Cosmology: The Origin and Evolution of the Universe
Chapter Twenty-Eight

1995

2002

Supernova 2002dd ($z = 0.95$)
Iclicker question

1. In the expansion of the universe, the expansion takes place
   A. only between objects separated by a vacuum; as a result, our bodies do not expand but the Earth-Moon system does.
   B. primarily in the huge voids between clusters of galaxies: "small" objects like galaxies or the Earth do not expand.
   C. only over distances about the size of a galaxy or larger; consequently, our galaxy expands but the solar system does not.
   D. between all objects, even between the atoms in our bodies, although the expansion of a person is too small to be measured reliably.
The expanding universe emerged from a cataclysmic event called the Big Bang

- The universe began as an infinitely dense cosmic singularity which began its expansion in the event called the Big Bang, which can be described as the beginning of time
- During the first $10^{-43}$ second after the Big Bang, the universe was too dense to be described by the known laws of physics
Time History of the Universe
Before recombination:

- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.
Primordial Nucleosynthesis: 1 second after the explosion - formation of Helium
After recombination:
- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent: Collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.
The microwave radiation that fills all space is evidence of a hot Big Bang.

The spectrum of the cosmic microwave background.

Blackbody curve for $T = 2.725$ K: the COBE data fit this with remarkable accuracy.

Each small square is a data point from COBE.
The background radiation was hotter and more intense in the past

- The cosmic microwave background radiation, corresponding to radiation from a blackbody at a temperature of nearly 3 K, is the greatly redshifted remnant of the hot universe as it existed about 380,000 years after the Big Bang.
- During the first 380,000 years of the universe, radiation and matter formed an opaque plasma called the primordial fireball.
When the temperature of the radiation fell below 3000 K, protons and electrons could combine to form hydrogen atoms and the universe became transparent.
Iclicker question

3. At an age of 380,000 years, the temperature of the universe had fallen to 3000 K, and electrons could then combine with protons to produce hydrogen gas instead of roaming freely through space. What major transition occurred as a consequence of this change in the universe at this time?

A. The universe would have lost its electrical charge suddenly to become electrically neutral.
B. The present laws of physics were applicable to the properties of the universe for the first time.
C. The universe became transparent to light for the first time.
D. Nuclear fusion no longer occurs below this temperature, and so, general fusion throughout the universe would have ceased.
Iclicker question

2. I thought that the Big Bang was hot! If the cosmic microwave background radiation is the radiation left over from the Big Bang, why then is it only 3 K?

A. The Big Bang itself was hot, but the temperature decreased as the universe expanded, and the temperature now is 3 K.

B. It is not from the Big Bang itself—it is from cold, intergalactic hydrogen clouds that are left over from the Big Bang.

C. The Big Bang itself was hot, but by the time the universe became transparent the temperature had already decreased to 3 K.

D. The Big Bang was not hot—its temperature was the same as we observe it now from the cosmic background radiation.
Iclicker question

4. The cosmic background radiation comes from a time in the evolution of the universe

A. when protons and neutrons were first formed.
B. when the big bang first began to expand.
C. when gamma rays had enough energy to destroy nuclei.
D. when electrons began to recombine with nuclei to form atoms.
The observable universe extends about 14 billion light-years in every direction from the Earth.

We cannot see objects beyond this distance because light from these objects has not had enough time to reach us.
• How the Universe went from a smooth particle soupe to a complex system of galaxy and large scale structure?

"Wrinkles"
or Hills & Valleys

Accumulation in Valleys
Careful analysis of COBE data showed that the cosmic microwave background radiation is not completely ISOTROPIC (fluctuations ~100 micro K) -> the radiation preserved a record of the variations of fluctuations of matter.
In 2001…new satellite: WMAP -> revealed the large-scale structure of the universe
Observations of temperature variations in the cosmic microwave background indicate that the universe is FLAT or nearly so, with a combined average mass density equal to the critical density.
If $\rho_0$ is greater than $\rho_c$, the density parameter $\Omega_0$ has a value greater than 1, the universe is closed, and space is spherical (with positive curvature)
If $\rho_0$ is equal to $\rho_c$, the density parameter $\Omega_0$ is equal to 1 and space is flat (with zero curvature).
If $\rho_0$ is less than $\rho_c$, the density parameter $\Omega_0$ has a value less than 1, the universe is open, and space is hyperbolic (with negative curvature).
The shape of the universe indicates its matter and energy content.

<table>
<thead>
<tr>
<th>Geometry of space</th>
<th>Curvature of space</th>
<th>Type of universe</th>
<th>Combined average mass density ($\rho_0$)</th>
<th>Density parameter ($\Omega_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>positive</td>
<td>closed</td>
<td>$\rho_0 &gt; \rho_c$</td>
<td>$\Omega_0 &gt; 1$</td>
</tr>
<tr>
<td>Flat</td>
<td>zero</td>
<td>flat</td>
<td>$\rho_0 = \rho_c$</td>
<td>$\Omega_0 = 1$</td>
</tr>
<tr>
<td>Hyperbolic</td>
<td>negative</td>
<td>open</td>
<td>$\rho_0 &lt; \rho_c$</td>
<td>$\Omega_0 &lt; 1$</td>
</tr>
</tbody>
</table>

- The curvature of the universe as a whole depends on how the combined average mass density $\rho_0$ compares to a critical density $\rho_c$. 
If the universe is closed, light rays from opposite sides of a hot spot bend toward each other ...

If the universe is flat, light rays from opposite sides of a hot spot do not bend at all ...

If the universe is open, light rays from opposite sides of a hot spot bend away from each other ...

(a) and as a result, the hot spot appears to us to be larger than it actually is.

(b) and so the hot spot appears to us with its true size.

(c) and as a result, the hot spot appears to us to be smaller than it actually is.
3 Kinds of Big Bang Universes

Two Dimensional Analogues

Curves back on itself (like the surface of a balloon)
High density of matter/energy

Uncurved
"Critical" density

Curved like a saddle
Low density

Our Universe
Flatness of the Universe

Matter Density: is only 0.27 of the critical density or 27% of the matter in the Universe
Dark Energy is 73% of the Universe!
Observations of distant supernovae reveal that we live in an accelerating universe.

- Observations of galaxy clusters suggest that the average density of matter in the universe is about 0.27 of the critical density.
- The remaining contribution to the average density is called dark energy.
- Measurements of Type Ia supernovae in distant galaxies show that the expansion of the universe is speeding up.
- This may be due to the presence of dark energy in the form of a cosmological constant, which provides a pressure that pushes the universe outward.
Accelerating Universe: 1998

Distant (high z) supernovae fainter than expected.

This was the AAAS discovery of the year in 1998.

Δ causes acceleration!
Data on velocity vs distance - 1929
Data on velocity vs distance-1995
Much better!
Universe #2 expands at a faster constant rate than Universe #1, so a galaxy at a given distance $d$ has a greater recessional velocity in Universe #2 than in Universe #1.
This graph corresponds to a universe that expanded more slowly in the past, so that the expansion has sped up.

This graph corresponds to a universe that expands at a constant rate.

This graph corresponds to a universe that expanded more rapidly in the past, so that the expansion has slowed down.
Cosmologist actually run computer simulations to track how matter collect into valleys.

$z = 28.62$
The best fit to the data is this curve: A flat universe with dark energy.

If data are in the blue area, the expansion of the universe is speeding up.

Each data point represents a particular Type Ia supernova.

If data are in the red area, the expansion of the universe is slowing down.

This curve assumes a flat universe with no dark energy. This is a poor fit to the data (distant supernovae are fainter than this curve predicts).
Iclicker question

5. Whether the universe is open, closed or flat depends on the ________ in the universe.
   A. luminosity of the matter
   B. density of matter
   C. temperature of matter
   D. radius of the big bang