Lecture 27: Cosmology

Lecture Topics

- Colliding Galaxy Simulations
- The expanding universe
- Cosmology
  - The cosmological principle
- The Age of the Universe
- The Big Bang
Colliding Galaxies

- Sometimes galaxies get together
- Can result in
  - Burst of star formation (call a starburst) and/or
  - Funneling of material to a black hole at the center (activating an AGN)
- More modest mergers can occur which resort in the formation of larger galaxy or simple distort the disk of a galaxy (a with the merging of a small satellite into the host galaxy).
The Antennae (NGC 4038-39)

Stephan’s Quintet
The Expanding Universe

- Hubble compared the distances he measured for galaxies with their Doppler shift of spectral lines.
- He discovered that the universe is expanding!
  - Galaxies show redshifted spectral lines.
- The greater the distance, the higher the recession velocity.
Hubble’s law

Recession velocity is proportional to distance:

\[ v = H_0 \cdot d \]

\( H_0 \sim 70 \text{ km/sec/Mpc} \)

Distance and redshift

- Using Hubble’s law, the distance to a galaxy can be determined by its redshift, \( z \).

\[ z = \frac{\lambda - \lambda_o}{\lambda_o} \]

\( \lambda_o = \text{rest wavelength} \)

- Redshift resulting from the Hubble flow is often called the cosmological redshift.

- At low velocities, \( z \sim v/c \) (the Doppler effect).
Cosmology

- **Cosmology** is the study of the structure and evolution of the universe.

- On every scale observed so far the universe shows structure:
  - stars form star clusters and galaxies
  - galaxies form galaxy clusters and superclusters, and large structures

**Distribution of Galaxies on the Sky**
Galaxy Distribution

Large scale structure

- Structures ~ 200 Mpc in size are seen.
- This is much less than the most remote QSOs which are ~ 4000 Mpc distant.
  - Note this is estimated from the time for light to travel from the QSO to us – not strictly correct.
- The most extensive surveys cover only ~ 1/1000 of the observable universe!
  - Like trying to determine the appearance of the earth from a map of Rhode Island.
Structure of the universe (cont’d)

- A 300 Mpc cube anywhere in the universe contains ~100,000 galaxies.
  - excluding faint dwarf ellipticals and irregulars
- The total number of galaxies is roughly

\[
\frac{4\pi}{3} \left[ \frac{4000}{300} \right]^3 \times 10^5 \approx 10^9 \text{ galaxies}
\]

Better estimates give 125-150 \times 10^9 \text{ galaxies}

The Cosmological Principle

- Cosmologists make two assumptions known as the cosmological principle:
  1. The universe is homogeneous.
     - smooth on the largest scales
  2. The universe is isotropic.
     - looks the same in every direction
Homogeneous and Isotropic

- If a figure is isotropic from more than one point, it must also be homogeneous.

Deep Galaxy Simulation

Note: The Universe is not homogeneous and isotropic but it is in a statistical sense (that is, on average).
Lec 27: Cosmology

There is no center to the universe!

- Hubble’s law is very special.
- If we are galaxy A, the velocities are:
  
  ![Diagram showing velocities between galaxy A and B]

- What do people on galaxy B see?
  
  ![Diagram showing velocities between galaxy A and B]

- The same expanding universe!

Olbers’s Paradox

- For a static, uniform density, infinite universe the sky should be bright!
  
  - Everywhere you look you should see a star.

- Answer:
  
  - The universe is not infinite due to its finite age.
  - It is not unchanging in time.
In-Class Question – #1

The Cosmological Principle assumes that

a) Galaxies are moving away from us with a speed proportional to distance
b) The Universe is homogeneous
c) The Universe is isotropic

\[ \Rightarrow \text{d) b and c} \]

\[ \text{e) a, b, and c} \]

In-Class Question – #2

Assume Hubble's law is 75 km/sec/Mpc and a galaxy is moving away from us at 7500 km/sec. How far away is the galaxy?

\[ \text{a) 100 Mpc} \]
\[ \text{b) 150 Mpc} \]
\[ \text{c) 300 Mpc} \]
\[ \text{d) 7500 Mpc} \]
\[ \text{e) can't tell} \]

Hubble's law tells us that for galaxies:

\[ v = H_o \cdot d \quad \Rightarrow \quad d = \frac{v}{H_o} \]

\[ \Rightarrow \quad d = \frac{7500 \text{ km/sec}}{75 \text{ km/sec/Mpc}} = 100 \text{ Mpc} \]
The Age of the Universe

- Hubble’s law tells us that for galaxies:
  \[ v = H_0 \cdot d \]

- Since the universe is expanding, galaxies were closer together in the past.
- Extrapolating backwards, all the galaxies were on top of one another!
- When was this?

How it looks

![Graph showing the relationship between recession velocity and galaxy distance.](image)
Age (cont’d)

- If the Universe has been *expanding uniformly*, the distance a galaxy has covered (relative to each other) is:
  \[ d = vt \]

- So that the time to move this distance is:
  \[ t = d/v \]

- Using Hubble’s law we have:
  \[ v = H_o d \quad \Rightarrow \quad t = \frac{d}{H_o d} \quad \Rightarrow \quad t = \frac{1}{H_o} \]

Age (cont’d)

- Suppose \( H_o = 100 \) km/sec/Mpc, an estimate of the age of the universe is:
  \[ t = \frac{1}{H_o} = \frac{1 \text{ sec}}{100 \text{ km/sec/Mpc}} = \frac{1 \text{ yr}}{3 \times 10^7 \text{ sec/Mpc}} = \frac{10^6 \text{ pc}}{1 \text{ Mpc}} = \frac{3 \times 10^{19} \text{ km}}{1 \text{ Mpc}} = 10^{10} \text{ yr} \]

- Or
  \[ H_o = 100 \quad \Rightarrow \quad t = 10 \times 10^9 \text{ years} = 10 \text{ billion years} \]
  \[ H_o = 50 \quad \Rightarrow \quad t = 20 \times 10^9 \text{ years} = 20 \text{ billion years} \]
  \[ H_o = 71 \quad \Rightarrow \quad t = 14 \times 10^9 \text{ years} = 14 \text{ billion years} \]
Historical Measurements of $H_0$

![Graph showing historical measurements of $H_0$]

Today: 71 km/sec/Mpc

The Big Bang

- The present location and velocities of galaxies are a result of a primordial blast known as the **BIG BANG**.
  - THE BEGINNING OF THE UNIVERSE
  - THE BEGINNING OF TIME?!

- What is the BIG BANG?
  - The Big Bang was NOT an explosion in an otherwise empty universe.
  - The Big Bang involved the entire universe.
  - At the beginning the Big Bang happened everywhere at once.
Expansion of the Universe

- As the Universe expands
  - Galaxies move further apart
  - Photons “stretch” (get redshifted)
- The 2-D analog is an expanding sphere
- Thus the cosmological redshift we see is due to the expansion of space itself.

Simulation from Wayne Hu’s web page:
http://background.uchicago.edu/