**Cosmology**

Chapter 26

**What is Cosmology?**

- Cosmology is the study of the Universe
  - The Creation, Evolution, Nature, and Content
- We have discussed the Content of the universe all semester
- What about the creation and evolution (and very nature) of the universe?

**The Nature of the Universe**

- Why is the sky dark?
  - It shouldn’t be
  - This fact is sometimes called Olber’s Paradox
- If space is infinite and static then no matter which direction you look you should always run into some object.
  - Therefore the entire sky should be illuminated
  - Part of the solution is interstellar absorption

**What do we know?**

- We know that space and time are actually tied together as space-time
  - General Theory of Relativity
- We know that the universe is expanding

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*Note*

- The theories and ideas of cosmology seem really speculative and over the edge. With further careful examination, this is found not to be the case. Like other areas of astronomy, cosmology is filled with many interconnected, detailed observations.
Space-Time Review

- The General Theory of Relativity (1915)
  - Gravity and acceleration can’t be distinguished
  - Mass causes distortions in space-time
    - i.e. Gravity

Another way to say it...

- This led Einstein to the idea that gravity also effects clocks, lengths, etc.
- In this view gravity can be viewed as a bending or warping of space itself
- Far from any massive object space is flat
- Near massive objects it is bent into a ‘well’

A Static Universe

- Many Astronomers wanted a Static Universe
- Even Einstein wanted a Static Universe
  - General Relativity naturally predicts an expanding Universe

Expansion Questions

- What is expanding?
- How do we know the universe is expanding?
- Does it predict any observed Phenomena?

Expansion Answers

- What is expanding?
  - Space-time
- How do we know the universe is expanding?
  - The expansion of the Universe was found by Edwin Hubble in the 1920’s
  - Using redshifts (not Doppler)
- Does it predict any observed Phenomena?
  - Olber’s paradox is solved this way

Expanding Universe?

- What exactly is expanding?
  - Remember - General Relativity doesn’t treat space as rigid
- It is space itself which is expanding, not material expanding into space
- From our point of view it would be easy to say we are the center of the expansion
Expansion of Space

- What is it expanding into?
  - Nothing
- What is expanding?
  - Intergalactic space is expanding
  - Galaxies are not expanding in size
  - Regions of strong gravity aren’t expanding

Center of the Expansion

- However, every galaxy sees every other galaxy as moving away
- Each thinks they are the center

Expansion Effects

- The farther away a galaxy is, the faster it is moving away from us.

Cosmological Redshift

- Once upon a time there was a line on a balloon. It was a happy line. Then the balloon got blown up. Now the line was much bigger. It wasn’t so happy anymore…
- A photon travels through space
  - As it travels space expands and the photon’s wavelength is stretched out
  - This causes the photon to be redshifted
- This is called the Cosmological Redshift

Assumptions in our Models of the Universe

- Homogeneous
  - Every region is like every other region
  - This is true over large regions
- Isotropic
  - If you look in different directions you see the same things
  - This is a general statement
- Together these two constitute the Cosmological Principle
- There is no special location in space

Models

- Models that obey the Cosmological Principle have proven successful in matching observation
- General Relativity is based on the Cosmological Principle
- We will assume a homogeneous and isotropic Universe in all further discussions
- We will discuss the current leading scientific theory about the origin of the Universe: The Big Bang
The Big Bang
• From Hubble we learned that the Universe is expanding
• Remember the Crab Nebula
  – Astronomers ran the explosion back to its origin
  – We can do something similar with the Universe
• We can conclude that in the past all matter was confined in a smaller volume

In the Beginning…
"In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move."

In the Beginning…
• Point of Ultra-high density
  – To expand from here we explode... With a REALLY BIG BANG!
• In the 1940’s George Gamov made just such a suggestion

*Note*
• In 1950 Sir Fred Hoyle coined the phrase ‘Big Bang’ to describe the event. He did not like the idea because it implied a moment of creation and he was quite the agnostic
• It is interesting that Fred Hoyle was one of the minority of astrophysicists who didn’t believe in some form of the Big Bang Model

The Big Bang
• The Big Bang ‘explosion’ is not like the explosions we see on the Earth
• The Big Bang Explosion actually carried the space with it, we can only talk about the time since the Big Bang

When did the Big Bang Happen?
• From Hubble’s Law we know that:
  \[ v = H_0 \cdot d \]
  – \( v \) is the recessional velocity
  – \( d \) is the separation
• Or \( H_0 = v / d \)
When?
- In the Big Bang we start with two objects moving apart: they were together when the Universe began.
- We find $T_0 = \frac{d}{v}$
  - separation distance/recessional velocity
  - where $T_0$ = time since the Big Bang

When did the Big Bang Happen?
- Therefore $T_0 = \frac{1}{H_0}$
- If we use $H_0 = 72$ km/sec/Mpc we find a value for the age of the Universe of 13.6 billion years.
- There are a few troubles with this age...

Looking into the Past
- If we accept 14 billion years as the age of the Universe, then we can only see 14 billion lys into space.
- There is a sphere around us with a 14 billion ly radius beyond which we can't see.
- This sphere is called the *Cosmological Horizon*.
- The *Observable Universe* is located inside this sphere.

The Beginning of the Big Bang
- The Universe was a point of infinite density:
  - Sometimes called the *Cosmic Singularity*.
  - Time is meaningless before the Big Bang.
- The laws of Physics as we know them didn't start working until a short time after the Big Bang.

Planck Time
- $10^{-43}$ seconds old
- Energy and mass are equivalent according to Einstein:
  - Energy fluctuations must have generated a gravitational field.

Planck Era
- The time before the Planck time.
- We can't explain what happened in the universe during this time:
  - We can't link general relativity and quantum mechanics.
The GUT Era

- Four Forces govern the universe we live in
  - Gravity
    - Dominates large-scale action
  - Electromagnetic
    - Dominates chemical and biological reactions
  - Strong force
    - Binds atomic nuclei together
  - Weak force
    - Mediates nuclear reactions

ElectroWeak Force

- Under extreme circumstances the weak and electromagnetic forces become indistinguishable
- High temperature or energy
- Like water, ice, vapor

GUTs

- Theories that predict the merging of electroweak and strong forces
  - Even higher energies
- Some also believe in a SuperGUT that merges all 4 forces
  - Supersymmetry
  - Superstrings
  - Supergravity

*Note*

- Planck time marks the instant when gravity separates from the other 3 forces
- Gravity “froze out”

GUT Era

- Lasts until $10^{-38}$ seconds
- And the universe has cooled to $10^{29}$K
- At this point the strong force “freezes out”
  - It is possible that an enormous amount of energy is released at this point...
Inflation

• In $10^{-38}$ seconds parts of the universe the size of the nucleus of an atom grow to the size of the solar system

Electroweak Era

• Lots of intense radiation fills space
• Matter/antimatter pairs are spontaneously created and subsequently destroyed
• Expansion and cooling continue
  – Temp drops to $10^{15}$ K (100 million x hotter than core of sun)
  – Age = $10^{10}$ seconds
  – Electromagnetic and weak forces “freeze out”

Particle Era

• Photons and particles are equally represented
  – e-, neutrinos, and quarks
• Age 0.0001 seconds old
  – Temp too cool for quarks (confinement starts)
  – Protons and neutrons are created in excess
• At 0.001 seconds the Particle era ends and the temperature is $10^{12}$K

Era of Nucleosynthesis

• At this point the universe as existed for a time shorter than the blink of an eye
• Protons and neutrons attempt to combine
  – Universe is still too hot though
  – Only 25% stay combined (as He)
• Era ends at about 3 minutes
• Temperature is still $10^{9}$K
  – Density too low for fusion to continue

Era of Nuclei

• The universe is a HOT Plasma!
• Ages to 380,000 years
• Temperature is now 3000 K
• The Universe is NOW transparent
  – The photons left stream across the universe as the cosmic microwave background

Era of Atoms and Galaxies

• The universe is a sea of atoms and plasma that begin to form into protogalactic clouds
• At 1 billion years old the universe enters the Era of Galaxies

And now you know… the REST of the story….
Other Evidence

- Up until now we have talked about the Big Bang model.
- The expansion of the Universe is not enough to prove the Big Bang.
- Is there any other evidence that the Big Bang really happened?
- The answer begins at Bell Labs.

Radio Noise

- We will start our story just outside Princeton, New Jersey at the Bell Telephone Laboratories.
- In the 1960’s two physicists were working on communication satellites – Arno Penzias and Robert Wilson.
- They found an annoying background noise in the radio signal.

Left-overs

- Penzias happened to meet an astronomer who told him about *The Big Bang*.
- One of the side-effects of the big bang was left over radiation...(all that heat had to go somewhere).
- After comparing notes it was found that Penzias and Wilson had discovered the CMB.

What was the Noise?

- The story begins in 1945 with Ralph Alpher and Robert Hermann.
  - They proposed that the Early Big Bang must have been hot.
- In the 1960’s Dicke and Peebles decided that most of the He we see in the Universe could be formed in the early years.
What was the Noise?
- The Universe was very hot in the beginning
- As the universe expanded it also cooled
- What happens to photons as the universe expands?
  - Just how much are photons redshifted?
    - All the way to the microwave region
    - The temperature should be just a few K above absolute zero

Cosmic Microwave Background
- More Studies were done
- Other antenna’s were built
- Theory said the temperature of the CMB should be a few K above absolute zero
- The CMB should also be uniform
  - But what about the clumps needed for future galaxies?

COBE Satellite
- NASA launched a satellite in the early 90's
- This was the Cosmic Background Explorer or COBE for short
- It plotted the blackbody curve of the background
- The nearly perfect blackbody curve corresponded to a temperature of 2.726 K
- But COBE found other interesting features

Variation Found by COBE
- COBE found an interesting variation
- It is related to the motion of the Milky Way and the orbit of the Solar System
  - This causes slight red and blue shifts in the background radiation
- The temperature measurement allows us to prove that Dicke and Peebles were right about the He

Little Bumps in the Background
- The background is not completely isotropic
- COBE found very small, $10^{-4}$ K, in the background
- These are likely the seeds needed to build galaxies
  - This also helps prove WIMP’s exist

Inflationary Epoch
- Quantum ripples defined by the wavelength of the photon cause irregularities
- Irregularities are seeds for density enhancements
  - Unfortunately we don’t know the amplitude of the ripples…
Smoothness

• Seems logical
• But why do we have a uniform Temperature?
  – INFLATION!
• Equalized before inflation

A Tripod of Evidence for the Big Bang

• Hubble Law
  – Universally observed by all astronomers
  – The first great evidence of a finite universe?
• Cosmic Microwave Background
  – Observed right where predictions indicate
  – Variations fit Big Bang models well
• Predictions from Stellar Nucleosynthesis
  – Not enough He can be produced in early stars
to match observations