

Cosmology



- The cosmological principle
- The expanding universe
 - Olbers's paradox
 - Big-bang
 - Redshifts
- The fate of the universe
- Age of the Universe
- The geometry of space
- The cosmic microwave background

Cosmology

- The study of the structure and evolution of the universe is Cosmology.
- The universe is
 -
- On every scale observed so far the universe shows structure:
 -
 -
 -

Large-scale Structures

- Structures ~ 200 Mpc in size have been seen.
- This is much less than the most remote QSOs which are over ~ 8000 Mpc distant.
- The most extensive surveys cover only ~ 1/1000 of the observable universe!
- A 300 Mpc cube anywhere in the universe contains ~100,000 galaxies.
 - excluding faint dwarf ellipticals and irregulars
- Recent estimates indicate the total number of galaxies are roughly 125-150 billion.

The Cosmological Principle

Cosmologists make two assumptions known as the *cosmological principle*:

1. The universe is *homogeneous*
 - at the very largest scales, the universe is uniform.
 - things are pretty much the same all over.
 - the same physical concepts apply everywhere.
2. The universe is *isotropic*
 - looks the same in every direction.
 - the universe has no preferred directions.

Note: These assumptions are based on sketchy data, theoretical insight, and philosophical preference

Implication of The Cosmological Principle

cosmological principle implies that:

1. there can be no edge to the universe

•

2. there is no center

•

No Center to The Universe

Hubble's law is very special.

☐ If we are galaxy A, the velocities are:



☐ What do people on galaxy B see?

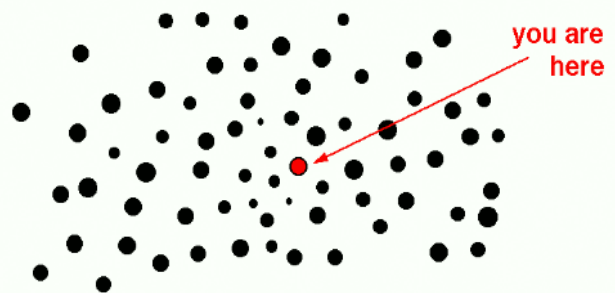


☐ The same expanding universe!

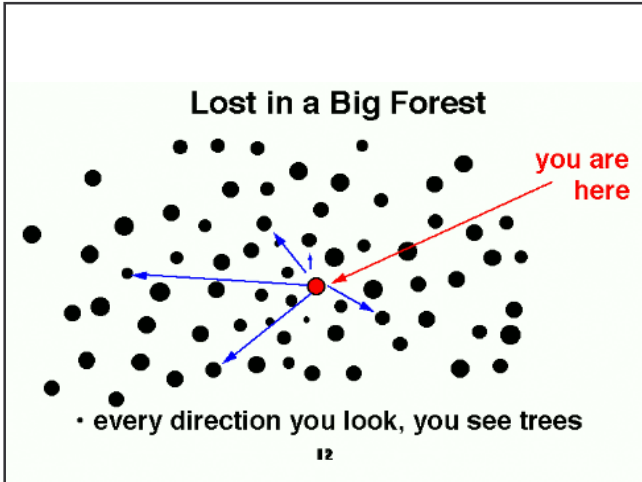
Olbers's Paradox

- ✓ Why is the universe dark?
- ✓ For a, static (unchanging), infinitely old, infinitely large, and uniform universe
 - the sky should be bright!
- ✓ Everywhere you look you should see a star.

Lost in a Big Forest



- everything is the same for a long way in all directions



Olbers's Paradox

The answer:

Expansion of Universe

Hubble's law:

- ∨ distant galaxies recede rapidly
- ∨ the greater the distance, the more rapid the recession

$$v = H_o \times d$$

- ∨ H_o is the Hubble constant = 65 km/s/Mpc
- ∨ Hubble's law must obey the Cosmological Principle.
- ∨ Everything must be expanding from everything.
- ∨ For example:
 - a loaf of bread with raisins
 - as the bread rises, the distance between raisins increases

Universe Expanding

In our example:

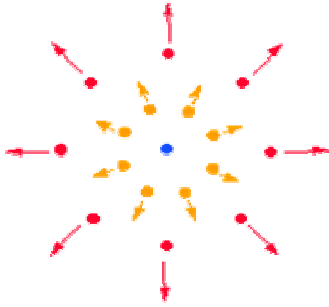
- ∨ the amount of expansion depends on the initial distance between raisins.
- ∨ the rate of expansion depends on the distance between raisins.

In the universe:

- ∨
- ∨

Expanding Universe

How it looks?



The Age of the Universe

Hubble's law tells us that for galaxies:

$$v = H_o \times d$$

- 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?

Time =

The Age of the Universe

□ Inserting Hubble law:

$$\text{time} = \text{distance} / (H_o \times \text{distance})$$

□ Suppose $H_o = 65 \text{ km/sec/Mpc}$, an estimate of the age of the universe is:

$$t = \frac{1}{H_o} = \frac{1}{65 \frac{\text{sec}}{\text{km}} \text{Mpc}} \times \frac{1\text{-yr}}{3 \times 10^7 \text{-sec}} \times \frac{10^6 \text{ pc}}{1 \text{ Mpc}} \times \frac{3 \times 10^{13} \text{ km}}{1 \text{ pc}}$$

$$= 15 \times 10^9 = 15 \text{ billions years old.}$$

But.....

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

- ∅ If the expansion were faster in the past:
 - Expansion would be slowed down by the gravity of all the matter and energy in the Universe.
 - T_0 would overestimate the age of the Universe.
- ∅ If the expansion were slower in the past:
 - Expansion might be accelerated by a non-zero cosmological constant (Λ).
 - T_0 would underestimate the age of the Universe.

The Big Bang

The present location and velocities of galaxies are a result of a primordial blast known as the **BIG BANG**.

It marked:

q
q

If we run the clock backwards far enough, eventually the Universe would be

- zero size and therefore infinite density
- infinitely hot

This initial state must have existed at some finite time in the past. We call this very hot, very dense initial state the "Big Bang".

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.

Look Back Times

- q As we look further out in the universe we are seeing it at earlier times!
 - It takes a long time for light to get here.
- q Telescopes are thus "time machines" which allow us to look at the early universe.

The Fate of the Universe ??

Will the Universe:

- expand forever
- stop
- reverse expanding and collapse

For better understanding of fate of universe the best analogy is:

Launch of a spacecraft from the surface of Earth (which depends on *escape speed*).

Escape Speed

For example: Consider a planet; shot a spacecraft from the surface (single shot)

Velocity higher
than escape
velocity.

object escapes

Velocity lower
than escape
velocity.

object does not escape

There are two options:

trajectory

At the escape velocity (intermediate between the high and low velocity cases) the spacecraft just escapes (**marginally bound**).

The Fate of the Universe

In our example,

Fate of a spacecraft depends:

- § on escape velocity
- § which in turn depends
- § gravity in turn depends on

Similarly,

Fate of Universe depends on:

§

Critical Density

If the density of Universe is:

- High:

- Small:

The *critical density*

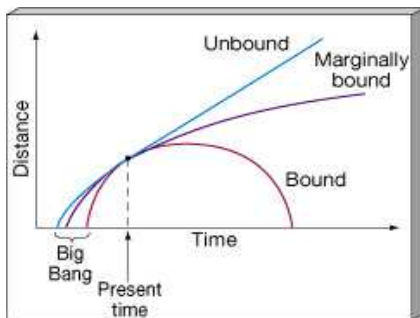
For $H_0 = 65 \text{ km/sec/Mpc}$:

§ Critical density $\sim 8 \times 10^{-27} \text{ kg/m}^3$, or about 5 H-atoms/m³

§ This corresponds to 0.1 Milky Way galaxy/Mpc³

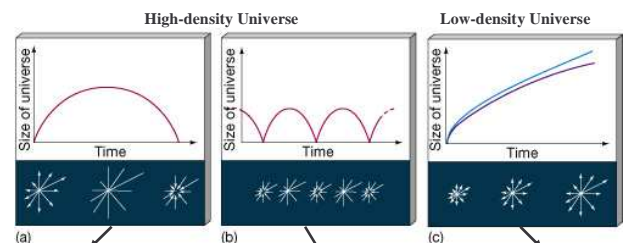
At critical density Universe will be **marginally bound**.

Possible Fate of the Universe



Based on density there are three possible Universes.

Possible Fate of the Universe



Big crunch: the entire universe will shrink towards a superdense, superhot singularity and experience a "heat death", in which all matter and life are destined to be burnt up.

Universe will "bounce" into a new phase.
Oscillating universe: no beginning no end.

Cold death: all radiation, matter, and life are eventually destined to freeze.

How to Determine the Future of Our Universe

For this we need to measure the average density of the Universe.

Scientists use *cosmic density parameter* (Ω_M):

§ Ω_M is defined as the ratio of the actual density to the critical density. Sometimes this is simply denoted by Ω .

Measuring Ω_M

For $H_0 = 65 \text{ km/sec/Mpc}$, Critical density is $\sim 8 \times 10^{-27} \text{ kg/m}^3$

And to determine actual density of universe there are two ways :

Galaxy Counts -

- Directly measure amount of mass in the universe.

Deceleration of the Universe -

- Measure how much faster galaxies were moving in the past.

Galaxy Counts

- ∅ Count galaxies within some large parcel of space.
- ∅ Adding up their mass and then dividing by volume of that space gives density of universe little less than 10^{-28} kg/m^3 .
- ∅ This yields $\Omega_M \sim 0.01$.
- ∅ But..... this misses most of the mass.
- ∅ Masses can be found from (gravity):
 - the motions of stars in galaxies
 - the motions of galaxies in clusters
- ∅ We can't "see" > 90% of the mass in the universe, except by gravity!
- ∅ Possible presence of dark matter:
 - MACHOs (Massive Compact Halo Objects)
 - WIMPs (Weakly Interacting Massive Particles)
- ∅ Correcting for the missing mass due to dark matter (that we know) gives $\Omega_M \sim 0.2$ to 0.35 . result → *Expanding universe*

Deceleration of the Universe

Assumption: rate of expansion should decrease.

- ∅ We need a "standard candle" to measure distances and recessional velocities independently.
- ∅ It is difficult to find a standard candle.
- ∅ Galaxies were different in the past.
- ∅ Type Ia Supernovae now appear to work very well. (Caused by accretion onto a white dwarf.)

A Funny Thing Happened ...

- Type Ia SN results indicate that the universe is accelerating!
Acceleration \Rightarrow the expansion rate is increasing
- Contrary to our initial bias that it should be decelerating
Deceleration \Rightarrow the expansion rate is slowing

Result again → *Expanding universe*

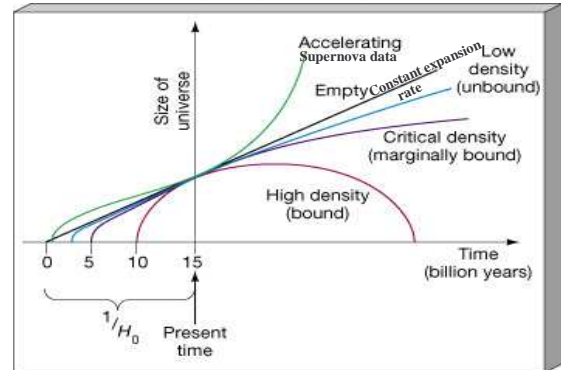
Possible cause of Acceleration

We still don't know the exact cause of acceleration of the Universe.

One possibility is: “vacuum pressure”.

- ∅ Vacuum pressure is the force associated with empty space and effective only on very large scales. Sometimes it is simply known as *cosmological constant*.
- ∅ Its influence increases as the universe expands.
- ∅ This is the repulsive force that acts against the attractive force of gravity.
- ∅ This pressure is caused by neither matter nor radiation, so it is simply referred as *dark energy*.
- ∅ Computer models including this force can fit the observational data though we still don't know its physical properties.

Age of the Universe (again)



Age of the Universe (again)

- For $H_0 = 65$ km/s/Mpc, the age of a critical-density universe without dark energy is about 10 billion years.
- This age estimate conflicts with the 10–12-billion-year ages of globular clusters derived from studies of stellar evolution.
- If there is no dark energy, then the density of the universe must be significantly less than critical, or Hubble's constant must be less than 65 km/s/Mpc.
- The inclusion of dark energy increases the age of the universe to 14 billion years, consistent with cluster ages.

The Shape of the Universe

- ∅ All forms of matter attract each other via their mutual gravity.
- ∅ Relativity tells us that:
 - Energy is equivalent to mass ($E=mc^2$), so all forms of energy in the Universe gravitate as well.
 - Matter & energy tells spacetime how to curve.
- ∅ The combined matter and energy density of the Universe determines its global geometry.

Curvature of the Universe

The geometry of the Universe depends on the total density of matter and energy:

$\Omega > 1$: High-Density Universe ()

§
§
§

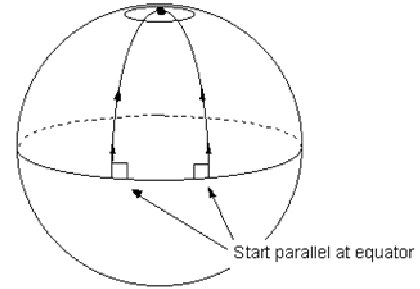
$\Omega < 1$: Low-Density Universe ()

§
§
§

$\Omega = 1$: Critical-Density Universe ()

§
§
§

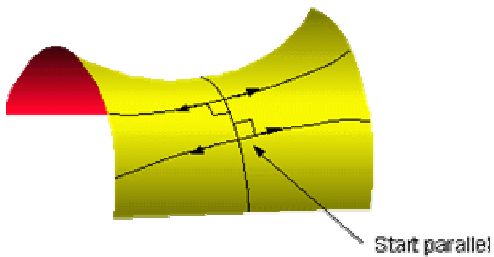
Sphere analogy with a Closed Universe



Parallel straight lines cross (converge)!

Space is curved so much that it bends back on itself and “closes off” making this bound universe finite in size.

Shape analogy with an Open Universe



Parallel straight lines diverge!

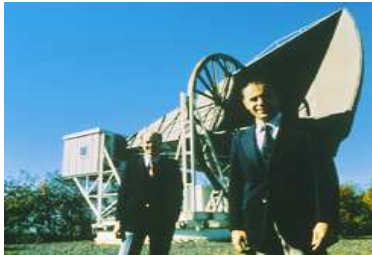
A low-density, unbound, saddle curved universe is infinite in extent.

How far back in time we can see?

Is there any way to study the universe beyond the most distant quasars?

Cosmic Microwave Background

Discovery: discovered by accident in 1964, by Arno Penzias and Robert Wilson (won Noble Prize in 1978).

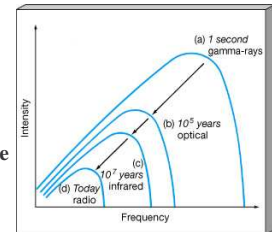


Prediction: predicted in early 1940s, a long before its discovery, by astronomers at Princeton University.

Cosmic Microwave Background

Origin:

- in the beginning universe was hotter.
- the gas temperature was about 10,000 K.
- with the expansion of universe, the initially high-energy radiation become redshifted to lower and lower temperature.
- its present temperature is ~ 3K.



The existence of CMB is direct evidence that universe expanded from a hot dense state (Big-Bang).

Possible Fates of the Universe

Let's give the last word to the obligatory poets...

- "Some say the world will end in fire.

Some say in ice.

From what I've tasted of desire

I hold with those who favor fire.

But if it had to perish twice,

I think I know enough of hate

To say that for destruction ice

Is also great

And would suffice.

" Robert Frost, *Fire and Ice* (*Harper's Magazine*, Dec 1920)

- "This is the way the world ends

This is the way the world ends

This is the way the world ends

Not with a bang but a whimper.

" T.S. Eliot, *The Hollow Men* (1924)

Thanks for collection of poems to:
Prof. W. Pogge (OSU)