Exploring the Early Universe

Chapter Twenty-Nine

Guiding Questions

1. Has the universe always expanded as it does today, or might it have suddenly "inflated"?
2. How did the fundamental forces of nature and the properties of empty space change during the first second after the Big Bang?
3. What is antimatter? How can it be created, and how is it destroyed?
4. Why is antimatter so rare today?
5. What materials in today's universe are remnants of nuclear reactions in the hot early universe?
6. How did the first galaxies form?
7. Are scientists close to developing an all-encompassing "theory of everything"?

The Isotropy Problem

Our cosmic light horizon

Cosmic light horizon for A

Radiation from A takes 13.7 billion years to reach us

Cosmic light horizon for B

Radiation from B takes 13.7 billion years to reach us

Earth

A

B
The newborn universe may have undergone a brief period of vigorous expansion

- A brief period of rapid expansion, called inflation, is thought to have occurred immediately after the Big Bang
- During a tiny fraction of a second, the universe expanded to a size many times larger than it would have reached through its normal expansion rate

Inflation explains why the universe is nearly flat and the 2.725-K microwave background is almost perfectly isotropic
Inflation was one of several profound changes that occurred in the very early universe.

### Table 29.1: The Four Forces

<table>
<thead>
<tr>
<th>Force</th>
<th>Range</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>$10^{25}$ GeV</td>
<td>quarks</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$10^{16}$ GeV</td>
<td>photons and charged particles, radiation</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-2}$ GeV</td>
<td>quarks, electrons, neutrinos, radiation, weak decay</td>
</tr>
<tr>
<td>Gravitational</td>
<td>$10^{-35}$ m</td>
<td>everything, binding atoms, gravity</td>
</tr>
</tbody>
</table>

Four basic forces—gravity, electromagnetism, the strong force, and the weak force—explain all the interactions observed in the universe.

- Grand unified theories (GUTs) are attempts to explain three of the forces in terms of a single consistent set of physical laws.
- A supergrand unified theory would explain all four forces.
- GUTs suggest that all four physical forces were equivalent just after the Big Bang.

- However, because we have no satisfactory supergrand unified theory, we can as yet say nothing about the nature of the universe during this period before the Planck time ($t = 10^{-43}$ s after the Big Bang).
- At the Planck time, gravity froze out to become a distinctive force in a spontaneous symmetry breaking.
- During a second spontaneous symmetry breaking, the strong nuclear force became a distinct force.
- This transition triggered the rapid inflation of the universe.
- A final spontaneous symmetry breaking separated the electromagnetic force from the weak nuclear force; from that moment on, the universe behaved as it does today.
During inflation, all the mass and energy in the universe burst forth from the vacuum of space.

- Heisenberg’s uncertainty principle states that the amount of uncertainty in the mass of a subatomic particle increases as it is observed for shorter and shorter time periods.
- Because of the uncertainty principle, particle-antiparticle pairs can spontaneously form and disappear within a fraction of a second.
- These pairs, whose presence can be detected only indirectly, are called virtual pairs.

As the early universe expanded and cooled, most of the matter and antimatter annihilated each other.

- A virtual pair can become a real particle-antiparticle pair when high-energy photons collide.
- In this process, called pair production, the photons disappear, and their energy is replaced by the mass of the particle-antiparticle pair.
- In the process of annihilation, a colliding particle-antiparticle pair disappears and high-energy photons appear.
The Origin of Matter - Nucleosynthesis

- Just after the inflationary epoch, the universe was filled with particles and antiparticles formed by pair production and with numerous high-energy photons formed by annihilation.
- A state of thermal equilibrium existed in this hot plasma.
- As the universe expanded, its temperature decreased.
- When the temperature fell below the threshold temperature required to produce each kind of particle, annihilation of that kind of particle began to dominate over production.
- Matter is much more prevalent than antimatter in the present day universe.
- This is because particles and antiparticles were not created in exactly equal numbers just after the Planck time.

A background of neutrinos and most of the helium in the universe are relics of the primordial fireball.

- Helium could not have been produced until the cosmological redshift eliminated most of the high-energy photons.
- These photons created a deuterium bottleneck by breaking down deuterons before they could combine to form helium.
Galaxies are generally located on the surfaces of roughly spherical voids.

Galaxies formed from density fluctuations in the early universe.
Astronomers use supercomputers to simulate how the large-scale structure of the universe arose from primordial density fluctuations.
Models based on dark energy and cold dark matter give good agreement with details of the large-scale structure.

(a) Galaxy cluster Abell 1835

(b) IR 1916

IR 1916 cannot be seen at visible wavelengths... but is observable at longer wavelengths.

\[ \lambda = 540 \text{ nm} \quad \lambda = 1260 \text{ nm} \quad \lambda = 1650 \text{ nm} \quad \lambda = 2160 \text{ nm} \]

Determining the redshift of IR 1916.
Theories that attempt to unify the physical forces predict that the universe may have 11 dimensions

- The search for a theory that unifies gravity with the other physical forces suggests that the universe actually has 11 dimensions (ten of space and one of time), seven of which are folded on themselves so that we cannot see them
- The idea of higher dimensions has motivated alternative cosmological models

Key Words
- annihilation
- antimatter
- antiparticle
- antiproton
- cold dark matter
- cosmic light horizon
- density fluctuation
- deuterium bottleneck
- electroweak force
- elementary particle physics
- false vacuum
- flatness problem
- gluon
- grand unified theory (GUT)
- graviton
- Heisenberg uncertainty principle
- hot dark matter
- inflation
- inflationary epoch
- intermediate vector boson
- isotropy problem (horizon problem)
- Jeans length
- Kaluza-Klein theory
- Lamb shift
- M-theory
- nucleosynthesis
- pair production
- position
- quantum electrodynamics
- quantum mechanics
- quark
- quark confinement
- spontaneous symmetry breaking
- strong force
- supergrand unified theory
- theory of everything (TOE)
- thermal equilibrium
- threshold temperature
- virtual pair
- weak force