Lecture 34: The Big Bang

Readings: Sections 28-3 and 28-6

Key Ideas:

Big Bang Model of the Universe
- Universe starts in a hot, dense state in the past
- Universe expands & cools with time

Cosmological Redshift & Lookback Time

Critical Density
- Determines the geometry of the Universe and its expansion history

Hubble Time
- Estimate of the Age of the Universe

Expansion of the Universe

Universe is observed to be expanding today
- Evidence: Hubble's Law

As the Universe *expands*, it *cools*

In the past, it must have been:
- Smaller
- Denser
- Hotter

than it is today….

The Big Bang

If we run the clock back far enough, eventually the Universe would be
- Very small and very high density
- Very, very hot and opaque.

This initial state must have existed at some *finite* time in the past.

We call this very hot, very dense initial state and subsequent expansion

THE BIG BANG

Foundations of the Big Bang

An infinitely dense & hot Universe in the past follows naturally from three basic *physical* assumptions:

1. General Relativity is valid on cosmic scales
2. The Universe is *homogenous* and *isotropic* on cosmic scales.
3. The energy of the vacuum is either zero or very small (the Cosmological Constant: Λ)

All of these assumptions are testable.

The Big Bang is Testable

These basic assumptions are plausible:

Supported by empirical data for the most part

Have a reasonably sound physical basis

But, they are not *required* to be true

Real Test:

Does the Big Bang Model explain the properties of the observed Universe?

Expansion & Hubble's Law

As the Universe expands:

Space gets stretched in all directions

Matter is carried along with expanding space.

The distances between galaxies get larger with time

The Big Bang predicts Hubble's Law exactly.

Cosmological Redshift

Expansion of space stretches light:

Wavelengths get stretched into redder wavelengths

The greater the distance, the greater the stretching

Result:

The redshift of an object gets larger with distance

The Big Bang naturally explains the observed Cosmological redshifts.

Cosmic Lookback Time

Light moves at a finite speed:

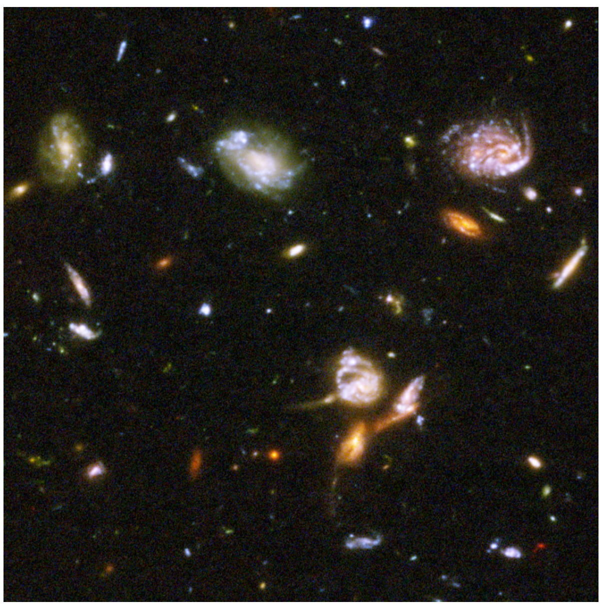
Takes time for light to reach you from a distant source.

Example, we see the Sun as it was ~8.5 minutes ago due to the light-travel time.

At cosmic distances:

The deeper we look into the Universe, the further we *look-back in time* to when the Universe was *younger & smaller.*

Very Distant=High Redshift=Very Young Galaxies



Credit: Hubble Space Telescope

The Shape of the Universe

All forms of matter *attract* each other via their *mutual gravity.*

Relativity tells us:

Energy & matter are equivalent ($E=mc^2$)

Matter & energy tells spacetime how to curve

The combined matter and energy density of the Universe determines its *global geometry.*

The Density Parameter: Ω_0

The geometry of the Universe depends on the total density of matter & energy

See Figure 28-15

<u>High Density</u>:
  Positively curved (spherical) geometry
<u>Low Density:</u>
  Negatively curved (hyperbolic) geometry
<u>Dividing Line:</u> Critical Density
  Universe is Flat: no curvature

$$\Omega_0 = \left(\frac{\text{average density}}{\text{critical density}}\right)_{Now}$$

critical density=density needed for a flat Universe

Geometry of the Universe

If $\Omega_0 > 1$: Positive curvature
  Finite & unbounded
  Spherical Universe
  Parallel light rays converge
If $\Omega_0 < 1$: Negative curvature
  Infinite, hyperbolic Universe
  Parallel light rays diverge
If $\Omega_0 = 1$: Critical, flat Universe
  Infinite, flat Universe
  Parallel light rays stay parallel

See Figure 28-15

<u>General Relativity</u>
  Matter and energy cause spacetime to curve
  Curved spacetime tells matter and light how to move

Bottom Line

Light follows different paths depending on the curvature of the Universe. This much be taken into account when viewing light coming from large distances.

Back to the Beginning

The Universe is expanding now.
In the past:
- Universe was smaller
- Galaxies were closer together in space

If we go back far enough in time:
- All galaxies (matter) in one place.

How far back=”Age of the Universe”

Road Trip Analogy

You leave Columbus by car for Florida, but leave your watch behind.
How long have you been on the road?
- Your average speed=100 km/h
- Your odometer reads: distance=230 km

Time since you left: time=distance / speed
- T=230 km / 100 km/h = 2.30 hours

The Hubble Time: T_0

Hubble’s Law says
- A galaxy at distance *d* away has a recession speed, $v=H_0 d$

If locally, *v* is its average speed, then
- $T_0 = d/v$
- But since $v=H_0 d$, $T_0=d/H_0 d=1/H_0$

HUBBLE TIME: $T_0 = 1/H_0$

Estimate of the Age of the Universe

But…

Cosmic expansion is not expected to be constant over all times:

If faster in the past

Expansion slowed by gravity of massive objects

T_0 would <u>overestimate</u> the age of the Universe

If slower in the past:

Accelerated by a non-zero cosmological constant Λ

T_0 would <u>underestimate</u> the age of the Universe

So, How Old is it Really?

Need two hard-to-measure numbers:

Hubble Parameter, H_0

How fast the universe is expanding *now*

Density Parameter, Ω_0:

How the matter & energy density affected the expansion rate in the past

Can include an Ω_Λ term that enhances the expansion rate

Needed to determine the *expansion history*

What is our Universe like?

Flat: $\Omega=1$ ($\Omega_m=0.3$, $\Omega_\Lambda=0.7$)

Accelerating: $\Omega_\Lambda=0.7$

Current expansion rate: $H_0=70\pm7$ km/sec/Mpc

Best Estimate of the Age:

14.0 ± 1.4 Gyr