravitational field.

Galileo's observations of sunspots proved that the heavens change in time. Hubble showed that the universe is not static. Measures of gravitational accelerations have shown that there is a massive form of matter that does not interact with regular matter (dark matter). Our view of the universe is in a constant state of flux.

1.5   The Dilemma of Cosmology and Cosmological Principles

We are only able to make measurements from Earth... this is not an ideal situation from a scientific point of view. We'd like to change views to see what changes and what doesn't. This problem is "solved" by the Copernican Principle.

1.5.1   The Copernican Principle

We assume that Earth is not "special" in any particular way with regards to its position in the universe. In other words, our local sample of the universe is no different from more remote and inaccessible places. This is related to two more fundamental principles in physics:

- **Relativity:** The laws of physics (whatever they are) do not depend of space and time.

- **Occam's Razor:** Physical explanations of natural phenomena should be as simple as possible.

These are not proven by any means, but they seem a reasonable assumption since they have not been effectively disproven to date.

1.5.2   Homogeneity and Isotropy

An alternative way to state this principle is to assume that the universe is homogeneous and isotropic. That is, the universe is the same in any direction and in any location. This means that there is no "special" place in the universe. As has been shown in simulations, the universe appears to form a **cosmic web**. Matter and energy chunk together in filaments and form voids. So, on large enough scales, the universe looks the same in every place, but if we zoom in, filaments and voids will obviously be different. Thus, homogeneity and isotropy are valid in the *large-scale limit*.

1.5.3   Perfect Cosmological Principle

An outdated theory was the perfect cosmological principle. This principle assumed that the universe was homogeneous, isotropic, and *time-invariant*. However, observations have shown that the universe has indeed changed throughout time, so this is no longer a valid assumption in Cosmology.

1.5.4 Anthropic Cosmological Principle

The anthropic cosmological principle states that the fact that we exist to observe the universe makes now a special point in time. This more philosophical argument is sort of like quantum mechanics on steroids and can be used to explain some properties of the universe, but it is not a very accepted argument in physics.

March 31, 2011

2 Galaxies

2.1 The Size of the Universe

2.1.1 Our Place in the Universe

We reside in the Milky Way galaxy. Many people still today mix up the "Universe" with "The Milky Way." However, the observable universe is strictly larger, as it contains many *many* galaxies. In the past, though, this was not always clear.

2.1.2 From Nebulae to Galaxies

In older times, anything we now know to be a galaxy was simply regarded as a **nebula**, which comes from the Latin for cloud. Many of these were catalogued by the French astronomer Messier and put in his famous Messier catalogue, which is a list of things that aren't comets. It was actually a great debate as to how large these "nebulae" even were. In the 1920's, a debate between Harlow Shapley and Heber Curtis erupted as to the precise nature of nebulae. Shapley argued that they resided within our own galaxy (galactic) whereas Curtis argued that they were outside of our galaxy, as little island universes (extragalactic). Ultimately this argument went nowhere since simply looking at an object tells you nothing about its size or distance (without knowing either).

It was left to Edwin Hubble to solve this problem. Hubble discovered Cephid variables in M31. Since Cephid variables are standard candles (we *know* what its true luminosity is), he was able to calculate the distance to M31 by using flux arguments:

$$F = \frac{L}{4\pi d^2}$$

Example A Cephid in IC4182 has a period of 42 days and an apparent magnitude of $m = 22.0$ in the V band. From the period luminosity relation of Cephid variables,, we know that the absolute luminosity is $M = -6.5$ in the V band. If we recall the relationship between the apparent and absolute magnitude:

$$m = M + 5\log(d/pc) - 5$$

Inverting this equation, we get

$$d = 10^{0.2(m-M+5)} \, \text{pc}$$

So in this case, $d = 5 \times 10^6$ pc. □

Using this technique, Hubble discovered that M31 is 70 kpc across (comparable to the Milky Way) and 150 kpc away from us. Now we know that there are billions of such galaxies. In fact, in just one square degree (about the size of the moon in the sky), there are tens of thousands of visible galaxies. One need only point a large enough telescope in that direction. Overnight, people realized that the universe was many times large than they had ever thought.

2.1.3   An Idea of the Immense Size of the Universe

The universe is *much* bigger than the Milky Way, containing billions of galaxies, each one tens of kpc in size. In fact the visible universe is of order of gpc, or gigaparsecs, equivalent to *millions* of times that of the Milky Way.

2.2   Types of Galaxies

Hubble classified galaxies under a fairly general scheme. The two largest classes of galaxies are spirals and ellipticals. The spiral galaxies are further divided up into barred spirals and regular spirals. Unclassifiable galaxies are called irregular. Classifying galaxies by shape is called analyzing their **morphology**.

2.2.1   Elliptic Galaxies

Elliptic Galaxies are classified by how elliptic they appear to us in the sky. The roundest elliptical galaxies are called E0 galaxies. More elliptic galaxies (like E6) are more elliptic. The number is given by

$$n = \left(1 - \frac{b}{a}\right) \times 10$$

where a and b are the semi-major and -minor axes of the apparent ellipse in the sky.

It's also helpful to look at the spectrum of a galaxy to identify what elements are present in it as well as how hot or cold the constituent materials are. Elliptic galaxies emit a lot of redder light, implying that they are composed primarily of older stars. Additionally, elliptical galaxies have very little gas and dust in them.

2.2.2   Spiral Galaxies

Spiral galaxies have a central bulge and then spiral arms coming out from the center. Additionally, many (about 3/4) develop instabilities which manifest themselves as bars from the center. Spiral galaxies exhibit emission lines and have bluer light. This tells us that there are many young stars as well as interstellar gas and dust.

2.2.3   Lenticular Galaxies

Lenticular (S0) galaxies are more or less a "transition" class of galaxies between elliptical and spiral galaxies. They exhibit a central bulge, but they don't exhibit spiral arms. Instead, they are generally rotationally symmetric about their main axis. Popular theories of lenticular galaxies state that they may just be old, tired spiral galaxies.

2.2.4 Summary of Galaxy Types

Galaxies are not free to take on any shape they wish. They generally fall into one of four classes: spiral, elliptic, lenticular, or irregular, with Elliptic galaxies having older stars and spiral galaxies containing younger stars.

2.3 Structure of Galaxies

2.3.1 Rotational Support

The shapes of the galaxies are supported by rotation in spiral galaxies and pressure in elliptical galaxies. We can use the rotation rate to calculate a galaxy's mass via

$$\frac{GM}{R^2} = \frac{v^2}{R}$$

so

$$M(R) = \frac{v^2 R}{G}$$

Where $M(R)$ is the mass held within a radius R. We are often able to measure the speeds of stars in a galaxy via their doppler shifts, and then we can calculate the distance from the center via the small angle formula and other nifty tools.

2.3.2 Pressure Support

It has been found that Elliptical Galaxies are not rotating fast enough for rotational support alone to hold their shape. Instead, the pressure of the galaxy holds it in its shape, much like the air pressure in a balloon keeps it from collapsing. However, its not the gas and dust (of which there is very little) that is causing the pressure, but the actual movement of the stars.

From a spectrum, we can measure the pressure, σ, and from the distance, we infer the size rR. Then using the Virial Theorem, we obtain

$$M = \frac{k\sigma^2 R}{G}$$

where k is a constant of order unity that varies with the nature of the galaxy in question.

2.4 Type Ia Supernovae

2.4.1 Standard Candles

If we know the intrinsic luminosity of an object and we measure the apparent flux, we can obtain the distance to that object. Thankfully, there are certain objects whose luminosity we know, no matter where they are. These objects are called "standard candles." We have already seen one very useful variety of standard candles: Cephid Variables. These help us determine distances out to a certain distance, but we need more powerful tools to prober further out.

2.4.2 Conditions for a Type Ia Supernova

When a binary system consists of a white dwarf and a large companion star who has overvilled its Roche Lobe, material from the companion star flows onto the surface of the white dwarf. Eventually, the mass gets too high and the white dwarf exploades, causing a Type Ia supernova, which is a known brightness.

April 5, 2011

2.5 Cosmological Distances and Hubble's Law

In 1923, Hubble showed that M31 was 750 kpc away, but the question of how large the universe was was still wide open. Hubble continued to search for standard candles (typically cepheids) to find the distances to more and more galaxies. In this process, he began taking spectra to see what other galaxies were made of, and to his surprise, he found out that the galaxies he was measuring were all actually moving *away* from us!

2.5.1 Doppler Effect and Redshift

Hubble made this discovery by observing a doppler shift in the absorption and emission lines he observed, much in the way that when you hear a siren at a higher pitch than usual, you know it's coming at you and when it's heard at a lower pitch than usual, you know it's moving away from you. This same process applies to light, except that it appears redder (longer wavelength) when it is moving away from us and bluer (shorter wavelength) when it is moving towards us.

If we measure an absorption or emission line in the lab to be λ_0, but then measure the same line from a receding source to be λ, we define the **redshift** to be

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

for z much smaller than 1 (typically $z \leq 0.1$, the receding velocity is simply given by $v = zc$. For larger z, we use a relativistic formula:

$$v = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}c$$

where c is the speed of light.

2.5.2 Hubble's Law

Not only did Hubble find that most galaxies were moving away from us (redshifted), he also noticed that the further away they were, the faster they were receding. After studying many galaxies, he found that the redshift (or velocity) is proportional to distance, giving rise to **Hubble's Law**. That is, if you see two galaxies, and one is twice as far away as the other, than that galaxy is also moving away twice as fast as the other. Mathematically, the law takes on the form

$$v = H_0 d$$

where v is the recessional velocity and d is the distance to the galaxy. Hubble first measured the constant that now bears his name, H_0 to be around 500 km/s/Mpc, however current measurements show it being

$$H_0 = 73.8 \pm 2.4 \text{ km/s/Mpc}$$

Hubble's original measurement greatly overestimated the rate at which the universe was expanding. His mistake was largely due to using standard candles that weren't very standard. However, now that we have a better measurement of Hubble's constant, we can do a lot with it. It is arguably the most important number in cosmology. If we know the redshift of a galaxy, we effectively no how far away it is by the grace of Hubble's Law. Thus, astronomers tend to prefer to talk of velocities in terms of redshift rather than the more traditional means since redshift is what we actually measure. Worthy of note though is that redshifts don't measure speed in the general sense, but rather the rate at which the universe is expanding (i.e. objects aren't expanding throughout space away from each other, rather *space itself* is expanding).

That all being said we still do not have *that* precise of a value for H_0. We know it to within 3% of it's value (similar to you knowing your own height to within 3 inches of its actual value). Getting more accurate values for H_0 is an active area of research. Also worthy of note is that not *all* galaxies are redshifted. For instance, the Andromeda galaxy is actually moving *towards* us (and will collide with us in a few billion years). Hubble's law only applies on very large scales, between different clusters of galaxies.

2.5.3 Expansion of the Universe and the Meaning of the Hubble Constant

Hubble's law tells us that the universe is expanding. That is, all points in space are spreading out. It's not that galaxies are in motion through space all away from each other (they *are* moving, but in more or less random directions). Rather, space itself is expanding. Since the further we look, the faster galaxies are moving away from us, we know that the Hubble constant tells us about the age of the universe. In fact, a good estimate of the age of the universe is simply the inverse of the Hubble constant:

$$T_0 = \frac{1}{H_0}$$

April 7, 2011

2.6 Large-Scale Structure

Galaxies are not isolated. Instead, they tend to exist in groups, which we call... groups. For instance, the Milky Way is part of "The Local Group." Larger scale collections of galaxies are called clusters, or superclusters. This is a product of the tendency of matter to collect in clumps and filaments. Even a map of the sky shows galaxies existing prevalently on filaments that make up the cosmic web.

2.6.1 Morphology-Density Relationship

More often, very dense clusters typically have older galaxies. Thus, they are often yellower in appearance and consist largely of elliptical and lenticular galaxies. This relationship has been studied as a function of redshift, and it suggests that in the past, spiral galaxies were more prevalent.

It thus seems likely that younger galaxies are more typically spiral galaxies, which then combine over time to form inert elliptical galaxies.

2.6.2 Sizes of Clusters

Clusters are inherently gravitationally bound systems, but they do not rotate. Thus, they keep from collapsing by pressure, much like how elliptical galaxies keep from collapsing. And much like elliptical galaxies, we can measure the mass of a cluster via the Virial Theorem:

$$M = k\sigma^2 R/G$$

2.7 Galactic Collisions

Cosmic collisions happen on timescales of billions of years. Thus, we cannot understand how galaxies collide by studying one collision. Rather, we study many different galactic mergers all at different stages of colliding.

2.7.1 Effects of Mergers

One common feature of collisions is **tidal tails**, which are parts of the galaxies that are less affected by gravity and are thus dragged behind each constituent galaxy. Additionally, a **starburst** effect may occur, where the centers of the galaxies become overly dense, causing a sharp increase in star formation. Collisions can also cause dramatic changes in morphology, i.e. spirals merging into an elliptical galaxy.

2.7.2 Changes in Morphology

Collisions can also cause dramatic changes in morphology, i.e. spirals merging into an elliptical galaxy. It is presently thought that almost all elliptical galaxies were formed from the merger of spirals.

The field of galaxy mergers is still a very active area of research.

2.8 Dark Matter

We can determine the mass of a galaxy by observing the orbits of the constituent particles around the center of a galaxy by using Kepler's Third Law. Current measurements show that there is far more mass in galaxies than can be accounted for by ordinary means. There are two solutions to this problem:

1. **Dark Matter**: There is an extended halo of dark matter that we cannot detect by any means other than by noticing its gravitational effect

2. **Gravity Problem**: Perhaps our current understanding of the gravitational force is flawed.

2.8.1 Crash Course on Particle Physics

Most of the mass we encounter in our daily life is due to quarks, one of the fundamental particles. Most of matter is made of **baryons** (heavy particles like protons and neutrons) and **leptons** (lighter particles like electrons and neutrinos).

2.8.2 Dark Matter in Clusters

Most of the baryonic mass in clusters is hot gas. This gas does not have time to cool down on relevant time scales. We are able to then measure the presence of this gas via telescopes (Chandra, for example), since it emits X-Rays. However, baryonic mass only accounts for a very small fraction of the total mass of a cluster. One topic of discussion that kept Astronomers busy for a very long time is whether or not dark matter is baryonic.

2.8.3 Constituency of the Universe

73% of the energy of the universe is mysterious **dark energy**. Another 23% is made of cold dark matter. The reaming 4% is atoms.

April 12, 2011

2.8.4 Evidence: Gravitational Lensing

Recall that gravity is not really a force in the strictest sense. Rather, mass bends space around it. This in turn causes light to be curved around massive objects. This can cause the light from objects in the sky to appear to arrive from incorrect positions. Obviously the more massive an object is, the more it will bend light. This phenomenon is known as **Gravitational Lensing**.

Strong Lensing   Sometimes, this effect is so strong that a galaxy that is actually behind another galaxy will appear multiple times around the nearer galaxy. Effective the light has been bent around the galaxy via multiple different paths. This is called **Strong Lensing**. This is not at all unlike the effects of the stem of a wine glass on a source behind it. In that case, though, the differing index of refraction of the glass causes the refraction, not gravity.

Given a set of images from gravitational lensing, astronomers can measure the average image separation (average separation between mirror images). This, in turn, can be used to estimate the mass of the "lens galaxy." As it turns out, the mass of matter in the galaxy that we can detect alone cannot account for the degree of lensing that we see. This is further evidence for the existence of dark matter.

Weak Lensing   Suppose we are viewing a distant galaxy with no other galaxies in the way. There will still be some **Weak Lensing** due to ambient gravitational effect. This is manifested through shearing and slight bending of images. This tends to make a group of galaxies appear sheared tangentially, often forming ring-like structure, which tells us that there is some mass in the middle of the "ring" that is lensing the image.

2.8.5 The effect of Dark Matter and Gravitational Lensing on the Hubble Constant

Gravitational lensing is also a useful tool in measuring the size and age of the universe. This is done by using the fact that strong gravitational fields tend to "slow" down time. Thus, as light travels close to a lens, it takes longer than it normally would.

Sometimes with multiple images, we can see the same event at different times. This is because differences and path lengths cause light from the event to take different times to get to Earth. Shorter path lengths take less time, but often go through denser material, which slows the light down. This competition between the two effects can help us determine distances to galaxies and thus the size of the universe.

Recall the substructure problem, where we found that clusters and galaxies should look roughly the same (albeit on different size scales). There are two ways to explain this:

1. The Cosmological Model is wrong. Perhaps the assumptions we are using are simply not valid to explain how the universe works.

2. Dark Matter Satellites. Perhaps there are enough satellites of galaxies, but they are composed mostly of dark matter. Perhaps a supernova blew all of the gas and dust out of them and left only dark matter. In this case, gravitational lensing should be able to detect these. This is a relatively new area of research.

2.8.6 Candidates for Dark Matter: Machos and Wimps

Dark matter is not part of the standard model of particle physics. That being said, if neutrinos have even a little bit of mass, they could partially explain dark matter, but they cannot be the entire solution. One might ask whether or not we are even able to see all the ordinary matter that exists. There was indeed a debate in science years ago about whether or not dark matter was baryonic (made of protons, neutrons, etc.) or not. Obviously by Occam's razor, we'd prefer that dark matter be baryonic so that we don't have to introduce an exotic particle to the theory.

The Search for Baryonic Dark Matter Scientists have found warm intergalactic gas that accounted for some missing mass. It was detected by X-Ray telescopes and was not visible by conventional means, but it was not nearly enough to account for the missing mass. It's rather difficult to hide baryonic gas since they will emit and absorb light to a level we can detect.

MACHOs The only other option for hidden baryonic matter would be in compact objects like white dwarfs, neutron stars, brown dwarfs, or black holes. These objects are often called MACHOs, which stands for **MA**ssive **C**ompact **H**alo **O**bjects. For comparison, a white dwarf is about the size of Earth, despite having the mass of the sun. Neutron stars are also much more dense. However, there is not enough of these exotic objects to account for the dark matter. Similarly, we can detect brown dwarfs and the like, and they cannot account for the dark matter, either. Black Holes are much more difficult to detect since they themselves don't give off any radiation. Our only effective way to detect black holes is through a type of gravitational lensing called **microlensing**. They are such effective gravitational lenses, they brighten the objects the lens. After much study, though, it has been found that black holes, too, are unable to account for the dark matter.

WIMPs   An appealing solution to the problem is the existence of WIMPs (**W**eakly **I**nteracting **M**assive **P**articles). We say they are "weakly" interacting since they interact *only* through the weak nuclear force (i.e. they *don't* interact through the electromagnetic force, and thus, light). An alternative to WIMPs are massive neutrinos ("Hot Dark Matter"), but this idea has grown out of favor.

Scientists are currently conducting experiments underground to detect WIMPs by using Earth's natural shielding to prevent cosmic rays and other radiation from interfering with their experiments. So far, none have been discovered.

Neutrinos   We know that neutrinos are very numerous (several hundred per cubic centimeter). If they don't have mass, they don't oscillate between different types of neutrinos. However, we notice that they in fact do oscillate between different types, so they do have mass, but how much mass, we are not certain. However, we have determined an upper bound on the mass of a neutrino which forbids them from being a sufficient explanation for the dark matter problem.

Temperatures of Dark Matter   Cold dark matter would not be moving very fast, which allows for sufficient "clumping" of mass. Warm and hot dark matter move much faster, which would result in a smoother universe, which is not what we observe, so we tend to favor cold dark matter theories.

2.8.7   Another Option: A Misunderstanding of Gravity (MOND)

A theory that was popular in the eighties and nineties is MOND: **MO**dified **N**ewtonian **D**ynamics. This theory was a replacement of Newton's gravity that behaved differently in weak gravitational fields. It was a very elegant field that was proven wrong by experiment in an almost comically quick fashion. The basic idea behind MOND was that in the weak field, gravitational force is proportional to R^{-1} rather than Newton's normal R^{-2}. Unfortunately, this didn't work out.

Various examples, most notably the Bullet Cluster, shatter these theories by showing the dark matter mass not interacting in a cluster collision while interacting gases lingered in between the two resultant clusters. (Look up images and videos online to see how this works!)

April 14, 2011

3   Quasars, Active Galaxies, and Gamma Ray Bursts

An **Active Galactic Nucleus (AGN)** is the center of an "active" galaxy, that is, a galactic center with exceptionally bright and compact nuclear regions. The source of energy in an AGN is gravity, quite often in the form of a supermassive black hole. Things like blazars, QSO's, quasars, and radio galaxies are also common examples of AGN phenomena. These names are often annoying and pedantic, but we're stuck with them now.

3.1   Quasars

Quasars were first discovered in 1940 as powerful radio sources, though now we know that about 90% of them are not very radio loud. They were objects that appeared to be stars whose spectra

showed emission lines, which is quite strange, as most galaxies show absorption lines. Adding to the mystery was how these wavelengths were severely red-shifted. If these redshifts were in fact due to universal expansion, quasars had to be thousands of times brighter than the Milky Way.

In 1963, M. Schmidt found Hydrogen Ballmer lines with redshifts $z = .158$, confirming that the mysterious objects were indeed extragalactic. It was later found that, though they were very faint, each quasar resided in a host galaxy. If we discard the spectrum of the quasar, we recover the normal spectra of galaxies.

Since their discovery, we've discovered quasars up to $z = 6$. The presence of quasars peaked at about 2 billion years after the big bang, and declined sharply ever since. They aren't made much any more, likely due to the dramatically slowed-down star formation rate.

3.1.1 Variability of a Quasar

Quasars are are very variable. That is, the flux from a quasar changes on a day-to-day basis! This means that they must be very small objects, so that different parts of it can "communicate" with itself so it gives off a more or less uniform signal. This is because the relative time scale for changes must be longer than $\tau \sim D/c$ where D is the characteristic size of the object. This reflects the fact that no signal could travel from one end of the object to the other in any time less than τ.

3.1.2 Power Source of Quasars

In order to be this small and yet so luminous, the energy source driving it must be extremely efficient. Nuclear fusion can no longer account for this, so gravity must be powering these objects.

3.1.3 Seyferts and Radio Galaxies

Seyferts are dim, radio-quiet quasars that reside primarily in spirals. **Radio Galaxies** are large galaxies with a quasar at its center that is loud in radio. A common feature of radio galaxies are powerful jets that are collimated over distances much larger than the size of their host galaxies. These jets typically only last a few hundred millions years.

3.1.4 Emission Mechanisms

AGNs use two types of emission mechanisms: Blackbody radiation and synchrotron radiation. As we have studied before, the intensity of blackbody radiation will always peak at a certain wavelength and decline in either direction thereafter. Synchrotron radiation, however, has a linear relationship between intensity and frequency.

Gas spirals in towards a black hole, forming an accretion disk. The gas gets very hot and begins radiating black body radiation. Some particles are launched on the jets at relativistic speeds from the poles of the black holes. These jets are sometimes far more powerful than anything in the galaxy.

3.2 Unified Model for AGN

It has been asked whether or not all the different types of AGNs are completely different. The Unified MOdel of AGN posits that they are all indeed the same. The effects we observe differ only due to inclination effects. The standard AGN would then consist of a black hole, accretion disk, and jets. Depending on what angle we view the AGN, we observe different amounts of radio emission, jets, etc. However, some AGNs change in type from year to year, implying that inclination effects are not all that define how we see the AGN.

It is becoming evident that probably all galaxies contain a super-massive black hole. They are only active, then, for short periods of time. The black hole in the galaxy seems to exert a lot of control over the evolution of its host galaxy. As we know, the Milk Way itself hosts an extraordinarily dim, super-massive black hole at its center. This has been observed by noting the motions of stars very near the center of the galaxy.

3.3 Gamma Ray Bursters (GRBs)

GRBs are super-energetic *flashes* of gamma rays, not unlike what happens when nuclear weapons are detonated in the atmosphere. They come in two types:

1. Long-Duration (2-100 seconds)

2. Short-Duration (.01-2 seconds)

The distribution of GRBs is isotropic, suggesting that they are not in the disk of the Milky Way (we would expect them to be in the disk if they were nearby since that is where most objects in the Milky Way are located). Their nature remained elusive until 1997, when the first afterglow was detected. Absorption lines were measured with $z = 0.835$: the GRB was 7 billion light years away! Such afterglows are typically found in the outskirts of galaxies. Thus, we surmise they are related to some dramatic event in a massive star's life.

3.3.1 Source of GRBs

As it turns out, GRBs are powerful jets from dying stars. They are the result of **hypernovae**, which are extremely energetic supernovae. The event, which is a collapsar, emits an extremely powerful jet that we see only if it is pointed in our direction.

April 21, 2011

4 Cosmology

4.1 Philosophy of Scientific Theory

Modern science is all about proposing and testing theories. In fact, physics is often divided into two great realms: theoretical physics and experimental physics. Theorists try to create theories to explain observed phenomenon and to predict other properties of the universe. Experimental physicists, on the other hand, probe the properties of the universe through new experiments, giving

new problems to the theorists as well as testing the theories put forth.

Any good scientific theory must be logically self-consistent (it cannot contradict itself) that describes the behavior of a related set of natural or social phenomenon. For instance, Newton's three laws of motion are self-consistent and accurately predict and describe the motion of bodies through space. Any good theory must originate from (or be supported by) experimental evidence. A theory that is self-consistent but is untestable is not of high value (cough cough. . . string theory). Words we like to describe a good scientific theory are **predictive**, **logical**, and **testable**. No theory is permanent. They must be tentative, open to be included in a yet wider theory. For example, Newton's laws of motion are not quite correct, but quantum mechanics and general relativity reduce to Newtonian mechanics in the large and slow limit. Finally scientists typically prefer their theories to be simple rather than overly convoluted (Occam's Razor).

4.2 Olbers' Paradox

When we look up at the sky, we can mostly all agree that it is dark. Interestingly, this simple fact caused a great paradox in our understanding of the universe. This is because Newton had proposed that the universe was eternal and infinite. If it were not infinite (i.e. it had edges), gravitational attraction would eventually cause it to collapse. Since it is eternal and this has not happened, we infer that the universe must be infinite. He also assumed space to be flat (don't worry about what that means yet), and that time and space are independent quantities.

The problem with this is that since the universe is infinite and eternal, we should se stars wherever we look in the sky. Any line of sight must eventually reach a star, since the universe is infinite and eternal. Thus, the entire sky should be completely illuminated at all times with the infinite number of stars. Olbers' first noticed this paradox and proposed that there was some sort of cosmic fog that was drowning out light. However, we know that such a fog would absorb light and then re-emit it in all directions, so we would still see it (albeit perhaps at a different wavelength). Thus, this solution did not work.

4.3 The Big Bang

The solution to Olbers' paradox came in the form of the Big Bang theory. The key factor here is that the universe is finite in time in this theory. Thus, we can only see out as far as the distance light has had time to travel, solving the white-out problem. Additionally, a finite universe in time likely mandates that stars were not always shining during the entire history of the universe. Additionally, the big bang theory is consistent with the observed expansion of the universe.

4.4 The Age of the Universe

The age of the universe is given by $T_0 = 1/H_0$, which, after converting the units, gives a current age of about 14 Gyrs. These calculations can only be made accurate if we know how much mass and dark energy there is in the universe. For example, for a simple Einstein-de Sitter Universe (i.e. a closed Universe with no dark energy), the age of the universe is $2/3$ of that, so approximately 9 billion years. When we measure the age of Earth using carbon dating and other techniques, we see that it is no more than 5 billion years. Other tests show similar results for the sun. Even globular clusters, some of the oldest objects in the universe, don't show evidence of being older

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than 14 billions years old. We know this from studying the HR diagrams of these clusters and seeing where stars turn off the main sequence. Finally, even determinations of redshifts of the most distant galaxies don't reveal a discrepancy with the 14 Gyr value, adding to the pile of evidence in support of the big bang theory.

April 26, 2011

4.5   Evidence for the Big Bang

4.5.1   Singularities

When dealing with a **singularity**, we must conceive of something which is reduced down to a single point. In regular space, though, we have at least three spatial dimensions. How then, can something with three spatial points be reduced to a single point? We are not entirely sure how this happens, or even if that is what happens. In fact, quantum mechanics must be used to describe things on such small scales. Virtually all quantities are **quantized**, or broken up into sums of a very small quantity, called a **quantum**. A fundamental limit of time is the **Plank Time**:

$$t_p = \sqrt{\frac{Gh}{c^5}}$$

This quantization of space and time makes it difficult to talk about how something could become a singularity. A quantum theory of gravity is necessary to study such phenomena.

4.5.2   The Cosmic Microwave Background

The Cosmic Microwave Background (CMB) was detected on accident and is thought to be the leftover remnants of the radiation given off by the big bang. Interestingly, it was already present in data taken by Dnuham and Adams of the properties of CN in the interstellar medium back in 1937. They noticed that the CN was excited, giving an average temperature of 3 K everywhere in space, but they didn't realize what they had found, so they did not receive the Nobel Prize.

Early on in the universe, it was so hot that hydrogen and helium were in a plasma state. The radiation from the big bang was tied up in this plasma since radiation cannot travel easily through it. However, once conditions allowed for neutral atoms to form, the radiation was allowed to escape, showing us the surface of last scattering, which is what COBE and WMAP show us. A group of physicists (initially Alpher and Hermann, and then Dicke and his group at Princeton) had predicted such radiation, from the so-called big bang nucleosynthesis theory. The CMB was predicted to be thermal, at a temperature of about 5 K, and isotropic. Note, if it were anisotropic, this would indicate a preferred direction for the big bang, which would indicate a center of the universe, which makes no sense.

Big Bang as Thermal Blackbody Radiation   It was predicted that the CMB would be thermal, meaning it would show a blackbody spectrum, as given by Planck's Equation:

$$B_\lambda = \frac{c^2}{\lambda^5} \frac{1}{\exp \frac{hc}{\lambda kT} - 1}$$

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The COBE mission indeed found this result: the CMB had a blackbody distribution following the Planck formula. The temperature was found to be 2.725 K, which was very much in agreement with theoretic predictions.

Isotropy and Homogeneity   Recall that **isotropy** is invariance under rotation and **homogeneity** is invariance under translation. COBE told us that the universe is more or less isotropic, but it did not tell us that it was homogeneous. However, if the universe were inhomogeneous, the only way we would see isotropy in COBE would be if we were in the center of the universe. Thus, we invoke the Copernican principle, that is, Earth is not in a special place in the universe. Thus, we deduce that the universe is more or less homogeneous.

In truth, COBE did *not* measure complete isotropy. If it had, we would not expect galaxies to form since matter would have been completely evenly distributed. Instead, small fluctuations were found (on the order of .001% differences), indicating initial fluctuations in the density of the universe, allowing for the formation of galaxies, stars, planets, and us. Later on WMAP gave us a more detailed look at the CMB, and soon, the Planck mission will give us an even more detailed view of the CMB. Interestingly, a precise measurement of the CMB anisotropy tells us other properties like the geometry of the Universe.

4.5.3   Horizons and the Horizon Problem

Light travels at a finite speed, so we can only see to a finite distance, that is, the speed of light multiplied by the age of the universe (approximately). This is called the **cosmic horizon**. Since time moves on and the universe expands, horizons evolve. For example, if the universe is accelerating in its expansion, we would expect for things to move beyond our horizon. Given enough time, we would be very lonely in the universe, since all other objects would be outside of our horizon.

The Horizon Problem   We observe that two objects that are outside of each others' horizons (but within our own), that the CMB radiation is the same at both. However, these two points have never been **causally connected**, that is, light has not had time to get from one to the other. Thus, there is no reason to suppose that the temperature would be the same at both locations. The only way we know to explain this is through **inflation theory**, which states that at some point in the universe's history, space expanded at a speed faster than the speed of light. This does not violate relativity, since it is the expansion of space that is faster than the speed of light, *not* an object's velocity.

May 3, 2011

4.5.4   Chemical Composition of the Stars

The sun is made primarily of Hydrogen (74% by mass) and Helium (25% by mass). The rest of the sun is made of "metals", which is astrophysics talk for elements heavier than Helium. These make up the remaining 1% of the sun's mass. The interesting thing is that the amount of helium present is much higher than we would expect from fusion power alone. In fact, helium content in the entire universe is about 25% by mass, which appears to be too high.

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The big bang theory provides a solution to this problem by allowing helium to be produced during the big bang. While nuclei did start out as hydrogen nuclei (single protons), the early high temperature and pressure of the universe allowed for thermonuclear fusion to take place, forming much of the helium that we observe today. In fact, the big bang theory successfully predicts the correct abundances of all heavier elements.

We can find out when this happened by studying redshifts. During expansion, the radiation remained a black body, but wavelengths stretch by a factor of $1 + z$. At redshift z, a photon of wavelength would have a wavelength

$$\lambda = \frac{\lambda_0}{1 + z}$$

The relation between T and T_0 is then (omitting lengthy derivation)

$$T = T_0(1 + z)$$

We then have

$$T_{\text{He}} = T_0(1 + z_{\text{He}})$$

which then requires

$$1 + z_{\text{He}} = T_{\text{He}}/T_0$$

Since we know that $T_0 = 3$ K, we can plug in the temperature at which fusion occurs for T to determine that Helium fusion occurred up until $z = 1,000,000$. So we see that the big bang theory explains the abundance of Helium in the universe since early on, the universe was hot enough to support spontaneous fusion.

4.6 Matter Density of the Universe

We have encountered several types of matter/energy thus far: radiation, neutrinos, baryons, dark matter, and dark energy. We wish to know just how much of these there are in the universe.

4.6.1 Radiation

How much light is there in the universe? The well-defined value we already have is the energy density. From this we can compute the density of the CMB because it radiates as a black body. Using the Stefan-Boltzmann law, we get the mass density being

$$\rho_{\text{rad}} = 4\sigma T^4/c^3$$

Plugging in the known values for T and the constants c and σ, we get

$$\rho_{\text{rad}} = 4.6 \times 10^{-31} \text{ kg/m}^3$$

However, it's more convenient to write this down in terms of the critical density, which is the amount of energy and matter needed to close the universe, which is defined as

$$\rho_{\text{crit}} = 3H_0^2/8\pi G = 9.5 \times 10^{-27} \text{ kg/m}^3$$

In these units, our observed mass density is

$$\rho_{\text{rad}} = 4.8 \times 10^{-5}\rho_{\text{crit}}$$

Calling the ratio of the density to the critical density Ω_{rad}, we have

$$\Omega_{\text{rad}} \sim 5 \times 10^{-5}$$

This value, Ω_{rad} becomes useful in determining the shape of the universe, as we'll see.

4.6.2   Neutrinos

We have limits on the neutrino mass density which come from oscillations, which we've measured with some precision.

4.6.3   Baryons

People have counted the amount of mass in visible baryons. The inventory is taken from stars, planets, warm intergalactic gas that we can observe.

4.6.4   Dark Matter

We account for dark matter by observing gravitational effects and then accounting for what is due to baryonic matter. The remaining mass must be from dark matter. We estimate this by finding the ratio of dark matter to baryonic matter in clusters. This number is then assumed to be representative of all matter in the universe. Then this number is applied to the fraction of baryons to get $\Omega_{\text{dark}} = .23$.

4.6.5   Dark Energy

Most of the energy in the universe appears to be of a mysterious form called dark energy (largely because we don't understand it). Dark energy "repels" instead of attracting, and therefor causes the expansion of the universe to accelerate instead of slowing down. One form of dark energy is the cosmological constant (Λ), introduced by Einstein a long time ago, and this is a purely geometrical term... in other words, it need not be "something." Rather, it could just be a property of spacetime. According to measurements, we have $\Omega_{DE} = 0.72$.

4.7   Brief History of the Universe

We know the relative proportion os stuff in the universe nowadays. How do quantities scale with z? How does volume scale? Since volume scales as the third power of the length dimension, redshift affects it as

$$V = V_0(1 + z)^{-3}$$

As an example, at $z = 9$, the universe was

$$V = V_0(10)^{-3} = V_0/1000$$

So the universe was one thousandth the size it is now at $z = 9$!

Photons behave a bit differently though. There is an extra term of $(1 + z)$ to account for photon stretching. So we have

$$\rho_{\text{rad}} = \rho_{\text{rad},0}(1 + z)^4$$

and thus

$$\Omega_{\text{rad}} = \Omega_{\text{rad},0}(1+z)^4$$

Do to this extra term of $(1+z)$, we surmise that there was a time in the universe were radiation dominated the energy content of the universe. Nowadays, we see that matter dominates. There was necessarily a time when the two had equal contributions. Dividing the two contributions and setting them equal to unity, we see that at $z = 5,000$, the two had roughly equal contributions.

Interestingly, since the cosmological constant is... well... constant, it was not very significant long ago. In fact, it has only been relevant in recent times (z=.4, or 4 Gyrs ago). From now on, the cosmological constant will dominate the energy of the universe. This is somewhat remarkable since we don't usually assume we live in a special time or place, but this is indeed a special time as the cosmological constant is beginning to dominate.