Guiding Questions
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 Hubble law describes the continuing expansion of space
The redshifts that we see from distant galaxies are caused by this expansion, not by the motions of galaxies through space.

The redshift of a distant galaxy is a measure of the scale of the universe at the time the galaxy emitted its light.

A wave drawn on a rubber band...

...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.

The spectrum of the cosmic microwave background.

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

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

- 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 shape of the universe indicates its matter and energy content.

- 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).

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.
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
### Key Words

- average density of matter
- Big Bang
- closed universe
- combined average mass density
- compression
- cosmic background radiation
- cosmic microwave background
- cosmic light horizon
- cosmic singularity
- cosmological constant
- cosmological principle
- cosmological redshift
- cosmology
- critical density
- dark energy
- dark energy density parameter
- dark-energy-dominated universe
- density parameter
- era of recombination
- flat space
- homogeneous
- hyperbolic space
- isotropic
- lookback time
- mass density of radiation
- matter density parameter
- matter-dominated universe
- negative curvature
- observable universe
- Olbers’s paradox
- open universe
- Parsec
- plasma
- positive curvature
- primordial fireball
- radiation-dominated universe
- recombination
- relativistic cosmology
- spherical space
- zero curvature

### Table 28-2: Some Key Properties of the Universe

<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>73.7</td>
</tr>
<tr>
<td>Density parameter, $\Omega_m$</td>
<td>Combined mass density of all forms of matter in the universe, divided by the critical density</td>
<td>0.12 ± 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 ± 0.04</td>
</tr>
<tr>
<td>Density parameter for ordinary matter, $\Omega_b$</td>
<td>Mass density of ordinary matter in the universe, divided by the critical density</td>
<td>0.049 ± 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>0.75 ± 0.04</td>
</tr>
<tr>
<td>Age of the universe, $T_0$</td>
<td>Epoch time from the Big Bang to the present day</td>
<td>13.7 ± 0.2 × 10^9 years</td>
</tr>
<tr>
<td>Age of the universe at the time of recombination</td>
<td>Epoch time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation</td>
<td>13.7 ± 0.2 × 10^9 years</td>
</tr>
<tr>
<td>Redshift 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>1000 ± 1</td>
</tr>
</tbody>
</table>

*Values are from the latest WMAP data (NASA/WMAP Science Team)*