Cosmology I

1995

2002

Supernova 2002dd
(z = 0.95)
1. What does the darkness of the night sky tell us about the nature of the universe?
2. As the universe expands, what, if anything, is it expanding into?
3. Where did the Big Bang take place?
4. How do we know that the Big Bang was hot?
5. What was the universe like during its first 380,000 years?
6. What is “dark energy”? How does the curvature of the universe reveal its presence?
7. Has the universe always expanded at the same rate?
8. How reliable is our current understanding of the universe?
The darkness of the night sky tells us about the universe – this is known as Olbers’ Paradox

- The Cosmological Principle
  - Most cosmological theories are based on the idea that on large scales, the universe looks the same from any location (this is known as homogeneity) and in every direction (this is known as isotropy)
- Speak of an edge to the universe?
  - Does it make sense?
- Speak of a center of the universe?
  - Does it make sense?
The universe is expanding

The expansion of the universe spreads the galaxies apart
The Hubble law describes the continuing expansion of space.

Six chocolate chips are evenly spaced within an unbaked cake.

Each chocolate chip has moved farther away from all the other chips.
(a) Five galaxies spaced 100 Mpc apart

(b) The expansion of the universe spreads the galaxies apart
The redshifts that we see from distant galaxies are caused by this expansion, not by the motions of galaxies through space.

A wave drawn on a rubber band …
The redshift of a distant galaxy is a measure of the scale of the universe at the time the galaxy emitted its light.

... increases in wavelength as the rubber band is stretched.
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
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.
The microwave radiation that fills all space is evidence of a hot Big Bang.

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 spectrum of the cosmic microwave background.
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.
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.
The abundance of helium in the universe is explained by the high temperatures in its early history.

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 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 $\rho_0$ 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).
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 ...

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

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

... and as a result, the hot spot appears to us to be smaller than it actually is.
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.
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
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.
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).
Gray area: No Big Bang (density of matter could never have been infinite)

Recent observations indicate that $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$.

The values of $\Omega_m$ and $\Omega_\Lambda$...

...must lie within the blue area to agree with Type Ia supernova data...

...and must lie within the green area to agree with cosmic microwave background data...

...and must lie within the brown area to agree with galaxy cluster data.

Red line: Universe expands at a steady rate

Solid black line: Boundary between perpetual expansion and eventual recollapse

Dashed black line: No dark energy ($\Omega_\Lambda = 0$)

Blue line: Universe is flat ($\Omega_0 = 1$)

This model, for which $\Omega_m = 1.00$, and $\Omega_\Lambda = 0.00$, has been ruled out by observations.

Expansion is speeding up

Expansion is slowing down

Universe expands forever

Universe recollapses

Universe is closed

Universe is open
Since about 5 billion years ago, the density of dark energy in the universe ($\rho_\Lambda$) has been greater than the density of matter ($\rho_m$).
Primordial sound waves help reveal the character of the universe

- Temperature variations in the cosmic background radiation are a record of sound waves in the early universe.
- Studying the character of these sound waves, and the polarization of the background radiation that they produce, helps constrain models of the universe.

Data points come from measuring the cosmic microwave background.

Several cosmological parameters can be determined by fitting the best theoretical curve to the data.
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Significance</th>
<th>Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble constant, $H_0$</td>
<td>Present-day expansion rate of the universe</td>
<td>$71^{+4}_{-3}$ km/s/Mpc</td>
</tr>
<tr>
<td>Density parameter, $\Omega_0$</td>
<td>Combined mass density of all forms of matter and energy in the universe</td>
<td>$1.02 \pm 0.02$</td>
</tr>
<tr>
<td>Matter density parameter, $\Omega_m$</td>
<td>Combined mass density of all forms of matter in the universe, divided by the critical density</td>
<td>$0.27 \pm 0.04$</td>
</tr>
<tr>
<td>Density parameter for ordinary matter, $\Omega_b$</td>
<td>Mass density of ordinary atomic matter in the universe, divided by the critical density</td>
<td>$0.044 \pm 0.004$</td>
</tr>
<tr>
<td>Dark energy density parameter, $\Omega_\Lambda$</td>
<td>Mass density of dark energy in the universe, divided by the critical density</td>
<td>$0.73 \pm 0.04$</td>
</tr>
<tr>
<td>Age of the universe, $T_0$</td>
<td>Elapsed time from the Big Bang to the present day</td>
<td>$(1.37 \pm 0.02) \times 10^{10}$ years</td>
</tr>
<tr>
<td>Age of the universe at the time of recombination</td>
<td>Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation</td>
<td>$(3.79^{+0.08}_{-0.07}) \times 10^5$ years</td>
</tr>
<tr>
<td>Redshift $z$ at the time of recombination</td>
<td>Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$</td>
<td>$1089 \pm 1$</td>
</tr>
</tbody>
</table>

*Values are from the first year of WMAP data. (NASA/WMAP Science Team)